A study on expected blockage time of left turning vehicles under the influence of pedestrians at signalized intersections

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Existing capacity estimation methods of left turning vehicles do not explicitly consider pedestrian platoon maneuver under the influence of traffic signal settings, crosswalk length and bidirectional interactions of pedestrians. This study aims to propose a method to estimate the expected blockage time that pedestrian platoon occupies the conflict area, considering the characteristics of pedestrian platoon maneuvers. The existing time dependent pedestrian presence probability model is applied by re-estimating the parameters of the model. This model was applied to calculate expected blockage time of waiting pedestrian platoon. In addition, estimation of expected blockage time by the proposed method is compared with the observed waiting pedestrian blockage time and conflict-area passing time of first left turning vehicle i.e. unused time of left turning vehicle after the onset of green. It was found that the proposed model can represent the blockage time comparing observed blockage time of waiting pedestrians and unused time of first left turn vehicle at signalized crosswalks.

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

1. INTRODUCTION

At signalized intersections, crossing pedestrians and vehicles may have shared space and time on the crosswalk based on the assigned signal timing design. If there is a shared space or time with in the assigned green time of pedestrians and vehicles then the interaction of crossing pedestrians and vehicles is an unavoidable condition. Mostly, in signal timing design practitioners assigned shared signal timing for crossing pedestrians and left turning vehicles. When crossing pedestrians share signal timing with left turning vehicles, the effective green time can be divided into two general portions of blockage time interval and available passing time interval. The blockage time interval can be defined as the necessary time for near-side and far-side waiting pedestrians platoon to cross the shared space. As a basic assumption, waiting pedestrians start to cross in a group; due to that, there will be the longest pedestrian-vehicle interaction time interval. At this portion of the green time it is difficult for left turning vehicles to pass the crosswalk. The remaining time with in the assigned green time will be the second portion i.e. available passing time interval for left turning vehicles. At the second portion, left turning vehicles may interact with randomly arriving pedestrians, however the influence on their movement is not significant compared with the waiting pedestrian influence. The influence of waiting pedestrian on left turning vehicles may depend on number of pedestrians, crossing pedestrian’s behavior and geometric layout of the crosswalk. Understanding pedestrian behavior along the crosswalk and quantify their effect on left turning vehicles is essential for signal timing design and evaluating the operational performance of signalized intersections.

Therefore, the objective of this paper is to propose and evaluate an estimation method of the expected blockage time of left turning vehicles under the influence of waiting pedestrians at signalized crosswalks.

2. LITERATURE REVIEW

(1) Crossing pedestrian behavior

The influence of pedestrians on left turning vehicles movement is highly related with the crossing behavior of pedestrians. Crossing behavior of pedestrians can be influenced by different factors when they cross along the crosswalk of signalized intersections like by their age, walking speed, gender and time of day etc.

A research by Akash et.al.[1] and Abinav et.al.[2] on the analysis of pedestrian crossing behavior by considering pedestrian characteristics like age, gender and that of carrying baggage influence on crossing speed and waiting time showed that there is a significant variation in waiting time and crossing speed due to the difference in the composition of crossing pedestrians. Goh and Lam[3] studied the relationship of pedestrian flow volume and walking speed, the study revealed that the pedestrian flow volume had significant effect on walking speed. Zhang et al.[4] analyzed and modeled pedestrian walking speed at signalized crosswalks considering crosswalk length and signal timing. Their empirical analysis showed that, pedestrian walking speed increases as pedestrian green time proceeds. Moreover, their findings implied that longer crosswalks correspond to higher walking speed. Because of that, the duration of time that crossing pedestrians stay at the crosswalk is highly dependent on these factors.

