A STUDY OF THE BI-DIRECTIONAL PEDESTRIAN FLOW CHARACTERISTICS IN HONG KONG MASS TRANSIT RAILWAY STATIONS

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abstract : This paper investigates the bi-directional pedestrian flow characteristics in the Hong Kong Mass Transit Railway (MTR) stations. Surveys were conducted in MTR stations and the data collected were used to study the speed-flow relationships and the effects of the bi-directional pedestrian flow on passageway and stairway in MTR stations. The speed-flow functions for these pedestrian facilities were calibrated. The relationships between the reduction of effective capacity and directional distribution of pedestrian flow were determined, and the effects of directional distribution on the reduction of walking speed at capacity were also investigated. The results could be used as the basis for the development of pedestrian simulation models for underground stations in Hong Kong and/or in other Asian cities.

1. INTRODUCTION

The Hong Kong Mass Transit Railway (MTR) is a metropolitan underground/elevated railway with average number of 2.38 millions weekday passengers. As the pedestrian movements in MTR stations are critical during the peak periods, the knowledge of pedestrian flow characteristics in MTR stations could help in the design and improvement of the pedestrian facilities in these stations.

The pedestrian's speed-flow relationship is of prime importance of the design of pedestrian facilities. In recent years the research efforts in studying the pedestrian's speed-flow relationship have focused on the surface pedestrian facilities (Older, 1968; Navin *et al*, 1969; Fruin, 1971; Tanaboriboon *et al*, 1986; Lam *et al*, 1995). Comparatively, less attention have been given to the pedestrian's speed-flow relationship in underground stations. These previous related studies can be found in Harris (1991), Daly *et al* (1991) and Cheung *et al* (1997). It should be noted that the works reported so far have not been taken into account for the effects of bi-directional pedestrians flow. In this paper, the pedestrian's speed-flow relationships together with the bi-directional pedestrian flow characteristics on pedestrian facilities in Hong Kong MTR stations were studied. The results could be incorporated in the pedestrian simulation models for station design/improvement of the Hong Kong MTR stations.

2. MTR SYSTEM IN HONG KONG

The MTR system in Hong Kong comprises three lines with a combined route length of 43.2 kilometres. Figure 1 shows the MTR network together with the 38 stations. The network is served by 759 cars assembled into eight-car trains. Each car has five automatic doors and is connected together to comprise a 40-doors train with capacity of 2500 passengers. During peak periods trains are fully loaded and operated at one to two minutes headway with 30 seconds dwelling time at each station. As there are high passenger volume, short train headway and limited capacity of the pedestrian facilities, it was considered necessary to enhance the stations capacities and ensure the passenger safety. The pedestrian movements in the MTR stations would be the critical issue for station improvement and/or design.

