Modeling the Effects of Rainfall Intensity on Pedestrian Speed-Flow Relationships

Chao Yang SHI [a,b], Mei Lam TAM [b], William H.K. LAM [b] and Qingquan LI [c,a]

[a] *State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, China*

Email: chaoyangshi@whu.edu.cn

[b] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China*

Email: trptam@polyu.edu.hk; william.lam@polyu.edu.hk

[c] *Shenzhen Key Laboratory of Spatial Smart Sensing and Services, Shenzhen University, China*

Email: qqli@whu.edu.cn

ABSTRACT

Walking behavior in rainy conditions is very different from that without rain. This paper aims to study the effects of rainfall intensity on pedestrian walking behavior at signalized crosswalks. In the paper, fundamental diagrams such as speed-flow relationships are calibrated in various rainy conditions. The impacts of rainfall intensity on the reduction of walking speed are empirically investigated. Controlled experiments are conducted to collect pedestrian data such as walking speed, flow, bi-directional flow ratio in both no-rain and rain conditions. A generalized pedestrian speed-flow function is proposed and calibrated, taking into account the effects of varied rainfall intensity. The generalized speed-flow function is useful for evaluating the performance of pedestrian facilities, particularly in Hong Kong and other Asian cites with relatively high annual rainfall intensity. The findings could provide better insights into the effects of rainfall intensity on pedestrian walking behavior for assisting engineers/planners in improving the design and operation of pedestrian facilities.

Keywords: Pedestrians; fundamental diagrams; pedestrian speed-flow relationships; rainfall intensity

1. INTRODUCTION

In densely populated urban areas of Hong Kong, walking is a common mode of transport for providing connections between trip origins/destinations and public transport stations. It is also promoted as a sustainable mode of transport for its environmental friendliness and flexibility. A study conducted by the Hong Kong Transport Department in 2010 shows that the peak-hour pedestrian flow for a walkway in Causeway Bay of Hong Kong reaches 18,000 pedestrians/hour (Transport Department, HKSAR, 2010). To provide a safer and more efficient walking environment for such high pedestrian flow demand, the Hong Kong Transport Department has implemented various types of pedestrian schemes (e.g. pedestrian-only streets and traffic calming streets) in different areas since 2000.

As the majority of these pedestrian schemes/facilities are in open or semi-open areas, the travel behavior (e.g. walking speed and route choice) of pedestrians would be directly influenced by weather conditions. In turn, the level of service (LOS) of pedestrian facilities would be significantly affected, particularly in rainy days or under adverse weather conditions. Thus, there is a need to design efficient walking facilities with consideration of the impacts of weather conditions. In particular, crosswalks are essential facilities for both pedestrians and drivers. A better understanding of pedestrian walking characteristics at crosswalks is useful for design of intersections.

In the last decade, many studies have examined pedestrian flow characteristics and/or speed-flow relationships for walkways or signalized crosswalks (e.g. Lam and Cheung, 2000; Lam et al., 2002, 2003; Wong et al., 2010; Xie et al., 2013). For examples, Lam and Cheung (2000) calibrated the speed-flow relationships for various pedestrian facilities (e.g. walkway, signalized crosswalk) in Hong Kong based on the macroscopic flow data collected from field surveys. A generalized speed-flow relationship was calibrated by Lam et al. (2003) for the bi-directional pedestrian flow at indoor walkway in Hong Kong. They found that bi-directional flow ratio has a significant impact on the at-capacity walking speed and the maximum flow rate of the walkways in Hong Kong. Wong et al. (2010) and Xie et al. (2013) studied the bi-directional pedestrian streams with oblique intersecting angles.

The impacts of adverse weather conditions on vehicular traffic have been investigated in some previous studies (e.g. Camacho et al., 2010; Lam et al., 2013; Li et al., 2016; Prevedouros and Chang, 2005; Tam et al., 2007). However, few of the studies focused on the effects of rainfall intensity on pedestrian traffic. Walking behavior at signalized crosswalks in rainy conditions can be quite different from that in normal conditions without rain or from road traffic. Chang et al. (2011) found that the average walking speed in no-rain condition (1.22 m/s) was significantly higher than that in rainy conditions (0.85 m/s) through a field survey. Nevertheless, the studies for modeling pedestrian walking behavior in rainy or adverse weather conditions remained limited.

