Pedestrian Presence Probability Distribution under High Demand Conditions at Signalized Crosswalks

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This study investigates a change in pedestrian presence probability distribution by time under different combinations of subject and opposing pedestrian demand volumes at signalized crosswalks. The observed pedestrian presence probability distributions on a signalized crosswalk under a relatively high pedestrian demand conditions were compared with those estimated by an existing model. The result shows that the presence probability distribution is influenced by pedestrian space occupancy in the waiting area, opposing pedestrian flow condition and the number of crossing pedestrians.

Key Words: *signalized intersection, crosswalk, pedestrians, presence probability*

1. INTRODUCTION

At signalized intersections, the space designated for pedestrians to cross the road is crosswalk. Crossing pedestrians and vehicles may have shared space and time on the crosswalk based on the assigned signal timing design. Therefore, understanding pedestrian behavior along the crosswalk is essential for evaluating the safety and operational performance of signalized intersections.

Regarding safety, although pedestrians have priority over vehicles at crosswalks, more than one-third of the total traffic accidents in Japan occur with pedestrians at intersections, according to the report of National Policy Agency in Japan (2019)[1]. In Japan, one of the reasons for this is that pedestrians and turning vehicles mostly share the concurrent signal phase.

In addition to safety, the operational performance of signalized intersections in the view of vehicles' movement is strongly affected by the conflicts with crossing pedestrians along the crosswalk. Highway Capacity Manual[2] and a manual of Japan (JSTE)[3] considered the influence of pedestrians for estimating capacity of turning lanes.

Studies on pedestrians' crossing behaviors can be classified into microscopic and macroscopic analyses. While microscopic analyses treat individual pedestrian behavior, macroscopic ones do pedestrians as a flow and aggregate their behavior. This paper adopts the latter approach, a macroscopic analysis. Thus, characteristics of change in the pedestrian presence probability along the crosswalk are investigated.

The characteristics of crossing pedestrian presence probability along the crosswalk within the pedestrian green time (PG) are affected by various factors such as signal timing, crosswalk geometry, opposing pedestrian flow and pedestrian demand on the crosswalk. Zhang and Nakamura[4,5] analyzed and modeled pedestrian presence probability along several signalized crosswalks by considering signal timing, pedestrian arrival rate and crosswalk length as influencing factors. They found that pedestrian position distribution along the crosswalk dispersed when crosswalk length and elapsed time of PG increase. Moreover, it was found that the distributions will shift to the moving direction slowly and their variations become larger when pedestrian arrival rate increases. However, they analyzed the sites with relatively lower pedestrian traffic demand. Moreover, interaction with opposing pedestrian flow has not been investigated by them.

The objective of this paper is to analyze the impacts of opposing pedestrian flow, pedestrian space occupancy in the waiting area and high pedestrian demand condition on the profile of crossing pedestrian presence probability distribution by time, along the crosswalk of a signalized intersection under relatively high pedestrian demand conditions.

2. METHODOLOGY

(1) Pedestrian presence probability

Zhang and Nakamura modeled pedestrian presence probability on a signalized crosswalk as a function of time. From empirical data, the frequency distribution of pedestrians' presence along the crosswalk was plotted by observing pedestrian positions at time *t*. Then observed pedestrian presence probabilities are modeled by using the presence probability function of Weibull distribution. In that model, the shape parameter α and scale parameter β are estimated by linear functions of four influencing parameters (elapsed time of PG, pedestrian red time, crosswalk length and pedestrian arrival rate).

This model can effectively estimate the pedestrian presence probability by time along a signalized crosswalk by considering some influencing factors and is useful to predict pedestrian presence probability distribution. However, the impact of interaction with opposing pedestrian flow is not presented.

(2) Definition of terminology

In some cities in Japan, the basic layout of crosswalks at signalized intersections can consist of pedestrian walkway and cyclist pathway in parallel as shown in **Fig.1**.

In this paper, only the pedestrian movement along the horizontal axis (x) is considered and the y-axis position of pedestrians is projected along the horizontal axis.

Here in the analysis, pedestrian presence probability at time t and position x is defined as the number of pedestrians present at time t and position x divided by the total waiting pedestrian number of the cycle.

Crossing pedestrians at signalized intersection are classified by arrival timing in two groups:

Waiting pedestrian: pedestrian who arrived at the crosswalk before the onset of pedestrian green time.

Arriving pedestrian: pedestrians who arrive at the crosswalk after the onset of pedestrian green.

