Estimating the Minimum Required Width of Signalized Crosswalks Considering Bi-Directional Pedestrian Flow and Different Age Groups

Wael K.M. ALHAJYASEEN a, Hideki NAKAMURA b
Department of Civil Engineering, Nagoya University,
Furo-cho, Chikusa-ku, Nagoya 464-8603 Japan
a E-mail: wael@genv.nagoya-u.ac.jp
b E-mail: nakamura@genv.nagoya-u.ac.jp

Abstract: Existing manuals do not provide clear specifications for the required crosswalk width under different pedestrian demand volumes and characteristics. However, optimizing crosswalk configurations including width is an important concern to improve the overall performance of signalized intersections. The objective of this paper is to develop a methodology for estimating minimum required crosswalk width at different pedestrian demand volumes considering bi-directional flow and different pedestrian age groups. The developed methodology is based on modeling total pedestrian platoon crossing time which consists of discharge and crossing times. Discharge time is modeled by using shockwave theory while crossing time is modeled by applying aerodynamic drag theory. The developed models are then calibrated for crosswalks with mainly elderly or pupil pedestrian platoons. A set of criteria based on pedestrian crossing speed is developed to identify the minimum required crosswalk width. Finally, different required crosswalk widths are proposed for different pedestrian demand volumes and directional split ratios considering the effects of pupil and elderly pedestrian platoons.

Keywords: Crosswalk width, Crossing speed, Bi-directional flow, Age

1. INTRODUCTION

Crosswalks are portions of roadway designated for the use of pedestrians to cross the street whenever they have the right of way. They affect the performance of signalized intersections significantly in terms of mobility and safety. Characteristics of crosswalks including position and width define the vehicle’s stop line position, and therefore the required all-red interval. As crosswalks become wider or their position become further upstream, cycle length will increase because of all-red time requirement. Longer cycle lengths lead to longer delays and to the deterioration of the overall mobility levels of signalized intersections.

The width of a crosswalk depends primarily on the number of pedestrians who are expected to use the crosswalk at a given time. Existing manuals do not provide clear specifications for the required crosswalk width regarding different pedestrian demand volumes and characteristics. The recommended minimum width ranges from 1.8m (HCM, 2000) to 4.0m (Japanese Manual on Road Marking, 2004). Such unavailability of specifications leads to a wide range of experiences around the world. Japanese signalized intersections are often characterized by unnecessarily wide crosswalks even though pedestrian demand is not high while narrow crosswalks (1.8m) exist at many signalized intersections in the United States where pedestrian demand is expected to be low. Considering these different situations, it is necessary to develop a rational methodology that can provide planners and designers with recommendation regarding minimum required crosswalk width for different pedestrian demand volumes considering the bi-directional nature of pedestrian flows.
Quantifying the effects of bi-directional pedestrian flow and crosswalk width on pedestrian crossing speed and crossing time is a prerequisite to the optimization of the geometry and configuration of signalized crosswalks.

The objective of this paper is to develop a methodology to estimate the minimum required crosswalk width at signalized intersections for different pedestrian demand volumes considering bi-directional flow and pedestrian age groups. The structure of this paper is as follows: After introduction and literature review, total crossing time is modeled, followed by collecting the necessary data for parameter estimation and model calibration. Sensitivity analysis and validation of the developed models are presented and possible applications for the developed models are discussed. Then criteria for the minimum required crosswalk width are established. By using these criteria and the developed models, recommendations regarding minimum required crosswalk width values are proposed. Finally, the paper ends with summary of the results, conclusion and future works.

2. LITERATURE REVIEW

Manual on Uniform Traffic Control Devices (2003) in the US recommends a minimum crosswalk width of 6 ft (1.8 m). Meanwhile the Japanese Manual on Road Marking (2004) 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 and recommendations for minimum crosswalk widths at different pedestrian demand volumes are missing. To develop a methodology capable of estimating the minimum required crosswalk width for different pedestrian demand volumes, interactions between bi-directional pedestrian flow, crosswalk geometry, crossing time and speed should be carefully investigated.

Few studies addressed the issue of bi-directional pedestrian flow and its impact on crossing time at signalized crosswalks. Most of the existing works attempted to investigate the impact of bi-directional flow at other pedestrian facilities such as walkways and sidewalks. However, characteristics of the environment as well as pedestrian arrival pattern at crosswalks are different from other pedestrian facilities. Most crossing time estimation methodologies have been based on assumptions providing for start-up delay and a particular walking speed. The Pedestrian Chapter of the Highway Capacity Manual (2000) and Pignataro (1973) have formulations similar to equation (1).

\[
T = I + \frac{L}{S_p} + \left( x \frac{N_{\text{ped}}}{w} \right) \tag{1}
\]

where

- \(T\): total time (sec) required for all the crossing process
- \(I\): initial start-up lost time (sec)
- \(L\): crosswalk length (m)
- \(S_p\): walking speed (m/sec)
- \(x\): average headway (sec/ped/m)
- \(N_{\text{ped}}\): number of pedestrians crossing during an interval \(p\) from one side of the crosswalk
- \(w\): crosswalk width (m)

Equation (1) shows that the time spent on the crosswalk itself \((L/S_p)\) is independent of the bi-directional demand and crosswalk width.

The Japanese Manual on Traffic Signal Control (2006) presents a formula similar to equation (1) but the initial start-up lost time is included in the discharge time. The Manual on
Uniform Traffic Control Devices (2003) provides a procedure to estimate pedestrian crossing time (clearance interval) depending on average walking speed (4.0 ft/sec) and crosswalk length, which is similar to $L/S_p$ in equation (1). However, this procedure does not consider the effect of bi-directional pedestrian flow.

