Evaluating the Impact of Bulb-out on Driver Behavior and Perception at Midblock Crosswalks Under Varying Visibility Constraints

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Abstract: This study evaluates the impact of bulb-out on driver behavior and perception under varying visibility constraints at midblock crosswalks. A field experiment was conducted on a one-way road section in a closed test field, where a normal and bulb-out crosswalks were alternated, using ten participants as drivers. The experiment for each participant involved twenty driving scenarios with different conditions for crossing and sidewalk-walking pedestrians, and parked vehicle obstructions. Results indicate that bulb-out contributes to earlier and more controlled speed reductions and clarify pedestrian intent in the presence of sidewalk pedestrians. Extending sightlines of a pedestrian to the trajectory of an approaching vehicle, blocked ranges where pedestrian would be completely blocked by a nearby parked vehicle were determined. It was found that speed reduction in these ranges are greater than those scenarios without a parked vehicle. Questionnaire responses suggest that bulb-out induces higher driver caution.

Keywords: Midblock Unsignalized Crosswalks, Bulb-Out, Visibility, Vehicle-Pedestrian Interaction, Field Experiment

1. INTRODUCTION

1.1 Background

Pedestrians are the most vulnerable road users, facing higher risk of injury and fatality compared to vehicle occupants. Ensuring pedestrian safety, particularly at midblock crosswalks, remains to be a critical issue in traffic management. Studies indicate that midblock crossings account for a significant portion of pedestrian crashes, with non-compliance from drivers being a major contributing factor. For instance, in the United States, it was reported that over 70% of pedestrian fatalities occur at non-intersection locations, including midblock crosswalks, often due to insufficient driver yielding and high vehicle speeds (NHTSA, 2022). Similarly, in Europe, one research found that pedestrian priority laws are often disregarded at unsignalized crosswalks (ETSC, 2021). In Japan, despite the Road Traffic Law mandating vehicles to stop for crossing pedestrians at midblock crosswalks, a recent survey (JAF, 2024) reported that there were only 53% of drivers yielded for crosswalks in their observations.

It is assumed that drivers often fail to yield, especially in situations where pedestrian visibility is compromised. Several factors contribute to this issue, including roadside obstacles such as lighting poles, road signs, and parked vehicles, which obstruct a driver's view of crossing pedestrians. Moreover, distinguishing between crossing pedestrians from those merely walking along the sidewalks also adds another layer of complexity to driver decision-making.

To enhance pedestrian safety, various countermeasures such as high-visibility crosswalk markings, curb extensions, pedestrian refuge islands, raised crosswalks, and rectangular rapidflashing beacons have been implemented in the United States to address issues like inadequate visibility, excessive vehicle speed, and driver non-yielding at crosswalks (FHWA, 2018). In Japan, however due to lack of understanding of their actual effects, some of them have not yet been implemented. One of these measures is the curb extension, called "bulb-out", a traffic calming measure that extends the sidewalk or curb line into the parking lane or road shoulder, thereby reducing the effective street width. This design shortens pedestrian crossing distances and improves sightlines between drivers and pedestrians (FHWA, 2018).

While bulb-outs have been implemented in some countries such as the United States, Germany, and the Netherlands, the effects of its geometric design on driver's behavior and perception have yet to be investigated quantitatively. Beyond the effect of the bulb-out crosswalk itself, the presence of curb-side obstacles or sidewalk conditions upstream of midblock crosswalks may further influence driver behavior and perception. These factors can create uncertainty, affecting visibility, speed reduction, and driver yielding behavior. By implementing a bulb-out, uncertainty could be lessened by emphasizing the crossing intent of a pedestrian. Also, the strategic application of bulb-outs can help mitigate visibility constraints caused by roadside obstacles, further enhancing pedestrian detectability and improving driver yielding behavior. Interaction between these elements has not been thoroughly examined, thus understanding these effects is essential to developing data-driven safety interventions that can improve pedestrian-vehicle interactions at midblock crosswalks.

1.2 Objective

This study aims to investigate the quantitative effects of bulb-out on driver behavior and perception while considering visibility constraints, such as the presence of parked vehicles and other sidewalk pedestrians. By analyzing drivers' deceleration process under various scenarios, this research seeks to provide insights into how road design influences pedestrian safety and driver compliance.

1.3 Research Framework

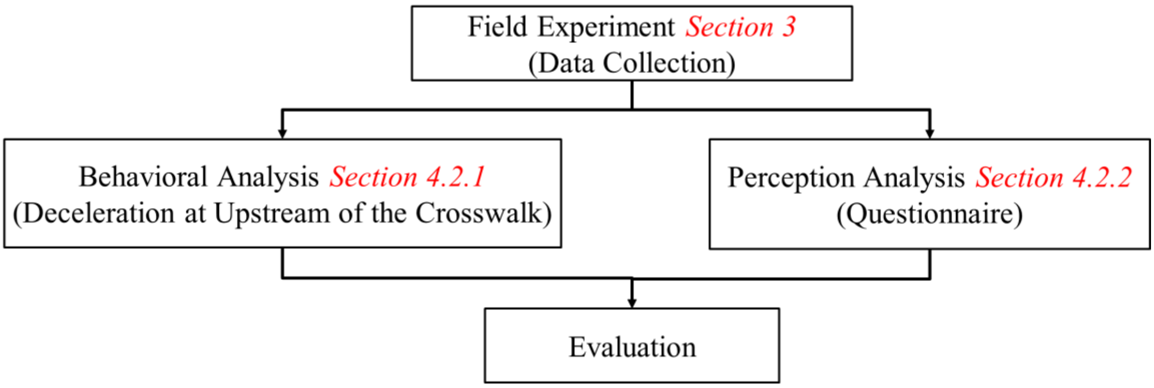


Figure 1. Research Framework

Figure 1 depicts the general framework of this research. In Japan, bulb-outs are not commonly applied in real-world roads. To compare crosswalks with and without bulb-outs and investigate their impact, other conditions should be as similar as possible. Virtual reality is one possible tool for such comparisons; however, it still has limitations in replicating real-world conditions, particularly in terms of perceived visibility and speed. To compare two different types of crosswalks under controlled conditions while preserving a certain degree of realism, this research conducted a field experiment to collect the data of drivers driving through the crosswalk. This data was then divided into two main analytical components: behavioral and perception analysis. The behavioral analysis focused on driver behavior, specifically examining the deceleration at the upstream of the crosswalk, while the perception analysis assessed drivers' perceived anxiety and visibility of pedestrians and vehicles based on the questionnaire. The insights from both analyses were then integrated in interpreting and evaluating the impacts of bulb-out under varying visibility constraints.

The rest of the paper is structured as follows: Section 2 presents a review of relevant literature and Section 3 introduces the field experiment conducted for the data collection. Section 4 presents the hypothesis and methodology in analyzing the data for drivers' behavior and perception, followed by the results and interpretation in Section 5. Section 6 provides conclusions and future work.

2. LITERATURE REVIEW

Bulb-outs are a pedestrian safety measure that improves visibility, shortens crossing distances, and reduces vehicle speeds at unsignalized crosswalks. According to the Federal Highway Administration (FHWA, 2018), curb extensions enhance sightlines between drivers and pedestrians and serve as a traffic-calming measure by discouraging high-speed turns. Their effectiveness is particularly notable at midblock crosswalks, where sight obstructions, such as parked vehicles, can compromise safety.

Empirical studies confirm their impact on driver behavior. Bella and Silvestri (2015), using a driving simulator experiment, found that bulb-outs led to earlier speed reductions, smoother deceleration, and higher yielding rates than other countermeasures such as parking restrictions and advanced yield markings. Improved pedestrian visibility was the primary factor influencing driver compliance, unlike parking restrictions, which improved sightlines but sometimes encouraged higher speeds due to the perception of a wider road. Advanced yield markings showed some improvement in yielding rates, but their effect on speed reduction was less significant than bulb-outs.

Sangphong et al. (2024) found that the presence of roadside parking near midblock crosswalks significantly reduced driver yielding rates, likely because parked vehicles obstruct pedestrian visibility, making it harder for drivers to detect crossing intent in time.

Beyond driver behavior, bulb-outs also influence pedestrian decision-making. Oe et al. (2025) found that bulb-outs encouraged pedestrians to wait closer to the curb, making their crossing intent clearer to drivers and reducing vehicle-pedestrian conflicts. Additionally, they help mitigate visibility issues caused by parked vehicles by extending the pedestrian waiting area beyond obstructions.

While previous studies have demonstrated the effectiveness of bulb-outs in improving pedestrian visibility and increasing driver yielding rates, they have primarily relied on either driving simulators or observational studies without systematically isolating visibility constraints. Moreover, most studies focus separately on either driver behavior or pedestrian visibility, without fully considering their interaction in complex road environments. This study addresses these gaps by examining driver behavior and perception under varying visibility constraints, including parked vehicles and sidewalk pedestrians, within a controlled field experiment.

