Effects of Bi-directional Pedestrian Flow Characteristics upon the Capacity of Signalized Crosswalks

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Abstract

Existing manuals do not provide clear specifications regarding the required crosswalk width under various pedestrian demand combinations and properties. Furthermore, they don’t offer any quantification regarding the effects of bi-directional flow and pedestrian flow composition upon capacity. This paper analyzes the effects of pedestrian age group and the interaction between bi-directional pedestrian flows on the capacity of signalized crosswalks. Three pedestrian age groups are defined: middle-age, pupils and elderly. A previous developed methodology for modeling pedestrian flows at signalized crosswalks is utilized to generate the fundamental diagrams of pedestrian flow. It is found that the maximum reduction in capacity occurs at roughly equal pedestrian flows from both sides of the crosswalk. Further, it is concluded that elderly pedestrians might cause a significant reduction in capacity up to 30%.

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keywords: Crosswalk capacity, bi-directional flow, walking speed, pupils, elderly

1. Introduction

Among various pedestrian facilities, signalized crosswalks are considered as complex and critical ones. The operational efficiency and safety performance of vehicular traffic and pedestrian flows are very important concern at these facilities where different users have to share the same space. Their geometry and configuration including width, position and angle directly affects the safety, cycle length and resulting delays for all users. The position and width of these facilities 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. Furthermore, at high pedestrian demand levels, providing insufficient crosswalk width to accommodate the bi-directional pedestrian flows may push pedestrians to cross from outside of the crosswalk which may compromise safety.

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 upon crossing speed and time when addressing pedestrian flow at signalized crosswalks. Therefore, quantifying the
impacts of crosswalk geometry and the interaction between bi-directional pedestrian flows on the capacity of crosswalks is a prerequisite for providing rational guidelines regarding crosswalk width.

This paper aims at analyzing the effects of bi-directional pedestrian flow and its composition on the quality of pedestrian flow at signalized crosswalks and further on the capacity of these facilities. The structure of this paper is as follows: after introduction and literature review, a previous developed theoretical methodology for modeling total crossing time is briefly described. 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 is presented. Finally the paper ends up with conclusion and future works

2. Literature Review

Few studies addressed the issue of bi-directional pedestrian flow and its impact on crossing speed and 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 operating conditions at crosswalks are different from other pedestrian facilities. Table 1 presents several existing empirical fundamental relationships from previous studies. All these studies based on uni-directional flows and on facilities other than crosswalks.

Table 1 Pedestrian speed-flow relationships from various studies

<table>
<thead>
<tr>
<th>Source</th>
<th>Country</th>
<th>Pedestrian flow type</th>
<th>Facility</th>
<th>Speed-Density relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older [12]</td>
<td>Britain</td>
<td>Shoppers</td>
<td>Walkways (Indoor)</td>
<td>$v = 1.31 - 0.34k$</td>
</tr>
<tr>
<td>Navin and Wheeler [11]</td>
<td>USA</td>
<td>Students</td>
<td>Walkways (Outdoor)</td>
<td>$v = 2.13 - 0.79k$</td>
</tr>
<tr>
<td>Fruin [5]</td>
<td>USA</td>
<td>Commuters</td>
<td>Walkways (Outdoor)</td>
<td>$v = 1.43 - 0.35k$</td>
</tr>
<tr>
<td>Lam et al. [8]</td>
<td>China</td>
<td>Mixed</td>
<td>Walkways (Indoor)</td>
<td>$v = 1.29 - 0.36k$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Walkways (Outdoor)</td>
<td>$v = e^{-0.38-0.57k}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Crosswalks</td>
<td>$v = 1.47e^{-0.347k^2}$</td>
</tr>
<tr>
<td>Virkler and Elayadath</td>
<td>USA</td>
<td>Mixed</td>
<td>Walkways (Indoor)</td>
<td>$v = 1.01e^{-0.247k}$</td>
</tr>
<tr>
<td>[18]</td>
<td></td>
<td></td>
<td></td>
<td>$(k&lt;1.07)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$v = 0.61\ln(0.432/k)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$(k&gt;1.07)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Crosswalks</td>
<td>$v = 1.02 - 0.36k$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(One way)</td>
<td>$v = 1.2 - 0.217\ln(100k)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Two way)</td>
<td>$v = 1.46 - 0.35k$</td>
</tr>
<tr>
<td>Teknomo [16]</td>
<td>Japan</td>
<td>Mixed</td>
<td>Walkways (Indoor)</td>
<td>$v = 1.21 - 0.22k$</td>
</tr>
<tr>
<td>Sarkar and Janardhan</td>
<td>India</td>
<td>Mixed</td>
<td>Walkways (Indoor)</td>
<td>$v = 1.23 - 0.26k$</td>
</tr>
<tr>
<td>Tanaboriboon and</td>
<td>Thailand</td>
<td>Mixed</td>
<td>Walkways</td>
<td></td>
</tr>
<tr>
<td>Guyano [14]</td>
<td></td>
<td></td>
<td>(Indoor)</td>
<td></td>
</tr>
<tr>
<td>Tanaboriboon et al. [15]</td>
<td>Singapore</td>
<td>Mixed</td>
<td>Walkways (Indoor)</td>
<td>$v = 1.23 - 0.26k$</td>
</tr>
</tbody>
</table>