Lam et al. (2003) investigated the effect of bi-directional flow on walking speed and pedestrian flow under various flow conditions at indoor walkways in Hong Kong. They found that bi-directional flow ratios have significant impacts on both the at-capacity walking speed and the maximum flow rates of the selected walkways. However, they did not investigate the effect of walkway’s dimensions on walking speed and capacity.

Golani and Damti (2007) proposed a model to estimate crossing time considering start-up lost time, average walking speed and pedestrian headways of the dominant and opposite platoon separately. Their proposed methodology is based on Highway Capacity Manual (2000) model, which was calibrated by using empirical data. They assumed that the impact of bi-directional flow is reflected on the headway between pedestrians when they finish crossing. Therefore, it is difficult to see how the interaction is happening and what the resulting deceleration is.

Alhajyaseen and Nakamura (2009) developed a methodology to model total pedestrian crossing time. In the proposed methodology total crossing time was divided into two parts: discharge time and crossing time. Their methodology was based on simple assumptions regarding the interaction time between the conflicting pedestrian flows. They assumed the interaction time as the time from the moment the subject and opposite pedestrian flow meet each other at the middle of the crosswalk to the moment the subject pedestrian flow reaches the end of the crosswalk. This paper is an extension of the previous work done by Alhajyaseen and Nakamura (2009) and aims to refine the assumptions regarding interaction time by considering the physical depth of the opposite pedestrian platoon.

3. MODELING TOTAL CROSSING TIME

3.1 Methodology

The total time needed by a platoon of pedestrians to cross a signalized crosswalk $T_t$, which is defined as the time from the beginning of pedestrian green indication until the pedestrian platoon reaches the other side of the crosswalk, is divided into discharge time $T_d$ and crossing time $T_c$. Discharge time $T_d$ is the time necessary for a pedestrian platoon to move from the waiting area and step inside the crosswalk, while crossing time $T_c$ is the time required to cross the crosswalk.

\[
T_t = T_d + T_c \tag{2}
\]

The discharge time $T_d$ is a function of pedestrian demand and crosswalk width. The definition of discharge time $T_d$ is similar to that of queue discharge time of vehicles waiting at the stop line of a signalized intersection, which is usually estimated through shockwave theory; hence, this theory is chosen for modeling pedestrian platoon discharge time as well.

Crossing time $T_c$ is dependent on pedestrian crossing speed, which is affected by the size of opposite pedestrian platoon and crosswalk width. This is analogous to a moving body facing a fluid which causes a reduction in its speed depending on its cross sectional area, the density of the fluid and the relative speed between them. This phenomenon is known as drag force theory and this analogy is used for modeling pedestrian platoon crossing time $T_c$. 

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The developed models are improved and presented in this paper.

3.2 Modeling Discharge Time $T_d$

Discharge time $T_d$ basically depends on pedestrian arrival rate, pedestrian red interval and crosswalk width. Shockwave analysis is used to estimate queue discharge time, which is equivalent to the time necessary for a pedestrian platoon to discharge at the edge of crosswalk (Figure 1). The start-up lost time $I$ is considered as part of discharge time $T_d$. Pedestrian arrival rate $A_1$ is assumed to be uniform. Moreover, it is assumed that pedestrians arrive in a unit of “pedestrian row” per second. The lateral distance that a pedestrian occupy $\delta$ is assumed to be a function of pedestrian demand and crosswalk width. However, for simplification, longitudinal distance $D$ between waiting pedestrians, which is the same distance between pedestrian rows, is assumed to be constant. By using shockwave theory, speed of stopping shockwave (due to arriving rows) and starting shockwave (due to discharging rows) can be estimated. Then the time necessary for waiting pedestrian rows to discharge after pedestrian green is displayed can be estimated using equation (3) (Alhajyaseen and Nakamura, 2009):

$$
T_d = \frac{-\delta A_1/w}{K_j - \delta A_1/wu_s} (C - g) \\
- \frac{Q_d}{Q_d/u_s - K_j} \left( \frac{-\delta A_1/w}{K_j - \delta A_1/wu_s} \right)
$$

Figure 1. Schematic formation of pedestrian rows at high demand
After estimating the necessary parameters from empirical data, equation (3) can be used to estimate the discharge time $T_d$ for any pedestrian demand volume as shown in Figure 7b) which is presented in Chapter 5.

### 3.3 Modeling Crossing Time $T_c$

The force on an object that resists its motion through a fluid is called drag. When the fluid is gas like air (Figure 2a)), it is called aerodynamic drag while if the fluid is liquid like water it is called hydrodynamic drag. Drag is a complicated phenomenon and explaining it from a theory based entirely on fundamental principles is exceptionally difficult. Pugh (1971) described the relation between drag $D$ and the relative velocity between air and a moving body in terms of a dimensionless group, the drag coefficient $C_d$. The drag coefficient is the ratio of drag $D$ (kg·m/s$^2$) to the dynamic pressure $q$ (force per unit area) of a moving air stream which is equivalent to the kinetic energy per unit volume of a moving solid body. Equation (4) presents the drag force $D$ (Pugh, 1974):

$$D = \frac{1}{2} C_d \rho u^2 A_p$$  \hspace{1cm} (4)

where

- $C_d$: the drag coefficient (dimensionless)
- $A_p$: the projected area of the moving body (m$^2$)
- $\rho$: density of air or fluid (kg/m$^3$)
- $u$: speed of the object relative to the fluid (m/s)

