The Hong Kong Polytechnic University

Department of Civil and Structural Engineering

Pedestrian Activity-Simulation Model for Hong Kong Congested Urban Areas

by

Jodie Yik Sze LEE

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

September 2009

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

____

Jodie Yik Sze LEE

ABSTRACT

In most of the densely populated urban areas, many pedestrians may walk directly to the transit stations but some pedestrians may well carry out discretionary shopping activities. They may go into the stores nearby and shop for several minutes or even spend an hour in the shops. If the shopping activities are not explicitly considered in the modeling of the pedestrian movements, the spatial distribution of the area and the temporal distribution of the pedestrians could be questioned. Thus, the duration of shopping activities is of prime importance that affects the pedestrian flows on streets by time of the day.

This research puts forward an activity-based approach to model and simulate the pedestrian travel and activity choice behaviors in a congested urban shopping area with empirical data collected for calibration and comparison. The pedestrian activity behaviors are explicitly taken into account in the newly developed Pedestrian Activity-Simulation (PAS) model which can be used for assessing the service performance of the pedestrian facilities. Traditionally, the pedestrian trip-based simulation model does not consider the activity behaviors. It is assumed that pedestrians walk from origin to destination purely without any activities performed on the way. The results from the model may be questioned if the traditional trip-based simulation model is adopted for simulating the pedestrian movements in a congested urban area without particular emphasis on the

pedestrian activity behaviors. This research does not only focus on the pedestrian movements, but involves a broad view of walking behaviors, such as the pedestrian activity and destination choices, how the bi-directional pedestrian flow affects walking speeds, the walking speed variations and the Level-of-Service (LOS) standards of the pedestrian facilities.

The newly developed PAS model consists of four necessary elements. They are: (i) the pedestrian activity and destination choice models, (ii) the generalized walking functions for signalized crosswalks and outdoor walkways, (iii) the walking speed variations with the uni-directional and bi-directional pedestrian flow effects and (iv) the time sliced pedestrian demands in terms of origin-destination matrices. The newly proposed PAS model is calibrated and compared with empirical data. A case study in a Hong Kong urban area has been carried out to assess the performance of the PAS model and the traditional trip-based simulation model.

In order to collect data for model calibration and comparison, a large-scale survey was conducted with the assistance of 70 surveyors on a typical Friday 5 August 05. Two survey periods were chosen, i.e. an off-peak period from 2 p.m. to 4 p.m. (without Pedestrian Scheme) and a peak period from 5 p.m. to 7 p.m. (with Pedestrian Scheme). Two types of surveys were conducted simultaneously: (a) an observational survey; and (b) a tracking survey. Data collected from the observational survey have been used to examine the generalized walking speed functions, walking speed variations and pedestrian demand in terms of origin-destination matrices. In addition, data would be generated from the tracking survey to calibrate the pedestrian activity and destination choice models.

An independent set of observed data is collected from the observational and tracking surveys so as to compare the simulation results. Comparisons are made between the observed data and the results simulated by the newly proposed PAS model. In addition, the performance of the newly developed PAS model and the traditional trip-based simulation model are examined. Comparison results highlight the limitations of using the traditional trip-based simulation model to simulate the pedestrian flows and the total journey time particularly when the pedestrian shopping activities are concentrated in a congested urban area. This feature confirms that the pedestrian activity behaviors are of prime importance when pedestrian movements in the densely populated urban areas are considered.

In connection to the above, the generalized walking time function for signalized crosswalks and the walking speed variation function are proposed and calibrated with the empirical data which take into account the bi-directional pedestrian flow effects. It is shown that different designs, depending on walking speeds for signalized crosswalks, are required as different bi-directional pedestrian flow effects would have significant impacts on determining the duration of the pedestrian green time at signalized crosswalks particularly in the congested urban areas with high pedestrian flows. Similar calibration of the generalized walking speed function is carried out for outdoor walkways. Finally, a new set of pedestrian LOS standards for signalized crosswalks is developed by using the data collected from the stated preference survey which is based on the perception of the respondents on the LOS boundaries which are derived explicitly for the different levels of the bi-directional flows regarding the area occupancy, pedestrian flow and walking speed at the signalized crosswalks. These newly developed LOS standards would be better able to assess the service performance of the signalized crosswalks as the bi-directional pedestrian flow effects are explicitly taken into account.

LIST OF PUBLICATIONS

Journal Papers:

1. Lee, J.Y.S. and Lam, W.H.K., 2008. Simulating pedestrian movements at signalized crosswalk in Hong Kong. *Transportation Research A*, 42, 1314-1325.
2. Lee, J.Y.S. and Lam, W.H.K., 2006. The variation of walking speeds on a uni-directional walkway and on a bi-directional stairway. *Transportation Research Record*, 1982, 122-131.
3. Lee, J.Y.S., Goh, P.K. and Lam, W.H.K., 2005. New level-of-service standard for signalized crosswalks with bi-directional pedestrian flows. *Journal of Transportation Engineering,* (Special Issue: Calibration and Validation of Highway Capacity Manual Models), 131(12), 957-960.
4. Lam, W.H.K., Lee, J.Y.S., Chan, K.S. and Goh, P.K., 2003. A generalized function for modeling bi-directional flow effects on indoor walkways in Hong Kong. *Transportation Research A*, 37, 789-810.

Conference Papers:

5. Lee, J.Y.S. and Lam, W.H.K., 2009. The effects of effective density on walking speeds at signalized crosswalk. *Proceedings of the 88th Transportation Research Board Annual Meeting*, Paper no. 09-3749 (CD-ROM).
6. Lee, J.Y.S. and Lam, W.H.K., 2008. A model of pedestrian activity and destination choices using observational data. *Proceedings of the 13th International Conference of the Hong Kong Society for Transportation Studies*, 687-696.
7. Lee, J.Y.S. and Lam, W.H.K., 2007. Bi-directional flow effects on pedestrian indoor and outdoor walkways in Hong Kong. *Proceedings of the 12th International Conference of the Hong Kong Society for Transportation Studies*, 321-330.
8. Lee, J.Y.S. and Lam, W.H.K., 2007. Modeling pedestrian activity and destination choices in Hong Kong congested urban area. *Proceeding of the 11th World Conference on Transport Research*, Paper no. 770 (CD-ROM).
9. Lee, J.Y.S. and Lam, W.H.K., 2007. Development of a pedestrian simulation model for Hong Kong congested urban area. *Proceedings of the 86th Transportation Research Board Annual Meeting*, Paper no. 07-1432 (CD-ROM).
10. Lee, J.Y.S. and Lam, W.H.K., 2006. Validation of pedestrian simulation model for signalized crosswalk in Hong Kong. *Proceedings of the 11th*

International Conference of the Hong Kong Society for Transportation Studies, 381-389.

11. Lee, J.Y.S. and Lam, W.H.K., 2006. The variation of walking speeds on a uni-directional walkway and on a bi-directional stairway. *Proceedings of the 85th Transportation Research Board Annual Meeting*, Paper no. 06-1985 (CD-ROM).
12. Lee, J.Y.S. and Lam, W.H.K., 2005. A study of pedestrian movements in Hong Kong urban area with and without pedestrianisation scheme. *Proceedings of the 10th International Conference of the Hong Kong Society for Transportation Studies*, 490-499.
13. Lee, J.Y.S., Lam, W.H.K. and Tam, M.L., 2005. Simulating pedestrian movements at signalized crosswalk in Hong Kong. *Proceeding of 6th Conference for Eastern Asia Society for Transportation Studies,* 1337-1351.
14. Lee, J.Y.S. and Lam, W.H.K., 2005. Pedestrian simulation-assignment model for a Hong Kong Mass Transit Railway station - calibration and validation. *Proceedings of the 6th Transportation Specialty Conference of the Canadian Society for Civil Engineering*, Paper no. TR-173 (CD-ROM).
15. Lee, J.Y.S., Shao, H. and Lam, W.H.K., 2004. Walking time variations at Hong Kong indoor walkways. *Proceedings of the 9th Conference of Hong Kong Society for Transportation Studies*, 380-389.

ACKNOWLEDGEMENTS

First of all, I would like to express my warmest appreciation to my project supervisor Prof. William H.K. Lam, Chair Professor and Associate Head of the Department of Civil & Structural Engineering, for his encouragement, generous patience and enlightening guidance throughout my PhD study. I can exploit my knowledge under his supervision. His critical comments and useful suggestions contributed this thesis much more than I can do by myself. Without his generous support, this research is not possible to be completed.

I do wish to thank Mrs. Elaine Anson for her kind help and support. My appreciation is also extended to Mr. Tony Yuen (Manager - Operations Planning of Planning & Development Department of the Hong Kong Mass Transit Railway Corporation Limited), Mrs. Monica Yuen (Secretary of the Hong Kong Institution of Engineers), Mr. Albert Chow (Director of Qualifications of the Hong Kong Institution of Engineers) and their team members for their assistance, advices and resources supplied during this research study.

I am also indebted to the Research Committee of The Hong Kong Polytechnic University for supporting of my research project and for awarding of the studentships and scholarships. I would especially like to thank my friends and former colleagues - Dr. Lara Jaillon, Dr. Susanna Tam, Dr. Karen Tam, Dr.

Francis Tong, Dr. Xu Gang, Dr. Eric Chan, Dr. Shao Hu, Dr. Wu Zixiao, Dr. Z. C. Li and Mr. Cheung Chung Yu for their kind help and encouragement.

Last but not least, I wish to express my intense gratitude to my parents, my husband - Jackson and my lovely daughter - Ki Ki. Without their endless love, support and encouragement during the past years, I cannot pursue my doctoral study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TERMINOLOGIES

The following acronyms are used throughout this thesis:

BL	Binary Logit
GBPR	Generalized Walking Time
LOS	Level-of-Service
LU	London Underground
MNL	Multinomial Logit
MTR	Mass Transit Railway
NB	North Bound
OD	Origin Destination
PAS	Pedestrian Activity-Simulation
PS	Pedestrian Scheme
PSM	Pedestrian Simulation Model
SB	South Bound

NOTATIONS

The following notations are used throughout this thesis unless otherwise specified.

a is the coefficient of the slope of the linear regression model;

a_0, a_1, a_2 and a_3 are the coefficients of the regression model of the effective capacity;

a_0, a_t and a_r are the coefficients to be determined;

b is the coefficient of the y-intercept of the linear regression model;

B and n are the parameters to be estimated;

B_1, m and n are the parameters to be estimated;

b_0, b_S, b_{S_1}, b_{S_2} and b_r are the coefficients to be determined;

C is the observed capacity (pedestrians/meter/minute) of a pedestrian facility under uni-directional flow condition;

C_{as} and C_{de} are the effective capacities (pedestrians/meter/minute) of stairways in ascending and descending directions;

C_{eff} is the fitted effective capacity (pedestrians/meter/minute) of facility at flow ratio r;

COV is the coefficient of variation in terms of the mean walking speed $\overline{S}$;

D_i is referred to the distance between the current location of the pedestrian and the destination i;

d_{ij} is the corresponding area occupancy of photo j of LOS i;

f_{ij} is the corresponding frequency of pedestrian preference on photo j of LOS i;

$\sum_{j=1}^{n} f_{ij}$ is the total number of respondents;

$GBPR\left(r, \frac{v}{C_{eff}}\right)$ is the unit walking time (seconds/meter) for pedestrians walking on a pedestrian facility at flow v under flow ratio r;

m / min refers to the meter(s) per minute;

m / sec refers to the meter(s) per second;

m^2 / ped refers to the meter square per pedestrian;

N is the total number of alternatives;

n is the n^{th} alternatives;

$ped / m / min$ refers to the pedestrian(s) per meter width per minute;

ped / m^2 refers to the pedestrian(s) per meter square;

P_n is the probability that alternative choice n is chosen;

P_{L} is the probability that a pedestrian intends to leave the area;

P_{Sh} is the probability that a pedestrian intends to go shopping;

P_i is the probability that a pedestrian intends to leave the area at destination i;

r is the flow ratio $(0 < r \leq 1)$;

R^2 is the coefficient of determination which is a measure to reflect the accuracy of the model equation adopted;

s_j is the standard deviation of the walking time of group j;

$s(v)$ is the pedestrian walking speed (meters/minute) at flow v;

$\overline{S}$ is the mean walking speed (meters/second);

SD_S is the standard deviation of the mean walking speed;

SD_t is the standard deviation of the mean walking time;

$s.e.(\beta)$ is the standard error of the coefficient β;

$t(v)$ is the unit walking time (seconds) at pedestrian flow v;

t_0 is the unit free flow walking time (seconds/meter);

t_{ij} is the i^{th} observed walking time (seconds) of group j;

$\bar{t}_j$ is the mean walking time (seconds) of group j;

$t_{\frac{\alpha}{2}}$ is the critical value of t at α significant level;

t_R is the relative time component which refers to the time difference between the current time and the time that pedestrians start the trip;

t_A is the absolute time which refers to the time elapsed since the implementation of the part-time pedestrian scheme within the area;

U_n is the utility of an alternative n;

v is the two-way pedestrian flow (pedestrians/meter/minute);

v_1 and v_2 are the major and minor flows on the walkways respectively;

v_{as} and v_{de} are the ascending and descending pedestrian flows (pedestrians/meter/minute) on stairways;

V_n is the structural component specified as linear in parameters of the utility function common to all elements related to choice n;

V_{St} and V_L are the utilities of staying St and leaving L respectively;

V_{Sh} and V_W are the utilities of shopping Sh and walking W respectively;

V_i is the structural utility of an alternative destination i;

x is the simulated data set;

x_{ij} is the standardized travel time variate for the i^{th} observation of group j;

$\bar{x}$ is the average of the simulated data set;

x_L is a dummy variable introduced to the utility of leaving L, V_L;

x_s is the shopping duration (seconds) which follows the exponential distribution;

y is the observed data set;

$\bar{y}$ is the average of the observed data set;

Z_{ij} is the standardized log-transformed travel time variate for the i^{th} observation of group j;

ε_n is the random component corresponding to V_n;

χ^2 is the Chi-square value;

λ is the parameter of the exponential distribution;

α is the "travel time variability ratio";

$\pi_{ij} = log_e(t_{ij})$;

$\bar{\pi}_j$ is the mean π_{ij} of group j;

β is the coefficient being examined;

β_R and β_A are the calibrated parameters of relative time component t_R and absolute time component t_A respectively;

β_{i} and β_{D} are the calibrated parameters of relative destination i and distance component D_i respectively;

1 INTRODUCTION

1.1 BACKGROUND

Hong Kong is one of the most densely populated cities in the world with land area of only 1,108 km^2 but a population of about 7 million people* in 2008. High-rise buildings and high occupancy rates of buildings in Hong Kong result in tremendous concentrations of people and a great deal of conflict between the needs of pedestrians and vehicles, not only imposing noise and air pollution but also threatening the lives of the pedestrians. Congestion on transportation network always occurs in Hong Kong urban areas particularly during the peak periods.

To cope with ever-growing traffic and transport problems, the Hong Kong Government (Transport and Traffic Survey Division, 1985) recognized the need of studying pedestrian flow characteristics particularly for the improvement of the walking environments and enhancement of the design of pedestrian facilities. In order to promote walking and improve the pedestrian circulation movements, Transport Department is adopting an environmentally friendly approach in

---

* Hong Kong Census & Statistics Department

Internet homepage: www.censtatd.gov.hk/hong_kong_statistics/statistics_by_subject/

managing traffic and transport matters and is committed to putting more emphasis on the interests of pedestrians. Since the year 2000, Transport Department* has been implementing various pedestrian schemes in several congested urban areas in Hong Kong so as to improve the walking environment. Three types of pedestrian schemes are implemented, namely: Full-time Pedestrian Street, Part-time Pedestrian Street and Traffic Calming Street. The details of the three pedestrian schemes and the pedestrian priority zone can be found in Appendices A and B respectively. However, no particular study focused on the pedestrian schemes has been located. Hence, it is interesting and useful to assess the impacts of the various pedestrian schemes particularly at the congested urban shopping areas. A sophisticated microscopic pedestrian simulation model is required to predict the pedestrian flows and delays within the area for assessing the service performance of the various pedestrian schemes.

1.2 MOTIVATION

Simulation models are normally used by the traffic engineers to plan, design and manage the pedestrian facilities. Traditionally, these simulation models are trip-based and do not consider the pedestrian activities. In these simulation models, it

* Hong Kong Transport Department

Internet homepage: http://www.td.gov.hk/transport_in_hong_kong/pedestrianisation/index.htm/

is assumed that pedestrians walk from origin to destination directly without performing any activities in between. However, pedestrians will probably engage in discretionary shopping activities during their walking trips within a shopping area. They may shop for few minutes or even extend their shopping to several hours. Their total journey time is normally higher than that involving no activities. Their activity choice preferences will definitely influence the spatial distribution of the area and the temporal distribution of the pedestrians.

Figure 1.1 shows the important inspiration for this thesis. An urban area is hypothesized and illustrated in Figure 1.1. Many pedestrians may walk from their origins to their destinations directly without any activities performed in between. These pedestrian trips can be reasonably modeled by any traditional trip-based simulation models. However, some pedestrians may perform shopping activities during their walking trips. Figure 1.1 shows an example of pedestrian performing shopping activities in the hypothetical urban area. After the pedestrian entered the hypothetical urban area from the origin, s/he visits Stores 1 and 2. The durations of the pedestrian staying in Stores 1 and 2 are t_{S_1} seconds and t_{S_2} seconds respectively. Thus, the total shopping duration of the pedestrian can be determined by summation of all the shopping durations. In Figure 1.1, it is estimated that the pedestrian will arrive at the destination at time t_D if the traditional trip-based simulation model is adopted to simulate the pedestrian movements in the hypothetical urban area. However, the pedestrian is actually still at Store 2 for shopping at time t_D. Thus, the reliability of the model results simulated by the traditional trip-based simulation model will be questionable if the pedestrian shopping activities are not taken into account in the model.

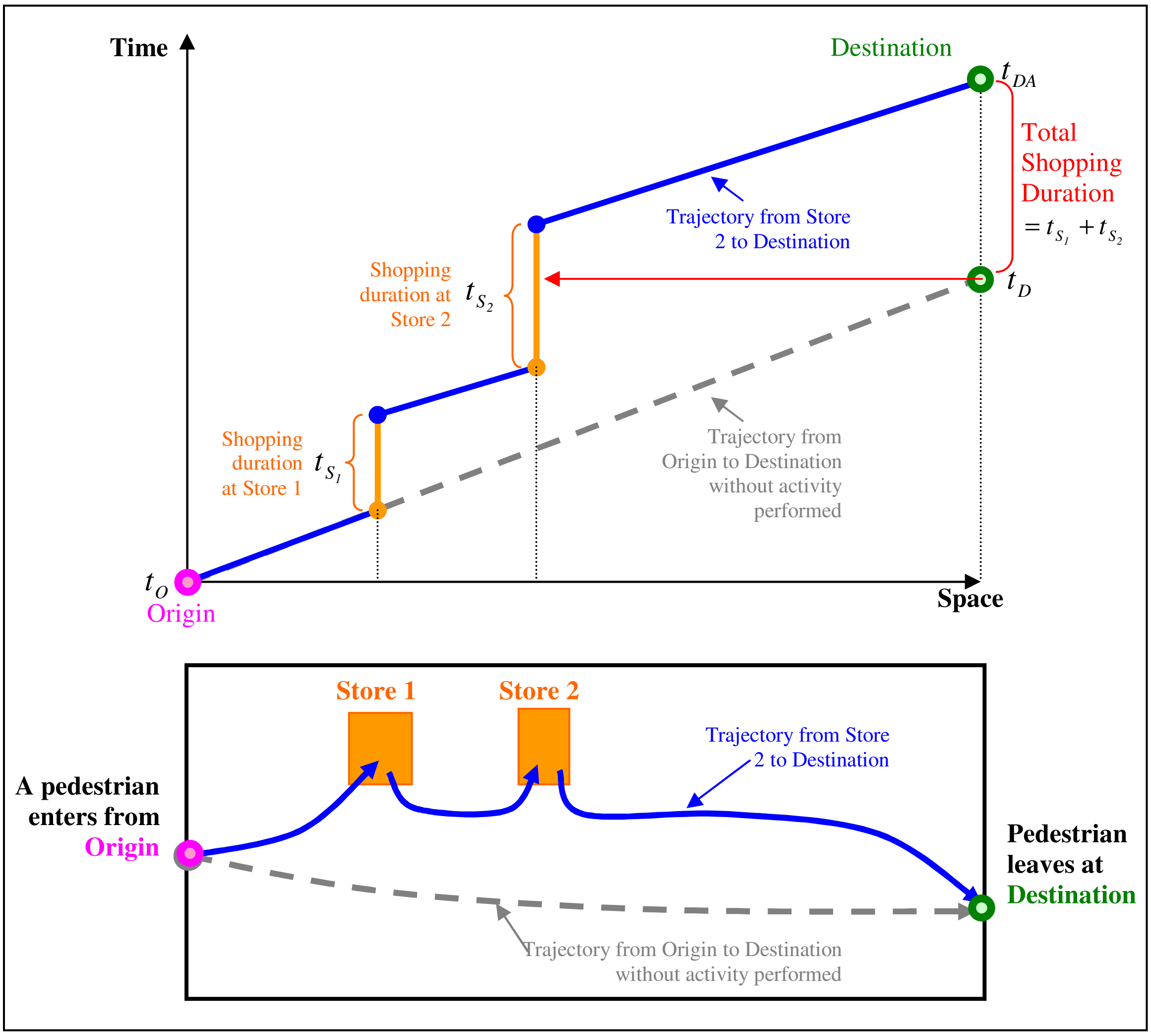


Figure 1.1 Difference between trips with and without activities

The shopping duration is an important attribute to consider in the pedestrian simulation model of a shopping area when the pedestrian activities are concentrated within the area. Applying the traditional trip-based model to simulate the pedestrian movements within the shopping area is inappropriate as the shopping duration is not explicitly taken into account in the model. Moreover, in practice, it is difficult to predict the change of pedestrian origin-destination flow pattern due to various responses of the pedestrians to the network improvements because pedestrians have different activity characteristics and preferences on the way to the destination as well as route choices particularly in Hong Kong urban areas with mixed land uses. Therefore, pedestrian activity and destination choices in Hong Kong congested urban areas should be well understood for the assessment of service performance of pedestrian facilities.

Among various pedestrian facilities, signalized crosswalks are one of the most complex facilities, with high risk for pedestrians in congested urban areas due to the fact that pedestrians and vehicles share the same road space but different time intervals, in accordance with the traffic signal cycles. The complexity of the traffic signals often creates problems since the provision and allocation of crossing time for pedestrians is usually apportioned from conflicting vehicular traffic flows. Therefore, the impacts of changing the duration of the pedestrian green and flashing green time is a worthwhile study endeavor. There is a need to develop a pedestrian simulation model for signalized crosswalks for the maximum realization of its capacity and safety of the pedestrians on the busy signalized crosswalks.

Additionally, when pedestrians walk on a facility facing a heavy opposing flow, they can not evade the opposing pedestrians easily. Thus, their walking speed reduces due to the heavy opposing pedestrian flows. Therefore, it is necessary to study the effects of the bi-directional pedestrian flows on various pedestrian facilities. If the bi-directional flow effects are considered, the pedestrian simulation model can estimate properly the walking time under the uni-directional and bi-directional flow conditions. With the knowledge of the bi-directional flow effects, a pedestrian simulation model can simulate the pedestrian movements within a congested urban area more accurately.

In general, clearly there is a demand for developing a microscopic pedestrian activity-simulation model for the congested urban areas which takes into account the bi-directional pedestrian flow effects on walking speeds, walking time variations and pedestrian preferences on the activity and destination choices. The advancement of modeling algorithms in this thesis together with the research studies on pedestrian behaviors, are indeed expected to contribute to the planning and design of the pedestrian facilities within a congested urban area.

1.3 MAIN CONTRIBUTIONS

This thesis describes a scientific approach to model the pedestrian activity behaviors in Hong Kong congested urban areas realistically. This section aims to delineate the main contributions that this research study is likely to make. There are seven main contributions of this study.

The first contribution is the development of a Pedestrian Activity-Simulation (PAS) model (Chapter 3). A part-time Pedestrian Scheme (i.e. pedestrian–only street from 4 p.m. to the midnight during weekdays) is implemented in the study area during the peak period. Time sliced pedestrian demands in terms of Origin-Destination (OD) matrices are derived on the basis of the data observed from the observational survey. These matrices are then incorporated into the PAS model together with the pedestrian activity and destination choice models (Chapter 4), the generalized walking time functions for outdoor walkways and signalized crosswalks (Chapter 5) and the walking time variations with the uni-directional and bi-directional pedestrian flow effects (Chapter 6). Pedestrians' activity and destination choices are also considered in the newly developed PAS model together with the shopping duration.

The second contribution of this thesis is to model the pedestrian activity behaviors in Hong Kong congested urban areas (Chapter 4). The pedestrian activity and destination choices are investigated empirically in this thesis. The relationship between the pedestrian travel demands and shopping activities is examined. Four decision models are calibrated, namely pedestrian staying or leaving choice model, shopping choice model, destination choice model and shopping duration model. By introducing the activity-based approach, a new avenue of pedestrian demand analysis is offered for pedestrian planning and policy evaluation. The pedestrians' activity and destination choices can be estimated so as to predict with a high degree of precision of the pedestrian origin-destination matrices and link flows in the congested urban areas.

The third contribution is to study the effects of the bi-directional pedestrian flows on the two pedestrian facilities: signalized crosswalks and outdoor walkways (Chapter 5). When pedestrians walk on a facility facing heavy opposing flows, they can not evade the other pedestrians walking from the opposite direction easily. Thus, their walking speeds reduce due to the heavy opposing pedestrian flows. The relationships between walking speed and pedestrian flow are examined for the outdoor walkways and signalized crosswalks under various bi-directional flow conditions. The generalized walking time functions for these two pedestrian facilities are calibrated which take into account the bi-directional pedestrian flow effects. The effects of the bi-directional pedestrian flows are also investigated empirically with particular emphasis on their effects on the walking time and the effective capacity for the different directional split of pedestrian flows. The calibrated generalized walking time functions can be further incorporated into the PAS model so as to consider the delays of pedestrians due to the heavy opposing pedestrian flows.

The variations of walking speeds on a facility are known to be an important factor influencing the pedestrian route choices. Therefore, the fourth contribution of this study is to investigate the walking speed variations under the uni-directional and bi-directional pedestrian flow conditions (Chapter 6) on various pedestrian facilities. The distributions of walking speeds are investigated. Moreover, the relationship between the average walking speeds and the variations is found based on the data collected from an observational survey. Models for walking speed variations are then calibrated taking into account the uni-directional and bi-directional pedestrian flow effects. These calibrated models can be further incorporated into the PAS model for estimating the variations of walking speeds under different pedestrian flow conditions.

The fifth contribution of this study is to compare the results simulated by the newly developed PAS model using an independent set of observed data (Chapter 7). The comparison consists of examining the reliability of the results given by the newly developed PAS model which can be used to estimate the pedestrian flows and the average walking time together with the walking time variations particularly when pedestrians are facing heavy opposing flows. The developed PAS model for the congested urban areas can be used to assess and evaluate the impacts of the various pedestrian schemes on the pedestrian circulation movements.

The sixth contribution of this study is to develop a new Pedestrian Simulation Model (PSM) for signalized crosswalks (Chapter 8). This PSM is capable of estimating the variation of walking speeds particularly under the bi-directional pedestrian flow condition so as to determine the minimum required duration of the pedestrian crossing time. The PSM is validated using an independent data set so as to examine the service performance of the signalized crosswalks. The validation results have shown that the new PSM can provide an accurate evaluation on the average walking speed and the standard deviation under different scenarios with particular emphasis on the effects of the bi-directional pedestrian flows. The advancement of the PSM will not only contribute towards an assessment of the effects of each improvement measure but also help evaluate the benefits of each alternative.

To assess the impacts of various pedestrian schemes such as the implementation of the part-time pedestrian scheme (or pedestrian-only street), a set of pedestrian Level-of-Service (LOS) standards for various facilities is a necessary indicator. The development of a new set of pedestrian LOS standards for signalized crosswalks is the seventh contribution of this study (Chapter 9). These newly derived LOS standards for signalized crosswalks explicitly take into account the bi-directional pedestrian flow effects and are expected to be directly applicable to Hong Kong or other Asian Cities with similar pedestrian physical characteristics and land uses.

1.4 THESIS OBJECTIVES

The main objective of this thesis is to model pedestrian activity behaviors in the congested urban areas. The research studies on pedestrian behaviors could be incorporated into the PAS model for assessing and evaluating the various pedestrian schemes implemented in the congested urban areas.

The specific objectives of this thesis are to:

- calibrate a newly developed PAS model for the congested urban areas by incorporating the generalized walking time functions, the walking time variations and the pedestrian activity and destination choice models to simulate the pedestrian movements (Chapter 3);
- model the pedestrian activity and destination choices in order to investigate the pedestrian behaviors and preferences for their activity choices in the congested urban areas (Chapter 4);
- calibrate the generalized walking time functions for signalized crosswalks and outdoor walkways to estimate the pedestrian delays due to the bi-directional pedestrian flow effects (Chapter 5);
- investigate the walking time variations under the uni-directional and bi-directional pedestrian flow conditions (Chapter 6);
- compare the PAS model results using an independent set of observed data (Chapter 7) so as to evaluate the reliability of the PAS model results and assess the impacts of the pedestrian schemes implemented in the congested urban areas;

- calibrate and validate a PSM for the signalized crosswalks in the congested urban areas to gauge the impacts of changing the durations of the pedestrian green and flashing green time (Chapter 8); and
- develop a set of new LOS standards for signalized crosswalks taking into account the bi-directional pedestrian flow effects (Chapter 9) so as to assess the performance of the crosswalk facilities.

1.5 STRUCTURE OF THIS THESIS

This thesis is composed of ten chapters. In the beginning of this thesis, Chapter 1 outlines the motivation, main contributions and objectives of this thesis. The context of this thesis is presented in a flowchart illustrated in Figure 1.2, which also shows the relationships and connections between chapters in this thesis. Chapter 2 introduces a comprehensive literature review of the previous research studies on the pedestrian movement behaviors. The reviewed pedestrian studies involve the: (i) pedestrian activity choice models, (ii) pedestrian simulation models, (iii) pedestrian flow characteristics, (iv) bi-directional flow effects on pedestrian facilities, (v) variations on walking time/speeds and (vi) LOS standards for the various pedestrian facilities.

The PAS model is developed and calibrated to simulate the pedestrian movements and activity behaviors in Hong Kong congested urban areas (Chapter 3). The pedestrian activity and destination choices models (Chapter 4) are calibrated empirically together with the distribution of the shopping durations. These models and distribution then serve as the necessary inputs for the PAS model.

Two more important components are also required in the PAS model. They are the calibrated generalized walking time functions (Chapter 5) and the walking time variations for the uni-directional and bi-directional pedestrian facilities (Chapter 6). The generalized walking time functions are calibrated for signalized crosswalks and outdoor walkways (Chapter 5) so as to predict the average walking time of pedestrians on the facilities under various congestion conditions. These calibrated functions focus on the effects of the bi-directional pedestrian flows on the facilities explicitly. However, the generalized walking time functions can only predict the average walking time on the facilities. The walking time variations are not considered in these functions. Therefore, walking time variations on the uni-directional and bi-directional pedestrian facilities are studied and investigated (Chapter 8) to glean insights regarding spreads in walking time connected with different pedestrian flows.

Subsequently, the results simulated by the newly developed PAS model is compared with an independent new set of observed data to justify the accuracy of the model results (Chapter 7). In addition, a PSM for signalized crosswalks is calibrated and validated so as to simulate the pedestrian movements on the crosswalks (Chapter 8).

In order to assess the service performance of the crosswalk facilities, a new set of LOS standards for signalized crosswalks is developed (Chapter 9). It explicitly takes into account the bi-directional pedestrian flow effects based on the pedestrian perceptions of the various service levels gathered from the interview surveys. Therefore, the pedestrian walking behaviors can be predicted with the use of the sophisticated microscopic PAS model for the congested urban areas.