To fill this gap, this paper aims to study the effects of rainfall intensity on pedestrian walking behavior. In the paper, fundamental diagrams such as speed-flow relationships are calibrated in various rainfall conditions. The impacts of rainfall intensity on the reduction of walking speeds are empirically investigated. Controlled experiments were conducted to collect the relevant pedestrian data such as walking speed, pedestrian flow, and bi-directional flow ratio in different rainy conditions. Generalized pedestrian speed-flow function is proposed and calibrated, taking into account the effects of varied rainfall intensity. The generalized speed-flow function is useful for evaluating the performance of pedestrian facilities, particularly in Hong Kong and other Asian cites with relatively high annual rainfall intensity.

The remainder of this paper is organized as follows. Data collection in the controlled experiments and extraction method are described in next section. Section 3 calibrates the pedestrian speed-flow relationships in various rainy conditions. The calibration results of the impacts of rainfall intensity on the average walking speed are discussed. Finally, the conclusions and future study are given.

2. DATA COLLECTION AND EXTRACTION

Controlled experiments were conducted in the Road Research Laboratory of the Hong Kong Polytechnic University in three separate days in 2016. The Laboratory is located on an off-street that provides an outdoor environment for experiments. A sprinkler system was set up at the experimental site to imitate real rainy conditions. The purpose of the controlled experiments is to measure the walking characteristics of pedestrians, e.g. speed, flow and flow ratio, under different rainfall intensity. More than 120 participants were recruited for these three controlled experiments. Participants wearing red or green windbreaker (with/without umbrella) were asked to walk in designated directions, either Stream A (in green color) or B (in red color), to model the bi-directional pedestrian stream under the controlled environments, as the site photo shown in Figure 1. Video cameras were installed to capture the movements of pedestrians crossing the measurement section.

As shown in Figure 1, there were two pedestrian streams A and B having opposite directions at the designed crosswalk. The video cameras were used to record the entry and exit times that pedestrians cross the pre-determined measurement section of the crosswalk. The difference of these two time records is the walking time. The walking speed (m/min) is then equal to the ratio of walking time and the length of the measurement section.

