Expectation-Driven Differences in Pedestrian Gap Acceptance toward Automated Vehicles

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Abstract -
As automated vehicles (AVs) become increasingly integrated into urban traffic, understanding their interaction with pedestrians is essential. This study investigates pedestrian gap acceptance in interactions with AVs and human-driven vehicles (HVs) using a virtual reality experiment with continuous locomotion on an omnidirectional treadmill. Vehicle behavior was intentionally held identical to isolate expectation-based effects of vehicle type. The analysis focused on unregulated crossings with systematically varied time-to-arrival (TTA). Gap acceptance was primarily driven by TTA. When directly comparing AV and HV crossing opportunities within mixed trials, participants showed higher acceptance rates for gaps followed by HVs. This preference became more pronounced after repeated exposure. Subjective measures were not associated with observed behavioral differences. These findings suggest that under specific conditions, pedestrian decisions may be influenced not only by objective vehicle behavior, but also by expectations associated with vehicle type.

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Introduction

As automated vehicles (AVs) gradually become integrated into urban traffic, understanding their interactions with vulnerable road users (VRUs) such as pedestrians becomes essential. While pedestrians have developed expectations about conventional human-driven vehicles (HVs) through experience, interactions with AVs may introduce uncertainty, as AVs differ in consistency, rule adherence, and communication, potentially requiring pedestrians to adapt their decision-making strategies.

Previous work on AV interaction has primarily focused on trust and cooperation from the driver perspective, while far less attention has been payed to pedestrians and other VRUs, despite the fact that they must also interpret and respond to the AVs' behavior (Jayaraman, et al., 2019).
Pedestrians typically infer vehicle intent from three sources: explicit communication (e.g., driver gestures or external human-machine-interface eHMIs; Dey, et al., 2021; Šucha, 2014), contextual cues such as traffic regulations (Havard and Willis, 2012), and implicit communication through vehicle kinematics (Rasouli and Tsotsos, 2019). While many studies have focused on explicit communication systems for AVs (Carmona, et al., 2021; Jayaraman, et al., 2019; Song, et al., 2023), no standardized communication system currently exists (Saleh, Hossny, and Nahavandi, 2017), making it important to study interactions under conditions where pedestrians must rely on other information sources.

At unregulated crossings, pedestrians rely on vehicle kinematics, trust, and prior expectations. As AVs are often associated with increased uncertainty, these expectations may directly shape crossing decisions (Jayaraman, et al., 2019; Rad, Almeida Correia, and Hagenzieker, 2020). Recent findings suggest that people respond differently to AVs and HVs even when vehicle behavior is identical. For example, Sun, Ge, and Qu (2024) showed in a simulator study, that drivers interacted differently with AVs compared to HVs despite identical kinematics and the only difference being the visual appearance of the vehicles. This indicates that expectations alone can influence behavior, which raises the question of whether pedestrians similarly adjust their crossing decisions based on perceived vehicle identity rather than observable motion cues. To isolate such expectation-based effects, the present study examines pedestrian interactions with AVs and HVs while keeping vehicle kinematics identical across conditions. The study focuses on unregulated crossings without explicit communication, where pedestrians must rely primarily on implicit expectations when deciding whether to cross.

Previous studies have often placed pedestrians directly at the curb using button-press tasks, simplified virtual reality (VR) setups, or projection-based environments. While these approaches provide strong



Figure 1: Omnideck, MoSAIC Laboratory at the Institute of Transportation Systems, Braunschweig

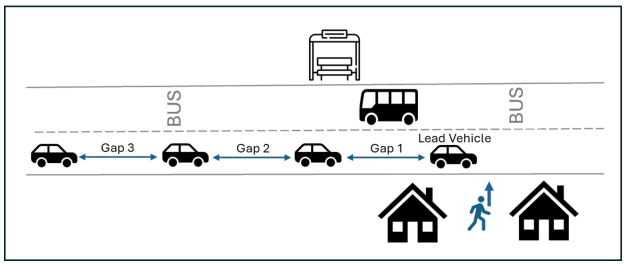


Figure 2: Example of the third street, where the bus stop was located.

experimental control, they constrain natural locomotion and remove the continuous approach phase that characterizes real-world street crossings. Since crossing decisions often begin already during approach rather than only at the curb (Gorrini, et al., 2018; Rasouli, Kotseruba, and Tsotsos, 2017), preserving continuous locomotion is important for capturing realistic pedestrian behavior.

To address this, in the present study an omnidirectional treadmill with a high-fidelity virtual environment is used. A realistic time-pressure task was additionally implemented to promote ecologically valid decision-making and reduce overly cautious simulator behavior. The present paper reports a focused analysis of a subset of conditions from a larger ongoing experimental study. Specifically, we analyze behavioral differences between AV and HV interactions in unregulated crossings, as well as potential adaptation effects over repeated exposure. Based on these considerations, the following research questions are addressed:

- Does pedestrian gap acceptance differ between interactions with AVs and HVs when vehicle behavior is held constant?
- Do potential differences emerge only after repeated exposure, indicating learning or adaptation effects over time?
- Do subjective impressions and expectations toward AVs relate to observed crossing decisions?

