AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator

Karthik Mahadevan[1], Elaheh Sanoubari[2], Sowmya Somanath[3], James E. Young[2], Ehud Sharlin[1]

[1]University of Calgary, Canada, [2]University of Manitoba, Canada, [3]OCAD University, Canada

{karthik.mahadevan, ehud}@ucalgary.ca, {e.sanoubari, young}@cs.umanitoba.ca, ssomanath@faculty.ocadu.ca

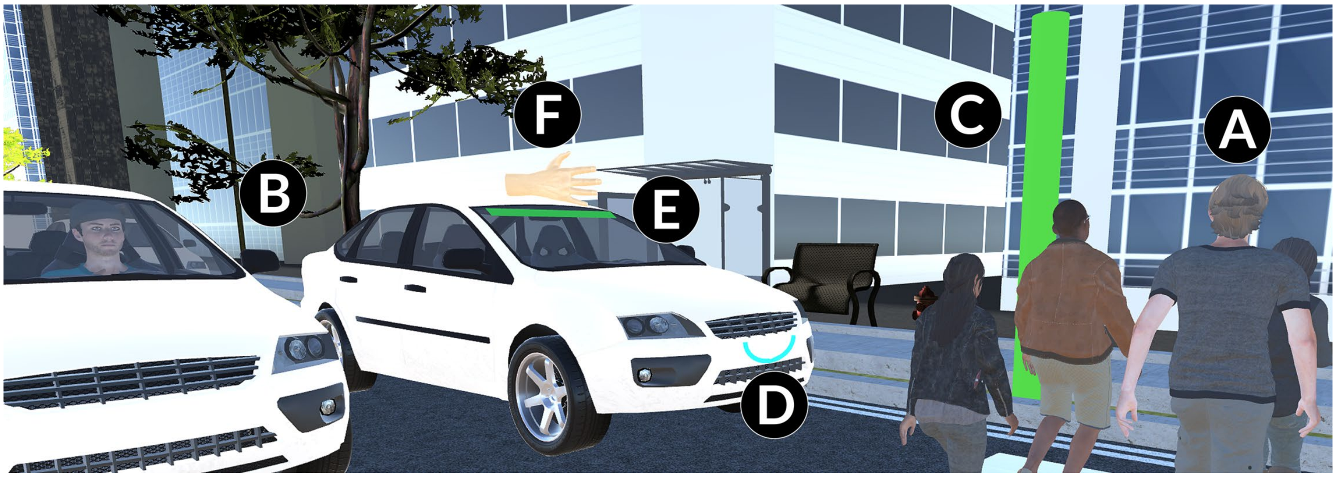

Figure 1: OnFoot: A VR pedestrian simulator designed to study AV-pedestrian interaction in mixed traffic. OnFoot simulates (A) other pedestrians, (B) AV and non-AVs, (C) street signals, and (D, E, F) interface cues communicating AVs' awareness and intent.

ABSTRACT

AV-pedestrian interaction will impact pedestrian safety, etiquette, and overall acceptance of AV technology. Evaluating AV-pedestrian interaction is challenging given limited availability of AVs and safety concerns. These challenges are compounded by "mixed traffic" conditions: studying AV-pedestrian interaction will be difficult in traffic consisting of vehicles varying in autonomy level. We propose immersive pedestrian simulators as design tools to study AV-pedestrian interaction, allowing rapid prototyping and evaluation of future AV-pedestrian interfaces. We present *OnFoot*: a VR-based simulator that immerses participants in mixed traffic conditions and allows examination of their behavior while controlling vehicles' autonomy-level, traffic and street characteristics, behavior of other virtual pedestrians, and integration of novel AV-pedestrian interfaces. We validated OnFoot against prior simulators and Wizard-of-Oz studies, and conducted a user study, manipulating vehicles' autonomy level, interfaces, and pedestrian group behavior. Our findings highlight the potential to use VR simulators as powerful tools for AV-pedestrian interaction design in mixed traffic.

DIS '19, June 23–28, 2019, San Diego, CA, USA

ACM ISBN 978-1-4503-5850-7/19/06…$15.00
https://doi.org/10.1145/3322276.3322328

Author Keywords

Autonomous vehicle-pedestrian interaction; mixed traffic; pedestrian simulator

CCS Concepts

• Human-centered computing ~ Virtual reality

INTRODUCTION

Making the decision to cross a street is a demanding task for pedestrians. Even in today's homogenous traffic where all vehicles have drivers, pedestrians may find street crossing difficult in dense traffic conditions where they may be unsure of the vehicle's next action and the driver's attentiveness. With the introduction of autonomous vehicles (AVs), a mixed traffic transition is expected wherein vehicles of all autonomy levels will occupy our streets [13, 31]. We expect mixed traffic conditions to pose challenges to pedestrians, drivers, and AVs, and to provide interesting interaction design opportunities.

At present, pedestrians have to focus on several elements while attempting to cross the street, including but not limited to traffic density, vehicle speed and distance, signals from drivers and vehicles [32, 33] and other pedestrians [23]. At unsignalized intersections, decision making can become more challenging as pedestrians have to rely heavily on vehicle and driver cues for their safety [22]. In mixed traffic, pedestrians will also have to gauge the awareness and intent of AVs which may be carrying distracted drivers or no drivers at all, further increasing the task difficulty.

To tackle the challenge of AV-pedestrian interaction, researchers have highlighted that it is important for AVs to communicate their *awareness* and *intent* to pedestrians using explicit interfaces [17]; that is, the vehicle acknowledging that it has seen the pedestrian, and providing cues on its next action. Past efforts were limited in scope to single vehicle-single pedestrian scenarios and stopped short of providing findings on ways in which AV-pedestrian interfaces may scale to complex mixed traffic scenarios [17] .

We are interested in pedestrians' decisions to cross streets when faced with mixed traffic. Past research has conducted naturalistic studies to examine pedestrian behavior in current homogenous traffic without AVs [25]. In contrast, AV-pedestrian research has primarily employed Wizard-of-Oz to provide the illusion of autonomous behavior [6]. Using Wizard-of-Oz to evaluate mixed traffic requires placing wizard-operated vehicles alongside manually-driven vehicles in real-world traffic conditions, which could be difficult and potentially dangerous for participants.

Parallel to past immersive driving simulators, we propose the use of pedestrian simulators in a novel context: the design and study of AV-pedestrian interaction in mixed traffic conditions. In this paper we present *OnFoot*: an immersive VR-based pedestrian mixed traffic simulator (Figure 1). OnFoot immerses pedestrians in mixed traffic conditions and allows researchers to examine their behavior in street crossing tasks while integrating novel AV-pedestrian interfaces and manipulating the autonomy level of the vehicles they encounter, the traffic and street characteristics, and the behavior of other virtual pedestrians. This paper outlines findings from three studies (design study, validation study, and mixed traffic study), and presents the OnFoot simulator and its use as an AV-pedestrian interaction design tool, enabling rapid prototyping and the safe evaluation of future AV-pedestrian interfaces in mixed traffic conditions.

RELATED WORK

The impact of mixed traffic on pedestrian behavior is mostly unexplored in the literature. We begin by pointing to a few instances of VR simulators that have recently been used to examine vehicle-pedestrian interaction both in current and autonomous traffic, which inspired the design of OnFoot. Then, we detail prior work on the factors influencing pedestrian behavior in current homogeneous traffic and overview some recent work that predicts future pedestrian behavior with the introduction of AVs. We considered these factors when designing mixed traffic conditions in OnFoot's simulation environment.

