Design Criteria for Crosswalk Width and Position at Signalized Intersections

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Abstract: Existing optimization methodologies for intersection operations assumes a fixed geometric design, however the geometry and operational system should be simultaneously optimized to produce the best performance. Signalized crosswalks are complex and critical pedestrian facilities. Their geometry and configuration directly affect the safety, cycle length and resulting delays for all users. As crosswalks become wider or they are placed further upstream, the cycle length will increase due to the all-red time requirement, which deteriorates the overall mobility levels of signalized intersections. In contrast, when crosswalk width decreases, the required minimum pedestrian crossing time increases due to the bi-directional pedestrian flow effects, which leads to longer cycle length. Furthermore, existing manuals and guidelines do not offer any specification for the required crosswalk width under various pedestrian demand conditions. This study aims to propose new criteria for designing crosswalk width at signalized intersections, which can optimize the performance from the viewpoint of vehicular traffic and pedestrians. The proposed methodology considers pedestrian demand and its characteristics (such as bi-directional flow effects), vehicle demand and the geometric characteristics of the intersection. The concept of optimized crosswalk width is proposed and demonstrated through a case study. Moreover, a comprehensive discussion regarding the merits and drawbacks of existing strategies on positioning crosswalks is presented. It was found that at signalized intersections, which are characterized by low pedestrian and high vehicle demands, crosswalk width of 2 meters is appropriate to minimize cycle length and resulting delays for all users including pedestrians.

Key words: Crosswalk width, cycle length, pedestrian delay, bi-directional flow, two-stage crossing.

1. Introduction

The operational efficiency of vehicular traffic and pedestrian flow are considered as important concern especially at signalized crosswalks where both of them have to share the same space. Crosswalks play a role in the performance of signalized intersections. Their geometry and configuration including width, position and angle affect directly the safety, cycle length and resulting delays for all users. As crosswalks become wider or their position becomes further upstream, the cycle length will increase due to the all-red time requirement, which deteriorates the overall mobility levels of signalized intersections. Simultaneously, when crosswalk width decreases, the required minimum pedestrian crossing time increases due to the bi-directional pedestrian flow effects, which leads to longer cycle length. Considering such a trade-off between crosswalk geometry and cycle length, it is significant to define reasonable geometric characteristics (width and position), which can optimize the overall performance.

1.1 Crosswalk Position

An important aspect of crosswalk configuration at signalized intersections is their position. Existing manuals do not provide universal rational specifications on where and how crosswalks should be positioned. In Japan, the position of crosswalks at signalized intersections is far from the corners of the intersection (Fig. 1a), which is usually associated with large corner radius leading to higher speeds of left
turning vehicles. Furthermore, this type of crosswalk configuration causes longer delays because of longer cycle lengths and it reduces the visibility of intersection users. Related authorities implement such kind of design to provide storage area for the right and left turning vehicles when they stop for pedestrians in order to avoid blocking the through traffic. Although such kind of consideration is not reasonable if an exclusive left turning lane is available or an exclusive left turning phase is in operation which is the most common condition at Japanese signalized intersections. Furthermore, authorities claim that such kind of setting provides safer crossing for pedestrians, however this viewpoint is not supported by any empirical studies. Thus, researches that investigate the safety performance of various intersection layouts are very necessary and needed.

In the United States, Europe and China, signalized intersections are characterized by compact layout. Crosswalks are positioned at the corners of the intersection as shown in Fig. 1b. Such layout will improve the mobility by reducing the cycle lengths of the signalized intersections. Furthermore, it is expected that such setting will provide better visibility for all users, so pedestrians can be noticed by turning vehicles more easily and vice versa. The Guidelines for Traffic Signals RiLSA [1] in Germany clearly emphasises the importance of installing crosswalks at the corners of the intersection, it says that “Pedestrian crossings should follow the direction of pedestrian streams and be established as near the edge of the parallel road as possible. If a crossing has to be placed back from the edge of the intersection due to right-turners on all-vehicle lanes, 5–6 m must not be exceeded”.

Another crosswalk configuration is Z-crosswalks as shown in Fig. 1c. This layout is not common; it is limited to some European countries such as France and England. This setting is not preferred from the viewpoint of pedestrians since the walking distance is longer (Z-shape) and elderly pedestrians or disabled pedestrians will face difficulties in crossing along a Z-shape crosswalk. Moreover, such crosswalk shape may increase the noncompliance of pedestrians who prefer to walk straightly which might lead to safety hazards. On the contrary, such layout will achieve mobility benefits since it will result in shorter clearance distance, simultaneously with providing storage area for turning vehicle.

