Autonomous Vehicle Visual Embodiment for Pedestrian Interactions in Crossing Scenarios

Virtual Drivers in AVs for Pedestrian Crossing

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ABSTRACT

This work presents a novel prototype autonomous vehicle (AV) human-machine interface (HMI) in virtual reality (VR) that utilizes a human-like visual embodiment in the driver's seat of an AV to communicate AV intent to pedestrians in a crosswalk scenario. There is currently a gap in understanding the use of virtual humans in AV HMIs for pedestrian crossing despite the demonstrated efficacy of human-like interfaces in improving human-machine relationships. We conduct a 3x2 within-subjects experiment in VR using our prototype to assess the effects of a virtual human visual embodiment AV HMI on pedestrian crossing behavior and experience. In the experiment participants walk across a virtual crosswalk in front of an AV. How long they took to decide to cross and how long it took for them to reach the other side were collected, in addition to their subjective preferences and feelings of safety. Of 26 participants, 25 preferred the condition with the most anthropomorphic features. An intermediate condition where a human-like virtual driver was present but did not exhibit any behaviors was least preferred and also had a significant effect on time to decide. This work contributes the first empirical work on using human-like visual embodiments for AV HMIs.

CCS CONCEPTS

• Human-centered computing; **• Human computer interaction (HCI)**; **• Empirical studies in HCI**;

KEYWORDS

Autonomous vehicle, visual embodiment, virtual reality, human-machine interface

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1 INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) estimates that in the US in 2017, 5,977 pedestrians were killed in traffic accidents, a number that continues to increase despite general decreases in motor vehicle traffic accident fatalities [26, 27].

The autonomous vehicle (AV), a vehicle that automatically steers, accelerates, decelerates, and has systems that actively aim to prevent collisions, promises to improve motor vehicle traffic safety [7]. This work concerns AV-pedestrian interactions (AVPI) in a scenario where pedestrians cross a street in front of an incoming vehicle in order to contribute to research improving pedestrian safety with AVs [28].

Pedestrians exhibit social behaviors in crossing scenarios, such as communicating with drivers through eye contact or behaving differently in groups versus alone [8, 9]. AVs remove the human driver from the crossing scenario, creating what Rasouli et al. call "a social interaction void" [31]. Researchers have created AV human-machine interfaces (HMIs) to investigate techniques for communicating AV driving intent to pedestrians in lieu of a human driver [28].

The current body of work on AV HMIs demonstrates pedestrian preference for very limited examples of human-like interfaces features [5, 21]. Humanoid and virtual human interfaces have been shown in other AV applications to have a positive effect on human perception of self-driving systems [19, 33]. This work addresses a gap in understanding of how human-like interfaces can impact AVPI in crossing scenarios. We thus investigate the following questions:

- **RQ1**: Can human-like visual embodiments used as AV HMIs positively influence pedestrian crossing behaviors
- **RQ2**: How human-like behavior further impacts pedestrian experiences

Figure 1: Participant (inset) looking towards a human-like virtual AV visual embodiment in a VR environment

To answer these questions, we created a prototype AV HMI featuring a virtual human-like driver in virtual reality (VR), seen in Figure 1, and used it to conduct a 3x2 within-subject experiment with 26 adults. We asked participants to walk across an urban crosswalk with an AV present in VR. One variable, the AV HMI, had levels: 1) no virtual driver, 2) virtual driver that only looks straight ahead, 3) virtual driver that looks at the pedestrians. The second variable had levels: 1) the car stops and 2) does not stop for pedestrians at the crosswalk. We observed their effects on pedestrian crossing time and crossing decision-making time as well as pedestrian AV HMI preference. These efforts culminate in the following contributions:

- A novel artifact demonstrating the use of a visual embodiment of a virtual driver as an AV HMI
- Empirical evidence showing that pedestrians prefer a visually embodied, anthropomorphic virtual agent over an AV HMI with less human-like features and no AV HMI at all.
- An experiment that investigates the impact of increasing human-likeness of an AV HMI on pedestrian crossing behavior.