Pedestrian Behavior at Crosswalks

Rasouli and Tsotsos [23] provide an in-depth overview of the factors that affect pedestrian behavior at crosswalks based on research into traditional vehicle-pedestrian and AV-pedestrian interaction. They categorize these into pedestrian factors and environmental factors. Pedestrian factors include pedestrian demographics, state such as their speed, abilities such as their estimation of speed and distance, characteristics such as their culture, and social factors such as group size. Environmental factors include traffic characteristics such as vehicle size, dynamic factors such as vehicle speed, and physical context such as weather. Amongst pedestrian factors, social factors such as group size have been shown to be a strong influencer of pedestrian behavior [23]. Rosenbloom examined the behavior of individual pedestrians at a traffic light intersection and found that people were more likely to break a red light when standing alone than when they were in a group [28]. We hypothesized that group behavior could have a similar effect on individual pedestrian behavior in mixed traffic and included it as a variable in the OnFoot simulator design.

Vehicle Communication with Pedestrians

Of particular importance to vehicle-pedestrian interaction research is the study of the communication between vehicles and pedestrians. This communication includes two types of cues: driver or pedestrian cues such as eye contact and hand gestures [11, 24] and vehicle cues such as its speed and stopping distance [32, 33]. In the AV-pedestrian interaction literature (such as in [17]), communication has received special attention since AVs will not have a driver on board to provide pedestrians with driver cues when they consider crossing a street.

A subset of these works employ motion-based vehicle cues to implicitly communicate AV behavior to pedestrians [1, 26, 29, 34]. However, as Rasouli and Tsotsos point out, there is evidence supporting the use of explicit communication cues beyond vehicle motion, such as by augmenting the vehicle with additional interfaces [23]. Lagström and Lundgren placed an LED strip on a car's windshield and demonstrated that cues provided by the strip were useful for pedestrians making crossing decisions [15]. Mahadevan et al. placed interface cues of varying modalities such as visual and auditory cues, on the vehicle, the street, and the pedestrian [17]. They found that AV-pedestrian interaction could be improved by the introduction of such interfaces. Matthews et al. found that the use of an LED display with text and audio messages on a vehicle helped pedestrians understand the vehicle's intent and trust it more [19]. Prior work provides further support for the inclusion of interfaces in AVs, for example, by adding warning displays [16], or an LED strip on the vehicle [9].

There is also recent work aimed at designing communication interfaces for AVs through VR. Chang et al. prototyped animated eyes on a vehicle and found that it increased participants' feeling of safety and helped them make quicker crossing decisions [3]. Clercq et al. placed interface cues (such as an animated smile) on a vehicle and similarly found that it increased participants' perception of safety [5]. Most recently, Deb et al. placed visual and auditory cues on an AV in an attempt to identify favorable visual and auditory features to build future interfaces [8]. In line with these recent efforts, we used OnFoot to rapidly design, integrate and evaluate multimodal AV-pedestrian interfaces within the immersive pedestrian simulator.

Evaluating AV-Pedestrian Interaction

When evaluating AV-pedestrian interaction, researchers have most strongly leaned on Wizard-of-Oz to provide the illusion of autonomy during studies [4, 15, 17, 29]. For example, Mahadevan et al. assessed single vehicle-single pedestrian interaction by conducting their studies in a closed-off parking lot [17]. Lagström and Lundgren asked participants to stand at the curb and imagine being at an uncontrolled intersection [15]. With the recent availability of commercial-grade virtual reality headsets, it is now being used to study conventional vehicle-pedestrian interaction [2, 18, 20]. For instance, Deb et al. built a VR simulator and showed that it can offer an immersive study platform to study interaction from the perspective of pedestrian safety [7]. Recently, some researchers have begun using VR simulators to examine aspects of AV-pedestrian interaction. For example, researchers used VR to examine pedestrian attitude towards AVs [21], and the level of trust they demonstrate towards them [12].

Our work builds on these recent efforts, expanding them to support the simulation of complex mixed traffic conditions, pedestrian group behavior, and AV-pedestrian interfaces' design and integration. To our knowledge, OnFoot is the first pedestrian immersive simulator supporting mixed traffic conditions, group pedestrian behavior, and enabling the design, integration and evaluation of multimodal interfaces for AV-pedestrian interaction.

UNDERSTANDING MIXED TRAFFIC

Designing mixed traffic is difficult given the innumerable variables impacting a pedestrian's crossing decision. To better understand what impacts pedestrians' crossing decisions, we conducted a preliminary design study. Using a methodology inspired by Design Charrettes [27], we recruited 6 (male) participants in the ages of 18-35 through word of mouth and asked them to prototype paper sketches of mixed traffic. The session lasted an hour and included 30 minutes of sketching and 30 minutes of group discussion.

For the sketching activity, participants paired up into three groups of two. Each group designed for scenarios in which AVs co-exist in mixed traffic. Participants were given 10 minutes to sketch their designs after which they presented them and received feedback.

Participants could customize their designs by adding: 1) types of pedestrians (regular, elderly, child, visually-impaired, and hearing-impaired), 2) types of vehicles (attentive driver in manual vehicle, distracted driver in manual vehicle, semi-autonomous SAE level 3 vehicle with a driver on board [30], and SAE level 5 vehicle [30] without passengers, and with passengers), 3) types of crosswalks (signalized crosswalk, crosswalk with stop sign), and 4) communication interfaces. We provided participants sample interface designs based on those proposed by prior work from Lagström and Lundgren [15] and Mahadevan et al. [17], but participants were free to create their own interfaces. Figure 2 shows a sample design.

Findings

We found that participants incorporated communication interfaces (such as an LED strip) on all semi-autonomous vehicles (SAE level 3 [30]), and AVs (SAE level 5 [30], with and without drivers) in mixed traffic. The communication interfaces varied between designs and included visual, auditory, and physical modalities. Further, interfaces were located both on the vehicle and as part of street infrastructure. While these findings are in-line with past research proposing interfaces for single AV-pedestrian interaction [3, 15, 17], our design study findings suggest that interfaces may continue to be important for mixed traffic. More importantly, our findings hint that semi-AVs can also benefit from interfaces as the driver's actions may not be providing reliable cues on the vehicle's state, awareness and intent depending on the current autonomy level that is active.