Method

Experimental Setup

The study was conducted using the Omnideck, an omnidirectional treadmill by *W5 Omnifinity AB* (see Fig. 1). The system consists of a circular platform (diameter 3.7 m) with motorized roll segments that continuously move users back toward the center, enabling unrestricted movement in all directions within a virtual environment (Guilfoyle and Thor, 2023; Theisen, et al., 2025). The virtual environment was presented via a *Varjo XR-3* head-mounted display.
Participants walked through a virtual city toward a destination that required crossing three sequential roads. The first two roads consisted of a single lane, while the third road additionally included a bus lane (see Fig. 2). However, all roads were designed to have the same overall width, ensuring comparable crossing distances across conditions. Vehicles approached from the left and were presented as either AVs or HVs. No explicit communication cues (e.g., driver gestures or eHMI) were present. Vehicle kinematics, including speed and braking behavior, were intentionally held identical across conditions, such that participants could only rely on implicit expectations associated with vehicle type when making crossing decisions.

On the third road, a bus approached from the right as part of a broader time-pressure task. However, the bus always passed the crossing area before the participant reached the road, ensuring that it did not influence crossing decisions.

Behavioral measures focused on pedestrians' gap acceptance decisions. Gap acceptance was defined as the crossing within a temporal gap between two consecutive vehicles within a traffic stream. Based on the position of the pedestrian relative to the sequence of vehicles, gaps were classified as accepted or rejected.
In addition, subjective measures were collected before and after the experiment, including familiarity with AVs, perceived likelihood of being detected by the vehicle, appropriateness of vehicle reactions, and safety concerns. These measures were explored in relation to observed behavioral differences.

Participants

A total of 25 participants took part in the study (30% female, 70% male; Age: M = 35 years, SD = 10.57). The ethics commission of the DLR determined that no formal ethical review was required. One participant was excluded from the behavioral analyses due to an incorrect simulator configuration during data collection. Thus, the final sample for the gap acceptance analyses consisted of 24 participants. Due to a technical issue with the questionnaire tool, subjective questionnaire data were only available for a subset of participants (n = 19).

Design and Procedure

A within-subjects design was used with vehicle type (AV vs. HV) as the main factor. Participants completed multiple crossing trials in which vehicles approached the pedestrian with a speed of 30 km/h and with systematically varied time-to-arrival (TTA), representing the temporal gaps between consecutive vehicles (5 s, 6 s, & 7 s).This paper reports a focused analysis of a subset of conditions from a larger experimental study. While the full design included additional crossing contexts, the present analysis focuses exclusively on unregulated crossings.

Across the experiment, each participant completed

10 unregulated crossing scenarios, including four mixed (AV and HV), three HV-only, and three AV-only conditions (N = 240 street trials overall). Each street trial included three consecutive gap opportunities.
Mixed trials were presented at the beginning and end of the experiment, in order to assess whether potential behavioral differences between interactions with AVs and HVs change after repeated exposure. The AV-only and HV-only conditions were counterbalanced across participants. Vehicle kinematics were identical for both vehicle types, ensuring that any observed differences in behavior could be attributed to vehicle type rather than kinematic differences.
To ensure that participants could reliably distinguish both vehicle types, written instructions were provided prior to the experiment, including an image of an AV. Vehicles differed clearly in visual appearance. All AVs looked identical and passengers were seated facing backwards, providing a salient visual cue that distinguished them from HVs. In contrast, HVs resembled conventional vehicles familiar to participants.

To encourage naturalistic decision-making, participants were instructed to reach a bus stop within a limited time window. Missing the bus resulted in a delay before the next trial. Remaining time and navigation instructions were continuously displayed on a virtual smartwatch worn on the right wrist.
Prior to the main experiment, participants completed training trials to familiarize themselves with the simulator and task.

Results

To investigate the influence of temporal gap size and vehicle type on pedestrian gap acceptance, generalized estimating equation (GEE) models were employed in combination with follow-up analyses such as Chi-square tests. GEE models were chosen to account for the non-independence of observations within participants.

Gap Acceptance

Across all unregulated trials, gap acceptance rates increased with increasing TTA, indicating that participants were more likely to cross when presented with larger temporal gaps. This was confirmed by a GEE model, which revealed a significant main effect of TTA ($\beta = 1.09, SE = 0.40, p = .007$).