1.2 Crosswalk Width

The width of a crosswalk depends primarily on the number of pedestrians who are expected to use it at a given time. From the viewpoint of pedestrians, wider crosswalks are better since it provides wider space and fewer interactions between opposing pedestrians, however this may negatively affect the overall operational performance. Existing manuals do not provide clear specifications for the required crosswalk width regarding different pedestrian demand volumes.
and properties; they just provide some recommendations about the minimum width. Ref. [2] in the US recommends a minimum crosswalk width of 6 ft (1.8 m). Meanwhile the Japanese Manual on Road [3] recommends a crosswalk width of 4.0 m and allows installation of crosswalks up to 3.0 m wide when pedestrian demand is expected to be low. However, rational reasons for these values are unclear. Such unavailability of specifications leads to a wide range of experiences around the world. Unnecessarily wide crosswalks often characterize Japanese signalized intersections, even when pedestrian demand is not high while narrow crosswalks exist at many signalized intersections in the United States where pedestrian demand is expected to be low.

The existing recommendations in the manuals and guidelines regarding the minimum crosswalk width do not consider the possible influences upon the operational system of signalized intersections, which affect all users including pedestrians. Therefore, it is necessary to develop rational criterion, which considers the interactions between the operational system and the geometric characteristics to provide planners and designers with recommendation regarding required crosswalk width, which can optimize intersection’s performance for all users.

The structure of this paper is as follows: After introduction and the literature review, the hypothesis in the relationship between crosswalk width and cycle length is defined. To validate this hypothesis and to demonstrate the concept of optimum crosswalk width, a case study with characteristics similar to ideal Japanese signalized intersections is designed. Then a comprehensive discussion about the effects of vehicle and pedestrian demand levels as well as various pedestrian crossing treatments on the optimum crosswalk width is presented. Finally, the paper ends up with summary of the results, conclusion and future works.

2. Literature Review

Although it is quite significant to investigate the interaction between various geometric elements of signalized intersections and the operational performance, there are no references in the literature about optimizing crosswalk geometry in order to minimize users delay including pedestrians at signalized intersections. Minimizing users delay through minimizing cycle length is a very critical issue, since the overall mobility and safety levels depend on it. Long signal cycle durations from optimizing vehicle flows and signal coordination for vehicles, have negative effects on pedestrian movements and may impose large delays on pedestrians [4]. Furthermore, long cycles may cause a safety hazard for pedestrians, thus one of the most effective measures to improve pedestrian safety and compliance is by making signals as comfortable as possible, and this is done by minimizing pedestrian waiting time [5].

A very important constraint in designing the cycle length at signalized intersections is the minimum required pedestrian crossing time. Enough time for pedestrians to finish crossing the street should always be secured during any phase where pedestrians have the right of way. Existing manuals and guidelines provided planners and designers with methodologies to estimate pedestrian crossing time requirements. Most of these methodologies have been based on assumptions regarding a particular walking speed such as Ref. [6] which assumes a speed of 1.2 m/s and Ref. [7] which assumes a speed of 1.0 m/s. Such kind of assumptions may overestimate the needed pedestrian crossing time at low pedestrian demand condition and underestimate the required pedestrian crossing time at high pedestrian demand condition due to the bi-directional flow effects.

Few studies addressed the issue of bi-directional pedestrian flow and its impact on crossing time and speed at signalized crosswalks and the resultant delays. Teknomo [8] proposed a microscopic pedestrian
simulation model as a tool to evaluate the impacts of a proposed control policy at signalized intersections on pedestrian behavior before its implementation. The developed model was used to demonstrate the effect of bi-directional flow at signalized crosswalks. It was found that at high pedestrian demand with roughly equal flow from each side of the crosswalk, the average crossing speed might drop up to one third compared to the uni-directional flow, which will result in large experienced delays while crossing.