DESIGNING AND VALIDATING ONFOOT

OnFoot is built using the Unity3D game engine and deployed on an Oculus Rift (Figure 1 and Figure 4). Informed by our preliminary design exercise and past literature, we designed the parameters of OnFoot (Figure 1). In our simulator we considered 19 factors under four categories. The initial set of variables relate to vehicle factors: vehicle autonomy, vehicle color, vehicle size, vehicle speed, vehicle slowdown characteristic at a crosswalk and stopping distance. The second set of variables relate to traffic and street characteristics: the number of vehicles on the street, traffic direction (one-way vs two-way), number of lanes, lane order of vehicles with different autonomy levels (fixed to specific lanes vs free flow), type of crosswalk intersection, type of street scene (rural vs urban environment), lighting conditions (day vs night), and weather (clear vs foggy). The third set of factors relate to pedestrians: group size, demographics, age and ability, and social norms. The final set of variables relate to interface prototypes for AVs as pro-

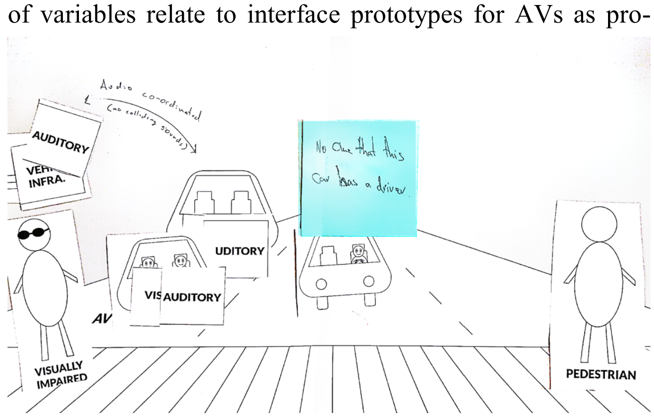

Figure 2: Sample design study outcome. The participant design shows a mixed traffic scenario where vehicles explicitly communicate with pedestrians through multimodal interfaces.

posed by Mahadevan et. al – vehicle-only, vehicle-street infrastructure, vehicle-pedestrian, and mixed [17].

In theory, OnFoot supports the manipulation of all these variables. However, from a practical standpoint, it is difficult to design a study that manipulates all of them, and so in practice we decided to first explore only a small subset of these factors based on evidence from past research on their importance. For instance, we were interested in group pedestrian behavior [23] and varied this in our studies. As mixed traffic is mostly unexplored in the literature, we varied the autonomy level of vehicles as a primary variable. We also varied the presence and type of AV-pedestrian interfaces to examine whether these interfaces, demonstrated to be effective in single AV-single pedestrian scenarios, would continue to be successful in supporting pedestrian crossing decisions in complex mixed traffic conditions.

Street and Traffic Characteristics

OnFoot's street environment includes a two-lane, one-way unsignalized street with painted lines and a yield sign (Figure 5). We can vary the number of vehicles in each lane as well as their autonomy level through a script that spawns them. Each lane currently contains vehicles of the same autonomy level (e.g. all SAE level 3 semi-AVs [30] reside in one lane). Manually-driven and semi-AVs occupy the lane closest to participants, making the driver easy to spot in VR (Figure 3). AVs could occupy either lane.

Vehicle Behavior

We opted to use a mid-sized vehicle in OnFoot as it is a commonly seen vehicle size on today's streets. We fixed its color to white to make it easy to spot in VR. Vehicle speed could be varied but was fixed at 50 km/h with small variations up to ±5 km/h to resemble organic traffic flow when multiple vehicles were on the road. To demonstrate mixed traffic, we added several vehicles to each lane. In mixed traffic, vehicles behind the front set of vehicles maintained a fixed following distance (~10 meters). When displaying stopping behavior, vehicles started slowing down when within 20 meters of the crosswalk, and fully stopped within 10 meters. When not stopping, vehicles maintained a fixed speed. These distances could be varied in OnFoot, while the car's AI is based on pre-set rules such as stopping at crosswalks or when spotting pedestrians.

We manipulated vehicles' autonomy levels in the mixed traffic study. Functionally, all vehicles in OnFoot drive in the same manner, but we modify the visual features of the vehicle to affect the perception of their autonomy level (see Figure 3). In manually-driven vehicles, we place a driver avatar in the vehicle. The driver performs one of two actions - scanning the road ahead through head and eye movement while in motion and initiating eye contact and initiating hand gestures with the participant when almost stopped. These actions are animations triggered based on the vehicle's distance to the participant. In OnFoot's current setting for semi-AVs (SAE level 3 [30]), the driver avatar stares at an electronic device at all times, regardless of whether the vehicle stops.

Pedestrian Characteristics

We placed AI-based virtual pedestrians (Figure 1) who crossed alongside participants in mixed traffic. Eight unique pedestrian models (varying in gender, ethnicity, and age) spawned near the participant in trials where we varied pedestrian behavior. We varied three conditions with respect to group pedestrian behavior. In the no-pedestrian condition, participants crossed the street by themselves. In the early crossers condition, the virtual pedestrians began crossing before vehicles fully slowed down at the crosswalk, while in the timely crossers condition, the virtual pedestrians waited until the vehicle almost stopped before crossing.

Interface Prototypes

We manipulated the presence (or lack thereof) of a communication interface in OnFoot. While several interface designs have been proposed in past work, we opted to test the mix of cue modalities (visual, auditory, and physical) and cue locations (on the vehicle, on the street, on the pedestrian) proposed by Mahadevan et al. [17]. Vehicle awareness was communicated upon seeing the pedestrian (fixed at 15 meters). When the vehicle planned to stop at the crosswalk, intent was communicated just before the vehicle fully stopped. We describe the AV-pedestrian prototypes we designed in OnFoot, below.

Vehicle-Only: incorporates a visual cue on the vehicle – an LED strip (Figure 1-E), and an auditory cue also on the vehicle. The LED strip shows 4 states: 1) red, indicating the vehicle is driving, 2) blue, indicating the vehicle sees a pe-

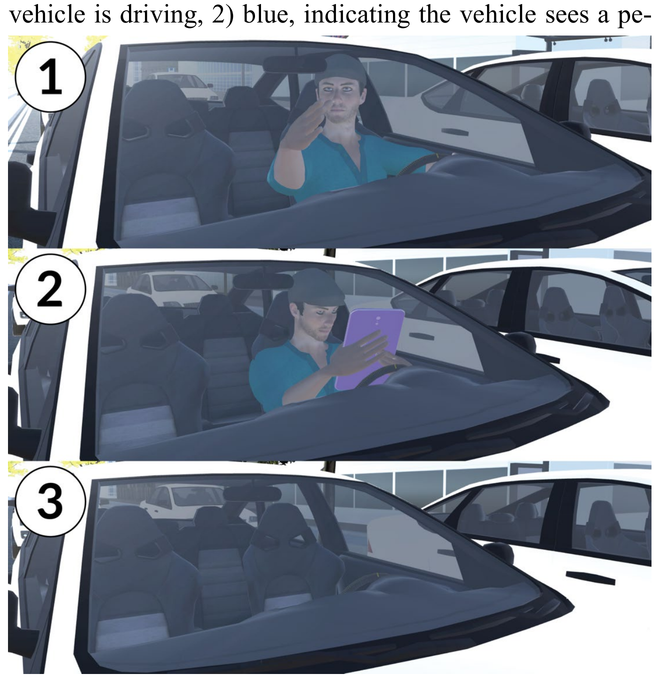

Figure 3: Vehicle autonomy levels: 1) Manually-driven vehicle with attentive driver, 2) Semi-autonomous (SAE 3) vehicle with distracted driver, 3) Autonomous vehicle (SAE 5).

destrian, 3) green, indicating the vehicle is about to stop, and 4) yellow, indicating the vehicle is about to start. After spotting a pedestrian, the strip remains blue until the vehicle is about to stop at which point it turns green. The audio cue accompanies these states by sounding a message, "stopping" if the vehicle is about to stop, and "starting" if the vehicle is about to start.