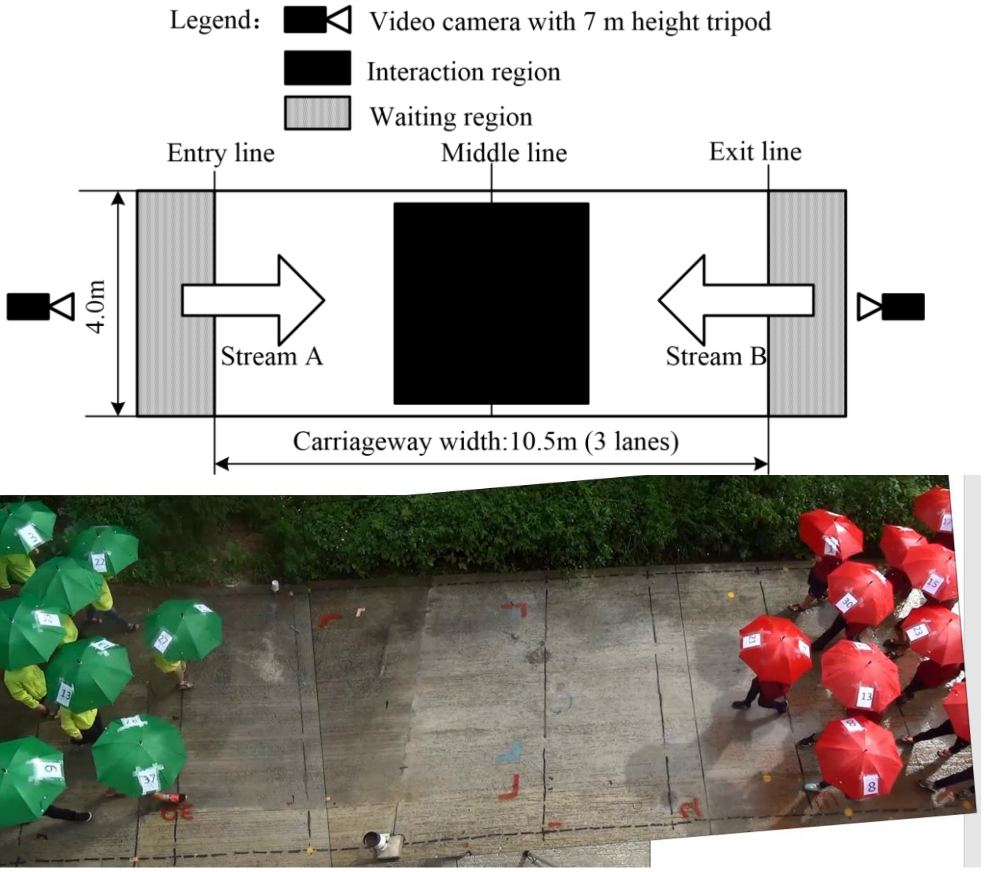


Figure 1. Schematic diagram of the designed crosswalk and snapshot of the experiment

To extract the pedestrian flow profiles at the crosswalks, the time of each pedestrian crossing the middle line of measurement section was recorded. This was achieved with the aid of a computer program, which was developed to complement the data extraction process. The pedestrians of streams A and B passing middle line were counted, respectively. Here, 1 second is divided into 30 frames. The one-way pedestrian flows v_A and v_B (pedestrian/min/m) are equal to the total number of pedestrians passing the middle line in unit time and unit width for streams A and B, respectively. The pedestrian flow for the Nth second is the sum of pedestrian flow from (N-14)th to (N+15)th frame as Figure 2 shown (Lee, 2010).

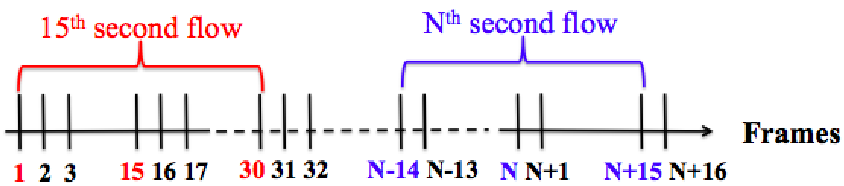


Figure 2. Measurement of pedestrian flow

The bi-directional flow ratio (r) is the proportion of one-way pedestrian flow out of the total two-way pedestrian flow. The one-way flow is the number of pedestrians passing through the middle line of a walking facility per meter width per second in one direction. It is necessary to define the major and minor flow directions of the pedestrian flow. The major flow direction would be the one where the flow ratio is greater than or equal to 0.5. Correspondingly, the direction is referred to be the minor flow direction when the flow ratio (r) of that direction is less than 0.5. It should be noted that the effects of pedestrian flow in either direction of the crosswalk should be similar when the crosswalk is flat with no gradient change.

When the volume of pedestrian flow in both directions of the crosswalk is known, the flow ratio (r) of each flow direction can be defined as follows:

$$r = \frac{v_A}{v_A + v_B} \geq 0.5; \quad \text{for major flow direction} \tag{1}$$

$$r = \frac{v_B}{v_A + v_B} < 0.5; \quad \text{for minor flow direction} \tag{2}$$

where v_A and v_B are the major and minor flows on the crosswalk, respectively.