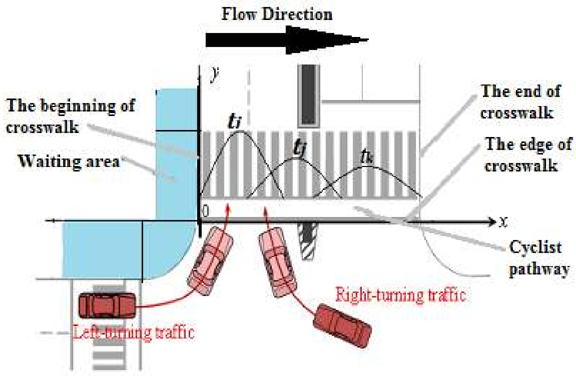

Fig.1 Layout of subject crosswalk and definition of basic terms

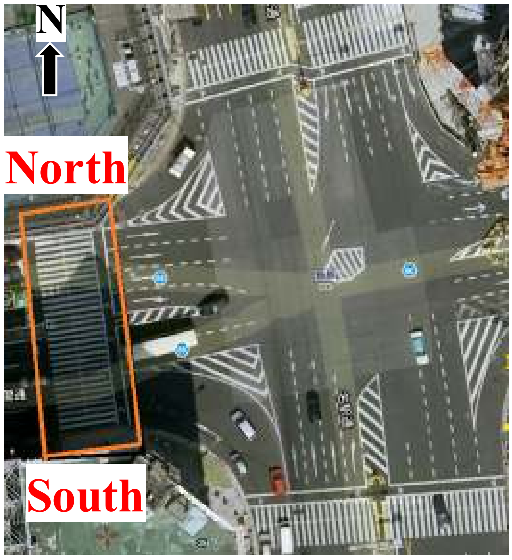

Fig.2 Observed intersection layout (Source: Google Earth)

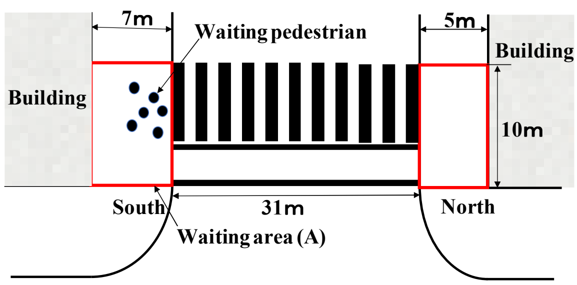

Fig.3 Pedestrian space at the waiting area

Waiting area A [m^2] is a space bounded by crosswalk and walkway width as shown in **Fig.3.** Space occupancy per waiting pedestrian can be defined as a space of the waiting area A [m^2] shown in **Fig.3** divided by the number of pedestrians inside at the onset of PG.

Table.1 Observed cycles

Cycle	Cycle starting time (hh:mm:ss)	Northbound			Southbound		
		Waiting pedestrian	Space occupancy per waiting pedestrian (m^2/ped)	Arriving pedestrian	Waiting pedestrian	Space occupancy per waiting pedestrian (m^2/ped)	Arriving pedestrian
1	8:16:39	47	1.19	12	9	4.44	5
2	9:01:58	48	1.17	14	10	4.00	4
3	9:31:16	43	1.30	11	10	4.00	2
4	10:05:56	16	3.50	15	26	1.54	4
5	10:11:16	16	3.50	4	13	3.08	6
6	10:16:37	25	2.24	3	18	2.22	9
7	10:19:17	22	2.55	5	14	2.86	6

At the onset of pedestrian green (PG), waiting pedestrians from both ends of a crosswalk start walking. After PG elapsed, pedestrian's presence probability along the crosswalk gradually changes because of a variation in walking speeds of individual pedestrians. This spreading situation is more significant for the waiting pedestrian group compared with arriving pedestrians, since arriving pedestrians enter the crosswalk with their desired walking speeds. However, waiting pedestrians start crossing from the position where they were standing.

3. DATA COLLECTION

(1) Study site

For the pedestrian presence probability distribution analysis at the crosswalk, Sasashima signalized intersection located in Nagoya, Japan is selected which has a high pedestrian demands throughout daytime. The subject crosswalk is found in the west leg of the intersection as shown in **Fig.2**. The selected crosswalk is 31m long, and cycle length and pedestrian green time (PG) assigned to the subject crosswalk are 160s and 30s, respectively. This site is one of the busiest intersections in Nagoya city regarding pedestrian flow.