#### 3.3.1 'Drag Force’ Caused by the Opposite Pedestrian Flow

To utilize the drag force concept for modeling interactions between bi-directional pedestrian flows, the following assumptions are made:

i) Opposite pedestrian demand is considered as a homogenous flow (Figure 2b)) with a density equal to the number of pedestrian $P_2$ waiting at the beginning of the green interval divided by an area equal to the width of the crosswalk multiplied by 1.0m.

ii) The subject pedestrian flow is considered as one body moving against the opposite pedestrian flow. Interactions occur along the projected area of all pedestrians in the subject flow which is defined as the sum of the widths of all pedestrians in the subject flow.
\[ A_p \approx \beta n \]  

where

- \( A_p \): the projected area of the subject pedestrian flow (m)
- \( \beta \): the average body width of one pedestrian
- \( n \): the number of pedestrians in the subject pedestrian flow \( P_1 \), shown in Figure 2b).

iii) The initial speed of the subject and the opposite pedestrian flow when they start crossing is assumed to be equal to their free-flow speed \( u_1 \) and \( u_2 \), respectively.

After substituting the previous assumptions in equation (4), the drag force equation becomes:

\[ D = 0.5 \cdot C_d \cdot \frac{P_1}{w} \cdot (u_1 + u_2)^2 \cdot \beta \cdot n \]  

Assuming that the average width of one pedestrian body \( \beta \) is 0.6 m, the drag force \( D \) becomes:

\[ D = 0.5 \cdot C_{Dadj} \cdot \frac{P_1}{w} \cdot (u_1 + u_2)^2 \cdot n \]  

where \( C_{Dadj} \) is the adjusted drag coefficient (dimensionless), and it is defined in equation (8).

\[ C_{Dadj} = \beta \cdot C_d \]  

3.3.2 Deceleration of the Subject Pedestrian Flow

The net force on a particle observed from an inertial reference frame is proportional to the time rate of change of its linear momentum (Momentum is the product of mass and velocity). Therefore this force is equal to the mass of the moving body \( M \) which is equivalent to the subject pedestrian demand \( P_1 \) multiplied by the average deceleration of the subject pedestrian flow \( a \). The final speed of a moving particle on a straight line with constant average deceleration according to the motion equations is:

\[ u_f^2 = u_i^2 - 2aL \]  

where

- \( u_i \): initial speed (m/sec) which is assumed to be equal to the free-flow speed \( u_1 \)
- \( u_f \): final speed (m/sec)
- \( a \): average deceleration (m/sec^2)
- \( L \): travelled distance (m).

Figure 3 shows the projection of pedestrian flow trajectory from both sides of a crosswalk. A major assumption of this methodology is that both opposing flows will start walking with their free-flow speed on a straight line until they meet in the crosswalk. The meeting point is dependent on the speed of the subject and the opposite pedestrian platoons. The time when the two pedestrian platoons will meet is defined in equation (10).

\[ t = \frac{L_o}{u_1 + u_2} \]
$L_o$: crosswalk length, $P_2$: opposite pedestrian demand, $P_1$: subject pedestrian demand, $T_c$: time necessary for subject pedestrian demand to cross the crosswalk, $t$: time from the beginning of crossing until the subject and the opposite pedestrian platoons meet in the crosswalk, $t_i$: interaction time, $l_i$: interaction distance, $u_1$ and $u_2$: free-flow speed of the subject and the opposite pedestrian flow respectively.

Figure 3. Time-space diagram of the conflicting pedestrian flows

The interaction distance $l_i$ is assumed to be equal to the physical depth of the opposite pedestrian platoon. The physical depth of the opposite pedestrian platoon can be estimated by utilizing the methodology used for modeling the discharge time $T_d$. Therefore, the physical depth $l_i$ of the opposite pedestrian platoon is defined in equation (11):

$$l_i = \frac{R_p}{K_j} = \frac{P_2 \cdot \delta}{w \cdot K_j}$$  (11)

where $R_p$ is the number of accumulated rows of the opposite pedestrian demand at the start of pedestrian green interval.

Figure 3 shows that resulting deceleration is averaged along the assumed interaction time. Therefore, the final speed can be defined as:

$$u_f = \frac{l_i}{t_i} = \frac{l_i}{T_c - \frac{L_o}{u_1 + u_2}(1 + \frac{u_2}{u_1}) + \frac{l_i}{u_1}}$$  (12)

where $T_c$ is crossing time of the subject pedestrian platoon and $l_i$ is the physical depth of the opposite pedestrian platoon.

If the physical depth of the opposite pedestrian platoon is longer than the remaining crossing distance ($L_o-u_1t$), the interaction distance will be equal to $L_o-u_1t$. Therefore, when estimating the interaction distance, the physical depth of opposite pedestrian platoon should be compared with the remaining crossing distance for the subject pedestrian platoon and the smaller one should be considered as the interaction distance. By substituting equation (12) in equation (9), the average deceleration of the subject pedestrian platoon becomes:
\[ a = \left[ \frac{u_i^2 - \left(\frac{1}{l_i} \left[ \frac{L_o}{u_i + u_2 (1 + \frac{u_2}{u_i})} \right]^2 \right]}{2l_i} \right] \]  

(13)

The net force \((\text{ped.m/sec}^2)\) that causes the deceleration of the subject pedestrian platoon is defined as the average deceleration \(a\) (equation (13)) multiplied by the mass of the subject pedestrian platoon \(M\) which is assumed to be equal to the subject pedestrian demand \(P_1\).