3. FIELD EXPERIMENT

The experiment took place at the University of Tokyo Kashiwa Campus Research Field (Institute of Industrial Science, The University of Tokyo, n.d.) on 23rd and 24th of October, and 1st of November, 2024. Each experiment consisted of 20 scenarios, during which a single participant drove a vehicle and completed a questionnaire. Including test drives and break time, the entire session took approximately 1.5 hours per participant. Maximum of four experiments were conducted on each day from 9 a.m. to 4 p.m. The experiment has been approved through the ethical review by the Office for Life Science Research Ethics and Safety, the University of Tokyo.

3.1.1 Field Settings

The Experiment Field (Institute of Industrial Science, The University of Tokyo, n.d.) is a closed test course, originally with two-lane road with 3.0 m lane width and 0.5 m shoulders for both sides. During the experiment, a portion of the course was converted to a one lane road with 3.25 m lane width to provide 1.5 m shoulder, reflecting a street design intended for multiple curbside functions, such as on-street parking, marked with tentative road markings. An unsignalized crosswalk was also tentatively paved at the midblock.

The driving direction was one-way, as indicated by the yellow arrow in Figure 2. Crossing pedestrians also followed a single pattern, approaching from the left-hand side of the vehicle. The highlighted blue region is the section of interest for this research, where only one side of the sidewalk is provided. No traffic lights were operational during the experiment and no other traffic sign were added in the closed test course. The pink and green boxes along the yellow arrow refer to the starting location and on-street parked vehicles that will be explained in Section 3.1.3, respectively. A speed limit was set as 30 km/h considering the safety during experiment operations.

As a basic visibility constraint, 6 white poles were settled along the section of interest with 6~13 m distance from each other, imitating any possible poles such as lighting poles.

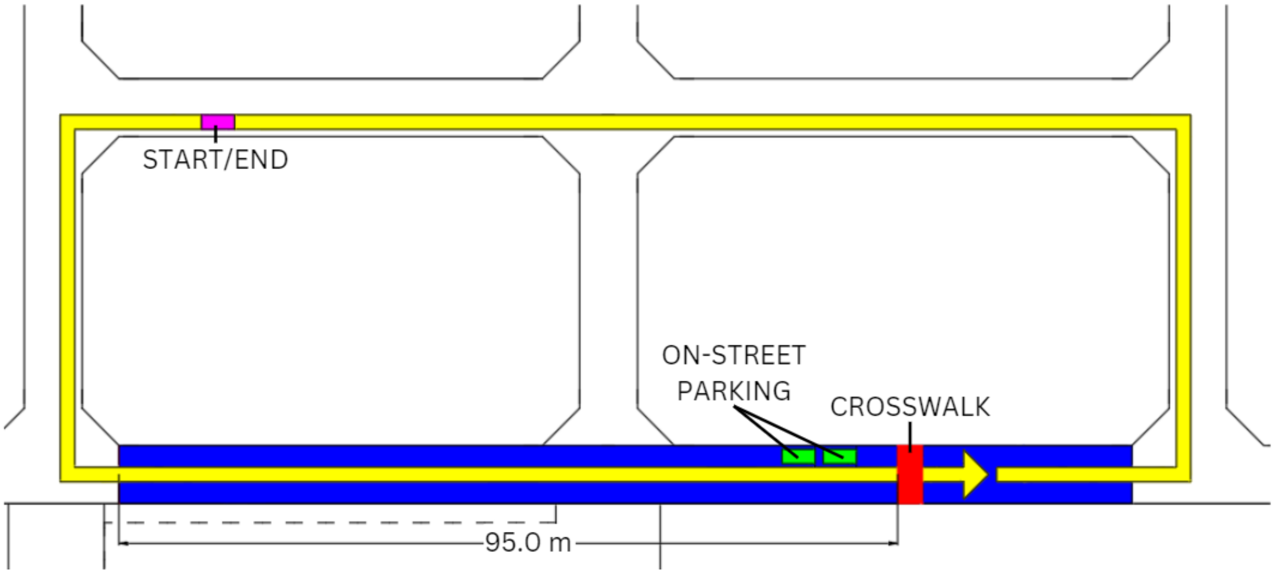


Figure 2. Experimental Set-up

3.1.2 Participants

A total of ten driver participants were outsourced from a recruiting agency for the experiment. The recruitment agency required participants to drive more frequently than once a month. There were five males and five females, and their ages were distributed between 30 to 49 years old. Hereafter, this paper calls each participant with his/her ID consists of "P" and the number from 1 to 10, such as P1.

A brief explanation on the purpose of the experiment, determining safer geometry of midblock crosswalks for pedestrians, was given, however assumed benefits of the bulb-out were not yet discussed. The participants were informed that crossing pedestrians may or may not exist depending on the scenarios. A speed limit of 30 km/h was given to the participants but were instructed to drive as close to their real-life driving during the experiment. To give the participants time to adjust to driving with the test vehicle (i.e., MAZDA2) and experiment, two rounds of practice driving were given before the experiment proper. After each driving scenario and at the end of the experiment, the participants were requested to answer the questionnaire, which will be explained in Section 4.2.2.

3.1.3 Scenarios

Crosswalk Geometry: Two types of crosswalks were tested for the experiment, the normal crosswalk (hereafter, abbreviated as "NR") and the bulb-out crosswalk (as "BO"). NR, which does not apply the bulb-out, includes 1.5 m of road shoulder as illustrated in Figure 4(a). BO extends the sidewalk to the roadway, occupying the shoulder width of 1.5 m as well as narrowing the lane width by 0.5 m, thus lessening the original crosswalk distance of 3.25 m to 2.75 m in Figure 4(b). To facilitate multiple experiments, the bulb-out had to be removable per participant. To mimic a real-life bulb-out crosswalk, beige cobblestone sheets and two planter boxes were laid out for the bulb-out.

In both types, crosswalk pavement is 3.0 m wide and consists of alternating white and black stripes with widths of 0.45 m, resembling a zebra pattern. The stop line is located 1 m upstream of the crosswalk.

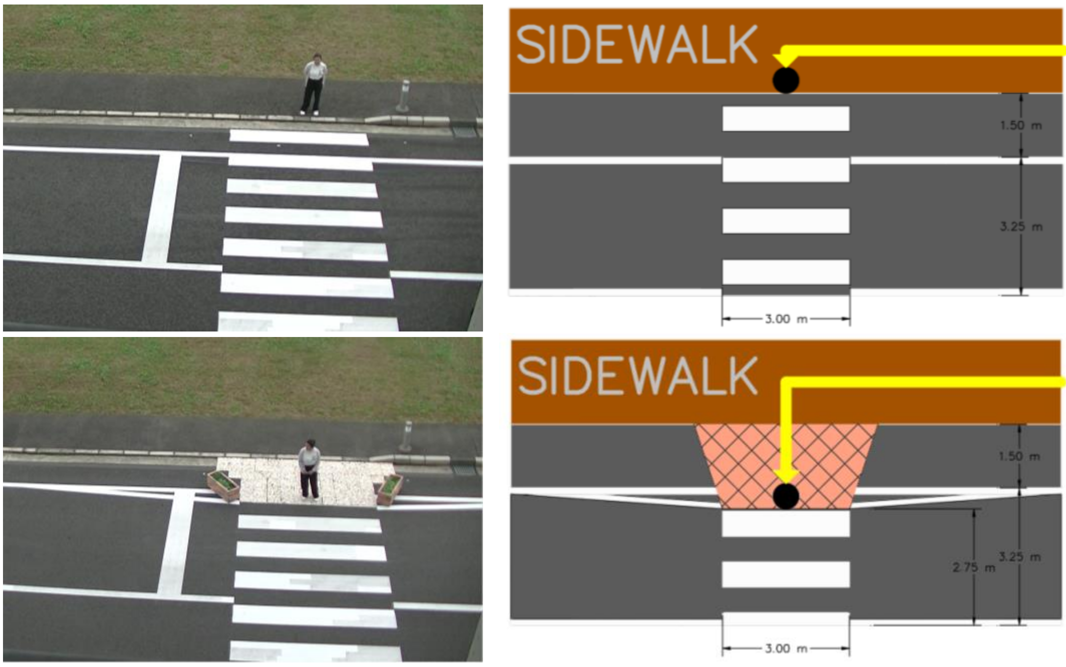


Figure 3. Types of Crosswalks: Normal (NR) (upper) and Bulb-out (BO) (bottom)

Crossing Pedestrian Arrival: There are five different crossing pedestrian arrivals for this experiment. "None" refers to absence of crossing pedestrian, while "Basic Arrival (BA)" refers to the scenarios with a crossing pedestrian at either normal and bulb-out crosswalk. The crossing pedestrian walks towards both the crosswalk and the vehicle as shown in the yellow arrows in Figure 3, and arrives the crosswalk when the vehicle is driving around 15-25 m upstream of the crosswalk. The only difference in basic arrival of crossing pedestrian for NR and BO is the waiting position of the crossing pedestrian. For the waiting position at normal crosswalk, the crossing pedestrian is still inside the sidewalk while in bulb-out crosswalk, the crossing pedestrian enters the bulb-out as shown in Figure 3. The waiting position is around 0.5 m away from the edge of the crosswalk.