Alhajyaseen et al. [9] developed a theoretical methodology to model total pedestrian crossing time. Pedestrian platoon crossing time is modeled by utilizing the aerodynamic drag force theory to estimate the reduction in crossing speed due to an opposite pedestrian flow. The proposed model was validated from empirical data. In the final formulation, the reduction in crossing speed is estimated as a function of pedestrian demands at both sides of the crosswalk, signal timing parameters and crosswalk geometry. It was found that at high pedestrian demand, a significant reduction in the crossing speed and increasing in the crossing time occurs due to the interactions between the bi-directional flows. Therefore, it was concluded that the interactions between opposing pedestrian flows are significant and should be considered in evaluating pedestrian flow at signalized crosswalks. In this paper, the developed theoretical methodology by Alhajyaseen, et al. [9] is utilized to estimate the minimum pedestrian crossing time requirements as a function of crosswalk width and pedestrian demand at both sides of the crosswalk.

3. Hypothesis

When determining cycle length at signalized intersections, there are two main constraints: the optimum vehicle green time $G_o$ and the minimum pedestrian green time $G_p$. As crosswalk width increases, pedestrian crossing time decreases due to the reduction in the interaction between opposing pedestrian flows, which leads to shorter cycle length. Meanwhile, when crosswalk width increases, all-red time increases because of the longer clearance distance. As all-red time increases, cycle length increases simultaneously. Therefore, a trade off relationship exists between crosswalk width and cycle length as shown in Fig. 2.

The optimum crosswalk width $w_o$, which is defined as the crosswalk width that produces the minimum cycle length, is dependent on intersection geometry, signal phasing plan, pedestrian and vehicle demand levels. As vehicle demand increases, the effect of pedestrian crossing time in defining cycle length decreases due to the availability of longer green for pedestrians. In this case increasing crosswalk width will cause a continuous increase in the cycle length. When pedestrian demand increases, the optimum crosswalk width $w_o$ increases also as shown in Fig. 2. Therefore, wider crosswalks are required to reduce the minimum pedestrian green time $G_p$ and the resulted cycle length. This paper aims to demonstrate the rationality and the significance of the trade-off relationship between crosswalk width and cycle length through a case study.

4. Methodology

Fig. 3 represents the analysis framework. By providing assumptions regarding intersection geometric characteristics, specific crosswalk width $w$, signal phasing plan (including lost and yellow times)
and vehicle demand ratios, the optimum cycle length \( C_{op} \) can be estimated by using Webster formula [10] as shown in Eq. (1). Then the effective green time \( G_{on} \) is assigned to each phase (Step 2 in Fig. 3).

\[
C_{op} = \frac{1.5L + 5}{1 - \sum_{n=1}^{\phi} \left( \frac{q}{s} \right)_n}
\]

(1)

where \( C_{op} \) is optimum cycle length (s), \( L \) is total lost time per cycle (s) which is estimated according to Eq. (2), \( (q/s)_n \) is maximum value of the ratios of approach flows to saturation flow rates for all traffic streams using phase \( n \) and \( \phi \) is number of phases.

\[
L = \sum_{n=1}^{\phi} l_n + AR
\]

(2)

where \( l_n \) is the lost time in phase \( n \) and \( AR \) is the total all-red times during one cycle.

After estimating the optimum cycle length \( C_{op} \), pedestrian demand and minimum pedestrian green time \( G_{pm} \) can be estimated (Step 2 in Fig. 3). A very important constraint here is that minimum pedestrian green time \( G_{pm} \) in phase \( n \) should be equal or smaller than optimum vehicle green \( G_{on} \) in the same phase. If the estimated minimum pedestrian green \( G_{pm} \) is longer than the optimum vehicle green \( G_{on} \), the green time for each phase is re-estimated depending on the minimum pedestrian green of phase \( n \) (Step 3 in Fig. 3). The resultant cycle length is used to re-estimate pedestrian demand and the minimum required pedestrian green \( G_{pi} \) again. This process is repeated until the estimated minimum pedestrian green \( G_{pm} \) in iteration \( i \) equals to that of the previous iteration \( G_{pm(i-1)} \). The final cycle length is the optimum cycle length for the assumed crosswalk width \( w \). The same analysis is repeated assuming various crosswalk widths.

For this case study, pedestrian arrival rate \( A \) at each side of the crosswalk is assumed to be equal and uniform (directional split ratio \( r \) is 0.5), therefore pedestrian demand at each side of the crosswalk can be estimated through Eq. (3) [9]:

\[
P_1 = P_2 = A(C - g_p + T_d)
\]

(3)

where \( P_1 \) and \( P_2 \) are subject and opposite pedestrian demands, \( C \) is cycle length, \( g_p \) is pedestrian green interval and \( T_d \) is discharge time of the pedestrian platoon.