3. CALIBRATION OF PEDESTRIAN SPEED-FLOW RELATIONSHIP UNDER VARIED RAINFALL INTENSITY

3.1 Observed and Fitted Relationships of Walking Speed, Pedestrian Flow and Flow Ratio

Lam et al. (2003) proposed a generalized walking time function with bi-directional pedestrian flow ratio (GBPR) to model the bi-directional flow effects on pedestrian facilities at various flow conditions ranging from free-flow to congested-flow situations. Based on this, a generalized walking speed (GWS) function is proposed and is written as below:

$$GWS(v,r) = \frac{60}{GBPR(v,r)} = \frac{60}{t_0 + B_1 \cdot (r)^m \cdot (\frac{v}{C_{eff}})^n} \tag{3}$$

where $GWS(v,r)$ is the walking speed (m/min) for pedestrian walking on crosswalk at flow v and flow ratio r; $GBPR(v,r)$ is the unit walking time (seconds/m) for pedestrian walking on crosswalk at flow v and flow ratio r; t_0 is the unit free-flow walking time (seconds/m); r is the bi-directional flow ratio ($0 < r \leq 1$); v is the one-way pedestrian flow (ped/m/min); C_{eff} is the fitted effective capacity of crosswalk at flow ratio r, which can be expressed as $C_{eff} = a_0 + a_1 \cdot r + a_2 \cdot r^2 + a_3 \cdot r^3$ (Lam et al., 2002; 2003); B_1, m, n, a_0, a_1, a_2 *and* a_3 are the parameters to be estimated.

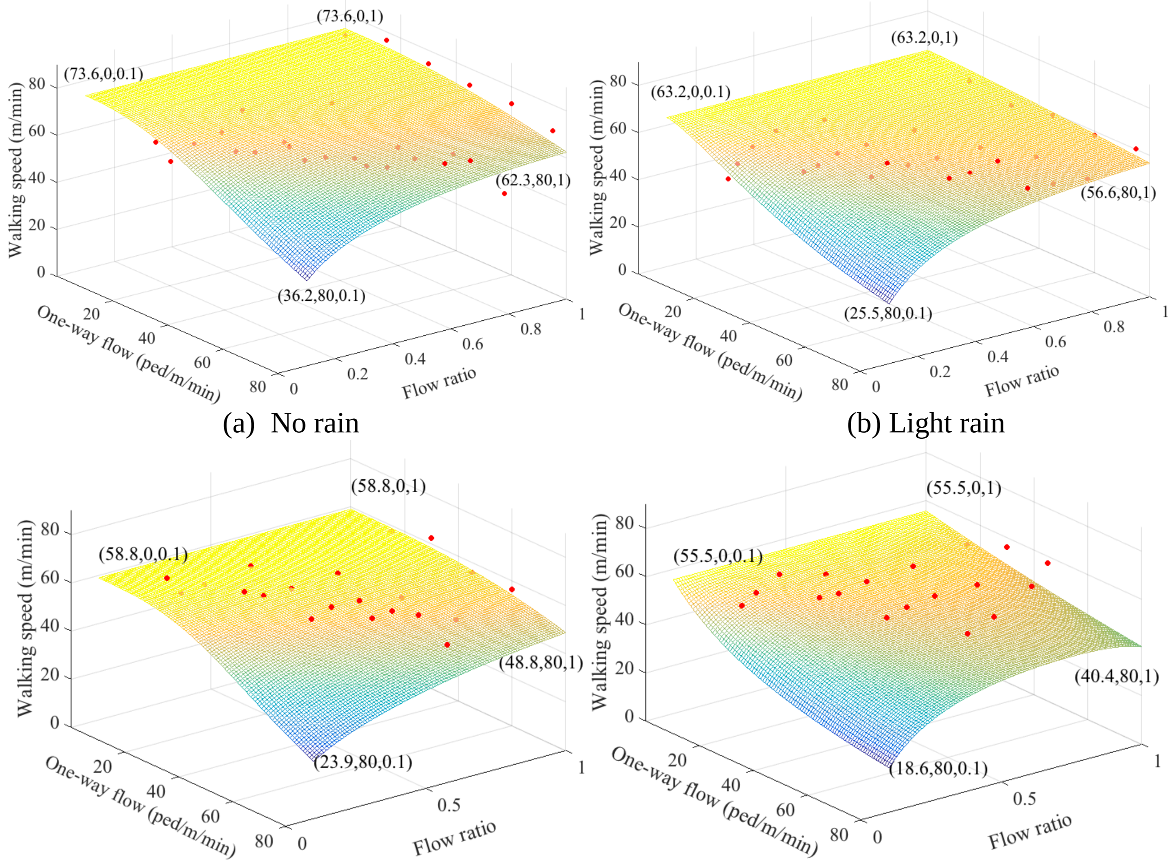
To study the walking speeds for pedestrians in rainy conditions practically, different levels of the rainfall intensity are designed (see Table 1) in the controlled experiments.

