A METHODOLOGY FOR INVESTIGATING EFFECTIVE RANGE OF LEADING PEDESTRIAN INTERVAL CONSIDERING SAFETY AND OPERATIONAL PERFORMANCE OF SIGNALIZED INTERSECTIONS IN JAPAN

Xin ZHANG*
Research associate, M.-Eng.
Department of Civil and Environmental Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, JAPAN
Tel: +81 (52) 789-3832
FAX: +81 (52) 789-3837
Email: zhang@genv.nagoya-u.ac.jp

Hideki NAKAMURA
Professor, Dr.-Eng.
Department of Civil and Environmental Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, JAPAN
Tel: +81 (52) 789-2771
FAX: +81 (52) 789-3837
Email: nakamura@genv.nagoya-u.ac.jp

Number of Words = 4453
Number of Figures = 7
Number of Tables = 4
Total Words Count = 4504+(7+4)*250 = 7254

Submission Date: 11/14/2016
*Corresponding Author

ABSTRACT

One of the measures to reduce the conflicts between pedestrians and left-turning vehicles at crosswalks of signalized intersections is to provide separate phases for pedestrians and curbside turning vehicles, such as exclusive pedestrian phase (EPP) or Leading Pedestrian Interval (LPI). LPI, which displays a few seconds of dedicated pedestrian green phase ahead of vehicle green phase provides better visibility of pedestrians to the drivers of turning vehicles, and a portion of pedestrians can be protected from the conflicting turning vehicles. From the viewpoint of safety and operational performance, LPI can be positioned between the concurrent pedestrian phase (CPP) which shares the same signal phase with adjacent vehicles, and the EPP which has a dedicated phase for pedestrians only. However, the application range of LPI depending on intersection layout and traffic conditions is still unclear. Thus, this study proposes a methodology for quantitatively evaluating the change level of pedestrian-vehicle conflict risk as pedestrian green time proceeds, and in conjunction with the evaluation of operational performance, the effective application range of LPI is investigated through a case study on typical situations at signalized intersections in Japan.

KEY WORDS: Leading pedestrian interval, Concurrent pedestrian phase, Exclusive pedestrian phase, Pedestrian safety performance, Operational performance

INTRODUCTION

Background

Signal timing of pedestrian phase plays an important role in the safety and mobility performance at signalized intersections. According to the annual report by the National Police Agency of Japan (*1*), approximately 20% of the total number of traffic accidents occurred during pedestrians walking on crosswalks at signalized intersections. The total number of traffic accidents is decreasing recently; however, there are still a high number of fatalities and injuries due to collisions between pedestrians and vehicles. Although pedestrians have the right of way on signalized crosswalks during pedestrian green phase, pedestrian-vehicle conflicts occur frequently, which can be considered as one of the most common safety problems at signalized intersections in Japan. This is because concurrent pedestrians phase (CPP) with adjacent vehicle phase is generally adopted and pedestrians can have a risk to conflict with the turning vehicles on the crosswalk. Japan has a left-hand traffic system, thus, this research first focuses on the conflicts between pedestrians and left turning (LT) vehicles which are the curbside turning vehicles.

One of the safety measures for pedestrians is to provide an exclusive pedestrian phase (EPP) by stopping all the vehicular movements. This can inhibit conflicting vehicular movements from crossing pedestrians, however results in longer delay and lower capacity for all the road users. Zhang et al. (*2*) validated that crossing pedestrians during the walk signal at an exclusive signal experienced absolutely lower interaction severity compared to those crossing during the green light with CPP. Recently, the Leading Pedestrian Interval (LPI) which provides several seconds of pedestrian green time ahead of concurrent turning vehicle's green time, has been introduced also in Japan as a safety measure for pedestrians. Some manuals (*3*,*4*) noticed that LPI can enhance the visibility of pedestrians in the intersection and emphasize their right of way to the drivers of turning vehicles. As well as, LPI can reduce the pedestrian-vehicle conflicts (*5*).

From the viewpoints of safety and operational performance, LPI can be positioned between the EPP and the CPP. However, the effective application range of LPI and the degree of improvement compared to the other two pedestrian signal phasing schemes have not been well understood considering pedestrian crossing progress depending on traffic conditions and layout of signalized intersections.

Objectives

The objectives of this paper are first to propose a methodology for quantitatively evaluating the change level of pedestrian-vehicle conflict risk as pedestrian green time proceeds, and then to investigate the effective application range of LPI in conjunction with evaluation of operational performance through a case study at a hypothesized signalized intersection in Japan.

LITERATUER REVIEW

Regarding the LPI application range, some examples have existed in several countries since several decades ago. The standard length of LPI in the city of Toronto is greater than 5sec or $(TL/2+PL)/W$, where TL is the crosswalk distance between the curb and the centerline without including parking lane, PL is distance on the crosswalk to clear the parking/merging lane if any, and W is walking speed of 1.0m/sec (*3*). Here, LPI is applied to ensure enough time for pedestrians to finish crossing at least a half of the crosswalk in order to increase visibility of pedestrians to the drivers of turning traffic.

In the Manual on Uniform Traffic Control Devices (MUTCD) (*4*) of the US, it is mentioned that “LPI should be at least 3 seconds in duration and should be timed to allow pedestrians crossing at least one lane of traffic or, in the case of a large corner radius, to travel far enough for pedestrians to establish their positon ahead of the turning traffic before the turning traffic is released”.

Fayish and Gross (*6*) found that implementation of LPI reduced 58.7% of pedestrian-vehicle crashes at 10 intersections in Pennsylvania by a before-after study with comparison groups. It is indicated that LPI can improve pedestrian safety performance.

In addition to the issues in operational performance mentioned above, many studies and manuals note that LPI can enhance the visibility of pedestrians. However, less attention is paid to what extent LPI can separate a portion of the pedestrians from the conflicting vehicular movements.

