Effects of Bi-directional Flow and Different Pedestrian Age-Groups on Capacity of Signalized Crosswalks*

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1. Introduction

Among various pedestrian facilities, signalized crosswalk is the most complex and critical one. Their geometry and configuration directly affect the safety, cycle length and resulting delays for all users. Understanding the behavior of pedestrian flow including the effects of bi-directional flow and crosswalk geometry on pedestrian crossing speed and time is a prerequisite for improving the geometric design and configuration of signalized crosswalks. In all the existing manuals and guidelines, pedestrian crossing speed is assumed as constant value no matter what the pedestrian demand is. In reality however, when pedestrian demand increases at both sides of the crosswalk, crossing speed decreases due to interaction between conflicting pedestrian flows.

Several methodologies have been developed to measure the effects of bi-directional pedestrian flow on the performance of pedestrian flow at walkways and sidewalks. However, few of them were calibrated and modified to reflect the special characteristics and operating conditions of signalized crosswalks.

This study aims to evaluate the effect of bi-directional flow on the capacity of signalized crosswalks. Furthermore, this study measures the possible effects of pupil and elderly pedestrians upon capacity of signalized crosswalks. A methodology developed by authors (2008[1]; 2009[2]) is utilized to generate the fundamental diagrams that represent the relationship between speed, flow and density of pedestrian flow at signalized crosswalks. These diagrams are used to estimate capacity of signalized crosswalks for various directional split ratios and pedestrian age-groups.

2. Literature Review

Few studies addressed the issue of bi-directional flow and its impact on crossing speed at signalized crosswalks. Most of the existing works in this respect attempted to investigate the impact of bi-directional flow at other pedestrian facilities such as walkways and sidewalks. However the characteristics of the environment as well as the pedestrian arrival pattern at crosswalks is different from other pedestrian facilities.

The Pedestrian and Bicycle Concepts chapter of the *Highway Capacity Manual* (2000)[3] presents the fundamental diagrams of pedestrian flow at walkways, sidewalks and crosswalks. These fundamental diagrams are for uni-directional pedestrian flow only, and there is no consideration on the bi-directional flow effects. 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 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.

Lam et al. (2003)[4] investigated the effects of bi-directional flow on walking speed and pedestrian flow under various flow conditions at indoor walkways in Hong Kong. They found that the maximum reduction in capacity is around 19% and it happens when directional split ratio is 0.9 versus 0.1 which is similar to what is proposed by *HCM* (2000)[3]. However, they did not investigate the effect of different walkway's dimensions on the walking speed and the capacity of the walkway.

Lee, et al. (2005[5]; 2008[6]) proposed a relationship between effective capacity of the 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 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* (2000)[3]. This is explained by that pedestrians at both sides of the crosswalks are dominant and formed as two uni-directional flows.

Teknomo (2006)[7] proposed a microscopic pedestrian simulation model as a tool to quantitatively evaluate impacts of a proposed control policy before its implementation. The developed model was used to demonstrate the effect of bi-directional flow. 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* (2000)[3] and *Lee, et al.* (2005[5]; 2008[6]) proposed.

Virkler, et al. (1984)[8] collected data from some relatively low-volume and high-volume signalized crosswalks and recommended an equation for uni-directional flow that also considers platoon size. However, they did not consider the impact of bi-directional pedestrian flow.

Golani, et al. (2007)[9] proposed a model to estimate crossing time considering start-up lost time, average walking speed, and pedestrian headways which are assumed to be a function of the sizes of the dominant and the opposite pedestrian platoons separately. The proposed model is based on *HCM* (2000)[3] model and was calibrated by using empirical data. The proposed model relates the impact of bi-directional flow to the headway between pedestrians when they finish crossing. So it is very hard to see how the interaction occurs and

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Table 1: Summary of surveyed sites characteristics

	Intersection name	Crosswalk position	Dimensions $w(m) \times L_o(m)$	Survey hours	Pedestrian demand	Pedestrian age-group	Application purpose
Site 1	Nishi-Osu	East leg	$4.0m \times 25.4m$	09:00-10:30	Low	Middle-age	u_o, δ , C_{Dadj}
Site 2	Imaike	East leg	$7.2m \times 21.5m$	13:00-15:00	Medium	Middle-age	u_o, δ, C_{Dadj}
Site 3	Sasashima	East leg West leg	$8.0m \times 19.0m$ $10m \times 31.3m$	07:00-09:30 07:00-09:30	High	Middle-age	K_j, Q_d, δ
Site 4	Mizuho-Kuyakusho	North leg East leg	$6.0m \times 21.5m$ $6.0m \times 9.5m$	07:00-09:30 07:00-09:30	High	Pupil	u_o, K_j, Q_d ,δ, C_{Dadj}
Site 5	N/A*	Midblock	$4.0m \times 15.0m$	08:30-10:00	Medium	Elderly	u_o, C_{Dadj}