Table 1. Level of Rainfall Intensity

Level	Rainfall intensity (mm/h)
No rain	0 – < 1.0
Light	1.0 – < 2.5
Moderate	2.5 – < 10.0
Heavy	10.0 – 30.0

The observed and fitted relationships between walking speed and one-way pedestrian flow for various flow ratios under different rainfall intensity are presented in Figure 3(a-d) respectively. In Figure 3(a), the observed average walking speeds at certain flow v and flow ratio r in no-rain condition are fitted with the GWS function. The coefficient of determination (R^2) is 0.91, which reflects the accuracy of the fitting results. It implies that more than 90% of the observed average walking speeds are well fitted. The free-flow walking speed (73.6 m/min) was found to be slightly higher than that (69.1 m/min) of Lee's (2010) result on signalized crosswalks. It may be due to the measurement area (18.2m×14.5m) in Lee (2010) is much larger than that of this study (10.5m×4m). As shown in Figure 3(a), the at-capacity walking speed decreases from 62.3 m/min to 36.2 m/min when flow ratio decreases from 1.0 to 0.1. When pedestrians face heavy opposing pedestrian flow, they usually weave through the opposing pedestrians and would have little freedom in choosing their walking speeds. Thus, the pedestrian walking speeds would be reduced significantly in the minor flow direction. Moreover, the bi-directional flow effects are significant in the minor flow when the flow ratio on a crosswalk is much less than 0.5. For example, the walking speed reduces by 50% (from 73.6 m/min to 36.2 m/min) with the increase of one-way pedestrian flow when the flow ratio is equal to 0.1.

In general, as shown in Figure 3, the walking speeds are gradually reduced with increase in rainfall intensity. For major flow direction ($r \geq 0.5$), the walking speeds are not easily affected by rainfall intensity and one-way pedestrian flow. However, for minor flow direction, walking speeds are reduced by more than 50% when one-way flow increases from 0 to 80 ped/m/min, as shown in Figure 3(a-d).



(a) No rain (b) Light rain

(c) Moderate rain (d) Heavy rain

(62.3, 80, 1) represents (walking speed = 62.3 m/min, one-way flow = 80 ped/m/min, flow ratio = 1)

Figure 3. Comparison of the observed and the fitted average walking speeds for various pedestrian flows and flow ratios under different rainfall intensities

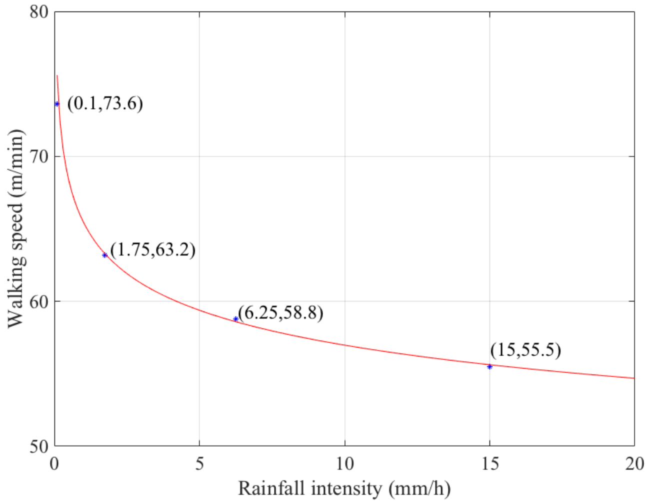
3.2 Calibration of the Free-flow Walking Speed in Rainy Condition