(2) Existing guidelines

Despite of that, the existing guidelines or researches do not fully consider the effects of these factors on pedestrian flows for estimating turning vehicle capacity. Highway Capacity Manual (HCM)[5] and a Planning and Design of at-grade Intersections - Basic Edition -; Guide for Planning, Design and Traffic Signal Control of Japan (JSTE manual, hereafter)[6] considered the influence of pedestrians for estimating capacity of turning lanes. The basic idea to consider the pedestrian impact is based on the time occupancy of crossing pedestrians within green time. Zhang et al.[7] quantitatively analyzed pedestrian impact on the capacity of right-turn vehicles at signalized intersections. They applied pedestrian-grouping model based on gap acceptance theory to estimate potential capacity. Chen et al.[8] studied impact of pedestrian traffic on saturation flow of left-turn at urban intersections; they found that 93% of left-turn vehicles slowed down due to the presence of pedestrians. However, in the manuals and also other studies use the number of pedestrians as a factor without considering the bi-directional pedestrian flow, pedestrian platoon effect and change in geometric layout of the crosswalk.

(3) Pedestrian presence probability observation and modeling

At the onset of green, pedestrians waiting at sidewalks simultaneously starts to cross from both side of the crosswalks. Generally speaking, these pedestrians forming platoons at the onset of green significantly contribute to block turning vehicle flows. Therefore, the maneuver of pedestrian platoons needs to be investigated to understand the influence on left turning vehicles. Zhang and Nakamura[9,10] 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. However, they analyzed the sites with relatively lower pedestrian traffic demand. Moreover, interaction with opposing pedestrian flow has not been investigated by them.

Therefore, in order to propose a method for estimating expected blockage time of left turning vehicles due to pedestrians at signalized crosswalks, the pedestrian presence probability model proposed by Zhang and Nakamura[9] (Hereafter, Zhang's model) is adjusted considering the interaction of subject and opposing pedestrian flow.

Emagnu et al.[11] observed and re-estimated the pedestrian presence probability distributions by following the same methodology as Zhang's model considering the opposing pedestrian flow as an additional influencing parameter. The result showed that for the coefficients α and β of the Weibull distribution pedestrian presence probability model, elapsed time has a positive impact to both α and β, which shows pedestrian platoon dispersed in the direction of flow when elapsed time increases. Crosswalk length has a negative impact to α, suggesting that there are the wider distributions along the longer crosswalk. On the longer crosswalks, pedestrian platoon tends to disperse.

The number of subject direction waiting pedestrian q_s shows that higher q_s results in the wider distribution. For the number of opposite direction waiting pedestrian q_o, the impact is positive for α. With increase in q_o the distributions become compacted. This is because the high demand of opposing pedestrians will impede the pedestrian platoon to disperse. The re-estimated model showed a good fitting for high pedestrian demand crosswalks compared with Zhang's model.

With the assumption of waiting pedestrians influence left turning vehicles significantly, the re-estimated model is used to estimate the expected blockage time of waiting pedestrians. Since this model represents the expected duration of pedestrian presence at the conflict-area with the assumption of the probability for the left turning vehicle to pass the conflict-area while waiting pedestrians are crossing is minimum. However, to validate this assumption analysis of the first left turning vehicle passing time is necessary. Consequently, in this study the first left turning vehicle unused time is compared with the estimated expected blockage time of waiting pedestrians.

3. METHODOLOGY

(1) Definition of terminology

Fig.1 shows the conceptual layout of a crosswalk at a signalized intersection.

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. By following the assumption of Zhang and Nakamura[9], it is assumed that the first 8 sec of PG is enough in average for the waiting pedestrians to discharge from the beginning of the crosswalk with a walking speed of 1m/sec. Therefore, the waiting area length is taken as 8m from the beginning of crosswalk.

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

Conflict-area: a shared space by crossing pedestrians and turning vehicles on the crosswalk as shown in **Fig.1**.

Near-side pedestrian: are coming from the nearest side of the crosswalk to left turning vehicles.

Far-side pedestrian: opposite side from the near-side pedestrian flow, this is the farthest side of crosswalk for left turning vehicles.

Subject direction flow: pedestrian flow in the direction of pedestrian presence analysis.

Opposing direction flow: is pedestrian flow from the other side of the crosswalk (Opposite to the subject direction flow).

Blockage time (BT): time interval when waiting pedestrians platoon occupied the conflict-area.