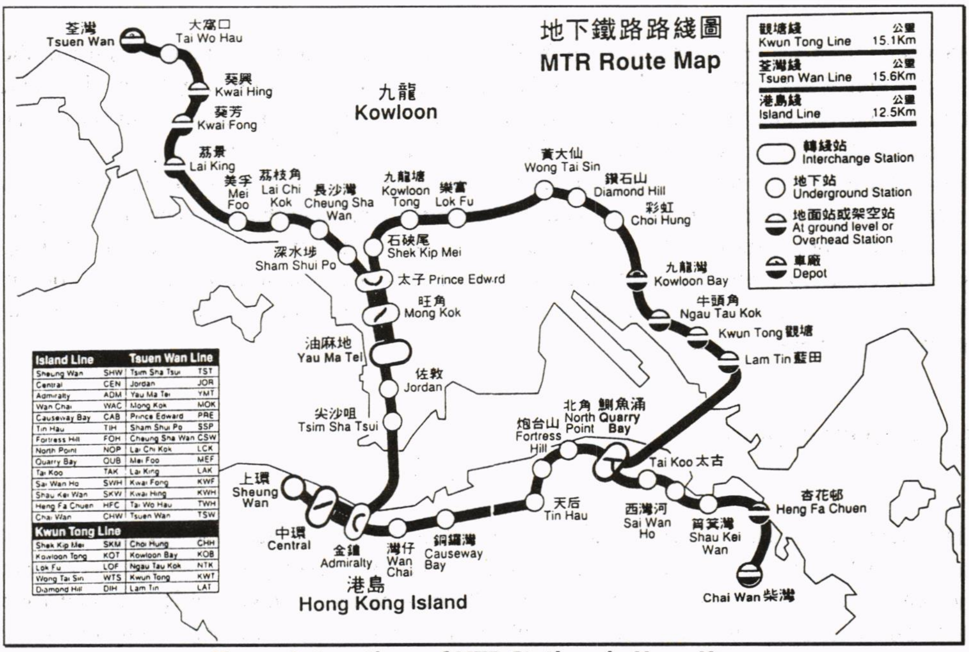

Figure 1. Locations of MTR Stations in Hong Kong

3. DATA COLLECTION

Surveys were conducted in six MTR stations to investigate the bi-directional pedestrian flow characteristics on the passageway and stairway. Time-lapse photography technique was used to gather the data for analysis. With the use of video recording equipment, the data required could be extracted from the video records for subsequent analysis. To increase the accuracy of the measurement, a time code in 1/25 second was mapped on the video images before data extraction. Data extraction was aided by using computer as a counting device. Therefore, the flow profile of the pedestrian was obtained by counting the pedestrians passing through the centre line of the measurement section. The results were stored in a computer file for subsequent analysis. The time taken by a pedestrian to transverse a test section was measured from the video recording, with respect to the corresponding flow profile in the computer file. A statistical package SPSS was used to calibrate the speed-flow functions. The parameters of the speed-flow functions were estimated by using the non-linear regression technique.

4. RESULTS

4.1 Speed-flow Functions by Pedestrian Facilities

The relationship between walking speed and pedestrian flow can be derived by the following two equations:

$$\mu = \frac{d}{t(v)} \qquad (1)$$

where:

μ is the walking speed (metres/second);
d is the length of the measurement section (metres);
$t(v)$ is the travel time (seconds) at flow v; and
v is the pedestrian flow (pedestrians/metre width/minute).

The equation adopted for estimating the travel time at flow v is based on the well-known BPR (Bureau of Public Road, 1964) function which has been widely used for the prediction of travel times on road network. This BPR function is also consistent with the function employed in the PEDROUTE (Halcrow Fox and Associates, 1994) - a pedestrian simulation software. The BPR function is given as below:

$$t(v) = t_0 + B \times (\frac{v}{C})^n \qquad (2)$$

where:

B, n are the parameters to be estimated;
C is the capacity of pedestrian facility (pedestrians/metre width/minute);
$t(v)$ is the travel time (seconds) at flow v;
t_o is the free flow travel time (seconds); and
v is the pedestrian flow (pedestrians/metre width/minute).

The physical characteristics of the pedestrian facilities and the observed maximum pedestrian flows are displayed in Table 1 together with the number of observations for each type of pedestrian facilities. Considering hard edge effects, an effective width is determined for the facilities to reflect the usable space for passenger movements.

Table 1. Observed Maximum Flows and Physical Characteristics of Pedestrian Facilities

Pedestrian facility	No of sites	Physical characteristics	Observed maximum flow
Passageway	3	Width = 2.5m to 3.3m length = 7.5m	92 peds/m/min
Stairway (ascending)	3	Width = 1.8m Tread width = 305mm, step riser height = 150mm	70 peds/m/min
Stairway (descending)	3	Width = 1.8m Tread width = 305mm, step riser height = 150mm	80 peds/m/min

With the obtained data, the speed-flow relationships given in (1) were fitted by using non-linear least square regression technique. Table 2 summarises the results for each type of pedestrian facility. Figure 2 shows the variation of walking speed and pedestrian flow data for passageway.