2 RELATED WORK

2.1 Human Traffic is Social

The human traffic experience is a social one. Human drivers communicate with other drivers and with pedestrians through nonverbal behaviors, such as advancing or stopping in a certain way [30]. Indeed, a pedestrian crossing field study conducted by Rasouli et al. found that 90% of situations they observed contained nonverbal communication between the pedestrian and the driver [27]. This research in turn motivates the development of AV HMIs to make up for the removal of the human driver from these social situations.

2.2 The case for human-like features in AV HMIs

Literature on AV HMIs spanning many different interaction techniques indicate that pedestrians frequently prefer the presence of some sort of AV HMIs, especially those that are regarded as easier to understand [e.g. 2, 3, 5, 13, 17, 18, 22, 25]. Our work experiments with a new AV HMI interaction technique that can impact pedestrian crossing behavior by addressing the particularly human nature of the "void" that prior work has aimed to fill.

Recent work on virtual agent embodiment has shown that human-like interface techniques can positively impact the social relationship humans have with intelligent systems [e.g., 15, 16, 19, 33]. In prior research on AV HMIs, we find limited use of human like features, such as hand-shaped cutouts or smiley faces [5, 21]. In this work, we demonstrate a novel AV HMI prototype that combines ideas from both current AV HMI research and virtual agent embodiment research.

2.3 Investigating AV HMIs in Virtual Reality

VR environments have been frequently used to investigate pedestrian crossings not only to reduce risk compared to real-world experiments, but also to increase scenario replicability and provide flexibility in building experiment scenarios [25]. Many have utilized VR to simulate an immersive virtual pedestrian crossing experience [e.g. 4, 10, 25, 31]. While we may perceive that advanced dashboard projection, dedicated monitor, or other specialized vehicle hardware may be used in the future to display the visual embodiment, given current technology VR also allows us to much more easily create a full-size, human-like virtual visual embodiment for an AV HMI.

3 METHODS

3.1 Experimental Design

We conducted a within-subjects experiment with three AV HMI levels x two car stopping scenarios per condition x two trials = 12 tests per participant. Trials were blocked by AV HMI condition and car stopping condition, with order of conditions randomized within each block, resulting in a randomized complete block design. In each test, participants make a decision whether to walk across the crosswalk in front of an approaching AV. For each trial and each condition, the car will come to stop in front of the crosswalk in one test and will not stop at all in the other.

3.1.1 *Independent Variables.*

Our experiment had two independent variables: 1) AV HMI and 2) Whether the AV stops for the pedestrian. For the AV HMI variable, there were three levels: no AV HMI (or "no driver"), a non-interactive visually embodied agent (or "static driver"), and a visually embodied agent that looks at the pedestrian (or "driver that looks"). An example of each condition can be seen in Figure 2. We have chosen conditions that represent incremental increases in human-like features, similarly to recent work evaluating the impact of visual embodiments on perceptions of virtual agents [13]. Furthermore, we did not choose any condition where the driver explicitly communicates to the pedestrian to reflect that in some cultures, such as in certain western European countries, drivers are expected to avoid doing so to prevent errors in the drivers' judgment from endangering pedestrians. The AV stopping condition was included to prevent participants from learning to assume that the car will stop for them every time.

Figure 2: From left to right: "no driver," "static driver," "driver that looks."

3.1.2 Dependent Variables. To understand the impact on quantitative crossing behavior, we measured 1) time to cross (TTC) the intersection and 2) time to decide (TTD) to cross. TTC is how long it takes for a pedestrian to cross the road. TTD is how long the pedestrian waited before initiating crossing behavior, similar to other related studies [5, 29]. We also ask participants for: 3) their preference of AV HMI condition and 4) their subjective feelings of safety for each AV HMI condition.

