

ANALYZING THE IMPACT OF CROSSWALK TYPES AND VEHICLE MANEUVERS ON PEDESTRIAN CROSSING BEHAVIOR ON UNSIGNALIZED CROSSWALKS IN VIRTUAL REALITY ENVIRONMENT

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Crashes involving pedestrians are particularly common at unsignalized mid-block crosswalks where sometimes vehicles don't yield for pedestrians. For safer crosswalks, not only encouraging safe yielding of drivers, but also improving pedestrians' cognitions and reactions to the vehicles are important. Virtual Reality (VR) environment is expected as an effective tool to analyze the conflicts in depth, while the pedestrian behaviors in VR is not valid well. This study aims to validate pedestrian behavior in the VR and to examine the influence of crosswalk types, vehicle approach speed, on pedestrian crossing and decision-making behaviors. Comparing with the real-world data, pedestrian crossing speed in VR was lower than the real-world and pedestrians waited at farther distance from crosswalk in VR as compared to real-world. The results of the behavior analysis revealed that the higher vehicle speed increased the tendency of pedestrian gap acceptance, leading to a higher rate of unsafe crossings. Pedestrian crossing speeds were higher when they were in the conflict area. Refuge islands increased the percentage of safe crossings especially when vehicles were approaching from far side.

Key Words : *Pedestrian Crossing Behavior, Unsignalized crosswalk, Gap Acceptance, Pedestrian Safety*

1. INTRODUCTION

Pedestrians are regarded as the most vulnerable road users to traffic crashes. As per the report of the World Health Organization (WHO)¹, more than 22% of road crash fatalities worldwide are pedestrians. In Japan, around 36% of road crash fatalities were related to pedestrians and this count is increasing each year². 34% of all these crashes occur on unsignalized midblock crosswalks where pedestrians have abso-

lute priority to cross during pedestrian-vehicle interaction³.

One of the key factors for traffic crashes is non-yielding behavior of drivers. As per a survey, only 30% of the drivers yield for pedestrian on unsignalized crosswalks in Japan even though pedestrians are provided the absolute priority at unsignalized crosswalks by the laws⁴. Considering this, many of the studies have been linked with how to improve vehicle maneuvers. It has been shown that various types of geometric improvements such as two-stage crossings

would improve the yield rate of vehicles and reduce vehicle approaching speed toward crosswalks⁵⁾. Driver behavior as well as pedestrian behavior are both essential in defining the safety performance of conflicts between both road users. For example, in case of very high vehicle yield rate at unsignalized crosswalks, pedestrians always expect vehicles to yield for them and pay less attention towards the approaching vehicles. Despite of high yield rate, some drivers do not yield for the pedestrians and under such circumstances pedestrians may face some serious conflicts if they adopt the usual crossing behavior. Such interactive behaviors have to be analyzed for further understanding of crash mechanisms and proposal of effective countermeasures.

In order to safely observe the interactions of road users and conduct in-depth analysis, recently researchers use pedestrian VR environment⁶⁾. VR is convenient to control vehicles' approaching behavior, patterns and other variables which is impossible to achieve in the real-world. Furthermore, it provides the freedom of repeating the experiments as well. Meanwhile, despite that VR can be a promising tool for safety analysis, there are still limited number of studies regarding pedestrian safety assessment using VR. It is also important to check reliability of pedestrian behavior in VR for safety evaluation.

Therefore, the objective of this study shall be two-fold.

- To validate the feasibility of VR environment for pedestrian safety analysis.
- To analyze the impact of the refuge island, vehicle speeds and accepted gaps of crossing pedestrians on pedestrian behavior as well as safety measures as an example of VR-based safety analysis.

The remainder of the paper shall proceed as follow, Past studies and literature review are summarized in Section 2 of the paper. Section 3 presents the methodology and protocols for the experimentation and data collection. In section 4 of the paper, the comparison between pedestrian crossing behavior in VR and real-world is presented as an approach to validate the VR environment. While in Section 5, results and data analysis are discussed. Section 6 summarized the conclusions and future studies of this research.

2. LITERATURE REVIEW

Recently some studies about pedestrian behavior at unsignalized crosswalks have been carried out under different conditions. In Japan, a study on evaluation of unsignalized mid-block crosswalk was conducted by Ishiyama et al⁷⁾. The effect of mid-block cross-

walk was analyzed by considering pedestrian crossing time, speed and pedestrian gap acceptance. The relevance of pedestrian gap acceptance of vehicle speed and positions were confirmed. However, pedestrians' detailed maneuvers such as speed change in the crosswalks, crossing timing are not analyzed. In another study, Murai et al⁸⁾ checked the effect of provision of staggered crosswalk in Miyazaki, Japan. Authors checked the effect of geometry modification on pedestrian safety by Post Encroachment Time (PET), Change in vehicle approach speed, pedestrian delay, pedestrian crossing behavior and jaywalking. It was observed that mid-block refuge island helped the pedestrians in more safe crossing, and mobility was increased by reducing the pedestrian crossing time. Pedestrian jaywalking behavior was also reduced in mid-block staggered crosswalk case. However, their study was limited in a single crosswalk with refuge island and did not consider the effect of geometry.