In regard to evaluate level of pedestrian-vehicle conflict, Hubbard et al. (*7*) proposed the percentage of compromised pedestrian crossings as a means to quantify the negative impact of turning vehicles on pedestrian service and as a pedestrian level of service (LOS) measure at signalized intersections. For example, if the percentage compromised exceeds 15%, then it may be appropriate to implement LPI or other enhancement. It is still unclear under which conditions of intersections the LPI can be effectively applied considering the operational performance. The appropriate length of LPI should also be clarified considering traffic characteristics and geometric layout of signalized intersections in Japan.

In order to design the pedestrian signal timing, it is important to understand the progress of pedestrians crossing. In the previous analysis, authors (*8*) analyzed the pedestrian presence probability at any time and position during pedestrians crossing and developed a spatiotemporal distribution model of pedestrian density on crosswalks. Based on this model, the number of pedestrians that completely passed through the conflict area can be estimated and it is expected to utilize it for evaluating pedestrian-vehicle conflict levels on signalized crosswalks.

METHODOLOGY

Pedestrian Signal Phasing Schemes

The CPP start simultaneously with the adjacent vehicle signal phase in Japan. During CPP, all crossing pedestrians have opportunities to conflict with the adjacent curbside turning vehicles. The capacity of the vehicular flow is also strongly influenced by the pedestrian demand and crossing time. During LPI, if pedestrians can finish crossing the conflict area of the crosswalk, they can be completely separated from conflicting vehicular movement. After LPI, the adjacent turning vehicles are given the green signal and they need to yield to pedestrians who are already in the crosswalk. In the case of EPP, all pedestrians may be completely separated by stopping all the vehicle movement. However, a dedicated pedestrian phase should be applied to allow enough time for pedestrians to finish crossing on all crosswalks. Thus, it will reduce the intersection capacity.

Since this research only focuses on the conflict between pedestrians and LT vehicles, it is assumed that an exclusive phase for right turning movement is provided for each approach. In the case of Japan, only permitted LT vehicles will enter the intersection during vehicle green indication and left turns on red (LTOR) are not allowed.

Definitions of Pedestrian Crossing Progress

According to the previous analysis of authors (*8*), pedestrian crossing direction is defined as pedestrian approaching side. Near-side means the side where pedestrians and curbside turning vehicles have conflicts and far-side is the opposite side as shown in Figure 1. In this study, near-side pedestrians are firstly analyzed as an example, and far-side pedestrians are assumed as bilateral symmetry of near-side pedestrians.

A coordinate transformation of pedestrian position is done and the horizontal axis x is parallel to the edge of bicycle crossing path as shown in Figure 1. In order to consider the position where pedestrians wait on the sidewalk, the origin of the horizontal axis is defined at the location d (m) upstream from the beginning of near-side of the crosswalk as the edge of waiting area.

In order to spatiotemporally analyze the pedestrian crossing progress, pedestrian presence probability is defined as the number of pedestrians at x and t divided by the total pedestrian number of the cycle. Some examples are conceptually illustrated in Figure 1. Here, the elapsed time of pedestrian green phase (PG) is defined as the time from the onset of PG and denoted by t (sec).

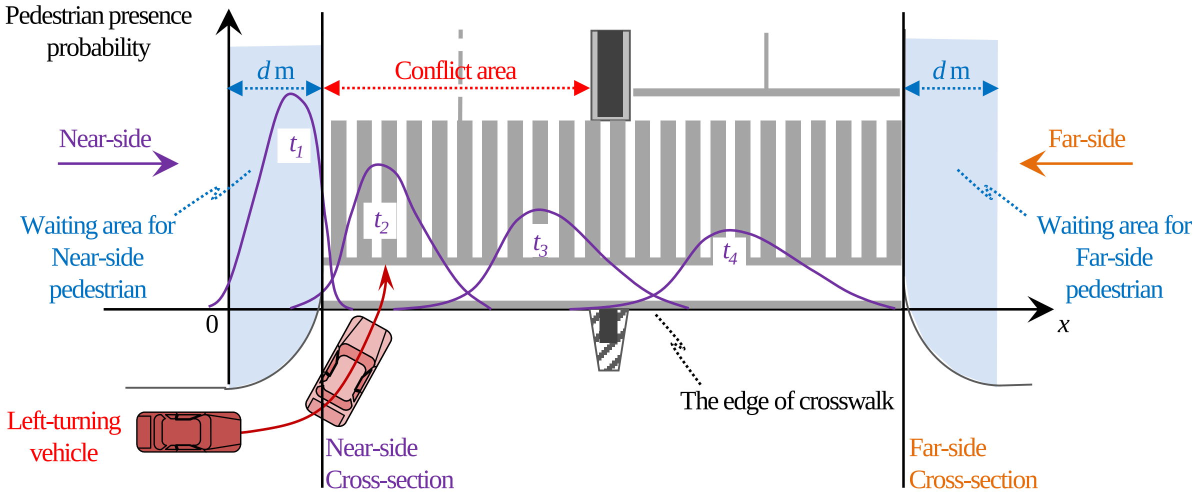


FIGURE 1 Definitions of pedestrian crossing progress

Modeling the Performance of Intersection

In order to quantitatively evaluate the performance of intersection, "pedestrian exposure time" is proposed as a safety measure, while pedestrian and vehicle delay, and degree of saturation are selected as operational measures. For simplification, arrival patterns of vehicles and pedestrians are assumed as uniform in this research.