Table 2. Travel Time Functions and Walking Speeds by Pedestrian Facilities

Facility	No. of samples	Parameters			Free flow walking speed (m/min)	Walking speed at capacity (m/min)	$R^{2\,(1)}$
		t_o	B	n			
Passageway	679	0.7294	0.9031	4.3331	82.26 [80.98,83.58]	36.75 [35.66,37.92]	0.8368
Stairway (ascending)	676	1.1623	1.1820	2.0847	51.62 [50.62,52.66]	25.59 [24.90,26.34]	0.8313
Stairway (descending)	692	1.0300	0.6333	2.4320	58.25 [57.59,58.91]	36.07 [35.35,36.82]	0.8458

Note : (1) R^2 is the coefficient of determination which is a measure to reflect the accuracy of the equation adopted.
* Figures in brackets indicate 95 percent confident intervals.
t_O, B, n are the parameters defined in equation (2).

In Figure 2, different distributions of the data points are observed for various ranges of flow. As the pedestrians are free to control their walking speeds at low pedestrian flows (i.e., low pedestrian density), the obtained speeds are less evenly distributed. When the pedestrian flow is high, pedestrians are less free to control their walking speeds as the pedestrian density is high. Similar results were obtained for stairway as shown in Figures 3 and 4 in the ascending and descending direction respectively.

Table 3 gives a comparison of capacities and walking speeds at capacity for passageway and stairway in both directions in the Hong Kong MTR and London Underground (LU) stations. It can be seen that for passageway and stairway in both directions, the MTR data show comparatively higher capacity, but slightly higher walking speeds than LU. The higher capacities in Hong Kong MTR stations can be partially explained by the smaller physique of Oriental people. In addition, Asian are more tolerant to invasion of space (Tanaboriboon *et al.*, 1986)