### 3.3.3 Model Development

The drag force caused by an opposite pedestrian flow should be equal to the force that causes the deceleration of the subject pedestrian flow. By equating the two forces and solving for the crossing time \(T_c\), the net equation becomes:

\[
T_c = \frac{l_i}{u_i} + \frac{L_o}{u_2 (u_i + u_2)} \left(1 + \frac{u_2}{u_i}\right) - \frac{l_i}{u_1} \frac{C_{\text{ped}}} {w} \left( u_i + u_2 \right)^2 \]  

(14)

Pedestrian demand is defined as the number of accumulated pedestrians during pedestrian red and flash green signal indications, and those who arrive during the discharge time. Therefore, opposite pedestrian demand can be presented as:

\[ P_2 = A_2 \times (C - g + T_d) \]  

(15)

where \(T_d\) is discharge time of the opposite pedestrian platoon.

After substituting equation (15) in equation (14), the average crossing time and walking speed of the subject pedestrian flow are given in equations (16) and (17), respectively.

\[
T_c = \frac{l_i}{u_i} + \frac{L_o}{u_2 (u_i + u_2)} \left(1 + \frac{u_2}{u_i}\right) - \frac{l_i}{u_1} \frac{C_{\text{ped}}} {w} \left( u_i + u_2 \right)^2 \]  

(16)

\[
u_f = \sqrt{u_i^2 - \frac{C_{\text{ped}} A_2 l_i (u_i + u_2)^2 (C - g + T_d)} {w}} \]  

(17)

Equations (16) and (17) are the final equations which represent how walking speed and crossing time vary with pedestrian demand combinations (bi-directional flow) and crosswalk geometry.

### 4. DATA COLLECTION AND PARAMETER ESTIMATION

#### 4.1 Data Collection

In order to estimate the required parameters and calibrate them for the effects of pupil and elderly pedestrian platoons, data was collected at various signalized crosswalks as summarized in Table 1. All of these sites are located in Nagoya City.
### Table 1. Surveyed sites characteristics

<table>
<thead>
<tr>
<th>Site</th>
<th>Intersection name</th>
<th>Crosswalk position</th>
<th>Dimensions (w(m) \times L_{o}(m))</th>
<th>Survey hours</th>
<th>Pedestrian demand</th>
<th>Pedestrian age-group</th>
<th>Application purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>Nishi-Osu</td>
<td>East leg</td>
<td>4.0m (\times) 25.4m</td>
<td>09:00-10:30</td>
<td>Low</td>
<td>Middle-age</td>
<td>(u_{o}, \delta, C_{Dadj})</td>
</tr>
<tr>
<td>Site 2</td>
<td>Imaike</td>
<td>East leg</td>
<td>7.2m (\times) 21.5m</td>
<td>13:00-15:00</td>
<td>Medium</td>
<td>Middle-age</td>
<td>(u_{o}, \delta, C_{Dadj})</td>
</tr>
<tr>
<td>Site 3</td>
<td>Sasashima</td>
<td>East leg</td>
<td>8.0m (\times) 19.0m</td>
<td>07:00-09:30</td>
<td>High</td>
<td>Middle-age</td>
<td>(K_{j}, Q_{d}, \delta)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>West leg</td>
<td>10m (\times) 31.3m</td>
<td>07:00-09:30</td>
<td>High</td>
<td>Middle-age</td>
<td>(K_{j}, Q_{d}, \delta)</td>
</tr>
<tr>
<td>Site 4</td>
<td>Mizuho-Kuyakusho</td>
<td>North leg</td>
<td>6.0m (\times) 21.5m</td>
<td>07:00-09:30</td>
<td>High</td>
<td>Pupil</td>
<td>(u_{o}, K_{j}, Q_{d}, \delta, C_{Dadj})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>East leg</td>
<td>6.0m (\times) 9.5m</td>
<td>07:00-09:30</td>
<td>High</td>
<td>Pupil</td>
<td>(u_{o}, K_{j}, Q_{d}, \delta, C_{Dadj})</td>
</tr>
<tr>
<td>Site 5</td>
<td>N/A*</td>
<td>Midblock</td>
<td>4.0m (\times) 15.0m</td>
<td>08:30-10:00</td>
<td>Medium</td>
<td>Elderly</td>
<td>(u_{o}, C_{Dadj})</td>
</tr>
</tbody>
</table>

*The crosswalk in front of Nagoya Daini Sekijyuji Hospital between Yagoto Nisseki and Yagoto intersections

### 4.2 Parameter Estimation

A major assumption of the modeling methodology is that subject or opposite pedestrian flow consists of the same age group. No consideration is taken regarding mixed pedestrian platoon situation. Three age groups are defined in this study, namely: middle age, elderly and pupils. The opposite pedestrian platoon is always assumed as middle-age pedestrian platoon.

As a first step, the required parameters were estimated for crosswalks with subject pedestrian flow of middle-age pedestrians, then parameters were estimated for crosswalks with pupil and elderly subject pedestrian platoons. However due to unavailability of required data, some parameters could not be empirically estimated. Therefore, their values were defined according to reasonable assumptions, which are explained in the following paragraphs.