The advanced modeling algorithm adopted in this research study together with the developed PAS model for the congested urban areas; do indeed, contribute to the prediction of the pedestrian activity behaviors and the assessment/evaluation of the impacts of the various pedestrian schemes. Moreover, the PAS model also helps in the design of pedestrian facilities in the congested urban areas because a systematic and scientific design of a facility is necessary for the maximum utilization of the facility's capacity and safety of pedestrians particularly under a heavy opposing pedestrian flow condition. Finally, the conclusions and recommendations for further research are presented in Chapter 10.

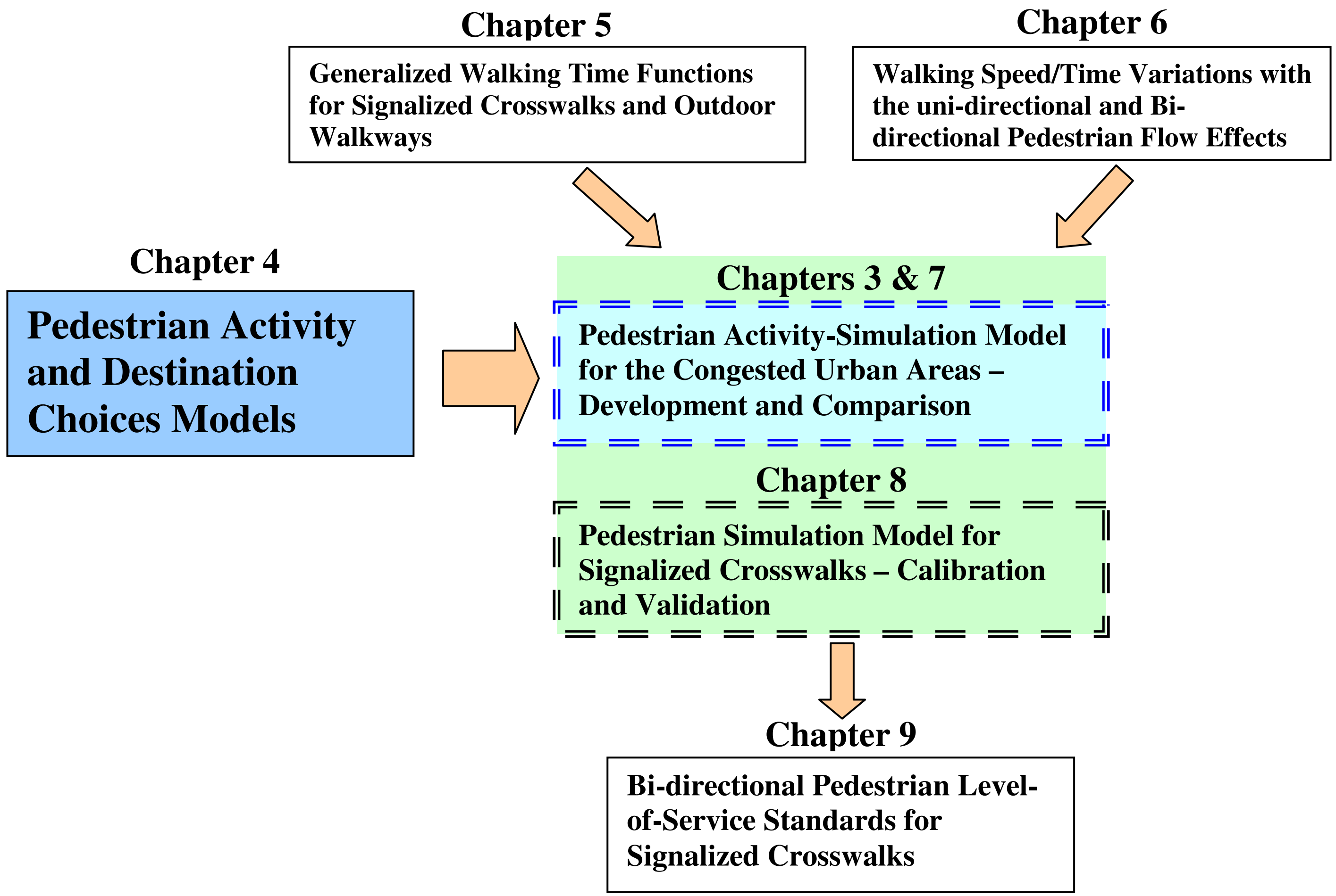


Figure 1.2 The flowchart of this thesis

2 LITERATURE REVIEW

2.1 INTRODUCTION

Chapter 1 gives the motivation of conducting this research, objectives of this study and an organization framework of this thesis. This chapter presents a comprehensive literature review of the previous related research on pedestrian studies. Previous research works can be classified into the following categories: the pedestrian activity choice models, the pedestrian simulation models, the pedestrian flow studies, the bi-directional flow effects on pedestrian facilities, the walking speed variations and the Level-of-Service (LOS) standards for pedestrian facilities.

There are 8 sections in this chapter. In Section 2.1, an introduction of this chapter is presented. Some previous research works on the pedestrian activity choice models are firstly reviewed and presented in Section 2.2. Subsequently, in Section 2.3, studies related to the pedestrian simulation models are discussed. Section 2.4 presents a review on the pedestrian flow studies together with the walking time functions. The research studies concerning the bi-directional flow effects on the pedestrian facilities are described in Section 2.5. Previous research works on the pedestrian studies for the walking speed variations are summarized in Sections 2.6.

Section 2.7 illustrates the studies related to the LOS standards for pedestrian facilities. Finally, a summary is presented in Section 2.8.

2.2 PEDESTRIAN ACTIVITY CHOICE MODELS

A number of models are found for predicting the pedestrian walking behaviors and demands in the urban areas. A pedestrian traffic model for town centers in Sweden was developed by Sandahl and Percivall (1972). The pedestrian demand relationship between larger retail centers and parking facilities was calibrated. Factors were identified for model development, such as the floor areas of retail centers, the parking facilities, the accessibility by bus, the number of street stalls and the seating places. Later, Pushkarev and Zupan (1975) investigated the urban spaces for pedestrians in Manhattan. Factors considered in their study were including the floor space, the walkway area and the number of transit facilities and etc. Desyllas et al. (2003) developed a regression model for predicting the pedestrian demands in London by using different variables to explain the observed numbers of pedestrians. Visibility was found to be the most important variable with consideration of the pedestrian demands.

A model estimating pedestrian movements in a downtown shopping area was developed by Borgers and Timmermans (1986a). The developed model was further divided into three sub-models, namely the destination choice, the route choice and the impulse stop models. Borgers and Timmermans (1986b) developed a micro-level simulation model to simulate the individual pedestrian behaviors by considering the city center entry points, the store location patterns and the pedestrian route choice behaviors. Later, Timmermans et al. (1992) compared a set of multinomial logit models derived from revealed choice data and a decomposition choice model derived from experimental data in terms of the predictive success in the content of consumer spatial shopping behaviors. A model predicting individual route choice behavior of pedestrians in the downtown shopping areas in Eindhoven and Maastricht was developed by Borgers and Timmermans (2004). It was found that the pedestrian decisions on the next link of their trips likely depend on a set of variables such as the walking distances and the location of stores. Walking distance was found to be the most important variable. A multinomial logit model was developed in terms of these variables. A multi-purpose shopping trip model was developed by Arentze et al. (2005) to assess the retail agglomeration effects in the Netherlands. In general, the retail agglomeration is the characteristics of retail supply such as the numbers and types of stores in a shopping center or the number of categories in a supermarket. It was found that the retail agglomeration effects help attract not only multi-purpose trips but also single-purpose trips. Recently, Zhu (2008) proposed a decision system to model and determine the pedestrian shopping behaviors. However, the time components used in the models are not collected in real life.

2.3 PEDESTRIAN SIMULATION MODELS

Good analytical, statistical, organizational and engineering skill must be required in the development of a simulation model. The main feature of any simulation package is to model the characteristics and interactions of all the elements of a system as faithfully as possible so as to predict the effects of the changes in the situation. There are 6 common simulation packages, namely SERVICE MODEL, AUTOMOD II, PEDROUTE (Halcrow Fox and Associates, 1994), STEPS, EGRESS and LEGION/VEGAS. In Hong Kong, the Mass Transit Railway (MTR) Corporation Limited (1998) compared and reviewed these 6 simulation packages.

The SERVICE MODEL is a simulation language program running under window operating system which was developed by the Promodel Corporation (2004). It provides flexibility and power for modeling any situations so as to provide interface sub-routines for modeling of the pedestrian flows and the facility's utilization. The simulation language provided by the SERVICE MODEL is adequate to handle both the normal and emergency situations. The model developer can completely control the approach, logic and degree of modeling details in the SERVICE MODEL so as to simulate the pedestrian flow and the facility's utilization under the normal situation and the regular special events. It also provides automatic error and consistency checking. Animated representation of the system is one of the major advantages and features of the SERVICE

MODEL. After the simulation run, it can also automatically tabulate and graph the simulation results.

After review of the 6 simulation packages, the MTR Corporation Limited adopted the SERVICE MODEL to simulate the pedestrian movements within the MTR stations. In the existing simulation model built for the stations by MTR Corporation Limited so far, the route choice is mainly based on a fixed proportion which is established through the observations or experiences of the station staff. Therefore, Lee (2002) developed a pedestrian route choice assignment program using the user equilibrium algorithm. The developed program was then further incorporated into the existing simulation model for the Causeway Bay MTR Station in Hong Kong to predict the route choices of the pedestrians within the station. In view of the above, the SERVICE MODEL is selected and adopted as the platform to develop the pedestrian activity-simulation model for Hong Kong congested urban areas.

In United Kingdom, London Underground developed its own in-house pedestrian simulation model which is the station congestion model to simulate the pedestrian delays occurring in various pedestrian facilities (Turner and Wradrop, 1951 & Turner et al., 1991). Pedestrian simulation software - PEDROUTE (Buckman and Leather, 1994) was developed by making use of the assignment procedures of SATURN (Van Vliet and Hall, 1986). Daamen (2004) and Hoogendoorn et al. (2003) carried out a research study to model passenger flows in the public transport facilities in Netherlands. Asano et al. (2007) developed a dynamic cell transmission-based pedestrian model. In Hong Kong, research works related to the pedestrians can be found in Lam and Cheung (1999). Pedestrian travel time functions for the various pedestrian facilities within the MTR stations had been calibrated. Then, the calibrated functions by facility types were incorporated into the PEDROUTE simulation model for validation. Quarry Bay and Causeway Bay MTR stations were selected for the model development using the PEDROUTE simulation package.

2.4 PEDESTRIAN FLOW STUDIES

Lam et al. (1995) conducted a comprehensive study of the pedestrian flow characteristics on the street levels in Hong Kong congested urban areas. They studied the pedestrian speed-flow relationships for the indoor and outdoor walkways, the signalized crosswalks, the light rail transit crosswalks and the stairways. In addition, the average walking speeds extracted from the previous studies in the various international cities were compared. The findings of Lam's paper laid a foundation for the development of the pedestrian planning and design standards in Hong Kong. Later, Lam and Cheung (2000) successfully calibrated and validated the relationships between the pedestrian flow and walking time for various facilities in Hong Kong. Different types of pedestrian facilities were examined such as the indoor and outdoor walkways, the signalized crosswalks with and without mid-blocks, the signalized and non-signalized crosswalks leading to the light-rail transit stations, and the other five types of walking facilities in the railway stations. The walking time functions of these facilities were calibrated empirically. Pedestrian flow characteristics on these facilities were also compared. The research findings can be used as a source of reference for the development of the pedestrian facilities in Hong Kong or other Asian countries with similar environments. However, the above studies are mainly confined to the uni-directional flow characteristics.

In United Kingdom, Older (1968) examined the pedestrian flow characteristics on footways in the shopping streets in Central London. Only shoppers were focused in the study. It was found that their observed speed-flow relations were slightly different from the other types of pedestrians. A comparison of the flow characteristics of shoppers in London (Older, 1968) together with commuters in New York (Fruin, 1987) was found in Pushkarev and Zupan (1975). Morrall et al. (1991) made a comparison of the pedestrian flow characteristics in Canada with the other Asian cities. In Germany, Oeding (1963) indicated the different speed-flow relationships for different types of pedestrians such as shoppers and commuters. Verlander and Heydecker (1997) carried out an empirical study of the pedestrian route choice in Netherlands. Griffiths et al. (1984a, b, c & 1985) conducted a comprehensive study on the delays at pedestrian crossings by using a simulation model. Daamen and Hoogendoorn (2007) carried out a research study to investigate the pedestrian flow-density relations in Netherlands.

Seneviratne and Morrall (1985a & b) carried out the research for pedestrians in Calgary. It was concluded that the pedestrian planning techniques for Asian countries should be based on the local pedestrian characteristics. Tanaboriboon et al. (1986) conducted a pedestrian characteristics study in Singapore. Later, Tanaboriboon and Guyano (1991) carried out the research on the pedestrian movements in Bangkok. In addition, it was stated in their studies that the local standards are required for the design of the pedestrian facilities in the Asian countries. Local authorities or governments should not adopt the western pedestrian design standards directly. Therefore, there is a need to develop a local set of the pedestrian design standards for Hong Kong or the other Asian countries with similar environments.

2.5 Bi-directional Flow Effects on the Pedestrian Facilities

The bi-directional pedestrian flows and its effects on the pedestrian flow characteristics have been gaining increasing recognition in the pedestrian research area. Unlike roadways where vehicle flows are separated by the direction, pedestrian walkways tend to operate in bi-directions or even multi-directions. This means that the solutions derived from the uni-directional flow assumptions may not be able to properly describe the pedestrian flows under the prevalent bi-directional flow condition. Blue and Adler (1999 & 2001) conducted a study to investigate the effects of the bi-directional pedestrian flows. The bi-directional emergent fundamental pedestrian flows were simulated by using the cellular automata micro-simulation method. Daly et al. (1991) calibrated the pedestrian speed-flow relationships for the walking facilities in the London underground stations. In addition, the effective capacities under the directional distributions of pedestrian flows were proposed. However, these proposed effective capacities have not been validated or supported by any empirical data.

A number of microscopic modeling approaches is proposed and developed by considering the pedestrian interaction and/or conflicts. A bi-directional pedestrian stream model with an oblique intersecting angle was developed by Wong et al. (2010). Seyfried et al. (2006) proposed to describe pedestrians as different individuals rather than as a whole as pedestrians are all separated entities. A number of discrete models had been proposed using the cellular automation approach (Yu and Song, 2007; Weng et al. 2007). Jiang and Wu (2007) modeled the pedestrian behaviors using lattice gas technique. A simulation of evacuation process using multi-grid model for pedestrian dynamics can be found by Song et al. (2006). Model considering the human behaviors and environmental influence can be found by Yu and Song (2007). The enhancement of these discrete models can realize the reliability of the modeling results of pedestrian dynamic. Recently, some research works can be found in relation to self-organization of pedestrian movements (Helbing et al., 2005; Moussaid et al., 2009).

Empirical studies have been conducted in Hong Kong in relation to the bi-directional pedestrian flow characteristics on a number of pedestrian facilities. These studies included Cheung and Lam (1997) for the transit stations, Lam et al. (2003) for the indoor walkways and Lam et al. (2002) for the signalized crosswalks. These studies highlighted the important role played by the bi-directional flow effects on the pedestrian flow characteristics. They investigated the relationships between the reduction of the effective capacity on the pedestrian facilities and the directional distribution of pedestrian flows. They also studied the effects of the bi-directional pedestrian flows on the reduction of at-capacity walking speed. For the signalized crosswalks, Lam et al. (2002) found that the effects of the bi-directional pedestrian flows are particularly significant with a heavy imbalance of the directional distribution split of pedestrians and the facility capacity approached. Walking speed and effective capacity of the signalized crosswalks reduce with the increasing imbalance of directional split of pedestrians. Lam et al. (2003) successfully calibrated the generalized walking time function for the indoor walkways (i.e. a more general function for estimating the pedestrian walking time taking into account the bi-directional pedestrian flow effects). The effects of the bi-directional pedestrian flows were investigated empirically with particular emphasis on the walking time.

In particular, pedestrians facing a heavy opposing flow may force an increase in the risk of accidents, discomfort due to conflicts, and delays caused by the inability to select their walking speeds especially under the high flow volumes

(Lam et al., 2002). In fact, Lam et. al (2002) highlighted the need to review the current Transport Planning and Design Manual (the code of practice and design in Hong Kong). It is necessary to ensure and provide the adequate safety of pedestrians on heavily used crossings, especially when the bi-directional flow effects are considered. In particular, the bi-directional flow effects may be significant at the MTR stations during peak periods when the high pedestrian flows are prevalent.

2.6 WALKING SPEED VARIATIONS

A study of the travel time variability for the trips by the private vehicles had been investigated in United State of America and United Kingdom by Herman and Lam (1974). They investigated various statistical properties of the observed travel time data. Sterman and Schofer (1976) concentrated on the bus travel time reliability at the North-western University. Richardson and Taylor (1978) carried out a study of the travel time reliability for the commuter journeys using private cars in Melbourne, Australia. They suggested that the reliability of the travel time for the vehicle journeys is considered to be a very important factor affecting the people choices on the various transportation modes. A minimization of the perceived variations in the daily travel time might be a vital factor in the choice of mode by each pedestrian.

Later, Taylor (1982) conducted a study regarding the travel time reliability for a work trip using two comparatively alternatives on the public transport modes in Paris which are the bus and underground rail (metro). He found that while the bus offered a potentially direct service in terms of its free travel time and route location. However, the metro provided a faster and more reliable service under the normal operating conditions. Taylor (1982) summarized his previous and other researchers' studies and suggested that the distributions of travel time variations for vehicles may be described as either normal distribution or log-normal distribution under different conditions. However, their studies are confined to vehicles only. The study in this thesis is believed to be the first to focus on the bi-directional flow effects of walking time and variations (also known as standard deviation) at the pedestrian facilities in Hong Kong.

A number of researchers in the previous studies successfully calibrated the relationships between mean travel time and its variation for vehicles. They empirically showed that the standard deviation (SD_t) of the vehicle travel time variations should be proportional to the square root of the mean travel time ($\bar{t}$) and the function is shown as follows:

$$SD_t = \alpha\sqrt{\bar{t}} \tag{2.1}$$

where:

SD_t is the standard deviation of the mean travel time;

$\bar{t}$ is the mean travel time; and

α is the "travel time variability ratio".

In the previous studies, the distributions of the travel time variations were successfully constructed by standardization in terms of the means of the section travel time and standard deviations for the vehicles. It was found that the observed distributions of the vehicle travel time data were well presented by the normal distribution but only for the congested data. Moreover, Smeed and Jeffcoate (1971) suggested that the normal distribution represented their data over the whole range of the observations. However, Richardson and Taylor (1978) found that the log-normal distribution might provide a better fit to the observed travel time variation data for the private cars than the normal distribution. Taylor (1982) later proved that the distributions of the travel time variations of the buses would be better represented by a normal distribution. In addition, Taylor (1982) also found that the metro data supported the earlier findings which were better fitted by a log-normal distribution. Therefore, the distributions of the travel time variations for the vehicles were constructed in terms of the standardized variate x_{ij} for the i th observation of group j. Then the standardized travel time variate x_{ij} is

$$x_{ij} = \frac{\left(t_{ij} - \bar{t}_j\right)}{s_j} \tag{2.2}$$

where:

t_{ij} is the i th observed travel time of group j;

$\bar{t}_j$ is the mean travel time of group j; and

s_j is the standard deviation of the travel time of group j.

Taylor (1982) concluded that the normal distribution was more suited to the congested links for the vehicles while the un-congested links had variations better described by the log-normal distribution. The standardized log-transformed travel time variate z_{ij} is

$$z_{ij} = \frac{\left(\pi_{ij} - \bar{\pi}_j\right)}{s_j} \tag{2.3}$$

where:

$\pi_{ij} = log_e\left(t_{ij}\right)$;

t_{ij} is the i^{th} observed travel time of group j;

$\bar{\pi}_j$ is the mean π_{ij} of group j; and

s_j is the standard deviation of the travel time of group j.

The distribution of z_{ij} data is equivalent to a log-normal distribution of t_{ij} data. This log-transformation excellent removed the right skewness of the travel time data. Therefore, the log-normal distribution might provide a better fit than the normal distribution so as to model the observed travel time data.

2.7 LEVEL-OF-SERVICE STANDARDS FOR THE PEDESTRIAN FACILITIES

The Level-of-Service (LOS) concept is often used at the road traffic facilities to evaluate the quality of the facility in question. The Highway Capacity Manual (Transportation Research Board, 2000) employs several LOS measures for the uninterrupted (walkways) and the interrupted (crosswalks) pedestrian facilities. LOS measure employed by the Highway Capacity Manual (Transportation Research Board, 2000) at the signalized crosswalks is the amount of congestion (quality-of-flow) faced by pedestrians who are traversing the crosswalk. The congestion levels on the facility also influence the pedestrian locomotion that leads the reductions on walking speed (Fruin, 1987).

A recent study by Goh and Lam (2004) highlighted the importance of the pedestrian LOS at the signalized crosswalks as an important indicator of the safety in the design of the interval of the pedestrian green time. The main factors affecting the quality-of-flow LOS are the circumstances under which pedestrians operate (flow volume, bi-directional flow and etc.) and the characteristics of pedestrians (age, sex, trip purpose and etc.). Nevertheless, despite the large number of possible crosswalk configurations, the pedestrian characteristics and the varying traffic conditions, the LOS standards does not explicitly account for these differences. This practice is due to the difficulty of incorporating different parameters into the design and evaluation process. Although the practice has, over the years, proven its effectiveness, the use of a normative design value is not without its shortcomings.

The LOS for pedestrians (Fruin, 1970) is an important concept in the design and evaluation of the pedestrian facilities. LOS standards for pedestrians would also provide a useful guide for the design of the pedestrian facilities. The walking speed, the pedestrian spacing, and the probability of conflict at the various traffic concentration are the major factor to determine each service level. Seneviratne and Morrall (1985b) considered the perceptions of the quality of service for the ranking and designing of the pedestrian facilities in which the characteristics of the trip makers, the characteristics of the trips and the physical features. Sarker (1993) proposed and defined six service levels for pedestrians according to the quality of the facility provided, namely safety, security, convenience and comfort, continuity, system coherence, and visual and psychological attractiveness of the environs.

Mori and Tsukaguchi (1987) conducted a study regarding the design and evaluation of the Asian pedestrian facilities. A new method for evaluating the service levels for the pedestrian facilities under different flow conditions. Gerilla et al. (1995) proposed the LOS standards in Manila for evaluating the pedestrian facilities according to the behavioral characteristics of pedestrians and their preferences to the factors that affecting their choices of routes. Khisty (1994) found that the qualitative environmental factors appear to be as important as the quantitative flows, speeds and density factors in the planning, designing, and evaluating of the pedestrian facilities. Landis et al. (2001) conducted a study to model the roadside walking environment using pedestrian LOS.

Henson (2000) summarized the latest research studies in relation to the LOS for the pedestrian facilities. He commented that the pedestrian LOS requires further research. Research related to the LOS standards for the signalized crosswalks in Hong Kong can be found in Lam and Lee (2001). Time for pedestrians in Hong Kong was found to be the most important factor of concern, with an interest in the environment of being low priority. A similar study related to the LOS for stairways in Hong Kong underground stations had been carried out by Lee et al. (2005). Lighting and clear visibility at the stairways was found to be the major factor of concern, with an interest in the environment of being low priority. This finding also confirmed the results observed in the previous LOS study for the signalized crosswalks.

The previous research studies have ensured that the design of a pedestrian facility should consider more qualitative factors (such as environmental factors) rather than only quantitative measures of effectiveness (such as speed, flow and density). This study is believed to be one of the first attempts that the effects of the bi-directional pedestrian flows are explicitly accounted for in the LOS standards for various pedestrian facilities. It is expected that this study will be highly useful in the planning, design and further improvement of the walking facilities in Hong Kong and other Asian cities as Asians in general have smaller physiques and more tolerant to the invasion of space.

2.8 SUMMARY

The objective of this chapter is to conduct a comprehensive literature review on the previous research works related to the pedestrian studies. After reviewed the previous related works, it was found that attention had been given to investigate the pedestrian flow characteristics in the different countries.

The aim of this research is to model the pedestrian activity behaviors in Hong Kong congested urban areas. Predicting pedestrian flows and walking time requires a sophisticated PAS model. The previous research studies on the pedestrian behaviors and characteristics, indeed, contribute to the modeling of the pedestrian activity choices and the development of PAS model for Hong Kong congested urban areas. It is hoped that the developed PAS model could be used as a source of reference for predicting the spatial distribution of the areas and the temporal distribution of the pedestrians accurately. The modeling framework of the pedestrian activity-simulation model is discussed in Chapter 3 together with a case study.

3 DEVELOPMENT OF THE PEDESTRIAN ACTIVITY-SIMULATION MODEL

3.1 INTRODUCTION

Chapter 2 gives a comprehensive literature review on the pedestrian research studies. The research studies involves the Pedestrian Activity-Simulation (PAS) models, pedestrian activity and destination choice models, the pedestrian flow studies, the bi-directional flow effects on the pedestrian facilities, the walking speed variations and the level-of-service standards for the pedestrian facilities. This chapter aims to describe the development of the PAS model for the case study. This chapter is an edited version of: Lee, J.Y.S. and Lam, W.H.K., 2007. Development of a pedestrian simulation model for Hong Kong congested urban area. *Proceedings of the 86th Transportation Research Board Annual Meeting*, Paper no. 07-1432 (CD-ROM).

An area is chosen for case study which is located at the most congested urban area in Hong Kong – Causeway Bay. Observational and tracking surveys were carried out within the chosen study area simultaneously to gather data. The collected data involved pedestrian flows generated from and attracted to each origin and destination, travel patterns of the pedestrians, total trip durations and activity durations. With the data collected, pedestrian Origin-Destination (OD) matrices can be constituted. They were then further incorporated into the PAS model. The PAS model was then developed together with other necessary elements, which are the generalized walking time functions for signalized crosswalks and outdoor walkways (in Chapter 5) and the walking speed variations (in Chapter 6).

There are 6 sections in this chapter. In Section 3.1, an introduction of this chapter is presented. The development of the pedestrian activity-simulation model is framed and discussed in Section 3.2. Then, a congested urban area in Hong Kong is selected for case study. The selection of the study area is also described in Section 3.3 together with the simulation software – SERVICE MODEL which is selected as a platform to develop the PAS model. The data collection, observational and tracking surveys are demonstrated in Section 3.4. The pedestrian OD matrices generated from the data collected are also outlined in Section 3.5. Finally, a summary is presented in Section 3.6.

3.2 DEVELOPMENT OF PEDESTRIAN ACTIVITY-SIMULATION MODEL

This chapter puts forward an activity approach for modeling and simulating pedestrian movements in congested urban areas which explicitly takes into account the pedestrian activity duration. Figure 3.1 illustrates the modeling framework of PAS model. The PAS model consists of six main components.

These components are network configuration, traffic schemes, generalized walking time functions of various facility types, walking speed variation, time sliced origin-destination flow matrices of pedestrian and pedestrian activity and destination choice models.

In order to develop the activity-based simulation model, network configuration is firstly constructed. Lengths of the simulation and time sliced period are defined. Areas are defined in the network figuration with dimensions and by facility types. Pedestrian walking time-density relationships by facility types and walking time variation are associated to each area taking into account the bi-directional flow effects. The capacity of each defined area is based on its dimension and pedestrian physical size. Locations of special infrastructure (i.e. signalized crosswalks, Pedestrianisation Scheme, etc.) and obstacles are defined in the model. Links are connected in between areas such that pedestrian can move from one area to another area.

Time sliced OD flow matrices for pedestrian trips are required to incorporate into the model through input component. As mentioned in Introduction Section, in order to improve pedestrian circulation, Hong Kong SAR Government started to implement a number of traffic improvement schemes such as Pedestrianisation Schemes in congested urban areas since 2000. Network configuration and pedestrian OD flow matrices will be changed as the implementation of these traffic schemes. After the time sliced OD flow matrices are loaded into the model, pedestrians are assigned to different origins.

By using the congestion level and directional distribution of pedestrian flows (i.e. flow ratio, r), walking time of a pedestrian to traverse a facility can be estimated by the generalized walking time function taking into account bi-directional flow effects and the walking time variation. Pedestrians would have chance to perform shopping activity during simulation. However, shopping activity is only considered in this model. The shopping location is depended on the store patronage. The higher the store patronage the higher chance of pedestrian would shop at. The shopping durations, the time and location of destinations of the pedestrians is generated by the pedestrian activity and destination choice models.

Model results such as pedestrian flows, walking time and densities can be obtained by tracking the pedestrians in the model while they are walking and performing activities. The newly proposed activity-based approach is then applied to a case study to assess the performance of the simulation approach. Comparison is made between an independent set of observed data from the surveys and the results simulated by the newly proposed activity-based approach and the traditional trip-based approach.

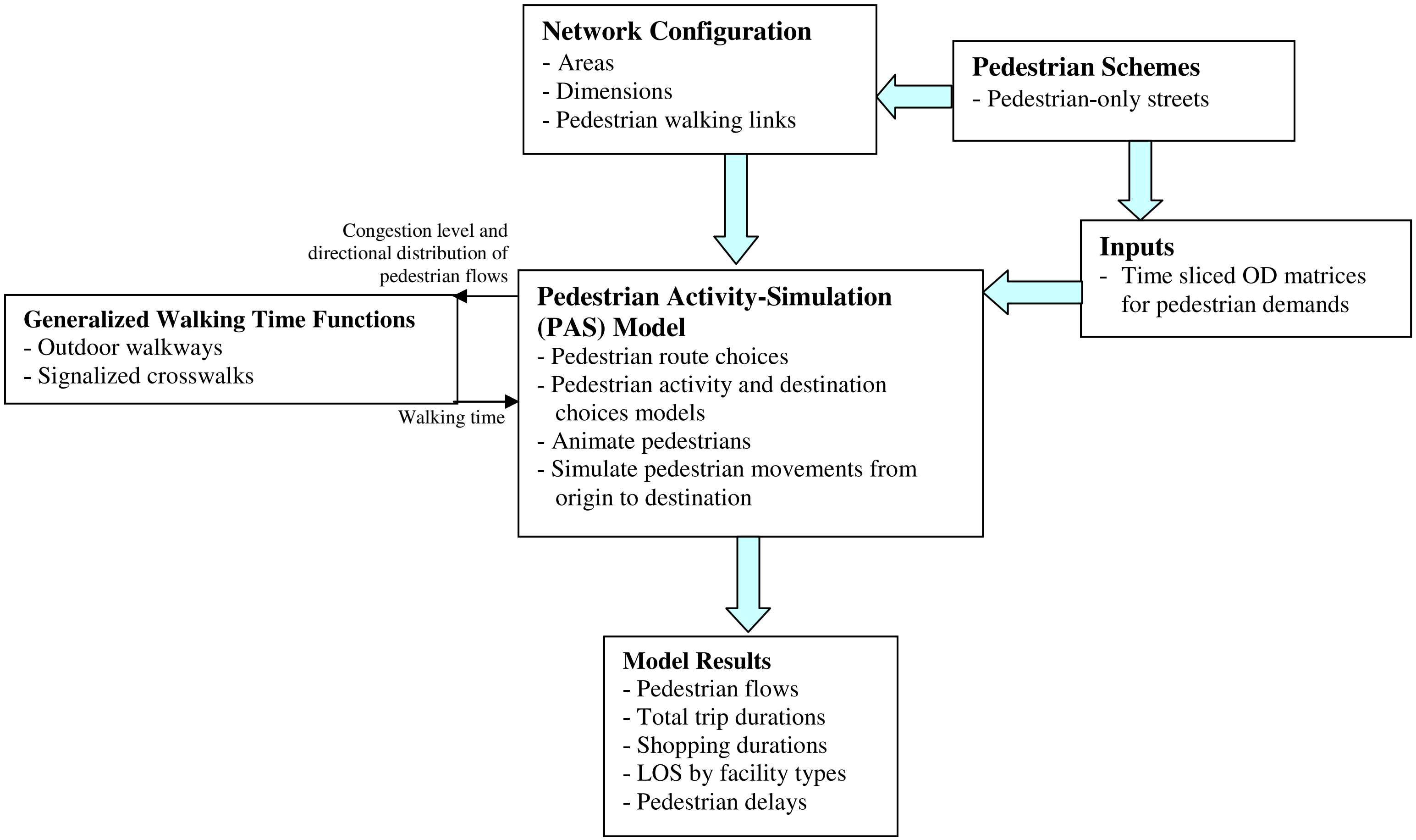


Figure 3.1 Modeling framework of the PAS model

3.3 A CASE STUDY

As mentioned in the literature review in Section 2.3, a comparison of 6 simulation packages is carried out by the Mass Transit Railway (MTR) Corporation Limited (1998). SERVICE MODEL was found to be capable as the platform for the development of the pedestrian simulation model. Lee (2002) calibrated and validated a pedestrian simulation-assignment model for the MTR station using the SERVICE MODEL as the simulation platform. Thus, in this research study, the SERVICE MODEL is also adopted to develop the PAS model for simulating pedestrian movements which explicitly takes into account the pedestrian activities.