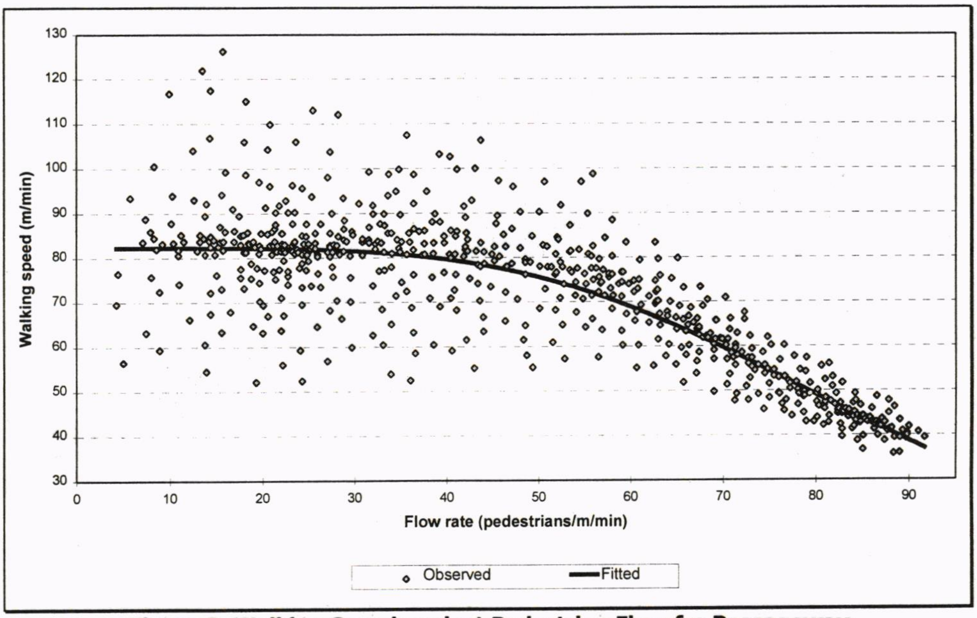

Figure 2. Walking Speed against Pedestrian Flow for Passageway

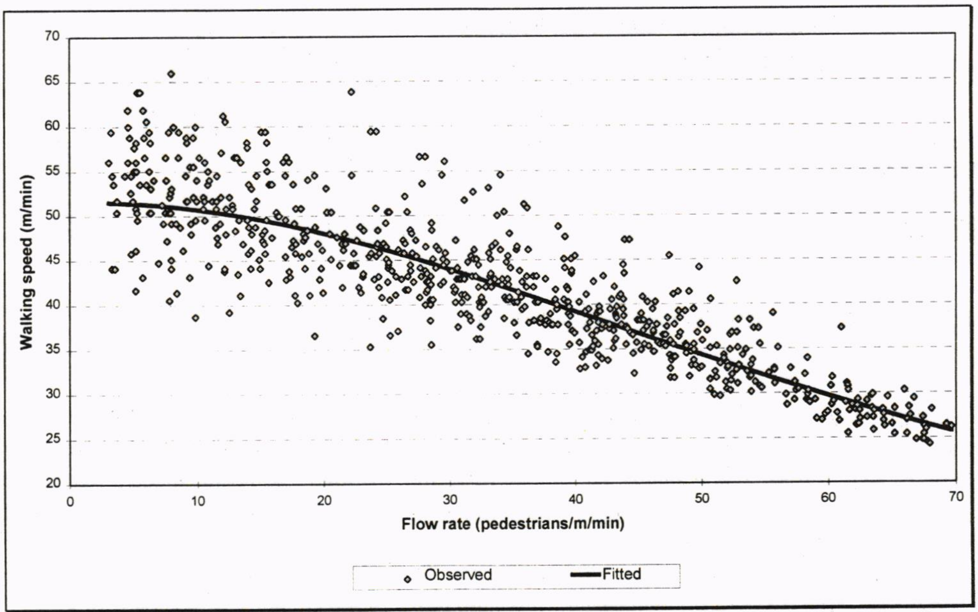

Figure 3. Walking Speed against Pedestrian Flow for Stairway in Ascending Direction

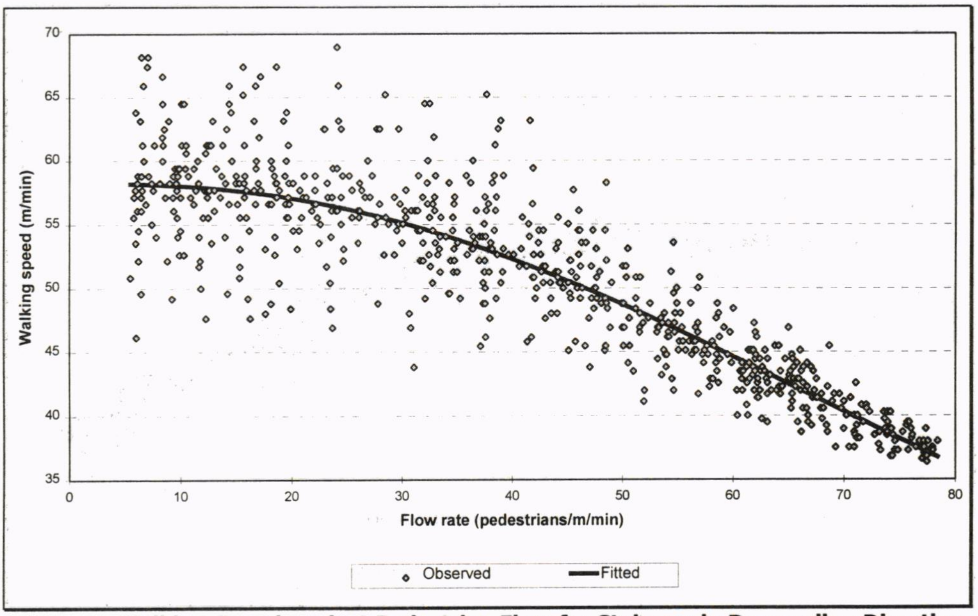

Figure 4. Walking Speed against Pedestrian Flow for Stairway in Descending Direction