In addition, a significant main effect of gap position was observed ($\beta = -2.43, SE = 1.20, p = .042$), indicating that participants were less likely to accept later gaps compared to earlier ones. No significant interaction between TTA and gap position was found. Fig. 3 shows gap acceptance as a function of TTA and gap position. While acceptance rates increased with TTA across all gaps, differences between gap positions are visible, with lower acceptance rates for later gaps. This likely reflects the sequential task structure, as later gaps were only encountered after earlier gaps had already been rejected. As a result, participants with a generally higher willingness to cross were more likely to accept earlier gaps, meaning later gaps were primarily encountered by more cautious participants. In addition, the first gap was evaluated during continuous approach, whereas later gaps were observed from a stationary position at the curb, potentially affecting movement dynamics and gap perception.

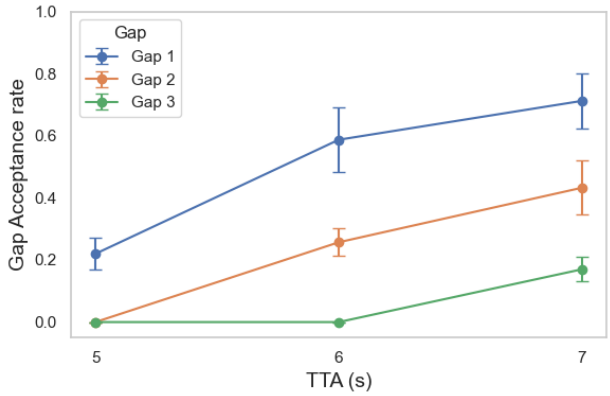


Figure 3: Gap acceptance by TTA and gap position (unregulated trials, excluding training). Values represent participant means; error bars indicate standard errors.

Vehicle-Type Effects on Gap Acceptance

The single-vehicle-type blocks showed no consistent differences between AVs and HVs. Instead, acceptance rates primarily reflected block order, with higher acceptance rates in the second block irrespective of vehicle type, suggesting a general learning or habituation effect.

Mixed trials were specifically designed to allow direct comparisons between interactions with both vehicle types within the same scenario. The following analyses therefore focus on these trials. In these trials, participants were repeatedly faced with immediate choices between gaps followed by either AVs or HVs, allowing a more direct comparison than in single-vehicle-type trials. Gaps were categorized according to the surrounding vehicles as either AV–HV or HV–AV. Across mixed trials, acceptance rates were consistently higher for gaps followed by HVs (37%) than for gaps followed by AVs (22%). This pattern was visible for both small gaps (29% vs. 12%) and intermediate gaps, where the strongest difference emerged (48% vs. 20%).

Mixed trials were presented at both the beginning and end of the experiment, in order to compare whether this preference changed after repeated exposure. Early trials showed no consistent pattern of vehicle-type differences, with only an isolated effect for the largest gap (7 s: $\chi^2 = 3.99, p = .046$). In contrast, late trials revealed significant differences for both small and intermediate gaps (5 s: $\chi^2 = 4.94, p = .026$; 6 s: $\chi^2 = 9.60, p = .002$), with higher acceptance rates for gaps followed by HVs. A GEE analysis confirmed this pattern, showing a significant vehicle-type effect for intermediate gaps in late mixed trials ($\beta = -2.87, SE = 1.013, p = .005$).

Subjective Measures

Although vehicle kinematics were identical across conditions, 31% of participants reported perceiving behavioral differences between AVs and HVs, while 47% reported perceiving no differences and 22% were undecided.

No significant differences between vehicle types

were found regarding perceived likelihood of being detected by the vehicle, perceived appropriateness of vehicle behavior, or safety concerns. Participants reported moderate familiarity with AVs (M = 2.85, SD = 0.75). Higher familiarity was associated with more positive evaluations of automated vehicle behavior, shown by a significant correlation with perceived appropriateness of vehicle reactions ($r(17) = .51, p = .027$). However, neither familiarity with AVs nor any subjective rating measures significantly predicted gap acceptance behavior.

Discussion

The present study investigated whether pedestrians respond differently to AVs and HVs when objective vehicle behavior is held constant. Across all trials, gap acceptance was primarily determined by the temporal and spatial characteristics of approaching vehicles, consistent with previous research (Oxley, et al., 2005; Rasouli and Tsotsos, 2019). However, analyses of mixed comparison trials, specifically designed to allow direct comparisons between both vehicle types within the same scenario, revealed systematic differences in crossing behavior. Participants more frequently accepted gaps followed by HVs, with effects becoming stronger after repeated exposure and most pronounced for intermediate gap conditions. While these differences were apparent in mixed trials, where participants had the choice of crossing either before an AV or an HV, single-vehicle-type trials were less sensitive to such effects, as participants had to select among gaps involving only one vehicle type. Since vehicle kinematics were intentionally identical across conditions, these differences cannot be explained by objective behavioral differences, but from expectation-based responses toward different vehicle types. This interpretation is supported by the observation that nearly one third of participants reported perceiving behavioral differences between AVs and HVs despite objectively identical vehicle behavior. Vehicle-type differences emerged primarily after repeated exposure and were strongest for intermediate temporal gaps, suggesting that expectation-based effects may become more relevant under conditions of greater decision uncertainty. In contrast, when gaps were clearly safe or unsafe, objective traffic cues such as TTA likely dominated decision-making regardless of vehicle type.