Recently, for such kind of studies, VR technology emerges as a promising tool for investigating human perception and behavior in highly controlled, immersive, and risk-free environments. There are two main kind of simulators generally used for VR. One can be Head Mounted Display (HMD) in which pedestrians have to wear a helmet or 3D goggles and it provides high-quality images and real immersion and the second type is CAVE simulators where a large number of screens are displayed around the pedestrian walking area which shows some virtual environment of road surrounding conditions. A comparative validation study between the two techniques was done by Pala et al.⁹⁾ and it was concluded that perception of the surrounding environment and approach vehicles was more realistic in HMD as compared to CAVE simulators. Tian et al¹⁰⁾ did a study regarding pedestrian behavior with respect to different vehicle approach speed and temporal gaps and it was observed in the results that pedestrians accept lower gaps and made more dangerous crossings while interacting with higher vehicle speed. Tapiro et al.¹¹⁾ studied the effect of surrounding conditions such as visual loadings and pedestrian age on pedestrian crossing behavior and it was revealed that childrens are more distracted by the surrounding environments and take more dangerous crossing as compared to the adult crossers.

Although the validation of VR data for better accuracy of behavior and linkage with real-world data is essential, the above-mentioned researches were not focused well on the reliability of VR experimental data. In this paper, toward comprehensive analysis of change in pedestrian crossing behavior under different geometries and approach vehicle patterns, the pedestrian behavioral data in VR is validated. Then, the

behavior analysis is applied to figure out the detailed pedestrian movement characteristics under a few selected conditions of geometry and vehicle maneuver settings.

3. METHODOLOGY

The experimental study was designed using the VR environment. Participants have to cross the road physically while observing the traffic and surrounding conditions in VR environment. The experiment was approved by the ethical committee of Graduate School of Environmental Studies in Nagoya University.

(1) Pedestrian Simulator

The VR experiment was designed in UC Win/Road version 15.1.2 and HTC VIVE Pro EYE HMD was utilized to experience the virtual environment. To track the location and the orientation of the HMD, 4 sensors were placed in such a way that they can track the whole HMD movement during crossing without any lag or disturbance. The area tracked by the VIVE was approximately 11m*4m. Unlike most of the experiments in the past, in which pedestrians either have to use a joystick or a push button to show their intention of crossing, the physical crossing of the pedestrians was made and their behavior during the whole crossing was examined. An example picture of a walking pedestrian with HMD during the experiments can be seen in **Fig.1**. The pedestrians' view at the initial position is shown in **Fig. 2**. Pedestrians can rotate their head and observe the surrounding environment. When the pedestrian walks or rotates the head, the view in the display moves accordingly. The surrounding environment and approach vehicles from a pedestrian view is shown in in **Fig.3**.

(2) Road Environment

In this experiment, two different types of crosswalks (No-Refuge Island and Refuge Island) were developed as in **Fig 4** and **Fig 5**. The fully immersed virtual environment represents a two-lane two-way collector road at the position of unsignalized mid-block crossing.

The width of the vehicle lanes was kept 3m in addition to 0.5m shoulders. These road specifications are aligned with the Commentary on Road Structure Ordinance for a design speed of 50km/h roads. In this study, the width of the crosswalk was kept at 4m, and in addition, a stop line was placed at 2m from the edge of the crosswalk. Two different types of geometries were designed such as No Refuge Island (No-RI) crosswalk and Refuge Island (RI) crosswalk as shown in **Fig.4** and **Fig.5**.



Fig. 1 Pedestrian crossing during VR Experiment



Fig. 2 Pedestrians' view at the start position in VR



Fig. 3 Pedestrians' view of surrounding environment in VR

In No-RI, a solid median line was provided between both opposite traffic lanes. While in the RI case, a 2.5m*4m refuge was provided which separated the opposite traffic lanes and provided a place for the pedestrians to safely wait for the approaching traffic from the far side. No Refuge Island (No-RI) case was considered as control case.

(3) Scenarios Design

In overall experiment framework, two types of scenarios were designed based on vehicle maneuvers: (i) Non deceleration scenarios and (ii) Deceleration scenarios. Non-deceleration scenarios were designed in such a way that vehicle do not stop for participants.

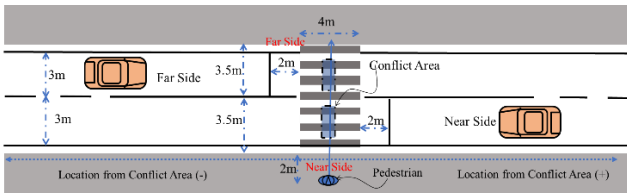


Fig. 4 Geometry of No Refuge Island (No-RI) crosswalk

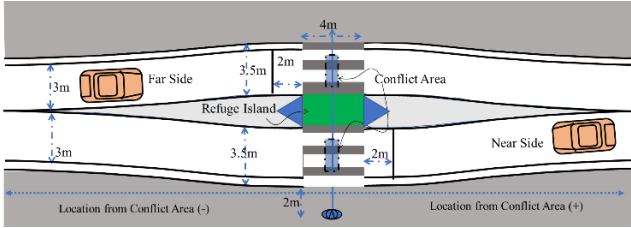


Fig. 5 Geometry of Refuge Island (RI) crosswalk

The purpose of these non-deceleration scenarios was to check the choice of gap acceptance and to check the behavior of pedestrians for relatively dangerous conflicts with vehicle non-yielding behavior. In the deceleration scenarios, vehicles stopped for the pedestrians with different deceleration rates. Their purpose was to investigate the effect of vehicle braking patterns on pedestrian behavior including the crossing initiation time and speed. Both types of scenarios were tested in combination with different other variables such as gaps, approach vehicle speed, deceleration patterns, and approach side of traffic.

