Quality of pedestrian flow and crosswalk width at signalized intersections

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A R T I C L E  I N F O

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A B S T R A C T

Among various pedestrian facilities, signalized crosswalks are the most complex and critical ones. Their geometry and configuration including width, position and angle directly affect the safety, cycle length and resulting delays for all users. Existing manuals do not provide clear and rational specifications for the required crosswalk width under different pedestrian demand combinations and properties. Furthermore, they do not consider the bi-directional flow effects on crossing speed and time when addressing pedestrian flow at signalized crosswalks. However, quantifying the effects of such interactions on the behavior of pedestrian flow is a prerequisite for improving the geometric design and configuration of signalized crosswalks. The objective of this paper is to develop a methodology for estimating the required crosswalk width at different pedestrian demand combinations and a pre-defined LOS. The developed methodology is based on theoretical modeling for total pedestrian platoon crossing time, which consists of discharge and crossing times. The developed models are utilized to generate the fundamental diagrams of pedestrian flow at signalized crosswalks. A comprehensive discussion about the effects of bi-directional flow and various pedestrian age groups on the characteristics of pedestrian flow and the capacity of signalized crosswalks is presented. It is found that the maximum reduction in the capacity of signalized crosswalks occurs at roughly equal pedestrian flows from both sides of the crosswalk. By utilizing existing LOS thresholds for pedestrian flow at signalized crosswalks, the required crosswalk widths for various pedestrian demand combinations are proposed for implementation.

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1. Introduction

Crosswalks are designated portions on a road, employed to assist pedestrians desiring to cross the street, and play a significant role in the mobility and safety performance of signalized intersections. Their characteristics 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 will cause longer delays and deteriorate the overall mobility levels of signalized intersections.

Crosswalk width 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 properties. 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 (1.8 m) exist at many intersections in the United States where pedestrian demand is expected to be very low. Considering these different situations, it is necessary to develop a rational methodology that can provide planners and designers with recommendations regarding required crosswalk width for various pedestrian demand volumes considering the bi-directional nature of pedestrian flow.

The objective of this paper is to quantify the effects of bi-directional flow and pedestrian flow composition on the quality of pedestrian flows at signalized crosswalks. Furthermore, it aims to estimate the required crosswalk width for various pedestrian demand combinations at a pre-defined LOS. The structure of this paper is as follows: after introduction and literature review, a previous developed methodology for modeling total crossing time is briefly described, followed by data collection and parameter estimation. Then, the fundamental diagrams of pedestrian flow are generated considering the effects of bi-directional flow and various pedestrian age groups. Comprehensive discussion about the effects of pupil and elderly pedestrian flows on the directional and total capacities of signalized crosswalks are presented. Existing LOS thresholds from the literature are utilized to define the required crosswalk width at various demand combinations.

2. Literature review

Manual on Uniform Traffic Control Devices [1] in the US recommends minimum crosswalk width of 6 ft (1.8 m). Meanwhile, the Japanese Manual on Road Marking [2] recommends 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 crosswalk widths at different pedestrian demand volumes are missing. To develop a methodology capable of estimating the required crosswalk width for different pedestrian demand volumes, the effects of bi-directional pedestrian flow and crosswalk geometry should carefully be investigated.

Few studies addressed the issue of bi-directional pedestrian flow and its impact on crossing time and speed 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 operating conditions at crosswalks are different. 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 HCM [3] provides a formula to estimate the total crossing time of pedestrian platoon at signalized crosswalks. In this formula, the time spent on the crosswalk itself is independent from the pedestrian demand, bi-directional effect and crosswalk width. Furthermore, the Pedestrian and Bicycle Concepts chapter of the HCM [3] presents the fundamental diagrams of uni-directional pedestrian flow at walkways, sidewalks and crosswalks. However, it is mentioned that for bi-directional pedestrian streams of roughly equal flow in each direction, a little reduction in the capacity occurs. This is referred to the separation in the walking path of the bi-directional flows, which will significantly reduce the interaction between them. Furthermore, the manual suggests that the maximum reduction in the capacity occurs at a directional split ratio of 0.9 versus 0.1.