"Early Arrival and Crossing" means that the crossing pedestrian arrives at the crosswalk earlier than BA, and cross without hesitation due to the large distance between the pedestrian and the vehicle, approximately 60m away from the crosswalk. "Early Arrival and Waiting" simulates an inattentive pedestrian who also arrived early at the crosswalk but is inattentive to their surroundings and approaching vehicle, thus providing the participant an option to either stop for the pedestrian or continue driving. These scenarios were prepared to prevent participants from becoming too familiar with the basic pedestrian arrival patterns.

A scenario that combines the presence of parked vehicle and crossing pedestrian arrival, “Arrival from Parking” refers when the crossing pedestrian comes out of the parked vehicle 5m away from the crosswalk. This is the only scenario where the crossing pedestrian is walking with their back to the vehicle and moving towards the same direction of the vehicle.

Presence of Sidewalk Pedestrians: To consider the complexity and confusion in drivers’ yielding decision, two types of other pedestrians were considered than crossing pedestrian mentioned in Section 3.1.3: sidewalk pedestrians (SWP) and nearby standing pedestrian (NSP).

The sidewalk pedestrians (SWP) walk along the sidewalk near the crosswalk. If there is a crossing pedestrian in the scenario, there would be two sidewalk pedestrians. The first pedestrian walks along the same direction of the vehicle, while the other one walk towards the vehicle. When there is no crossing pedestrian, the number of sidewalk pedestrians is three – in addition to the two sidewalk pedestrians mentioned above – and the additional pedestrian arrives similarly to crossing pedestrian but does not stop at the crosswalk and simply passes by.

A nearby standing pedestrian (NSP) stands at 8 m upstream from the crosswalk, to demonstrate a passenger who is waiting for an incoming bus/vehicle around the sidewalk. This pedestrian does not move from this position and uses a smartphone, acting inattentive during the scenario duration.

Presence of Parked Vehicles: In addition to the white poles, parked vehicles are one of the hardest visibility constraints for drivers to find crossing pedestrian and yielding decision. To check the impact of parked vehicles, on-street parking was also included in the scenarios. There were two values of clearance from the upstream edge of the crosswalk to the parked vehicle selected for this experiment, 5 m or 10 m. AASHTO (American Association of State Highway and Transportation Officials, 2021) recommends a 6 m clearance of on-street parking from the crosswalk, thus the distances of 5 m and 10 m were chosen to confirm this recommendation. In addition, Japan Road Traffic Law states that on-street parking is prohibited within 5 m from the both edges of the crosswalk.

In summary, a total of 20 scenarios were simulated with varying conditions of crosswalk geometry, crossing pedestrian arrival, presence of sidewalk pedestrians, and presence of parked vehicles. For the feasibility of changing crosswalk geometry, the normal crosswalk scenarios were simulated together, same with the bulb-out crosswalk. Considering the order of driving exposure under different crosswalk geometry, half of the participants (namely, participant 1, 3, 5, 8, and 10) started with the bulb-out crosswalk first, whereas the remaining participants (2, 4, 6, 7, and 9) started with the normal crosswalk. The scenarios were arranged in a fixed but carefully designed order, as shown in Table 1, to make it difficult for drivers to anticipate the upcoming scenario, particularly after the basic arrival scenarios in both NR and BO conditions. “Code” in Table 1 abbreviates the scenario’s conditions based on the types of crosswalks, crossing pedestrian arrival, presence of parking and/or other pedestrians, which will be used to cite for each scenario in the following sections of the paper.

Table 1. Order of Experiment Scenarios for P1, 3, 5, 8, and 10

Scenario No.	Code	Type of Crosswalk	Crossing Pedestrian Arrival	Presence of Parking/Other Pedestrians
1	BO_N_N	BO	None	None
2	BO_BA_N	BO	Basic Arrival	None
3	BO_BA_PV5	BO	Basic Arrival	Parking-5m
4	BO_N_SWP	BO	None	Sidewalk-Pedestrian
5	BO_AP_PV5	BO	Arrival from Parking	Parking-5m
6	BO_N_PV5	BO	None	Parking-5m
7	BO_BA_SWP	BO	Basic Arrival	Sidewalk-Pedestrian
8	BO_N_NSP	BO	None	Nearby-Standing-Pedestrian
9	BO_BA_PV10	BO	Basic Arrival	Parking-10m
10	NR_N_N	NR	None	None
11	NR_BA_N	NR	Basic Arrival	None
12	NR_N_PV5	NR	None	Parking-5m
13	NR_BA_SWP	NR	Basic Arrival	Sidewalk-Pedestrian
14	NR_BA_PV10	NR	Basic Arrival	Parking-10m
15	NR_N_SWP	NR	None	Sidewalk-Pedestrian
16	NR_EAC_N	NR	Early Arrival and Crossing	None
17	NR_N_NSP	NR	None	Nearby-Standing-Pedestrian
18	NR_AP_PV5	NR	Arrival from Parking	Parking-5m
19	NR_BA_PV5	NR	Basic Arrival	Parking-5m
20	NR_EA_N	NR	Early Arrival and Waiting	None

3.1.4 Data Collection

A GNSS recorder, GARMIN Oregon 790 TJ, was equipped in the vehicle that the participants drove. It collected the vehicle trajectory every one second based on GNSS including GNS, GLONASS, and QZSS. Four video cameras were set either inside or outside the vehicle in the field to record the experiment, as shown in Figure 4. The participants were also requested to wear heart-rate sensor and eye glasses to record their heart rates and eye movement, which were not analyzed in this study. All the data were synchronized using one global clock for the experiment.

Figure 4. Examples of Video Recordings During the Experiment

After each scenario, a short questionnaire was given to the participants to quickly assess their experience. Also, a short break occurred every five rounds of driving to minimize driver's fatigue as well as to change the road geometry and measurement equipment maintenance. After completing all the 20 scenarios, participants were given a final questionnaire which explains the assumed benefits of the bulb-out crosswalk and asks if they experienced the benefits through the experiment. Other questions include asking about the participants' real-life driving behavior.

4. HYPOTHESIS AND ANALYSIS METHOD

4.1 Hypothesis

The presence of sidewalk pedestrians and parked vehicles in some scenarios, along with the common roadside white poles in all scenarios increases the uncertainty and complexity in determining pedestrians' intent to cross the crosswalk. The main focus of this research is to understand the impact of this uncertainty and complexity on drivers' deceleration behavior upstream of the crosswalk and their perception.

As depicted in Figure 5, BO can improve drivers' visibility of waiting pedestrians who intend to cross because pedestrians standing inside the bulb-out are not obstructed by the roadside poles and fit within a narrower field of vision compared to those standing inside the sidewalk. This benefit may be emphasized with the presence of sidewalk pedestrians because the BO separates crossing pedestrians from other sidewalk pedestrians. Such a benefit may contribute to reducing the uncertainty and complexity in drivers' decision making, thus making smoother or more reasonable deceleration towards crossing pedestrian while avoiding unnecessary deceleration where there is no crossing pedestrian. In addition, the physical structure of the bulb-out and the narrowed traffic lane may also increase drivers' cautiousness, leading them to reduce their basic passing speed.

Figure 5. Examples of Driver's View of NR (Left) and BO (Right) with Sidewalk Pedestrians

The presence of parked vehicles largely affects drivers' visibility by blocking crossing pedestrian at some ranges. Here, the blocked range differs between BO and NR as well as the position of the parked vehicle. These visibility constraints increase the uncertainty of drivers, making their deceleration earlier or unstable than those without parked vehicles.

4.2 Analysis Indices

4.2.1 Behavioral Analysis on Deceleration Trend

To highlight and compare aforementioned impacts of the uncertainty and complexity due to visibility constraints on drivers' behavior in different scenarios, deceleration trends were extracted based on the speed profile. Here, the analysis was basically done from two viewpoints. One viewpoint is how much the uncertainty or complexity of the scenarios made drivers decelerate in advance to the minimum required (reversely, how much the uncertainty or complexity made deceleration late or more abrupt), which is applied for the scenarios with crossing pedestrian that required a full stop in front of the crosswalk. Another viewpoint is how much the uncertainty or complexity of the scenarios made drivers reduce the driving speed in the scenarios that theoretically did not require the vehicles to slow down because of the absence of crossing pedestrians.