Safety Performance

In order to evaluate the change level of pedestrian-vehicle conflict risk, pedestrian exposure time is defined as the product of the interval when pedestrians and LT vehicles can have conflicts and the number of pedestrians during the interval, as shown in Equation (1). In case of Japan, pedestrians are allowed to pass through crosswalks during pedestrian green (PG) and pedestrian flashing green (PFG) indications which seem to correspond to WALK and FLASHING DON'T WALK in US (*4*), respectively.

$$TE_j = \left(PG_j + PFG_j - LPI_j\right) \times Q_j \times \left(1 - PR_{con\_j}\right) \quad (1)$$

where, TE_j is pedestrian exposure time of pedestrian movement *j*, PG_j is pedestrian green time, PFG_j is pedestrian flashing green time, LPI_j is leading pedestrian interval which can be included in PG_j, Q_j is pedestrian flow, and PR_{con_j} is percentage of pedestrians completely passing through the conflict area.

Regarding PR_{con_j} as indicated in Equation (1), the following method was provided in the previous research of authors (*8*). Pedestrian presence probability for queuing pedestrians who arrived at crosswalk before PG, is modeled by using the probability density function (PDF) of Weibull distribution, and the results are shown in Table 1. Here, the shape parameter α and scale parameter β are assumed to follow a linear function of several independent variables: elapsed time of PG (t), crosswalk length (L), pedestrian red time (R_{ped}), and pedestrian arrival rate (q_j).

TABLE 1 Pedestrian Presence Probability Distribution Model

	Variables	Coefficients	t-value
Shape parameter α	Elapsed time of PG t (sec)	0.143	60.0
	Crosswalk length L (m)	-0.0949	-21.7
	Pedestrian red time R_{ped} (sec)	0.247	6.49
	Pedestrian arrival rate q_j (ped/sec)	-2.62	-14.9
	Constant	3.54	9.91
Scale parameter β	Elapsed time of PG t (sec)	1.30	389
	Pedestrian arrival rate q_j (ped/sec)	-1.04	-3.01
	Constant	6.49	115
Number of samples		996	
Log likelihood		-84407	
Initial log likelihood		-11583	
$\chi 2$ value		4128	
Adjusted R^2		0.244	

It was found that the distributions shift to the downstream of the crosswalk following the moving direction, and variations in the longitudinal direction on the crosswalk become greater as PG proceeds. Longer L and short R_{ped} correspond to greater variations of the presence probabilities. The distributions move slower and their variation became greater when q_j increased. Through comparing the distributions of observed and estimated values at different t as indicated in Figure 2, it was found that the estimated distributions mostly fit well to the observed ones.

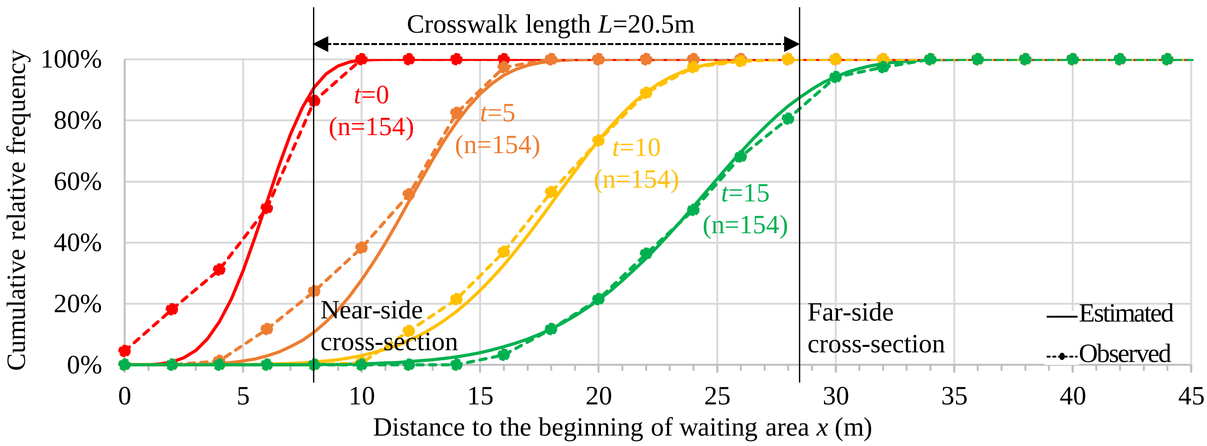


FIGURE 2 Comparison between Observed and Estimated Cumulative Pedestrian Presence Probability Distributions

Based on the developed model, pedestrian presence probability of near-side pedestrian $P_n(x, t)$ is shown by Equation (2) which is a weighted average of probabilities ($P_{nq}(x, t)$ and $P_{na}(x, t)$) and volumes (Q_{nq} and Q_{na}) for queuing and arriving pedestrians, respectively. Here $P_{na}(x, t)$ of arriving pedestrians who arrives at the crosswalk after PG is assumed to follow pedestrian arrival rate and to cross in a constant walking speed. Q_n is the pedestrian volume for near-side pedestrians which is the sum of queuing and arriving pedestrians.

$$P_n(x,t) = \frac{Q_{nq} \times P_{nq}(x,t) + Q_{na} \times P_{na}(x,t)}{Q_n} \tag{2}$$

PR_{con_n} at any t of near-side pedestrian is presented by Equation (3), and positions of the edges of the conflict area near to the near-side and the far-side are denoted by x_{con_i} and x_{con_j}, respectively.

$$PR_{con\_n} = \int_{x_{con\_j}}^{\infty} P_n(x,t)dx \tag{3}$$

In this paper, far-side pedestrian's presence probability $P_f(x, t)$ is calculated as bilateral symmetry of near-side pedestrian's. Thus, as with PR_{con_n}, PR_{con_f} at any t of far-side pedestrian is given by Equation (4).

$$PR_{con\_f} = \int_{-\infty}^{x_{con\_i}} P_f(x,t)dx = \int_{-\infty}^{x_{con\_i}} P_n((-x + L + 2d),t)dx \tag{4}$$

Finally, pedestrian exposure time of near-side pedestrian TE_n and far-side pedestrian TE_f can be calculated by Equation (1). The total pedestrian exposure time of both directions of pedestrian movements on one crosswalk TE_{naf} can be calculated as the sum of them. The total pedestrian exposure time of CPP, LPI and EPP are TE_{naf_CPP}, TE_{naf_LPI} and TE_{naf_EPP}, respectively.CPP is the most common signal phasing of the three types. In order to evaluate the variations in performance when CPP is altered to LPI or EPP, the increase rates of total pedestrian exposure time for LPI and EPP, R_{TE_LPI} and R_{TE_EPP} are defined as TE_{naf_LPI} and TE_{naf_EPP} divided by TE_{naf_CPP}, respectively.