The free-flow walking speeds in light, moderate and heavy rain conditions were selected for calibration. The function of the relationship between free-flow walking speeds and rainfall intensity I has been modeled and calibrated with experimental data by the nonlinear regression method. Several function forms such as polynomial, exponential and power functions were adopted. It was found that exponential function is the best form for modeling the relationship between free-flow speed and rainfall intensity (Lam et al., 2013). The relationship between free-flow walking speed and rainfall intensity is calibrated as (also see Figure 4)

$$V_f(I) = e^{4.1817 * I^{-0.0147}} \tag{4}$$

where I is rainfall intensity (mm/h); $V_f(I)$ denotes the free-flow walking speed (m/min).

As shown in Figure 4, the average free-flow walking speeds of pedestrians decrease with increasing rainfall intensity. The coefficient of determination (R^2) is 0.998, which shows a high accuracy of the fitting results. Due to safety considerations, pedestrians tend to walk slowly in rainy conditions. However, when the rainfall intensity increases to a certain extent, its impact on the walking speed becomes weak.



(1.75, 63.2) represents (rainfall intensity = 1.75 mm/h, walking speed = 63.2m/min)

Figure 4. Free-flow walking speeds under different rainfall intensities

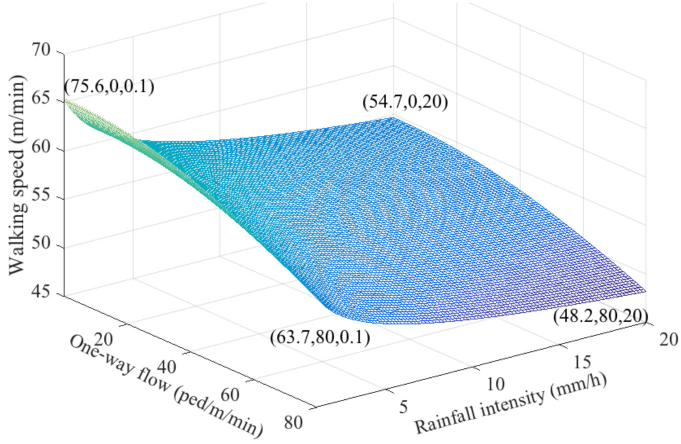
3.3 Calibration of the Generalized Walking Speed Function in Various Rainy Conditions

With the calibrated relationship of free-flow walking speed and rainfall intensity, the observed walking speed data at different pedestrian flows and flow ratios can be fitted with the generalized walking speed function, taking into account the effects of rainfall intensity, which is written as follows:

$$GWS(v,r,I)=\frac{60}{\frac{60}{e^{4.1817*I^{-0.0147}}}+0.0717\cdot r^{-0.7435}\cdot\left(\frac{v}{60.5022+26.2973\cdot r-0.5063\cdot r^{2}-12.0051\cdot r^{3}}\right)^{2}}$$
$$=\frac{e^{4.1817*I^{-0.0147}}}{1+1.1950*10^{-3}\cdot e^{4.1817*I^{-0.0147}}\cdot r^{-0.7435}\cdot\left(\frac{v}{60.5022+26.2973\cdot r-0.5063\cdot r^{2}-12.0051\cdot r^{3}}\right)^{2}} \quad (5)$$