The Manual on Uniform Traffic Control Devices [1] provides a procedure to estimate pedestrian crossing time (clearance interval) depending on average walking speed (4.0 ft/s) and crosswalk length, which is similar to the methodology proposed by HCM [3]. While the Japanese Manual of Traffic Signal Control [4] presents a formula similar to the one proposed by HCM [3], however the initial start-up lost time is included in the discharge time.

Lam, et al. [5] investigated the effect of bi-directional flow on walking speed under various pedestrian flow conditions at indoor walkways in Hong Kong. They found that the bi-directional flow ratios have significant impacts on both the at-capacity walking speeds and the maximum flow rates of the selected walkways. Moreover, Lee, et al. [6,7] applied the same methodology to develop a relationship between the effective capacity of subject pedestrian flow and directional split ratio at signalized crosswalks. They found that the maximum reduction in the crosswalk’s capacity is almost 15% and it occurs at a directional split ratio of 0.1 versus 0.9. However, the lowest reduction occurs at 0.5 directional split ratio, which is in accordance with their previous analysis on walkways and the HCM [3]. This is explained by that pedestrians at both sides of the crosswalks are dominant and formed as two uni-directional flows.

Teknomo [8] proposed a microscopic pedestrian simulation model, which can demonstrate the effect of bi-directional flow at signalized crosswalks. It was found that the maximum effects occur at a directional split ratio of 0.5 where the average speed of the bi-directional flow dropped up to one third compared to the uni-directional flow. This contradicts with what HCM [3] and Lee, et al. [6,7] proposed.

Alhajyaseen and Nakamura [9,10] developed a macroscopic methodology for modeling total pedestrian crossing time which was divided into two parts; discharge and crossing times. They provided a sophisticated approach for modeling discharge time through applying the analogy of shockwave theory. For modeling crossing time, the analogy of drag force theory was used. The developed models were validated by utilizing empirical data. Furthermore, they proposed a crossing speed criterion for designing crosswalk width [10]. However, it does not consider the pedestrian LOS to be achieved, which is dependent on the installed crosswalk width.

This paper is an extension of the previous work done by Alhajyaseen and Nakamura [9,10] and aims to use the developed models for generating the fundamental diagrams of pedestrian flow considering the bi-directional flow effects and various pedestrian age groups.

3. Modeling total crossing time

To better understand how the fundamental diagrams are generated, the methodology developed by authors [9,10] are briefly described in this chapter.

3.1. Methodology

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

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. Therefore, 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 dependent 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 its analogy is used for modeling pedestrian platoon crossing time $T_c$.

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 (Fig. 1). Start-up lost time $I$ is considered as a part of discharge time $T_d$. Pedestrian arrival rate $A_i$ 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 $6$ 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

![Fig. 1. Schematic formation of pedestrian rows at high demand.](image)
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 through Eq. (1).

\[ T_{d} = \frac{Q_{d}}{u_{o} - K_{j}} \left( \frac{-\delta A_{1}/w}{K_{j} - \delta A_{1}/w u_{o}} \right) (C - g) \]  

Where \( A_{1} \) is pedestrian arrival rate (ped/s), \( \delta \) is the lateral distance that a pedestrian can occupy along the crosswalk (m), \( w \) is crosswalk width (m), \( u_{o} \) is pedestrian free-flow speed at sidewalk (m/s), \( u_{o} \) is pedestrian free-flow speed at crosswalk (m/s), \( C \) is cycle length (s), \( g \) is pedestrian green interval (s), \( Q_{d} \) is maximum discharge rate (ped./row). By equating the two forces, and solving them for \( u_{f} \) of the subject pedestrian and \( u_{f} \) of the opposite pedestrian, the dimensionless 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 equal to the physical depth of the opposite pedestrian.

\[ u_{f} = \sqrt{\frac{u_{1}^{2} - C_{adj} P_{f} l_{i} (u_{1} + u_{2})^{2}}{w}} \]  

where \( C_{adj} \) is drag coefficient and \( l_{i} \) is the interaction distance between the opposing pedestrian flows, which is assumed to be equal to the physical depth of the opposite pedestrian flow. Eqs. (2) and (3) are final equations, which represent how walking speed and crossing time vary with the bi-directional flow effects and crosswalk geometry.