Several limitations should be considered. Although vehicle behavior was intentionally controlled to isolate expectation-based effects, this may have reduced ecological validity, as real-world differences between AVs and HVs often involve behavioral variation. In addition, repeated exposure may have introduced learning effects independent of vehicle type, and the sequential gap structure created differences between early and later crossing opportunities, as only the first gap was evaluated during continuous approach. Finally, the relatively small sample size limits generalizability.

Overall, the findings suggest that while objective traffic cues dominate most pedestrian decisions, expectation-based effects may influence behavior when pedestrians directly compare different vehicle types under conditions of uncertainty. Future studies should examine whether similar effects emerge in more naturalistic interactions involving more distinct behavioral differences between AVs and HVs.

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References

Carmona, J., Guindel, C., Garcia, F., and De La Escalera, A., 2021. eHMI: Review and guidelines for deployment on autonomous vehicles. *Sensors*, 21(9), p. 2912.

Dey, D., Matviienko, A., Berger, M., Pfleging, B., Martens, M., and Terken, J., 2021. Communicating the intention of an automated vehicle to pedestrians: The contributions of eHMI and vehicle behavior. *it – Information Technology*, 63(2), pp. 123–141.

Gorrini, A., Crociani, L., Vizzari, G., and Bandini, S., Nov. 2018. Observation results on pedestrian-vehicle interactions at non-signalized intersections towards simulation. *Transportation Research Part F Traffic Psychology and Behaviour*, 59, pp. 269–285. https://doi.org/10.1016/j.trf.2018.09.016.

Guilfoyle, R. and Thor, P., 2023. *Omnideck – Product Sheet*. Available at: ¡http://bit.ly/2VpakmL¿.

Havard, C. and Willis, A., 2012. Effects of installing a marked crosswalk on road crossing behaviour and perceptions of the environment. *Transportation Research Part F: Traffic Psychology and Behaviour*, 15(3), pp. 249–260.

Jayaraman, S. K., Creech, C., Tilbury, D. M., Yang, X. J., Pradhan, A. K., Tsui, K. M., and Robert, L. P. J., 2019. Pedestrian trust in automated vehicles: Role of traffic signal and AV driving behavior. *Frontiers in Robotics and AI*, 6, p. 117.

Oxley, J. A., Ihsen, E., Fildes, B. N., Charlton, J. L., and Day, R. H., 2005. Crossing roads safely: an experimental study of age differences in gap selection by pedestrians. *Accident Analysis & Prevention*, 37(5), pp. 962–971.

Rad, R. S., Almeida Correia, G. Homem de, and Hagenzieker, M., 2020. Pedestrians' road crossing behaviour in front of automated vehicles: Results from a pedestrian simulation experiment using agent-based modelling. *Transportation Research Part F: Traffic Psychology and Behaviour*, 69, pp. 101–119.

Rasouli, A., Kotseruba, I., and Tsotsos, J. K., 2017. Are they going to cross? a benchmark dataset and baseline for pedestrian crosswalk behavior. In: *Proceedings of the IEEE International Conference on Computer Vision Workshops*, pp. 206–213.

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*, 21(3), pp. 900–918.

Saleh, K., Hossny, M., and Nahavandi, S., 2017. Towards trusted autonomous vehicles from vulnerable road users' perspective. In: *Proceedings of the 2017 Annual IEEE International Systems Conference (SysCon)*. IEEE, pp. 1–7.

Song, Y., Jiang, Q., Chen, W., Zhuang, X., and Ma, G., 2023. Pedestrians' road-crossing behavior towards eHMI-equipped autonomous vehicles driving in segregated and mixed traffic conditions. *Accident Analysis & Prevention*, 188, p. 107115.

Šucha, M., 2014. Road users' strategies and communication: Driver–pedestrian interaction. In: *Proceedings of the Transport Research Arena (TRA)*. Vol. 1.

Sun, H., Ge, Y., and Qu, W., 2024. Greater prosociality toward other human drivers than autonomous vehicles: Human drivers' discriminatory behavior in mixed traffic. *Accident Analysis & Prevention*, 203, p. 107623.

Theisen, M., Bergen, M., Einhäuser, W., and Schießl, C., 2025. Head movements predict pedestrian crossing decisions earlier than walking speed. *Transportation Research Part F: Traffic Psychology and Behaviour*, 113, pp. 586–608.