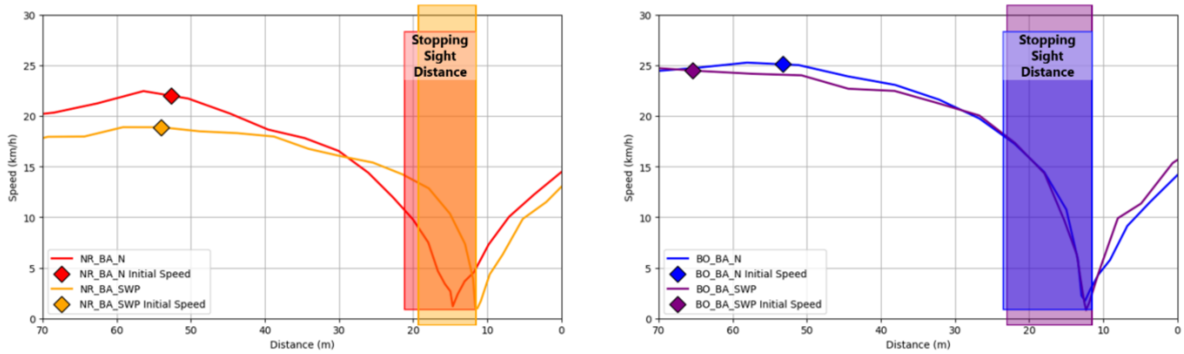


Figure 6. P8 Speed Profiles with/without Sidewalk Pedestrians along NR (left) and BO (right)

Figure 6 depicts examples of speed profiles in the scenarios with a crossing pedestrian and with/without sidewalk pedestrians under BO and NR conditions. In this figure, distance in the horizontal axis means the distance from the upstream edge of the crosswalk (0) to the vehicle. In NR, with sidewalk pedestrians (NR_BA_SWP), this participant made more abrupt deceleration compared to the scenario without sidewalk pedestrians (NR_BA_N). As for BO, there is minimal change in speed profile regardless of the presence of sidewalk pedestrians. This trend is the focus of the first viewpoint.

To extract earlier deceleration, the proportion of speed reduction at two different regions, upstream and downstream from the stopping sight distance was defined. The stopping sight distance is the distance required for a vehicle driving at a certain speed to make a full stop, taking account of the driver's reaction time followed by the constant deceleration. This can serve as a benchmark for evaluating how much earlier (more upstream) drivers decelerated than the minimum distance required by the stopping sight distance.

The stopping sight distance, SSD is mathematically calculated as follows:

$$SSD = Vt + \frac{V^2}{2a}$$

where,

V : initial driving speed in m/s,
t : brake reaction time in s,
a : deceleration rate in m/s^2

In this research, the initial speed was interpolated at the first instance when acceleration is 0 (diamond markers in Figure 6). This marks the initiation of the vehicle's deceleration phase, which varies across different scenarios and participants. The deceleration rate is assumed as 3.4 m/s^2 referring to the value of a comfortable deceleration rate in AASHTO (2018). Regarding the brake reaction time, one Japanese research (National Traffic Safety and Environment Laboratory, 2022) has concluded that the brake reaction time of Japanese drivers is 0.75s. Given that the experiment is a controlled closed course design and participants knew there was a crosswalk, this value was further reduced and assumed as 0.7s. Considering different preferred stopping positions from the crosswalk observed by each participant, the stopping sight distance was measured from the mean of each participant's stopped positions in all the scenarios that required a full stop. In Figure 6, the shaded boxes represent the calculated stopping sight distances based on different initial speeds, while their rightmost boundaries indicate the mean of stopping positions of this participant.

Based on this distance as a boundary, the road section upstream of the crosswalk was divided into two: closer upstream (within the stopping sight distance) and far upstream. Accordingly, the proportion of speed reduction outside of the stopping sight distance, $P_{outside}$, was calculated to see the amount of earlier deceleration than theoretically required as follows:

$$P_{outside} = \frac{S_{ini} - S_{boundary}}{S_{ini}}$$

where,

S_{ini} : initial speed at start of deceleration (acceleration = 0 m/s^2)

$S_{boundary}$: speed at the boundary between within and outside of the stopping sight distance measured from the stopping position,

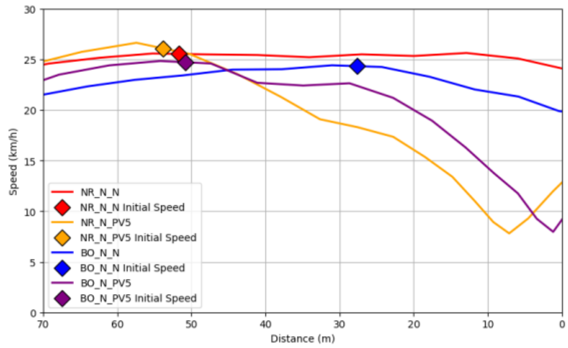


Figure 7. Speed Profiles without Crossing Pedestrians and with/without 5m Parked Vehicle (P4)

Another viewpoint was on the scenarios which did not require a full stop due to the absence of a crossing pedestrian. Figure 7 depicts examples of speed profiles in the scenarios without crossing pedestrian and with/without parked vehicles under BO and NR conditions. Obviously, the scenarios with parked vehicle (NR/BO_N_PV5) lead greater deceleration compared to those without (NR/BO_N_N). To extract the difference of these speed profiles, the average speed was taken from the start of deceleration (defined above) to the upstream edge of the crosswalk.

In addition, regarding the scenarios with a parked vehicle, the view of the sidewalk or bulb-out connected to the crosswalk was blocked in the certain range of the upstream section, as illustrated in Figure 8. This range was defined as "blocked range" in this study, and its impact on deceleration was analyzed by comparing the speed reduction made within this range.

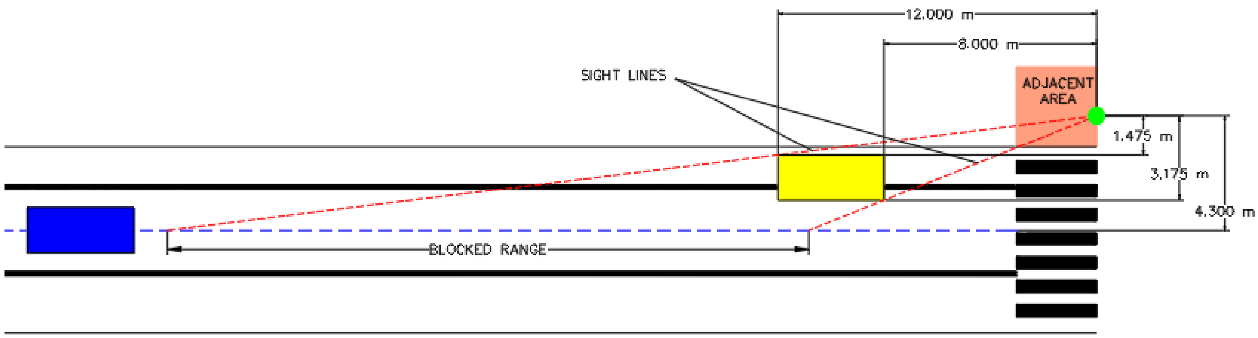


Figure 8. Definition of Blocked Range

The blocked range was defined as the range in the upstream of the crosswalk where drivers' view of the adjacent area was blocked due to the parked vehicle. Here, the adjacent area is the area where a crossing pedestrian, if he/she existed, approached the waiting position, as denoted by the orange area. Blockage of this adjacent area makes drivers difficult to confirm if there is a crossing pedestrian. Given this adjacent area, blockage area could be theoretically calculated based on the proportional relation of longitudinal and lateral distance of the parked or approaching vehicle with respect to the arriving pedestrian into the adjacent area, by extending the sight lines for the arriving pedestrian to the rear-left and front-right edges of the parked vehicle. Namely, longitudinal distance of the approaching vehicle in which the drivers' sight line is blocked by the parked vehicle, $LOND_V$, is calculated by the following equation, for each of these two sight lines.

$$LOND_V = \frac{LOND \times LATD_V}{LATD}$$

where,

$LOND$	: longitudinal distance of the parked vehicle, assumed as in Figure 8,
$LATD$	: latitudinal distance of the parked vehicle, assumed as in Figure 8,
$LATD_V$	: latitudinal distance of the approaching vehicle, assumed as in Figure 8,
$LOND_V$	: longitudinal distance of the approaching vehicle, assumed as in Figure 8.

The calculated $LOND_V$, distance with respect to the arriving pedestrian into the adjacent area, are then adjusted to reference the upstream edge of the crosswalk by subtracting 3 m or the width of the crosswalk. This adjusted $LOND_V$ for the sight lines toward the rear-left and front-right of the parked vehicle are the start and end of the blocked ranges, respectively. This range differs by the clearance of the parked vehicle from the crosswalks. Different arrival direction of crossing pedestrian into the adjacent area in the scenarios with a crossing pedestrian arriving from the parked vehicle (NR_AP_PV5 and BO_AP_PV5) also creates a different blocked range, as listed in Table 4.