The two directional flows are:

Northbound (NB) flow: flow headed to North direction and

Southbound (SB) flow: flow headed to south direction.

For the subject crosswalk, the waiting area A [m^2] is $70m^2$ for south side and $50m^2$ for north side.

(2) Traffic conditions

Observed cycles at the signalized intersection are summarized in **Table 1**. Only the crossing behaviors of waiting pedestrians are analyzed in this paper. The observed cycles are categorized into three groups for the pedestrian presence probability analysis as shown in **Table 2**, where:

Table.2 Group category

	Cycle	Subject direction	Opposing direction
Group 1	1	NB	SB
	2	NB	SB
	3	NB	SB
Group 2	1	SB	NB
	3	SB	NB
	4	NB	SB
Group 3	5	NB	SB
	6	NB	SB
	7	NB	SB

(a) Group one: High pedestrian demand in the subject direction interacting with low pedestrian demand of the opposing direction.

(b) Group two: Low pedestrian demand in the subject direction interacting with high pedestrian demand of the opposing direction.

(c) Group three: Balanced pedestrian demand in both directions.

(3) Data extraction

The positions of pedestrians at every 1s are manually extracted from observation videos by using the image processing system *Traffic Analyzer* (Suzuki and Nakamura[6]) then the coordinates in these images are converted to global coordinate through the projective transformation. Kalman smoothing method is applied to estimate trajectories and speeds of pedestrians at each time interval. Then pedestrian presence probability along the crosswalk is extracted at different elapsed time thresholds.

A coordinate transformation of pedestrian position is done referring to the edge of the crosswalk. The horizontal axis x is defined in parallel to the edge of bicycle crossing path and the vertical axis y is perpendicular to this line as shown in **Fig.1.** This pedestrian positon is used to calculate the pedestrian presence probability within a PG time.

4. ANALYSIS AND DISCUSSION

(1) Crossing pedestrian presence probability distribution

Fig.4, Fig.5, and **Fig.6** show cumulative presence probability distributions of crossing pedestrians along the crosswalk, for group one, group two and group three pedestrian flow categories, respectively. The observed pedestrian presence probability distribution is plotted by aggregating samples observed in all (three) cycles of each group. When the elapsed PG time increases, pedestrian presence probability distributions shift to the moving direction. The slope of the distribution line may change due to the variation in crossing pedestrians' walking speeds. The pedestrian presence probability distributions observed and estimated by the model by Zhang and Nakamura[4,5] clearly show significant difference in **Fig.4**. This can be considered because pedestrian volume at the observed intersection is under a medium to high demand condition, which is out of the application range of Zhang's model.

For all groups, from an elapsed time of 5s up to 15s the observed pedestrian presence probability distribution is positioned on the left side of the distribution estimated by the model. However, after an elapsed time of 20s, the gap between observed and estimated distributions becomes small.

For group two and three cases shown in **Fig.5** and **Fig.6**, which are of the bi-directional flow in a low demand condition versus a high demand condition and of the balanced flow from both sides, respectively, the observed pedestrian presence probability distributions are different from **Fig.4**. In these groups, a different trend can be found in the comparison between the observed and estimated pedestrian presence probability distributions particularly after a half of the crosswalk length or after the elapsed time of 25s. As shown in **Fig.5** and **Fig.6**, observed pedestrian presence probability distributions after the elapsed time of 25s are positioned on the right-hand side of the estimated ones, in particular at the bottom of the presence probability distribution curve. The shift to the right of the observed pedestrian presence probability distribution increases as elapsed time increases.

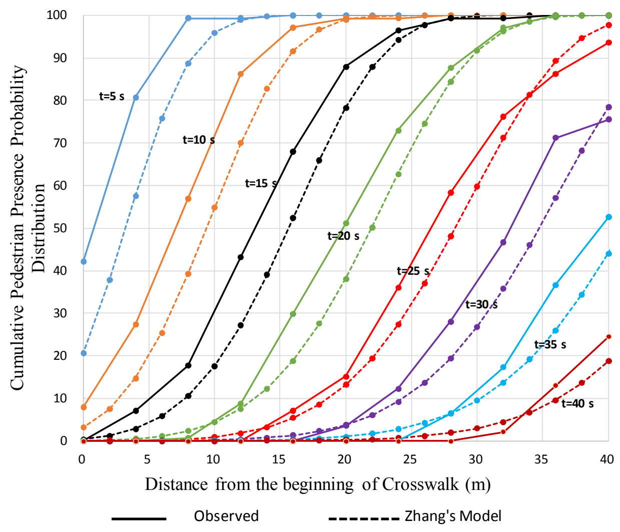

Fig.4 Observed group 1 pedestrian presence probability distribution compared with Zhang's model