Minimum pedestrian green time \( G_{pm} \) for phase \( n \) is estimated according to Eq. (4):

\[
G_{pm} = f(T_{da} + T_{ca})
\]

(4)

where \( T_{da} \) is the time necessary for pedestrians to discharge at the edge of the crosswalk in phase \( n \) (s), \( T_{ca} \) is pedestrian crossing time in phase \( n \) (s) and \( f \) is a modification factor to consider the 10th percentile pedestrian crossing time for safety considerations. Discharge time is a function of pedestrian demand and crosswalk width. While crossing time is a function of
pedestrian demand at each side of the crosswalk and crosswalk geometry. In all the existing manuals and
guidelines, a constant pedestrian crossing speed is
assumed to estimate the minimum required pedestrian
green $G_p$. In reality however, when pedestrian demand
increases at both sides of the crosswalk, crossing speed
decreases and crossing time increases due to the
interaction between opposing pedestrian flows.
Therefore, the methodology developed by Alhajyaseen
et al. [9] to estimate discharge and crossing times is
utilized.

Discharge time $T_d$ was modeled by using shockwave
theory, since its definition is similar to that of queue
discharge time of vehicles waiting at the stop line of a
signalized intersection. Crossing time $T_c$ was modeled
by utilizing the analogy of drag force theory to quantify
the reduction in walking speed due to an opposing
pedestrian flow. Drag force is defined as the force
generated when a moving body faces a fluid which
causes a reduction in its speed dependent on its cross
sectional area, the density of the fluid and the relative
speed between them.

Eqs. (5) and (6) represent the final models to
estimate pedestrian platoon discharging and crossing
times, respectively. Eq. (6) shows that crossing time $T_c$
is estimated as a function of the subject and opposite
pedestrian arrival rates ($A_1$ and $A_2$, respectively),
crosswalk width $w$ and length $L$, average free-flow
speed $u_o$ and signal timing parameters (cycle length and pedestrian green).

$$T_d = -\frac{2.532(A(C-g_p))^{0.87}}{0.627w^{0.87} + 1.244A(C-g_p)^{0.87} + 2.532(A(C-g_p))^{0.87}}$$  \hspace{1cm} (5)

$$T_c = \frac{L}{2u_o} \sqrt{\left(\frac{0.02A_1(A_1+A_2)^{0.87}}{w}L(u_o)^{(C-g_p)} + T_c\right)\left(\frac{L}{2u_o}\right)}$$  \hspace{1cm} (6)

The average free flow speed $u_o$ is estimated from
empirical data collected at two signalized crosswalks in
Nagoya City. 1.5-hour and 2-hour video tapes for the
crosswalks at the east legs of Nishi-Osu intersection (6
m wide $\times$ 25.4 m long) and Imaike intersection (7.2 m
wide $\times$ 21.5 m long) respectively are analyzed.
Nishi-Osu and Imaike intersections are characterized
by low to medium pedestrian demand with low
percentage of elderly pedestrians. All the considered
pedestrians were leading pedestrians who did not face
any opposite flow or turning vehicles. The free-flow
speed cumulative distribution is shown in Fig. 4.

Since the utilized discharging and crossing time
models are based on the average crossing speeds, a
modification factor $f$ is proposed as shown in Eq. (4).
This modification factor is applied to estimate the 10th
percentile total crossing time, thus the provided
minimum pedestrian crossing time will cover 90% of the
observed population for safety considerations. Fig. 4
shows how the modification factor $f$ is calculated.

For better insight into the effects of crosswalk width
on pedestrian flows, APD (average pedestrian delay) is
estimated. APD is composed from three parts: pedestrian
waiting delay because of red signal indication, pedestrian
discharging delay and pedestrian crossing delay as shown in Eq. (7):

$$APD = \left(\frac{0.5(C-g_p)^3}{C} + \frac{T_d}{P_t}\right) + \left(\frac{T_c - L}{u_o}\right)$$  \hspace{1cm} (7)

For simplification, average pedestrian waiting delay
due to signal timing is estimated according to the
formulation proposed by Ref. [6] as shown in Eq. (7).