Table 3. Comparison of capacities and walking speed at capacity for passageway and stairways in Hong Kong MTR and LU stations

Facility	Walking Speed at Capacity (m/min)		Capacity (peds/m/min)	
	MTR	LU	MTR	LU
Passageway	36.8	36.0	92	86
Stairway (ascending)	25.6	21.6	70	62
Stairway (descending)	36.1	33.6	80	68

4.2 Bi-directional Effects on Passageway and Stairway

When pedestrians walk on a facility facing heavy opposing pedestrian flows, they have to weave through the opposing pedestrians and would have little freedom to choose their speeds. Therefore, the capacity of the facility and the their walking speeds would be reduced. In this section, attempts were made to study the effects of bi-directional pedestrian flows on passageway and stairway. The effects were significant when the pedestrian flows are close to the capacity of the facilities. Therefore, it is of interest to study these effects when the pedestrian flows are close to the capacity of the facilities.

The bi-directional effects to be studied are given as follows:

- The relationships between the reduction of effective capacity of pedestrian facilities for individual direction and the directional distribution of pedestrian flows (R_{cap})
- The relationships between the reduction of walking speed in the minor flow direction at capacity and the directional distribution of pedestrian flows (R_{mspd})

When the pedestrian flow is bi-directional, the effective capacity for individual direction can be determined by considering the directional distribution of pedestrian flows. For instance, when the directional distribution of pedestrian flow is 50:50 on passageway, the effective capacity for individual direction is equal to half of the capacity of the passageway. Under this condition, pedestrians equally share the width of the passageway. However, as the capacity of stairway in the ascending direction is different from that in the descending direction, i.e., the obtained capacities for stairway in the ascending and descending direction are 70 peds/m/min and 80 peds/m/min respectively, the effective capacities for individual direction can be determined by considering the capacities of stairway in both directions and the directional distribution of pedestrian flows. For instance, when the directional distribution of ascending flow to descending flow is 35:40 on stairway, the effective capacity for individual direction is equal to half of the capacity of the stairway in the corresponding flow direction. Under this condition, pedestrians equally share the width of the stairway.

For sake of convenience, a flow factor (*F*) was introduced to calculate the effective capacity of passageway and stairway for individual direction. The effective capacity for individual direction is given as follow:

$$C_{eff} = C \times F \tag{3}$$

where:

C_{eff} is the effective capacity of passageway or stairway for individual direction;
C is the capacity of passageway or stairway in ascending or descending direction; and
F is the flow factor for passageway or stairway in ascending or descending direction.

The flow factors (*F*) for passageway and stairway in ascending and descending direction are given as follows:

For passageway

$$F_p = \frac{v1}{v1 + v2} \tag{4}$$

For stairway in descending direction

$$F_{sd} = \frac{\dfrac{v_{dn}}{C_{dn}}}{\dfrac{v_{dn}}{C_{dn}} + \dfrac{v_{up}}{C_{up}}} \tag{5}$$

For stairway in ascending direction

$$F_{su} = \frac{\dfrac{v_{up}}{C_{up}}}{\dfrac{v_{dn}}{C_{dn}} + \dfrac{v_{up}}{C_{up}}} \tag{6}$$

where:

C_{dn} and C_{up} are the capacities of stairway in the descending and ascending direction;

$v1$ and $v2$ are the main and opposing flows on passageway; and
v_{dn} and v_{up} are flows on stairway in the descending and ascending direction.

It should be noted that the flow factors for passageway and stairway are different. As discussed, the capacity of stairway in the ascending direction is different from that in the descending direction, the capacities of the stairway in both directions should be considered to determine the flow factor.