Vehicle-Street Infrastructure: incorporates a visual cue on the street – a street LED (Figure 1-C) and an auditory cue on the vehicle. The street LED has 3 states: 1) red, indicating it is unsafe to cross, 2) green, indicating the pedestrian can cross, and 3) yellow, indicating vehicles on the street will start driving soon. The auditory cue sounds the message "I see you" when the vehicle sees a pedestrian, and "cross" when it is safe for pedestrians to cross. The auditory and visual cues are triggered simultaneously but the audio cue only plays once.

Vehicle-Pedestrian: incorporates an animated face on the vehicle (Figure 1-D), and haptic feedback through a smartphone on the participant (Figure 4-B). The animated mouth exhibits two states: 1) fixed, with the mouth resembling a blank face when the vehicle is driving, and 2) smiling, indicated by a smile when the vehicle stops.

Mixed: incorporates a physical cue on the vehicle through an animated hand (Figure 1-F), a visual cue through a street LED (Figure 1-C), and an auditory cue on the pedestrian through the headset (Figure 4-A). The hand stays idle unless the vehicle is about to stop, at which point it moves from side to side to resembling the hand wave of a driver. The street LED works exactly as described in the vehicle-street infrastructure interface, and the auditory cue plays a message, "I see you" if the vehicle notices a pedestrian.

Validating OnFoot

To assess the validity of our OnFoot simulator as a viable testbed for examining AV-pedestrian interaction, we conducted a single AV-single pedestrian validation study with setups similar to prior published work done in VR [3, 5, 8], and using Wizard-of-Oz [4, 15, 17]. The setup involved participants standing near a virtual crosswalk and making crossing decisions in the presence of a single AV with and without communication interfaces. By using a setup similar to prior studies, arriving at similar results would help verify that the simulator environment was effective.

Participants. We recruited 10 participants in the age range of 18-35 (8 male, 2 female), who were all students from a variety of backgrounds including engineering and computer science. Participants were recruited through posters placed on our university campus and word of mouth. They received a remuneration of $10 for their participation.

Study Tasks. We designed two tasks – Task 1, to familiarize participants with our virtual environment, and Task 2 – the validation experiment. In Task 1, participants observed sample scenarios of an attentive driver, an AV without a driver, and an AV with a randomly selected interface.

In Task 2, participants encountered 7 scenarios. In each scenario, there were 2 trials - one where the vehicle stopped and another where the vehicle did not (giving a total of 14 trials). In scenarios 1 and 2, participants faced a vehicle with a driver on board who demonstrated attentive (Figure 3-1) and distracted (Figure 3-2) behaviors respectively. In scenario 3, participants encountered an AV without a driver on board or an interface (Figure 3-3). Scenarios 1-3 appeared in a fixed order. In Scenarios 4-7, participants saw each of the four interface prototypes described earlier in a balanced manner. We also randomized stopping and not stopping trials in each scenario.

Participants provided two metrics in each trial (Figure 6). They recorded their level of comfort in crossing (a continuous measure) and their decision to cross when the car approached the crosswalk (a discrete measure). Participants recorded their comfort scores using a slider in the OnFoot VR environment. The slider could be modified using the Oculus Remote (Figure 4-B), from a score of 1 (lowest) to 5 (highest). At the start of every trial, we reset the slider score to 3 indicating neither comfort nor discomfort. Participants also recorded their decision to cross using the Oculus Remote. We provided visual feedback on their decision through a button in the virtual environment, which was red (by default) and green when electing to cross.

Study Procedure. We began each OnFoot validation study session by collecting demographic information through a pre-study questionnaire. To ensure that participants were not highly susceptible of becoming sick during the VR experiment, we asked them to complete a simulation sickness questionnaire (SSQ) [14]. Upon verifying that their score was below the sickness threshold, we briefed the participant about the experiment and began the study.

Next, we introduced participants to Task 1, which lasted five minutes. After observing the sample scenarios, we asked participants to reflect on the similarities and differ-

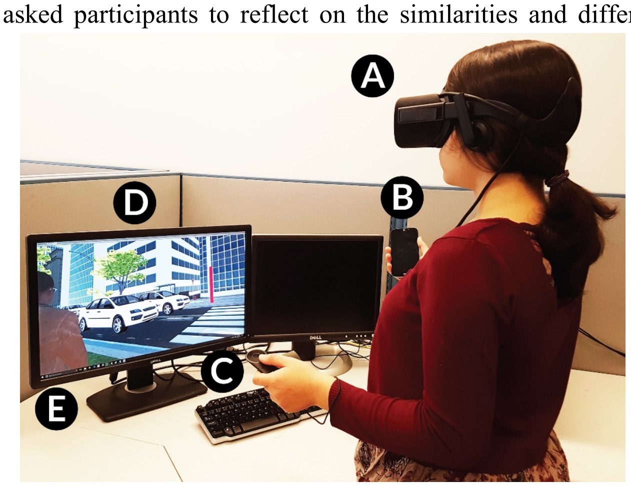

Figure 4: OnFoot Experimental setup: A – VR headset, B – Phone for physical cues (haptic feedback), C –Remote for providing comfort score and crossing decision, D – Virtual environment, E - Virtual pedestrians sharing the road with the participant.

ences between the real-world and the VR scene.

After Task 1, we introduced participants to Task 2 which lasted around 10 minutes. Figure 5-A shows a setup of the experiment. In each trial, a single vehicle spawned away from the participant, and during stopping trials, came to a stop in front of the crosswalk. The vehicle restarted after stopping for 5 seconds and drove away from the participant before respawning in the next trial.

At the end of the experiment, participants completed three questionnaires. We first elicited information about their confidence in the vehicle's awareness and intent through 5-point Likert questions. Next, we asked participants to list a cue they found most useful and a cue they found least useful for each scenario (of 7). Finally, participants filled out a questionnaire comparing the four interface prototypes against our baseline scenarios. Participants first compared the four interface scenarios against Scenario 1 (featuring an attentive driver) and then compared the four interface scenarios against Scenario 3 (an AV without a driver or communication interface). They also stated whether awareness and intent were more important to them. After filling out the questionnaires, we conducted a short semi-structured interview with participants asking them about their experience. Each study session lasted under an hour.

Findings. From the post-study interview, we learned that all participants acknowledged awareness and intent to be important factors that affected their crossing decisions, but 6 out of 10 participants mentioned that intent was more important. Due to potential interdependence between questions about participant confidence in vehicle awareness and intent (in the 7 scenarios), we ran a multivariate repeated measures ANOVA (with Bonferroni Correction to adjust for 7 scenarios). We found that using interfaces significantly increased how confident pedestrians were in the vehicle's awareness and intent (Wilk's $\lambda = 0.388$, $F(12, 106) = 5.357$, $p < 0.001$). Participants felt significantly more confident in *vehicle awareness* with the vehicle-only (M: 3.7) and the mixed interfaces (M: 3.9), compared to the no driver scenario (M: 1.5; $p < 0.001$ and $p < 0.004$ respectively). Participants also felt significantly more confident in *vehicle intent* with the vehicle-only (M: 4.0) and mixed interfaces (M: 4.1) compared to the no driver scenario (M: 2.0; $p < 0.008$ and $p < 0.008$ respectively).