Note: $v$ is average speed (m/sec) and $k$ is density (ped/m²).
Existing 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 [17] provides a formula to estimate the total crossing time of pedestrian platoons 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 [17] presents the fundamental diagrams of pedestrian flows at walkways, sidewalks, and crosswalks. These fundamental diagrams are for uni-directional pedestrian flows only, and there is no consideration on the bi-directional flow effects. However, it is mentioned that for bi-directional 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 pedestrian 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. This reduction results from the inability of the minor flow to use a proportionate share of the walkway.

The Manual on Uniform Traffic Control Devices [4] provides a procedure to estimate pedestrian crossing time (clearance interval) depending on average walking speed (4.0ft/sec) and crosswalk length, which is similar to the methodology proposed by HCM [17]. However, this procedure does not consider the effect of bi-directional pedestrian flow. The Japanese Manual of Traffic Signal Control [6] presents a formula similar to the one proposed by HCM [17], however the initial start-up lost time is included in the discharge time.

Lam, et al. [7] investigated the effect of bi-directional flow on pedestrian walking speed under various 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. However, they did neither investigate the effect of different walkway’s dimensions on the walking speed, nor the capacity of the walkway.

Lee, et al. [9, 10] proposed a relationship between the effective capacity of subject pedestrian flow and directional split ratio at signalized intersections. They concluded 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 [17]. This is explained by that pedestrians at both sides of the crosswalks are dominant and formed as two uni-directional flows.

Teknomo [16] proposed a microscopic pedestrian simulation model as a tool to quantitatively evaluate the impacts of a proposed control policy before its implementation. The developed model was used to 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 [17] and Lee, et al. [9, 10] proposed.

Alhajyaseen, et al. [1, 2] 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. Discharge time was modeled by applying the shockwave theory on the accumulating pedestrians at the edge of the crosswalk. While crossing time was modeled by utilizing the analogy of aerodynamic drag force theory. The developed models provide rational quantification for the effects of crosswalk geometry and the interaction between bi-directional pedestrian flows on the pedestrian crossing speed. Furthermore, Alhajyaseen, et al. [3] proposed guidelines regarding the required crosswalk width for different pedestrian demand levels and properties based on developed fundamental diagrams and existing pedestrian Level of Service LOS thresholds from the literature. In their paper, they concentrated on the discussion of the required crosswalk width to achieve a specific LOS threshold without considering crosswalk capacity. Therefore, they did not emphasize the effects of bi-directional pedestrian flows and different age groups on the capacity of crosswalks.

This paper is an extension of the previous work done by Alhajyaseen and Nakamura [1, 2, 3] and aims to quantify the impacts of bi-directional flow and various pedestrian age groups on the capacity of crosswalks.

3. Bi-directional Pedestrian Flow

The total time needed by a platoon of pedestrians to cross a signalized crosswalk $T_t$ 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 $T_t$ 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. 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. Thus, this theory was chosen for modeling pedestrian platoon discharge time as well (Alhajyaseen and Nakamura [2]). At low pedestrian demand, pedestrian destination affects the queuing position of pedestrians at the edge of the crosswalk before the start of pedestrian signal green interval; however this impact becomes negligible as pedestrian demand increases. Crossing time $T_c$ is dependent on pedestrian crossing speed, which is affected by the size of the bi-directional pedestrian platoons and crosswalk width. According to Alhajyaseen and Nakamura [2], pedestrian walking speed can be significantly dropped depending on the size of the opposite platoon, crosswalk width and some other factors. The conflicts between pedestrians while crossing make them slow down or change their path which will increase their total crossing time and simultaneously reduce their travel speed. 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 $T_c$ (Alhajyaseen and Nakamura [1]).