Although there are increasing trend of yielding on unsignalized crosswalk these days but still we often observe non yielding behavior of vehicles specially when they are in platoon which yields to safety risky for pedestrians. Therefore, this study aims to analyze pedestrian behavior with non-yielding vehicles in the common crosswalk layout and compare it with the behavior at a crosswalk with refuge island. Parameter values used and their notations are shown in **Table 1**.

Table 1 List of scenarios and their notations

Sr. No	Scenario	Notation
1	No-Refuge Island, 40 km/h , Near Side	No-RI-40-N
2	No-Refuge Island, 60 km/h , Near Side	No-RI-60-N
3	Refuge Island, 40 km/h , Near Side	RI-40-N
4	Refuge Island, 60 km/h , Near Side	RI-60-N
5	No- Refuge Island, 40 km/h , Far Side	No-RI-40-F
6	No- Refuge Island, 60 km/h , Far Side	No-RI-60-F
7	Refuge Island, 40 km/h , Far Side	RI-40-F
8	Refuge Island, 60 km/h , Far Side	RI-60-F

There were total of 8 scenarios of non-deceleration cases (2(Geometries) *2(Approach Speed) *2(Traffic Direction)). In addition to these non-deceleration

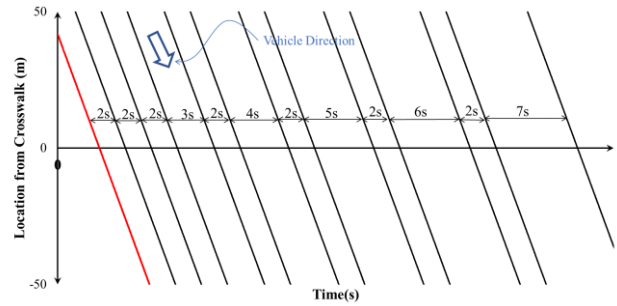


Fig.6 Time space diagram for near-side traffic

scenarios, there were some other scenarios where vehicle yield for the pedestrian were also added so that the pedestrians may expect the vehicles might stop. A total of 30, including deceleration and non-deceleration scenarios were tested for each participant. It is necessary to mention here that all the scenarios were randomized for all the participants to reduce the learning effect and predictivity of the vehicle maneuver.

The position of the participant at the start of each scenario was 2m behind the crosswalk. In near-side cases, the vehicles were approaching from the right side of the crosswalk while in far-side cases vehicles were approaching from the left side of the participant in far lane. In all 8 scenarios, a platoon of 4 vehicles with the front vehicle colored red was designed and pedestrians were instructed not to start crossing in front of the first red vehicle. They can start crossing after the first red vehicle. A temporal gap of 2s was kept between the vehicles in platoon while after the platoon, gaps of the following vehicles were increasing. An additional vehicle of a relatively short temporal gap (2s) was added to overcome the expectation of pedestrians of always increasing the gap between succeeding vehicles. The gaps were set (2,3,4,5,6,7,8) in ascending order because if a shorter gap comes after the relatively larger gap, then most of the pedestrians shall accept the larger gap, and the behavior against successive shorter gaps cannot be observed.¹²⁾ Maximum gaps for near-side and far-side were 7s and 8s respectively. The time space diagram for the near-side vehicles is shown in **Fig 6**.

(4) Experimental Procedure

On arrival, participants were briefed about the experiment as well as the purpose of the experiment. After the briefing, the consent form was signed by the participant. Then, before the start of the trials, the participants were asked to walk a distance of 9m without wearing HMD as if they are crossing a crosswalk and time was noted to calculate the average walking speed of the participants. Then participants were asked to wear HMD and walk through the vir-

tual crosswalk for at least 5 times for training purpose and to compare their speed within and without VR. If the pedestrian speed wearing HMD becomes almost equal to the walking speed without wearing HMD, it indicates that the participant is almost used to the VR environment and ready for the experiments. Otherwise, a few more trials were performed until participants become fully ready. It is noted that pedestrians were asked about motion sickness and health status after each trial and experiment. None of the participants felt motion sickness during experiments. Participants were given a short rest after every 10 scenarios. Completion of whole scenarios and trials took almost 90 minutes for each participant.

(5) Participants

40 participants including 11 females and 29 males participated in VR experiments. All participants were university students and age ranges from 18-24 years. All the participants confirmed that they didn't have any serious mobility problems or any medical conditions. Participants vision was also checked to ensure that all the participants have normal or corrected to normal vision to be able to observe everything in the VR correctly. Each participant was paid a compensation amount for their time.