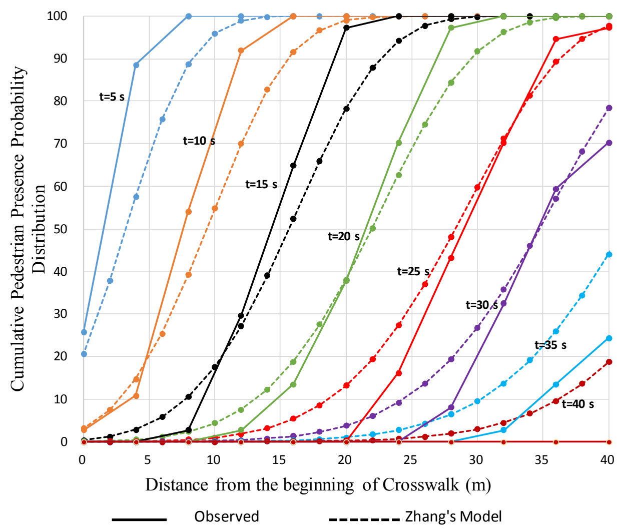

Fig.5 Observed group 2 pedestrian presence probability distribution compared with Zhang's model

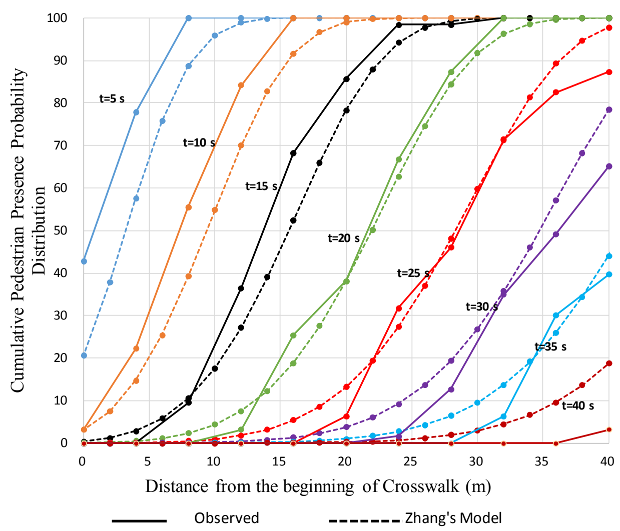

Fig.6 Observed group 3 presence probability distribution compared with Zhang's model

Three possible causes for this can be noted from the observations: reduction in crossing speed due to the high pedestrian demand condition, the effect of pedestrian flow in opposing direction, and pedestrian distribution in the waiting area.

(2) Interaction with opposing pedestrian flow

Pedestrian flow at the crosswalk is a bi-directional flow. Therefore, crossing pedestrian presence probability along the crosswalk is affected by the interaction with the opposing pedestrian flow. The difference in the pedestrian presence probability distribution before and after the interaction occurrence between the subject and opposing flows is quantitatively investigated by using Equation (1).

$$D(t) = D_{85}(t) - D_{15}(t) \qquad (1)$$

Where, $D_{85}(t)$ and $D_{15}(t)$ [m] are the positions of the 85th and the 15th percentile values of the cumulative pedestrian presence probability distribution curve at an elapsed time t, respectively. $D(t)$ is the difference of these values at time t.

When there is some influencing interactions between the two flows, the value of $D(t)$ at the interaction time will be shorten. This is due to the situation that, the leading pedestrians in the subject direction may reduce their walking speed when they face counter flow with high demand, while the following pedestrians keep their walking speed.

Here in this paper there are three groups which are grouped based on combinations of crossing pedestrian demand from each side of the crosswalk as shown in **Table 2**. One case of this condition for cycle 1 bi-directional flow is shown in **Fig.7**, here in the figure the bi-directional flow interacts between the elapsed time of 15s and 25s. A high demand NB pedestrian flow interacts with the opposing low demand SB pedestrian flow. The value of $D(t)$ for the NB pedestrian flow at an elapsed time of 15s, 20s and 25s are 12m, 14.5m, and 16m, respectively. For the opposite SB flow the values of $D(t)$ at an elapsed time of 15s, 20s and 25s are 8m, 9.5m, and 10m, respectively. Therefore, as it is observed from this computation, the increasing rate of $D(t)$ for SB pedestrian flow is less than that for NB flow. This is one implication of opposing direction high-pedestrian demand effect on the pedestrian presence probability distribution of low-pedestrian demand direction.