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

Table 2: Estimated and calibrated parameters

Parameter	Age group		
	Middle age	Pupils	Elderly
u_o	1.45	1.36	1.20
C_{Dadj}	$0.0307r^{1.346}$	$0.0362r^{1.346}$	$0.0384r^{1.346}$
K_j	1.10	1.29	1.10
δ	$2.5323(P/w)^{-0.383}$	$2.5486(P/w)^{-0.4513}$	$2.5323(P/w)^{-0.383}$

Caption: u_o: average pedestrian free-flow speed at crosswalks (*m/sec*), C_{Dadj}: adjusted drag coefficient, K_j: jam density (*ped.row/m*), P: pedestrian demand (*ped*), w: crosswalk width (*m*) and δ: lateral distance that a pedestrian can occupy while waiting at the edge of the crosswalk (*m*).

what the resulting speed drop is.

3. Methodology

The model proposed by authors (2008[1]; 2009[2]) is utilized to formulate the fundamental diagrams of pedestrian flow. The proposed model (Equation (1)) is based on drag force theory and it provides rational quantification of the effects of crosswalk geometry and bi-directional pedestrian flow on walking speed.

$$u_f = \sqrt{u_1^2 - \frac{C_{Dadj} P_2 l_i (u_1 + u_2)^2}{w}} \quad (1)$$

Where u_f is the final speed of the subject pedestrian flow, w is crosswalk width (m), P_2 is the opposite pedestrian demand (*ped*), C_{Dadj} is the adjusted drag coefficient (dimensionless), l_i is the interaction distance (m), u_1 and u_2 are the average free-flow speeds of the subject and the opposite pedestrian flows (*m/sec*), respectively.

The interaction distance l_i is assumed to be equal to the physical depth of the opposite pedestrian platoon l_2 which is defined by Equation (2).

$$l_i = l_2 = \frac{P_2 \delta_2}{w K_{j2}} \quad (2)$$

Where δ_2 is the lateral distance that a pedestrian can occupy along the crosswalk (m) and K_{j2} is jam density (*ped.row/m*) of the opposite pedestrian platoon. The lateral distance δ is modeled as a function of pedestrian demand per meter width of the crosswalk.

The value of the adjusted drag coefficient C_{Dadj} is assumed to be dependent on total pedestrian demand and their directional split ratio r, which is defined as the ratio of subject pedestrian demand to total pedestrian demand as shown in Equation (3).

$$r = \frac{P_1}{P_1 + P_2} \quad (3)$$

4. Data Collection and Parameter Estimation

In order to estimate the required parameters and to 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 shows the utilized data to estimate each parameter and **Table 2** presents the estimated and calibrated values for all parameters included in Equation (1). For elderly pedestrians, since data at different demand volumes was not available, it was assumed that their jam density K_j and estimated lateral distance δ are equal to that of middle-age pedestrians.

Authors (2008[1]; 2009[2]) validated the proposed model in the uncongested condition by using empirical data. However, it was not validated in the congested or at capacity conditions, which in reality are very difficult to be observed at signalized crosswalks.

5. Fundamental Diagrams

In order to estimate the fundamental diagrams, it was assumed that the opposing pedestrian flow consists of middle age pedestrians only. Meanwhile the resulted fundamental diagrams will be different if the opposite flow is pupil or elderly pedestrians.

The assumed initial speeds of the subject and opposite pedestrian flows are constant values. Therefore, the proposed model cannot estimate the fundamental diagrams of the uni-directional pedestrian flow.

It is assumed that the density of the subject pedestrian platoon K_1 is estimated by Equation (4).

$$K_1 = \frac{P_1}{l_1 w} \quad (4)$$

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 Equation (5).

$$l_1 = \frac{P_1 \delta_1}{w K_{j1}} \quad (5)$$

By substituting equations (2), (3), (4), (5) and the estimated parameters from **Table 2** in Equation (1), the flow-speed relationships for middle-age, pupil and elderly pedestrians are derived as shown in Equations (6), (7) and (8), respectively.

$$q_1 = (0.491 r^{0.064} (1-r)^{-0.383} u_{f1}) / (u_1^2 - u_{f1}^2)^{-0.236} \quad (6)$$