Causeway Bay, a substantial commercial and retail area, is one of the most popular shopping districts in Hong Kong. Figure 3.2 shows the location map of Causeway Bay in Hong Kong. It is flocked with people and heavy traffic throughout the day. Insufficient road space to accommodate both vehicular traffic and pedestrians may result in traffic accidents. The Hong Kong Government implemented a number of Pedestrian Schemes (PS)[1] and a Pedestrian Priority Zone[2] in the more crowded district in Hong Kong. The detail information of the Pedestrian Schemes and Pedestrian Priority Zone can be found in Appendices A

[1] information about Pedestrian Schemes can be found in "Pedestrian" from the Transport Department internet homepage http://www.td.gov.hk/transport_in_hong_kong/pedestrianisation/pedestrianisation/index.htm

[2] information about Pedestrian Priority Zone can be found in "Pedestrian Plan for Causeway Bay" from the Planning Department internet homepage http://www.pland.gov.hk/p_study/prog_s/pedestrian/pub_report/e_index.htm

and B respectively. The purposes are to improve the environment and safety for pedestrians and to give pedestrians priority in the use of road space. As the pedestrian movements within the congested urban areas are critical during the peak periods, an understanding or knowledge of peak hour pedestrian flow characteristics would help in the design and improvement of the pedestrian facilities in congested urban areas. Causeway Bay is then selected for case study.

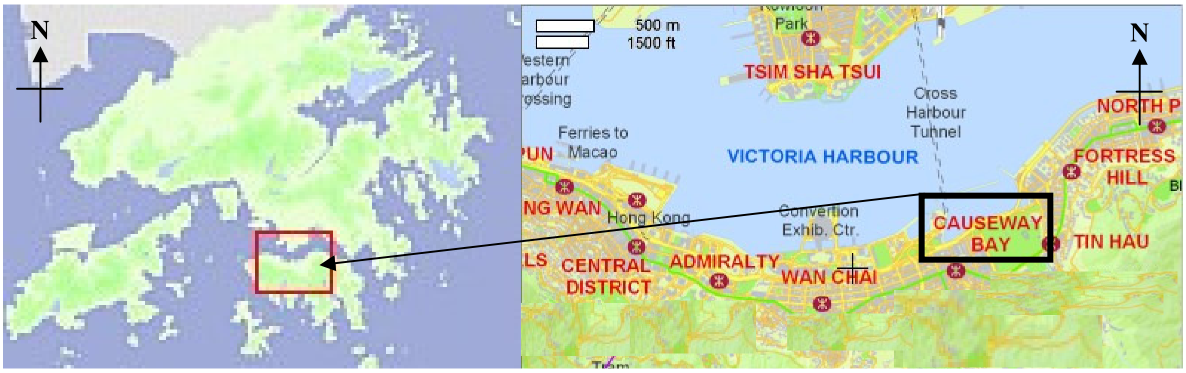


Figure 3.2 Location map of Causeway Bay

Figure 3.3 illustrates a part-time pedestrian-only street in Hong Kong. After the implementation of the part-time PS, pedestrians give the full priority to access on the roads during a specific time period. Thus, pedestrians now have more space and freedom, to walk and as no vehicular traffic is allowed on a pedestrian-only street in the area. Pedestrians may conduct more activities within this area. Because of this, an area at the heart of Causeway Bay, connecting to the MTR station, was selected for the case study. Figure 3.4 shows the geography of the chosen study area. A part time PS (i.e. pedestrian–only streets from 4 p.m. to the midnight during weekdays) was implemented within the study area as shown in

Figure 3.4. Hence, no vehicular access is allowed between 4 p.m. and midnight on weekdays making some roads within the study area free for pedestrians use as walkways during the time period. In Figure 3.4, the numbers in the circles are the OD coding which are discussed in Section 3.5.

Figure 3.3 A part-time pedestrian-only street

3.4 DATA COLLECTION

On Friday 5 August 2005, a large-scale of survey was conducted at the study area with the assistance of 70 surveyors. Two survey periods were chosen, an off-peak period from 2 p.m. to 4 p.m. (without PS implemented) and a peak period from 5 p.m. to 7 p.m. (with PS implemented). The selection of the survey period was based on the passenger data of the Causeway Bay MTR station provided by the MTR Corporation Limited. The passenger data are the daily records of the incoming and outgoing passenger demands of the Causeway Bay MTR station. It was found that the evening peak period (i.e. 5 p.m. to 7 p.m.) was the most congested period through out the day. The synchronization of the surveyors' stopwatches was of prime importance before the commencement of the surveys. Detail discussion on the survey methodology can be found in Appendices C and D. In order to collect data for the development of the PAS model and the modeling of the pedestrian activity and destination choices (in Chapter 4), two types of surveys were conducted simultaneously: (a) an observational survey; and (b) a tracking survey. The details of these two surveys are described below.

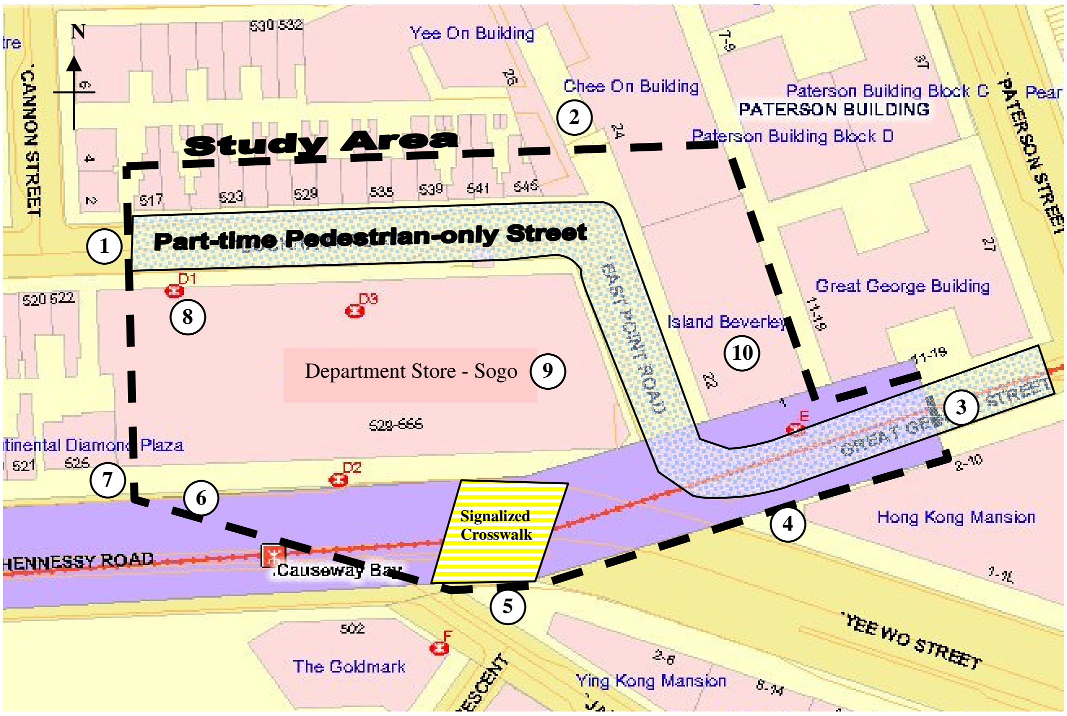


Figure 3.4 Geography of the chosen study area

3.4.1 Observational Survey

Twenty-two surveyors were responsible for counting the location flows. A stopwatch and two tally counters were given to each surveyor for measurement purposes. They were requested to count the total pedestrians crossing in both directions at the assigned locations, over 15-minute intervals. Seven video cameras were set up on the 10th floor of a building to simultaneously record the complex and high pedestrian flow movements at the selected locations. Using this method, the measurement error of the surveyors can be minimized. The videotapes recorded on-site were then further processed by mapping a time code on the video records before data extraction. The time code is encoded in 25 frames per second. Therefore, a precision level of 0.04 second can be achieved and the total number of pedestrians crossing the selected locations in the 15-minute intervals can be extracted in the laboratory from the video records. The pedestrian flows generated from and attracted to each origin and destination can be determined by using the location count and video recording techniques. Detail discussion on the observational survey can be found in Appendix D.

3.4.2 Tracking Survey

Forty surveyors were allocated to several major locations. High pedestrian flows were observed during the pilot survey at these locations. A stopwatch and maps were given to each surveyor for recording purposes. They were requested to follow an individual pedestrian or a group of pedestrians walking in the study area.

They were also required to record the following data on the maps: time at origin, origin location, time at destination, destination location, the actual walking path of each sample pedestrian(s), time when sample pedestrian(s) enter and exit a shop(s), party size and gender. By using the tracking survey technique, sufficient data were collected to gather the travel pattern of pedestrian within the study area. The collected travel patterns of the pedestrians together with the pedestrian flows generated from and attracted to each origin and destination can then be composed to constitute the pedestrian OD flow matrices. Detail discussion on the tracking survey can be found in Appendix C.

3.5 PEDESTRIAN ORIGIN-DESTINATION (OD) FLOW MATRICES

Pedestrian OD flow matrices can be constituted and generated from the data collected from the observational and tracking surveys. Table 3.1 shows the pedestrian OD flow matrix of the peak period (i.e. 5 p.m. – 7 p.m.). Table 3.2 lists the location descriptions to the corresponding OD numbers shown in Table 3.1. The detailed locations of each OD are also illustrated in Figure 3.4.

In Table 3.1, the pedestrian flows generated from and attracted to each origin and destination can only be collected by the observational survey. The travel pattern of pedestrians cannot be collected from the observational survey. Hence, a supplementary tracking survey is required to carry out simultaneously so as to determine the travel pattern of the pedestrians by tracking the walking path of each sampled pedestrian(s).

Table 3.1 Pedestrian OD flow matrix of peak period (5 p.m.-7 p.m.)

		Destination										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
Origin	**1**	0	842	1479	337	353	0	284	1233	3663	487	**10134**
	2	488	0	1223	147	1349	189	123	837	1413	523	**6584**
	3	671	805	0	199	2512	0	242	2427	1266	855	**9158**
	4	191	0	103	0	571	439	205	404	727	304	**2944**
	5	1136	965	3104	542	0	415	637	1645	2360	650	**11526**
	6	47	62	334	35	1148	0	146	225	1033	50	**3080**
	7	0	143	717	469	389	1063	0	155	1666	67	**4669**
	8	2067	1402	1197	737	1386	686	262	0	851	810	**9846**
	9	4064	1961	3187	674	2701	724	920	1021	0	794	**18367**
	10	549	934	834	65	736	70	32	699	419	0	**4597**
Total		**11977**	**7521**	**12366**	**3205**	**11438**	**3586**	**2851**	**9086**	**15250**	**4736**	**80822**

Table 3.2 Location description of the OD coding

OD No.	Location Description
1	Lockhart Road
2	World Trade Centre
3	Great George Street
4	Yee Wo Street
5	Golden Centre
6	Bus Stop
7	Hennessy Road
8	Entrances/Exits of MTR station
9	Department Store – Sogo
10	Shopping Mall

Figure 3.5 illustrates the layout of the PAS model. The network configuration was firstly constructed. The layout of the study area was created using the graphical software - AutoCAD and had been incorporated into the PAS model. In this newly

developed PAS model, the study area is referred to as the pedestrian network including outdoor walkways, traffic lanes, signalized crosswalks, street-level stores, a large department store, a shopping mall, Entrances/Exits of the Causeway Bay MTR station, a bus stop and all the origins/destinations at the street level.

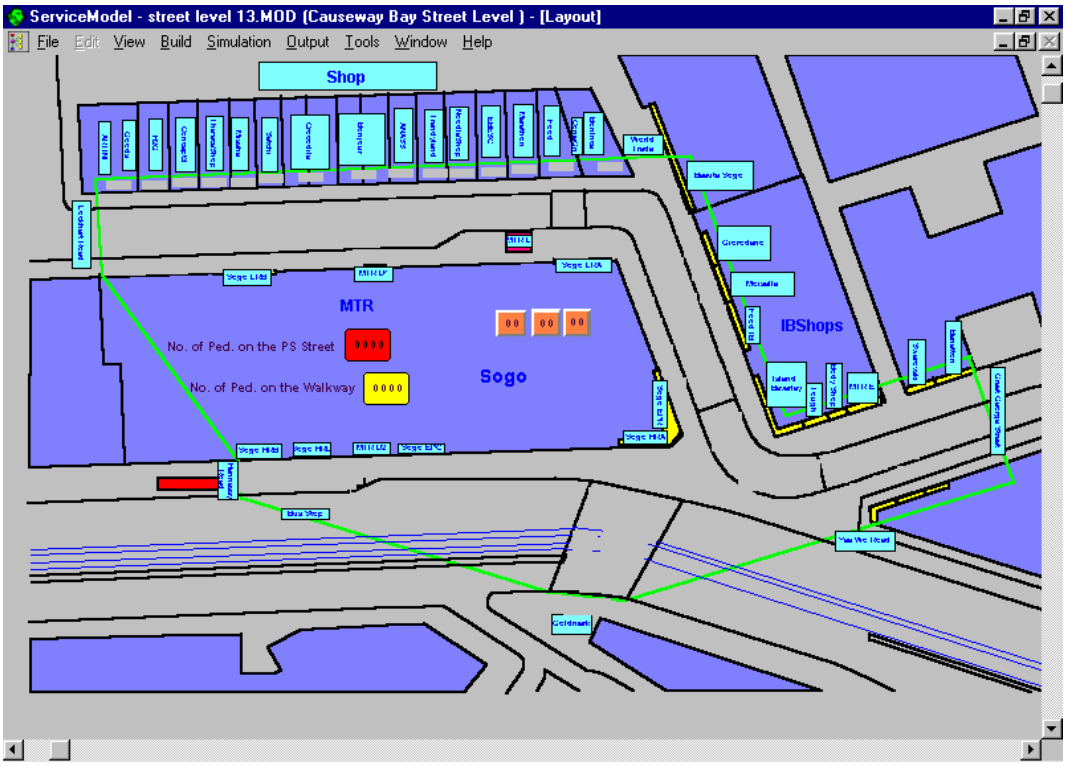


Figure 3.5 Layout of the PAS model

15-minute time interval was used for the analysis of the data collected for generating the pedestrian flow demands in terms of OD matrices. Therefore, eight time sliced OD matrices for pedestrian trips were extracted from the data collected at the study area for each time period. It was found that the pedestrian OD flow matrix from 18:30 to 18:45 was the one with the peak demand. It can be seen in

Table 3.1 that the majority of the pedestrians went to and from the large department store - Sogo. It is a 10-storey department store with a number of large shopping malls on the adjacent streets.

The layout of the study area is defined by locations. Locations are defined with the actual dimensions of the pedestrian facilities. The capacity of each defined location is based on its dimensions and the pedestrian physique. Each location has a speed-density characteristic allocated. Links are connected in between the locations such that pedestrians can move from one location to another. The pedestrian flows from one location to another depend on the number of people in the location and the time taken to move through the location.

Figure 3.6 shows the connection links defined in the PAS model. In total, there are 196 locations and 689 links in the pedestrian network. Table 3.3 lists the logos adopted in the PAS model together with their descriptions. Each dot represents an individual pedestrian. Figure 3.7 demonstrates the simulating condition of the study area using the traditional trip-based simulation model during the off-peak period. Dots in Figure 3.7 illustrate the pedestrian movements graphically within the study area.

Pedestrian facilities are classified into the outdoor walkways and the signalized crosswalks. The relationships between the walking speed and density for these two pedestrian facilities developed in Chapter 5 were then incorporated into the

PAS model to tabulate the walking time for each location. These relationships/functions explicitly take into account the bi-directional pedestrian flow effects. The detailed formulation of the generalized walking time functions for outdoor walkways and signalized crosswalks are discussed in Chapter 5.

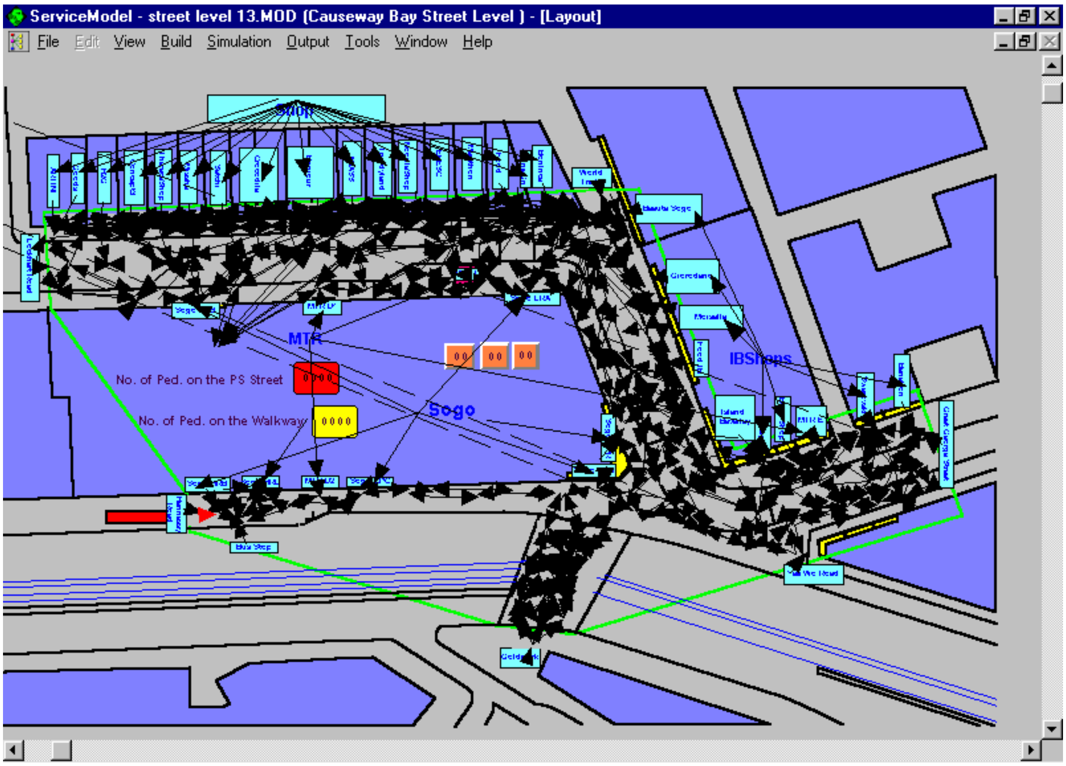


Figure 3.6 Network of the PAS model

The detailed construction of the time sliced OD matrices is presented in Section 3.4. The time sliced OD matrices were then incorporated into the PAS model as an important input component. As mentioned in Section 3.3, in order to improve the pedestrian circulation in Hong Kong congested urban areas, the Government has started to implement a number of PS such as part-time pedestrian-only streets in congested urban areas since 2000. Network configuration and pedestrian OD flow matrices would be changed after the implementation of the PS. After the time sliced pedestrian trip demands in term of OD matrices are loaded into the PAS model, pedestrians are assigned to the origin and entered to the study area. Then, the PAS model can be run after selection of the simulation run characteristics by the user such as off-peak or peak periods.

Table 3.3 Logos adopted in the PAS model and their descriptions

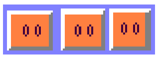
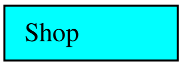
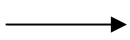
Logo	Description
	Single pedestrian
	Timer for the PAS model
	Street-level store
	Number of pedestrians on the PS street
	Number of pedestrians on the walkway
	Building
	Bus stop
	Network link

Figure 3.7 demonstrates the simulating condition during the off-peak period using a traditional trip-based simulation model. It should be noted that during the off-peak period, the part-time PS is not implemented. Pedestrians can only walk on the walkway as shown in Figure 3.7. As mentioned in Section 1.2, the traditional trip-based model assumed that pedestrians walk from their origins to their destinations directly. Thus, the pure walk trips are illustrated in Figure 3.7 only. It is assumed that pedestrians have not performed any shopping activities. However,

during the tracking survey, about 10% of the pedestrians who walked in the study area went shopping. Thus, if these pedestrian activities trips are simulated by the traditional trip-based model, the simulation results will be questioned.

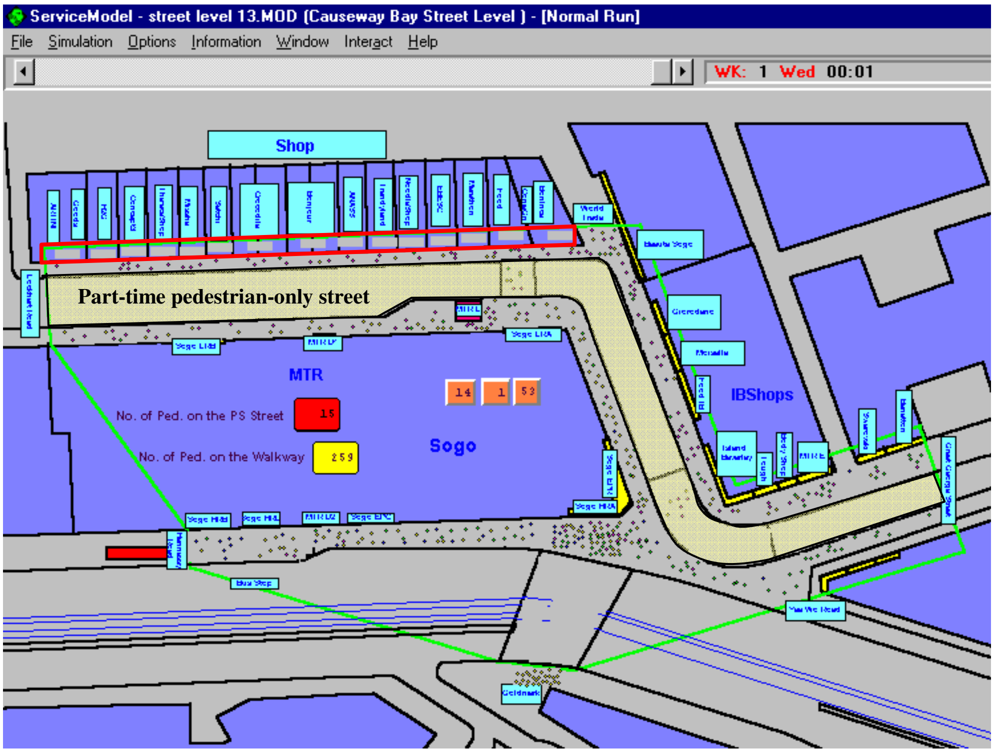


Figure 3.7 Simulation condition of the traditional trip-based model (off-peak period without PS implemented)

In this research study, the newly developed PAS model can overcome the above mentioned shortcoming resulted by the traditional trip-based simulation model as it can simulate the pedestrian activities movements and behaviors. Figure 3.8 illustrates the simulating condition during the peak period using the newly developed PAS model. In Figure 3.8, as the part-time PS is implemented within the study area, the road is served as a pedestrians' walkway. Thus, pedestrians can freely walk on the part-time pedestrian-only street during the peak period. As the pedestrian activities are taken into account in the PSA model, Figure 3.8 demonstrates that some pedestrians are performing shopping activities at the street-level stores. Therefore, the newly developed PAS model is more realistic to simulate the pedestrian movements in the study area than the traditional trip-based simulation model as the pedestrian activities are accounted for in the PAS model. The developed PAS model can simulate the pedestrian movements effectively by taking into account the bi-directional pedestrian flow effects on walking speeds and the walking speeds variations.

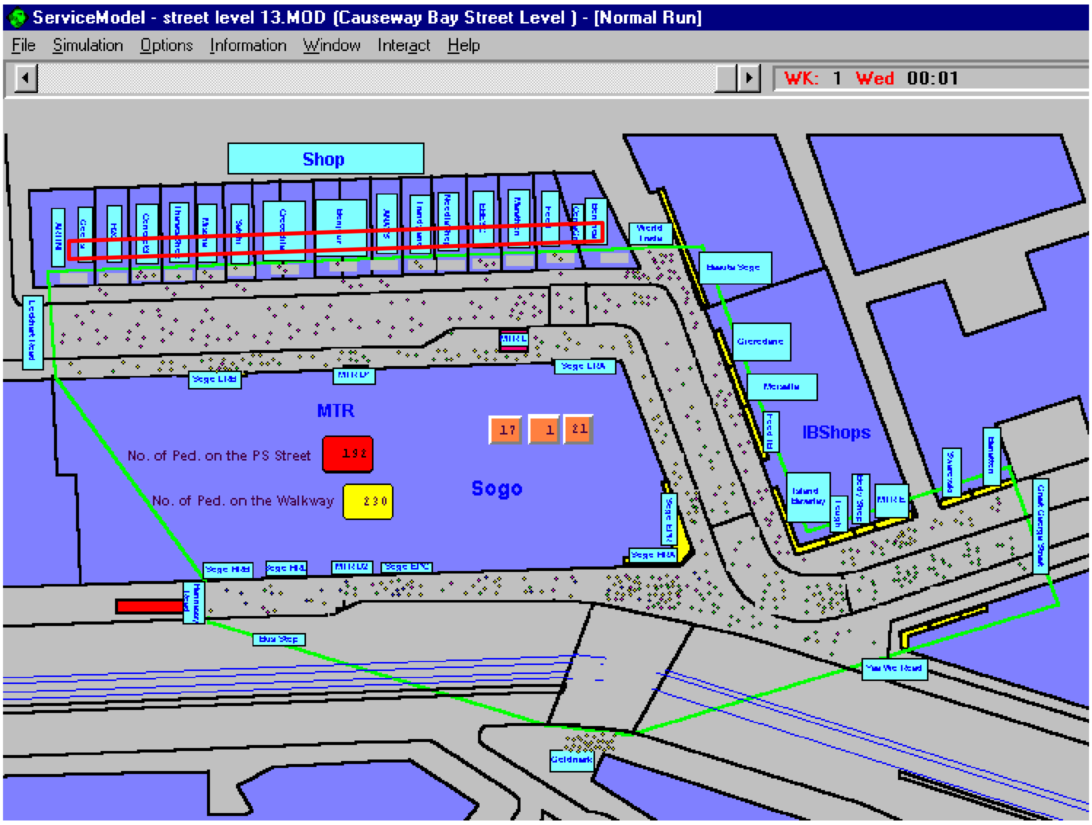


Figure 3.8 Simulation condition of the PAS model (peak period with PS implemented)

Once the PAS model is started, pedestrians are animated. By extracting the congestion levels and the directional distributions of pedestrian flows (i.e. flow ratio, r) from the PAS model during the simulation run, the walking time of pedestrians to traverse a facility can be estimated by the generalized walking time functions taking into account the bi-directional pedestrian flow effects. By using the calibrated pedestrian activity and destination choice models, the shopping durations, number of shops and destinations of pedestrians can then be predicted by updating the PAS model every second. The total simulation period of the PAS model is 120 minutes for each time period. Model results such as the pedestrian flows, walking time and densities by locations are stored in the computer files by tracing the animated pedestrians while they are walking and performing activities during the simulation run.

3.6 SUMMARY

The development of the PAS model is presented. An area in Causeway Bay was chosen for case study. The new PAS model was developed on the platform of the SERVICE MODEL to simulate the pedestrian movements within the study area. In order to collect sufficient data for model development, the observational and tracking surveys were carried out at the study area simultaneously. Data collected for model development are: (1) pedestrian flows at the chosen locations; (2) pedestrian OD flow matrices; and (3) pedestrian total trip and shopping durations.

The important input components of the PAS model are the time sliced OD flow matrices for pedestrian trips, the generalized walking time functions for outdoor walkways and signalized crosswalks, the walking speed variations, the network configuration, the pedestrian activity and destination choice models and the time duration of the part-time PS implemented. These inputs were then incorporated into the PAS model. The newly developed PAS model is capable to simulate the pedestrian movements for assessing the impacts of various PS such as changing the time duration of the implementation of the PS. The modeling of the pedestrian activity and destination choices are then discussed in Chapter 4.

4 MODELING THE PEDESTRIAN ACTIVITY AND DESTINATION CHOICES

4.1 INTRODUCTION

The newly developed PAS model is capable to simulate the pedestrian activity movements and behaviors. The modeling framework is discussed in Chapter 3. The data collection methodologies of the observational and tracking surveys are described. These two surveys are discussed particularly on their data extraction and analysis. The data collected and extracted are used to develop the PAS model. In this chapter, the modeling processes of the pedestrian activity and destination choices are described. This chapter is an edited version of: Lee, J.Y.S. and Lam, W.H.K., 2008. A model of pedestrian activity and destination choices using observational data. *Proceedings of the 13th International Conference of the Hong Kong Society for Transportation Studies*, 687-696.

The aim of this chapter is to calibrate the pedestrian activity and destination choice models in the congested urban areas. A modeling system is presented to determine the relationship between travel demand and pedestrian activity utility. Four decision models are recommended, namely the staying or leaving choice model, the shopping choice model, the destination choice model and the shopping duration distribution. Important factors affecting the pedestrian travel choices are identified. A tracking survey was conducted by tracing the walking paths of the sample pedestrians. Data collected during the tracking survey are used to calibrate the coefficients of the four decision models. The calibrated models are then incorporated into the PAS model as the important elements so as to derive the actual travel demand in the congested urban areas.

There are 5 sections in this chapter. An introduction of this chapter is firstly presented in Section 4.1. Then, the modeling framework of the four decision models is presented and described in Section 4.2. A case study with data collection is demonstrated in Sections 4.3 to gather data for the model calibration. After data were collected, calibration of the four decision models is then carried out. The calibrated results are presented in Section 4.4. Finally, a summary is presented in Section 4.5.

4.2 MODELING FRAMEWORK

4.2.1 Four Decision Models

A number of pedestrian shopping choice models had been calibrated in the previous studies. These models only consider the pedestrian choices on the store types. However, these studies did not taken into account the destination choices of the pedestrians and their activity durations simultaneously. Therefore, in this study, the pedestrian activity and destination choices are considered in the meantime. A modeling system is proposed to explicitly consider the pedestrian decisions or preferences on the activity and destination choices. This proposed system is to predict the distribution of pedestrian activities in space and time simultaneously and the distribution of pedestrian destination choices. Figure 4.1 shows the proposed modeling system. There are four decision choice models, namely the staying or leaving choice model, the shopping choice model, the destination choice model and the shopping duration distribution.

In Figure 4.1, when a pedestrian enters an area at an entry point (i.e. origin of this trip) and start his/her trip in the area, the staying or leaving decision can be defined as the pedestrian's choice between continuing to stay within the shopping area and planning to leave. After the pedestrian decided continuing to stay in the area (i.e. not to leave), the next issue that he/she needs to be considered is the decision on the shopping activity. The shopping choice model refers to the pedestrian preferences to perform shopping or not. If the pedestrian is not going to perform shopping, he/she would then continue walking in the area. However, if the pedestrian decides to go shopping, he/she will be randomly assigned to visit a store by the proportional distribution of the shopping records. The higher the patronage records of the stores, the higher the possibility for the pedestrians to visit the store. The duration of the pedestrian shopping at each store is derived from the shopping duration distribution. Once, the pedestrians plan to leave the shopping areas, pedestrians need to select a destination from the nearby exit (i.e. destination of this trip) to leave. The four proposed decision models can predict the universal pedestrian activity and destination choices, taking into account the shopping durations.