The definition of main direction is required for the study of the R_{cap}. For the stairway, the descending direction is defined as the main direction. Therefore, when F is equal to 0, it implies the flow on stairway is in the ascending direction; when F is equal to 1, it implies the flow on stairway is in the descending direction. While for the passageway, as the effects of pedestrian flow characteristics in either direction are the same, either direction can be defined as the main direction.

The definition of minor direction is required for the study of the R_{mspd}. When the flow factor for a direction is less than 0.5, that direction is said to be the minor direction. Under this circumstance, the pedestrians in the minor direction will face to heavy opposing pedestrian flow and their walking speeds in this direction should be reduced.

Statistical regression analysis was performed to determine the relationships of R_{cap} and R_{mspd} to flow factors. Initially linear relationships were adopted for analysis. However, the results were not favourable. Subsequently several forms of non-linear relationship were tested. The most satisfactory relationship was found to be the polynomial type of function. The functions obtained for the relationships of R_{cap} and R_{mspd} to flow factors are given as below and graphically displayed in Figures 3 and 4.

For passageway

$$R_{cap} = 0.3304F_p^6 - 0.9913F_p^5 + 0.6069F_p^4 + 0.4384F_p^3 + 0.2643F_p^2 - 0.6487F_p + 0.1936 \quad (7)$$

$R^2 = 0.999$

minor flow direction

$$R_{mspd} = -0.6693F_p^3 + 1.4043F_p^2 - 0.9938F_p + 0.2319 \quad (8)$$

$R^2 = 0.9971$

For stairway

$$R_{cap} = 8.1711F_{sd}^6 - 23.982F_{sd}^5 + 23.699F_{sd}^4 - 7.9182F_{sd}^3 + 0.506F_{sd}^2 - 0.52F_{sd} + 0.2752 \quad (9)$$

$R^2 = 0.9987$

minor flow in descending direction

$$R_{mspd} = 0.4153F_{sd}^3 + 0.8399F_{sd}^2 - 1.1713F_{sd} + 0.3275 \quad (10)$$

$R^2 = 0.999$

minor flow in ascending direction

$$R_{mspd} = 2.4412F_{su}^3 - 0.887F_{su}^2 - 0.86F_{su} + 0.3552 \quad (11)$$

$R^2 = 0.9992$

where:

R_{cap} is the reduction of effective capacity for passageway/stairway for individual direction (percent);
R_{mspd} is the reduction of walking speed in the minor flow direction at capacity (percent);
F_p is the flow factor for passageway;
F_{sd} is the flow factor for stairway in the descending direction; and
F_{su} is the flow factor for stairway in the ascending direction.

Note: The flow factors for R_{cap} ranged from 0 to 1 ($0 < F < 1$); and
The flow factors for R_{mspd} ranged from 0 to 0.5 ($0 < F < 0.5$).