Unused time: after the onset of green the elapsed time of first left turning vehicle (LTV) to pass the conflict-area.

Pedestrian crossing probability (PCP): the probability of waiting pedestrian platoon cross the reference section line (edges of the conflict-area) at elapsed time t.

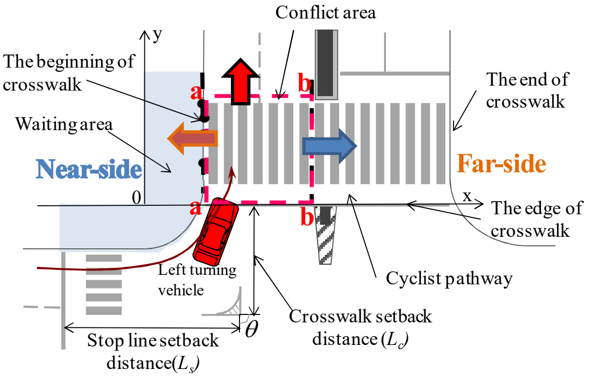

Fig.1 Layout of subject crosswalk and definition of basic terms

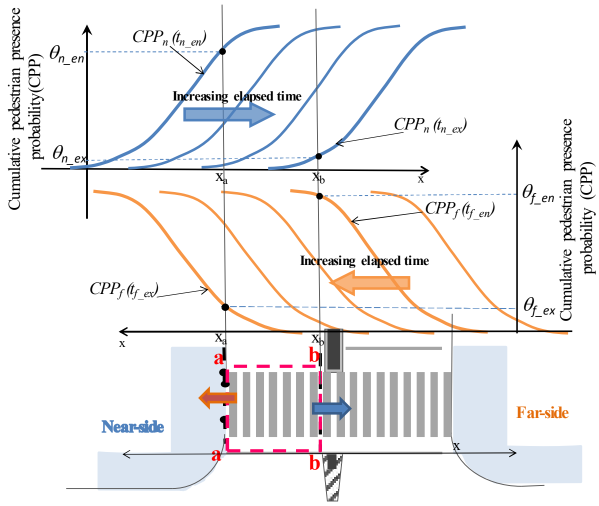

Fig.2 Pedestrian crossing probability of conflict-area

At the onset of pedestrian green (PG), waiting pedestrians from both edges of a crosswalk start walking. After PG elapsed, pedestrian's position along the crosswalk gradually changes because of a variation in walking speeds of individual pedestrians. In addition, there is an interaction between pedestrians crossing from two sides of the crosswalk. The significance of interaction may depend on the number of pedestrians from both sides of the crosswalk. This spreading and interaction situation is more significant for the waiting pedestrian platoon 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.

(2) Estimated expected blockage time

Table.1 Traffic conditions of observed sites

Intersection name	Subject crosswalk	Signal phase			Waiting pedestrian volume (ped/cycle)				Number of sample cycles	
		PG (s)	G(s)	Cycle length (s)	Near-side	Near-side Average	Far-side	Far-side Average	For pedestrian analysis	For LTV analysis
Kanayama	East	48-61	57- 71	148-174	0-13	5	0-10	4	39	22
Ueda	South	38-47	61-67	144-176	0-3	2	0-4	2	21	21
Nishiosu	North	38	52	160	0-4	3	0-3	2	22	22
Otsu-dori	West	37	54	160	1-13	6	2-12	5	36	14

Table.2 Geometric characteristics of observed sites

Intersection name	Subject crosswalk	Crosswalk geometry		Intersection angle θ (degree)	Setback distance of LTV stop line L_s (m)	Setback distance of subject crosswalk L_c (m)
		Length (m)	Width (m)			
Kanayama	East	16	6	93	21.4	7.4
Ueda	South	21	5	119	16.5	23.6
Nishiosu	North	32	6	75	17.6	16.3
Otsu-dori	West	34	6	91	21.5	15.5

As it is defined in a study by Emagnu et. al.[11] to estimate the expected blockage time for turning vehicles by waiting pedestrians, it is necessary to consider the clearance time of pedestrian flow from both sides of the crosswalk at the edges of the conflict-area as shown in **Fig.1**.