Fig.8 shows also a trend of $D(t)$ with an increasing elapsed time for the three groups by aggregating samples observed in all(three) cycles of each group. For all groups, $D(t)$ is increasing with increase in elapsed time, which shows there is pedestrian presence probability dispersion when elapsed time increases. However, the increasing rate of group two pedestrian flow is lower than other groups. This implies that when the bi-directional flow is low-pedestrian demand interacting with high-pedestrian demand, then the low-pedestrian demand direction presence probability distribution would be compacted due to interaction influence.

For Zhang's model, the value of $D(t)$ is increasing with increase in elapsed time. However, the model estimate does not fit with the observed pedestrian presence probability distribution. Especially, as it is shown in **Fig.8** the values of $D(t)$ for the model estimate of group two pedestrian presence probability distribution are greater than that of the observed pedestrian presence probability distribution. Since

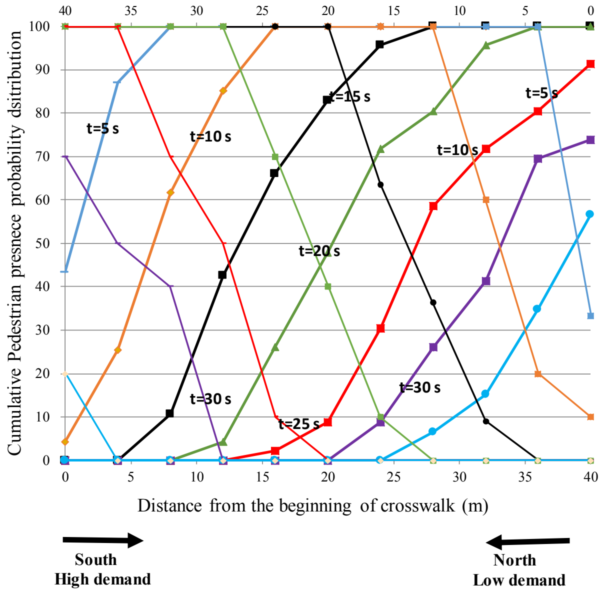

Fig.7 Bi-directional pedestrian presence probability distribution for cycle 1

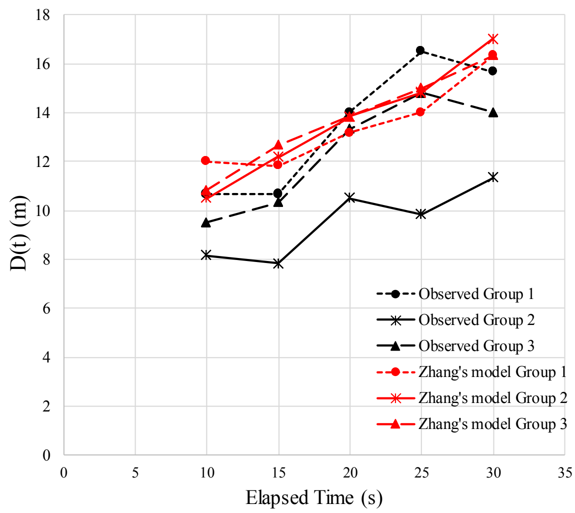

Fig.8 Horizontal distance difference of pedestrian presence probability distribution

group two cases are the interaction of low-pedestrian demand with high-pedestrian demand, the result implies, the impact of opposing high-pedestrian demand on the pedestrian presence probability distribution of low-pedestrian demand direction is not considered significantly in Zhang`s model.

(3) Pedestrian distribution in the waiting area

Waiting position of pedestrians affects the presence probability distribution of crossing pedestrians. In the waiting area, if the distribution of waiting pedestrian is scattered, then after the onset of green time, some of the pedestrians have longer discharge time to enter the crosswalk and the distribution of pedestrian presence probability along the crosswalk is expected to be wider. However, if they are densely waiting just in front of the crosswalk, pedestrian presence probability distribution is also concentrated in small space when they cross along the crosswalk.