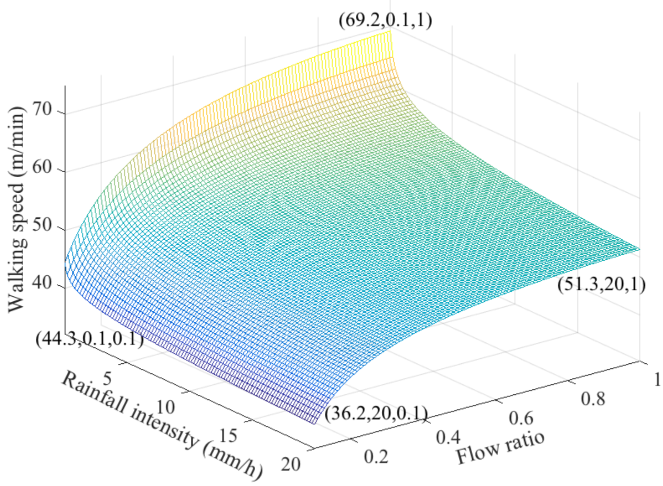
Based on the above function, the impacts of rainfall intensity and flow ratio on the walking speed can be obtained. The relationships of the average walking speed against rainfall intensity and pedestrian flow are shown in Figure 5, where the flow ratio r is set as 0.5. As shown in Figure 5, the maximum walking speed 75.6 m/min occurs at free-flow and no-rain condition. The minimum walking speed 48.2 m/min occurs at effective capacity and heavy rain condition, i.e. the pedestrian flow is 80 ped/m/min and rainfall intensity is 20 mm/h. Under the rainfall intensity 20 mm/h, the walking speed increases from 48.2 m/min to 54.7 m/min with the decrease in pedestrian flow from 80 ped/m/min to 0. The decreasing rate reaches 13.49%. For the case of pedestrian flow 80 ped/m/min, the walking speed decreases from 63.7 m/min to 48.2 m/min with the increase of rainfall intensity from 1 mm/h to 20 mm/h. The decreasing rate is 24.33%. Under free-flow condition, the walking speed decreases from 75.6 m/min to 54.7 m/min with the increase of rainfall intensity. The decreasing rate reaches 27.65%. The results indicate that the impact of rainfall intensity on the walking speed is significant. Pedestrian flow also has impact on the walking speed.

Figure 6 shows the relationships of the average walking speed against rainfall intensity and flow ratio, where the pedestrian flow v is set as 75 ped/m/min. As shown in Figure 6, the maximum walking speed 69.2 m/min occurs at uni-directional flow condition and light rain condition. The minimum walking speed 36.2 m/min occurs at minor flow direction and heavy rain condition, i.e. the flow ratio is 0.1 and rainfall intensity is 20 mm/h. Under the rainfall intensity 20 mm/h, the walking speed decreases from 51.3 m/min to 36.2 m/min with the change of flow ratio from major flow direction to minor flow direction. The decreasing rate reaches 29.43%. For the case of flow ratio equal to 1, the walking speed decreases from 69.2 m/min to 51.3 m/min with the increase of rainfall intensity from 0.1 mm/h to 20 mm/h. The decreasing rate is 25.87%. The results indicate that the impact of flow ratio on the walking speed is significant. Rainfall intensity, of course, has impact on the walking speed as discussed above.



(48.2, 80, 20) represents (walking speed = 48.2 m/min, one-way flow = 80 ped/m/min, rainfall intensity = 20 mm/h)

Figure 5. The impacts of pedestrian flow and rainfall intensity on walking speed (r = 0.5)



(51.3, 20, 1) represents (walking speed = 51.3 m/min, rainfall intensity = 20 mm/h, flow ratio = 1)

Figure 6. The impacts of rainfall intensity and flow ratio on walking speed (v = 75 ped/m/min)

4. CONCLUSIONS AND FURTHER STUDIES

The pedestrian stream parameters such as walking speed, pedestrian flow and bi-directional flow ratio are of crucial importance in design and evaluation of the pedestrian schemes/facilities. In this study, the effects of rainfall intensity on these key stream parameters and the pedestrian speed-flow relationships were investigated empirically.

Generalized speed-flow functions in no-rain and rainy conditions have been proposed in this paper. The effects of rainfall intensity on free-flow speed have also been modeled explicitly. Based on the walking speed, pedestrian flow, bi-directional flow ratio and rainfall intensity data collected from controlled experiments, the proposed generalized walking speed function were calibrated with consideration of rainfall intensity effects. The proposed generalized function can be used for assessing the performance of pedestrian schemes/facilities and modeling pedestrian walking behavior in conditions with various rainfall intensities.