Table 2. Blocked Ranges of Normal and Bulb-out Crosswalk

	Adjacent Area		Crossing Point			
			Normal		Bulb-out	
	Start (m)	End (m)	Start (m)	End (m)	Start (m)	End (m)
5m Parked Vehicle (PV5)	32.0	7.8	58.4	8.2	NA	29.4
10m Parked Vehicle (PV10)	46.6	14.6	87.0	15.6	NA	53.1
Arrival from 5m Parked Vehicle	26.2	6.8	58.4	8.2	NA	29.4

In the analysis, to confirm if this blocked range induces drivers' uncertainty, speed reduction without crossing pedestrian but with a 5m parked vehicle (NR_N_PV5 or BO_N_PV5) was calculated for the blocked range and compared to that without both crossing pedestrian and parked vehicle (NR_N_N or BO_N_N) in the same region. NR_N_N and BO_N_N do not have any blockage, thus speed reduction in that range is assumed to be the baseline speed reduction caused by the cautiousness of the drivers.

Wilcoxon signed rank tests were conducted to evaluate the statistical significance of differences in the aforementioned indices across scenario comparisons. A significance level of 0.05 was used to determine whether the differences were statistically significant based on the *p*-values. Effect size *r* was also reported to reflect the magnitude of these differences regardless of sample size, and was interpreted using Cohen's thresholds (Cohen, 1988): small ($r \geq 0.10$), medium ($r \geq 0.30$), and large ($r \geq 0.50$).

4.2.2 Perception Analysis

As mentioned in Section 3.1.2, a short questionnaire was given to the participants after each round of driving. The questionnaire was based on a Likert scale, requesting to answer the level of agreement/disagreement with the three statements presented in Table 3. Then, the answers were converted into the values listed in Table 4. Positive perceived anxiety refers to absence of anxiety while a negative value shows presence of anxiety. On the other hand, positive values for visibility indicate that the driver and vehicle are visible while negative values demonstrate lesser visibility.

Table 3. Short Questionnaire Content

Name	Statement
Anxiety	I feel anxiety or hesitation when approaching the crosswalk.
Driver's Visibility	It was easy to recognize whether there was pedestrian trying to cross the crosswalk.
Expected Pedestrian's View Visibility	I felt that the pedestrian could clearly see the vehicle I was driving (only when there was a pedestrian).

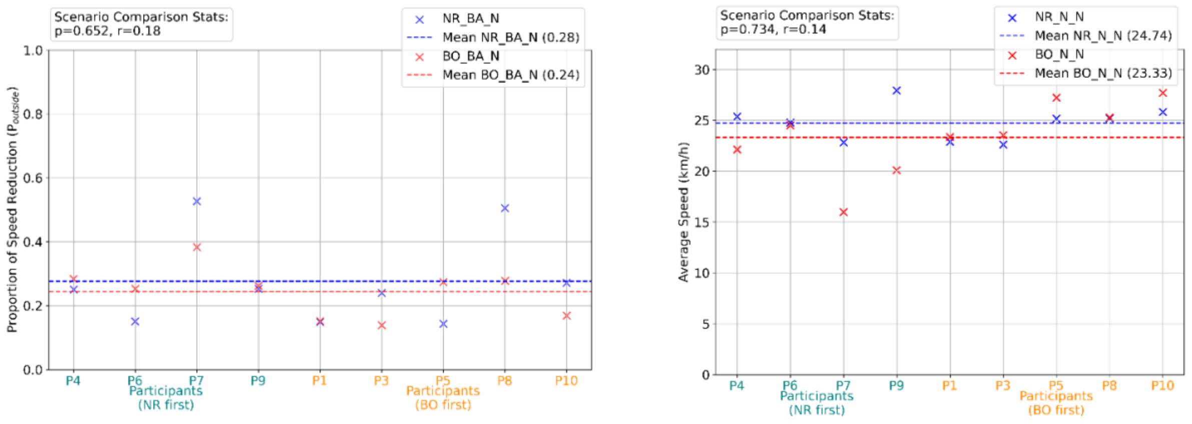
Table 4. Conversion of Values of Short Questionnaire

Name		Strongly Applicable	Mostly Applicable	Somewhat Applicable	Somewhat Not Applicable	Mostly Not Applicable	Not Applicable
Anxiety	Converted Value	-3	-2	-1	+1	+2	+3
Driver's Visibility		+3	+2	+1	-1	-2	-3
Expected Pedestrian's View Visibility		+3	+2	+1	-1	-2	-3

The questionnaire data was analyzed based on consistent patterns in the observed data, and additionally, binomial tests were conducted to provide supplementary context regarding perceptual tendencies ($p < 0.05$), though their interpretation was constrained by the sample size.

5. RESULTS

5.1 Basic Impact of Bulb-out



(The value of NR_N_N and NR_BA_N of P2 could not be calculated due to lack of recording.)

Figure 9. $P_{outside}$ and Average Speeds of Normal and Bulb-out Crosswalk

Figure 9 compares $P_{outside}$ and Average Speeds in the simplest cases, which involved neither sidewalk pedestrians nor a parked vehicle. To check for potential order effects, participants were grouped according to which crosswalk geometry they encountered first. Teal labels represent participants who drove through the normal crosswalk (NR) first, while orange labels indicate those who experienced the bulb-out crosswalk (BO) first.

In Figure 9, no significant difference in $P_{outside}$ was found between the basic arrival of crossing pedestrians at the two crosswalk geometries, NR_BA_N and BO_BA_N (p = 0.652, r = 0.18). Although BO narrows the lane width, the presence the of a crossing pedestrian appears to have a stronger influence on driver deceleration than the crosswalk geometry alone. Order effects were not clearly observed, as participants exhibited varied responses – some showed greater $P_{outside}$ in the crosswalk geometry tested first, while others did not.

For the simplest scenarios without crossing pedestrian and other elements, Figure 9 compares the average speed of NR_N_N and BO_N_N. It was hypothesized that the physical structure of BO would reduce approach speeds even in the absence of crossing pedestrian, but statistical analysis (p = 0.734, r = 0.14) did not provide evidence of such a speed reduction. This may be attributed to generally modest driving speeds throughout the experiment, likely due to field limitations and participants' gentle driving styles, resulting in only minor differences between the scenarios. Interestingly, drivers in the NR-first group showed lower average speeds in BO scenarios than those in the BO-first group, whereas such a trend was not observed for NR scenarios. This may be attributed to the fact that the NR-first group encountered the bulb-out crosswalk for the first time during the experiment, whereas the BO-first group had already experienced it during the test drive. This suggests that drivers reduced their speed more when encountering BO for the first time, possibly due to unfamiliarity – though this trend should be interpreted cautiously given the small sample size.

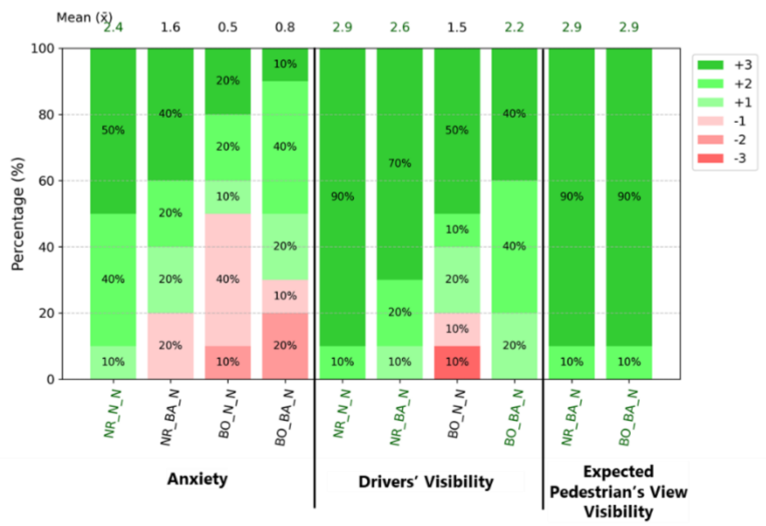


Figure 10. Perception Questionnaire of Normal and Bulb-out Crosswalk

Figure 10 indicates the questionnaire responses on these scenarios. Here, scenario labels and means that are highlighted by dark red or green indicates statistical significance ($p < 0.05$) towards positive or negative perception in binominal test. Figure 10 indicates that participants generally reported greater anxiety in BO scenarios compared to NR, suggesting greater caution despite the binomial test not reaching significance due to the limited sample size. This suggests that, while some participants felt increased anxiety in BO scenarios, the responses were relatively mixed. This may be attributed to the physical structure of BO being positioned closer to the driving lane, as well as the participants' lack of prior experience navigating through BO crosswalks. For drivers' visibility and expected pedestrian's view visibility, most responses were positive across all scenarios, which was also supported by the binominal test ($p < 0.05$). This indicates a consistent perception among participants that visibility was good, even with white poles present. Notably, BO_N_N, which was the first exposure to BO for most participants, did show more varied responses in anxiety and drivers' visibility, possibly reflecting initial unfamiliarity, but not to a degree considered statistically significant.