4.2.2 Multinomial Logit Model

Multinomial Logit (MNL) model is commonly used for both vehicular and pedestrian demand modeling in the transportation engineering. An assumption is made when the MNL model is used. Each individual attempts to choose the alternative choice, from an available choice set of the different alternatives. This procedure provides the maximum utility. The utility of an alternative n, U_n, can be expressed by:

$$U_n = V_n + \varepsilon_n \tag{4.1}$$

where V_n is a structural component specified as linear in parameters of the utility function, common to all elements related to choice n, and ε_n is the random component corresponding to V_n. It is assumed that the random component is independently and identically Gumbel distributed across individuals and alternatives leading to the MNL model.

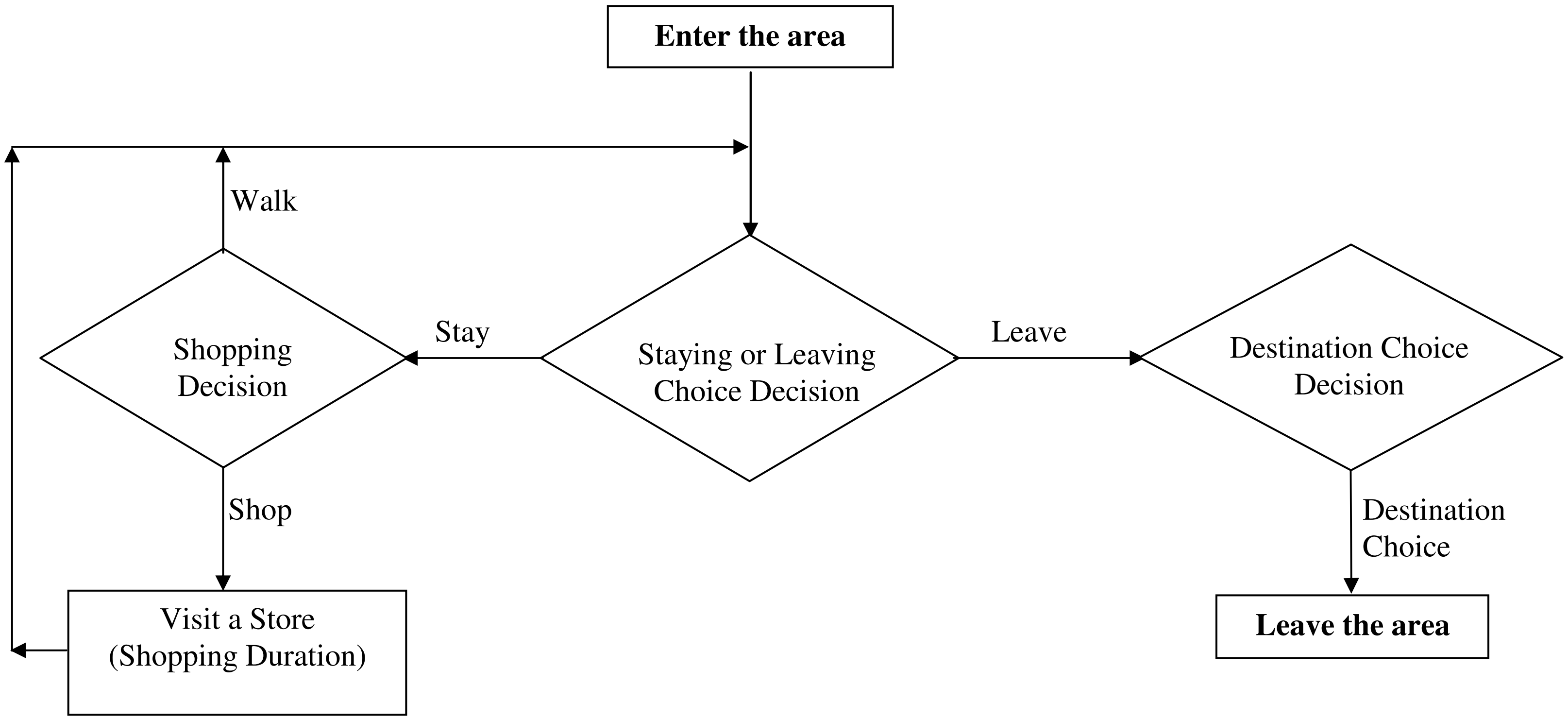


Figure 4.1 Flowchart of the proposed modeling system

The probability that a pedestrian chooses the alternative choice n is shown as follows:

$$P_n = \frac{\exp(V_n)}{\sum_{n'=1}^{N} \exp(V_{n'})} \tag{4.2}$$

where P_n is the probability that alternative choice n is chosen, and N is the total number of alternatives. Binary Logit (BL) model is a simplified form of the MNL model with only two alternative choices (i.e. $N = 2$). Due to its ease of estimation, interpretation and usefulness, the BL or MNL model has been widely used in the modeling of the pedestrian behaviors such as route and destination choices. For example, the MNL model has been used to model the pedestrian behaviors in the shopping areas and the pedestrian route choices for the retail facilities (Borgers and Timmermans, 1986a, 1986b & 2004). The BL and MNL models are attempted in this study for modeling the pedestrian activity and destination choices. By using the observed data collected from the tracking survey, the parameters of the pedestrian activity and destination choice models can be calibrated by a software package - LIMDEP (Greene, 2003).

4.3 CASE STUDY – CAUSEWAY BAY IN HONG KONG

Causeway Bay, a substantial commercial, retail area with other economic activities, was selected as the study area. Insufficient road space to accommodate both vehicular traffic and pedestrians may result in traffic accidents. In order to improve the environments and safety for pedestrians, the Hong Kong Government implemented various Pedestrian Schemes (PS) in the more crowded parts of Causeway Bay to give the priority to pedestrians regarding the use of road space. Thus, pedestrians now have more space as no vehicular traffic is allowed on a pedestrian-only street and pedestrians may conduct more activities within the areas. In view of the above, an area at the heart of Causeway Bay, connecting to the MTR station, was selected for the case study.

Figure 4.2 shows the geography of the chosen study area. A part time PS (i.e. pedestrian-only streets from 4 p.m. to the midnight during weekdays) was implemented within the study area as shown in Figure 4.2. Hence, no vehicular access is allowed between 4 p.m. and the midnight on weekdays, which makes some roads within the study area free for pedestrians use during the period.

4.3.1 Data Collection by Tracking Survey

On Friday 5 August 2005, a large-scale survey was conducted at the Causeway Bay study area. Detail of the tracking survey can be found in Section 3.4.2 and Appendix C. Two survey periods were chosen, an off-peak period from 2 p.m. to 4 p.m. (without PS implemented) and a peak period from 5 p.m. to 7 p.m. (with PS implemented). The selection of the survey period was based on the historical passenger data of the Causeway Bay MTR Station provided by the MTR

Corporation Limited. It was found that the evening peak period (i.e. 5 p.m. to 7 p.m.) was the most congested.

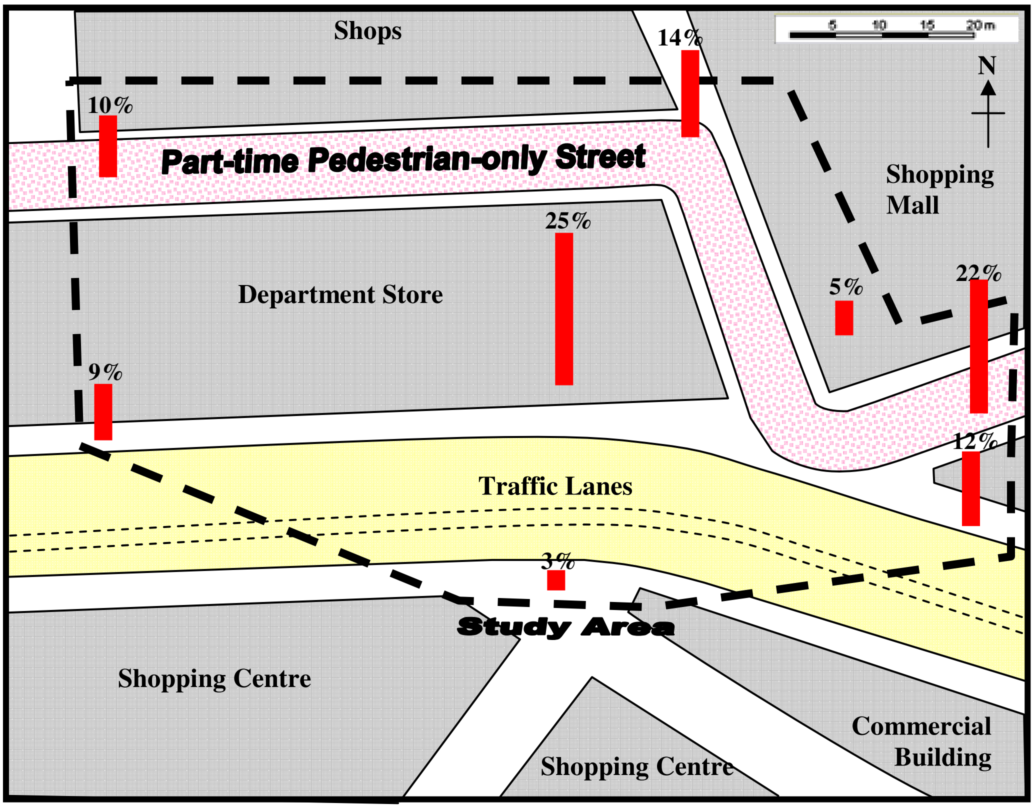


Figure 4.2 Distribution of pedestrians in exits

Before the commencement of the surveys, the synchronization of the surveyors' stopwatches was of prime importance. In order to collect data for the calibration of the proposed modeling system for predicting the pedestrian activity and destination choices, a tracking survey was conducted.

Forty surveyors were allocated to several major locations in which high pedestrian flows were observed at these locations during the pilot survey. A stopwatch and maps were given to each surveyor for recording purposes. They were requested to follow an individual pedestrian or a group of pedestrians walking in the study area. They were also required to record the following data on the maps given: time at origin, origin location, time at destination, destination location, the actual walking path of the selected sample pedestrian(s), time when the sample pedestrian(s) enter and exit the shop(s), party size and gender. By using the tracking survey technique, sufficient data were collected to calibrate the proposed four decision models to predict the pedestrian activity and destination choices.

4.3.2 Survey Results

Data collected from these surveys were briefly described in Lee & Lam (2005) and Appendix C. The survey results, by periods, are summarized in Table 4.1. The total number of pedestrian trips in the study area (street level) can be extracted from the data collected from the observational surveys. The observed total numbers of trips (matrix total) of the peak and off-peak periods were 80,822 and 51,378 respectively. The total number of samples taken from the tracking survey were 2422 pedestrians for the peak period (5:00 p.m.- 7:00 p.m.) and 2280 pedestrians for the off-peak period (2:00 p.m.- 4:00 p.m.) respectively.

Figure 4.3 shows the trip distributions of the indirect and direct trips by pedestrian arrival time. Direct trip means that pedestrians only pass through a study area without performing any activities, while indirect trip defines any trip where pedestrians perform some activities in a study area. The time interval for each vertical bar is 10 minutes.

Table 4.1 Summary of the survey results

	Off Peak Period (without PS implemented)	**Peak Period (with PS implemented)**
Time Period	2:00 p.m.- 4:00 p.m.	5:00 p.m.- 7:00 p.m.
Total No. of Trips Observed	**51, 378**	**80, 822**
Sample Size	2280	2422
Sample Group	1370	1408

The total numbers of the direct and indirect trips observed during off-peak period are 1222 trips and 148 trips respectively. Besides, the total numbers of the direct and indirect trips observed during peak period are 1257 trips and 151 trips respectively. The observed maximum numbers of the direct and indirect trips are 133 and 19 respectively during 5 p.m. to 5:10 p.m. During the peak period, PS was implemented in the study area enabling the section of road to serve as a pedestrian walkway. Vehicular access was restricted. Pedestrians were provided with safe and stress free space in which they can walk freely and at a personally chosen speed. More pedestrians are attracted to the study area to perform activities after the implementation of the part-time PS. Detail data analysis by demographic factors can be found in Appendix C.

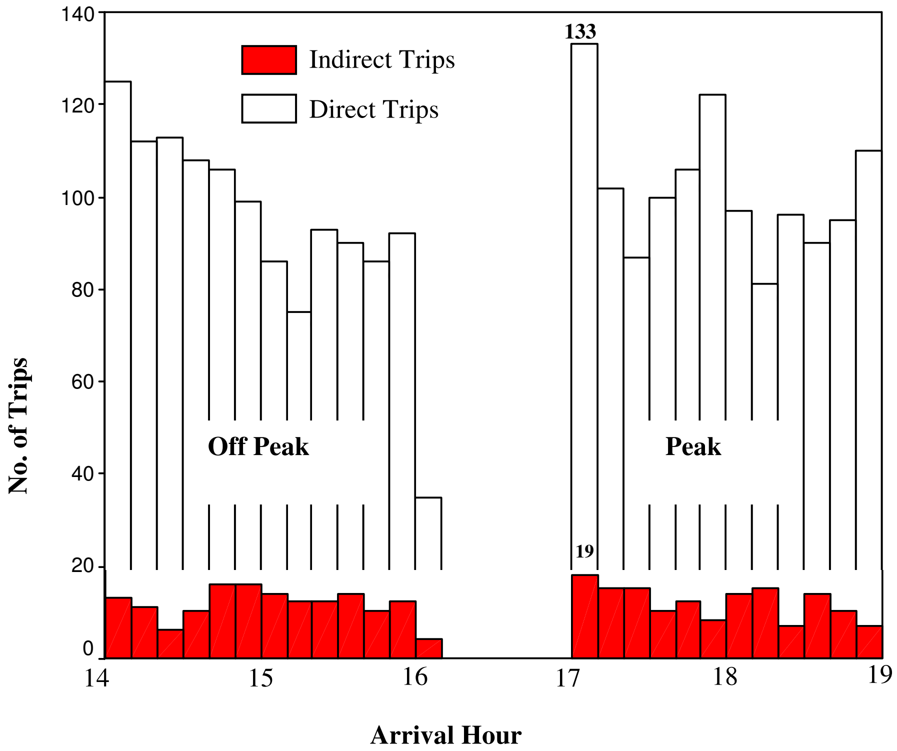


Figure 4.3 Trip distribution

The contrast of the numbers of trips between the indirect and direct trips can also be justified by the fact that pedestrians shopping at the street-level stores are only included in the indirect trips. Pedestrians going to and shopping at the large department store are excluded in the indirect trip category. The reason is that the trip duration data were collected manually.

During the tracking survey, surveyors were assigned to track the sampled pedestrians. Surveyors also recorded the pedestrians' walking path and time. It was observed during the pilot survey, the shopping durations of the pedestrians shopping at the large department store was generally very long (i.e. over 30 minutes). It is very costly for the surveyors to keep track of those pedestrian shopping trips in the large department store. Moreover, the survey periods were short (i.e. 2 hours each for off-peak and peak periods). Therefore, the entrances and exits of the department store were classified as the origin or destination. Trips for those pedestrians going into the department store without performing any activities at the street-level were classified as direct trip.

Figure 4.4 shows the trip duration distributions of the indirect and direct trips. The average trip durations of the direct and indirect trips are different obviously, being 73.9 seconds and 342.9 seconds respectively. Longer journey time of the indirect trips is observed than that of the direct trips. It was also found that 80% of pedestrians taking the direct trips use less than 111 seconds staying within the study area. Moreover, pedestrians taking the indirect trips use less than 476 seconds staying within the study area. Pedestrians taking the indirect trips stay longer in the study area than those opt for the direct trips. These differences can be explained by the fact that for those pedestrians with the direct trips, they only pass through the study area without performing any activities. For those pedestrians with the indirect trips, they perform some activities before they leave the study area such as shopping at stores and waiting for friends. Thus, pedestrians with the indirect trips have to stay in the study area longer to perform these activities.

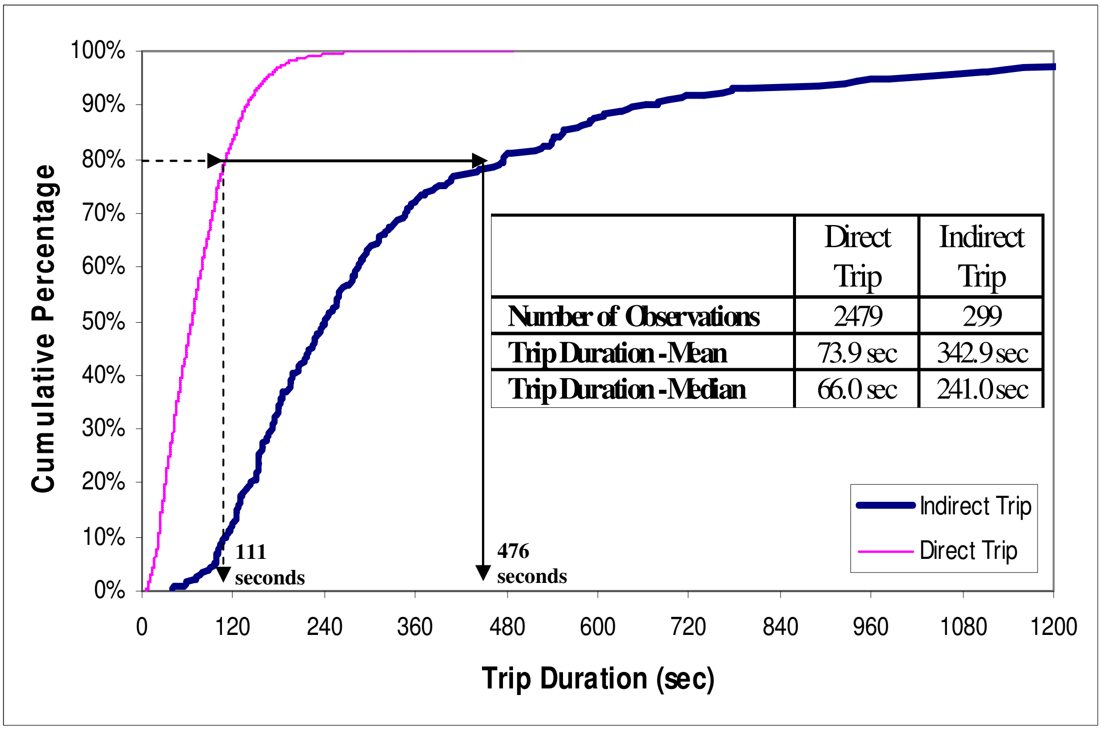


Figure 4.4 Trip duration distributions of the direct and indirect trips

4.3.3 Updating Time Interval

Figure 4.5 shows an example of a pedestrian walking in the study area. After the pedestrian walks in the study area at 17 hours 8 minutes and 1 second (i.e. 17:08:01), it is required to predict the pedestrian decision choice between continuing to stay and planning to leave. Data on when pedestrians decide to leave the area are not available in daily life. An updating time interval is therefore defined to estimate the time period that pedestrians will make decision. pedestrians will make a decision in a short period of time periodically (say every 10 seconds) to determine whether he/she continues to stay in the area or not.

Important factors affecting the pedestrian choices are identified. Two real time components are considered in the modeling process: Relative time t_R refers to the time difference between the current time and the time that pedestrians start the trip. Absolute time t_A refers to the time elapsed since the implementation of the part-time pedestrian street within the area. In Figure 4.5, after the sample pedestrian walked in the area, he/she needs to make decisions every 10 seconds to determine whether to leave the area or not. A sensitivity test on the updating time interval was carried out. The result is discussed later in Section 4.4.5.

4.4 MODEL CALIBRATION

4.4.1 Pedestrian Staying or Leaving Choice Model

4.4.1.1 Modeling

The decision of pedestrians staying in the study area is seen as a choice between two options: continue staying or leaving the study area. Therefore, the binary logit model was adopted and used for calibrating the pedestrian staying or leaving choice model. Two real time components are used in the model: Relative time t_R refers to the time difference between the current time and the time that pedestrians start the trip. Absolute time t_A refers to the time elapsed since the implementation of the part-time pedestrian scheme in the study area.

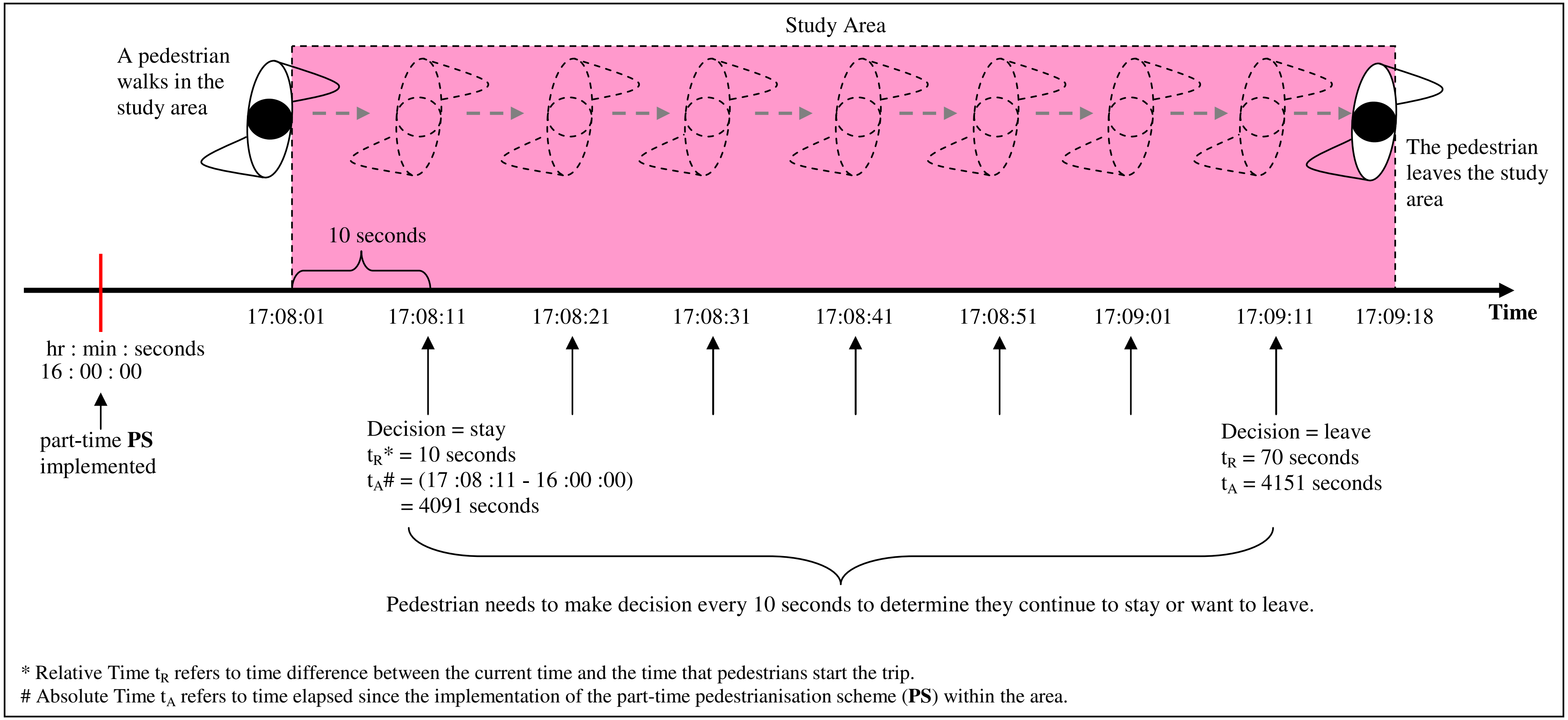


Figure 4.5 An example of a pedestrian walking within the study area

The structural utilities of staying St and leaving L, can be expressed by:

For staying choice: $V_{St} = \beta_R t_R + \beta_A t_A$ (4.3)

For leaving choice: $V_L = \beta_L x_L$ (4.4)

where V_{St} and V_L are the utilities of staying St and leaving L respectively. β_R and β_A are the calibrated parameters of relative time component t_R and absolute time component t_A respectively. A dummy variable x_L is introduced to the utility of leaving L, V_L. x_L equals to 1 when the pedestrian chooses to leave the area and 0 when the pedestrian chooses to stay in the area. β_L is the calibrated parameter of the dummy variable x_L. The probability that a pedestrian intends to leave the area:

$$P_L = \frac{exp(V_L)}{exp(V_L) + exp(V_{St})} \tag{4.5}$$

It is hypothesized that the probability of staying within the study area would decrease as both time components: relative and absolute time increase. This implies the values of parameters β_R and β_A of these two time components should be negative. Before the calibration of the pedestrian staying or leaving choice model, a number of explanatory factors have been considered based on the previous research studies. These explanatory factors are summarized in Appendix C. However, the effects of these factors are insignificant due to the size of the study area and the length of the study period.

4.4.1.2 Calibrated Results

Two important factors affecting the pedestrian staying or leaving choice are identified in order to calibrate the choice model of pedestrian staying or leaving decision within the study area. These factors are relative time (t_R) and absolute time (t_A). The calibration results of these parameters are shown in Table 4.2. A good estimation is achieved, as the goodness-of-fit of the pedestrian staying or leaving choice model is rather high (pseudo- $R^2 = 0.95$ and $\log-\text{likelihood} = -1017$).

Table 4.2 Calibration results of the pedestrian staying or leaving choice model

Parameters	**Coefficient**	**t-value**
Relative Time β_R	-0.04875	-245.13
Absolute Time β_A	-0.00068	-5.74
Constant Term β_L	-258.03318	-1113.95
Summary statistics		
Log-likelihood of the model	-1017	
Log-likelihood of the null model	-18924	
Likelihood ratio index	0.9463	
Number of cases	27304	

The parameters for the relative and absolute time variables are all significant under 95% confidence level. Coefficients of both parameters are negative as expected and are shown in Table 4.2. The coefficients of the parameters t_R and t_A are -0.04875 and -0.00068 respectively. This concludes that the utility of staying within the area decreases with the relative time increase. The more time the pedestrians spend within the area, the more likely he/she will get tired and then decide to leave. In addition, with increasing the absolute time (for example: 4 hours after the part-time PS was implemented within the area), the probability that pedestrians decided to leave is higher. It can be concluded that the pedestrian staying or leaving choice model performs very well in the pseudo-R^2 value and the values of the estimated parameters.

4.4.2 Shopping Choice Model

4.4.2.1 Modeling

The decision of pedestrian shopping can be interpreted as a choice between two options: shop at a store or continue to walk. It can be explained by the observation from the tracking survey that majority of the activities are shopping in the study area. Other activities such as waiting for friends are not critical and therefore not considered in this model.

Therefore, the BL model is adopted to calibrate the shopping choice model. Two real time components are found to be essential to include in the model. They are the relative time t_R and absolute time t_A components. Hence, the structural utilities of walking W and shopping Sh can be expressed by:

For walking choice: $V_W = \beta_R t_R + \beta_A t_A$ (4.6)

For shopping choice: $V_{Sh} = \beta_{Sh}$ (4.7)

where β_R and β_A are the calibrated parameters of relative time component t_R and absolute time component t_A respectively. The probability that a pedestrian intends to shop:

$$P_{Sh} = \frac{exp(V_{Sh})}{exp(V_W) + exp(V_{Sh})} \tag{4.8}$$

It is hypothesized that the probability of pedestrian shopping would increase as both time components: relative and absolute time increase. It can be explained by the fact that if pedestrians perform shopping activities, they need to stay in the store. As a result, the relative time would be longer. This implies that the values of parameters β_R and β_A of these two time components should be negative. Before the calibration of the shopping choice model, a number of explanatory factors have been considered based on the previous research studies. These explanatory factors are summarized in Appendix C. However, the effects of these factors are insignificant due to the size of the study area and the length of the study period.

4.4.2.2 Calibrated Results

Two important time components affecting the pedestrian shopping choice were identified in order to calibrate the shopping choice model. They are relative time (t_R) and absolute time (t_A) components. The calibration results of these parameters are shown in Table 4.3. The goodness of fit of the pedestrian shopping model is rather low (pseudo- $R^2 = 0.41$ and $log - likelihood = -441$). This can be partially explained by the fact that some types of the activities are not considered such as waiting for friends.

Table 4.3 Calibration results of the shopping choice model

Parameters	**Coefficient**	t **-value**
Relative Time β_R	-0.01063	-11.87
Absolute Time β_A	-0.000086	-0.58*
Constant Term β_{Sh}	-2.41579	-18.51
Summary statistics		
Log-likelihood of the model	-441	
Log-likelihood of the null model	-749	
Likelihood ratio index	0.40987	
Number of cases	2160	

Parameters of the relative time and constant term are significant under 95% confidence level except the one for the absolute time. Coefficients of the both parameters are negative as expected and are shown in Table 4.3. The coefficients of the parameters t_R and t_A are -0.01063 and -0.000086 respectively. This concludes that the utility of walking decreases with both relative and absolute time increase. More time the pedestrian spent within the area, the more likely s/he plans to go to a store to perform shopping. Moreover, with increasing the absolute time (for example: 3 hours after the part-time PS implemented within the area), the probability that pedestrians perform shopping is higher, as they leave from office and are free for shopping. It can be concluded that the shopping choice model performs fair in both pseudo-R^2 value and the values of the estimated parameters.

4.4.3 Destination Choice Model

4.4.3.1 Modeling

The destination choice decision of pedestrian can be seen as a pedestrian choice from the various exits/destinations. Therefore, a multinomial logit model is adopted to calibrate the pedestrian destination choice model. An important component is identified in the modeling process: Distance to the destination i -

D_i refers to the distance between the current location of the pedestrian and the destination i. Hence, the structural utility of an alternative destination i, V_i, can be expressed by:

For destination i: $V_i = \beta_i + \beta_D D_i$ (4.9)

where β_i and β_D are the calibrated parameters of relative destination i and distance component D_i respectively. It should be noted that the number of the alternative destination choices of each pedestrian are different. This can be explained by a 50-meter range which is defined for a pedestrian searching a destination to leave. Therefore, the destinations located farther than 50 meters from the current location of pedestrian is not considered as an alternative choice considered by that pedestrian.

The probability P_i that a pedestrian intends to leave the area at destination i:

$$P_i = \frac{exp(V_i)}{\sum_{n'=1}^{N} exp(V_{n'})} \qquad (4.10)$$

where N is the number of alternatives. It is hypothesized that the probability of destination i being selected would decrease as distance D_i increase. The closer the pedestrian to the destination, the higher the probability that the destination is being chosen. This implies the values of parameter β_D should be negative. Before the calibration of the destination choice model, a number of explanatory factors have been considered based on the previous research studies. These explanatory factors are summarized in Appendix C. However, the effects of these factors are insignificant due to the size of the study area and the length of the study period.

4.4.3.2 Calibrated Results

An important factor affecting the destination choices of pedestrians who intend to leave the study area are required to be identified in order to calibrate the destination choice model. This factor is the distance component which is defined as the distance between the current location of the pedestrian and the destination/exit.

In the case study, eight destinations are classified, namely 1) Lockhart Road; 2) To Excelsior Hotel; 3) Great George Street; 4) Golden Mark Shopping Mall; 5) Hennessy Road; 6) Public Transportation (MTR and Bus); 7) Department Store; and 8) Shopping Mall. The calibration results of the parameters are shown in Table 4.4. A good estimation is achieved, as the goodness-of-fit of the pedestrian destination choice model is high (pseudo- $R^2 = 0.69$ and $log - likelihood = -1733$).

All the estimated coefficients of the parameters are significant under 95% confidence level except β_5 for destination choice at Hennessy Road. Table 4.4 shows the calibration results of the coefficients of the parameters used in the pedestrian destination choice model. The coefficient of the distance component β_D is negative with the value of -0.08602 as expected. This concludes that the utility of the destination being chosen decreases with the relative distance to the destination increase. The shorter the distance of the pedestrian walks to the destination, the more likely s/he will select the destination and leave. It can be concluded that the pedestrian destination choice model performs well in both pseudo- R^2 value and the values of the estimated parameters.

4.4.4 Shopping Duration Distribution

4.4.4.1 Observed Data

In the congested urban areas, pedestrians may perform some activities during their trips such as shopping and waiting for friends. During the tracking survey, the majority of pedestrian activities are shopping. Therefore, shopping duration is of particularly importance to study. Shopping durations were extracted from the data collected from the tracking survey for investigation.