Fig. 2 depicts the concept of how to calculate expected durations that waiting pedestrian platoon blocks the conflict area using the pedestrian probability distribution. The upper part of figure in **Fig. 2** shows the time dependent trend of cumulative pedestrian presence probability distribution of nearside pedestrians. Let us define q_n as the number of near-side waiting pedestrians per cycle. As the time goes, the distribution moves toward right-hand side. In this figure, at time $t = t_{n\_en}$, the cumulative probability at cross section a ($x = x_a$) will be θ_{n_en}. This means that the expected number of $(1-\theta_{n\_en})q_n$ has been already passed the cross section a by that time. Suppose this expected number is equal to one as in Equation (2), by assuming the entry of the first waiting pedestrian. Then, the time t_{n_en} will be considered as the expected time that first pedestrian in the platoon arrives at the cross-section a.

$$(1-\theta_{n\_en})q_n = 1 \tag{2}$$

Actually, θ_{n_en}, x_a are given from the definition but t_{n_en} is the unknown variable. Therefore, the problem to be solved is to find out t_{n_en} so that Equations (2) and (3) are satisfied.

$$\theta_{n\_en} = \int_0^{t_{n\_en}} PPP_n(x_a, t)dt \tag{3}$$

Pedestrian presence probability (PPP) is modeled as a function of elapsed time as explained in the previous section. However, it is difficult to analytically solve the right-hand side of Equation (3). Therefore, numerical calculation is applied to obtain t_{n_en}.

Similarly, time t_{n_ex}, i.e. the expected exit time of the last near-side pedestrian from conflict area, is given by satisfying equations (4) and (5).

$$\theta_{n\_ex} \times q_n = 1 \tag{4}$$

$$\theta_{n\_ex} = \int_0^{t_{n\_ex}} PPP_n(x_b, t)dt \tag{5}$$

Where, θ_{n_ex} is cumulative probability at cross section $b(x = x_b)$.

Entering (t_{f_en}) and exit time (t_{f_ex}) of far-side pedestrian platoons are also derived by using **Fig. 2** following the same approach.

Thus, after the expected entry/exit times of both near-side and far-side platoons are obtained, total estimated expected blockage time by waiting pedestrian platoon, (Hereafter, estimated blockage time (BT)), will be calculated by Equation (6).

$$BT = min\begin{pmatrix} (t_{n\_en} - t_{f\_ex}), \\ (t_{n\_ex} - t_{n\_en}) + (t_{f\_ex} - t_{f\_en}) \end{pmatrix} \qquad (6)$$

The first term of the parentheses in the right-hand side of Equation (6) is the time gap between the entry time of the near-side first pedestrian and the exit time of the far-side last pedestrian, and the second one is the summation of the time difference between the entry time of the first pedestrian and exit time of the last pedestrian, for both near-side and far-side pedestrian flows.

The selection of the minimum value depends on crosswalk length, pedestrian demand and assigned signal timing. These factors influence the overlap time of the last pedestrian from near-side direction flow and first pedestrian of far-side direction flow.

(3) Unused time of the left turning vehicles

Unused time is measured from observation by recording the time when the back wheel of the first left turning vehicle pass the conflict-area, as shown in **Fig.1**.When left turning vehicles has the same onset of green time with pedestrians, and then at the beginning of green time they will not use some portion of assigned green time. This is due to the priority of crossing pedestrians. The magnitude of unused time depends on the number and crossing characteristics of waiting pedestrians. In addition, the geometric layout of the crosswalk may influence the passing time of the left turning vehicle.

(4) Study sites and traffic condition

For the pedestrian and left turning vehicles analysis, signalized intersections located in Nagoya, Japan are selected. The intersections have different pedestrian demand situations and crosswalk geometric characteristics. The geometric condition, traffic condition and signal settings of the selected signalized crosswalks are summarized in **Table 1** and **Table 2**. Only the crossing behaviors of waiting pedestrians are analyzed in this paper.