For participant comfort score data, due to the correlated and unbalanced nature of the data, we employed a Generalized Estimating Equation (with Bonferroni Correction) to assess

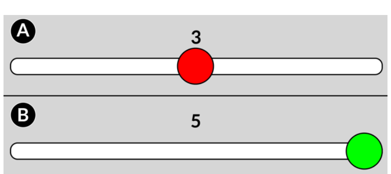

Figure 6: Slider used by participants in the OnFoot validation and mixed traffic studies, where: A – indicates comfort score of 3 and not crossing (red), and B – indicates comfort score of 5 and crossing (green).

Figure 5: Study setup, where A – VR simulator validation study with one vehicle, B – Mixed traffic evaluation study with multiple vehicles and pedestrians. P denotes the participant's position in the scene.

scenario and condition effects. Our results show that there is a statistically significant *scenario* x *condition* interaction ($\chi2(6) = 48.494$, $p < 0.001$). This means that the effect of each scenario (for example, no interface vs vehicle-only interface) varied between the vehicle's stopping and not stopping conditions. Performing pairwise comparisons of the scenarios under the stopping condition, we found participant comfort scores for the vehicle-pedestrian (M: 3.44) and mixed interfaces (M: 3.53) were significantly higher than comfort scores for the no driver scenario (M: 2.46; $p < 0.017$ and $p < 0.017$ respectively).

In the post-study questionnaire, participants compared the interface conditions (Scenarios 4-7) to the baseline condition without a driver (Scenario 3). We found that participants preferred an interface in 3 of the 4 conditions (excluding the vehicle-pedestrian interface). From a score of 1-5 on the Likert scale (with 1 reflecting that the interface was significantly worse and 5 reflecting that the interface was significantly better), the scores were: vehicle-only (M: 4.8, SD: 0.42), vehicle-street infrastructure (M: 4.3, SD: 0.67), vehicle-pedestrian (M: 3.3, SD: 1.06), mixed (M: 4.6, SD: 0.51). When participants ranked the four interfaces and the baseline condition (Scenario 3) in order of preference, the vehicle-only interface and vehicle-street infrastructure interface received 4 out of 10 votes for first place. The baseline condition (Scenario 3) received 6 out of 10 votes for fifth place (last) while the vehicle-pedestrian interface received 4 out of 10 votes for fifth place.

Comparison with Prior Studies. Broadly, our validation study findings provide further support for the usefulness of AV-pedestrian interfaces in single AV-single pedestrian condition. These results are similar to those observed in the real-world Wizard-of-Oz studies and those conducted using VR simulators. More specifically, our study results are comparable to those found by Mahadaven et al. as we tested interfaces similar to those they proposed [17]. Although our metrics of measuring the success of interfaces are different, overall, similar to these works, we also found qualitative and quantitative support for the use of explicit interfaces to communicate vehicle awareness and intent to pedestrians.

EVALUATING MIXED TRAFFIC

Informed by the related work and having validated our simulator, we used OnFoot to prototype mixed traffic. We conducted a study aimed at understanding how pedestrians make crossing decisions in complex mixed traffic scenarios. We describe the details of our evaluation here.

Participants. We recruited 12 participants for this study in the age range of 18-45 (7 male, 5 female). Participants were recruited through posters placed on our university campus and word of mouth and received a remuneration of $20. Participants were students from different backgrounds – including engineering, computer science, and psychology.

Study Task. Participants were immersed in a virtual crossing environment for 40 minutes. During this period, we presented them with 90 trials, split into 3 sets of 30 trials each. In each set, participants saw 4 vehicles of two autonomy levels at a time. AVs (SAE level 5 [30]) appeared in each set, while manually-driven and semi-AVs (SAE level 3 [30]) appeared in one set each. Manually-driven and semi-AVs always appeared in the lane closest to the participant. Set 1 included manually-driven vehicles and AVs, Set 2 included semi-autonomous vehicles and AVs, and Set 3 included AVs in both lanes. In each set, virtual pedestrian behavior changed (none, early crossers, late crossers) every 10 trials. Within each pedestrian behavior (10 trials), we varied 5 interface scenarios (no interface, vehicle-only, vehicle-street infrastructure, vehicle-pedestrian, and mixed), each with 2 trials. Within each scenario (2 trials), we toggled stopping and not stopping conditions of the vehicles.

Since we manipulated 3 variables – sets of vehicles, pedestrian behavior, interfaces, and also randomized vehicle stopping condition, we achieved a partial balancing of learning effects. We generated one combination of 90 trials, from which we created a 3 x 3 Latin Square based on set order (Set 1-0-2, Set 2-1-0, Set 0-2-1). We recruited 12 participants so that 4 participants saw each set order.

Study Procedure. Figure 5-B shows our study setup. In each trial, 4 vehicles spawned away from the participant and during stopping trials, came to a stop in front of the crosswalk. The vehicles restarted after stopping for 5 seconds and drove away from the participant before respawning in the next trial. Similar to our validation study, participants filled out demographic information and completed the simulation sickness questionnaire [14].

Prior to the study task, participants wore the VR headset while we showcased some of the study conditions, including types of drivers (attentive, distracted), groups of pedestrians, and communication interfaces. After familiarizing participants with the setup, they completed Set 1 (trials 1-30) and completed a short questionnaire reflecting on the trials they experienced during the set. Similarly, they completed Set 2 (trials 31-60) and Set 3 (trials 61-90). At the end of the study, we interviewed participants on their experience in the simulator.

	No Interface	**Interface**
Comfort (out of 5)	3.855	4.256
Time Difference (s)	0.1296	-0.446

Table 1: Average comfort score and time difference for No Interface and Interface Conditions.

Sources of Data. In each study session of 90 trials, vehicles stopped at the crosswalk in 45 trials. We assessed participants' crossing decisions for all trials when the vehicles stopped, yielding a total of 540 unique crossing opportunities (45 x 12). We determined the time difference between when the vehicles stopped at the crosswalk and when the participant first signaled their intent to cross using the remote. We used time difference and comfort score at the instant the participant decided to cross for the quantitative analysis. We also classified the time difference data from participants by placing them in one of three bins: early crossers, timely crossers, and late crossers. We recorded responses to mid-study questionnaires between sets (3 questionnaires in total) for each participant. We also recorded and coded our interview sessions.

Findings

Crossing Decisions and Comfort Scores. In our mixed traffic studies, 11 out of 12 participants crossed each time the vehicles stopped, while 1 participant crossed in 43 out of 45 trials. Of the two trials P10 did not cross in, one was by accident (and was expressed by them after the trial) and another was due to being faced with a semi-autonomous vehicle with a distracted driver on one lane and an autonomous vehicle without an interface on the other. To determine whether the presence of interfaces in the trials (appearing in 36 out of 45 trials per participant) affected when participants opted to cross, we conducted a one-way repeated measures ANOVA on participant comfort scores at the time of making the crossing decision. We found that participants reported significantly higher comfort scores when faced with an interface than without ($F(1,11) = 7.597$, $p < 0.019$). Performing a one-way ANOVA on time difference, we found that participants crossed before the vehicle stopped when they had interfaces (negative time difference) versus after the vehicles stopped when they did not have interfaces ($F(1, 11) = 15.875$, $p < 0.002$). Table 1 shows the average values of our metrics between the interface and no interface conditions.