Table 1 shows the utilized data to estimate each parameter and Table 2 presents the estimated and calibrated values for all parameters included in equations (3) and (16) which are estimated as follows:

i) To define a value for pedestrian free-flow speed at crosswalks \(u_{o}\), only leading pedestrians who did not face any opposite pedestrian flow or turning vehicles were considered. Figure 4 shows the free-flow speed cumulative probability distribution of three pedestrian age groups. The observed average free-flow speed is assumed as the free-flow speed of pedestrians at crosswalks \(u_{o}\).

ii) Lam and Cheung (2000) studied pedestrian walking speed at different walking facilities and they found that pedestrian’s free-flow walking speed at outdoor walkways is lower than that of signalized crosswalks by 17%. However, for the purpose of this study pedestrian free-flow speed at sidewalks \(u_{s}\) is assumed to be 20% less than that at crosswalks. Table 2 presents the adopted free-flow speed at sidewalks \(u_{s}\) for middle-age, pupil and elderly pedestrians.

iii) In order to define the jam density \(K_{j}\), estimated jam densities on different sites are averaged. It should be noted that the jam density, which is used in the proposed discharge time model, is the jam density in the unit of pedestrian row per meter. Therefore, it is assumed that the minimum lateral distance \(\delta_{min}\) that a pedestrian can occupy along the crosswalk width is 1.0m, including the lateral clearance distance between waiting pedestrians. As a result, the jam density \(K_{j}\) in the unit of pedestrian row per meter is defined as:

\[
K_{j} = K_{j}(\text{ped.} / m^2) \times \delta_{min} \quad (\text{ped. row/m})
\]  

(18)

Table 2 shows the jam density \(K_{j}\) for middle-age and pupil pedestrians. However, for elderly pedestrians, it was assumed that the jam density of elderly pedestrian is equal to that of middle-age pedestrians since data at high demand was not available.
Table 2. Estimated and calibrated parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Middle age</th>
<th>Pupils</th>
<th>Elderly</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_o$</td>
<td>1.45</td>
<td>1.36</td>
<td>1.20</td>
</tr>
<tr>
<td>$C_{D,adj}$</td>
<td>0.0307 $r^{1.346}$</td>
<td>0.0362 $r^{1.346}$</td>
<td>0.03837 $r^{1.346}$</td>
</tr>
<tr>
<td>$u_s$</td>
<td>1.16</td>
<td>1.09</td>
<td>0.94</td>
</tr>
<tr>
<td>$K_j$</td>
<td>1.10</td>
<td>1.29</td>
<td>1.10</td>
</tr>
<tr>
<td>$Q_d$</td>
<td>0.45</td>
<td>0.52</td>
<td>0.37</td>
</tr>
<tr>
<td>$\delta$</td>
<td>2.5323 $(P/w)^{0.383}$</td>
<td>2.5486 $(P/w)^{-0.4513}$</td>
<td>2.5323 $(P/w)^{-0.383}$</td>
</tr>
</tbody>
</table>

Caption:
$u_o$: pedestrian freewflow speed at crosswalks (m/sec), $C_{D,adj}$: adjusted drag coefficient, $u_s$: pedestrian freewflow speed at sidewalks (m/sec), $K_j$: jam density (ped.row/m), $Q_d$: Maximum discharge rate (ped.row/sec) and $\delta$: lateral distance that a pedestrian can occupy a long crosswalk width (m).

Figure 4. Free-flow speed cumulative distributions for different pedestrian age groups

iv) Maximum discharge flow rate $Q_d$ was observed at crosswalks with very high pedestrian demand. The average observed discharge rate at high pedestrian demand crosswalks is assumed as the maximum discharge flow rate $Q_d$. Table 2 shows the average observed discharge rate for middle-age and pupil pedestrians. Maximum discharge flow rate $Q_d$ for elderly pedestrians is assumed to be equal to that of middle-age multiplied by an adjustment factor $M_f$ which is defined according to equation (19).

$$M_f = 1 - \frac{u_o(\text{middle age}) - u_o(\text{elderly})}{u_o(\text{middle age})}$$ (19)

v) The average lateral distance that a pedestrian can occupy $\delta$ at different demand values was estimated for middle-age and pupil pedestrians by utilizing equation (3). The lateral distance $\delta$ is modeled as a function of pedestrian demand per meter width of the crosswalk. A preliminary statistical analysis was performed to determine the best function to represent the relationship between $\delta$ and pedestrian demand per meter width of the crosswalk. As shown in Figure 5, the power function was found to best describe this relationship. Figure 5a) shows that at high pedestrian demand, $\delta$ becomes very close to 1.0m which is in accordance with the previous assumption that $\delta_{min}$ is equal to 1.0m. However Figure 5b) shows that pupil occupy smaller lateral distance than middle-age pedestrian at high demand which means that pupil can adopt to denser platoons. Such phenomenon is also in accordance with the observed jam density for pupil as it was higher than that of middle-age
pedestrian. For elderly pedestrian, the developed model for middle-age pedestrian was used to estimate the lateral distance $\delta$ (Table 2), since data at different demand volumes was not available.