(6) Experimental Measures:

a) Gap Acceptance

Pedestrian gap acceptance can be defined as the temporal gap between the two vehicles, which the pedestrians chose to cross the road as shown in Fig.7.

b) Crossing Initiation Time (CIT)

It refers to the time difference between when the last vehicle left the conflict area and when pedestrian entered the crosswalk. This indicates how much time a pedestrian took to start crossing after the last vehicle passed. The conceptual illustration of CIT is shown in Fig. 7

c) Crossing Speed

This refers to the pedestrian speed while crossing the road during experiments. It can be calculated by total distance covered by the pedestrians during crossing divided by the time taken to complete the crossing. Time is denoted as the time difference between when pedestrians step in on crosswalk and time when pedestrians step out of crosswalk after completing the crossing.

d) Post Encroachment Time (PET)

It is defined as the time between the moment that the first road user leaves the path of the second road user and the moment that the second road user reaches the path of the first ¹³⁾. In this study, PET shall be the time taken by the front of the vehicle to reach at the conflict area after the pedestrian leaving the conflict area.

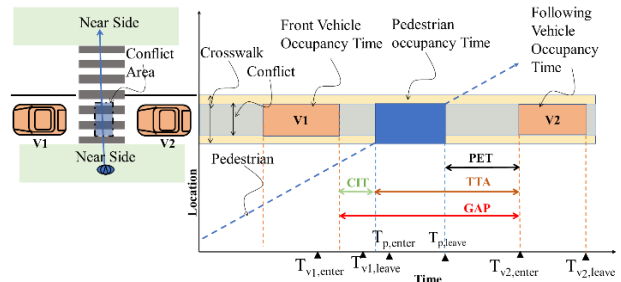


Fig. 7 Road details a conflict area location for RI case

4. VR VALIDATION

Before going to discuss the results, it is essential to conduct the validation so that it's easy to understand the degree of deviation of VR results from the real-world data. This shall also help in considering the more critical factors to achieve maximum significant results in future.



Fig. 8 Observation Site in Yaizu

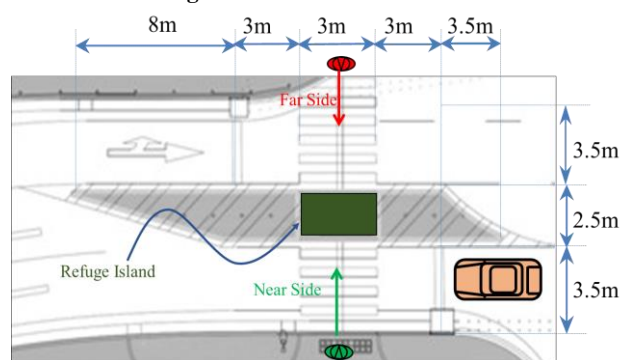


Fig. 9 Section Details of Refuge Island ⁴⁾

Two basic validations regarding the perception of distance and crossing speed of the pedestrians in VR and real-world data shall be made here. Distance perception shall be done with respect to waiting location of the pedestrians from the crosswalk. Real-world data of pedestrian waiting location and speed profile was obtained. A refuge Island crosswalk in Yaizu

city in Shizuoka prefecture, Japan, (Fig. 8) was selected to be replicated in the VR environment with identical layout for data collection. The picture with detail of field data collection location is shown in Fig.9.

(1) Distance Validation

Distance validation was done with respect to waiting location of the pedestrians at crosswalks in real-world and in VR environment. A total of 35 pedestrian-vehicle interactions at the near side of the crosswalk were observed and the waiting location of the pedestrian is referred to the distance from the start of the crosswalk where the pedestrians stopped or slowed down to observe the approaching vehicle and then started crossing. During this, only the pedestrians interaction with vehicles approaching from near side were considered. Cumulative curve for pedestrian waiting location at the crosswalk is shown in Fig.10.

Average pedestrian waiting location in real word cases was 0.62m with standard deviation of 0.23m. While the pedestrian waiting location in VR was 1.49m with standard deviation of 0.44m. It is clearly visible that pedestrians waited at larger distance from the crosswalk in VR as compared to the real-world. ANOVA at significance level of 0.05 was performed and it was observed that this different in waiting location was highly significant ($F(1,74) = 106.08, p < 0.05$). The reason behind this is the difference between vertical Field of View (FOV) of natural human eye and HMD display. According to the specification provided by the manufacturer, FOV for HMD VIVE Pro EYE used in this study was 110° while a normal human eye vertical FOV is around 140°¹⁴. The FOV for HMD and the natural human eye is illustrated in Fig. 11.

From Fig.11, h represents the eye height from the ground, Δ_{EYE} and Δ_{HMD} represents the vertical FOV angle of human eye and HMD respectively. L_{EYE} and L_{HMD} represents the distance that cannot be observed when pedestrian is looking straight. It can be referred as blind distance. Suppose the elevation and depression angles are equal, L_{EYE} and L_{HMD} can be calculated by Equations (1) and (2), respectively.

$$L_{HMD} = \frac{h}{\tan\left(\frac{\Delta_{HMD}}{2}\right)} \quad (1)$$

$$L_{EYE} = \frac{h}{\tan\left(\frac{\Delta_{EYE}}{2}\right)} \quad (2)$$

By assuming the value of $h = 167\text{cm}^{15}$, 140° and 110° for Δ_{EYE} and Δ_{HMD} respectively, the value of L_{EYE} and L_{HMD} is estimated as 0.69m and 1.16m respectively. This indicates that for natural eye view, the