The results showed that rainfall intensity has significant impacts on walking speeds. The average walking speeds and the free-flow speeds decrease as rainfall intensity increases. It was also found that the walking speeds in rainy conditions decrease greater than that in no-rain condition with increasing pedestrian flows. In this study, the effects of rainfall intensity on pedestrian walking behavior have been calibrated with experimental data for signalized crosswalks. Similar studies should be carried out to consider the impacts of rainfall intensity for design, operation and evaluation of various pedestrian facilities in Hong Kong or in other Asian cities with relatively high annual rainfall intensity.

In this paper, the effects of the proportion of umbrella usage on pedestrian walking behavior are ignored when studying the effects of varied rainfall intensity. The effects of proportion of umbrella usage should be examined in future study.

5. ACKNOWLEDGEMENTS

The work described in this paper was jointly supported by grants from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 5243/13E) and the Research Committee of The Hong Kong Polytechnic University (Project No. 1-ZVFJ).

6. REFERENCES

Camacho, F.J., Garcia, A. and Belda, E. (2010) Analysis of impact of adverse weather on freeway free-flow speed in Spain. *Transportation Research Record*, 2169, 150-159.

Chang, C.Y., Woo, T.H. and Wang, S.F. (2011) Analysis of pedestrian walking speeds at crosswalks in Taiwan. *Proceedings of the Eastern Asia Society for Transportation Studies*, 8, 1186-2200.

Lam, W.H.K. and Cheung, C.Y. (2000) Pedestrian speed/flow relationships for walking facilities in Hong Kong. *Journal of Transportation Engineering*, 126(4), 343-349.

Lam, W.H.K., Lee, J.Y.S. and Cheung, C.Y. (2002) A study of the bi-directional pedestrian flow characteristics at Hong Kong signalized crosswalk facilities. *Transportation*, 29(2), 169-192.

Lam, W.H., Lee, J.Y., Chan, K.S. and Goh, P.K. (2003) A generalised function for modeling bi-directional flow effects on indoor walkways in Hong Kong. *Transportation Research Part A: Policy and Practice*, 37(9), 789-810.

Lam, W.H.K., Tam M.L., Cao, X.Q. and Li, X.M. (2013) Modeling the effects of rainfall intensity on traffic speed, flow, and density relationships for urban roads. *Journal of Transportation Engineering*, 139(7), 758-770.

Lee, J.Y.S. (2010) Pedestrian activity-simulation model for Hong Kong congested urban areas. Ph.D. Thesis, The Hong Kong Polytechnic University, Hong Kong.

Li, J., Lam, W.H.K. and Li, X. (2016) Modeling the effects of rainfall intensity on the heteroscedastic traffic speed dispersion on urban roads. *Journal of Transportation Engineering*, 142(6), 05016002.

Prevedouros, P.D. and Chang, K.W. (2005) Potential effects of wet conditions on signalized intersection LOS. *Journal of Transportation Engineering*, 131(12), 898-903.

Tam, M.L., Chen, B.Y. and Lam, W.H.K. (2007) Assessment of rainfall impacts on vehicular travel speeds. *Proceedings of the 12th International Conference of Hong Kong Society for Transportation Studies*, Hong Kong, 421-430.

Transport Department, Hong Kong Special Administrative Region (HKSAR) (2010) Study on Pedestrian Subways and Related Traffic Improvement Measures in Causeway Bay, TD181/2008.

Wong, S.C., Leung, W.L., Chan, S.H., Lam, W.H.K., Yung, N.H.C., Liu, C.Y. and Zhang, P. (2010) Bi-directional pedestrian stream model with oblique intersecting angle. *Journal of Transportation Engineering*, 136(3), 234-242.

Xie, S.Q., Wong, S.C., Lam, W.H.K. and Chen, A (2013) Development of a bidirectional pedestrian stream model with an oblique intersecting angle. *Journal of Transportation Engineering*, 139(7), 678-685.