Operational Performance

Capacity of vehicular traffic

Capacity Ca_i of vehicular movement i of each lane can be calculated as a product of saturation flow rate s_i and effective green time G_i of the movement i divided by cycle length C as shown in Equation (5).

$$Ca_i = s_i \times \frac{G_i}{C} \tag{5}$$

In the Manual on Traffic Signal Control of Japan (*9*), base saturation flow rates of through (TH) lane s_T, LT lane s_L and right turning (RT) lane s_R are 2000pcphgpl, 1800pcphgpl and 1800pcphgpl, respectively. The passenger car is the only vehicle type considered in this paper. Regarding the shared LT lane, adjusted saturation flow rate s_{LT} can be calculated by s_T and the adjustment factor α_{LT}. The α_{LT} is influenced by G_i, pedestrian volume Q_j and the percentage of LT vehicles P_{LTV} on the shared LT lane. The total lost time consisting of start-up and clearance lost times is assumed to be equivalent to the sum of amber time Y and all-red time AR.

Road User Total Delay

The arrival rate of vehicular movement i of each lane in one cycle is assumed as λ_i. When G_i starts, the departure flow rate of vehicular movements is assumed as saturation flow rate s_i. The total delay D_i of vehicular movement i of each lane in one cycle can be calculated as Equation (6).

$$D_i = \frac{\lambda_i \times (C-G)^2}{2 \times (1-\rho_i)} = \frac{s_i \times \lambda_i \times (C-G)^2}{2 \times (s_i - \lambda_i)} \tag{6}$$

Where, ρ_i is the flow ratio of vehicular movement i of each lane, presented by λ_i / s_i.

As indicated in Figure 3, the arrival rate of pedestrian movement j is assumed as q_j and the total delay D_j of pedestrian movement j can be determined by Equation (7).

$$D_j = \frac{q_j \times (C - PG_j + t'_j) \times (C - PG_j)}{2} \tag{7}$$

Where, t'_j is the first several seconds of PG_j which is enough for the queuing pedestrians to discharge from the beginning of the crosswalk in average.

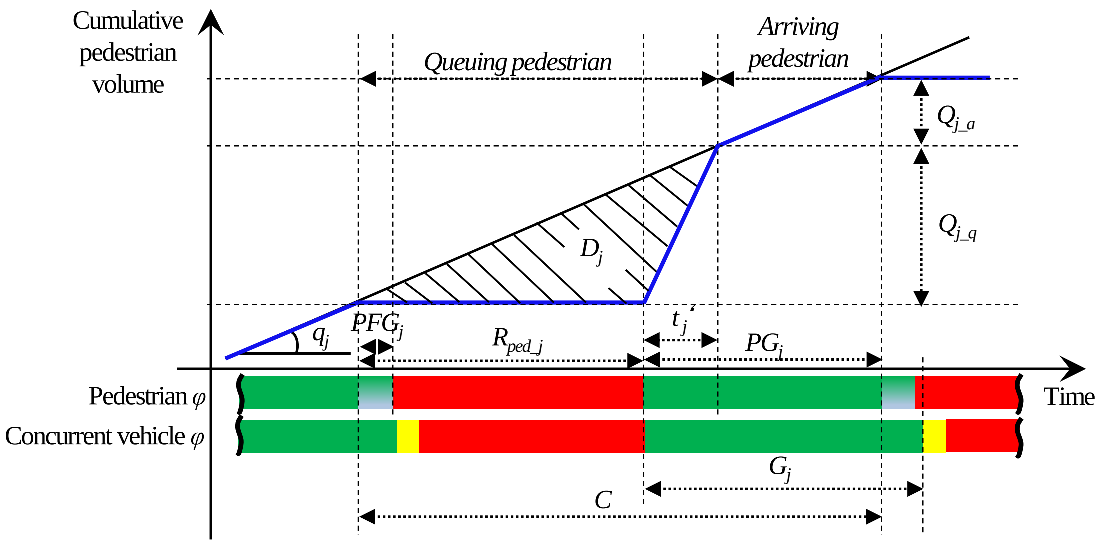


FIGURE 3 Concept of pedestrian movement *j*

In order to evaluate the total delay of all users in the adjacent road D_{user}, delay of vehicles is considered as delay of passengers. Here the average number of passengers in each vehicle is assumed to be 2.0, then the D_{user} can be calculated by Equation (8).

$$D_{user} = 2.0 \times D_{veh} + D_{ped} \tag{8}$$

Thus, the road user total delays of CPP, LPI and EPP are denoted by D_{user_CPP}, D_{user_LPI} and D_{user_EPP}, respectively. As well as pedestrian exposure time, the increase rates of road user total delay for CPP, LPI and EPP, R_{Duser_CPP}, R_{Duser_LPI} and R_{Duser_EPP} are defined by D_{user_CPP}, D_{user_LPI} and D_{user_EPP} divided by D_{user_CPP}, respectively.