Mid-Study Questionnaires. Participants evaluated the usefulness of each of the following cues in making their crossing decisions: (1) vehicle motion, (2) cues on the vehicle, (3) cues on the street, (4) cues on the pedestrian, and (5) pedestrian behavior. 5-point Likert score results exhibit that for both awareness and intent information, vehicle motion and cues on the vehicle were most useful while cues on the pedestrian (participant) were least useful. Participants also evaluated the usefulness of the 4 interface prototypes and cue modalities that consisted them. The vehicle-only interface was the most popular.

Interviews. We asked participants if they considered awareness and intent to be important. 10 out of 12 participants stated both to be important, while 2 out of 12 only believed one to be important. P13 said, *"Usually, I don't look for that (intent). If I know I've been seen (awareness), then it's enough"*. In contrast, P9 said, *"Awareness can lead to intent, but not necessarily. Once you've seen me (awareness), what are you going to do (intent)?"*.

DISCUSSION

In this section, we share design considerations and insight gained through the OnFoot pedestrian simulator, relating to the interplay between vehicles, pedestrians, and interfaces in mixed traffic scenarios.

Using Pedestrian Simulators as a Design Tool

In both OnFoot studies, all participants stated that the crossing experience in our simulator was similar to their real-world experience. For instance, P11 said, *"When there was a real driver, I behaved basically the same as I would in the real world"*. Similar quotes were echoed throughout our mixed traffic study. We see our OnFoot findings as further evidence that pedestrian simulators can be valuable tools to approximate real-world pedestrian behavior and could be immensely useful in research into mixed traffic.

From a researcher's perspective, OnFoot's VR environment offers incredible flexibility in study design. Adding a new testing variable is as simple as writing a few lines of code, as opposed to using Wizard-of-Oz. For example, redesigning or modifying the behavior of an AV-pedestrian interface prototype in VR can be done with ease, whereas in the real-world, a new implementation could be limited by hardware. VR also offers the ability to more accurately collect participant data in real-time, such as, for example, the time it takes to make a crossing decision or other qualitative measurements such as comfort level. Further, one of the defining characteristics of mixed traffic is scale – the number of vehicles and pedestrians on the street. In OnFoot's VR environment there is comparatively no cost to scaling – which allowed us to revisit past research in more realistic and complex traffic conditions.

Arguably the most beneficial aspect of OnFoot usage of VR and the Unity3D game engine is its support for rapid prototyping and reproducibility of studies. For example, in our mixed traffic study, we ran 90 trials per participant, yet they were experienced in a similar way by all participants. It is also evident that many other equally interesting vehicle-pedestrian interaction problems could be featured in VR and validated with a high standard of realism. For example, in the longer-term future, if all vehicles are autonomous, it is possible that we may no longer need fixed intersections. Such vehicles would be able to stop anywhere, at any time, creating dynamic intersections. Prototyping and testing such an idea in the real-world would be costly and prohibitively dangerous, but this future design scenario can be safely prototyped and tested presently in OnFoot.

Designing Interfaces for Mixed Traffic

Our results suggest that interfaces can help pedestrians navigate mixed traffic and make safe crossing decisions. However, how to design such interfaces while considering scale and mixed traffic is still an open question. We highlight some considerations that could support the design of future AV-pedestrian mixed traffic interfaces, below.

Interface Locations. While interface cues can be placed on the vehicle, the street, and the pedestrian [17], our mixed traffic study results suggest that the vehicle could be the best location for them. By endowing each vehicle with clear awareness and intent information in mixed traffic, pedestrians will be able to gauge individual vehicle awareness and intent and identify AVs from other vehicle types (especially if there are visual cues present). In mixed traffic, pedestrians will already be looking for driver cues from some vehicles, so placing interface cues on the vehicle makes it easier for pedestrians to decide whether to use information from a driver or an interface. However, their exact location on the vehicle is still not clear. We had success with placing the LED strip on the vehicle's windshield, but some participants felt the animated smile was misplaced in its location near the vehicle's grill. P5 said, *"I didn't find it obvious enough. Plus, you had to actually look down at the car, and in the U.K., we have number plates on the front as well."*

If required, cues could also be placed on the street, which received support from 9 out of 12 participants. We suggest that street cues only be used at busier intersections where it may be hard for pedestrians to gauge each individual vehicle's awareness and intent. However, pedestrians would have to trust that AVs are well integrated and accurately base their actions on street infrastructure in order for such cues to be effective. This is a shift from today's traffic lights, which are a rule of the road, but are occasionally broken by drivers. P10 points out, *"The idea I got was it said that it was safe to stop, but it didn't feel like the cars were basing their decision on that. It's more of a rule than definitive action"*.

Cue Modalities. Our results also support the use of visual and auditory cues in mixed traffic. While there are many visual cues that one could use to denote vehicle awareness and intent, the LED strip seemed to provide cues clearly distinguishing awareness and intent information through colors and animation. In mixed traffic, this would allow pedestrians to recognize if, for example, a single car in a fleet of AVs fails to acknowledge them. However, visual cues, especially if they are colors, have to correctly and unambiguously reflect vehicle awareness or intent. For example, we designed the colors red and green on the LED strip in the OnFoot cues to indicate that the vehicle was not stopping and stopping, respectively. However, some participants found it counterintuitive, since brake lights are usually red and indicate that the vehicle is stopping.

There was also positivity towards auditory cues especially in mixed traffic with several vehicles. P11 said, *"Even though the street LED turned green, I waited until both cars said 'cross' till I decided to cross".* However, we think that scale and mixed traffic both present major challenges for the usage of auditory cues. While they could support pedestrians with visual impairment or distracted pedestrians, auditory cues may be drowned out by the sheer number of vehicles on streets in mixed traffic, especially in more crowded cities. Further, ambient noise which we did not include in our current OnFoot scenarios, could also drown out auditory cues. However, we think they can still be used along with dedicated street infrastructure in busier intersections, assuming all AVs in its vicinity will adjust their actions based on it.

Crossing Strategies in Mixed Traffic

Since we examined pedestrian behavior in mixed traffic through the OnFoot VR simulator, we cannot claim that the strategies participants developed to deal with mixed traffic will directly map to the real-world. However, our preliminary findings suggest that pedestrians deal with mixed traffic by assessing the types of vehicles on the road as well as how much information they provide them and adjust their behavior accordingly. We classified most participants (9 out of 12) as timely crossers - they waited for vehicles to fully stop before crossing – irrespective of the types of vehicles, interfaces, or pedestrian behavior they encountered. We now discuss some factors that may affect pedestrian behavior based on our mixed traffic study.

Influence of Group Vehicle Behavior. The composition of traffic based on vehicles' autonomy level may have played a role in pedestrian crossing strategy. Although we did not find statistical significance supporting this, our classification of crossing decisions shows that participants made more early crossing decisions in the presence of manually-driven vehicles with attentive drivers in one lane and AVs in the other (68 out of 538) versus when there were vehicles with a distracted driver (48 out of 538) in one lane. We also found individual instances through video analysis where participants made improper decisions based on the mix of vehicles present. For example, one participant crossed the street when faced with an AV that communicated it was safe to cross through an interface, alongside a vehicle with a distracted driver who also slowed down and stopped but did not explicitly communicate. P11 said, *"So there I saw the smiley face and decided to cross, but then I realized that the other car had a distracted driver. I could have definitely endangered my life".* Even though the participant had a clear view of both vehicles, their decision to cross was made by observing the AV, hinting at an overreliance that pedestrians may develop on AVs that behave predictably.