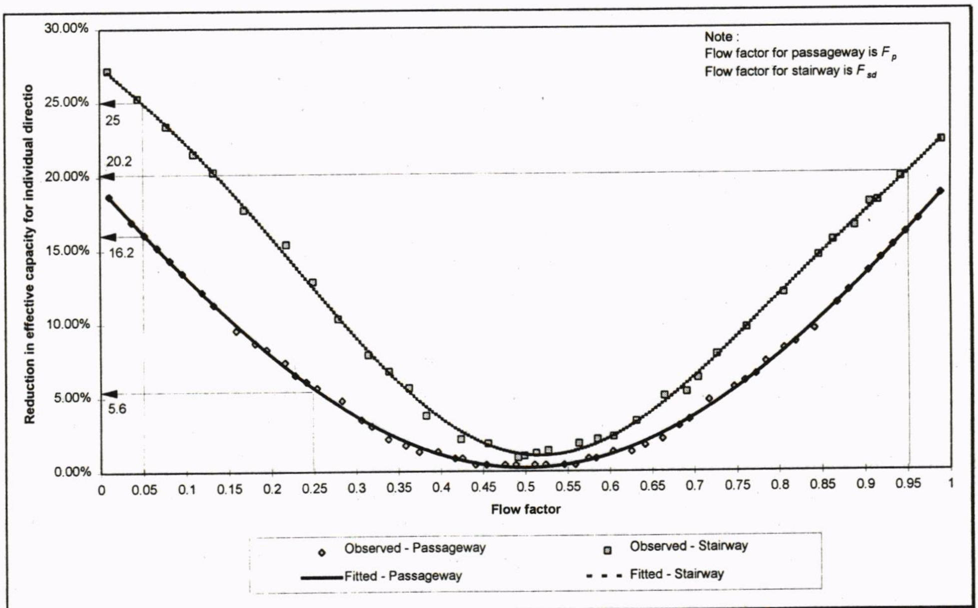

Figure 3 Reduction of Effective Capacity for Individual Direction Against Flow Factor

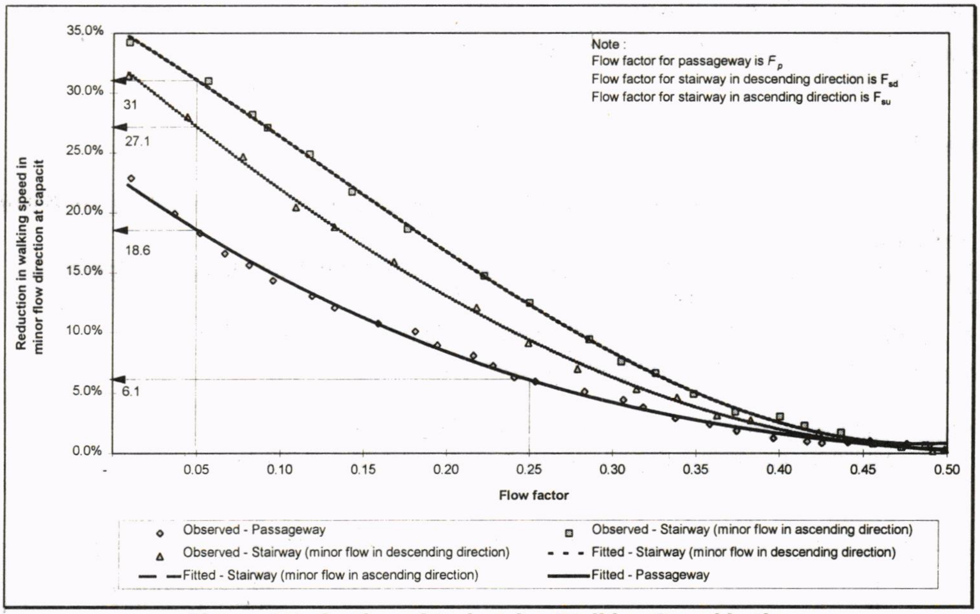

Figure 4 Reduction of Pedestrian Walking Speed in the Minor Direction at Capacity Against Flow Factor

It can be seen that R_{cap} and R_{mspd} increase with increasing imbalance of the directional split of pedestrians. For instances, it was found in Figures 4 and 5 that when the flow factor for passageway is 0.25 the reduction in R_{cap} and R_{mspd} are 5.6 and 6.1 percent respectively; for flow factor is 0.05, it increases to 16.2 and 18.6 percent respectively. The reduction in R_{cap} and R_{mspd} increase with increasing imbalance of the directional split of pedestrians can be explained that the smaller volume minor flows are dominated by the larger volume opposing flows, therefore forcing the pedestrians in the minor direction to weave through the oncoming crowd of pedestrians. Hence, the effective capacities for individual direction and the walking speeds of pedestrian are reduced. When the directional distribution is relatively balanced i.e., when flow factor is equal to 0.5, the effect of bi-directional pedestrian flow is not substantially different from that of uni-directional pedestrian flow. Pedestrians form directional streams that minimise conflict with the opposing flow; each stream occupies an effective walkway which is proportional to its share in the total flow, and the reduction of effective capacity for individual direction and hence walking speed would be minimal.