Degree of Saturation

Degree of saturation (DS_i) of signal phase for vehicular movement i is also referred to as volume-to-capacity ratio. It is calculated by vehicular volume Q_i and capacity Ca_i of vehicular movement i as shown in Equation (9).

$$DS_i = \frac{Q_i}{Ca_i} = \frac{\lambda_i \times C}{s_i \times G_i} \tag{9}$$

CASE STUDY

Basic Components of Case Study

The intersection layout and demand conditions of a hypothesized intersection for a case study are shown in Figure 4. The intersection has four legs and the geometry is point-symmetry. The East-West street is the major street with three inflow lanes: shared LT, TH and RT lanes. The North-South street is the minor street with two inflow lanes: shared LT and RT lanes. There is an exclusive (protected) RT phase for each approach and it is assumed that RT vehicles can use this phase only. The lane volumes of vehicles and pedestrians, and percentage of LT vehicles on the major and minor streets (P_{LTV_Maj} and P_{LTV_Min}) are given as indicated in the figure.

Regarding the basic settings for the case study, considering the fact that most urban signalized intersections are coordinated and it is unrealistic to flexibly change cycle length of only the subject intersection when the signal plan is modified, C is fixed as 120sec here. For simplification, lost time for EPP, CPP and LPI are also fixed as 22sec, 18sec and 18sec. The s_{LT} can be calculated by α_{LT} which is dependent on the concurrent G_i, Q_j, and P_{LTV}. EPP has no pedestrian influence of shared LT lane for saturation flow rate, then α_{LT} of major and minor streets are 0.95 and 0.96. Regarding the pedestrian influence for saturation flow rate of CPP and LPI, it is assumed as a high level of crossing pedestrians and α_{LT} of major and minor streets are 0.67 and 0.76.

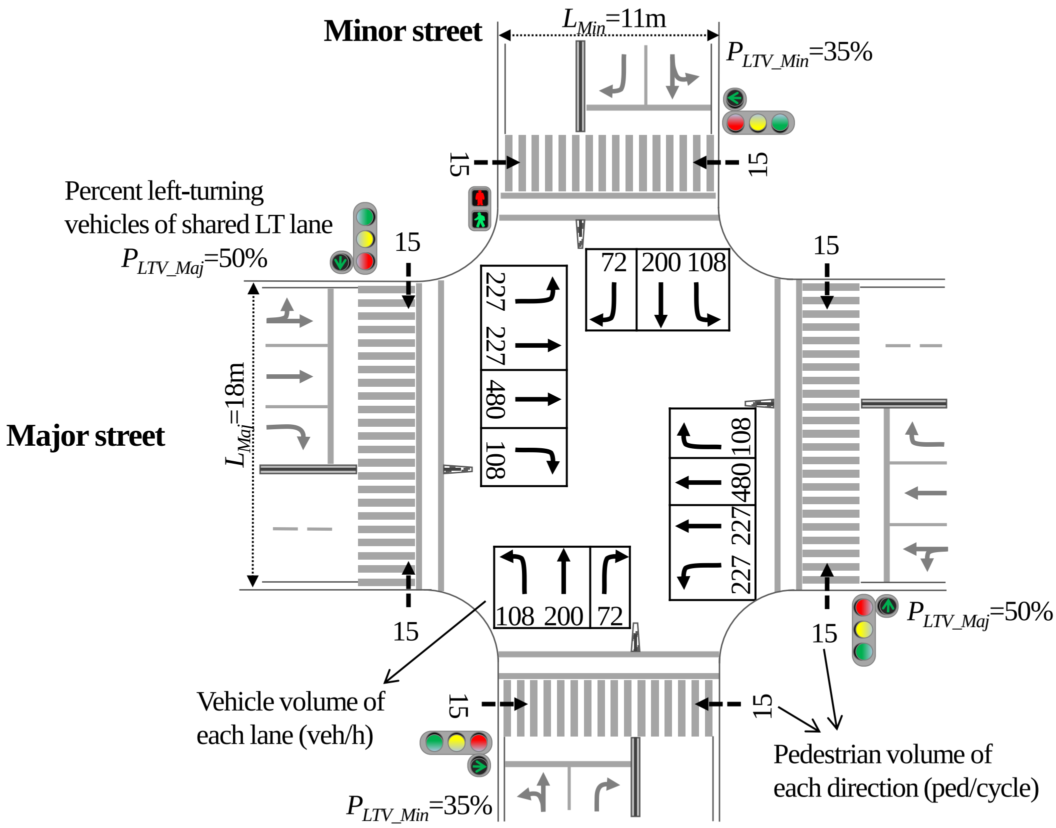


FIGURE 4 Intersection Layout and Demand Conditions for Case Study

Signal Timing Setting

For the comparison of the safety and operational performance of an intersection by applying CPP, LPI and EPP, their signal phasing schemes and timings are very important and the setting procedures are outlined as shown in Figure 5.

All discussions of intersection performance in this paper are for undersaturated conditions only. Since EPP has to completely separate pedestrians from vehicular movements, DS_i for the case of EPP is the highest of the three types. Therefore, EPP is set first and the Q_i of each lane as shown in Figure 4 is given as DS_i=0.8. Then CPP is designed based on Q_i of EPP. Note that the sum of PG_i and PFG_i should be longer than the necessary crossing time which is the product of pedestrian walking speed v_{ped} and L. Finally, based on the signal timing of EPP, LPI is designed by hypothesizing that a portion of the beginning of the G_i for adjacent vehicular movement is diverted to LPI_j. It is important to keep DS_i of adjacent vehicular movement lower than 0.8 even after this diversion to LPI_j.