In another instance, an AV indicated that a participant could cross via an interface, but the participant waited until a vehicle next to it with a driver also explicitly communicated its intent to stop before crossing. Here, the distrust of human-driven vehicles (with drivers inside who could be distracted or make mistakes) may have prevented the participant from crossing quickly.

In our studies, we included the scenario of a distracted driver inside the vehicle, making it ambiguous for participants to identify the vehicle's autonomy level. While some participants interacted with the vehicle in mixed traffic as though the driver was distracted, others assumed that the vehicle was autonomous at that instant. This highlights a potential problem of semi-AVs sharing the road in mixed traffic, as our design exercise predicted – the difficulty for pedestrians to assess who is in control of the vehicle's operation. Such vehicles could allow varying levels of disengagement from the driving process [30]. For example, some may require the driver to periodically place their hands on the steering wheel [10]. Especially during their introduction, pedestrians may not be used to the idea of drivers appearing so distracted in semi-AVs. For example, P3 said, *"I'm pretty skeptical about software bugs in autonomous vehicles, but distracted drivers were scarier".* While prior work and our results suggest that full AVs (SAE level 5 [30]) will need to communicate with pedestrians, we think the same will extend to semi-AVs (SAE level 3 [30]). Similar to the ideas suggested by Lagström and Lundgren [15], we think such SAE level 3 semi-autonomous vehicles will need to indicate whether they are running autonomously at any given moment, and if so, would need to communicate in a manner similar to fully autonomous vehicles.

Influence of Interfaces. Vehicles with and without interfaces also impacted pedestrians' crossing strategy in mixed traffic. 11 out of 12 participants explicitly stated in the interview that seeing vehicles without interfaces made them more careful when crossing. When seeing both vehicles with distracted drivers and AVs without interfaces, the issue became exacerbated as both vehicle types did not explicitly communicate with the participant.

Influence of Group Pedestrian Behavior. Although our quantitative evaluation of the impact of group pedestrian behavior on participant scores did not yield significant results, 6 out of 12 participants cited their presence as a factor which may have influenced their crossing strategy. P12 said, *"I just followed the other pedestrians' actions. You can feel social pressure. If people are waiting, you are going to wait, but if you are alone, you can make the decision and not be observed."* Though a minor difference, participants made crossing decisions earlier (64 out of 538) when other pedestrians also crossed slightly earlier, compared to when there were no other pedestrians (55 out of 538) or timely crossers (54 out of 538). However, we emphasize that not all our participants felt that pedestrians impacted their decisions. P5 said, "*I would rather rely on my own eyes than follow other pedestrians blindly*".

Limitations

In this work, we provide a first exploration of AV-pedestrian interaction design in mixed traffic conditions using OnFoot, an immersive VR pedestrian simulator. There are some initial limitations, however, that need addressing. We recruited a small sample size of participants and focused on a specific setting – unsignalized crosswalks. Participants were not allowed to physically walk across the street, which may have caused them to cross more often in our simulator. In real-world crossing, many factors such as speed or stopping distance of vehicles could vary (*"There is more randomness in real life such as a guy who speeds up or a guy who cuts red lights" [P8]).* Capturing such intricacies of the real-world is a challenge in virtual environments and could have some impact on the results. The technical limitations of our Oculus Rift realization of OnFoot may also have had an effect on participant crossing – such as its inability to provide a wide field of view, its display resolution making it difficult to gauge distances of vehicles from afar, and its poor sound localization. These are all aspects that people could gauge more easily in the real world. Despite these shortcomings, our findings indicate that participants thought OnFoot provides a fairly realistic representation of the crossing task.

CONCLUSION AND FUTURE WORK

Our paper highlights the complexity of AV-pedestrian interaction in mixed traffic conditions, and the challenges of designing, prototyping and evaluating in this space. Due to the difficulties of conducting mixed traffic studies in the real-world, we propose an immersive VR pedestrian simulator as a potential platform for exploring the complexities of pedestrian interaction design in mixed traffic. We conducted an initial design study to better understand the design space of a simulator for mixed traffic scenarios. Informed by our design study, we implemented OnFoot, an immersive VR simulator integrating a set of interfaces for communicating AV awareness and intent information to pedestrians. We explored the viability of OnFoot as a valid testbed by replicating past studies in a single AV-single pedestrian validity study. Our validity study results confirmed prior study results about the usefulness of communication interfaces in single AV-single pedestrian interaction. We then performed a formal mixed traffic study using OnFoot and provide a first examination of AV-pedestrian interaction in complex mixed traffic conditions. Our mixed traffic study findings highlight that the explicit use of interfaces for the communication of awareness and intent from all vehicles could be essential for pedestrians facing mixed traffic. Further, our findings suggest an interplay between vehicle autonomy levels, interfaces, and pedestrians which influence pedestrian crossing behaviors.

There are several directions for future work. In our current work, we explored a subset of factors that can affect pedestrian behavior at a crosswalk. In the future, we would like to explore a larger subset of factors such as vehicle size and speed, all easily supported by OnFoot. In addition, to improve the realism of our immersive simulator, we would like to explore allowing participants to physically walk across the street using room-level tracking, investigating two-way streets as well as more radical views of future streets and pedestrianization approaches We also plan to scale our OnFoot VR simulator to augmented reality, enabling studies in naturalistic settings, on physical roads, but with physical vehicles replaced by synthetic ones.

We expect the challenges of mixed traffic to become evident on our roadways in the near future. Our work highlights how this interaction design opportunity can be pursued using a pedestrian VR simulator as a design and evaluation testbed, and hence, alleviate the safety and accessibility limitations posed by real-world testing.

ACKNOWLEDGEMENTS

We would like to thank Dr. Tak Fung for his expertise and support in statistical analysis and reporting. This work was supported by NSERC Discovery Grant, Project RT732275.

REFERENCES

[1] Beggiato, M., Witzlack, C., Springer, S. and Krems, J. 2018. The Right Moment for Braking as Informal Communication Signal Between Automated Vehicles and Pedestrians in Crossing Situations. *Advances in Intelligent Systems and Computing*. 1072–1081.

[2] Bhagavathula, R., Williams, B., Owens, J. and Gibbons, R. 2018. The Reality of Virtual Reality: A Comparison of Pedestrian Behavior in Real and Virtual Environments. *Proceedings of the Human Factors and Ergonomics Society 2018 Annual Meeting* (2018), 2056–2060.

[3] Chang, C., Toda, K., Sakamoto, D. and Igarashi, T. 2017. Eyes on a Car : an Interface Design for Communication between an Autonomous Car and a Pedestrian. *Proceedings of the 9th ACM International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '17)*. (2017), 65–73. DOI:https://doi.org/10.1145/3122986.3122989.

[4] Clamann, M., Aubert, M. and Cummings, M.L. 2017. Evaluation of Vehicle-to-Pedestrian Communication Displays for Autonomous Vehicles. *Transportation Research Board 96th Annual Meeting* (2017).

[5] de Clercq, K., Dietrich, A., Núñez Velasco, J. P., de Winter, J., & Happee, R. 2019. The Effects of External Human-Machine Interfaces of Automated Vehicles on the Crossing Behaviour of Pedestrians. *Human Factors: The Journal of the Human Factors and Ergonomics Society*. (2019).