Figure 4.6 illustrates the observed distribution of the shopping durations. Majority of pedestrians use less than 5 minutes for shopping as the stores at the street-level are the corner stores. The floor areas of the stores are small. Therefore, pedestrians may not stay in each store for a long time (say over 10 minutes) if they are not buy something in the store. However, pedestrians may need to stay longer if they want to buy something in the stores and they may need to try the cloths or shoes for fitting. Thus, the observed maximum shopping duration is 26 minutes.

Table 4.4 Calibration results of the pedestrian destination choice model

Parameters	**Coefficient**	***t*-value**
Distance β_D	-0.08602	-33.73
Lockhart Road β_1	1.41137	7.62
To Excelsior Hotel β_2	1.72123	11.50
Great George Street β_3	2.42888	16.50
Golden Mark β_4	1.70143	11.91
Hennessy Road β_5	0.14263	0.75*
Public Transportation β_6	0.74760	4.82
Department Store β_7	1.47878	10.44
Summary statistics		
Log-likelihood of the model	-1733	
Log-likelihood of the null model	-5648	
Likelihood ratio index	0.69287	
Number of cases	2716	

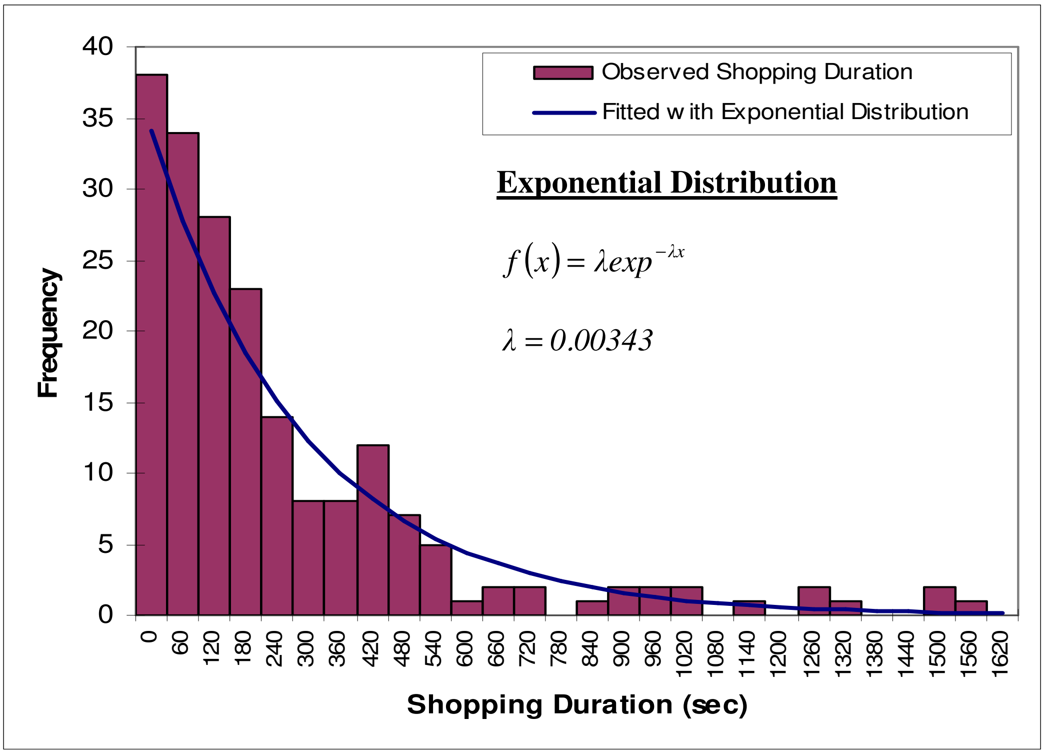


Figure 4.6 Observed distribution of shopping durations

4.4.4.2 Modeling and Calibrated Results

For the sake of predicting the shopping duration, a number of distributions (such as exponential and gamma distributions) were tested and fitted with the observed data. It is found that the exponential distribution is the best fit for the observed shopping duration than the other distributions tested. Hence, the probability density function of the exponential distribution can be expressed as follows:

$$f(x_s) = \lambda exp^{-\lambda x_s} \tag{4.11}$$

where x_s is the shopping duration (seconds) which follows the exponential distribution and λ is the parameter of the exponential distribution.

The calibrated coefficient of the parameter λ equals to 0.00343. Chi-square test was preformed using the observed data and results predicted by the exponential distribution. The calculated χ^2 is much less than the critical one (i.e. 8.815 versus 38.885). It implies that the exponential distribution is fitted to model the shopping duration. The calibrated shopping duration distribution is then incorporated into the PAS model for estimating the shopping duration at the street-level stores.

4.4.5 Sensitivity Test on Updating Time Interval

As mentioned in Section 4.3, data on when pedestrians decided to leave the area is not feasible to get from real life. Therefore, in this study, it is assumed that their staying or leaving decision choice and the shopping choice are considered by using an updating time interval. It is assumed that pedestrians will make a decision in a period of time periodically to determine whether they continue to stay in the area or they want to leave. The time period is defined as the updating time interval.

A sensitivity test on the updating time interval was carried out. Different updating time intervals are used for testing. The results are shown in Figure 4.7. It was found that 10 seconds is an appropriate time interval for model calibration. It is hypothesized that the more time a pedestrian spends within the area, the more likely he/she becomes tired. The chance that he/she will continue staying in the area will be lower. Thus, the probability that he/she leaves the area will be higher. For those pedestrians staying in the area, the more time a pedestrian spends in the area, the more likely he/she is plan for shopping.

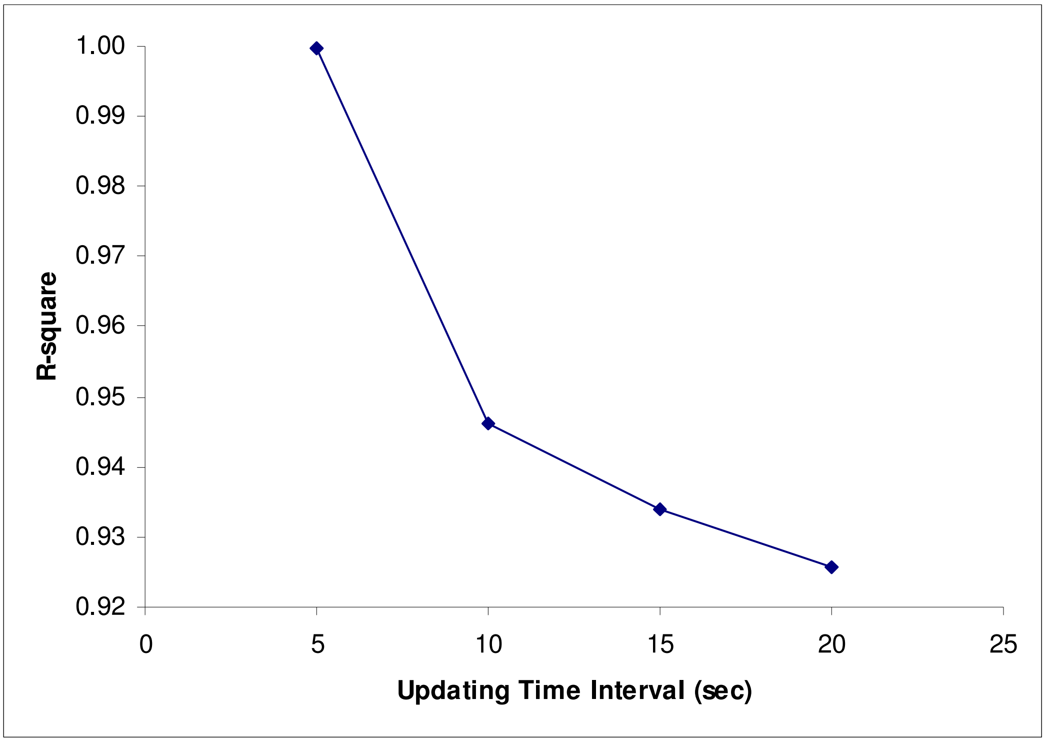


Figure 4.7 Results of sensitivity test on updating time interval

4.5 SUMMARY

The calibration of the pedestrian activity and destination choice models was carried out. A modeling framework was proposed for estimating the pedestrian activity and destination choices using four decision models, namely the staying or leaving choice model, the shopping choice model, the destination choice model and the shopping duration distribution. These four decision models were calibrated using the observed data gathered from the tracking survey to determine how various factors affecting the pedestrian decisions within the area. Relative time, absolute time and distance were the three important factors concerning by the pedestrians who continuously stay in the area and perform shopping.

The estimated results of pedestrian staying or leaving choice model indicate that negative effects of both relative and absolute time are found in relation to the pedestrian staying or leaving choices. The utility of leaving the area is increasing when the time pedestrians spent in the area is also increasing. The calibrated results indicate that negative effects of both relative and absolute time components are found on the shopping choice model. Pedestrians who spent more time within the area are likely to perform shopping after work. Moreover, the calibrated results reported that negative effect of distance components is found on the pedestrian destination choice model. Pedestrians would more likely to select the destination in which distance between the current location of the pedestrian and the destination is the shortest. Shopping durations are found to be followed the exponential distribution. Majority of pedestrians use less than 5 minutes to shop as the stores at street-level are corner stores.

The four calibrated functions for modeling the pedestrian activity and destination choices are further incorporated into the pedestrian activity-simulation model proposed in Chapter 3. In addition, the other important input of the pedestrian activity-simulation model is the generalized walking time (GBPR) functions for outdoor walkways and signalized crosswalks. The calibration of the GBPR functions is discussed in the Chapter 5.

5 GENERALIZED WALKING TIME FUNCTIONS FOR SIGNALIZED CROSSWALKS AND OUTDOOR WALKWAYS

5.1 INTRODUCTION

The modeling of the pedestrian activity and destination choices is presented in Chapter 4. The four decision models are calibrated using empirical data, namely the staying or leaving choice, the shopping choice, the destination choice and the shopping duration models. These models are then further incorporated into the newly developed Pedestrian Activity-Simulation (PAS) model to simulate the pedestrian movements and activity preferences in the congested urban areas. This chapter aims to describe the calibration of the generalized walking time functions for outdoor walkways and signalized crosswalks. This chapter is an edited version of two papers: 1) Lam, W.H.K., Lee, J.Y.S., Chan, K.S. and Goh, P.K., 2003. A generalized function for modeling bi-directional flow effects on indoor walkways in Hong Kong. *Transportation Research A*, 37, 789-810; and 2) Lee, J.Y.S. and Lam, W.H.K., 2007. Bi-directional flow effects on pedestrian indoor and outdoor walkways in Hong Kong. *Proceedings of the 12th International Conference of the Hong Kong Society for Transportation Studies*, 321-330.

The relationships between walking speed and pedestrian flow are examined at both outdoor walkways and signalized crosswalks under various bi-directional flow conditions. The generalized walking time functions for these two pedestrian facilities are calibrated using observed data collected from surveys which explicitly take into account the bi-directional flow effects. The effects of bi-directional pedestrian flows are also investigated empirically with particular emphasis on their effects on walking time and effective capacity under different directional split of pedestrians.

There are 6 sections in this chapter. In Section 5.1, an introduction of this chapter is presented. The effects of the bi-directional pedestrian flows on facility are introduced in Section 5.2. The model formulation of the newly proposed generalized walking time (GBPR) function and the traditional walking time (BPR) function are presented in Section 5.3. Two types of pedestrian facilities: outdoor walkway and signalized crosswalk are selected for case study which is presented in Section 5.4. The bi-directional flow effects on effective capacity and at-capacity walking speed are demonstrated in Section 5.5. Finally, a summary is presented in Section 5.6.

5.2 THE EFFECTS OF THE BI-DIRECTIONAL FLOWS ON PEDESTRIAN FACILITIES

This chapter aims to investigate the effects of the bi-directional pedestrian flows. When the number of pedestrians on a facility is very low and pedestrians are only facing little opposing pedestrian flow, they should have more freedom to choose their walking speeds and easily overtake other pedestrians. If the number of pedestrians on the facility continuously increases and approaches the facility's capacity, in addition to a heavy pedestrian flow in the opposing direction, pedestrians in either directions will have less freedom to choose their walking speeds. Pedestrians are required to follow others in the same direction and it is not easy for them to bypass others. Thus, the effective capacity of a facility and the walking speeds will be reduced when the pedestrian flow increases. The bi-directional flow effects are significant when the pedestrian flows are close to the capacity of the facility. A more detailed explanation on the bi-directional flow effects can be found in Lam et al. (2003).

Cheung and Lam (1997) discussed briefly the characteristics of the bi-directional flow effects in passageways and on stairways with particular emphasis on how they affect the walking time and effective capacity for different directions of flow. When there are bi-directional pedestrian flows on a facility, the effective capacity for an individual direction can be determined by taking into account the directional distribution of pedestrian flows. For walkways, when the directional distribution of the pedestrian flow is 50:50, the effective capacity for an individual direction can be considered as half of the capacity. Therefore, the pedestrians in either directions share the width of passageway equally. There are significant effects when the pedestrian flows are close to the capacity of the facility, or there is an uneven directional split of pedestrians (Cheung and Lam, 1997; Blue and Adler, 2001). When the pedestrian flows of both directions are known, the flow ratio of an individual flow can be found.

5.2.1 Flow Ratio

The flow ratio (r) is the proportion of one-way pedestrian flow out of the total two-way pedestrian flow. Two-way flow is the total number of pedestrians passing through a pre-determined section of a walking facility per meter width per minute in two directions. It is necessary to define the major and minor flow directions of the pedestrian flow. The effects of the pedestrian flow in either direction on a pedestrian facility are the same. Therefore, either directions can be defined as the major flow direction if the flow ratio is greater than 0.5. Correspondingly, the direction is said to be a minor flow direction of the pedestrian flow when the flow ratio (r) for that direction is less than 0.5. When the pedestrian flows of both directions of pedestrian facilities are known, the flow ratio (r) of an individual flow is defined as follow:

$$r = \frac{v_1}{v_1 + v_2} \tag{5.1}$$

where:

v_1 and v_2 are the major and minor flows on the pedestrian facilities respectively.

5.3 *MODEL FORMULATION*

5.3.1 Walking Time Function under Uni-directional Pedestrian Flow Condition

Lam and Cheung (2000) investigated the relationships between walking speed and pedestrian flow for different types of walking facilities in Hong Kong. These relationships are mainly confined to uni-directional flow condition. Walking speed can be found once the walking time and the corresponding pedestrian flows for the selected pedestrians are known, by using the following equation:

$$s(v) = \frac{60}{t(v)} \tag{5.2}$$

where

v is the total pedestrian flow (pedestrians/meter/minute);

$t(v)$ is the unit walking time (seconds) at pedestrian flow v; and

$s(v)$ is the pedestrian walking speed (meters/minute) at flow v.

The well-known BPR function (Bureau of Public Roads, 1964) has been widely used for the estimation of link travel time on road network. In the initial stage, the BPR function was adopted to calibrate the walking time function for signalized crosswalks under uni-directional flow condition. Satisfactory results were obtained.

Therefore, BPR function is used as a start to estimate the walking time on a pedestrian facility. It is also consistent with the function employed in the PEDROUTE (Halcrow Fox and Associates, 1994) – pedestrian simulation software. The formula is given as below and defined as the walking time function for a pedestrian facilty:

$$t(v) = t_0 + B \times \left(\frac{v}{C} \right)^n \tag{5.3}$$

where:

B and n are the parameters to be estimated;

v is the pedestrian flow (pedestrians/meter/minute);

C is the observed capacity (pedestrians/meter/minute) of a pedestrian facility under uni-directional flow condition;

t_0 is the unit free-flow walking time (seconds/meter); and

$t(v)$ is the unit walking time (seconds/meter) at flow v.

The relationships between pedestrian flow, walking time and flow ratio are investigated to test for both uni-directional and bi-directional pedestrian flows. These are based on the BPR function, which in itself is a simplification of vehicle flow dynamics. There are 2 reasons to use the BPR function to estimate the walking time. The first reason is that based on the contribution gleaned from the previous studies (Buckman and Leather, 1994; Halcrow Fox and Associates, 1994; Cheung and Lam, 1997; Lam and Cheung, 2000; Lam et al., 1995, 2002 & 2003). BPR function can be initially adopted to model the relationship between pedestrian flow and walking time. However, the BPR function is confined to the uni-directional flow condition only like vehicular traffic. The second reason is that based on the observed data collected from the video records. It should be noted that the BPR function can better than fit with the walking data collected under uni-directional flow condition than other types of models reviewed. The observed data show that the free-flow walking speed was constant up to a certain pedestrian flow under uni-directional flow condition. The walking speed decreases as the pedestrian flow increases. Data under uni-directional flow condition can be modeled by the BPR function like vehicular traffic.

As pedestrians are very different in how they behave, their movements are varied on some facilities which are bi-directional (passageway) or even multi-directional (concourse). However, the BPR function is inadequate to model the pedestrian movements under bi-directional flow condition or even multi-directional flow conditions. From the video records collected, there is an ‘‘observed phenomenon’’ of the bi-directional effects on the minor flow direction that can be described as follows: When the number of pedestrians on a facility is very low, they face little opposing flow and have more freedom to choose their walking speeds and easily overtake other people on the facility. However, when pedestrian flow in the opposing direction is heavy, they then have less freedom to choose their walking speeds as it is not easy to bypass other pedestrians. Thus, the effective capacity of a facility and the walking speeds of the pedestrians will be reduced when the opposing pedestrian flow increases. The bi-directional flow effects are varied and become significant when the pedestrian flows are close to the capacity of the two-way facility. Therefore, the effects of bi-directional pedestrian flow (i.e. flow ratio r) on a pedestrian facility must be considered when estimating the walking time on a bi-directional facility. Thus, Equation 5.4 is the GBPR function taking into account the flow ratio r with the basis of the BPR function. The calibrated GBPR function can estimate the walking time for various flow conditions ranging from free-flow to congested-flow (at-capacity) situations and from uni-directional to bi-directional flow conditions.

5.3.2 Generalized Walking Time Function under Bi-directional Pedestrian Flow Condition

The above mentioned BPR function is confined to the uni-directional pedestrian flow. On a pedestrian facility, pedestrian flows are normally bi-directional or even multi-directional. In this study, bi-directional pedestrian flow is only considered but not multi-directional flow. When the pedestrian flows of both directions are known, the flow ratio (r) can be determined and calculated by Equation 5.1. Therefore, a GBPR function is proposed which takes into account the bi-directional flow effects on pedestrian facilities at various flow conditions ranging from free-flow to congested flow situations. Details regarding this newly proposed GBPR function and its merits can be found in Lam et al. (2003).

The GBPR function is extended from the traditional BPR function which takes into account the effect of the flow ratio (r). The GBPR function was calibrated to determine the relationship between the walking speed against the two-way pedestrian flow and flow ratio. This is given as follows:

$$GBPR\left(r, \frac{v}{C_{eff}}\right) = t_0 + B_1 \times (r)^m \times \left(\frac{v}{C_{eff}}\right)^n \tag{5.4}$$

where:

$$B = B_1 \times (r)^m \tag{5.5}$$

$$C_{eff} = a_0 + a_1 \times r^1 + a_2 \times r^2 + a_3 \times r^3 \tag{5.6}$$

t_0 is the unit free-flow walking time (seconds/meter);

r is the flow ratio $(0 < r \leq 1)$;

v is the two-way pedestrian flow (pedestrians/meter/minute);

C_{eff} is the fitted effective capacity (pedestrians/meter/minute) of a pedestrian facility at flow ratio r;

a_0, a_1, a_2 and a_3 are the coefficients of the regression model of the effective capacity;

B_1, m and n are the parameters to be estimated; and

$GBPR\left(r, \frac{v}{C_{eff}}\right)$ is the unit walking time (seconds/meter) for pedestrians walking on a pedestrian facility at flow v under flow ratio r.

After the GBPR function for pedestrian facilities was proposed, a statistical package, SPSS (Norusis, 1994) was adopted to calibrate the GBPR functions for the outdoor walkways and signalized crosswalks. The parameters of the GBPR functions were estimated by using the non-linear regression technique. The curves of effective capacity and speed reduction for minor flows (with a less than 50% flow rate) argue for the following behavioral rationale: People in a minor flow direction constantly need to switch positions with heading individuals of a large crowd. Conversely, pedestrians in the minor flow direction also have less freedom in choosing directions to avoid conflict. The disadvantage of traveling in a minor flow, especially at a small flow rate means that it is harder to form a stream and be separated from the major opposing flow. When the minor flow rate increases from a very small percentage to 50%, the chance for people from a minor flow direction to gain effective capacity by forming streams increases, giving rise to the gradual dissipation of the interspersed flow condition to a dynamic multiple lane flow, and eventually, to a separated flow condition.

5.4 CASE STUDY

In order to calibrate the proposed GBPR function, two types of pedestrian facilities were selected for case study, data collection and analysis. These two types of pedestrian facilities are:

- Outdoor walkway (effective width = 2.3 meters and length of measurement section = 5.4 meters)
- Signalized Crosswalk (effective width = 14.5 meters and length of measurement section = 18.2 meters)

Observational surveys were carried out at the two selected pedestrian facilities in Hong Kong during the peak and off-peak periods. Detail information of the observational survey can be found in Appendix D. Figure 5.1 and Figure 5.2 show the selected outdoor walkway and signalized crosswalk respectively. To collect data such as walking time (or walking speed) along the facilities and pedestrian flow rate, a time-lapse photography technique was adopted (Cheung and Lam, 1997 & 1998; Cheung, 1998). With the use of video recording equipment, the pedestrian flow rate and the corresponding walking time data can be extracted from the video records in the laboratory.

To increase the accuracy of the measurement, a time code in 1/25 second was mapped on the video images before data extraction. A sample of the time code is shown in Figure 5.1. Detail information of the data extraction methodology can be found in Appendix D. The data comprise the walking time of the pedestrians, the corresponding flows and bi-directional flow distributions.

Figure 5.1 Outdoor walkway

Figure 5.2 Signalized crosswalk

5.4.1 Calibration Results

After the GBPR function for pedestrian walking time was proposed, a statistical package, SPSS (Norusis, 1994) was adopted to calibrate the GBPR functions for the outdoor walkways and signalized crosswalks. The parameters of the GBPR functions were estimated by using the non-linear least squares regression technique. This non-linear least squares technique is minimizing the sum of the squares of the errors of the model predictions. The unknown parameters of the proposed non-linear model can be estimated by fiting the observations. The basis of the method is to approximate the model to refine the parameters by successive iterations.

Table 5.1 summarizes the calibrated results of the parameters of the GBPR functions for the selected facilities. The collected samples at the signalized crosswalk are 2225 which is much less than those on the outdoor walkway (i.e. 7267). This can be explained by the fact that the variation in walking speeds on the outdoor walkway is much larger than that at the signalized crosswalk. Pedestrians can only traverse the signalized crosswalk within a limited time period i.e. the pedestrian green and flashing green periods. Thus, their walking speeds are more homogenous. More samples on the outdoor walkway are required to extract from the video records to ensure the collected samples are representative.

Note that R^2 is the coefficient of determination, which reflects the accuracy of the model equation adopted. The closer the R^2 value to 1, the greater the model fit. The R^2 values are all greater than 0.6. The calibration results and their effects are described in the following. It should be noted that t_0 is the unit free-flow walking time. The value of power term m is the effect of the imbalance of directional pedestrian split. The value of power term n is the effect of the v/C_{eff} ratio. All the coefficients of the parameters are significant based on the t -values. Detailed comparisons on the values of these three estimated parameters are as follows:

5.4.2 Effects of the Free-flow Walking Time t_0

When the pedestrian flow is very small (i.e. $v/C_{eff} \approx 0$), the value of the GBPR function should then be close to the free-flow walking time t_0 (i.e. $GBPR(r,0) = t_0$). Obviously from Table 5.1, the free-flow walking time at signalized crosswalks is comparatively longer than that on outdoor walkways (i.e. 0.868 seconds/meter for signalized crosswalks vs 0.760 seconds/meter for outdoor walkways). Thus, the free-flow walking speed on outdoor walkways is comparatively higher than those obtained at signalized crosswalks. This can be partially explained by the location of the selected outdoor walkway which is close to the entrance of the underground railway station and bus stops. Therefore, pedestrians pass through the selected outdoor walkway to take the public transport and their walking speeds are comparatively faster than those walking on signalized crosswalks.

Table 5.1 The calibration results of the GBPR functions

Walkway	Total Sample Size	Parameters #				Observed Maximum Flow (ped/m/min) C ^	R^2 *
		t_0 (*t*-value)	B_1 (*t*-value)	m (*t*-value)	n (*t*-value)		
Signalized Crosswalk	2225	0.868 (80.6)	0.364 (25.1)	-0.418 (-9.5)	2.280 (36.9)	78.5	0.651
Outdoor Shopping	7267	0.760 (192.1)	0.710 (69.4)	-0.427 (-14.9)	3.374 (48.9)	84.0	0.672

Notes: # t_0, B_1, m and n are the parameters defined in Equation 5.4.

* R^2 is the coefficient of determination which reflect the accuracy of the function adopted.

^ Observed maximum flow is found under uni-directional flow condition ($r = 1.0$).

5.4.3 Effects of the v/C_{eff} Ratio

When the pedestrian flow on a facility continuously increases and approaches the facility's capacity (i.e. $v/C_{eff} \approx 1$), the value of the GBPR function should then be close to the at-capacity walking time (i.e. $GBPR(r,1) = t_0 + B_1 \times r^m$). It can be seen that from Table 5.1, the values of the power term n of the v/C_{eff} ratio for outdoor walkways and signalized crosswalks are both positive (i.e. 2.280 for signalized crosswalks vs 3.374 for outdoor walkways). The curvature n of the GBPR function for signalized crosswalks is comparatively more linear than the one for outdoor walkways.

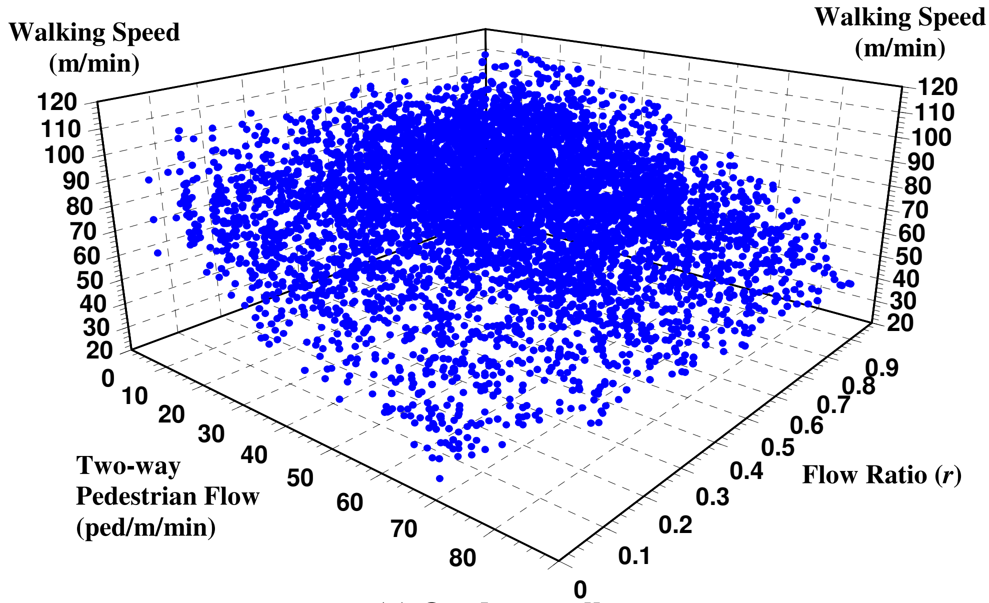
5.4.4 Effects of the Flow Ratio r

The increment of the imbalance of the directional pedestrian split implies a decrease of the flow ratio (e.g. flow ratio r decreases from 1.0 to 0.1). It should be noted from Table 5.1 that the values of the power term m of the flow ratio for outdoor walkways and signalized crosswalks are both negative (i.e. -0.418 for signalized crosswalks vs -0.427 for outdoor walkways). This implies that the walking speeds on both outdoor walkways and at signalized crosswalks decrease with the increment of the imbalanced directional pedestrian split (e.g. r decreases from 1.0 to 0.1). The bi-directional flow effects on the outdoor walkways are significantly greater than that at the signalized crosswalks. This can be partially explained by the fact that the observed maximum flow at outdoor walkways is higher than that at signalized crosswalks (i.e. 84.0 pedestrians/meter/minute for outdoor walkways vs 78.5 pedestrians/meter/minute for signalized crosswalks).

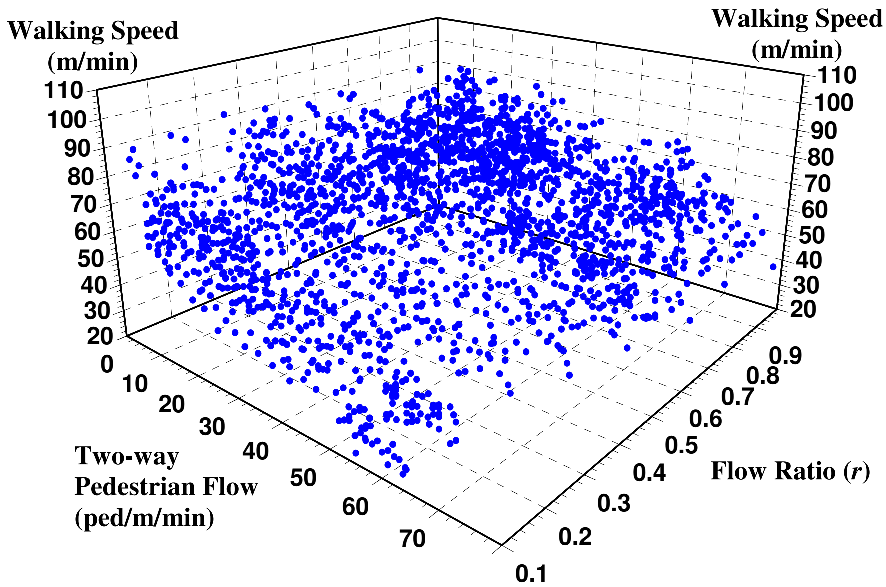
5.4.5 Observed and Fitted Relationships between Pedestrian Flow, Walking Speed and Flow Ratio

Figure 5.3(a) and Figure 5.3(b) graphically show the observed data collected on the outdoor walkway and at the signalized crosswalk respectively. The observed relationships between pedestrian flow (two-way) and walking speed under various flow ratios for outdoor walkways and signalized crosswalks are also illustrated in Figure 5.3(a) and Figure 5.3(b) respectively. The total number of samples shown in Figure 5.3(a) is 7263 while there are 2225 samples shown in Figure 5.3(b). The walking speed variation under free-flow condition (i.e. $v/C_{eff} \approx 0$) is comparatively larger than those under at-capacity condition (i.e. $v/C_{eff} \approx 1$). Walking speeds decrease with increasing pedestrian flows and imbalance of the directional pedestrian split on the selected facilities.

Figure 5.4(a) and Figure 5.4(b) illustrate the calibrated GBPR functions for outdoor walkways and signalized crosswalks. The following two observations can be seen in Figure 5.4(a) and Figure 5.4(b). In Figure 5.4(a), as the flow ratio decreases from 1.0 to 0.1, the at-capacity walking speed on outdoor walkways decreases from 40.8 meters/minute to 22.6 meters/minute. Moreover, the observed maximum flow decreases from 84.0 pedestrians/meter/minute (i.e. $r = 1.0$) to 64.0 pedestrians/meter/minute (i.e. $r = 0.1$), as the increment of the imbalanced directional pedestrian split. Similar observation can also be found in Figure 5.4(b) for signalized crosswalks.