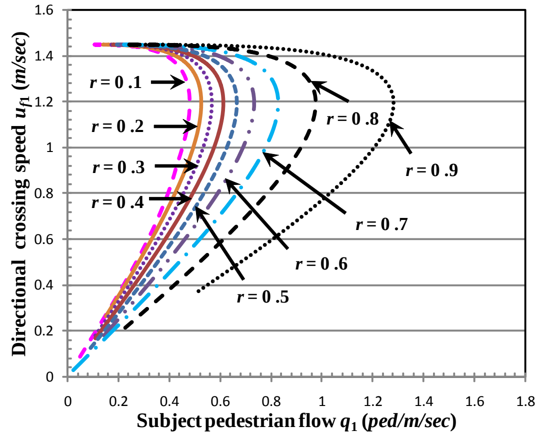

Figure 1: Speed-flow relationship for middle-age pedestrians

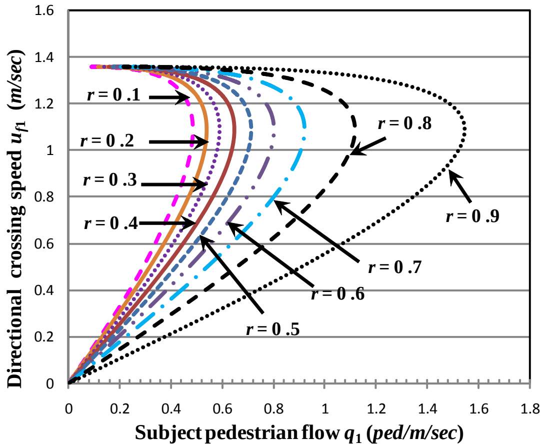

Figure 2: Speed-flow relationship for pupils

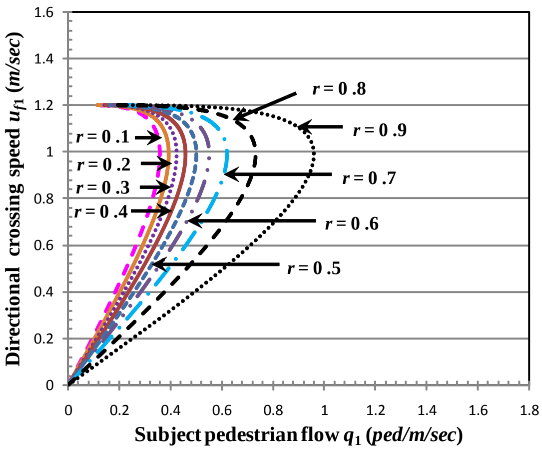

Figure 3: Speed-flow relationship for elderly

$$q_1 = (0.569r^{0.075}(1-r)^{-0.451}u_{f1})/(u_1^2 - u_{f1}^2)^{-0.279} \quad (7)$$

$$q_1 = (0.486r^{0.064}(1-r)^{-0.383}u_{f1})/(u_1^2 - u_{f1}^2)^{-0.236} \quad (8)$$

Where q_1 is the subject pedestrian flow (*ped/m/sec*), u_{f1} is the final speed of the subject pedestrian flow (*m/sec*) and u_1 is the average free-flow speed of the subject pedestrian flow (*m/sec*).

Figures 1, **2** and **3** represent the speed-flow relationship for the subject flow of middle-age, pupil and elderly pedestrians respectively. As directional split ratio increases the maximum subject flow (capacity) also increases. Furthermore, when directional split ratio is 0.9,

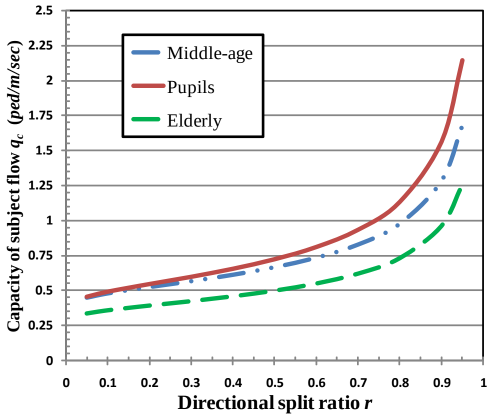

Figure 4: Directional capacity for different age-groups

a 25% 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 pedestrian is higher than that of middle age pedestrians. This is referred to ability of pupils to form more dense platoons than middle-age pedestrians. However *HCM* (2000)[3] proposes a smaller uni-directional flow capacity of pupil pedestrians. Furthermore, the speed at capacity for middle age subject pedestrian flow is always higher than that of pupil and elderly pedestrians.