To investigate this situation pedestrian space occupancy at the waiting area is computed for all cases of waiting pedestrians and the result is shown in **Table 1**. At an elapsed time of 5s, the percentage of waiting pedestrians in the waiting area is extracted from the pedestrian presence probability distribution curve. **Fig.9** shows the pedestrian space occupancy for all groups related to the percentage of pedestrian remain in the waiting area at an elapsed time of 5s. In observed cycles, when the pedestrian space increase, the percentage of pedestrian remaining at the waiting area at an elapsed time of 5s will decrease. Because waiting pedestrians may quickly enter the crosswalk. This makes the slope of pedestrian presence probability distribution curve milder.

When the percentage of pedestrians remaining at the waiting area correlated with increasing waiting pedestrian demand as shown in **Fig.10**, there is an increasing trend up to pedestrian demand of 25 pedestrians per cycle. However, after that, the increase in pedestrian demand does not affect the percentage of waiting pedestrian in the waiting area. The percentage of pedestrians remaining in the waiting area is highly correlated with pedestrian space compared with pedestrian demand.

Regarding the percentage of remaining pedestrians estimated by Zhang's model, the trend is not changing significantly with increase in pedestrian space occupancy and also with increase in pedestrian demand. This is one reason that the estimated distribution curve does not fit exactly to the observed cycles.

5. CONCLUSION

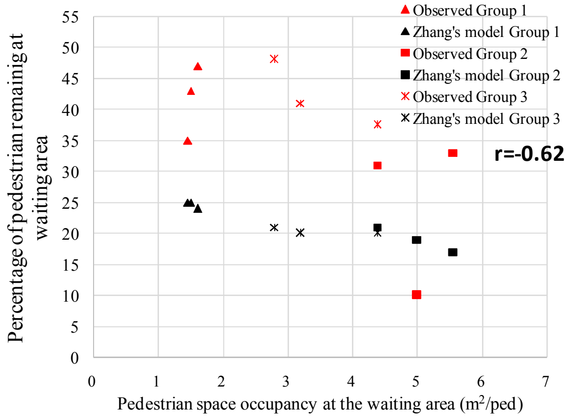

Fig.9 Pedestrians remaining in the waiting area at different pedestrian space occupancy of t=5s

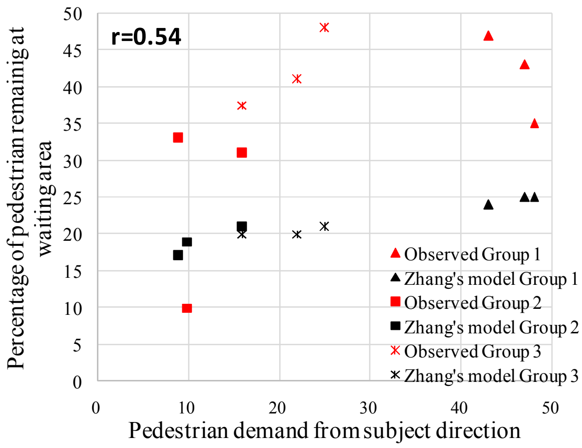

Fig.10 Pedestrians remaining at waiting area at different demand condition of t=5s

To ensure the safety of crossing pedestrians and investigate the operational performance of the intersection, an effective way of pedestrian presence probability distribution estimation along the crosswalk with time is necessary. This situation is significant at high pedestrian demand signalized crosswalks. In this study, impact of opposing pedestrian flow interaction, pedestrian space occupancy at the waiting area and bi-directional pedestrian demand condition are investigated at relatively high pedestrian demand signalized crosswalk. The analysis shows that when the demand for bi-directional pedestrian flow is unbalanced, the low demand direction flow pedestrian presence probability distribution is influenced at the interaction time. In addition, pedestrian space occupancy in the waiting area has an inverse relationship with the discharge time of waiting pedestrians.

The comparison with Zhang`s model shows that, there is a difference between estimated and observed pedestrian presence probability distribution. The reasons for the difference are, the effect of unbalanced bi-directional pedestrian flow, the interaction of opposing pedestrian flow and pedestrian space in the waiting area are not considered in the model. Therefore, these influencing factors must be considered when modeling pedestrian presence probability.

As a future work, by considering the influencing factors discussed above, pedestrian presence probability distribution by time will be modeled. This is useful to predict pedestrian presence probability distribution along the crosswalk at planning and operational analysis of signalized crosswalks.

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