(a) Outdoor walkway



(b) Signalized crosswalk

Figure 5.3 Observed data on (a) outdoor walkway (b) signalized crosswalk

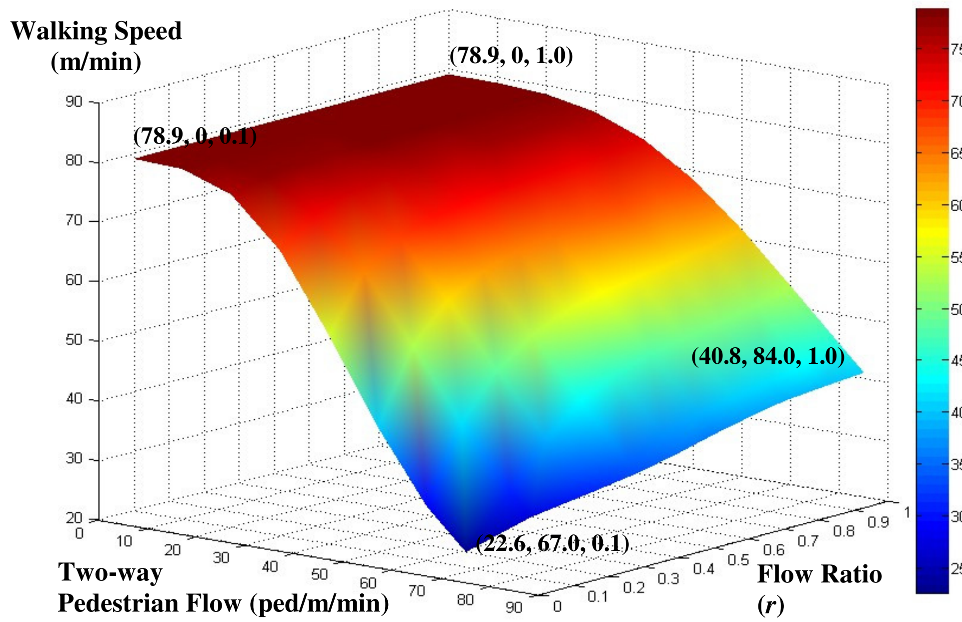
When the number of pedestrians on the facility continuously increases and reaches the facility's capacity together with a heavy pedestrian flow in the opposing direction, pedestrians in the minor flow direction then have less freedom to choose their walking speeds. They are required to follow other pedestrians in the same direction as they have no space and are not easy to bypass other pedestrians. Under a very congested situation, their walking speed reduces more rapidly than those pedestrians passing through a less congested facility. Thus, the bi-directional flow effects on the outdoor walkways are more significant than that at the signalized crosswalks.

5.5 BI-DIRECTIONAL FLOW EFFECTS ON EFFECTIVE CAPACITY AND AT-CAPACITY WALKING SPEED

When pedestrians walk on a pedestrian facility facing heavy opposing pedestrian flows, they usually weave through the opposing pedestrians and would have little freedom to choose their walking speeds. Thus, the capacity of the facility and the pedestrian walking speeds would be reduced, particularly in the minor flow direction.

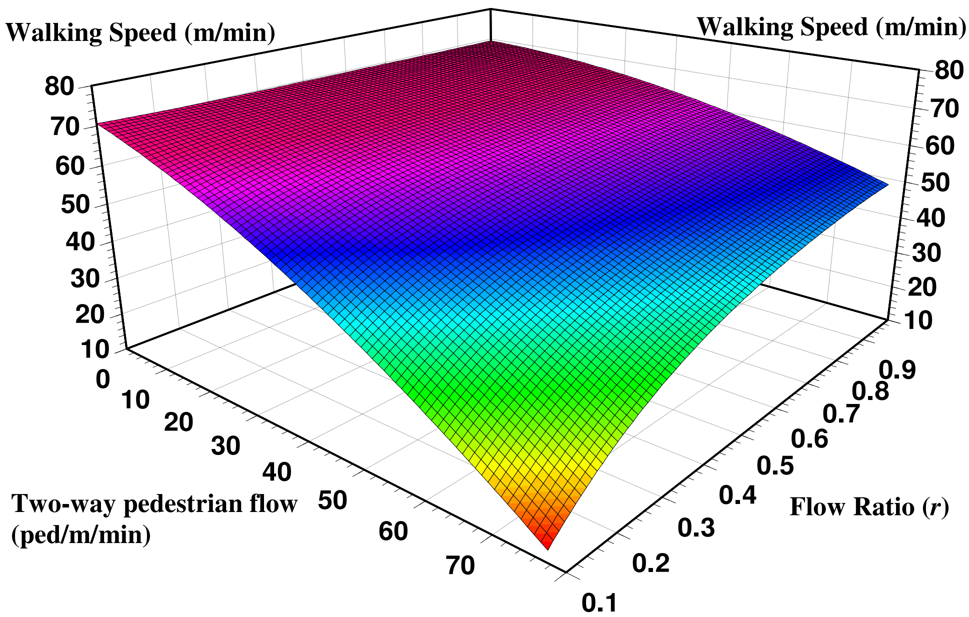
Therefore, the effects of bi-directional pedestrian flow (or flow ratio) to be studied in this section are:

- ➢ The relationships between the effective capacity of a pedestrian facility and the flow ratio (r); and
- ➢ The relationships between the at-capacity walking speed and the flow ratio (r).



Note: (78.9, 0, 1.0) refer to (walking speed, pedestrian flow, flow ratio)

(a) Outdoor walkway



b) Signalized crosswalk

Figure 5.4 GBPR functions for (a) outdoor walkway (b) signalized crosswalk

Generally, the bi-directional flow effects are more significant in the minor flow direction particularly when the flow ratio is less than 0.5. When the flow ratio is close to 0.5, pedestrians in both directions will split evenly from each other to minimize the conflicts. However, when the flow ratio closes to 0.1, the pedestrians in the minor flow direction will share the width of the facility in a proportion less than 10%. The reason is that at this flow ratio, pedestrians in the minor flow direction will have a great deal of conflicts and have less freedom to choose their speeds with the heavy opposing flow. As a result, both walking speed and facility's capacity in the minor flow direction will be reduced significantly. In addition, the reductions of effective capacity and walking speed in the minor flow direction will increase when the total pedestrian flow continuously increases. Thus, the effects of bi-directional flows become significant as the pedestrian flow reaches the facility's capacity. Further detail regarding the bi-directional flow effects on effective capacity and at-capacity walking speed can be found in Lam et al. (2002 & 2003).

5.5.1 Reduction of Effective Capacity

Statistical regression analyses were performed to determine the relationship of the flow ratio against the effective capacity. The calibration results for the effective capacity for outdoor walkways and signalized crosswalks are shown as follows:

Outdoor Walkways: $C_{eff} = 61.27 + 83.89 \times r - 105.00 \times r^2 + 43.83 \times r^3$ (5.6)

Signalized Crosswalks: $C_{eff}(r) = 60.84 + 27.86r - 0.22r^2 - 10.84r^3$ (5.7)

where

r is the flow ratio $(0 < r \leq 1)$ of a pedestrian facility; and

C_{eff} is the estimated effective capacity (pedestrians/meter/minute) of a pedestrian facility at flow ratio r.

Figure 5.5 graphically shows the observed effective capacities against the flow ratios for outdoor walkways and signalized crosswalks together with the fitted regression relationship. It can be seen from Figure 5.5 that with increasing imbalance of the directional split of pedestrians, the effective capacity decreases particularly significant in the minor flow direction (i.e. flow ratio decreases from 0.5 to 0.1) on both facilities. The effective capacities for outdoor walkways and signalized crosswalks are 84.0 pedestrians/meter/minute and 78.5 pedestrians/meter/minute respectively under the uni-directional flow condition (i.e. $r = 1.0$). They decrease generally to 82.4 pedestrians/meter/minute for outdoor walkways and 75.3 pedestrians/meter/minute for signalized crosswalks when flow ratio (r) equals to 0.5. However, they then decrease sharply to 68.7 pedestrians/meter/minute for outdoor walkways and 64.5 pedestrians/meter/minute for signalized crosswalks when the imbalance of directional pedestrian flow is heavy (i.e. $r = 0.1$).

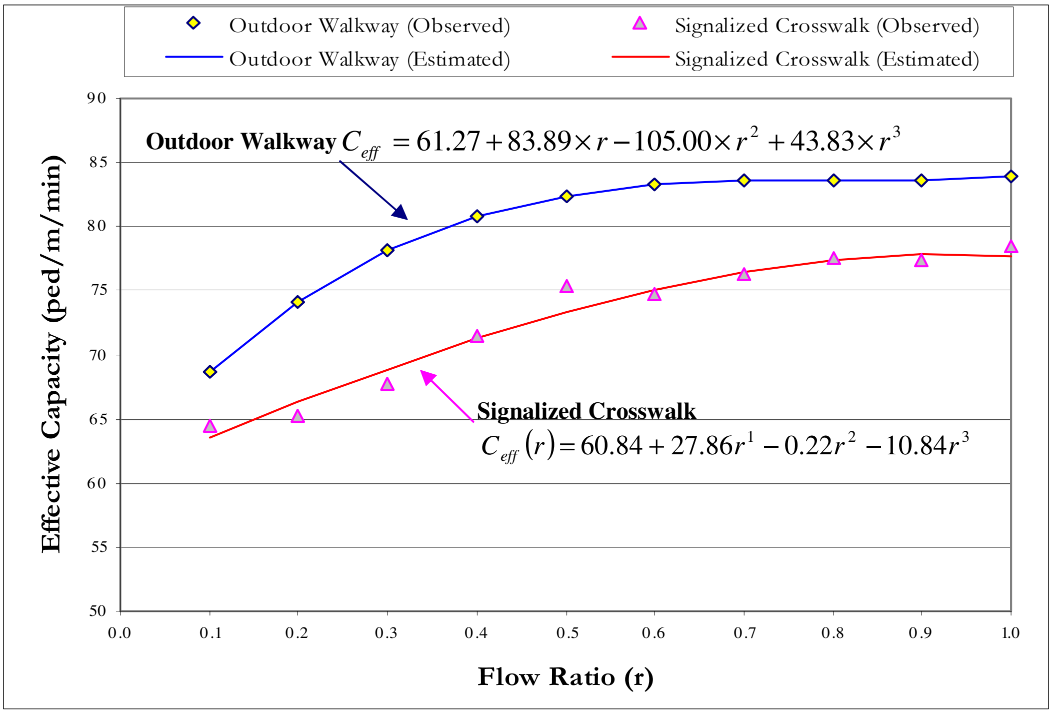


Figure 5.5 Effective capacities for outdoor walkway and signalized crosswalk under different flow ratios

5.5.2 Reduction of At-capacity Walking Speed

Figure 5.6 illustrates the at-capacity walking speeds against the flow ratios for outdoor walkways and signalized crosswalks together with the GBPR function (i.e. confined to at-capacity condition only). It can be seen from Figure 5.6 that the at-capacity walking speeds decrease with increasing imbalance of the directional split of pedestrians, which are particularly significant in the minor flow direction (i.e. flow ratio decreases from 0.5 to 0.1) on both facilities. The at-capacity walking speeds for outdoor walkways and signalized crosswalks are 38.6 meters/minute and 41.3 meters/minute respectively under the uni-directional flow condition (i.e. $r = 1.0$). They decrease generally to 36.8 meters/minute for outdoor walkways and

40.0 meters/minute for signalized crosswalks when the flow ratio (r) equals to 0.5. However, they then further decrease sharply to 23.6 meters/minute for outdoor walkways and 29.3 meters/minute for signalized crosswalks when the imbalance of directional pedestrian flow is heavy (i.e. $r = 0.1$).

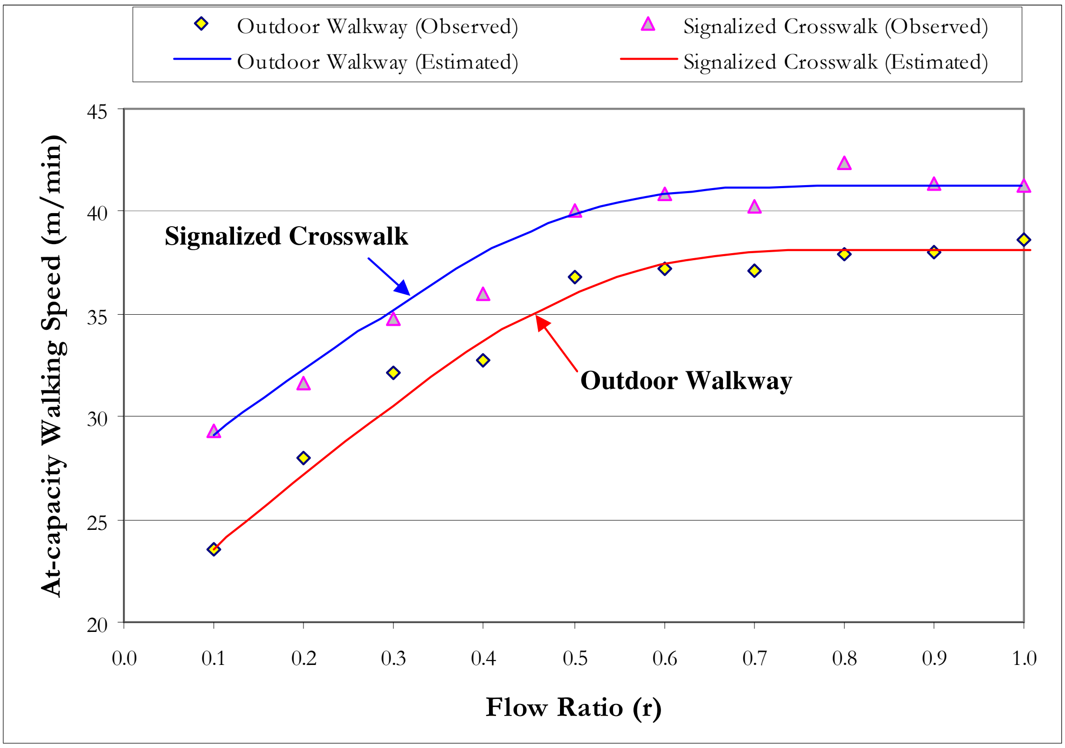


Figure 5.6 At-capacity walking speeds for outdoor walkway and signalized crosswalk under different flow ratios

It should also be noted that the at-capacity walking speeds for outdoor walkways are comparatively lower than those for signalized crosswalks. This can be partially explained by the fact that the effective capacities or the observed maximum flows on outdoor walkways are higher than those observed at signalized crosswalks (i.e. 84.0 pedestrians/meter/minute for outdoor walkways versus 78.5

pedestrians/meter/minute for signalized crosswalks). Therefore, the at-capacity walking speeds at signalized crosswalks are higher than those observed on outdoor walkways.

In summary, it was found that both effective capacity and at-capacity walking speed generally decrease with increasing imbalance of the directional split of pedestrians. It may be partially explained that pedestrians in the minor flow direction are forced to weave through the opposing flow of pedestrians. Thus, the at-capacity walking speeds and the effective capacities of the facilities in the minor flow direction reduce significantly when the flow ratio changes from 0.5 to 0.1. However, when the flow ratio is equal to 0.5, the effects of bi-directional pedestrian flows is not substantially different from that of the uni-directional flow of pedestrians. Under this circumstance, pedestrians would form directional streams that minimize the conflicts with the oncoming crowd. Therefore, the at-capacity walking speeds and effective capacities would be close to those observed under the uni-directional flow.

5.6 SUMMARY

Pedestrians behavior differently when they walk on various pedestrian facilities. Walking speeds of pedestrians under different imbalance of directional pedestrian split are of prime importance in a study of modeling and designing of pedestrian facilities. In this chapter, a comparison is newly made on the bi-directional pedestrian flow characteristics on outdoor walkways and at signalized crosswalks in Hong Kong congested urban areas. The relationship between walking speed and pedestrian flow under various flow conditions have been examined for the outdoor walkways and signalized crosswalks.

Higher maximum flow rates or effective capacities for outdoor walkways are observed on various flow ratios when compared with those found at signalized crosswalks. At-capacity walking speeds observed on outdoor walkways are comparatively lower than those observed at signalized crosswalks. The effects of bi-directional pedestrians flow are significant on both outdoor walkways and signalized crosswalks when the pedestrian flows are close to the capacities together with the imbalance of directional split of pedestrians. However, it was found that the bi-directional pedestrian flow effects on both effective capacity and at-capacity walking speed on outdoor walkways are more significant than those at signalized crosswalks.

The GBPR functions for outdoor walkways and signalized crosswalks are newly proposed and calibrated. The calibrated GBPR functions are then further incorporated into the Pedestrian Activity-Simulation Model for estimating the average walking time on outdoor walkways and signalized crosswalks. However, the GBPR function only considers the average walking time on the facility. The walking time variations are not explicitly taken into account in the GBPR functions. The walking time/speed variations are investigated in Chapter 6.

6 WALKING SPEED/TIME VARIATIONS

6.1 INTRODUCTION

The calibration of generalized walking time (GBPR) functions for signalized crosswalks and outdoor walkways are presented in Chapter 5. The GBPR functions take into account the bi-directional pedestrian flow effects which are then further incorporated into the PAS model to simulate the pedestrian movements. However, the GBPR functions do not consider the walking speed/time variations. This chapter aims to investigate the walking speed variations under the uni-directional and bi-directional flow conditions. This chapter is an edited version of: Lee, J.Y.S. and Lam, W.H.K., 2006. The variation of walking speeds on a uni-directional walkway and on a bi-directional stairway. *Transportation Research Record*, 1982, 122-131.

This chapter is the first pioneer to focus on the walking speed variations under both uni-directional and bi-directional pedestrian flow conditions. The relationship between the mean walking speed and its standard deviation is proposed taking into account the bi-directional flow effects. In order to calibrate the proposed relationship, observational surveys were carried out at the selected pedestrian facilities. Two types of pedestrian facilities were selected for data collection and analysis which are an uni-directional walkway and a bi-directional stairway in the underground station. Observational data were collected to calibrate the relationship between the mean walking speed and its standard deviation taking into account the bi-directional flow effects. The distributions of walking speed data are also investigated.

There are 8 sections in this chapter. In Section 6.1, an introduction of this chapter is presented. The model formulations of the traditional travel time variations, newly proposed walking speed and time variations are presented in Section 6.2. Two types of pedestrian facilities: the uni-directional walkway and the bi-directional stairway are selected for case study is presented in Section 6.3. The methodologies of data collection and extraction are discussed in Section 6.4. The data analysis method together with the observed data is shown in Section 6.5. The calibration of the relationship between the mean walking speed and its variation is illustrated in Section 6.6. The distributions of the observed walking time are demonstrated in Section 6.7. Finally, a summary is presented in Section 6.8.

6.2 MODEL FORMULATION

6.2.1 Travel Time Variations

A number of researchers (Herman and Lam, 1974, Sterman and Schofer, 1976, Richardson and Taylor, 1978 & Taylor, 1982) have successfully calibrated the relationship between mean travel time and its variation for vehicles. They show that the travel time variation (SD_t) of vehicles should be proportional to the square root of the mean travel time ($\bar{t}$).

$$SD_t = \alpha\sqrt{\bar{t}} \tag{6.1}$$

where:

SD_t is the standard deviation of the mean travel time;

$\bar{t}$ is the mean travel time; and

α is the "travel time variability ratio".

6.2.2 Walking Speed Variations

Therefore, a number of formulations from such previous studies have been further applied for calibrating the relationship between mean walking speed and its standard deviation. Tests were carried out so as to check the goodness-of-fit of these functions. The proposed models for the relationship between mean walking speed and standard deviation for the uni-directional and bi-directional pedestrian facilities are summarized as follows:

For uni-directional pedestrian facilities:

$$SD_S = b_0 \times \bar{S}^{b_S} \tag{6.2}$$

For bi-directional pedestrian facilities:

$$SD_S = b_0 + b_{S_1} \times \overline{S} + b_{S_2} \times \overline{S}^2 + b_r \times r \tag{6.3}$$

where:

SD_S is the standard deviation of the mean walking speed;

$\overline{S}$ is the mean walking speed (meters/second);

r is the flow ratio ($0 < r \leq 1$); and

b_0, b_S, b_{S_1}, b_{S_2} and b_r are the coefficients to be determined.

6.2.3 Walking Time Variations

The relationship between mean walking time and its standard deviation was also tested against a number of formulations. The proposed models for the relationship between mean walking time and standard deviation for pedestrian facilities are summarized as follows:

For uni-directional pedestrian facilities: $SD_t = a_0 \times \bar{t}^{a_t}$ (6.4)

For bi-directional pedestrian facilities: $SD_t = a_0 \times \bar{t}^{a_t} \times r^{a_r}$ (6.5)

where:

SD_t is the standard deviation of the mean walking time;

$\bar{t}$ is the mean walking time;

r is the flow ratio ($0 < r \leq 1$); and

a_0, a_t and a_r are the coefficients to be determined.

6.3 CASE STUDY

Cheung and Lam (1998) investigated pedestrian choice between escalators and stairways in Hong Kong MTR stations during peak hours. Generally pedestrians choose their desired paths for horizontal dimensions based mainly on the shortest walking time, shortest walking distance or a combination of both (Cheung and Lam, 1998). However, pedestrian movements/route choices within the underground stations involve movements in both horizontal and vertical dimensions. In the vertical dimension, excluding lifts, choice is between the escalators and stairways. Pedestrians take into account effort expended when climbing a grade, regardless of whether the route involves the shortest walking time and distance (Cheung and Lam, 1998). Cheung and Lam's results can be formed the basis for an analysis of pedestrian' choice between escalators and stairways.

Pedestrian walking behavior for vertical pedestrian facilities such as the stairways can be influenced by the facility characteristics. It is believed that the walking speed/time difference between using escalators and stairways is one of the critical factors affecting pedestrian's decision making. Under the at-capacity condition, it is assumed that pedestrians are forced to confine their movement pace to that of the operating speed of the escalator. Therefore, the measurement of the walking speed variation were conducted on a walkway leading to the escalator.

The physical characteristics of the chosen pedestrian facilities are given in Table 6.1 including the effective width, length, tread width and step riser height. The selected walkway leading to an escalator is located at the Causeway Bay MTR station. The selected bi-directional stairway is located at the Mongkok MTR station. These stations are two of the busiest MTR stations in Hong Kong.

Table 6.1 Physical characteristics of the selected pedestrian facilities

Pedestrian facility	Physical characteristics
Walkway Leading to Escalator	Length = 5 m
Stairway	Effective width = 1.94 m Length = 5.58 m Tread width = 0.31 m Step riser height = 0.16 m

6.4 DATA COLLECTION AND EXTRACTION

6.4.1 Data Collection - Time-Lapse Photography

A time-lapse photography technique was adopted by Cheung (1998) and used to gather data from various pedestrian facilities at the selected underground stations. This technique is particularly effective when detailed investigation is required, as a permanent record can then be kept. This technique can minimize the number of on-site measurement errors when the pedestrian flows are heavy and complex. In this study, a hand-held video camera was used, together with a lightweight tripod, to obtain a stable image during data collection. Reference marks on the ground were made with tapes to delimitate the measurement section before the video recording survey commenced. Surveys were conducted during the morning peak (i.e. 8 a.m. - 10 a.m.), off-peak (i.e. 2 p.m. - 4 p.m.) and evening peak (i.e. 5:30 p.m. - 7:30 p.m.) periods on Fridays on 19 January, 26 January, 2 February, 9 February and 16 February 2001 in the Causeway Bay and Mongkok MTR stations. After the survey was conducted, data extraction from video records was carried out in the laboratory.

6.4.2 Data Extraction

The videotapes recorded on-site were further processed by mapping a time code on the video records before data extraction. As the time code is encoded in 25 frames per second, a precision level of 0.04 seconds can be achieved. A real-time video capture board and a movie-editing package (i.e. Studio MP10) were used. Therefore, the video records can be displayed on a computer.

The data extracted from the video records were: (1) pedestrian flows (pedestrians/meter/minute); and (2) walking speeds (meters/second). The data extraction was accomplished using a semi-automatic process together with a computer program used as a counting device. Extracted data were then stored in a computer file. The computer system clock was firstly synchronized with the time code mapped on the video records as mentioned in the above paragraph. A detailed description of data extraction is given in Lee (2002).

6.5 DATA ANALYSIS

6.5.1 Grouping Data

After data extraction, the pedestrian walking speed with the corresponding flow was determined so as to calibrate the relationship between the mean walking speed and its standard deviation. In order to define the congested condition, the at-capacity walking speed and queuing delay were used as the reference point. It was found that when pedestrian flow is close to the effective capacity of the facility, queues form causing walking time delay. Therefore, when there is no walking time delay (walking speed ≥ at-capacity walking speed), the corresponding pedestrian flow is categorized under the un-congested condition. When there is walking time delay due to queuing (i.e. walking speed ≤ at-capacity walking speed), the corresponding pedestrian flow is categorized under the congested condition.

In order to calculate the mean walking speed and its standard deviation, groups should be formed by using the pedestrian flow range (i.e. 10 pedestrians/escalator/minute for the walkway leading to the escalator, and 10 pedestrians/meter/minute for the stairway). Hence, the mean walking speed with its standard deviation of each group can be calculated. It should be noted that there are two mean walking speeds and standard deviations at the same flow range, one for congested data and another for the un-congested data.

6.5.2 Flow Ratio (r)

The pedestrian flow can be determined as uni-direction for walkways leading to escalators. However, the pedestrian flows at stairways are most likely to be bi-direction. Therefore, in order to calibrate the relationship between the mean walking speed and standard deviation for stairways, the bi-directional flow effects should also be considered. These effects in passageways and on stairways have been briefly discussed in Cheung and Lam (1997).

When there is bi-directional pedestrian flow on a pedestrian facility, the effective capacity of this facility in an individual direction (i.e. one-way pedestrian flow direction) can be determined by taking into account the directional distribution of pedestrian flows. When the directional distribution of the pedestrian flow for the passageways is 50:50, the effective capacity of the passageways in the individual direction can be considered as half. Therefore, the pedestrians in either directions share the width of the passageway equally. However, the effective capacity in the ascending direction for stairways is different from that in the descending direction. Therefore, the capacity in each direction has to be considered differently, when determining the flow ratio (r), the latter ranging from 0.1 to 1.0.

Lam et al. (2003) defined the major flow direction as the pedestrian flow direction with a flow ratio greater than or equal to 0.5. Correspondingly, when the flow ratio of that direction is less than 0.5, the direction is said to be the minor flow direction.

The flow ratios for stairways in ascending and descending directions can be determined as follows:

For stairways in ascending direction: $$r_{S_{as}} = \frac{\frac{v_{as}}{C_{as}}}{\frac{v_{as}}{C_{as}} + \frac{v_{de}}{C_{de}}} \tag{6.6}$$

For stairways in descending direction: $$r_{S_{de}} = \frac{\frac{v_{de}}{C_{de}}}{\frac{v_{as}}{C_{as}} + \frac{v_{de}}{C_{de}}} \tag{6.7}$$

subject to

$$v_{as} \leq C_{as} \tag{6.8}$$

$$v_{de} \leq C_{de} \tag{6.9}$$

$$0.0 < r_{S_{as}}, r_{S_{de}} \leq 1.0 \tag{6.10}$$

where:

v_{as} and v_{de} are the ascending and descending pedestrian flows (pedestrians/meter/minute) on the stairways respectively; and

C_{as} and C_{de} are the effective capacities (pedestrians/meter/minute) of stairways in ascending and descending directions respectively.

6.5.3 Observational Results

Figure 6.1 illustrates the observed relationship between the walking speed and pedestrian flow on the walkways leading to the escalator. The capacity of the walkway leading to the escalator was found to be 120 pedestrians/escalator/minute which is the same as that found in Cheung (1998). It was found that the at-capacity walking speed is 0.31 meter/second. Data with a walking speed greater than 0.31 meter/second is categorized in Figure 6.1 as the un-congested data. Data with a walking speed lower than 0.31 meter/second is categorized as congested data. The variation of walking speeds for the un-congested data are comparatively larger than those of congested.

Figure 6.2(a) and Figure 6.2(b) show the observed relationships between the walking speed and pedestrian flow on the stairways in the ascending and descending directions respectively. The walking speed variation for the congested data is smaller than that of the un-congested data. The stairway capacities at flow ratio equals to 1.0 are found to be 67 pedestrians/meter/minute in the ascending direction and 78 pedestrians/meter/minute in the descending direction respectively.

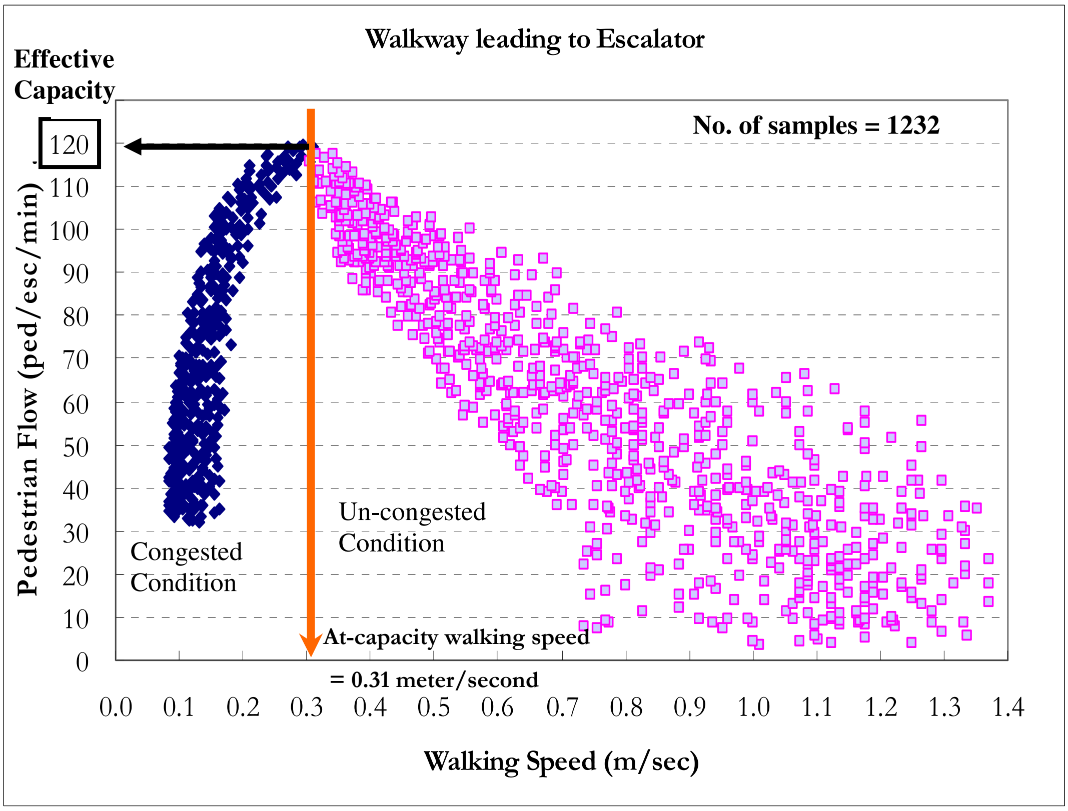
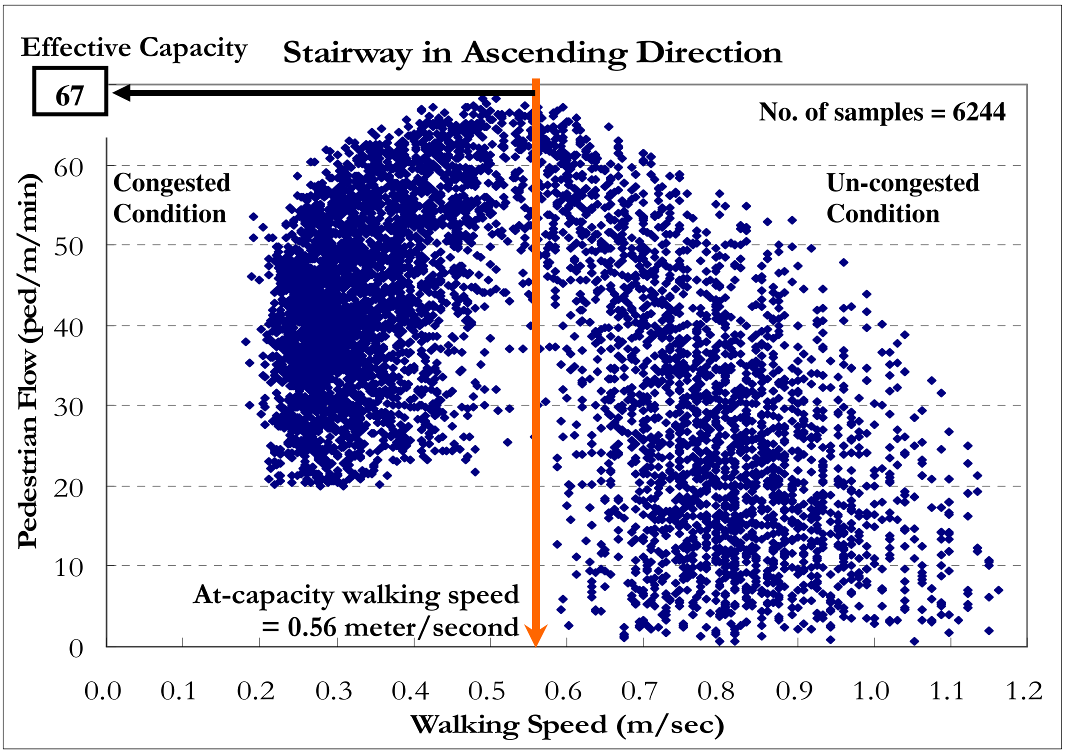
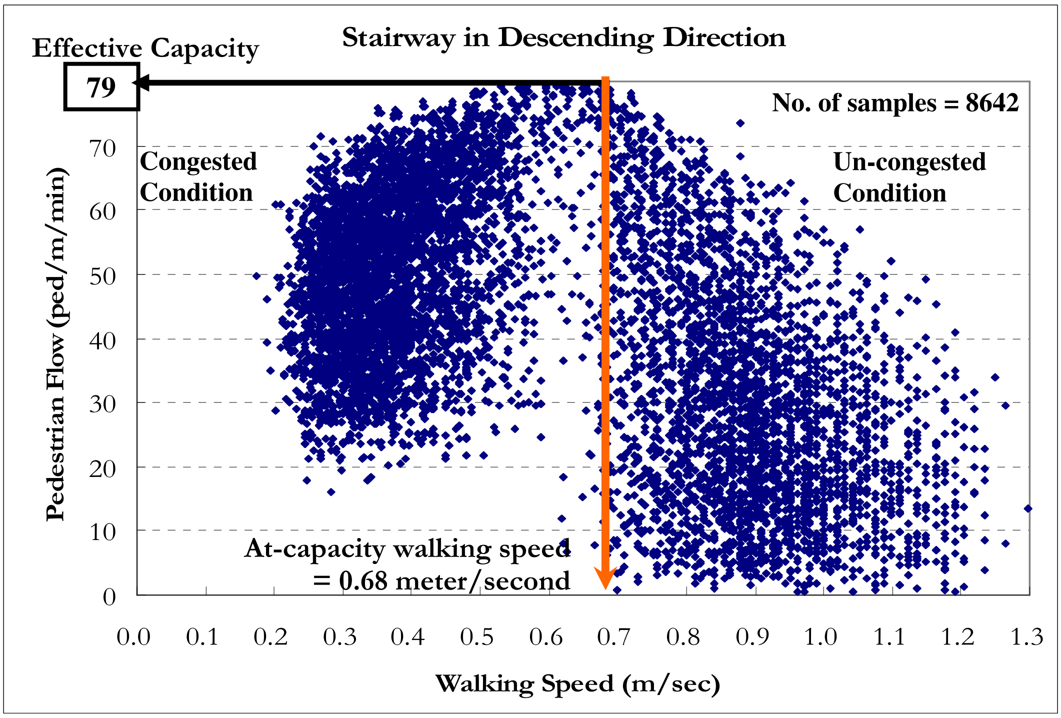


Figure 6.1 Observed relationship between walking speed and pedestrian flow for walkways leading to escalator (area = 7.5m^2)

With increasing imbalance of the directional pedestrian split (i.e. when $r = 0.1$) in Figure 6.2(a) and Figure 6.2(b), the stairway capacities reduce to 53 pedestrians/meter/minute in the ascending direction and 60 pedestrians/meter/minute in the descending direction respectively. This reduction is mainly because the movement of pedestrians in the minor flow directions are in the strong conflicts with the oncoming crowd, and the space available to them is reduced.