6. Capacity Function of Signalized Crosswalks

By assuming that the derivative of subject pedestrian flow $q_1$with respect to its speed u_{f1} is equal to zero, then we can estimate the function of speed at capacity. By substituting it in the flow-speed relationship, the capacity functions for middle-age, pupil and elderly pedestrians are shown in Equations (10), (11) and (12) respectively.

$$q_c = 0.535r^{0.064}(1-r)^{-0.383} \quad (10)$$

$$q_c = 0.556r^{0.075}(1-r)^{-0.4513} \quad (11)$$

$$q_c = 0.401r^{0.064}(1-r)^{-0.383} \quad (12)$$

Figures 4 shows the drop in the capacity of the subject pedestrian flow with reducing the directional split ratio. At 0.1 directional split ratio, the capacities of subject flow of pupil and middle-age pedestrians are almost the same. However, the difference between them increases as directional split ratio increases. At directional split ratio of 0.9, the capacity of subject flow of pupil pedestrians is 20% higher than that of middle-age pedestrians.

Figure 5 shows the change in the total capacity of the crosswalk with directional split ratio. The maximum reduction in the capacity occurs at a directional split ratio of 0.5. When the subject flow is composed of middle-age pedestrians and the directional split ratio is 0.5, it results in a 37% reduction in the total capacity. This contradicts with what *HCM* (2000)[3] and *Lee, et al.* (2005[5]; 2008[6]) concluded. They suggest 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. However, this

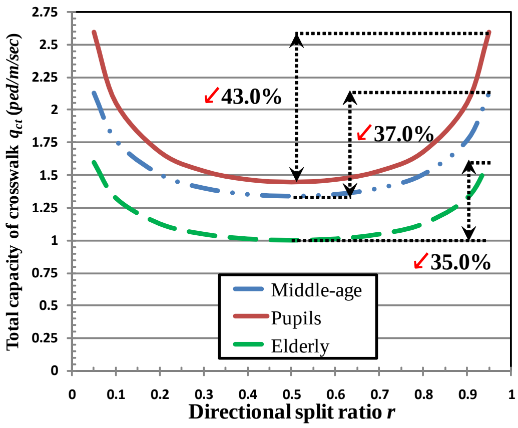

Figure 5: Total capacity for different age-groups

phenomenon does 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. Therefore, the maximum interaction and reduction in the speed occurs at a directional spilt ratio of 0.5.

Figure 6 presents an example of pedestrian trajectories for one of the busiest cycles at the east-leg of Imaike intersection (7.2*m* wide × 21.5*m* long) in Nagoya City. The analyzed pedestrians are those who were waiting at both sides of the crosswalk while the red light was being displayed. Total demand is 22 pedestrians with directional split ratio of 0.5. Red trajectories are for pedestrians from the right side and blue ones are for those from the left side. 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 the total capacity increases as the directional split ratio approaches 0.5 where the maximum reduction occurs.

7. Conclusions and Future Works

In this paper, the methodology proposed by authors to model the speed reduction due to the bi-directional flow effect is utilized to estimate the capacity of signalized crosswalks for various directional split ratios and pedestrian age-groups.

Signalized crosswalks are pedestrian facilities with unique characteristics. Their relatively short length, the existence of signal timing and motorized traffic significantly affect the characteristics of pedestrian flow. Therefore, this should carefully be considered when addressing pedestrian flow at these facilities.

It was found that the maximum reduction in the total capacity of signalized crosswalks occurs at a directional split ratio of 0.5 with an average value of 37% when the subject flow consists of middle-age pedestrians. Meanwhile the minimum reduction occurs at 0.1 or 0.9 directional split ratio with an average value of 11% when

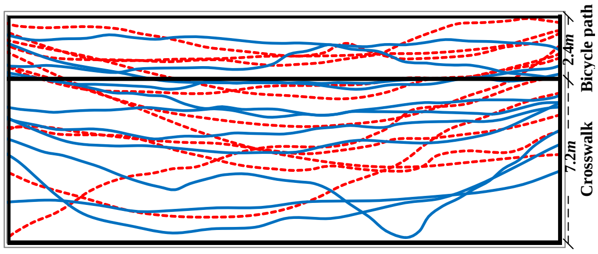

Figure 6: Observed pedestrian trajectories at 0.5 directional split ratio (Imaike Intersection, East-leg)

subject flow is middle-age pedestrians.

Furthermore, it was found that the total capacity when subject flow is pupil pedestrians is higher than that of middle-age pedestrians. However, the total capacity when subject flow is elderly pedestrians is always lower than that of middle-age pedestrians.

The assumed initial speeds of the subject and opposite pedestrian flows (u_1 and u_2) are constant values. However, when the density of pedestrian platoon increases, the initial speed decreases. This may leave a significant effect on performance of the proposed model and the resulted capacities.

The proposed methodology was validated under the uncongested conditions only. Therefore, a validation at capacity and congested conditions is preferred.

So far the main focus of the study was only on crosswalk width. Yet, another important aspect for crosswalk configuration optimization is crosswalk position. The effects of crosswalk position on intersection delay and capacity, and conflicts between pedestrians and turning vehicles need to be studied.

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