5.2 Impact Under the Presence of Sidewalk Pedestrians

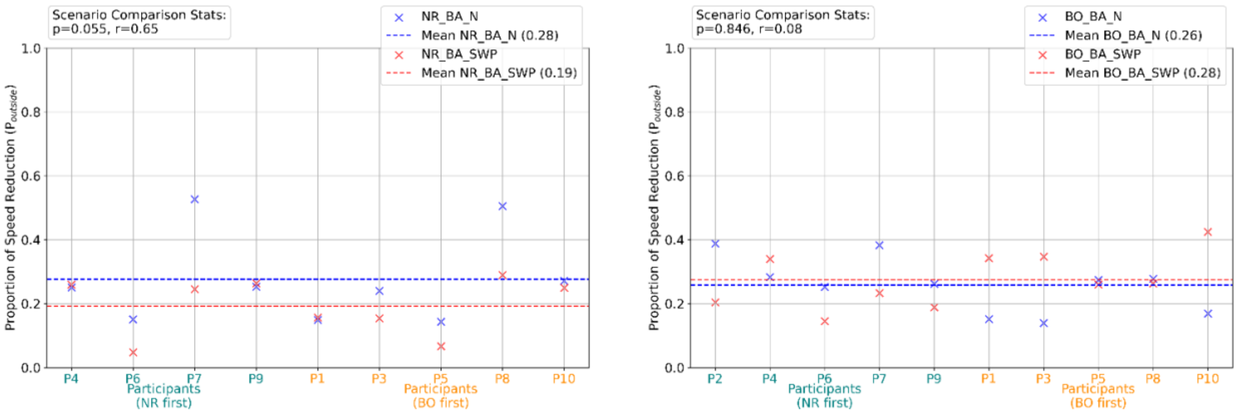


Figure 11. $P_{outside}$ of Normal and Bulb-out Crosswalks with Sidewalk Pedestrians

Figure 11 compares scenarios with a crossing pedestrian and added sidewalk pedestrians. In NR, mean $P_{outside}$ was lower in NR_BA_SWP than NR_BA_N (p = 0.055, r = 0.65), meaning a greater proportion of deceleration occurred within the SSD region, suggesting that participants had greater speed reduction closer to the crosswalk. This likely reflects increased uncertainty among participants, who may have been unsure if any sidewalk pedestrians intended to cross, prompting more pronounced deceleration closer to the crosswalk. In contrast, BO scenarios showed no significant difference (p = 0.846, r = 0.08), indicating more consistent driver behavior. The clear crossing intent in BO likely helped drivers distinguish sidewalk pedestrians. This is seen particularly in P7 and P8, whose $P_{outside}$ values were nearly identical for BO_BA_N and BO_BA_SWP.

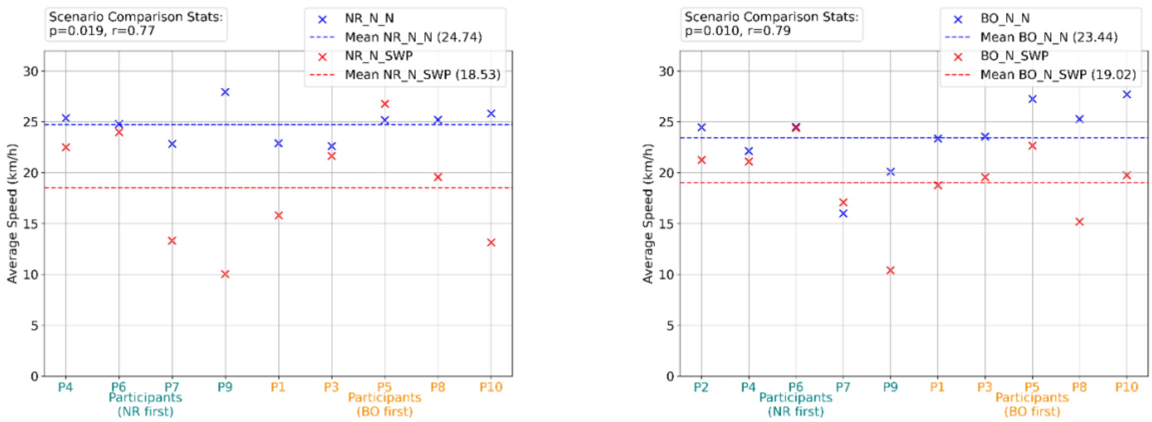


Figure 12. Average Speeds of Normal and Bulb-out Crosswalks with Sidewalk Pedestrians

In the scenarios without crossing pedestrian (Figure 12), both NR and BO have shown a notable decrease in average speeds when sidewalk pedestrians are present (NR: p = 0.019, r = 0.77; BO: p = 0.010, r = 0.79). This confirms that the addition of sidewalk pedestrians contributes to greater uncertainty for the participants, prompting them to be prepared for unexpected crossing. This effect is observed in both crosswalk types; however, the decrease in average speed between the crosswalk types is slightly less pronounced for BO (mean difference in NR = 6.21 km/h, BO = 4.42 km/h). This may be because the bulb-out design emphasizes crossing intent, leading participants to decelerate specifically for crossing pedestrians only and be less influenced by the presence of other sidewalk pedestrians.

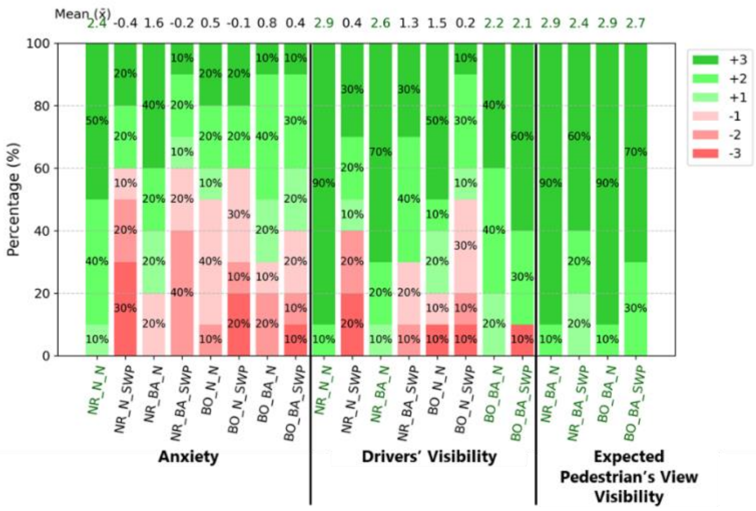


Figure 13. Perception Questionnaire of Normal and Bulb-out Crosswalk with Sidewalk Pedestrians

Based on the questionnaire results in Figure 13, the addition of SWP led to increased anxiety ratings for both NR and BO crosswalks, with a larger increase in NR. Since the physical design of BO inherently heightens driver anxiety, participants are already more cautious upon noticing a BO, which reduces the severity of any further increase in anxiety. Anxiety rating tended to increase with the addition of sidewalk pedestrians, with most participants reporting higher anxiety in these scenarios compared to scenarios without sidewalk pedestrians. For drivers' visibility, the presence of additional pedestrians reduced the proportion of positive ratings in both crosswalk types, but the majority of responses in the BO_BA_SWP remained positive. The binomial test confirmed that perception of drivers' visibility remained significantly positive for BO scenarios with crossing pedestrians, with or without the addition of other sidewalk pedestrians. This suggests that BO contributed in differentiating between crossing and sidewalk pedestrians. Expected pedestrian's view visibility stayed highly positive in all scenarios, likely due to clear sightlines without physical obstructions.

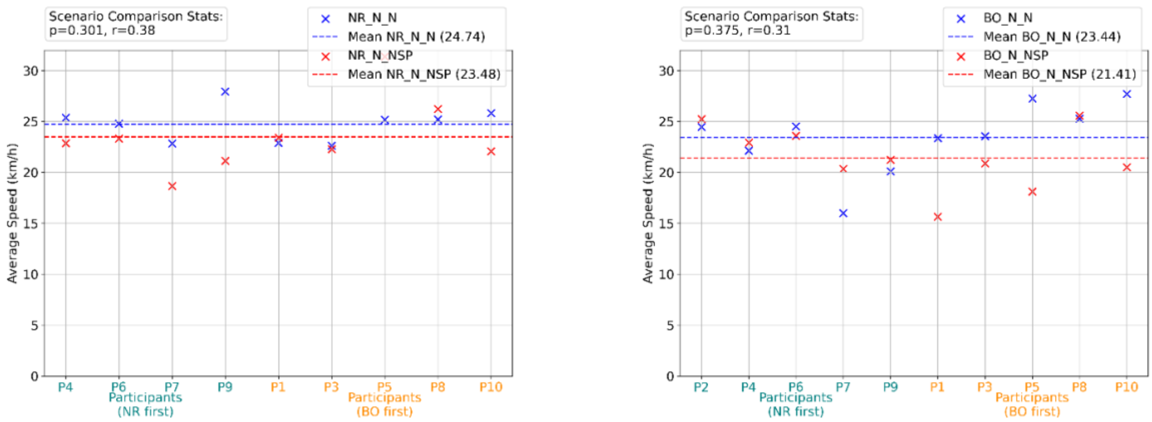


Figure 14. Average Speed of Normal and Bulb-out Crosswalks with Nearby Standing Pedestrians

Figure 14 shows that the nearby standing pedestrian (NSP) led to lower average speeds in both NR and BO, though the reduction was smaller than with sidewalk pedestrians and not statistically significant (NR: p = 0.301, r = 0.38; BO: p = 0.375, r = 0.31). While some drivers appeared cautious when approaching the NSP, others seemed to judge early that the NSP had no crossing intent, resulting in mixed speed reduction trends. Further investigation is needed to understand how drivers interpret pedestrian's crossing intent and speed control.