3.2 Hypotheses

- H1. TTC is highest for the condition with the most human-like features (driver that looks > static driver, no driver), regardless of car stopping.
- H2. TTD is the lowest for the condition with the most human-like features (driver that looks < static driver, no driver), regardless of car stopping.
- H3. Participants will prefer the condition with the most human-like features (driver that looks > static driver, no driver).
- H4. Participants will feel safest with the most human-like features (driver that looks > static driver, no driver), regardless of car stopping.

H1 and H2 are based off of intuitive feelings of how a pedestrian may feel if they are presented with an AV HMI that makes them feel safer and more confident about crossing. H3 and H4 reflect prior work that demonstrates improved relationships between humans and intelligent systems with human-like visual embodiments.

3.3 Measures

The software running the virtual environment logs the beginning of a trial, marked by the AV beginning to move from far away, and when participants enter and leave volumes representing the crosswalk space. Figure 3 outlines these volumes. TTC is the time difference between entering and leaving the crosswalk. TTD is the difference between the trial start and entering the crosswalk.

To measure participants' preference for AV HMI condition, we asked participants after the experiment to identify which condition they preferred the most as well as the one they preferred the least, and why. To measure participants' feeling of safety, we asked participants after each test to rate their feeling of safety entering the crosswalk using a Likert scale, similar to the recent VR AV HMI experiment conducted by Deb et al. [5].

3.4 Procedure

Participants were briefed on the experiment and provided demographic information. This briefing includes an explanation that the virtual driver represents an interface, not a human driver. Participants were given time to familiarize themselves in VR with the setting, AV HMI conditions, trial procedures, and to practice crossing the street.

For each trial, participants stood at the crosswalk as shown in Figure 3. Then, the AV approached the intersection from the participant's right. Participants crossed the street when they felt safe to do so. After crossing, participants verbally responded to the subjective question on feelings of safety. All trials were performed in the same setting. After completion of the final trial, participants responded to a semi-structured interview debrief. This experiment design and

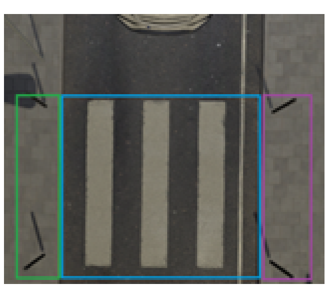

Figure 3: Left: Overhead view of zones used to compute TTC and TTD. Right: Overview of the crossing scene, with AV approaching and white dummy indicating where pedestrian starts crossing.

Figure 4: Left: Real world view of pedestrian crossing the street in the virtual environment with platforms visible in the bottom right and center-left simulating curbs. Right: Virtual view of pedestrian waiting for AV to stop.

procedure is similar to other experiments that have been conducted in VR and in real-world for AV HMI evaluation [e.g., 5, 18, 21].

3.5 Apparatus

Participants wore an HTC Vive Pro VR head-worn display, with two HTC Vive base stations running on a Windows desktop to create a VR tracked space measuring 4.3m by 1.8m, as seen in Figure 4. We developed the virtual environment using Unity 2019.4.11. The environment mimics an urban setting with a crossing at a one-way street, as can be seen in Figure 4. We chose to use a zebra crossing to mimic similar studies, both virtual and in the field [e.g. 5, 23]. The virtual vehicle had engine noise and wheel noises localized spatially to the vehicle to enhance realism.

3.6 Data Analysis

To evaluate H1 and H2, we performed a repeated-measures two-way ANOVA on TTC and TTD with multiple comparisons for significance. In addition, we conducted post hoc pairwise comparisons to better understand the main effects. We analyzed Likert scale responses using the non-parametric Wilcoxon Signed-Rank test due to an insufficient sample size to use other techniques such as ANOVA. In addition, we counted the frequency of the preferred HMI condition and used the Chi-Squared test to evaluate significance.