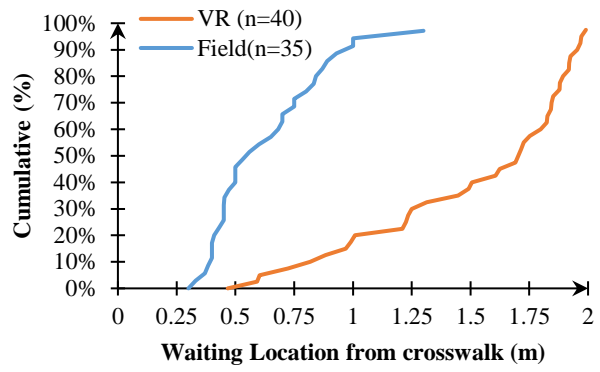


Fig. 10 Pedestrians waiting location distribution in VR and Real-world data

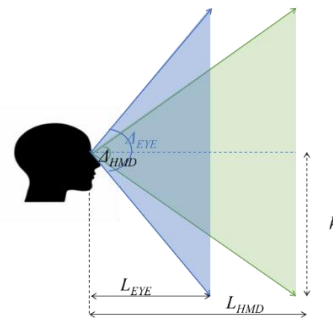


Fig. 11 HMD and eye FOV illustrate diagram

blind area is quite small as compared to HMD. This caused the pedestrians' underestimation of the distance to the crosswalk in VR.

The authors measured FOV with and without HMD using their own eyes. The measured L_{EYE} and L_{HMD} were 1.9m and 0.6m, respectively. The estimated L_{EYE} was similar to the measured one, while the measured L_{EYE} was much larger than the estimation. One of the possible reasons is that the elevation and depression angles may not be the same but the HMD may have larger elevation angle. The detailed characteristics of FOV need to be further investigated in the future. While wearing HMD, the pitch angle required for the pedestrians to look at their standing position was 49.7°, which is significantly higher than the normal human eye of 20°. This implies that the pedestrians' actual range of FOV was even smaller than the range estimated from the officially noted FOV.

(2). Crossing Speed Validation

Pedestrian crossing speed was also compared and validated. Fig.12 shows average pedestrian crossing speed profiles. Each vehicle lane was divided in 3 sections and at the center, there was a section of refuge island. L1, L2, L3 represent three sections of the first lane while L4, L5, L6 represent the three sections of 2nd lane. RI indicates the section of refuge island in between the two lanes. The crossing speed is the

average travel speed of each section, with or without the existence of approach vehicles in VR and field observation.

Firstly, when there are no conflicts with vehicles, average pedestrian speed in VR and the field are almost same except at the end of crosswalk (L6). As in real world, the pedestrian's actual destination is somewhat very far from the edge of the crosswalk while in VR due to some limited space and pedestrian perception about just crossing the crosswalk, pedestrians reduced its speed before reaching its destination.

In the case of the conflict, pedestrian speed in the real-world was significantly higher than the VR. Actually, pedestrians with VR tend to walk in slow speed in the initial condition. Although we have asked participants during trainings sessions in VR before the experiment to walk in their normal speed, it seems that they were not enough used to accelerate more than the speed they trained. In conflict cases, pedestrians in VR also reduced their speed at the end of crosswalk. In the meantime, relative speed profile up to L4 seems similar in VR and the field. This means that except the last part of the crosswalk, relative trend of the speed profile is valid in this experiment.

Although we have found some differences in pedestrian crossing speed and waiting location at the side walk between VR and real-world, the application of VR environment for relative comparison of pedestrian behavior between different simulated situations is valid and reliable (relative validity).

4. ANALYSIS AND RESULTS

The result and discussion for different pedestrian behavioral parameters are discussed in this section.

(1) Gap Acceptance

a) Effect of Vehicle Speed

Fig 13 and Fig 14 are showing the cumulative curve of the pedestrian gap acceptance for near side and far side cases, respectively. Since the size of the gaps was presented in ascending order in the experiment, then if a participant accepted a specific gap, it means he rejected smaller gaps presented to her/him in the same scenario. It was observed that with increase in the speed of the approaching vehicle, pedestrians accepted shorter gaps as shown in Fig. 13 where the cumulative curve shifted towards left for higher speeds. Similar kind of trend was observed with the far-side cases as well as shown in Fig. 14. These results are in accordance with a recent study by Tian at al.¹⁰⁾

One way ANOVA was performed on all the samples with same geometry and different approach