In order to simplify the developed theoretical model without losing much of the accuracy, we assumed that all pedestrians on the same movement walk with an average speed for the whole crosswalk (Travel Speed). The developed methodology assumes three pedestrian age-groups; middle-age, pupils and elderly. The developed model is utilized to estimate the average speed of the subject pedestrian flow after the interaction with the opposite flow as shown in Equations (1), (2) and (3) for middle-age, pupil and elderly subject pedestrian flows respectively. The opposite pedestrian flow is assumed to consist mainly of middle age pedestrians. These equations show that the crossing speed of subject pedestrian platoon is function of crosswalk geometry, pedestrian demand at each side of the crosswalk and free-flow speed.

$$v_s^{Middle-age} = \sqrt{v_s^{FF}} - \frac{0.0706\left(\frac{v_s^{FF}}{P_s + P_o}\right)^{1.346} + v_s^{FF}}{w^{1.617}}$$

$$v_s^{Pupil} = \sqrt{v_s^{FF}} - \frac{0.0716\left(\frac{v_s^{FF}}{P_s + P_o}\right)^{1.346} + v_s^{FF}}{w^{1.549}}$$

$$v_s^{Elderly} = \sqrt{v_s^{FF}} - \frac{0.0883\left(\frac{v_s^{FF}}{P_s + P_o}\right)^{1.346} + v_s^{FF}}{w^{1.617}}$$

Where $v_s$ is the average speed of the subject pedestrian flow after the interaction with the opposite pedestrian flow (m/sec), $v_s^{FF}$ and $v_o^{FF}$ are the average subject and opposite free-flow speeds (m/sec) respectively, $P_s$ and $P_o$ are the subject and opposite pedestrian demands (ped.) respectively and $w$ is crosswalk width (m).

The free-flow speed was empirically observed for three different pedestrian age groups. Four sites in Nagoya city are videotaped. The characteristics of the observed sites are shown in Table 2. In data processing, leading
pedestrians who did not face any opposite pedestrian flow or turning vehicles were only considered. Figure 1 shows the free-flow speed cumulative probability distribution for the three pedestrian age groups.

To validate the proposed models, average crossing speed was measured under different directional demand ratios and compared with the estimated speeds from the proposed models. Figure 2 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 proposed methodology which is based on the concept of Drag Force theory, estimates the speed directly after the interaction with the opposite pedestrian 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 2 shows that for some data points the estimated speeds are higher than observed values. These points extracted from the data collected at Imaike intersection when pedestrian demand was low. If pedestrians walk slowly 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 estimated and observed values were not significantly different at 95% confidence level.
a) Speed–flow relationship for subject flow of middle-age pedestrians.

b) Speed–flow relationship for subject flow of pupil pedestrians.

c) Speed–flow relationship for subject flow of elderly pedestrians.

Figure 3 Fundamental Diagrams for the bi-directional pedestrian flows at signalized crosswalks

4. Speed-Flow Relationship

In order to estimate the fundamental diagrams, the density of the subject pedestrian platoon $k_s$ (ped/m²) is defined by Equation (4).

$$k_s = \frac{P_s}{l_s w}$$  \hspace{1cm} (4)

Where $P_s$ is the subject pedestrian demand (ped), $l_s$ is the physical depth of the subject pedestrian platoon (m) and $w$ is crosswalk width (m). By utilizing Equations 1, 2, 3 and the observed free-flow speeds, the flow–speed relationships for the subject pedestrian flow can be derived as shown in Figure 3. Crosswalk capacity is defined as the maximum possible pedestrian outflow per meter width of the crosswalk (ped/m/sec).

In order to consider the relative demand between the subject and opposite pedestrian flows, the term directional split ratio $r$ is introduced. It is defined as the ratio of subject pedestrian demand to total pedestrian demand at both sides of the crosswalk. As directional split ratio decreases the maximum subject pedestrian flow (capacity) decreases,
meanwhile the speed at capacity increases (Figure 3). 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 pedestrians 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, it requires more complicated procedure to be rationally modeled.

Figure 3b shows that the speed at capacity for subject pedestrian flow of pupils is lower than that of middle-age pedestrians. At the same time, the density of pupil pedestrian platoon is higher than that of middle-age pedestrians, which results in close capacity values. Furthermore, the capacity and speed at capacity for subject pedestrian flow of elderly are always lower than that of middle-age and pupil pedestrians as shown in Figure 3c.

5. Effect of Pedestrian Age-Group on the Capacity of Signalized Crosswalks

Figure 4 demonstrates the effect of bi-directional flow on the directional and total capacities of signalized crosswalks when the subject and opposite pedestrian flows consist of middle-age pedestrians. As directional split ratio increases the maximum subject flow (capacity) also increases. The maximum estimated reduction in the capacity is 25.3% and it occurs at directional split ratio of 0.5, while the minimum reduction in the capacity is 3.8% at directional split ratio of 0.1 versus 0.9 as shown in Figure 4. This is in accordance with Teknomo’s [16] results. HCM [17] suggested that the minimum reduction in the 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 flows are likely to separate their paths forming two uni-directional flows because of the long walking distance. 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 relatively 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
The crossing speed occurs at roughly equal bi-directional flows. Furthermore, the estimated maximum reduction in the capacity (25.3%) is higher than the expected maximum reduction (15%) by HCM [17].