3.7 Participants

We recruited 26 participants for our study from around a university campus, 18-66 years old (M = 24.0, SD = 9.7), 15 of male and 11 female. They were recruited through email and word of mouth. This number of participants is similar to those of recent experiments studying AVPI in virtual reality [e.g., 5, 21]. Participants were compensated $10 for their time.

4 RESULTS

Every pedestrian looked before crossing and no pedestrian was hit by the AV.

4.1 Effect of Conditions on TTC

Table 1 shows descriptive statistics on TTC. We conducted a two-way repeated measures ANOVA to understand the effect of AV HMI and car stopping on TTC, as seen in Table 2. There was a significant effect of car stopping condition on TTC. There was not a significant effect of AVI HMI condition on TTC. There were also no significant interaction effects; $F(2, 50) = 1.924$, $p = 0.157$. Therefore we cannot support H1.

4.2 Effect of Conditions on TTD

Table 1 shows descriptive statistics on TTD. We conducted a two-way repeated measures ANOVA to understand the effect of AV HMI and car stopping on TTD, as seen in Table 2. There was a significant effect of both car stopping and AV HMI on TTD. A post hoc pairwise comparison revealed differences between the static driver condition and both the no driver and driver that looks conditions (both **p = 0.033**). The pairwise comparison found no difference between TTD for the no driver and driver that looks conditions ($p = 0.989$). There were no interaction effects between the two variables; $F(2,50) = 1.841$, $p = 0.169$. Therefore we cannot support H2.

Table 1: Mean TTC and TTD in seconds

	AV HMI condition	**Car does not stop**	**Car stops**
TTC	No driver	4.88 ± 0.37	3.81 ± 0.18
	Static driver	4.53 ± 0.29	4.25 ± 0.28
	Driver looks at pedestrian	4.51 ± 0.36	4.02 ± 0.19
TTD	No driver	3.27 ± 0.05	4.83 ± 0.01
	Static driver	3.13 ± 0.04	4.80 ± 0.01
	Driver looks at pedestrian	3.28 ± 0.06	4.81 ± 0.01

Table 2: ANOVA results for TTC and TTD

	Variable	df	F	p value
TTC	Car stops	(1,25)	12.01	**0.002**
	AV HMI	(2,50)	0.38	0.687
TTD	Car stops	(1,25)	2978	**<0.001**
	AV HMI	(2,50)	3.24	**0.048**

Table 3: Descriptive statistics on safety ratings

AV HMI Condition	Car does not stop	Car stops
No driver	5.75 ± 1.08	5.87 ± 0.95
Static driver	5.77 ± 1.08	5.50 ± 1.33
Driver looks at pedestrian	5.94 ± 1.19	5.81 ± 1.11

Rating of 1-7, where 1 indicates feeling "very unsafe" and 7 indicates feeling "very safe" when entering the crosswalk

Table 4: Frequency of preference for each AV HMI condition

AV HMI Condition	Preferred most	Preferred least
No driver	1	11
Static driver	0	15
Driver that looks at you	25	0
X^2 value	< 0.001	0.001

4.3 Effect of Conditions on Reported Safety

We conducted a non-parametric Wilcoxon Signed-Rank test to observe any effect of AV HMI condition and car stopping condition on feelings of safety when crossing the road. There was no significant effect of car stopping condition on reported feeling of safety; $F(1,25) = 0.885$, $p = 0.356$. There was also no significant effect of AV HMI condition on feelings of safety; $F(2,50) = 1.847$, $p = 0.168$. Descriptive statistics can be seen in Table 3. Therefore, H4 was not supported.

4.4 Participant Preference for AV HMI Condition

Of 26 participants, 25 preferred the driver that looks condition and 1 preferred the no driver condition. 11 least preferred the no driver condition and the other 15 least preferred the static driver condition, as seen in Table 4. This supports H3.