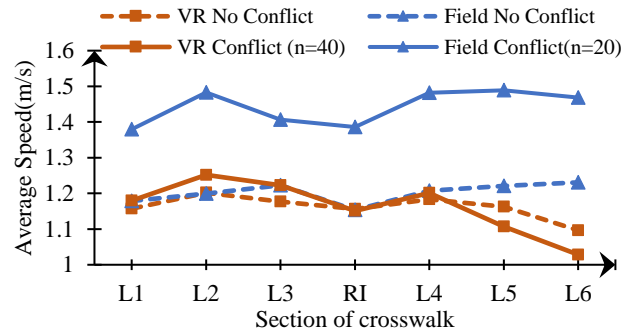


Fig. 12 Comparison of pedestrian speed in VR and Field

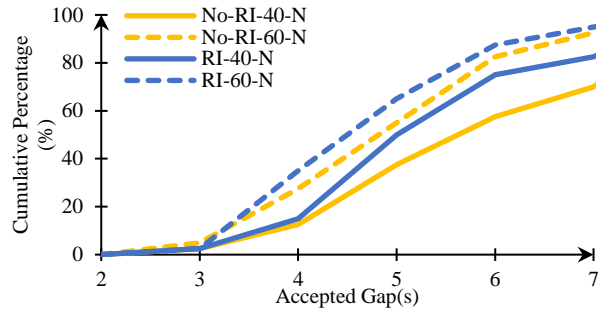


Fig. 13 Gap Acceptance of pedestrians for near side cases

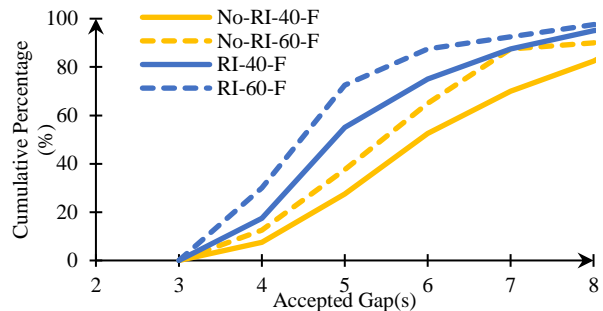


Fig. 14 Gap Acceptance of pedestrian for far side cases

Speeds. Significant effect of geometry and speed of the approaching vehicle was found on the pedestrian gap acceptance ($F(7,274)=3.99, p < 0.05$).

As the result was statistically significant so a Tukey post hoc test was performed to check the effect between each pair of the variables. Post hoc test revealed that pedestrian gap acceptance with respect to speed was statistically insignificant in all the cases except No-RI-N ($F(1,66)=4.48, p < 0.05$) and RI-F ($F(1,75)=4.99, p < 0.05$).

The difference of pedestrian gap acceptance implies that pedestrians underestimate the arrival time of vehicles in high speed.

b) Effect of Far Side Traffic

The pedestrian gap acceptance with introduction of far side traffic was increased in both type of geometries. ANOVA results showed significant difference between the gap acceptance distributions of 40km/hr and 60km/hr vehicle speed in the case of No-RI. ($F(1,59)=$

5.05 , $p < 0.05$ and $F(1,71) = 5.34$, $p < 0.05$, respectively). With the introduction of RI, no statistically significant difference was found between near side and far side traffic ($F(1,69) = 0.97$, $p > 0.05$ and $F(1,75) = 0.18$, $p > 0.05$ for 40km/h and 60km/h, respectively). In No-RI-F cases, pedestrians' distance to conflict area was increased and the pedestrians accepted significantly larger gaps for safe crossings taking the entry time to the crosswalk into account. Meanwhile with RI, the pedestrians' distances to the conflict area of the far side traffic and the near side traffic become the same. Therefore, no significant difference in gap acceptance was observed.

c) Waiting Location

Fig. 15 presents the relationship between gap acceptance and waiting location with respect to geometry and traffic direction. Results reveal that, in near-side traffic, with both geometries, pedestrian average waiting location against gap acceptance was almost similar and ANOVA showed no significant difference in waiting locations. With increase in accepted gap, pedestrian waiting location distance from the crosswalk increased. This indicates that participants with larger accepted gaps were more reluctant to initiate crossing or come near the crosswalk to accept gap. Similar trend was observed in the far-side traffic scenarios but the waiting location during far-side traffic was closer to the crosswalk as compared to near-side traffic. As there was no vehicle coming from near side and pedestrians didn't feel any danger even if they are waiting on the crosswalk.

In RI-F cases, waiting location of the pedestrians almost remain same and ANOVA revealed that there was no significant difference in the waiting location for RI-F cases with respect to accepted gaps.

(2) Crossing Speed

For the detailed analysis of pedestrian speed variation, each lane of the crosswalk was divided into three sections and the average speed was calculated in each section as shown in **Fig.16**. The results revealed that in near-side traffic, pedestrians started the crosswalk at a higher speed and reached their maximum speed in the middle of the crosswalk and then pedestrian speed decreased. In case of No-RI-F, pedestrian speed increased throughout the crossing and reached maximum speed when a pedestrian was in the conflict portion and then started decreasing at the end of the crossing. In RI cases, in near traffic, pedestrian speed was highest in first lane sections and then pedestrian speed considerably decreased at refuge island where pedestrians checked for the far side traffic. As there was no far-side traffic approaching in near-side cases, pedestrians just slowed down at refuge island and again started crossing with a lower