5. Case study

A typical Japanese signalized intersection with a
typical stage-based signal control is assumed for the
case study. Two pedestrian crossing treatments are assumed. The first one is ordinary pedestrian crossing, where pedestrians share the phase with the vehicles on the same direction as shown in Fig. 5a. The second treatment is two-stage pedestrian crossing where pedestrians need to wait in the middle island after crossing the first part of the crosswalk, until the green indication is displayed to give them the right of way to cross the second part of the crosswalk as shown in Fig. 5b. The geometric configurations, signal-phasing plans and the two assumed pedestrian crossing treatments are shown in Fig. 5. In order to insure a complete crossing for pedestrians before the next conflicting vehicle movements are released, pedestrian clearance red time interval $R_p$ is introduced as shown in Fig. 5. $R_p$ is estimated according to Eq. (8):

$$R_p = f(L/u_s)$$

Table 1 shows the assumed vehicle demand ratios, lost and yellow times. Two vehicle demand scenarios were assumed. The first one is balanced vehicle demand, while the second is unbalanced vehicle demand where a large portion of the total demand ratio $(q/s)_t$ is assigned to one phase. The all-red intervals after $\phi_2$ and $\phi_4$ are estimated by Eq. (9) [11]:

$$AR_n = 3.6L_{cn}/v_{dn}$$

where $AR_n$ is all-red time for Phase $n$, $L_{cn}$ is clearance distance between the stop line and furthest point of potential conflict with vehicles or pedestrians of the next phase ($m$) and $v_{dn}$ is design speed (km/hr) in phase $n$. The design speeds for $\phi_2$ and $\phi_4$ are assumed as 20 km/hr.

![Fig. 5 Geometric characteristics and phasing plans of the case study.](image-url)
### Table 1  Vehicle demand ratios, Lost and yellow times.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Lost time $t_a$</th>
<th>Yellow time $t_y$</th>
<th>Vehicle demand ratio $(q/s)_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_1$</td>
<td>3s</td>
<td>3s</td>
<td>0.35 $(q/s)_t$</td>
</tr>
<tr>
<td>$\phi_2$</td>
<td>1.5s</td>
<td>-</td>
<td>0.15$(q/s)_t$</td>
</tr>
<tr>
<td>$\phi_3$</td>
<td>3s</td>
<td>3s</td>
<td>0.35$(q/s)_t$</td>
</tr>
<tr>
<td>$\phi_4$</td>
<td>1.5s</td>
<td>-</td>
<td>0.15$(q/s)_t$</td>
</tr>
</tbody>
</table>

$(q/s)_t = \sum_{i=1}^{n} (q/s)_i$.

For the purpose of this study, medium pedestrian arrival rate $A$ is defined as $0.1 \leq A < 0.2$ ped/s, while high pedestrian arrival rate is defined as $A \geq 0.2$.

### 6. Analysis Results

#### 6.1 Ordinary Pedestrian Crossing Treatment

6.1.1 Scenario 1 “Balanced vehicle demand”

Fig. 6a presents three relationships, the independent variable in all these relationships is crosswalk width $w$, while the depended variables are cycle length, average pedestrian delay $APD$ and pedestrian crossing speed respectively. In order to draw Fig. 6a several assumptions are made, constant pedestrian arrival rate ($A = 0.05$ ped/s) and variable total vehicle demand ratio $(q/s)_t$ ranging from 0.4 to 0.75. As vehicle demand increases, the optimum crosswalk width $w_o$ decreases. In this case optimum vehicle green time $G_o$ becomes longer than minimum pedestrian crossing time $G_p$, therefore, any increase in crosswalk width causes an increase in cycle length because of all-red time requirement. Moreover, Fig. 6a shows that at low pedestrian demand and vehicle demand ratio $(q/s)_t$ of 0.55 or more, the optimum crosswalk width $w_o$ is about 2 m. The minimum proposed crosswalk width is 4 m [3]. Such wider crosswalks lead to longer cycle lengths (the shaded area in Fig. 6a) and as a result longer delays for all users. The proposed optimum crosswalk width may result in pedestrian crossing speed around 1.0 m/s as shown in Fig. 6a this means that the quality of pedestrian flow might not be high, thus wider crosswalks can be installed to provide better quality or higher LOS while crossing. Although wider crosswalks will impose bigger total delays due to the longer cycle lengths.

Fig. 6b shows the relationships between crosswalk width and cycle length, average pedestrian delay $APD$ and pedestrian crossing speed by assuming a constant total vehicle demand ratio ($(q/s)_t = 0.6$) and a variable pedestrian arrival rate ranging from 0.05 to 0.25 ped/s. As pedestrian arrival rate increases, the optimum crosswalk width increases also since minimum pedestrian green time becomes more significant in defining the cycle length which is in accordance with the defined hypothesis in this paper. Moreover, the minimum average pedestrian delay $APD$ occurs at the optimum crosswalk width $w_o$ (Fig. 6b) since the main component in $APD$ is waiting delay which is dependent on cycle length and the assigned pedestrian effective green interval.