One experimenter coded participants' responses for their reasons for their preferences to extract common themes. 8 participants cited feelings of safety and 18 participants cited feelings of being seen, acknowledged, or the AV being aware of their presence when discussing their preferred condition. When discussing their least preferred condition, 8 participants discussed difficulties understanding what the AV's intentions were, 16 participants cited feelings of not being seen, acknowledged, or the AV not being aware of their presence, and 3 participants mentioned not feeling safe. For example, participants often said that the virtual driver looking at them made them feel like the "the car was aware" (P7), as opposed to feeling that the vehicle is "completely unaware" when there is only a static driver. Another participant stated that "I don't trust people when they are not paying attention or looking at me in traffic" (P11).

Participants also frequently gave their recommendations for features that they think would be beneficial for crossing. 10 participants suggested adding supplemental modalities for AV HMI, such front facing brake lights (P16) or speed indicators (P14), to the AV. 4 participants suggested adding additional social behaviors to the virtual driver, such as gestures to communicate with the pedestrian.

5 DISCUSSION

5.1 Participants prefer virtual human AV HMIs, if done right

Participants' comments on their preferences may indicate perception of the AV's competence. Such an interpretation would agree with the work from Lee et al. where human-like appearances positively impacted bystander perception of intelligence, safety, and trustworthiness of a miniature AV [16]. In our work, the difference in implementation between the two virtual driver conditions is a mere 15 degree rotation of the virtual driver's head towards the pedestrian. Participants' sensitivity to this fact as evidenced by their clear preference for the driver that looks condition and dislike for the static driver could be explained by the "uncanny valley" effect, where human-likeness just short of realism elicit unfavorable perceptions [24]. Future work exploring the effects of increasing human-likeness and behavior affect pedestrian perceptions of an AV can clarify the extent of the "uncanny valley" effect in this domain. For example, Hock et al. demonstrate a human-like avatar designed to look like a projection to avoid appearing too real—how would such a technique function in an AVPI setting [12]?

Participants' interface recommendations are similar to designs that have been prototyped and evaluated in current literature [e.g., 13]. Future work can shed more light on the way that different interface modalities compare, contrast, and even interact with virtual human AV HMIs. Lastly, these suggestions may also imply that the participants felt that the virtual human AV HMIs alone were not enough to satisfactorily communicate vehicle intent.

5.2 Potential effects on crossing behavior and safety

Participants' discomfort from the static driver may be the cause of change in TTD, but future work is required in order to better understand the direction of change in TTD. Repeating the study with a larger sample size may shed light on this result as well as yield significant results that we did not observe here.

In the end, participants still expressed concerns of feeling uncertain or uncomfortable crossing in front of AVs without an HMI, especially when also given the experience of crossing in front of an AV with visible HMI features. Indeed, quantitative measures of crossing behavior do not capture the importance of improving the richness and quality of social interactions. Further study using measures such as the Temple Presence Inventory [20] or Deb et al.'s Pedestrian Receptivity Questionnaire [4] would be valuable.

The participant comments also notably contrast with the generally high mean safety ratings. One way to interpret this is that the VR environment may not be entirely ecologically valid for assessing feelings of safety, perhaps because participants know that there is no "real" risk in crossing the road in VR. Future studies may consider performing evaluations in augmented/mixed reality, involving real cars.

6 CONCLUSION

This paper presents the empirical work utilizing a human-like virtual visual embodiment prototype used as an AV HMI to help pedestrians in a VR crossing scenario. Our experiments show a preference for the most human-like condition. On the other hand, a human-like visual embodiment AV HMI without corresponding behavior was preferred even less than no AV HMI at all. Participant interviews revealed that they preferred the virtual driver that looks condition because it made them feel more seen, acknowledged, safe, and confident in crossing the road. In the future, we may imagine that technology will be advanced enough to allow AVs to each sport a virtual driver for pedestrians to see and interact with. These visual embodiments could take on any combination of different appearances and behaviors. This work takes the first step in using empirical results to help understand how human-like virtual visual embodiments used as AV HMIs can impact AVPI.

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