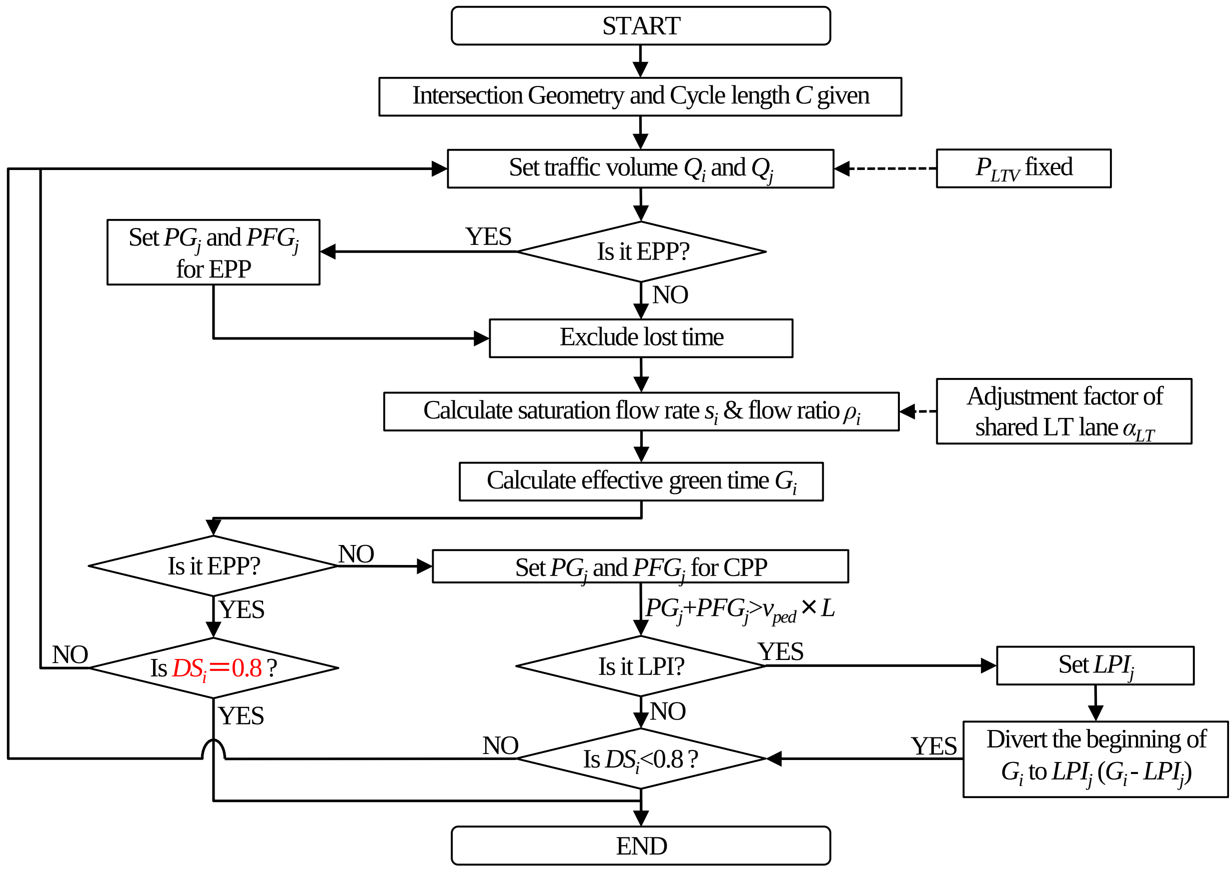
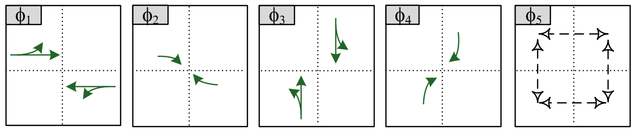


FIGURE 5 Signal Timing Setting procedure

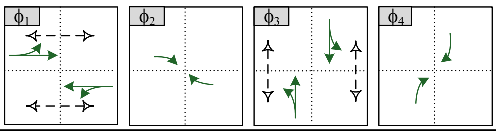
The signal phase sequences and timings of EPP, CPP and LPI based on the procedure mentioned above are shown in Tables 2 – 4, respectively. In Table 2, φ_5 is EPP and its length is determined by the necessary crossing time on longer crosswalks on the major street. Signal phase sequences of CPP shown in Table 3 have four phases only, and CPP of crosswalks on major and minor streets are sharing φ_1 and φ_3 with adjacent LT and TH vehicles, respectively. To apply LPI lengths of major and minor streets which are LPI_{Maj} of φ_1 and LPI_{Min} of φ_4 in Table 4, the first several seconds of φ_1 and φ_3 in Table 3 are diverted, respectively. The maximum value of LPI is determined by DS_i of adjacent vehicle phases that are not greater than 0.8. In this setting procedure, G_i of each vehicular movement is proportional to flow ratio, thus the G_i of the major street is greater than that of the minor street. In order to investigate the impact of the signal phase on the adjacent LT and TH vehicles, the length of exclusive RT phase of the three types are assumed to be same.

TABLE 2 Signal Phase Sequence and Timing of EPP

Movement		Signal Phasing (sec)													Cycle length (sec)
		φ_1		φ_2			φ_3		φ_4			φ_5			
		1	2	3	4	5	6	7	8	9	10	11	12	13	
Major street	LT&Th vehicle														
	RT vehicle														
Minor street	LT&Th vehicle														
	RT vehicle														
All direction pedestrian															
EPP		36	2	9	3	4	24	2	6	3	4	14	9	4	120
Singal phase sequence															

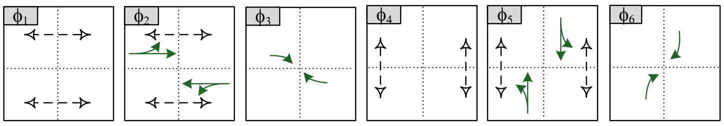
Green Amber Red Exclusive RT phase Pedestrian flashing green

TABLE 3 Signal Phase Sequence and Timing of CPP

Movement		Signal Phasing (sec)														Cycle length (sec)
		φ_1				φ_2			φ_3				φ_4			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Major street	LT&Th vehicle															
	Pedestrian															
	RT vehicle															
Minor street	LT&Th vehicle															
	Pedestrian															
	RT vehicle															
CPP		43	6	5	2	9	3	4	19	9	5	2	6	3	4	120
Singal phase sequence																