(a) Stairway in ascending direction



(b) Stairway in descending direction

Figure 6.2 Observed relationships between walking speed and pedestrian flow on stairways (a) in ascending direction (b) in descending direction

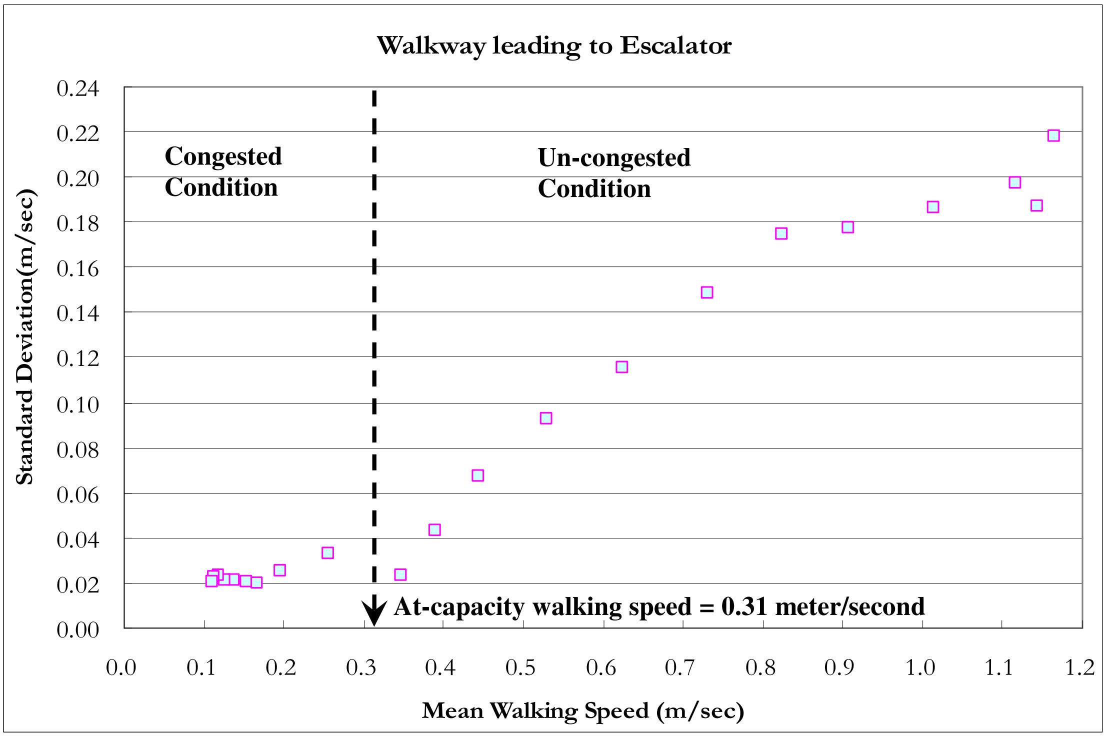
The at-capacity walking speed on the stairways in the ascending direction decreases from 0.56 meter/second under the uni-directional flow condition (i.e. $r = 1.0$) to 0.42 meter/second under the heavy opposing flow condition (i.e. $r = 0.1$). Similar results were found on the stairways in the descending direction; the at-capacity walking speed decreases from 0.65 meter/second when $r = 1.0$ to 0.48 meter/second when $r = 0.1$. These findings are consistent with the results found in the previous studies (Cheung, 1998, Cheung and Lam, 1997, Lam et al., 2002 & 2003). The observed data is grouped by using the pedestrian flow together with the flow ratio. The mean walking speed with the corresponding standard deviation by flow ratio on stairways in the ascending and descending directions can therefore be determined. The results are discussed in the following section.

6.6 CALIBRATION OF THE RELATIONSHIP BETWEEN MEAN WALKING SPEED AND VARIATION

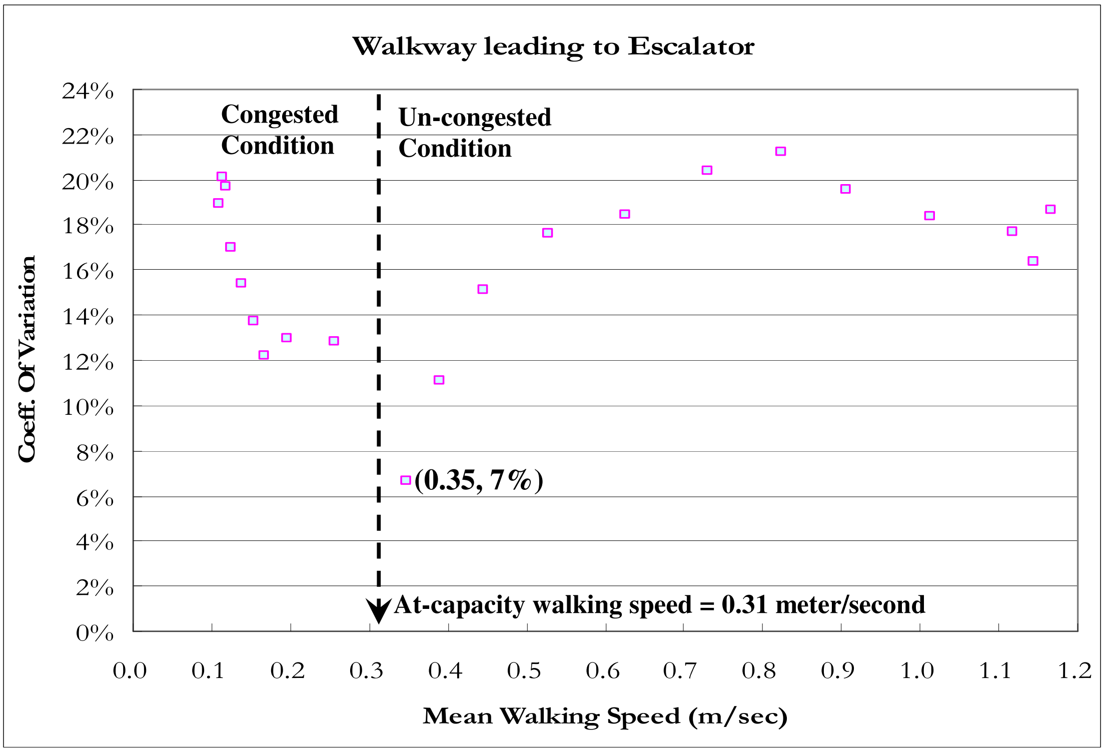
In order to calibrate the relationship between mean walking speed $\overline{S}$ and standard deviation SD_S, the observed data were grouped as indicated in Section 6.5.1. The mean walking speed with the corresponding standard deviation of each group for the walkways leading to the escalator was calculated and is shown in Figure 6.3(a). It can be seen that the standard deviation decreases in correlation with the decrease in the mean walking speed. The mean walking speed sharply decreases from 1.17 meters/second with $SD_S = 0.22$ meter/second to 0.35 meter/second with $SD_S = 0.02$ meter/second under the un-congested condition. However, it can also be observed from Figure 6.3(a) that under the congested condition, the mean walking speed decreases slowly with the standard deviation. Similar results can be observed bi-directionally on the stairways.

The Coefficient of Variation, $COV = SD_S / \bar{S}$ can be expressed in terms of the mean walking speed $\bar{S}$. The coefficient of variation is plotted against the mean walking speed in Figure 6.3(b). It can be observed that the coefficient of variation decreases with the decreasing of the mean walking speed, until the mean walking speed is close to at-capacity walking speed. The coefficient of variation is smallest, being only 7%, when the walking speed approaches the at-capacity one. The walking speed variation is smallest when the pedestrian flow is close to the facility's capacity.

Under congested condition, the coefficient of variation sharply increases with the decreasing mean walking speed. This can be partially explained by the fact that under heavy congested condition, pedestrians walk slowly in the wake of other pedestrians. However, some pedestrians may hurry by weaving through the crowd. Thus, their walking speed is faster than those pedestrians who follow the crowd.



(a) Standard deviation



(b) Coefficient of variation

Figure 6.3 Observed relationships between mean walking speed and (a) standard deviation (b) coefficient of variation

Similar results can be found for both ascending and descending directions on the stairways. The mean walking speed for the stairways in the ascending direction decreases from 0.87 meter/second with $SD_S = 0.14$ meter/second to 0.37 meter/second with $SD_S = 0.10$ meter/second under flow ratio equals to 1.0. When the flow ratio equals to 0.1, the mean walking speed decreases from 0.82 meter/second with $SD_S = 0.12$ meter/second to 0.29 meter/second with $SD_S = 0.05$ meter/second.

When the flow ratio equals to 1.0, the mean walking speed for the stairways in the descending direction decreases from 0.92 meter/second with $SD_S = 0.09$ meters/second to 0.38 meter/second with $SD_S = 0.09$ meter/second. It also decreases from 0.93 meter/second with $SD_S = 0.13$ meter/second to 0.29 meter/second with $SD_S = 0.05$ meter/second when the flow ratio = 0.1. The reduction of standard deviation for the stairways in the ascending walking speed is comparatively higher than those in the descending condition. This can be partially explained by the energy expended walking up a stairway being greater than that expended when walking down.

6.6.1 Calibration Results

Initially the relationships between the mean walking speed and the standard deviation were calibrated by applying Equation 6.2 firstly for the walkway data. R^2 is the coefficient of determination which is a measure to reflect the goodness-of-fit of the model equation adopted. Indeed, the closer the parameter R^2 value is equal to 1, the higher the proposed function accuracy. The calibration results are summarized in Table 6.2.

The calibrated results were satisfactory with $R^2 = 0.97$. However, when a similar function was applied to the bi-directional use of the stairways, taking into account the flow ratio, the calibrated results were not satisfactory. Therefore, Equation 6.3 was applied for the bi-directional use of the stairway. The calibration results are shown in Table 6.2. The function coefficients are also shown in Table 6.2 together with t-values.

The relationships between the mean walking time and standard deviation for the three chosen facilities were calibrated. Equation 6.4 was adopted for the walking time data of the walkway. This function was found to be an excellent fit with the observed data (i.e. $R^2 = 0.96$). Therefore, the same formulation was applied to the stairway. However, the calibration results were not satisfactory without introducing the variable - flow ratio. Therefore, a more generalized function for mean walking time against standard deviation was proposed for stairways taking into account the bi-directional flow effects.

Table 6.2 Calibration results of the relationships between mean walking speed/time and its standard deviation

Facilities	Parameters#	Coefficient	Standard Error	Calculated $\|t\|$-Value	R^2
Relationship between walking speed and its standard deviation					
Walkway Leading to Escalator	b_0	0.1841	0.0052	35.22	0.97
	b_S	1.1522	0.0792	14.54	
Stairway in Ascending Direction	b_0	0.9891	0.0188	52.61	0.66
	b_{S_1}	-0.2349	0.0751	3.13	
	b_{S_2}	0.2981	0.0651	4.58	
	b_r	0.0009	0.0062	0.15*	
Stairway in Descending Direction	b_0	0.1748	0.0202	8.65	0.53
	b_{S_1}	-0.3893	0.0753	5.16	
	b_{S_2}	0.3607	0.0596	6.05	
	b_r	-0.0236	0.0062	3.81	
Relationship between walking time and its standard deviation					
Walkway Leading to Escalator	a_0	0.0929	0.0188	4.95	0.96
	a_t	1.2792	0.0979	13.07	
Stairway in Ascending Direction	a_0	0.1155	0.0090	12.77	0.82
	a_t	1.3119	0.0710	18.49	
	a_r	0.0546	0.0353	1.55*	
Stairway in Descending Direction	a_0	0.1028	0.0054	18.99	0.93
	a_t	1.5733	0.0514	30.63	
	a_r	0.0546	0.0192	2.17	

Notes: # Parameters are defined in Equations 6.2 to 6.5.
* the values of parameters are not significantly different from zero at 95% confident.

It can be seen from Table 6.2 that the impacts of walking time variability ratio a_0 for the stairway in both directions (i.e. 0.115 in ascending and 0.1028 in descending) are higher than those for the walkway leading to the escalator (i.e. 0.0929). This can be partially explained by walking energy expended climbing up and down a gradient being comparatively higher than walking energy expended in a horizontal dimension. Greater variation of descending walking time on the stairway was observed for similar reason. For the stairway, the impact of walking time variability ratio is 1.3119 in the ascending direction and 1.5733 in the descending direction against 1.2792 for the walkway leading to the escalator.

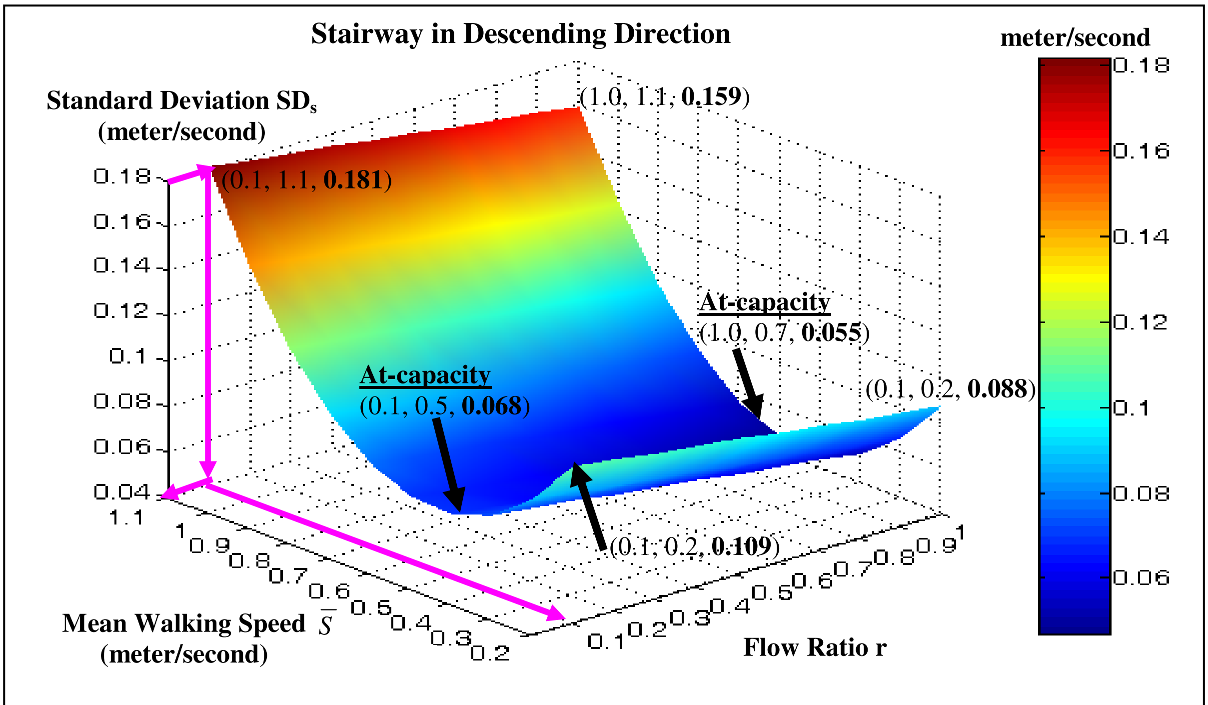
The bi-directional flow effects on walking speed variation on stairways in both directions were observed. Therefore, the walking speed variation could then be estimated in terms of mean walking speed and flow ratio. The estimated walking speed variation for stairways in the descending direction is plotted against the mean walking speed and flow ratio as shown in Figure 6.4(a). It can be seen that under the un-congested condition, the standard deviation decreases in correlation with the decrease in the mean walking speed.

Under heavy opposing flow (i.e. flow ratio = 0.1), the walking speed variation sharply decreases from 0.181 meter/second with $\overline{S} = 1.1$ meters/second to 0.068 meter/second with $\overline{S} = 0.5$ meter/second for the un-congested condition. It can also be observed from Figure 6.4(a) that under the congested condition, the mean walking speed decreases with the increase of the standard deviation (i.e. from 0.068 meter/second with $\overline{S} = 0.5$ meter/second to 0.109 meter/second with $\overline{S} = 0.2$ meter/second). However, under the uni-directional flows (i.e. flow ratio = 1.0), the walking speed variation decreases from 0.159 meter/second with $\overline{S} = 1.1$

meter/second to 0.055 meter/second with $\overline{S}=0.7$ meter/second for the un-congested condition.

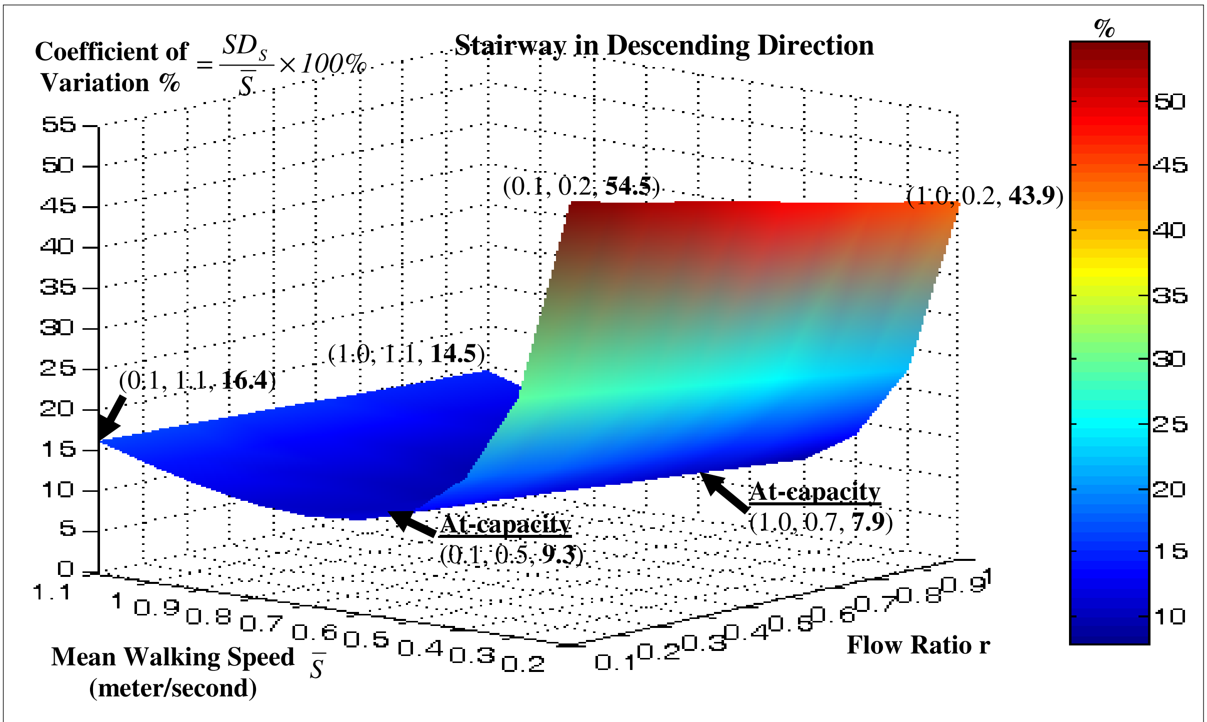
Whereas, under the congested condition, the mean walking speed decreases with the increase in the standard deviation (i.e. from 0.055 meter/second with $\overline{S}=0.7$ meter/second to 0.088 meter/second with $\overline{S}=0.2$ meter/second). In addition, the bi-directional flow effects on Coefficient of Variation (COV) on stairways in both directions were also quantified. The estimated COV for stairways in the descending direction is illustrated graphically against the mean walking speed and flow ratio in Figure 6.4(b). It can be seen that under the un-congested condition, the COV decreases in correlation with the decrease in the mean walking speed.

Under heavy opposing flow (i.e. flow ratio = 0.1), the COV decreases from 16.4% with $\overline{S}=1.1$ meters/second to 9.5% with $\overline{S}=0.5$ meter/second for the un-congested condition. However, under the congested condition, the mean walking speed decreases while the COV sharply increases (i.e. from 9.5% with $\overline{S}=0.5$ meter/second to 54.5% with $\overline{S}=0.2$ meter/second). However, under the uni-directional flows (i.e. flow ratio = 1.0), the COV decreases from 14.5% with $\overline{S}=1.1$ meters/second to 7.9% with $\overline{S}=0.7$ meter/second for the un-congested condition. Under the congested condition, the mean walking speed decreases while the COV sharply increases (i.e. from 7.9% with $\overline{S}=0.7$ meter/second to 43.9% with $\overline{S}=0.2$ meter/second).



Note: * Figures in the bracket refers to (flow ratio, mean walking speed, **standard deviation**)

(a) Standard deviation



Note: * Figures in the bracket refers to (flow ratio, mean walking speed, **coefficient of variation %**)

(b) Coefficient of variation

Figure 6.4 Estimated relationships between mean walking speed, flow ratio and (a) standard deviation (b) coefficient of variation

6.7 THE DISTRIBUTION OF OBSERVED WALKING TIME

A number of researchers have successfully constructed the observed travel time distribution in which travel time were standardized in terms of section means travel time and standard deviations for vehicles. They found that the congested travel time data distribution presented the normal distribution well (Taylor, 1982). Smeed and Jeffcoate (1971) suggested that the normal distribution was better represented by their data over the whole range of observations.

Richardson and Taylor (1978) found that the log-normal distribution might provide a better fit for the observed travel time data for private cars than the normal distribution. Taylor (1982) later found that the distribution of bus travel time was better represented by a normal distribution. In addition, Taylor (1982) found that the metro travel time data was better fitted by a log-normal distribution.

The observed walking speed data for the three pedestrian facilities were first tested as a possible fit for the normal and log-normal distributions. However, by using the goodness-of-fit - Chi-square χ^2 test, it was found that walking speed data were significantly different from both normal and log-normal distributions. Therefore, the distributions of the observed walking time data for the three pedestrian facilities were constructed in terms of the standardized variate x_{ij} for the i^{th} observation of group j. The distributions are shown in Figure 6.5 together with a normal distribution curve, for comparison. The standardized walking time variate x_{ij} is

$$x_{ij} = \frac{\left(t_{ij} - \bar{t}_j\right)}{s_j} \tag{6.11}$$

where

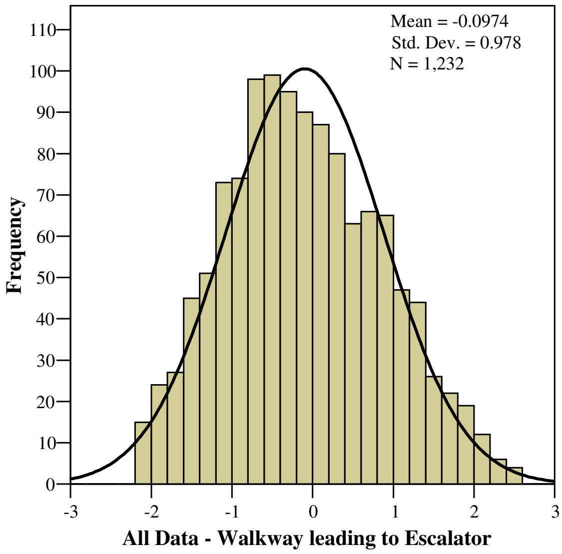
t_{ij} is the i^{th} observed walking time (seconds) of group j;

$\bar{t}_j$ is the mean walking time (seconds) of group j; and

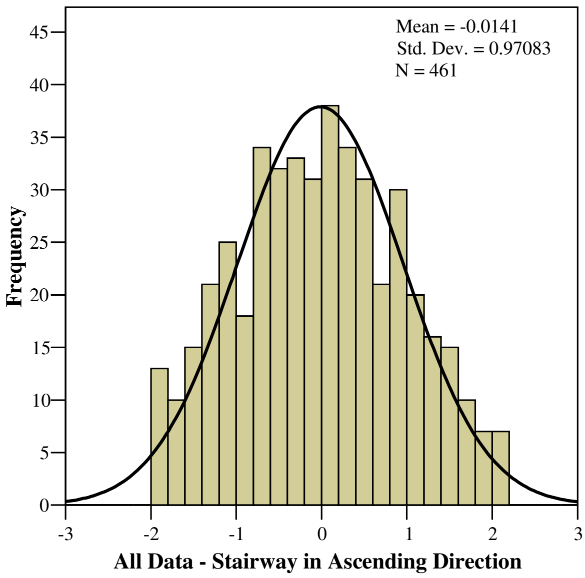
s_j is the standard deviation of the walking time of group j.

The standardized walking time variate x_{ij} reflects the variation of individual observation of the corresponding group mean, of each on a normalized scale. It should be noted that the x_{ij} distribution for the bi-directional stairways with flow ratio = 1.0 (i.e. uni-directional) are presented in Figure 6.5, only. The fit of x_{ij} distribution with the standardized normal distribution $N(0,1)$ was then tested using Chi-square χ^2 test with a degree of freedom (dof). The domain of the distribution of all x_{ij} for the walkways leading to the escalator was about (-2.6, +3.0). The domain of the distribution of all x_{ij} for the stairways in the ascending and the descending direction were about (-2.3, +2.3) and (-2.1, +2.5) respectively. The calculated Chi-square χ^2 values were 27.37 (dof = 23) for the walkways leading to escalator, 28.22 (dof = 21) for the stairways in the ascending direction and 29.17 (dof = 21) for the stairways in the descending direction respectively.

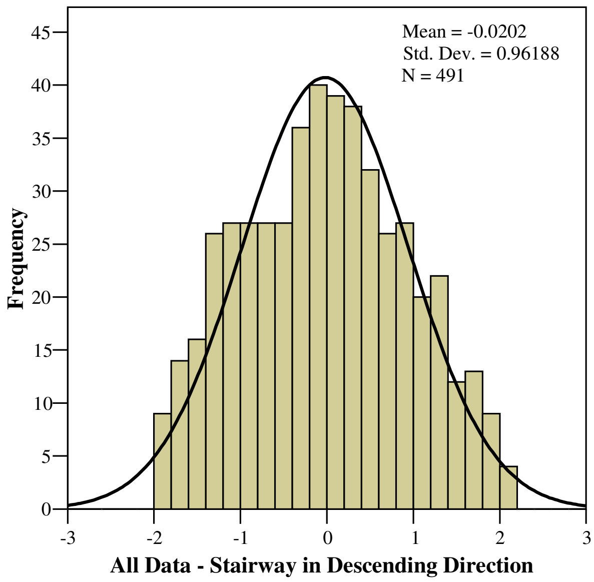
Using the Chi-square χ^2 test with a 95% confident, normal distribution provided a good fit for all of the observed data for the three selected pedestrian facilities.



(a) Walkway leading to escalator



(b) Stairway in ascending direction



(c) Stairway in descending direction

Figure 6.5 Observed distributions of walking time data for (a) walkway leading to escalator (b) stairway in ascending direction (c) stairway in descending direction

6.8 SUMMARY

This chapter reveals the characteristics of walking speed variations. Three types of pedestrian facilities, namely a walkway accessing an escalator, stairways in both ascending and descending directions are selected for case study.

The relationships between the mean walking speed and its variation for the three selected pedestrian facilities were calibrated and illustrated. It was found that standard deviation decreased with the reduction of the mean walking speed under the un-congested condition. The walking speed variation increased sharply with the decreasing mean walking speed under the congested condition. The walking speed variation was found to be the smallest when the pedestrian flow approached the capacity of the stairway or walkway facilities. The walking time distributions for these three selected facilities were also considered and derived. The normal distribution provided an excellent fit for all walking time data.

The findings on walking speed variations together with the calibrated generalized walking time functions of outdoor walkways and signalized crosswalks are further incorporated into the PAS model as necessary inputs. After all the inputs are incorporated into the PSA model, the model results are then compared with an independent set of observed data in order to assess the service performance of the developed PAS model. The comparison results are discussed in Chapter 7.