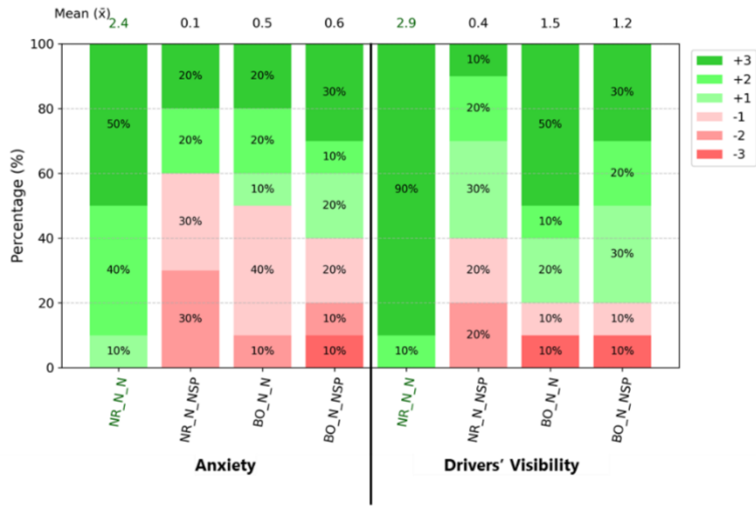


Figure 15. Perception Questionnaire of Normal and Bulb-out Crosswalk with NSPs

Perceived anxiety increased for both NR and BO with the introduction of NSP, with a greater increase toward negative ratings in NR. For drivers' visibility, both NR and BO scenarios received negative ratings with the addition of NSPs, though this was more pronounced in NR_N_NSP.

5.3 Impact Under the Presence of a Parked Vehicle

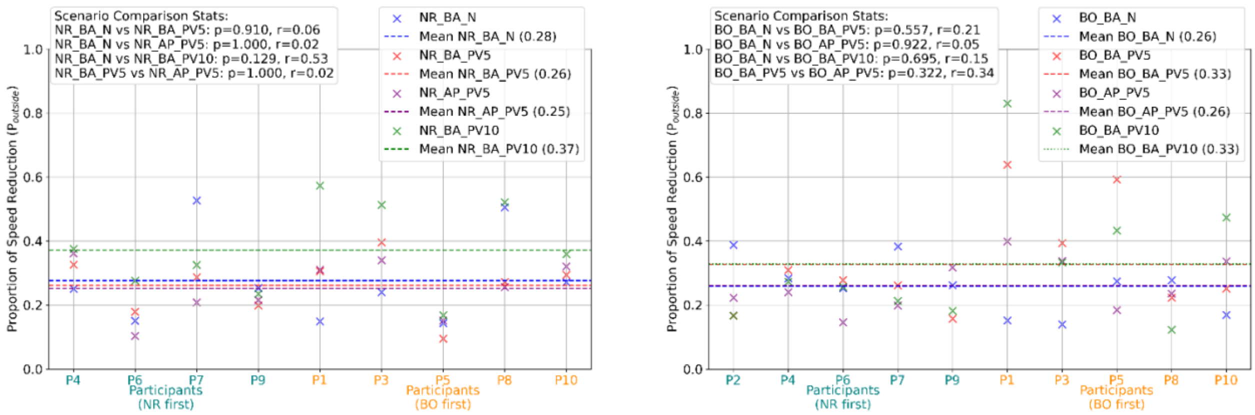


Figure 16. $P_{outside}$ of Normal and Bulb-out Crosswalks with Parked Vehicles

Figure 16 examines the impact of parked vehicles in scenarios with a crossing pedestrian, either at basic arrival (BA) or arrival from parking (AP). In all parked vehicle conditions, the vehicle occupied the 1.5 m shoulder and slightly encroached into the traffic lane (Figure 8), narrowing the effective lane and introducing a physical obstruction that may have prompted drivers to adopt a lower desired speed when passing. Among the NR scenarios, NR_BA_PV10 had the highest mean $P_{outside}$, with a large effect size (r = 0.53) when compared to NR_BA_N, despite a p-value of 0.129. This increase may reflect two factors: the parked vehicle likely encouraged drivers to slow down earlier due to perceived lane narrowing, and the blocked range caused by the upstream location of the vehicle (46.6 – 14.6m) extended beyond the SSD, increasing caution. In contrast, NR_BA_PV5 and NR_AP_PV5 showed $P_{outside}$ values similar to NR_BA_N, likely because their blocked ranges overlapped with the SSD, reducing their impact. In BO scenarios, mean $P_{outside}$ values were similar across conditions, but individual responses varied more, possibly due to the combination of BO and parked vehicles.

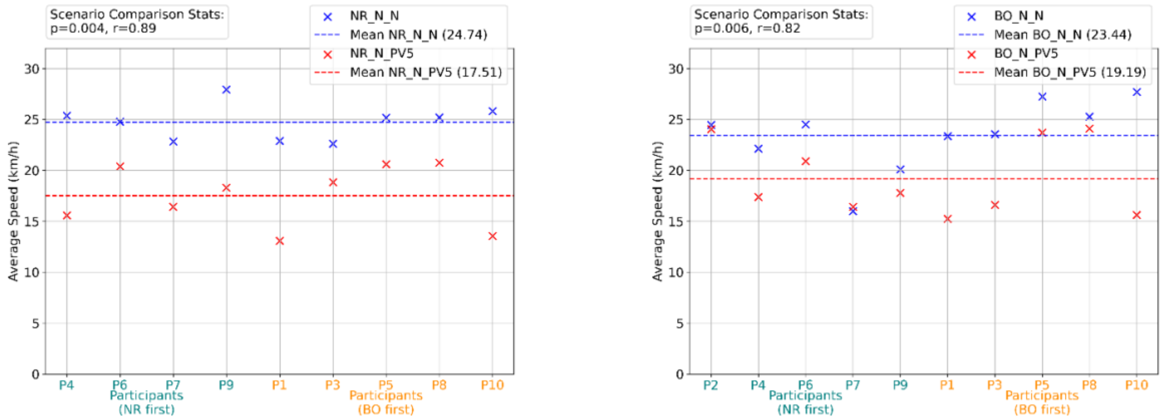


Figure 17. Average Speed of Normal and Bulb-out Crosswalks with Parked Vehicles

Figure 17 visualizes the impact of parked vehicle in scenarios without a crossing pedestrian. The presence of a parked vehicle 5 meters upstream from the crosswalk (PV5) led to a clear decrease in average speeds for both NR and BO scenarios (NR: p = 0.004, r = 0.89; BO: p = 0.006, r = 0.82), with the reduction more pronounced in NR. While both crosswalk types showed reduced speeds, the difference was less apparent in the BO scenarios. The BO design improves sightlines, enabling drivers to regain visibility of the crossing pedestrian's standing position farther upstream, as shown in Table 2. This helps them confirm pedestrian absence earlier, reducing the need for strong deceleration.

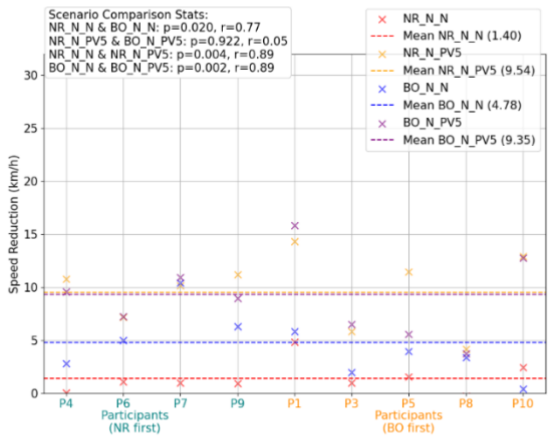


Figure 18. Speed Reduction of NR/BO_N_N and NR/BO_N_PV5 at Blocked Range

To confirm the effect of parked vehicle blockage, Figure 18 compares speed reductions within the blocked range. All comparisons involving parking (NR_N_N vs NR_N_PV5 and BO_N_N vs BO_N_PV5) showed significant differences with large effect sizes (NR: p = 0004, r = 0.89; BO: p = 0.002, r = 0.89), indicating that a parked vehicle substantially increased speed reduction. In NR_N_PV5, drivers slowed down at least 4 km/h more than NR_N_N, reflecting the impact of limited visibility. In BO, the additional reduction from BO_N_PV5 compared to BO_N_N was smaller, likely because BO already encourages cautious driving within this upstream range (32.0 – 7.8m) even without a parked vehicle. A significant difference between NR_N_N and BO_N_N (p = 0.020, r = 0.77) further supports the idea that BO inherently induces speed reduction. Lastly, the insignificant difference between NR_N_PV5 and BO_N_PV5 (p = 0.922, r = 0.05) suggests that the parked vehicle might have concealed the BO, leading to similar driver behavior. This analysis focuses specifically on the blocked range, where most deceleration occurred, in contrast to the broader average speeds analysis in Section 5.1, which were calculated over a wider range and may have included reacceleration after confirming absence of pedestrians.