The results obtained for stairway is similar to those obtained for passageway i.e., R_{cap} and R_{mspd} increase with increasing imbalance of the directional split of pedestrians. However, the effects for stairway are more significant than that for passageway (for same flow factor, the R_{cap} and R_{mspd} for stairway are less than that obtained for passageway). It can be partially explained that the stairway is less flexible than passageway as the former involves the movement of pedestrians in vertical dimension, the pedestrians need to pay extra efforts for walking on grade. Besides, the manoeuvrability of pedestrians on stairway in the ascending direction is lower than that in the descending direction, hence, it tends to make the pedestrians on stairway more sensitive to opposing flows. Therefore, the effects of R_{cap} and R_{mspd} for stairway are more significant than that for passageway.

As the movement of pedestrians on stairway involve in both directions, the R_{cap} and R_{mspd} would be different when the predominant flows are in the ascending or descending direction. For instances, when flow factor is 0.05, the R_{cap} for predominant flow in the descending and ascending direction are 20.2 percent and 25 percent respectively; while the R_{mspd} for the minor flow in the descending direction and ascending direction are 27.1 percent and 31 percent respectively. As the manoeuvrability of the pedestrians on stairway in the descending direction is higher than that in the ascending direction, the pedestrians on stairway in the descending direction are comparatively easier to choose their speeds and less sensitive to the opposing pedestrians.

The results of R_{cap} and R_{mspd} can be incorporated in the speed-flow relationships as follows:

$$\mu_{re} = \frac{d}{t_0 + B \times \left(\frac{v}{C \times F \times (1 - R_{cap})}\right)^n} \tag{12}$$

and the walking speed in the minor direction is:

$$\mu_{rem} = \mu_{re} \times \left(1 - \left(\frac{v}{C \times F \times (1 - R_{cap})}\right)^n \times R_{mspd}\right) \tag{13}$$

where:

μ_{re} is the resultant walking speed (m/min) for individual direction due to the effects of bi-directional flow on R_{cap};
μ_{rem} is the resultant walking speed (m/min) in the minor direction due the effects of bi-directional flow on R_{mspd};
B, n are the parameters;
C is the capacity of passageway/stairway (pedestrians/metre width/minute);
d is the measurement length (metres);
F is the flow factor for individual direction;
R_{cap} is the reduction of effective capacity of passageway/stairway for individual direction (percent);
R_{mspd} is the reduction of walking speed in the minor flow direction at capacity (percent);
t_o is the free flow travel time (seconds); and
v is the pedestrian flow for individual direction (pedestrians/metre width/minute).

5. CONCLUSIONS

It was found in this paper that the capacities of passageway and stairway obtained in Hong Kong MTR stations are higher than that in LU stations. Moreover, the pedestrians in Hong Kong MTR stations tend to walk comparatively faster than in LU stations when the flows on stairway or on passageway are close to the capacities.

For the effects of the bi-directional pedestrian flow on passageway and stairway, it was found that the reduction of the effective capacity of the facilities for individual direction and the reduction of walking speed in the minor flow direction at capacity increase with increasing imbalance of directional split of pedestrians. The bi-directional pedestrian flow effects on stairway are more significant than that on passageway.

Furthermore, the reduction of the effective capacity of stairway for predominant flow in the descending direction is less than that in the ascending direction; and the reduction of pedestrian walking speed in the minor flow in the descending direction is less than in the ascending direction.

In this paper the bi-directional flow characteristics for passageway and stairway in Hong Kong MTR stations have been studied. It is hoped that the findings in this study further contribute to the field of pedestrian planning for the design/improvement of underground stations.

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