4. ESTIMATED BLOCKAGE TIME

(1) Observed entry/exit time from empirical data

a) Impact of number of waiting pedestrian on entry/exit time

Fig.4 and **Fig.5** show the pedestrian entry/exit time and first LTV exit time observation for different cycles of Kanayama and Nishiosu crosswalks, respectively. The correlation r between the first pedestrian entry time from near-side/far-side and the number of waiting pedestrian per cycle shows a decreasing trend for Kanayama crosswalk as shown in **Fig.4,** even if the correlation is weak this gives as a hint about the entry time behavior, i.e. when higher numbers of waiting pedestrians are in the waiting area the first pedestrian intend to enter

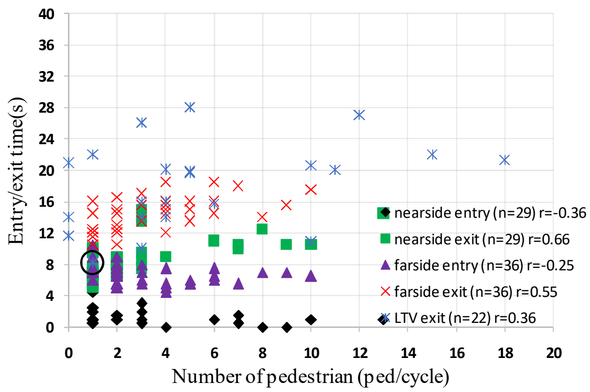

Fig.4 Entry/exit time under different number of pedestrian per cycle of Kanayama crosswalk

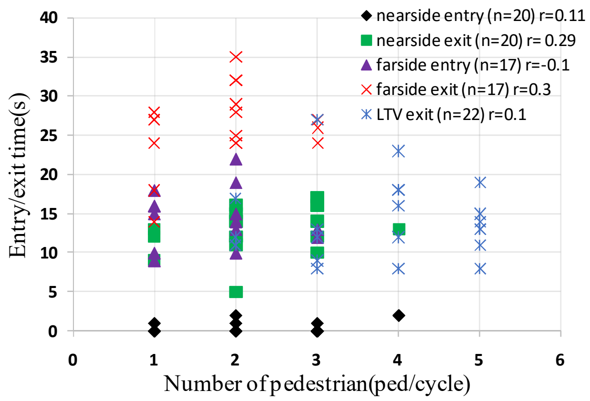

Fig.5 Entry/exit time under different number of pedestrian per cycle of Nishiosu crosswalk

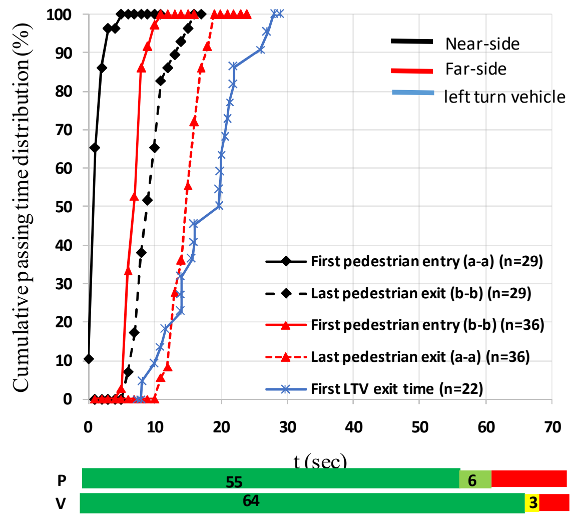

Fig.6 First pedestrian entry, last pedestrian exit and first LTV exit time distribution at Kanayama crosswalk

the conflict-area quickly, to avoid overtake by other pedestrians. While the correlation between the last pedestrian exit time from near-side/far-side and the number of waiting pedestrian per cycle have an increasing trend for both Kanayama and Nishiosu crosswalks. These implies that, when there is higher number of waiting pedestrians the last waiting pedestrian crossing time is slower, due to the pedestrian group platoon dispersion and the interaction with other pedestrians there will be speed reduction.