Green Amber Red Exclusive RT phase Pedestrian flashing green

TABLE 4 Signal Phase Sequence and Timing of LPI

Movement		Signal Phasing (sec)																Cycle length (sec)
		φ_1	φ_2				φ_3			φ_4	φ_5				φ_6			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
Major street	LT&Th vehicle																	
	Pedestrian																	
	RT vehicle																	
Minor street	LT&Th vehicle																	
	Pedestrian																	
	RT vehicle																	
LPI		LPI_{Maj}	43-LPI_{Maj}	6	5	2	9	3	4	LPI_{Min}	19-LPI_{Min}	9	5	2	6	3	4	120
Singal phase sequence																		

Green Amber Red Exclusive RT phase Pedestrian flashing green

Discussion of the Results Regarding Intersection Performance

Based on the methodology proposed above, the results of the case study on the safety and operational performance are discussed below.

Increase Rate of Total Pedestrian Exposure Time

The results of increase rate of total pedestrian exposure time R_{TE_CPP}, R_{TE_LPI} and R_{TE_EPP} of the crosswalks on major and minor streets are illustrated in Figure 6. It is indicated that EPP can reduce pedestrian exposure to zero, in brief, there is no pedestrian-vehicle conflict. R_{TE_LPI} of all crosswalks decrease as LPI length increases. It is found that R_{TE_LPI} change sensitively when LPI is between 6 and 14sec which can reduce R_{TE_LPI} to approximately 80~30%.

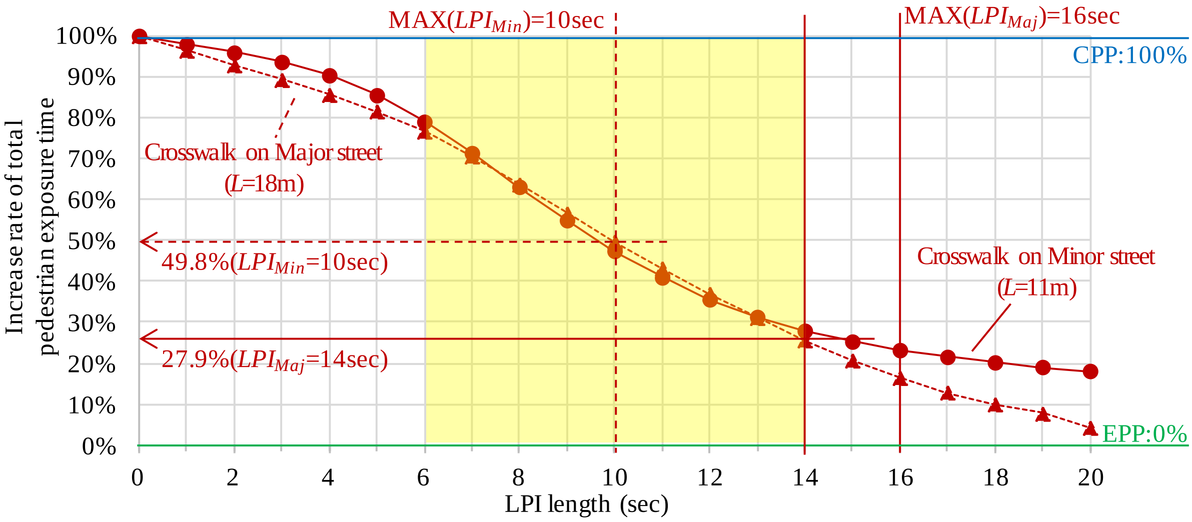
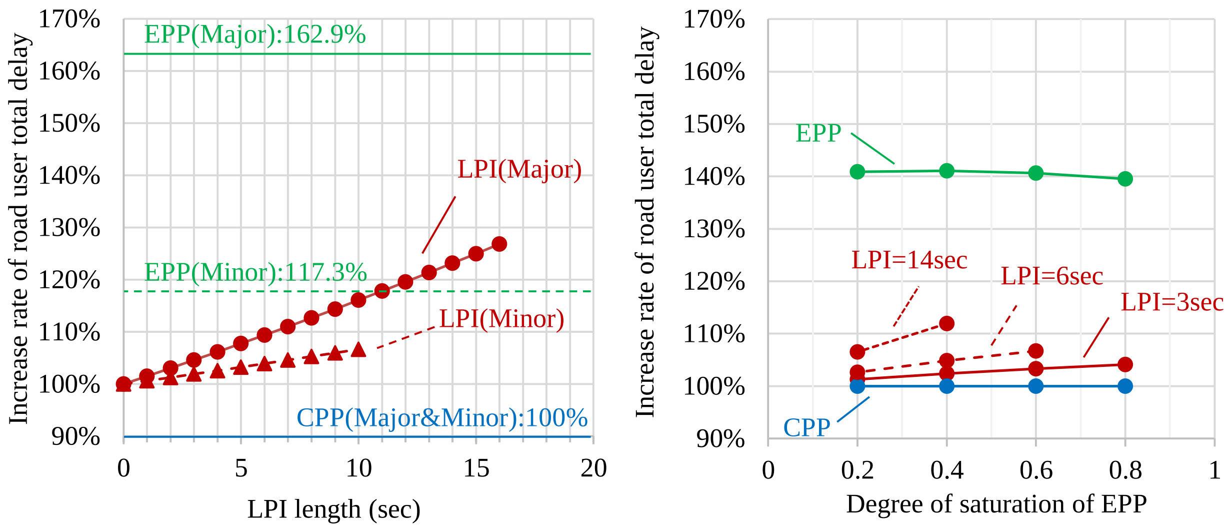