[6] Dahlbäck, N., Jönsson, A. and Ahrenberg, L. 1993.

Wizard of Oz studies - why and how. *Knowledge-Based Systems*. (1993). DOI:https://doi.org/10.1016/0950-7051(93)90017-N.

[7] Deb, S., Carruth, D.W., Sween, R., Strawderman, L. and Garrison, T.M. 2017. Efficacy of virtual reality in pedestrian safety research. *Applied Ergonomics*. 65, (2017), 449–460. DOI:https://doi.org/10.1016/j.apergo.2017.03.007.

[8] Deb, S., Strawderman, L.J. and Carruth, D.W. 2018. Investigating pedestrian suggestions for external features on fully autonomous vehicles: A virtual reality experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*. 59, (2018), 135–149. DOI:https://doi.org/10.1016/j.trf.2018.08.016.

[9] Florentine, E., Ang, M.A., Pendleton, S.D., Andersen, H. and Ang, M.H. 2016. Pedestrian Notification Methods in Autonomous Vehicles for Multi-Class Mobility-on-Demand Service. *Proceedings of the Fourth International Conference on Human Agent Interaction - HAI '16*. (2016), 387–392. DOI:https://doi.org/10.1145/2974804.2974833.

[10] Full Self-Driving Hardware on All Cars: *https://www.tesla.com/en_CA/autopilot*.

[11] Guéguen, N., Meineri, S. and Eyssartier, C. 2015. A pedestrian's stare and drivers' stopping behavior: A field experiment at the pedestrian crossing. *Safety Science*. (2015). DOI:https://doi.org/10.1016/j.ssci.2015.01.018.

[12] Jayaraman, S.K., Creech, C., Robert Jr., L.P., Tilbury, D.M., Yang, X.J., Pradhan, A.K. and Tsui, K.M. 2018. Trust in AV: An Uncertainty Reduction Model of AV-Pedestrian Interactions. *Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction - HRI '18*. (2018). DOI:https://doi.org/10.1109/ACC.2000.876920.

[13] Jorge, C.C. 2018. On Social Interactions and the Emergence of Autonomous Vehicles On Social Interactions and the Emergence of Autonomous Vehicles. *Proceedings of the 4th International Conference on Vehicle Technology and Intelligent Transport Systems*. March (2018). DOI:https://doi.org/10.5220/0006763004230430.

[14] Kennedy, R.S., Lane, N.E., Kevin, S. and Lilienthal, M.G. 1993. Simulator Sickness Questionnaire : An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*. 3, 3 (1993), 203–220. DOI:https://doi.org/10.1207/s15327108ijap0303.

[15] Lagström, T. and Lundgren, V.M. 2015. AVIP - Autonomous vehicles interaction with pedestrians. *Ph.D. Dissertation. Thesis.* (2015).

[16] Li, Y., Dikmen, M., Hussein, T.G., Wang, Y. and Burns, C. 2018. To Cross or Not to Cross : Urgency-Based External Warning Displays on To Cross or Not to Cross : Urgency-Based External Warning Displays on Autonomous Vehicles to Improve Pedestrian Crossing Safety. *AutomotiveUI '18 ACM 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. (2018). DOI:https://doi.org/10.1145/3239060.3239082.

[17] Mahadevan, K., Somanath, S. and Sharlin, E. 2018. Communicating Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. (2018). DOI:https://doi.org/10.1145/3173574.3174003.

[18] Mai, K., Pande, A. and Mastako, K. 2018. Evaluation of PC-Based Virtual Reality as a Tool to Analyze Pedestrian Behavior at Midblock Crossings. *Transportation Research Board 97th Annual Meeting* (2018).

[19] Matthews, M., Chowdhary, G. and Kieson, E. 2017. Intent Communication between Autonomous Vehicles and Pedestrians. *arXiv preprint*. (2017).

[20] Morrongiello, B.A., Corbett, M., Foster, A. and Koutsoulianos, S. 2018. Using Virtual Reality to Examine the Effects of Peer Modeling on Child Pedestrian Behavior. *Transportation Research Board 97th Annual Meeting* (2018).

[21] Pillai, A. 2017. Virtual Reality based Study to Analyse Pedestrian Attitude towards Autonomous Vehicles. *Thesis.* (2017).

[22] Rasouli, A., Kotseruba, I. and Tsotsos, J.K. 2017. Agreeing to cross: How drivers and pedestrians communicate. *IEEE Intelligent Vehicles Symposium, Proceedings.* (2017).

[23] Rasouli, A. and Tsotsos, J.K. 2019. Autonomous Vehicles That Interact With Pedestrians: A Survey of Theory and Practice. *IEEE Transactions on Intelligent Transportation Systems*. (2019).

[24] Ren, Z., Jiang, X. and Wang, W. 2016. Analysis of the Influence of Pedestrians' eye Contact on Drivers' Comfort Boundary during the Crossing Conflict. *Procedia Engineering*. 137, (2016), 399–406. DOI:https://doi.org/10.1016/j.proeng.2016.01.274.

[25] Risser, R. 1985. Behavior in traffic conflict situations. *Accident Analysis and Prevention*. (1985). DOI:https://doi.org/10.1016/0001-4575(85)90020-X.

[26] Risto, M., Emmenegger, C., Vinkhuyzen, E.,

Cefkin, M. and Hollan, J. 2017. Human-Vehicle Interfaces: The Power of Vehicle Movement Gestures in Human Road User Coordination. *Driving Assessment: Proceedings of the 9th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. (2017), 186–192.

[27] Roggema, R. 2014. The Design Charrette. *The Design Charrette*. September. (2014), 15–34. DOI:https://doi.org/10.1007/978-94-007-7031-7_2.

[28] Rosenbloom, T. 2009. Crossing at a red light: Behaviour of individuals and groups. *Transportation Research Part F: Traffic Psychology and Behaviour*. 12, 5 (2009), 389–394. DOI:https://doi.org/10.1016/j.trf.2009.05.002.

[29] Rothenbucher, D., Li, J., Sirkin, D., Mok, B. and Ju, W. 2016. Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles. *25th IEEE International Symposium on Robot and Human Interactive Communication, RO-MAN*. (2016). DOI:https://doi.org/10.1109/ROMAN.2016.7745210.

[30] SAE International. 2016. U.S. Department of Transportation's New Policy on Automated Vehicles Adopts SAE International's Levels of Automation for Defining Driving Automation in On-Road Motor Vehicles. (2016). DOI:https://doi.org/P141661.

[31] Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T. and Merat, N. 2018. Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognition, Technology and Work*. (2018). DOI:https://doi.org/10.1007/s10111-018-0521-z.

[32] Schmidt, S. and Färber, B. 2009. Pedestrians at the kerb - Recognising the action intentions of humans. *Transportation Research Part F: Traffic Psychology and Behaviour*. 12, 4 (2009), 300–310. DOI:https://doi.org/10.1016/j.trf.2009.02.003.

[33] Sucha, M., Dostal, D. and Risser, R. 2017. Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis and Prevention*. 102, (2017), 41–50. DOI:https://doi.org/10.1016/j.aap.2017.02.018.

[34] Zimmermann, R. and Wettach, R. 2017. First Step into Visceral Interaction with Autonomous Vehicles. *Automotiveui 2017: Proceedings of the 9Th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. (2017), 58–64. DOI:https://doi.org/10.1145/3122986.3122988.