![Figure 5. Modeling occupied lateral distance $\delta$](image1)

![Figure 6. Adjusted drag coefficients $C_{Dadj}$ for different age groups](image2)

vi) The value of adjusted drag coefficient $C_{Dadj}$ according to aerodynamic drag is dependent on the kinematic viscosity of the fluid, projected area and texture of the moving body. In the pedestrian’s case, drag coefficient is assumed to be dependent on pedestrian demand at both sides of the crosswalk and their directional split ratio. The data, which was collected at sites 1 and 2, was utilized to estimate $C_{Dadj}$ for middle-age pedestrian (Table 1). Pedestrian demand in each cycle at each direction, average pedestrian trajectory length, and average crossing time in the same cycle were extracted from the video tapes. Then by using equation (16), $C_{Dadj}$ was estimated and modeled in terms of the directional split ratio $r$ which is the ratio of subject pedestrian demand to total pedestrian demand (Figure 6). For pupil and elderly pedestrians, developed model for middle-age pedestrians was calibrated and used. The average vertical shift between the data points of elderly pedestrians and the drag coefficient model of middle-age pedestrians was considered as the adjustment factor. Then it was assumed that the adjusted drag coefficient model for elderly pedestrians is
equal to that of middle-age pedestrians multiplied by the estimated adjustment factor (Figure 6). The same procedure was used to estimate the adjusted drag coefficient model for pupil. After estimating all required parameters, equations (3), (16) and (17) can be used to estimate discharge time, crossing time and crossing speed for any pedestrian platoon at a specific crosswalk width and length.

5. SENSITIVITY ANALYSIS AND VALIDATION

Figure 7a) shows how crossing time varies with crosswalk width under a combination of opposing pedestrian demands, $P_1$ and $P_2$. When crosswalk width becomes larger for a specific demand, crossing time decreases until it becomes almost constant (free-flow condition). But when crosswalk width becomes smaller for a specific demand, crossing time increases, until it reaches a point where opposing flows block each other causing a drastic increase in crossing time. Figure 7b) shows the drop in average walking speed due to the effects of bi-directional pedestrian flow. As the crosswalk width decreases for a specific pedestrian demand, the interactions increase causing reduction in the average walking speed. The drop in the walking speed continues with reducing crosswalk width until a point where the speed drops drastically. This tendency is reasonable if we assume that pedestrian cannot walk outside the crosswalk.

To validate the proposed models, average crossing speed was measured under different directional demand ratios and compared with the estimated speed from the proposed model. Figure 8a) illustrates the differences between measured and estimated crossing speed for different age groups. As it was expected, estimated speeds from the developed model are lower than observed values. This tendency is logical since the developed model estimates the speed directly after the interaction with the opposite flow while observed speed is the average speed through all the crossing process and it is measured by dividing pedestrian trajectory length to crossing time. However Figure 8a) shows that for some data points estimated speeds are higher than observed values. These points were extracted from the data collected at Imaike intersection when pedestrian demand was low. If pedestrians walk slow at low demand (limited interactions), this can be referred to their desired speed which is not considered in the proposed methodology. A paired t-test was performed and the result showed that the estimated and observed values were not significantly different at 95% confidence level.

The estimated discharge time $T_d$ by equation (3) is compared with observed data and the estimated discharge time using the formulations in Highway Capacity Manual (2000) and Japanese Manual on Traffic Signal Control (2006) as shown in Figure 8b). By comparing the
mean absolute percentage error and root mean square error, it is obvious that the proposed model produces more accurate and reliable results. Furthermore, the existing formulations always tend to underestimate the necessary discharge time for large pedestrian platoons. The tendency of the proposed discharge time model is more consistent with the observed data.

Estimated average pedestrian walking speed ($m/sec$)

Measured average pedestrian walking speed ($m/sec$)

<table>
<thead>
<tr>
<th>Imaike and Nishi-Osu (Middle-age)</th>
<th>Mizuho-Kuyakusho (Pupil)</th>
<th>Yagoto Nisseki (Elderly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute percentage error range: 0.01%-15.28%</td>
<td>Mean absolute percentage error (3.38%)</td>
<td>Root mean square error (RMSE) = 0.07</td>
</tr>
</tbody>
</table>

**Figure 8. Validations of the proposed models**

6. MODEL APPLICATIONS

The developed models can be utilized for different applications such as assessing pedestrian signal timing. The existing methodologies for the estimation of minimum required pedestrian green (equation (1)) depend on constant average walking speed and crosswalk length to estimate total crossing time. HCM (2000) and Japanese Manual on Traffic Signal Control (2006) assume an average pedestrian crossing speed of 1.2 m/sec and 1.0 m/sec, respectively. Estimated total crossing times $T_c$ according to the proposed model, HCM (2000) and Japanese Manual on Traffic Signal Control (2006) are compared and presented in Figure 9. For this purpose, one hour video tape of site 1 was analyzed. Pedestrian demand was low to medium and composed mainly of middle-age pedestrians. The analyzed data is different from the one used for modeling drag coefficient and validating the proposed crossing speed model. By comparing the mean absolute percentage error and the root mean square error (Figure 9), it is found that the proposed model produces more accurate and reliable results. Furthermore,
HCM (2000) and Japanese Manual on Traffic Signal Control (2006) overestimate the minimum required green time for small pedestrian platoons and tend to underestimate the minimum required green time for large pedestrian platoons since they do not consider the drop in speed due to the interactions between opposing pedestrian flows. However, the main objective behind the proposed methodology is to rationally define the minimum required crosswalk width for different pedestrian demand volumes and directional split ratios considering bi-directional flow and different pedestrian age groups.

![Figure 9. Minimum required pedestrian green time comparison](image)

7. MINIMUM REQUIRED CROSSWALK WIDTH CRITERIA

Pedestrian flow at signalized crosswalks could be uni-directional or bi-directional. If pedestrian demand flows from one side of the crosswalk only, then it is called uni-directional flow. However, when pedestrian demand flows significantly from both sides of the crosswalk it is called bi-directional flow. In the case of uni-directional flow, crossing time remains almost constant because pedestrians will not face any conflict. Meanwhile discharge time increases as crosswalk width decreases. In this case, the main factor that defines the required crosswalk width is the maximum waiting time that a pedestrian can wait before discharging. However when pedestrian flow is bi-directional, interactions between the subject and the opposite pedestrian flows become the main factor that control the total crossing time. Therefore, the resulting deceleration or reduction in the walking speed is the main factor that defines the minimum required crosswalk width in the case of bi-directional pedestrian flow.