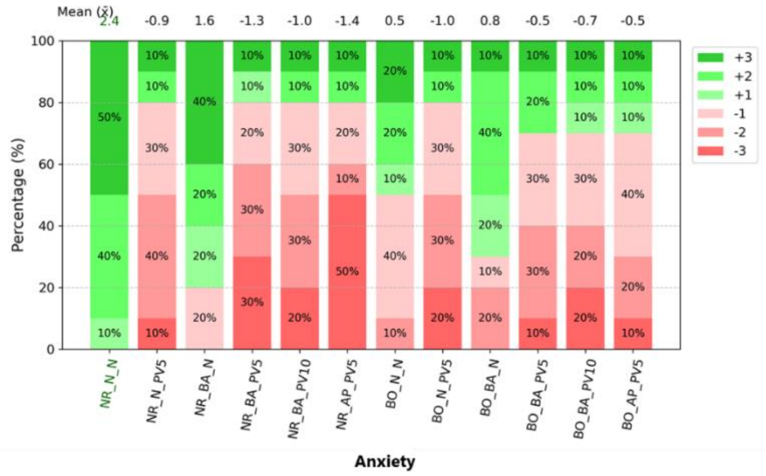


Figure 19. Perceived Anxiety of Normal and Bulb-out Crosswalk with Parked Vehicle

Figure 19 shows that parked vehicles increased participants' anxiety in NR, especially when a pedestrian appeared from a parked vehicle (NR_AP_PV5), likely due to the sudden appearance and uncertainty of crossing intent because of absence in eye contact. Increase in anxiety caused by the parked vehicle is slightly smaller in BO than in NR, likely because of earlier confirmation of presence or absence of pedestrians in BO. Also, anxiety is less sensitive to parking distance or pedestrian arrival pattern in BO compared to those in NR.

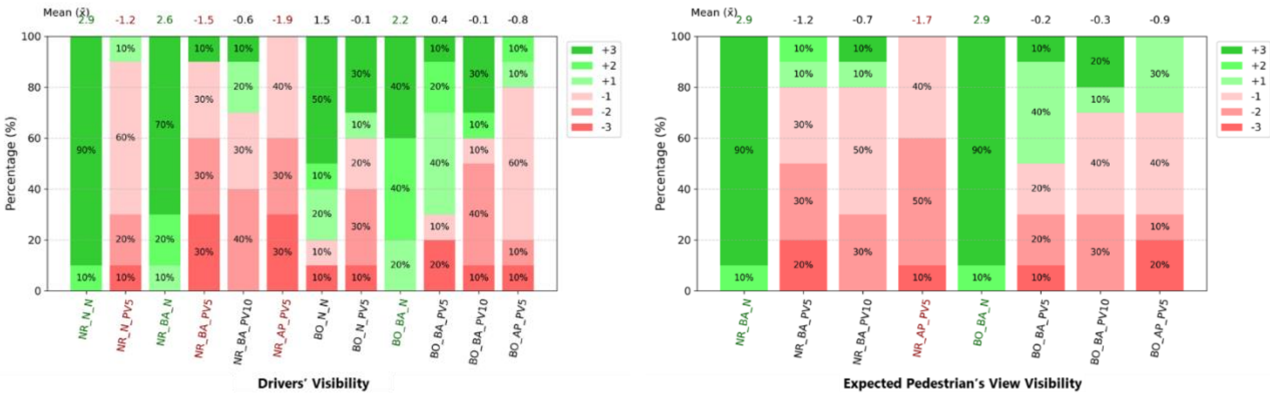


Figure 20. Perceived Drivers' Visibility (left) and Expected Pedestrian's View Visibility (right) of Normal and Bulb-out Crosswalk with Parked Vehicle

Figure 20 illustrates how parked vehicles reduced both drivers' visibility and expected pedestrian's view visibility caused by the parked vehicle. Visibility obstructions within the blocked range made it more difficult to spot pedestrians, as reflected in questionnaire ratings. Scenarios NR_N_PV5, NR_BA_PV5, and NR_AP_PV5 were rated significantly negatively, indicating a consistent perception of diminished visibility. For expected pedestrians' view visibility, NR_AP_PV5 was rated significantly negative, highlighting the impact of a parked vehicle on obstructing the pedestrian's view, especially when the pedestrian suddenly appears from the parked vehicle. Although parked vehicles consistently reduced visibility ratings in both crosswalk types, the BO configuration appeared to slightly mitigate these effects, possibly due to improved sightlines and increased driver awareness provided by BO's advantages.

6. CONCLUSION

6.1 Findings

This study aimed to evaluate the effects of bulb-out crosswalks, parked vehicles, and pedestrian presence on driver behavior and perception based on the controlled field experiments. While generalizability is limited due to the sample size and fixed scenario order, several consistent patterns were observed.

In scenarios with a single crossing pedestrian, no significant differences in deceleration trends were observed between normal and bulb-out crosswalks, suggesting that crossing pedestrian presence, rather than geometry, primarily influenced driver behavior. In contrast, in basic scenarios without pedestrians or parked vehicles, bulb-outs did not significantly affect average speeds from the onset of deceleration to the crosswalk. However, a significant speed reduction was observed closer to the crosswalk (32.0 – 7.8m), likely due to the influence of the bulb-out's physical influence on drivers' desired speeds.

When pedestrians were walking and one of them attempted to cross, driver behavior in normal crosswalk scenarios was more varied, likely due to uncertainty about pedestrian intent. Bulb-out scenarios had more similar responses to scenarios with only a crossing pedestrian, suggesting its geometry helped drivers distinguish between crossing and non-crossing pedestrians. Even with only sidewalk pedestrians, average speeds were reduced in both crosswalk types, possibly due to anticipatory caution. This effect was less pronounced in bulb-out scenarios, possible because crossing intent was more easily inferred based on pedestrian positioning relative to the bulb-out.

Parked vehicles encroached into the lane, narrowing it and acting as physical obstructions. In crossing pedestrian scenarios, they created blocked ranges that hid pedestrians from view. When parked farther upstream, these blocked ranges extended beyond the stopping sight distance, prompting earlier deceleration in anticipation of a potential crossing. A greater proportion of speed reduction occurred upstream in such cases. Even without crossing pedestrians, parked vehicles reduced speed, reflecting heightened caution. This effect was less pronounced in bulb-out crosswalks, where improved sightlines allowed earlier confirmation of pedestrian absence.

Perception results reinforced the aforementioned trends. Anxiety increased in complex scenarios, especially with parked vehicles or sidewalk pedestrians. However, bulb-outs helped mitigate this increase by reducing uncertainty in decision-making. Even without visibility constraints, its physical structure induced a baseline level of caution, lessening anxiety increases when other elements were added. In contrast, normal crosswalks initially had lower anxiety but showed sharper increases. In scenarios with parked vehicles, bulb-outs resulted in lower anxiety, likely because improved sightlines helped drivers confirm pedestrian presence or absence earlier. Visibility ratings followed a similar trend: participants rated bulb-outs more positively in complex scenarios, particularly when both crossing and sidewalk pedestrians were present or when visibility was limited by parked vehicles.

Overall, the findings suggest that bulb-out crosswalks may contribute to safer and more consistent driver behavior by influencing both speed control and perception. The physical structure and design encouraged lower approach speeds, helped drivers distinguish between crossing and non-crossing pedestrians, and improved sightlines in the presence of parked vehicles. Given the limited sample size, fixed scenario order, controlled setting, potential familiarity with the test environment over time, and fixed visibility conditions, these trends should be interpreted with caution. While some behavioral trends were observed across participants, individual driving characteristics also contributed to varied responses. Nonetheless, they offer early insights into how bulb-outs can influence driver behavior and perception, which future studies could validate under more varied and dynamic urban conditions.

6.2 Future Works

Future research will expand how pedestrian arrival timing, driver gaze, and foot movement relate to speed reduction and visibility response. Further experiments with larger, more diverse samples, repeated trials, and randomized scenario orders within crosswalk type may help validate these results. Considering driver demographics and personality traits is also recommended to explain variability.

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