Figures 5 and 6 illustrate the effects of pedestrian age group on the directional and total capacities of signalized crosswalks, respectively. When directional split ratio is 0.9, a 27.6% reduction in the capacity is found when the subject flow is composed of elderly pedestrians compared to that of middle-age pedestrians. However, the capacity of a signalized crosswalk with subject flow 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 ability of pupils to form more dense platoons than middle-age pedestrians. As directional split ratio increases the difference in capacities between pupil and middle-age subject pedestrian flows increases. At 0.9 directional split ratio, 6% reduction in the capacity of crosswalks with pupil subject pedestrian flow occurs compared to that of middle-age pedestrians. This is in accordance with HCM [17] which proposes a smaller uni-directional flow capacity of pupil pedestrians.
Table 3 Reduction in the total capacity of signalized crosswalks due to various pedestrian age-groups

<table>
<thead>
<tr>
<th>Subject Pedestrian Flow</th>
<th>Directional Split Ratio</th>
<th>Bi-directional</th>
<th>Uni-directional</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Capacity ped/m/sec</td>
<td>% * Reduction</td>
<td>Capacity ped/m/sec</td>
</tr>
<tr>
<td>Middle-age</td>
<td>1.52</td>
<td>-</td>
<td>1.18</td>
</tr>
<tr>
<td>Pupil</td>
<td>1.50</td>
<td>0.01</td>
<td>1.16</td>
</tr>
<tr>
<td>Elderly</td>
<td>1.38</td>
<td>9.21</td>
<td>0.98</td>
</tr>
</tbody>
</table>

* The reduction in crosswalk’s total capacity compared to the capacity at the same directional split ratio when subject pedestrian flow is middle-age.

Figure 6 shows the effect of pedestrian age group on the total capacity of signalized crosswalks assuming that the opposite flow consists of middle-age pedestrians. It is clear that the curve of middle-age pedestrians is symmetrical, since the subject and opposite flows consist from the same age-group. For pupil and elderly pedestrians, the curve is not symmetrical. If directional split ratio is very small, this means that the subject pedestrian flow (pupil or elderly) is the minor flow, meanwhile the opposite pedestrian flow (middle-age) is the major flow. As directional split ratio increases the effect of pupil or elderly pedestrians increases, which will cause more reduction in the total capacity of the crosswalk. Therefore, at high directional split ratios, the total crosswalk’s capacity is lower than the total capacity at small directional split ratios, since the pupil or elderly pedestrian flow becomes the major flow which results in bigger reduction in the total capacity.

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 for crosswalks with subject flow of middle-age or pupil pedestrians are almost the same. However if the subject flow is elderly pedestrians, 9.21% reduction in the capacity occurs. At directional split ratio of 0.9, 6.58% reduction in the total capacity is estimated when subject flow consists of pupils compared to that of middle-age pedestrians, while 28.95% reduction in the total capacity occurs if subject flow consists of elderly 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. So in reality, crosswalks function ideally (pedestrians walk inside crosswalk borders) until a point near capacity, where pedestrian speed start to be significantly affected. At that time pedestrians start to walk outside the crosswalk to avoid conflicts and to maintain their speed.

6. Conclusions

The developed theoretical methodology for modeling pedestrian crossing time by Alhajyaseen and Nakamura [1, 2, 3] was utilized to analyze the characteristics of pedestrian flows at signalized crosswalks and to generate the fundamental diagrams considering the bi-directional flow effects and crosswalk geometry. The impacts of pedestrian flow characteristics and crosswalk geometry upon the capacity are analyzed.

It is concluded that the interactions between opposing pedestrian flows affect significantly the behavior of pedestrians at crosswalks and thus the resulting speeds. The fundamental diagrams of pedestrian flow are generated and presented for three pedestrian age groups (Middle-age, pupil and elderly). By utilizing these diagrams, the capacities of signalized crosswalks considering various directional split ratios and pedestrian age groups are estimated and compared. 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. The estimated maximum reduction in the capacity is higher than the expected maximum reduction (15%) by HCM [17]. Furthermore, It was found that the existence of high proportion of elderly pedestrians may cause severe reduction in the average crossing speed and the capacity of signalized crosswalks, while the effect of pupil pedestrians seems to be very limited. Therefore, it is recommended to consider providing wider crosswalks at the
intersection with high demand of elderly pedestrians in order to reduce the bi-directional flow effects upon their speed.

Empirical studies on analyzing pedestrian behavior at high demand levels and their constraint to the physical limitations of crosswalks is very necessary to assist the rationality of the proposed fundamental diagrams.

References