The developed criteria in this study are only valid for crosswalks with bi-directional pedestrian flow. The required crosswalk width criteria are based on the pedestrian crossing speed which is termed as realized speed $u_r$ in this study. It was assumed that the realized speed $u_r$ depends on total pedestrian demand $P_t$ and directional split ratio $r$. Moreover, it is assumed that it falls between two thresholds, free-flow speed $u_o$ and minimum crossing speed $u_{min}$.
$u_m$. Figure 10a) defines the relationship between realized speed $u_{rd}$ and directional split ratio $r$. A parabolic relation is assumed and defined in equation (20).

$$u_{rd} = f(r) = 4(u_o - u_m)r^2 - 4(u_o - u_m)r + u_o$$ \hspace{1cm} (20)

Figure 10b) defines the relationship between the realized speed $u_{rp}$ and the total pedestrian demand at both sides of the crosswalk $P_t$. It was assumed that when total pedestrian demand $P_t$ increases, the realized speed $u_{rp}$ decreases until it becomes almost equal to the minimum crossing speed $u_m$ (Figure 10b). Therefore a negative exponential relationship is assumed between the realized speed $u_{rp}$ and total pedestrian demand $P_t$ (equation (21)).

$$u_{rp} = f(P_t) = (u_o - u_m)e^{-u_t}$$ \hspace{1cm} (21)

![Figure 10. Realized speed criteria](image)

The final realized speed $u_r$ is defined as the average of $u_{rd}$ and $u_{rp}$ as shown in equation (22).

$$u_r = \frac{u_{rd} + u_{rp}}{2}$$ \hspace{1cm} (22)

By defining rational values for free-flow speed $u_o$ and minimum crossing speed $u_m$, the realized speed $u_r$ can be estimated directly through equations (20), (21) and (22). Free-flow speed $u_o$ depends on the type of pedestrian platoon which is defined as one of three types: middle age, pupil or elderly. In order to define the value of the minimum crossing speed $u_m$, samples of pedestrians who walked outside the borders of the crosswalk because of the high pedestrian demand were observed. These samples were extracted from site 3. The speed of those pedestrians falls between 1.0 and 1.1 m/sec; however the proposed model estimates lower speeds as it is explained in the sensitivity analysis section. Therefore, a speed of 0.9 m/sec was assumed as the minimum crossing speed $u_m$ for all pedestrian age groups.

8. MINIMUM REQUIRED CROSSWALK WIDTH

To determine the value of the minimum required crosswalk width, the developed crossing speed model (equation (17)) is utilized. By substituting the realized speed $u_r$, crosswalk length and expected pedestrian demand at both sides of the crosswalk, the corresponding required crosswalk width can be estimated. Tables 3 and 4 present the proposed minimum crosswalk
width values for different pedestrian demand volumes and directional split ratios at 6-, 4- and 2-lane carriageways. The width of a vehicle lane was assumed as 3.5m while a 0.5m separation median was assumed between the two directions of traffic. Therefore, the widths of 6-, 4- and 2-lane carriageways are assumed as 21.5m, 14.5m and 7.5m, respectively. It was found that the minimum required crosswalk width at 2-lane carriageways is less than the required one at 4- or 6-lane carriageways. Furthermore, the minimum required crosswalk width for pupil and elderly pedestrians is wider than the required one for middle-age pedestrian. Pupil and elderly pedestrian have less ability to avoid conflicts with opposite pedestrian flow, which results in higher reduction in their speed. Therefore, wider crosswalks are required for pupil and elderly pedestrians to achieve the required design speed.

Table 3. Minimum required crosswalk width at 6- and 4-lane carriageways

<table>
<thead>
<tr>
<th>Total Pedestrian Demand ( P_t )*</th>
<th>Directional split Ratio ( r )</th>
<th>0.25 or 0.75</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Middle-age</td>
<td>Pupil</td>
<td>Elderly</td>
</tr>
<tr>
<td>( P_t \leq 10 )</td>
<td>1.60m</td>
<td>2.00m</td>
<td>2.60m</td>
</tr>
<tr>
<td>10&lt; ( P_t \leq 20 )</td>
<td>3.00m</td>
<td>3.60m</td>
<td>4.70m</td>
</tr>
<tr>
<td>20&lt; ( P_t \leq 30 )</td>
<td>4.20m</td>
<td>5.10m</td>
<td>6.80m</td>
</tr>
<tr>
<td>30&lt; ( P_t \leq 40 )</td>
<td>5.50m</td>
<td>6.70m</td>
<td>8.90m</td>
</tr>
<tr>
<td>40&lt; ( P_t \leq 50 )</td>
<td>6.80m</td>
<td>8.30m</td>
<td>11.00m</td>
</tr>
</tbody>
</table>