b) Relationship between unused time and far-side last pedestrian exit time

First LTV exit time is less than the exit time of far-side last waiting pedestrian for most of the cycles in Nishiosu crosswalk as shown in **Fig.5**, as the pedestrian demand at Nishiosu crosswalk is lower and crosswalk length is long, then first LTV will have a chance to pass the conflict area before the far-side last waiting pedestrian arrive. However, for most of observed cycles of Kanayama crosswalk as shown in **Fig.4** it is greater than the last exit pedestrian from far-side. For cycles like the one located by black circle in **Fig.4**, unused time of first LTV is below the far-side last waiting pedestrian exit time, this is one example for those cycles either near-side or far-side with 0 ped/cycle, the unused time will be very short compared to others. For some observed cycles as shown in **Fig.4** unused time of first LTV is greater than far-side last waiting pedestrian exit time even if there is low number of waiting pedestrian per cycle condition, which may indicate that geometric layout of the intersection (crosswalk setback distance, turning radius, intersection angle etc.) has additional effect on the LTV exit time. The observed intersections have different geometric layout as shown in **Table 3**. Therefore, the unused time of the first LTV may show higher value even at low pedestrian demand condition, due to the lag in arrival time from the stop line.**Fig.4** shows higher value of unused time at low waiting pedestrian demand condition, since the stop line setback distance of Kanayama crosswalk (shown in **Table 3)** is longer compared with others.

c) Order of cumulative distribution of pedestrian entry/exit time and unused time

Fig.6 and **Fig.7** shows observed cumulative distribution of the first waiting pedestrian's entry time, the last waiting pedestrian's exit time and the unused time of first LTV from the conflict-area at each cycle of Kanayama crosswalk and Nishiosu crosswalk, respectively. The variation of first and last waiting pedestrians' enter and exit time distributions are greater for Nishiosu crosswalk compared with Kanayama crosswalk. This is due to the longer crosswalk situation at Nishiosu crosswalk

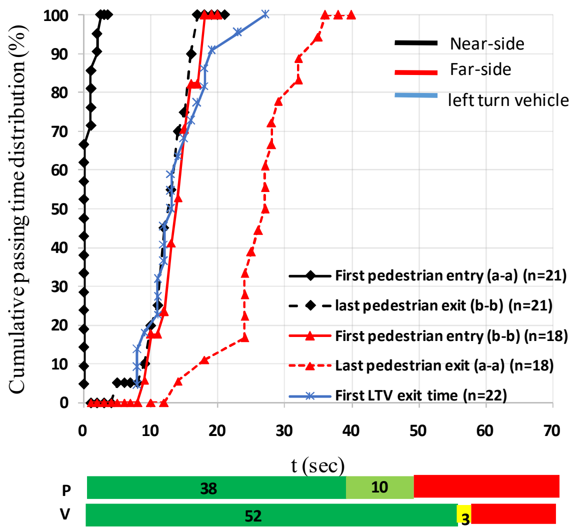

Fig.7 First pedestrian entry, last pedestrian exit and first LTV exit time distribution at Nishiosu crosswalk