The relationships between pedestrian crossing speed and crosswalk width in Fig. 6 represent the effects of bi-directional pedestrian flow and crosswalk geometry (length and width). As crosswalk width decreases average pedestrian crossing speed decreases due to increasing the interactions between the opposing pedestrian flows.

6.1.2 Scenario 2 “Unbalanced vehicle demand”

Fig. 7 presents the analysis results assuming unbalanced vehicle demand. Fig. 7a assumes constant pedestrian arrival rate ($A = 0.05$ ped/s) and variable vehicle demand ratio, while Fig. 7b assumes constant total vehicle demand ratio ($(q/s)_t = 0.6$) and variable pedestrian arrival rate. It is assumed that the north and south approaches are the major vehicle demand approaches, therefore longer green is assigned to them ($\phi_1$). While vehicles in the minor approaches and pedestrians crossing the major approaches have the right of way in $\phi_3$, these users will receive shorter green and longer red. Therefore the accumulated pedestrian demand at the north and south crosswalks ($\phi_3$) is bigger than that at the west and east crosswalks ($\phi_4$). The presented APD and average crossing speed in Fig. 7 are
Fig. 6  Optimum crosswalk width, APD and pedestrian crossing speed for Scenario 1 “Balanced vehicle demand” and ordinary pedestrian crossing.

(a) Constant pedestrian arrival rate $A = 0.05$ ped/s

(b) Constant total vehicle demand ratio $(q/s)_t = 0.6$

By comparing Figs. 6a and 7a, we can see that the optimum crosswalk width $w_o$ at the same total vehicle demand ratio is wider in Scenario 2 than Scenario 1.
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Fig. 7 Optimum crosswalk width, APD and pedestrian crossing speed for Scenario 2 “Unbalanced vehicle demand” and ordinary pedestrian crossing.

This is referred to the larger accumulated pedestrian demand in $\phi_3$ than that of $\phi_1$. Therefore, the optimum widths of the crosswalks included in $\phi_1$ and $\phi_3$ are different. Wider crosswalks are required to minimize...
cycle length at the north and south approaches (ϕ) because of the larger accumulated pedestrian demand. However, at the west and east approaches (ϕ), narrower crosswalks are required in order to minimize cycle length. The optimum crosswalk widths for all approaches at very high vehicle demand ratio and low pedestrian arrival rate is around 2 m, which is similar to that of Scenario 1. Furthermore, Fig. 7 shows that the optimum crosswalk width insures the minimum average pedestrian delay APD, although the resultant average pedestrian crossing speed is between 0.9 and 1.1 m/s, which is lower than the average free-flow speed (1.45 m/s).

6.2 Two-Stage Pedestrian Crossing Treatment

Two-stage crossing refers to the case in which a pedestrian crossing has to be completed in two stages. Some traffic engineers prefer the use of two-stage crossing design when the street to be crossed is wide [12]. A common case is that the wide street is usually the major road where vehicle demands are high which requires a greater portion of the cycle. Since the major road is wide, pedestrians wishing to cross need long green interval. However, those pedestrians are served concurrently with the associated vehicle phases on the minor streets, which must be extended to accommodate the pedestrian interval. This extension increases vehicle delays on the major approaches. An appropriate phasing design with two-stage crossing could solve this issue and provide better service for all users. It is noted that applying this policy is depended on providing a safe island for pedestrians to wait in the middle of the road. This island must be wide enough to accommodate the expected pedestrian demand. Therefore, intersections with high pedestrian demand are not potential places for implementing this policy. Usually it is applied at intersections with low to medium pedestrian demand.

Fig. 8 illustrates the analysis results assuming balanced and unbalanced vehicle demand scenarios. Pedestrian arrival rate A is assumed as constant value of 0.1 ped/s. This arrival rate is considered as medium pedestrian demand level.

The relationships between crosswalk width and cycle length for vehicle demand Scenarios 1 and 2 in Fig. 8 shows clearly that pedestrian crossing time requirement has no effect on cycle length due to the long green intervals available for pedestrians in all approaches (Fig. 5). Moreover, by comparing the relationships between crosswalk width and cycle length in Figs 6-8, it is clear that two-stage pedestrian crossing policy results in lower cycle length, which is associated with lower average pedestrian delays APD. Therefore, it is concluded that two-stage policy is superior to normal pedestrian crossing policy due to the lower cycle length and delays for all users.