Table 4. Minimum required crosswalk width at 2-lane carriageways

<table>
<thead>
<tr>
<th>Total Pedestrian Demand ( P_t )*</th>
<th>Directional split Ratio ( r )</th>
<th>0.25 or 0.75</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Middle-age</td>
<td>Pupil</td>
<td>Elderly</td>
</tr>
<tr>
<td>( P_t \leq 10 )</td>
<td>1.50m</td>
<td>1.80m</td>
<td>2.60m</td>
</tr>
<tr>
<td>10&lt; ( P_t \leq 20 )</td>
<td>2.70m</td>
<td>3.30m</td>
<td>4.60m</td>
</tr>
<tr>
<td>20&lt; ( P_t \leq 30 )</td>
<td>3.80m</td>
<td>4.70m</td>
<td>6.50m</td>
</tr>
<tr>
<td>30&lt; ( P_t \leq 40 )</td>
<td>5.00m</td>
<td>6.20m</td>
<td>8.50m</td>
</tr>
<tr>
<td>40&lt; ( P_t \leq 50 )</td>
<td>6.20m</td>
<td>7.60m</td>
<td>10.50m</td>
</tr>
</tbody>
</table>

Table 5 compares the minimum required crosswalk widths with the existing ones at two signalized crosswalks. The crosswalk at the east leg of Imaike intersection is characterized by medium pedestrian demand. The existing width is 7.2m but the minimum required width according to the proposed methodology is 5.4m. The crosswalk installed at the east leg of Nishi-Osu intersection is characterized by very low pedestrian demand but due to the regulations in the Japanese manuals, the installed width is 4.0m. However, the minimum required width according to the proposed methodology is 2.0m.

Table 5. Comparison between existing crosswalk width and proposed one

<table>
<thead>
<tr>
<th>Crosswalk</th>
<th>Length ((m))</th>
<th>Pedestrian Demand</th>
<th>Directional split ratio ( r )</th>
<th>Age group</th>
<th>Existing width ((m))</th>
<th>Minimum width ((m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaike</td>
<td>21.5</td>
<td>25</td>
<td>0.5</td>
<td>Middle-age</td>
<td>7.2</td>
<td>5.4</td>
</tr>
<tr>
<td>Nishi-Osu</td>
<td>25.5</td>
<td>10</td>
<td>0.5</td>
<td>Middle-age</td>
<td>4.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Maximum observed pedestrian demand during the survey period at both sides of the crosswalk.

One of the other concerns about installing narrow crosswalks is visibility from drivers. According to the Japanese Manual on Road Marking (2004), the width of the stop line marking should not be less than 0.45m wide. This requirement is based on the ability of drivers to recognize narrow lines on the pavement under different weather conditions. The narrowest proposed crosswalk width from Tables 2 and 3 is 1.5m, which is about three times
wider than the required stop line width. Therefore, it can be concluded that the proposed narrow crosswalks are visible from drivers.

9. CONCLUSION AND FUTURE WORK

Through this study, the minimum required crosswalk width values for different pedestrian demand volumes and directional split ratios are proposed for implementation considering three pedestrian age groups (middle-age, pupil, and elderly). The proposed minimum crosswalk width values are estimated for crosswalks with bi-directional pedestrian flow. These values are based on rational and flexible methodology. If authorities want to provide higher level of service for pedestrians, they can increase the minimum crossing speed \( u_m \) and then re-estimate the minimum required crosswalk width. Increasing the minimum crossing speed \( u_m \) is the same as increasing the design speed of a pedestrian facility which will require the implementation of wider crosswalks to reduce the interactions between the opposing pedestrian flows, thereby resulting to higher pedestrian crossing speeds.

At low pedestrian demand, the proposed minimum crosswalk width is between 1.5\( m \) and 2.0\( m \), which is similar to the proposed values by the Manual on Uniform Traffic Control Devices (2003). In Japan, signalized crosswalks with low pedestrian demand are characterized by minimum width of 3.0\( m \). However the implementation of narrow crosswalks (1.5\( m \) to 2.0\( m \)) when pedestrian demand is expected to be low can improve the performance of signalized intersections by reducing the required all-red time which will reduce the cycle length.

The crossing time model \( T_c \) proposed by Alhajyaseen and Nakamura (2009) was improved. The interaction time definition was modified to consider the physical depth of the opposite pedestrian platoon. These modifications improved the performance of the crossing time model \( T_c \). This led to higher coefficient of correlation when modeling the adjusted drag coefficient \( C_{Dadj} \) \( (R^2 \) is 0.42, Alhajyaseen and Nakamura, 2009) and better validation results. The final formulation of crossing time \( T_c \) provides a rational quantification for the effects of crosswalks geometry and bi-directional pedestrian flow on walking speed and crossing time. The developed total crossing time model produces a better estimation of the necessary discharge and crossing times for a pedestrian platoon. Existing methodologies for the estimation of the minimum pedestrian green time interval underestimate the necessary time for large pedestrian platoons to cross a signalized intersection, which can cause a threat to pedestrian safety.

Due to unavailability of the required data for pupil and elderly pedestrian, some parameters could not be estimated and therefore, assumptions were made to define their values. Thus, more efforts should be put to collect and analyze the required data for pupil and elderly pedestrians.

So far the main focus of the study was only on crosswalk width. Yet, another important aspect of crosswalk configuration optimization is crosswalk position. Existing manuals do not provide rational specification 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, which is usually associated with larger corner radius leading to higher speeds of left turning vehicles. Furthermore, this type of crosswalk configuration causes longer delays and reduces the visibility of intersection users. Meanwhile the implementation of compact intersections through installing crosswalks at the corners of intersections will improve safety and mobility, which leads to better performance. Therefore, the effects of crosswalk position on intersection delay and capacity, and conflicts between pedestrians and turning vehicles need to be studied.
REFERENCES