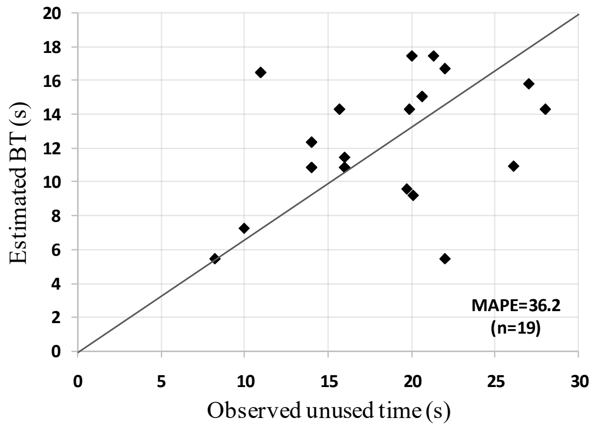

Fig.8 Comparison of estimated and unused times per cycle for Kanayama crosswalk

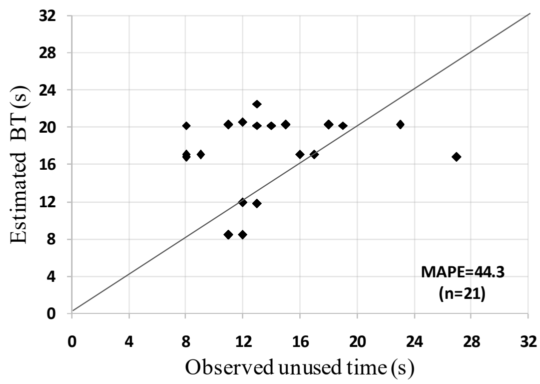

Fig.9 Comparison of estimated and unused times per cycle for Nishiosu crosswalk

pedestrians crossing speed may significantly vary.

As it is shown in **Fig.6,** the cumulative passing time distribution of first LTV is located after the far-side last waiting pedestrian's exit time distribution for Kanayama crosswalk. On the other hand, for Nishiosu crosswalk case shown in **Fig.7** the passing time distribution of the first LTV is located between the near-side last waiting pedestrian's distribution and the far-side first waiting pedestrian's distribution. The reason behind this difference is mainly due to the variances in pedestrian demand and crosswalk length of the two crosswalks. When the number of waiting pedestrians is higher, the possibility is high for the far-side first pedestrian to arrive at the conflict-area before the near-side last pedestrian exit. Similarly, in shorter crosswalks the far-side first waiting pedestrians will arrive quickly before the near-side last waiting pedestrians exit from the conflict-area.

Therefore, from the above observations we can understand that the blockage effect of left turning vehicles under the influence of pedestrians depends on the entry and exit times of waiting pedestrians, waiting pedestrian demand and geometric layout of the intersection.

(2) Validation of estimated blockage time

The estimated blockage time is compared with the observed unused time as shown in **Fig.8** and **Fig.9** for Kanayama and Nishosu crosswalks, respectively. For both Kanayama and Nishosu crosswalks some of the scatter plots of the observed cycles are far from the 45-degree line and the MAPE value is slightly higher than the acceptable range, that implies the estimation method may need some modification to consider the basic points discussed in the above sections which causes the fluctuation in blockage time estimation per cycle.

(3) Comparison of blockage times and unused time

As it is shown in **Fig.10** the estimated blockage times are compared with observed blockage times and unused times of first LTV. The observed and estimated blockage times are plotted using the average number of waiting pedestrians. The unused time is the average of the observed unused times per cycle. In general, the trend of estimated blockage times compared with others follow similar trend.

From the observations it is found that there are very low pedestrian demands on Ueda and Nishiosu crosswalks. Therefore, there is a gap between the last near-side pedestrian exit time and the entry time of first far-side pedestrian. In this case there are not overlap time between near-side pedestrian platoon blockage time and far-side pedestrian platoon blockage time. Then the first LTV vehicles have a chance to pass before the far-side pedestrian arrive the conflict-area. It will result in short unused time of LTV. Therefore, as it is shown in **Fig.10** the

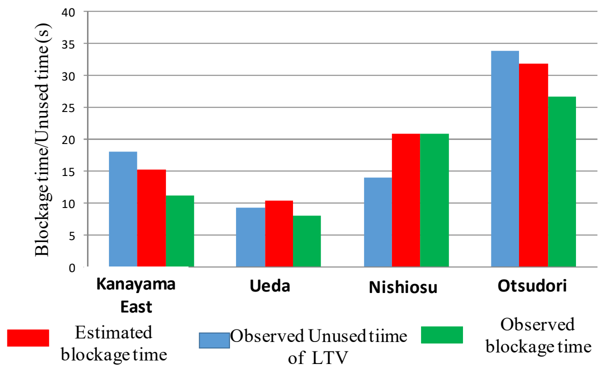

Fig.10 Comparison of observed and estimated blockage times and observed unused time of LTV