4. Parameter estimation

In order to estimate the required parameters, data was collected at various signalized crosswalks as summarized in Table 1. All of these sites are located in Nagoya City, Japan. A major assumption of the modeling methodology is that subject or opposite pedestrian flow consists mostly of the same age group. No consideration is taken regarding mixed pedestrian platoon situation. Three age groups are defined in this study; middle-age, elderly and pupils. The opposite pedestrian platoon is assumed as middle-age pedestrian platoon for all cases. Table 1 shows the utilized data to estimate each parameter and Table 2 presents the values for all parameters included in Eqs. (1) and (2).

Firstly, required parameters were estimated for crosswalks with subject flow of middle-age pedestrians, then parameters were estimated for crosswalks with pupil and elderly 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.

The lateral distance \( \delta \) is empirically estimated and modeled as a function of pedestrian demand per meter width of the crosswalk (Alhajyaseen and Nakamura [9,10]) as shown in Table 2. The value of adjusted drag coefficient \( C_{adj} \) 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 demands at both sides of the crosswalk and their directional split ratio. The empirical data was utilized to estimate \( C_{adj} \) (Table 1). Pedestrian demand in each cycle at each direction, average pedestrian

![Fig. 2. Applying drag force concept on bi-directional pedestrian flows at crosswalk.](image)
trajectory length, and average crossing time in the same cycle were extracted from the video tapes. Then by using Eq. (2), \( CD_{\text{adj}} \) was estimated and modeled in terms of directional split ratio \( r \) (Table 2) which is defined according to Eq. (4).

\[
f = \frac{P_1}{P_1 + P_2}.
\]

After estimating all required parameters, Eqs. (2) and (3) can be used to estimate crossing time and speed for any pedestrian platoon at specific crosswalk geometry.

5. Speed–flow relationship

In order to produce the fundamental diagrams, the density of the subject pedestrian platoon \( K_1 \) (ped/m²) is defined by Eq. (5).

\[
K_1 = \frac{P_1}{l_1 w}
\]

Where \( P_1 \) is the subject pedestrian demand (ped) and \( l_1 \) is the physical depth of the subject pedestrian platoon (m) which is defined by Eq. (6).

\[
l_1 = \frac{P_1 \delta_1}{W K_1}
\]

By substituting Eqs. (4)–(6) and the estimated parameters from Table 2 into Eq. (2), the flow–speed relationships for middle-age, pupil and elderly pedestrians are derived as shown in Figs. 3–5, respectively. As directional split ratio decreases the maximum subject pedestrian flow (capacity) decreases, meanwhile the speed at capacity increases. This is referred to the inability of minor pedestrian flow to maintain its speed, thus capacity occurs at higher speeds. In contrast, as directional split ratio increases the subject pedestrian flow becomes the dominant therefore its density can reach higher values than that of the minor flow which results in higher capacities and lower speeds at capacity. Furthermore, as the subject pedestrian flow increases because of increasing its density due to either decreasing crosswalk width or increasing subject pedestrian demand, the interactions increase causing reduction in the average walking speed. This tendency is reasonable if we assume that pedestrian cannot walk outside the crosswalk. Therefore, it is expected that the average walking speed will drop as the demand increases for a specific crosswalk width, until it reaches almost zero where no pedestrian can walk any more. However, in reality at high pedestrian demand if crosswalk width is not sufficient, pedestrians walk outside the borders of the crosswalk to avoid conflicts. Such phenomenon is not considered here, since it requires more complicated procedure to be rationally modeled.