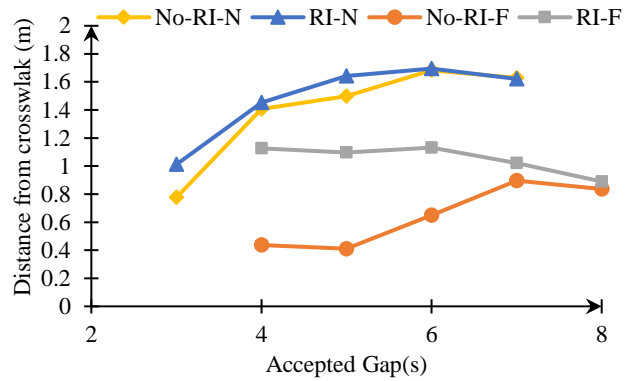


Fig. 15 Pedestrian gap acceptance and waiting location

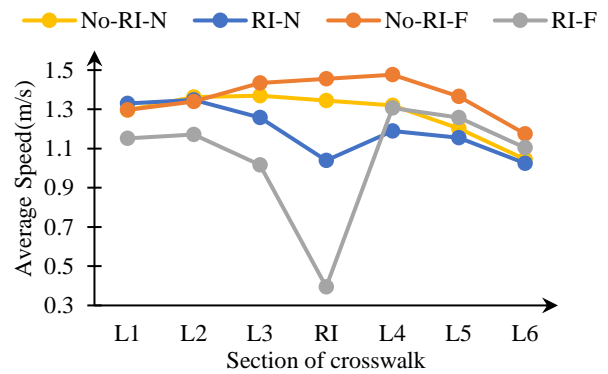


Fig. 16 Pedestrian Speed variation with geometries

speed as compared to the speed in 1st half of the crosswalk

On the other hand, in RI-F cases the average pedestrian speed was low during first lane of crosswalk and then pedestrians slowed down to almost stopping at refuge island section. After finding suitable gap pedestrian speed again start increasing in 2nd lane and it was considerably higher than the 1st lane speed

Pedestrian crossing speed on both halves of the crosswalk was calculated. The 1st half of the crosswalk refers to the crosswalk section in the first lane or near-side lane while 2nd half of the crosswalk represents the far-side lane of the crosswalk. The results for the average speed of all the participants in the first half and 2nd half of the crosswalk with respect to approach vehicle directions and geometries are shown in **Table 2**.

Table 2: Pedestrian average crossing speed on crosswalk

Sr. No	Scenario	1 st Half (m/s)	2 nd Half(m/s)
1	No-RI-N	1.37	1.23
2	RI-N	1.34	1.18
3	No-RI-F	1.35	1.39
4	RI-F	1.16	1.29

The ANOVA results for change in speed with respect to traffic direction and geometry are shown in **Table 3**. In the presence of near-side traffic, there was no significant difference in pedestrian crossing

Table 3: ANOVE statistical results for pedestrian crossing speed on different lanes of crosswalk

Sr. No	Factors			df	F statistics	p value
	No-RI/RI	Near side/Far side	1 st Lane/2 nd Lane			
1	○	Near	1 st Lane	(1,159)	0.89	0.34
2	○	Near	2 nd Lane	(1,159)	2.72	0.10
3	○	Far	1 st Lane	(1,159)	33.4	<0.05*
4	○	Far	2 nd Lane	(1,159)	6.69	<0.05*
5	No-RI	Near	○	(1,159)	15.29	<0.05*
6	RI	Far	○	(1,159)	26.9	<0.05*
7	No-RI	Near	○	(1,159)	0.2	0.65
8	RI	Far	○	(1,159)	21.4	<0.05*

○ Compared Variable

*Significance at 0.05

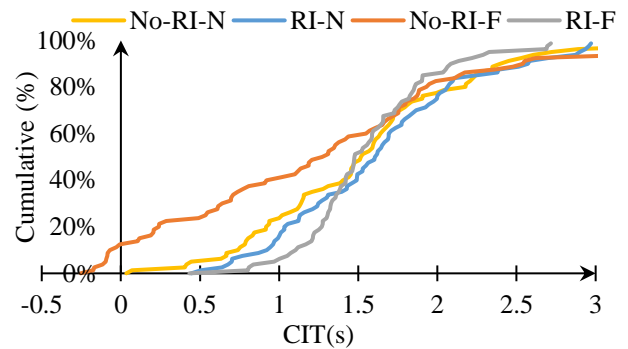
speed with respect to crosswalk geometries in both halves of the crosswalk. In far-side traffic, the speed of the participants in RI cases was significantly lower than the No-RI cases in both halves of the crosswalks. While a significant difference in crossing speed between 1st half and 2nd half was observed in all cases except No-RI-F case.

(3) Crossing Initiation Time (CIT)

CIT is dependent on the speed as well as the reaction time of the pedestrians. CIT distribution with respect to crosswalk geometry and traffic direction is shown in **Fig. 17**. It can be observed that in near side cases no significant difference was found in CIT values between different scenarios. The reason is all pedestrians conflict area location and waiting location was same irrespective of crosswalk geometry as discussed in section 3(e). In No-RI-F cases, pedestrian waiting location was closer to the crosswalk which resulted in lower CIT values. In No-RI-F, some pedestrians step up into the crosswalk before the vehicle leaves the conflict area. While CIT in RI was higher than No-RI-F but lower than the No-RI-N. The relatively higher CIT is associated with the pedestrian waiting location at refuge island in pursuit of safe gap. In some cases, pedestrians did not completely stop at refuge island and continued their crossing after slowing down on refuge island which resulted in shorter cumulative CIT values due to reduction of reaction time. In addition, it was also observed that pedestrian facing higher approach vehicle speed have more CIT than lower speed cases, but this difference was insignificant in all cases.

(4) Post Encroachment Time (PET)

PET was calculated as safety performance indicator. Higher PET value represents more safe crossing for the pedestrians. PET considering geometry, approach vehicle speed and traffic side was obtained. **Fig.18** represents the PET values for near side traffic while **Fig.19** represents the PET values for far side traffic.