Regarding the optimum crosswalk width, installing the minimum possible crosswalk width is recommended to minimize cycle length, as shown in the relationship between crosswalk width and cycle length in Fig. 8. However, crosswalk width affects directly pedestrian flow, which means that very narrow crosswalks may results in uncomfortable crossing and large delays for pedestrians while crossing. At intersections where two-stage pedestrian crossing is implemented, total vehicle demand ratio (q/s) is less than 0.55 and pedestrian demand is low to medium (< 0.1 ped/s), a crosswalk width of 2.0 m is reasonable since the resulted pedestrian crossing speed is higher than 1.0 m/s according to the utilized pedestrian speed model. This crosswalk width is in accordance with the proposed 1.8 m minimum crosswalk width [2] for low pedestrian demand cases.

One of the common concerns about installing narrow crosswalks is the visibility from drivers. According to Ref. [3], vehicle stop line should not be less than 0.45 m wide. This requirement is based on the ability of drivers to recognize narrow lines on the pavement under different weather conditions. A crosswalk width of 2 m is about four times wider than the minimum required stop line width; therefore, it can be concluded that the proposed narrow crosswalks are visible from drivers.
Fig. 8  Optimum crosswalk width, APD and pedestrian crossing speed for two-stage pedestrian crossing treatment.
7. Conclusion and Future Works

This study deals with the mutual impacts between the geometric design and operational system of signalized intersection, which is a missing link in the chain of research regarding signalized intersections. Existing optimization methodologies for the operational system at intersections assumes a fixed geometric design, however to produce the best performance, the geometry and operational system should be optimized simultaneously.

Minimizing cycle length is a very important concern, not from the viewpoint of drivers only but from the viewpoint of pedestrians also, since waiting delay is the main component in the experienced delay by pedestrians. However, at high pedestrian demand pedestrian may experience uncomfortable crossing and significant delays due to the interaction between bi-directional flows.

In this study a framework is proposed to define the proper crosswalk width at various pedestrian demand levels which can optimize the performance of the intersection. The trade-off between crosswalk width and cycle length is demonstrated and the concept of optimum crosswalk width is proposed. Crosswalk width affects directly cycle length and thus the mobility levels of signalized intersections. The optimum crosswalk width ensures the minimum delay for all users including pedestrians; however, it may negatively affect the quality of pedestrian flow at crosswalks. When pedestrian arrival rate is low ($A < 0.1$ ped/s) and vehicle demand is high ($(q/s) \geq 0.55$), the installation of wide crosswalks such as the proposed 4 m minimum crosswalk width [3], will lead to longer cycle lengths and delays for all users. Thus, a crosswalk width of 2 m is appropriate to minimize cycle length and the resultant delays. This is consistent with the proposed 1.8m minimum crosswalk width [2]. At intersections with unbalanced vehicle demands, wider crosswalks are recommended at the approaches with the higher vehicle demand ratios to minimize cycle length. This is referred to the longer red times experienced by pedestrians crossing the major vehicle demand approaches, therefore the accumulated number of pedestrians is bigger while the available pedestrian green is shorter. Thus, wide crosswalks are required to shorten pedestrian crossing and discharging times.

Existing strategy in positioning crosswalks far upstream at Japanese signalized intersections results in longer cycle lengths and delays for all users, while compact intersections which are the most common layout in USA and Europe produces shorter cycles and lower delays. Furthermore, compact intersections improve the visibility between various users and impose lower turning vehicle speeds, which are expected to improve the overall safety levels of signalized intersections. In order to concretize this conclusion, the effects of crosswalk position upon the interactions between turning vehicles and pedestrians should be investigated.

Through this study, the efficiency of two-stage pedestrian crossing is analyzed. It is concluded that two-stage pedestrian crossing is an effective tool to eliminate the effect of pedestrian crossing time requirements, which affects positively in reducing cycle length and the total delays for all users including pedestrians. However, an important concern is the safety of pedestrians waiting at the island in the middle of the road. Thus studying the interactions between drivers and pedestrians while waiting in the island is important. Furthermore investigating the applicability of various protection equipments at the median island to secure pedestrian safety is also significant.

References

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