6. Model applications

The developed methodology can be utilized for wide range of applications such as the evaluation of pedestrian flow at signalized intersections, assessing pedestrian signal timing and improving the geometric design of crosswalks.

6.1. Capacity of signalized crosswalks

Fig. 6 demonstrates the effect of bi-directional flow on the directional capacity and the total capacity of signalized crosswalks when the subject and opposite pedestrian flows consist of middle-age pedestrians. The maximum estimated reduction in capacity is 25% and it occurs at directional split ratio of 0.5, while the minimum reduction in capacity is 4% at directional split ratio of 0.1 versus 0.9 as shown in Fig. 6. This supports Teknomo’s [8] results while it contradicts with what HCM [3] and Lee, et al. [6,7] concluded that the minimum reduction in capacity occurs at 0.5 directional split ratio. This phenomenon is true at long walkways or sidewalks with minor interruptions to the pedestrian flow where the two bi-directional

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Age group</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_o )</td>
<td>Middle-age</td>
</tr>
<tr>
<td>( C_{\text{adj}} )</td>
<td>0.03077</td>
</tr>
<tr>
<td>( u_s )</td>
<td>0.147</td>
</tr>
<tr>
<td>( K_1 )</td>
<td>1.10</td>
</tr>
<tr>
<td>( Q_d )</td>
<td>0.45</td>
</tr>
<tr>
<td>( \delta )</td>
<td>2.5323 ( P/W )</td>
</tr>
</tbody>
</table>

\( u_o \): pedestrian free-flow speed at crosswalks (m/s), \( C_{\text{adj}} \): adjusted drag coefficient, \( u_s \): pedestrian free-flow speed at sidewalks (m/s), \( K_1 \): jam density (ped/row/m), \( Q_d \): Maximum discharge rate (ped/row/s), \( \delta \): lateral distance that a pedestrian can occupy a long crosswalk width (m).
flows are likely to separate their paths forming two uni-directional flows. However, this phenomenon may not occur if pedestrian flow is interrupted by cross flows from the sides, which is the most common situation at sidewalks. At signalized crosswalks due to the generally short length and the special operating conditions such as signal timing, pedestrians behave in some different way. Pedestrians wait along the whole width of the crosswalks at both sides, then when the pedestrian green is displayed, they start crossing. The two opposing flows merge without a separation into two uni-directional flows, which makes the maximum reduction in the crossing speed occurs at roughly equal bi-directional flows. Furthermore, the estimated maximum reduction in capacity (25%) is higher than the expected maximum reduction (15%) by HCM [3].

Fig. 7 presents an example of pedestrian trajectories for one of the busiest cycles at the east leg of Imaike intersection in Nagoya City, Japan. The analyzed pedestrians are those who were waiting at both sides of the crosswalk while the red light was being displayed. Total demand is 35 pedestrians. Red trajectories are for pedestrians from the right side (16 pedestrians) and blue ones are for those from the left side (19 pedestrians). Although pedestrian demand is not very high, it is clear that the two pedestrian flows tend to merge rather than separating their paths, which increases the interaction between them. This supports the previous conclusion that the interaction between the bi-directional flows and the reduction in total capacity increases as the directional split ratio approaches 0.5 where the maximum reduction occurs.

Fig. 8 illustrates the effect of various pedestrian age groups on the directional capacity of crosswalks. The capacity of signalized crosswalk with subject flows of pupil pedestrians is almost equal to that of middle-age pedestrians if directional split ratio is less than 0.5. This is referred to the ability of pupils to form more dense platoons than middle-age pedestrians, although their speed is lower. As directional split ratio increases the difference in capacity between pupil and middle-age subject pedestrian flows increases. At 0.9 directional split ratio, 6.6% reduction in capacity of crosswalks with pupil subject pedestrian flow occurs compared to that of middle-age pedestrians. This is in accordance with HCM (2000) which proposes a smaller uni-directional flow capacity for pupil pedestrians.