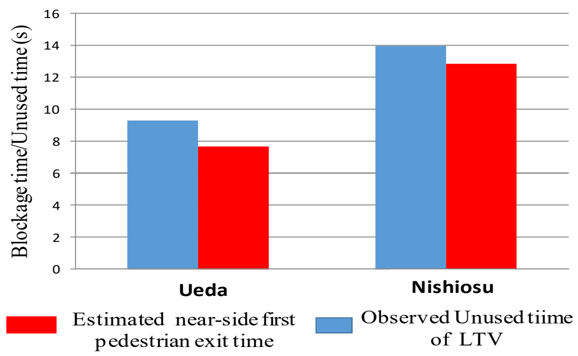

Fig.11 Comparison of observed unused time of LTV and estimated blockage times by near-side pedestrians

observed unused time (blue color) is shorter than proposed method estimation (red color) for Ueda and Nishiosu crosswalks. Furthermore, since the Nishiosu crosswalk is longer than Ueda crosswalk, the larger difference between observed unused time of LTV and proposed method estimation can be found. Consequently, it is not reasonable to compare blockage time and unused time at low pedestrian demand condition, rather it will be good to compare unused time with near-side first pedestrian exit time.**Fig.11** shows the comparison of unused time and near-side first pedestrian exit time for Ueda and Nishiosu crosswalks, as it is shown in **Fig.11** unused time has almost equal value with near-side first pedestrian exit time. Therefore, unused time can be reasonably estimated by near-side first pedestrian exit time at low pedestrian demand conditions.

Kanayama and Otsu-dori crosswalks have higher number of pedestrians compared with the others. Therefore, the possibility is less for the far-side first pedestrian to arrive at the conflict-area before the near-side last pedestrian exit from the conflict-area, due to this the blockage time is determined by the entry time of the near-side first pedestrian and the exit time of the far-side last pedestrian. The proposed method estimation is slightly larger than the observed ones for Otsu-dori and Kanayama crosswalks; the possible reason is related with the variation in number of pedestrians per cycle. The proposed method used the average number of pedestrians while the observed blockage times are calculated per cycle and then averaged. In addition, the unused time of first LTV at Kanayama and Otsu-dori crosswalks are larger than the proposed method estimated blockage times. The possible reason is related with the arrival time of turning vehicles from stop line to the crosswalk. As it is shown in **Table 2**, for Kanayama and Otsu-dori crosswalks the LTV stop line setback distance is longer compared with others, due to this sometimes even at low pedestrian demand condition LTV may take long time to arrive and pass the crosswalk. Therefore, in this case unused time has extra time (in addition to pedestrian blockage time).

Estimated blockage time of Otsu-dori crosswalk is relatively greater than other crosswalks. Therefore, when crosswalk length is long the pedestrian presence distribution become wide along the crosswalks and the blockage time will be larger due to the dispersion of crossing pedestrians along the crosswalk. The blockage time is inversely related with the available crossing time for turning vehicle within the green interval, when blockage time increase then the available time for turning vehicles will decrease. This must be balanced by proper signal timing design.

5. CONCLUSION

In this study, waiting pedestrian presence probability along the crosswalk was observed and re-modeled by considering the impact of influencing factors. For consideration of signal timing influence, PG elapsed time is used as a variable. Crosswalk length is used as an influencing factor to consider the effect of crosswalk geometry. In addition, the number of subject and opposing pedestrians are included as variables in the model. Then the model is applied to estimate the blockage time of waiting pedestrians.

The blockage time was estimated for the observed signalized crosswalks, and the result imply that pedestrian presence probability model can be used to efficiently estimate the expected blockage time of crossing pedestrians on left turning vehicles. The analysis of estimated expected blockage time showed that when crosswalk length and pedestrian demand increase, blockage time will increase. In addition, the comparison of the blockage time with observed crossing time between the first and last pedestrians in waiting pedestrian platoon showed similar results for all observed crosswalks. The analysis also showed that the blockage time can reasonably represent unused time of first LTV.

As a future work, by considering the pedestrian presence probability model and the estimation methodology of expected blockage time, the left-turn lane capacity can be estimated.

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