**Fig. 17** Pedestrian Crossing Initiation Time distribution

Smaller PET values were observed in VR as compared to normal real-world crossings. Shorter PET values in VR are linked with pedestrian distance underestimation which resulted in farther waiting location from crosswalk, higher CIT and ultimately lower PET values. PET values were also influenced by decrease in the speed of pedestrians at the end of crosswalk.

From **Fig. 18**, pedestrians make more dangerous crossings while conflicting with higher speed vehicle irrespective of type of crosswalk. PET values were lower for 60km/h as compared to 40km/h. This trend was observed in all the cases irrespective of geometry or side of the approaching traffic. Pedestrian accepted shorter gaps in higher speed which resulted in lower PET values. Lower PET are also linked with farther waiting location due to lower FOV value of HMD and high CIT. The number of short PET crossings were higher in RI-N than the No-RI-N cases. In RI-N, PET was further affected by speed reduction at the end of the 1st lane or conflict area.

Fig. 19 shows the pedestrian crossing in presence of far side traffic. No-RI crosswalk and higher speed has the highest cumulative percentage of pedestrians with short PETs. This increase is associated with sudden reduction in speed of the pedestrians in VR and longer distance to complete crossing. While it has been observed that refuge island helped the pedestrians in making the safe crossing. As in far side case, pedestrians already passed the first half of

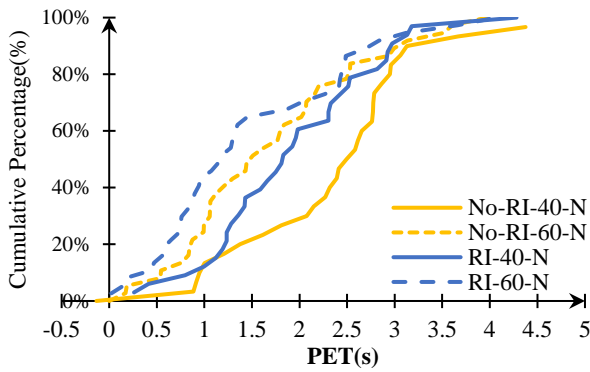


Fig.18 PET values for pedestrians facing near side traffic

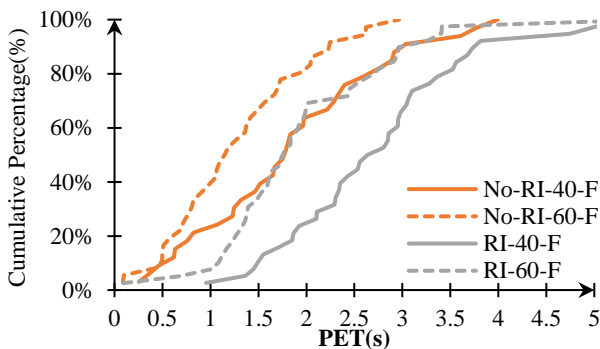


Fig. 19 PET values for pedestrians facing near side traffic

crosswalk, and they anticipated the location of RI correctly and waited on the RI relatively near the start of 2nd lane which helped them to decrease their CIT as discussed in section 4(3) and resulted in higher PET values. The possible improvements for calculating the PET more precisely can be adjustment for the speed profile for VR data. Constant speed at the end of VR crosswalk can be applied as observed in the field.

CONCLUSIONS

This study analyzed the pedestrian's crossing behavior with respect to crosswalk geometries of with and without refuge island, approach vehicle speed and approaching vehicle direction. Pedestrian behavior comparison in real-world and VR Environment was also validated.

Pedestrian distance perception and waiting location estimation in VR was relatively farther from crosswalk as compared to real-world which increased the CIT and ultimately reduced the PET values in VR. In addition, during real-world crossing, pedestrian do not slow down at the end of the crosswalk while in VR environment they reduced their speed because of space limitation and close destination.

Pedestrian accepted shorter gaps while conflicting

with higher speed vehicles. In near side traffic there was no significant difference in gap acceptance due to geometry but in far side traffic cases, pedestrians accepted significantly shorter gaps in presence of refuge island.

Pedestrian speed in VR was lower than the pedestrian speed in real-world crossing cases. Pedestrian speed was high in the conflict area in both geometries and traffic direction. In case of refuge island, pedestrians reduced their speed significantly at refuge island while in NO-RI case, pedestrian speed was almost constant during crossing.

Pedestrians average waiting location distance from crosswalk was maximum in near end cases irrespective of geometry and was minimum in No-RI-F cases. With high vehicle approach speed, pedestrians took more risky crossings in all cases. This is associated with lower accepted gap in high speed.

This study mainly focused on the pedestrian behaviour against non-yielding approaching vehicles in future it can be extended against yielding vehicles with different braking patterns. As in this study, it was observed that pedestrians reduced their speed at the end of crossing due to limited space available and pedestrians' destination location, so in future VR experiments should be done in larger space and destination for pedestrians should be set at least 2 meters away from the end of the crosswalk so that this effect can be minimized. As pedestrian speed in VR is lower than the field speed so proper instructions and training in VR environment before the start of the experiment are necessary for future studies. In analysis, different adjustment factors to replicate the pedestrian field behaviour in VR can be made in the future and pedestrian behaviour modelling under different conditions will be a valuable addition to this research.

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