For better insight into the effects of various pedestrian age groups on the total capacity of signalized crosswalks, Table 3 is presented. When directional split ratio is 0.1, the total capacities of crosswalks with subject flow of middle-age and pupil pedestrians are almost the same. However if the subject flow is composed of elderly pedestrians, 9.2% reduction in capacity occurs. At directional split ratio of 0.9, a significant reduction in the total capacity by 29% is found when the subject flow consists of elderly pedestrians compared to that of middle-age pedestrians.

It is important to mention here that it is very difficult to observe capacity conditions due to the physical characteristics of crosswalks. At near capacity conditions, it was observed that pedestrians tend to walk outside of the crosswalk to avoid conflicts. Therefore, the objective of estimating crosswalk’s capacity here is to quantify the effects of bi-directional flow and pedestrian age groups on the characteristics of pedestrian flow.

6.2. Crosswalk width estimation

By utilizing the proposed crossing speed model (Eq. (2)), the required crosswalk width to achieve a specific pedestrian crossing...
speed by assuming pedestrian demand at both sides of the crosswalk can be estimated. The specific speed here refers to a defined LOS threshold. However, existing manuals and guidelines do not provide any LOS standards for pedestrian flow at signalized crosswalks considering the bi-directional effects.

Lee et al. [11] proposed a set of LOS standards for signalized crosswalks, which consider the bi-directional pedestrian flow effects. An interview survey technique on pedestrian stated preference was used to determine the respective congestion boundaries for each service level. They explicitly defined the LOS boundaries for different directional split ratios (0.1–1.0). The subjects are mainly middle-age pedestrians. By utilizing these LOS standards and the developed theoretical model in this paper, the required crosswalk widths at specific pedestrian demand combination and pre-defined LOS are estimated as shown in Table 4. At low pedestrian demand as shown in Table 4(a), the installation of 1.8 m crosswalks as recommended by Manual on Uniform Traffic Control Devices [1] will result in LOS D. While the implementation of 4 m crosswalks as recommended by the Japanese Manual on Road Marking [2] will result in LOS A, not only at low pedestrian demand but also at medium demand.

It is noted that the LOS standards should be different for various pedestrian age groups. However, such detailed LOS specifications are still missing.

7. Conclusions

The developed methodology for modeling total pedestrian crossing time by authors [9,10] was utilized to generate the speed–flow relationships for pedestrian flows at signalized crosswalks considering the effects of bi-directional flow and various pedestrian age groups.

These diagrams showed that the characteristics of pedestrian flow at signalized crosswalks are different from those at walkways or sidewalks. Several factors might contribute to these differences, such as the generally short length of crosswalks, the traffic signal operations and the impacts by motorized traffic.
Furthermore, it was found that the maximum reduction in the total capacity of signalized crosswalks (25%) occurs at a directional split ratio of 0.5 while the minimum reduction (4%) occurs at 0.1 versus 0.9 directional split ratio.

Moreover, it was concluded that the existence of a large portion of elderly pedestrians might lead to a significant reduction in the total capacity by 29% at directional split ratio of 0.9. Meanwhile in most cases, total capacity is slightly affected by pupil pedestrians.

Through this study, the required crosswalk widths for different pedestrian demand combinations at a pre-defined LOS are proposed for implementation. These widths are based on the LOS thresholds proposed by Lee, et al. [11] which are estimated for pedestrian flows that mainly consist of middle-age pedestrians. The proposed widths are based on rational and flexible methodology. If authorities want to provide higher level of service for pedestrians, they can increase the installed crosswalk width.

The focus of this study was only on crosswalk width, but another important aspect of crosswalk geometry and configuration is crosswalk position. In Japan, crosswalks are generally placed far from the corners of the intersection, which is associated with larger corner radius leading to higher speeds of left turning vehicles. Meanwhile in Europe and the US, signalized intersections are characterized by compact layout through installing crosswalks at the corners of intersections. To define the most proper layouts, the effects of crosswalk position on intersection delay and capacity, and conflicts between pedestrians and turning vehicles need to be studied.

References