FIGURE 6 Analysis Results of Increase Rate of Total Pedestrian Exposure Time

Increase Rate of Road User Total Delay

Figure 7(a) illustrates the results of increase rate of road user total delay R_{Duser_CPP}, R_{Duser_LPI} and R_{Duser_EPP} of major and minor streets. Here, vehicle volumes are adjusted so that the degree of saturation of EPP becomes 0.6 in order to reserve a certain period of PG which can be converted to LPI. It is noted that only the vehicle volume is changed to meet the condition of DS and then that volume is applied to all the three models. Since R_{Duser_CPP} is the standard for each case, all R_{Duser_CPP} are 100%. Among CPP, LPI and EPP, it can be found that both R_{Duser_EPP} of major and minor streets are the highest, especially on the major street. It is because when EPP is utilized, the G_i of vehicle and pedestrian signal phases are very short resulting in longer delay, especially longer pedestrian delay on the major street. R_{Duser_LPI} of major and minor streets become larger when LPI length increases, and the maximum values of LPI_{Maj} and LPI_{Min} are 16 sec and 10 sec, respectively when DS becomes 0.8 as illustrated in Figure 6. Overall, it is indicated that LPI is better than EPP from the viewpoint of total delay.

In order to investigate the impact of vehicular volume based on the DS_i of EPP (0.8, 0.6, 0.4 and 0.2) on increase rates, the sums of major and minor streets are taken and the results are shown in Figure 7(b). Basically, there are similar tendencies with the results in Figure 7(a). Regarding EPP, R_{Duser} of the three types are almost same and at a high level. In the cases of LPI=3, 6 and 14 sec, it is indicated that R_{Duser} increase as LPI lengths become longer. Moreover, the available range of LPI becomes shorter when DS_i of EPP increases.



(a) DS=0.6 **(b) Sum of Major and Minor Streets**

FIGURE 7 Analysis Results of Increase Rate of Road User Total Delay

Thus, according to the results of Figure 6 and 7 above, the effective application range of LPI_{Maj} and LPI_{Min} are 6~14sec and 6~10sec, respectively. Since longer LPI will further reduce pedestrian exposure time, LPI_{Maj} and LPI_{Min} are selected as the maximum value of the range, 14sec and 10sec. The R_{TE_LPI} of the crosswalks on minor and major streets are reduced to 27.9% and 49.8% as shown in Figure 6, while the R_{Duser_LPI} of major and minor streets are increased to 123.1% and 106.7% respectively.

CONCLUSIONS

In this paper, pedestrian exposure time was proposed as a surrogate measure for quantitatively evaluating pedestrian-vehicle conflict risk at signalized crosswalks. The effective application range of LPI was investigated through a case study, in conjunction with operational performance. The performance of CPP and EPP were also discussed for comparison to LPI.

Considering pedestrian crossing progress, it was found that both R_{TE_LPI} of the crosswalks on major and minor streets change effectively during LPI (6~14sec) which can reduce R_{TE_LPI} to approximately 80%~30%.

Regarding the road user total delay, it was confirmed that EPP is at the highest level, especially on major streets. The total delay of vehicles becomes greater when LPI length increases, and the maximum LPI length of major and minor streets are 16sec and 10sec, respectively, depending on the degree of saturation. By changing the vehicular volume based on degree of saturation of EPP, the increase rates of EPP are similar while those of LPI increase as vehicular volume increase. In the cases of changing LPI length, it was indicated that R_{Duser_LPI} increases as LPI lengths become longer. Overall, the effective application ranges of major and minor street are 6~14sec and 6~10sec, respectively. This LPI range is only for those intersections with geometries similar to the hypothesized intersection in the case study.

Finally, by using the methodology proposed in this paper, it became possible to discuss the signal phasing schemes and timing with only inputting the intersection geometry and traffic volumes. However, several issues were not discussed in this paper, such as the impact of pedestrian volume, the variation of saturation flow rate after applying LPI, and so on; and they should be considered in the future work.

REFERENCES

1. National Police Agency in Japan. Statistics on traffic accidents in 2015 (in Japanese). http://www.e-stat.go.jp/SG1/estat/GL08020103.do?_toGL08020103_&listID=000001150496&requestSender=search. Accessed July 30, 2016.
2. Zhang, Y., Mamun, S.A., Ivan, J.N., Ravishanker, N. and Haque, K.. Safety Effects of Exclusive and Concurrent Signal Phasing for Pedestrian Crossing. *Journal of Accident Analysis and Prevention*, Vol. 83, 2015, pp. 26-36.
3. Saneinejad, S. and Lo, J.. Leading Pedestrian Interval Assessment and Implementation Guidelines. Presented at 94th Annual Meeting of the Transportation Research Board, Washington D. C., 2015.
4. U.S. Department of Transportation, Federal Highway Administration (FHWA): Manual on Uniform Traffic Control Devices (MUTCD). 2009.
5. Houten R. V., Retting R. A., Farmer C. M. And Houten J. V., Field Evaluation of a Leading Pedestrian Interval Signal Phase at Three Urban Intersections. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1734*, Transportation Research Board of the National Academies, Washington, D.C., 2000, pp.86-92.
6. Fayish A. C. and Gross F., Safety Effectiveness of Leading Pedestrian Intervals Evaluated by a Before–After Study with Comparison Groups. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2198*, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp.15-22.
7. Hubbard, S. M. L., R. J. Awwad, and D. M. Bullock. Assessing the Impact of Turning Vehicles on Pedestrian Level of Service at Signalized Intersections: A New Perspective. In *Transportation Research Record: Journal of the Transportation Research Board, No.2027*, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 27-36.
8. Zhang, X. and Nakamura, H., A Study on the Spatiotemporal Pedestrian Density Distribution at Signalized Crosswalks for Safety Assessment, Presented at the 14th World Conference on Transport Research, Shanghai, China. 2016.
9. Japan Society of Traffic Engineers: Manual on Traffic Signal Control, Revised Edition (in Japanese). 2006.