7 COMPARISON OF THE PEDESTRIAN ACTIVITY-SIMULATION MODEL AND THE TRADITIONAL TRIP-BASED SIMULATION MODEL

7.1 INTRODUCTION

The effects of uni-directional and bi-directional pedestrian flows on walking speed variations are presented in Chapter 6. The quantified effects are then further incorporated into the PAS model to simulate the pedestrian movements within the congested urban areas. In this chapter, the results simulated by the developed PAS model is compared with an independent set of observed data from the surveys. In addition, the reliability of the model results is compared between the PAS model and the traditional trip-based simulation model. This chapter is an edited version of: Lee, J.Y.S., 2009. Calibration of the pedestrian activity-simulation model for Hong Kong urban areas. *Proceedings of the 14th International Conference of the Hong Kong Society for Transportation Studies*, 1, 107-116. (Outstanding Student Paper Award of 2009 – 2nd Runner-up)

The objective of this chapter is to examine the performance of the developed PAS model which explicitly takes into account the pedestrian activity behaviors. An independent set of observed data was collected and used to test the accuracy of the results simulated by the PAS model and the traditional trip-based model. Therefore, a comparison was made between the observed data and simulation results including the total trip durations, the shopping durations and the pedestrian flows at screenlines.

There are 4 sections in this chapter. In Section 7.1, an introduction of this chapter is presented. Then, comparisons are made between the observed data and the results simulated by the newly developed PAS model and the traditional trip-based simulation model. The comparisons between the observed data and simulation results are presented in Section 7.2. Section 7.3 illustrates the results of hypothesis testing between the observed data and results simulated by the PAS model. Finally, the findings are summarized in Section 7.4.

7.2 COMPARISONS BETWEEN THE OBSERVED DATA AND SIMULATION RESULTS

An independent set of data was collected and extracted from the observational survey carried out at the chosen study area on a typical Friday 5 August 2005. A part-time PS is implemented after 4 p.m. every weekday in the study area. The choice of the survey period is based on the time period of the PS implemented and the historical passenger flow data provided by the MTR Corporation Limited.

The objective of the comparisons between the independent set of observed data and simulation results is to justify the results given by the newly developed PAS model and the traditional trip-based model. The following data were observed and used for the comparisons with the simulation results:

- Total trip durations
- Shopping durations
- Pedestrian flows at two screenlines

7.2.1 Total Trip Durations

Pedestrian total trip durations were extracted from the surveys by tracing the walking path and time of the sampled pedestrians. The observed distribution of total trip durations is summarized in Figure 7.1. It can be seen from Figure 7.1 that most pedestrians stay less than three minutes in the study area. This finding implies that majority of the pedestrians (about 90%) pass through the study area without performing any activities. This implication may be explained by the fact that the temperature in Hong Kong in August is high (i.e. an average of over $30^{0}C$) and the weather is hot. Pedestrians are not willing to stay or walk outdoor for a long time. They may only traverse the study area and go to other shopping malls with air-conditioning. These direct trips can be easily modeled or simulated by a traditional trip-based simulation model.

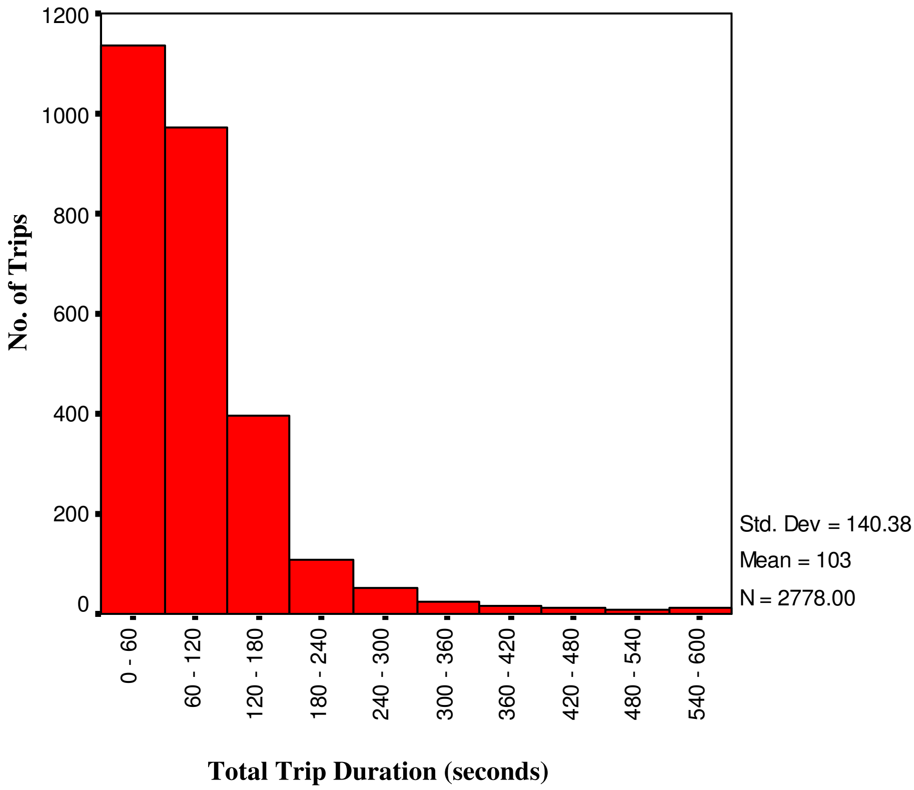


Figure 7.1 Observed distribution of total trip durations

From the observational and tracking surveys, it was found that about 10% of pedestrians would shop at the street-level stores. These pedestrians would stay longer within the study area. The total trip durations of these pedestrians are generally longer than those pedestrians without performing any activity. The traditional trip-based simulation model is only confined to simulate pedestrian trips without performing any activity. If the traditional trip-based simulation model is used to predict the pedestrian movements particularly in a congested shopping urban area, the simulation results will be questioned. It is necessary to take into account the shopping behaviors of the pedestrians. Thus, the PAS model is newly developed which explicitly takes into account the shopping behaviors of pedestrians.

As mentioned, the newly developed PAS model can simulate the pedestrian movements particularly in the congested shopping urban areas. An independent set of observed data was collected and used to test the accuracy of the model results simulated by the PAS model and the traditional trip-based model. A comparison on the total trip durations was made between the observed data and simulation results. The comparison results are shown in Table 7.1.

From the tracking surveys, the numbers of collected tracking trips were 1370 for the off-peak period and 1408 for the peak period respectively. The total number of pedestrian trips generated from and attracted to the study area are 51378 for the off-peak period and 80822 for the peak period, which are obtained from the observational survey. It is observed from the surveys that on average pedestrians spend 98.4 seconds staying in the study area during off-peak period. The total trip durations simulated by the PAS model are close to the observed average with some minor underestimations (about 4.3%). However, the matching between the observed total trip durations and the simulation results by the traditional trip-based simulation model is much worse. The traditional trip-based simulation model underestimates the total trip durations with 17.8% on average. The deviation can be explained by the fact that the traditional trip-based simulation model considers the pure walk trips only. Indirect trips, pedestrians performing activities, are not covered in this traditional trip-based simulation model. The durations of the pedestrian activities are not considered in the traditional trip-based simulation model. The model results of the total trip durations simulated by the newly developed PAS model are much better than those simulated by the traditional trip-based model. Therefore, the PAS model can effectively and accurately model the pedestrian activity behaviors in the congested urban areas.

Table 7.1 Comparisons between observed and simulated total trip durations

		Total Trip Duration (seconds)		
		Observed	Simulated	
			Activity-based	Trip-based
Off-peak Period (2 p.m. - 4 p.m.)	**Mean (Error %)***	98.4	94.2 **(-4.3%)**	80.9 **(-17.8%)**
	Standard Deviation	132.1	103.3	50.6
	Sample Size	1370	51378	
Peak Period (5 p.m. - 7 p.m.)	**Mean (Error %)**	107.1	96.4 (-10.0%)	83.5 (-22.0%)
	Standard Deviation	148.0	120.0	66.4
	Sample Size	1408	80822	

Note: Error % refers to the percentage of underestimating or overestimating of the model results.

For the comparison results of the peak period in Table 7.1, higher deviation is obtained between the observed data and the simulated results. On average, it was observed that pedestrians spend 107.1 seconds within the study area during the peak period. Pedestrians spend more time within the study area during the peak period than the off-peak period. Pedestrians are generally not in a hurry during the peak period (i.e. 5 p.m. - 7 p.m.) as they just leave from work. They tend to walk slower and are free to perform activities. Thus, pedestrians would stay longer within the study area during the peak period than those during the off-peak period. Moreover, the accuracy of simulating the total trip durations by using the PAS model can be retained with the overall underestimation percentage of 10%. However, if the traditional trip-based simulation model is used to model the pedestrian movements within the study area during the peak period, the overall accuracy of the model results are not reliable. The underestimation percentage reaches 22%.

7.2.2 Shopping Durations

As the chosen study area is a congested shopping area, pedestrians may perform some activities such as shopping and waiting for friends. During the tracking survey, the majority of pedestrian's activities are shopping. Shopping duration was extracted from the tracking data for investigation. The observed shopping duration is proved to fit with the exponential distribution shown in Section 3.4.4.

After the simulation run of the PAS model, the simulated shopping durations were extracted and are illustrated in Figure 7.2. The general trend and shape of the simulated shopping durations are similar and fitted with those of the observed shopping durations shown in Figure 4.6. However, the average shopping duration of the observed data is 293 seconds while that of the simulated results is 279 seconds. This discrepancy can be partially explained by the fact that there are few observed trips with shopping duration higher than 900 seconds while the exponential distribution cannot capture these trips with a long shopping duration. Hence, on average, the observed shopping duration is longer than that of the simulated one. This phenomenon can also be explained by the standard deviation of the mean shopping duration. It is consistent that the standard deviation of the observed data (i.e. 338 seconds) is much higher than that of the simulated (i.e. 282 seconds).

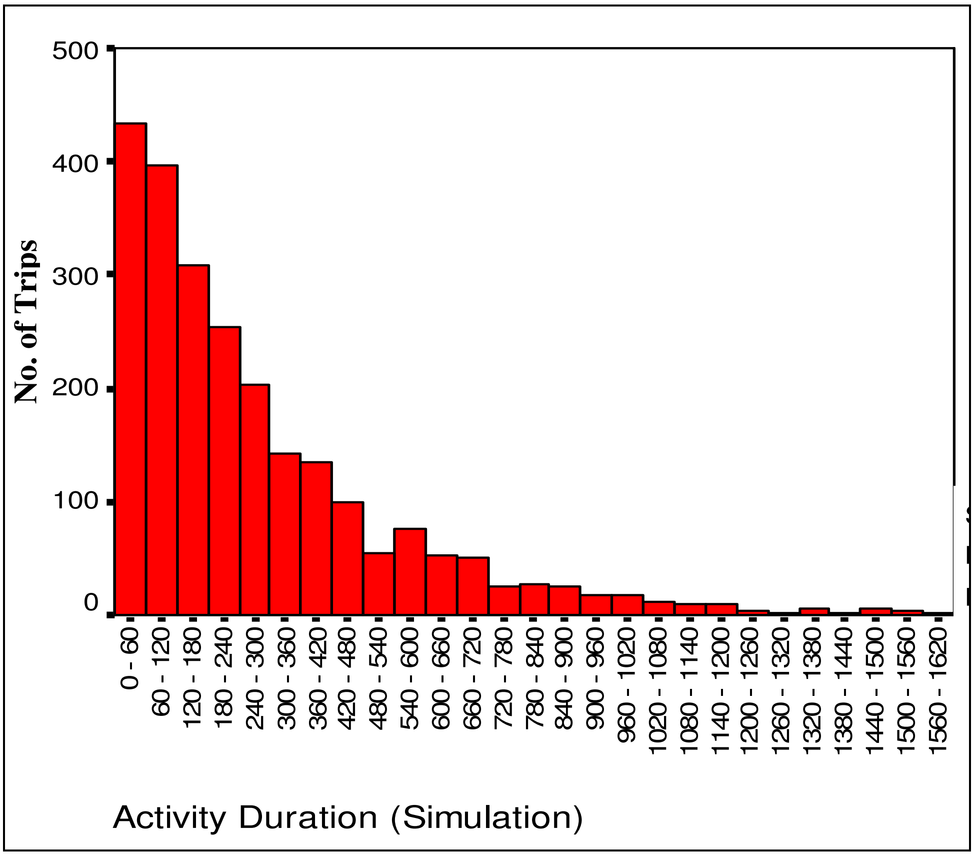


Figure 7.2 Simulated distribution of shopping durations

Chi-square test was preformed using the observed data and simulated shopping durations given by the PAS model. The calculated χ^2 is much less than the critical one (i.e. 8.815 vs 38.885), which implies that the distributions of the observed and the simulated shopping durations are not significantly different. This finding implies that the exponential distribution is suitable for modeling the shopping durations.

7.2.3 Pedestrian Flows at Screenlines

In this section, comparison is made between the observed pedestrian count and the simulated results at the two screenlines. The locations of the two chosen screenlines are illustrated in Figure 7.3. The choice of screenline locations for counting the two-way pedestrian flows depended on the pedestrian flows at the locations within the study area. The location with higher pedestrian flows is more likely to be chosen.

As shown in Figure 7.3, screenline 1 is located on the southern part of the study area. It separates the walkway along the Hennessy Road into two parts. Screenline 2 is located at the middle of the part-time pedestrian-only street. During the survey periods, two-way pedestrian flows at each screenline location were observed by manual counting.

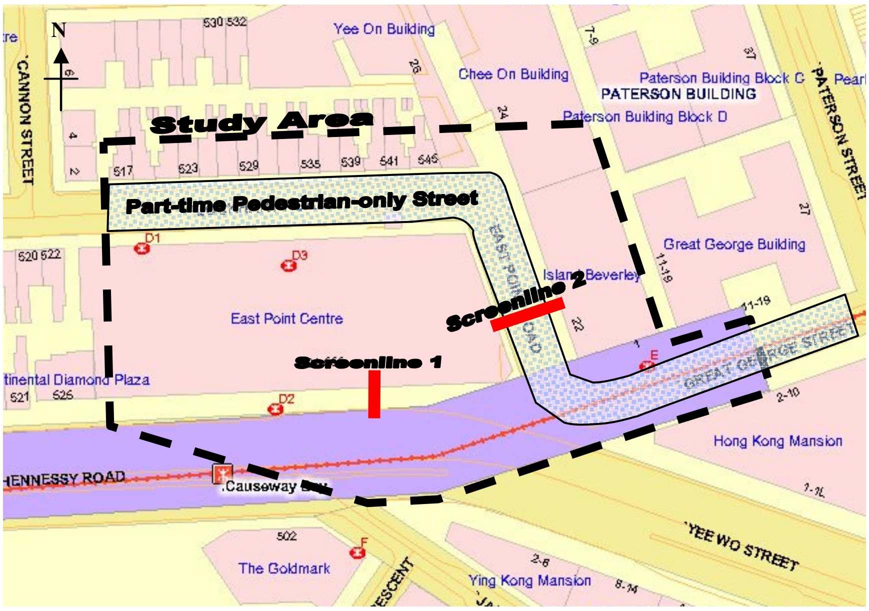
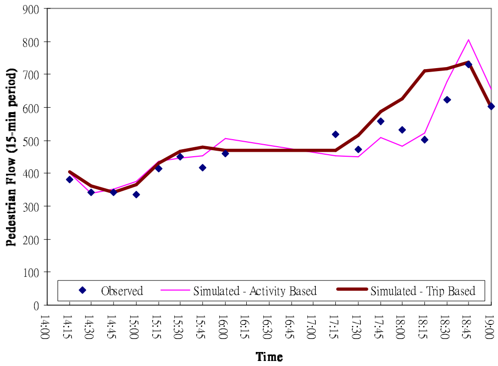


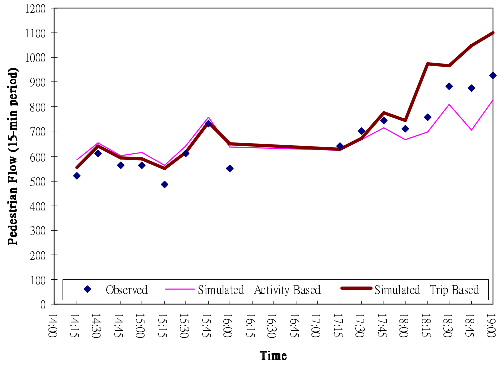
Figure 7.3 Locations of screenlines

The distributions of pedestrian flows by direction by screenline over time are summarized in Figure 7.4. The y-axis shows the number of pedestrians by a 15-minute period while the x-axis lists the two time periods. The two time periods are the off-peak and peak periods. The off-peak period is from 2 p.m. to 4 p.m. where the peak period is from 5 p.m. to 7 p.m. Two set of the simulation results are shown in Figure 7.4 together with the observed pedestrian flows by a 15-minute period. In Figure 7.4, data plotted with pink and brown color lines are the model results simulated by the new developed PAS model and the traditional trip-based model respectively.

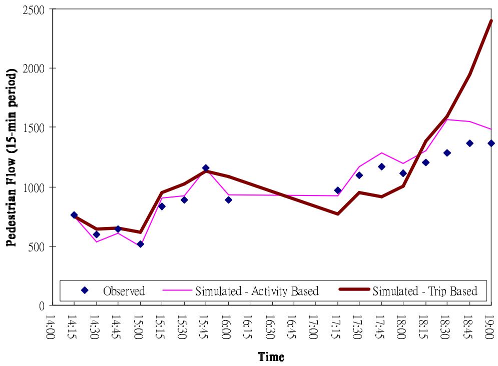
It can be observed from Figure 7.4 that the total number of pedestrians passing through the screenline during the peak period is higher than that of the off-peak period. During the peak period, PS is introduced within the study area enabling the section of road to serve as a pedestrian walkway. Vehicular access is restricted. Pedestrians are provided with safe and stress-free space in which to move freely and at a personally chosen speed. More pedestrians are attracted to the study area to perform activities after the implementation of the part-time PS.



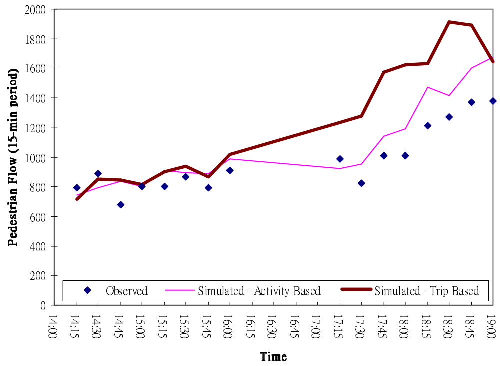
(a) Screenline 1 West Bound



(b) Screenline 1 East Bound



(c) Screenline 2 North Bound



(d) Screenline 2 South Bound

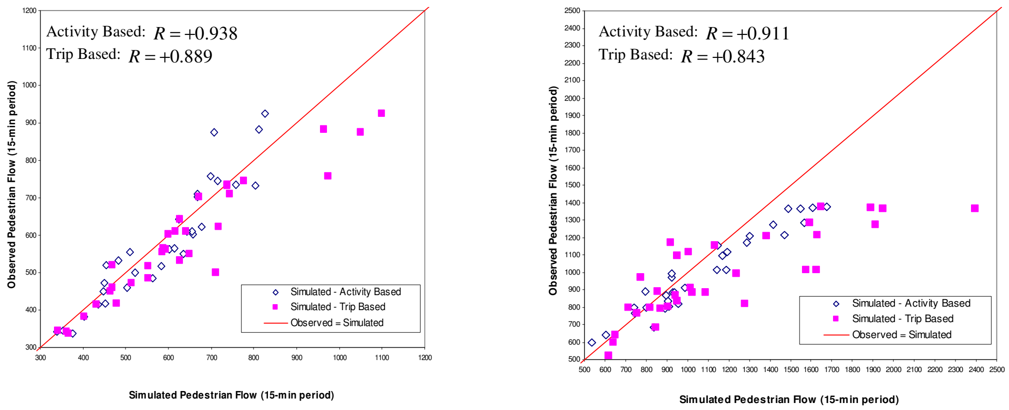
Figure 7.4 Total number of pedestrians by screenline by time period

In Figure 7.4(a) and Figure 7.4 (b) compare the simulated and observed numbers of pedestrians passed through screenline 1 in the west and east bound directions respectively. By using the PAS model, the simulation results fit the observed data perfectly before 4 p.m. Minor underestimation and overestimations are obtained after 6 p.m. However, huge deviation can be observed by comparing the observed pedestrian flows and the model results simulated by the traditional trip-based model.

The observed numbers of pedestrians passed through screenline 2 in the north and south bound directions are compared with the simulated results in Figure 7.4(c) and d) respectively. The observed and simulated numbers of pedestrians are close to each other during the off-peak period. Overestimation is obviously observed during the peak period. This discrepancy can be partially explained by the larger number of observations in relation to screenline 1. As the pedestrian flows were counted by the surveyors on-site manually, measurement error may be large due to the high pedestrian flows.

In order to quantify the accuracy of the results simulated by the newly developed PAS model and the traditional trip-based simulation model, comparisons are made by correlating the observed pedestrian flows and the simulated results by screenlines and shown in Figure 7.5.

In Figure 7.5(a) and Figure 7.5(b) show the comparison of the 15-minute pedestrian flows at screenlines 1 and 2 respectively. It can be seen that in Figure 7.5(a), the simulation results of screenline 1 from both models fit the observed pedestrian flows well. However, overestimation on the pedestrian flows is observed by using the traditional trip-based simulation model particularly during the peak period.



(a) Screenline 1 **(b) Screenline 2**

Figure 7.5 Pedestrian flows by screenline

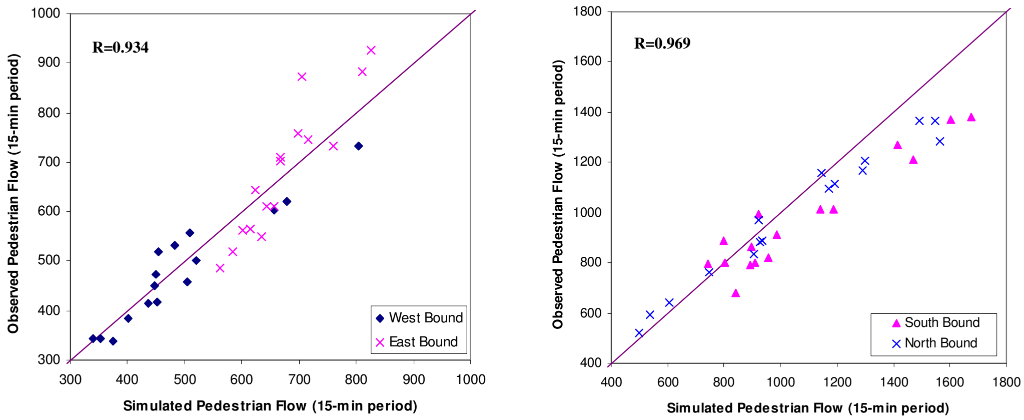
7.3 HYPOTHESIS TESTS BETWEEN THE OBSERVED DATA AND SIMULATION RESULTS

An independent set of data was collected from the observational and tracking surveys. It was then used to compare with the simulation model results. A simple linear regression model (i.e. $y = ax + b$) was fitted with the simulated and observed data set so as to test the reliability of the model results. The set of observed data is served as the dependent variable y and the set of simulated results is served as the independent variable x.

The hypothesis testing was also performed to examine the significance of the value of parameters a and b in the linear regression model. If the values of the coefficients, b is close to 0 and a close to 1, the simulated results are likewise close to the observed data (i.e. $y = x$ if $a = 1$ and $b = 0$). Thus, a null hypothesis was set for $a = 1$ and $b = 0$ with 95% confident that was used for testing. A simple correlation test was preformed so as to test the correlation between the observed data and simulated results. This test was measured by the R. The correlation coefficient R is varying from -1 to +1. A "-1" indicates perfect negative correlation, and "+1" indicates perfect positive correlation between observed data and the simulation results.

7.3.1 Pedestrian Flows by Screenline

A comparison is made between the observed and simulated pedestrian flows by direction by screenline. The comparison results of the screenlines 1 and 2 are shown in Figure 7.6(a) and Figure 7.6(b) respectively. *Y*-axis shows the simulated number of pedestrians by a 15-minute period while the *x*-axis shows the observed one. A line is plotted in Figure 7.6 with observed values equal to the simulated results. The scatter points are concentrated along the line when the pedestrian flow is low. It seems that when the pedestrian flow is high, some overestimation and underestimation on the pedestrian flows are observed. This deviation can be partially tolerated as the observed number of pedestrian flows is large. As the pedestrian flows were counted by the surveyors on-site manually, measurement error may be large due to the high pedestrian flows.



(a) Screenline 1 **(b) Screenline 2**

Figure 7.6 Comparisons between the observed and simulated pedestrian flows by screenline

A simple correlation test was also preformed so as to test the correlation between the observed data and the simulated results. In Figure 7.6, the values of correlation coefficient R are 0.934 for screenline 1 and 0.969 for screenline 2 respectively. They imply that the observed and simulated values are highly correlated. This indicates that the simulated results highly match with the observed data.

The results of the hypothesis testing on the pedestrian flows by screenline together with the computed t-values are presented in Table 7.2. The coefficients a (i.e. slope of the simple regression line) for the screenlines 1 and 2 are 1.074 and 0.833 respectively. Their computed t-values are 14.321 and 24.517 respectively. The critical values of coefficients a are both 2.04, which are much lower than the computed t-values. Therefore, with 95% confident (i.e. $\alpha = 0.05$), there is strong evidence to reject the null hypothesis for parameters a. This implies that the parameters a for both screenlines are not equal to 1.

Table 7.2 Hypothesis test results on the pedestrian flows by screenline

	Screenline 1	**Screenline 2**
Number of observation	32	32
Correlation Coefficient R	0.934	0.969
Coefficient of a	1.074	0.833
Standard error of a	0.075	0.034
Computed t-value of a	14.321	24.517
Coefficient of b	-45.474	204.098
Standard error of b	44.850	37.921
Computed t-value of b	-1.014	5.382
Critical values	± 2.04	± 2.04

The estimated values of parameter b (i.e. constant term of simple regression line) for the screenlines 1 and 2 are -45.474 and 204.098 respectively while their computed t-values are -1.014 and 5.382 respectively. The critical values of parameters b are both ± 2.04. It should be noted that the computed t-value of parameter b of the screenline 1 is lower than the critical one while it is contrary for the screenline 2. Therefore, with 95% confident (i.e. $\alpha = 0.05$), there is no sufficient evidence to reject the null hypothesis for parameter b for screenline 1. This implies that the parameter b for the screenline 1 is equal to 0. However, there is sufficient evidence to reject the null hypothesis for parameter b for the screenline 2 with 95% confident. This indicates that the parameter *b* for screenline 2 is not equal to 0.

After hypothesis testing on the pedestrian flows at the two screenlines, it is proved that the observed data and simulated results are highly correlated. For the screenline 1, slope is equal to 1.074 and intercept equal to 0. The slope greater than 1 implies that the PAS model underestimated the pedestrian flows with about 7.4% on average. However, for the screenline 2, slope is equal to 0.833 and intercept is equal to 204.098. The slope is less than 1. It implies that the PAS model overestimated the pedestrian flows at the screenline 2 with about 17% on average.

Overestimation and underestimation on the pedestrian flows at the screenlines are observed when the pedestrian flow is high, especially at the screenline 2. This discrepancy can be partially tolerated as the pedestrian flow at the screenline 2 is complex. A number of stores are located along the part-time pedestrian-only street while the screenline 2 is destined at the middle of the street. Pedestrians may shop or window shopping along the street. Moreover, as the pedestrian flows were counted by the surveyors on-site manually, measurement errors may be large due to the high pedestrian flows and the various activities performed.

7.4 SUMMARY

A PAS model was developed to simulate the pedestrian movements within the study area taking into account the pedestrian activities. This newly developed PAS model can simulate the pedestrian movements with the activity choices considered. The observational and tracking surveys were carried out at the selected study area. The objectives of the surveys are collected data for model development and comparison. Data collected for model development are: (1) pedestrian flows at the chosen locations; (2) pedestrian O-D flow matrices; and (3) pedestrian total trip and shopping durations.

The objective of this chapter is to examine the service performance of the newly developed PAS model. An independent set of the observed data was collected and extracted from the surveys so as to compare the model results given by the newly developed PAS model and the traditional trip-based simulation model. Therefore, a comparison was made between the observed data and simulation results including the total trip durations, the shopping behaviors and the pedestrian flows at the two screenlines.

Comparison results highlight the inability of using the traditional trip-based simulation model to simulate the pedestrian flows and total trip duration particularly when the pedestrian activities are active in the study area. This feature shows that the pedestrian activity duration is of prime importance to consider in the simulation model.

By using the newly developed PAS model, satisfactory results were obtained by comparing the observed data and simulated pedestrian flows at the two selected screenlines as well as the total trip and shopping durations. The newly developed PAS model has a good prediction on the pedestrian flows at the two chosen screenlines, especially during the off-peak period. During the peak period, the pedestrian flows are much higher than those during off-peak period. Thus, the pedestrian movements are more complex. Overestimation and underestimation on the pedestrian flows at screenlines are tolerated during the peak period than the off-peak period.

Exponential distribution is found to be the best fit for modeling the shopping duration. This is supported by comparing the observed shopping duration with the simulated results. Shopping activity is the dominant activity among the others. The majority of pedestrians use less than 5 minutes for shopping. The floor areas of the stores are small as the stores at the street-level are corner stores. Therefore, pedestrians may not stay long in the stores. Moreover, the values of the correlation coefficient R and the hypothesis tests on the estimation of the coefficients a and b for the linear models indicate that the correlation between the observed data and the simulated results by the PAS model are high. A pedestrian simulation model for signalized crosswalks is developed taking into account the bi-directional pedestrian flow effects. The calibration and validation of the Pedestrian Simulation Model (PSM) are presented in the Chapter 8.

8 CALIBRATION AND VALIDATION OF THE PEDESTRIAN SIMULATION MODEL FOR SIGNALIZED CROSSWALKS

8.1 INTRODUCTION

The pedestrian activity and destination choices are modeled and discussed in Chapter 4. The generalized walking time (GBPR) functions for signalized crosswalks and outdoor walkways are calibrated in Chapter 5. Relationship between average walking time and its standard deviation is proposed and calibrated in Chapter 6. These models/functions are then further incorporated into the PAS model to simulate the pedestrian movement taking into account the activity choices. The results simulated by the newly developed PAS model are compared with the observed data in Chapter 7. This chapter aims to describe the development, calibration and validation of a Pedestrian Simulation Model (PSM) for signalized crosswalks. This chapter is an edited version of: Lee, J.Y.S. and Lam, W.H.K., 2008. Simulating pedestrian movements at signalized crosswalk in Hong Kong. *Transportation Research A*, 42, 1314-1325.

This chapter presents a new PSM for signalized crosswalks in Hong Kong. This PSM can estimate the variations of walking speeds particularly on the effects of bi-directional pedestrian flows so as to determine the minimum required duration of pedestrian crossing time. Video records taken from the observational surveys at a selected crosswalk in an urban area were used to extract the required data for model calibration. It is observed from the video records that pedestrians may not have enough time for them to pass through the crosswalk during the pedestrian green and flashing green time periods with a heavy opposing flow. This observation implies that the durations of the pedestrian green and flashing green time of the signalized crosswalks should vary due to the effects of bi-directional pedestrian flows. The new PSM is also validated using an independent data set so as to examine the reliability of the simulation results. The advancement of this PSM can be applied to assess the effects of each improvement measure and to evaluate the benefits of each scenario in practice. Moreover, this calibrated and validated PSM is a part of the PAS model to simulate the pedestrian movements in the congested urban areas.

There are 5 sections in this chapter. In Section 8.1, an introduction of this chapter is presented. Data are collected from the observational survey to calibrate the PSM for signalized crosswalks. Model calibration is demonstrated in Sections 8.2. Section 8.3 presents the validation of the model results so as to assess the model reliability. A case study is chosen and discussed in Section 8.4 with model results. Finally, a summary is presented in Section 8.5.

8.2 MODEL CALIBRATION

In this thesis, as mentioned in Section 2.3, the SERVICE MODEL was selected as the platform for developing the model to simulate the pedestrian movements. In order to develop the PSM for signalized crosswalks, data such as pedestrian arrival patterns, stop/cross probability during flashing green time, pedestrian walking time and delays at each signal cycle were extracted from the video recorded from the observational survey.

8.2.1 Experimental Site

A signalized crosswalk at Causeway Bay was selected for model calibration. The selected crosswalk is one of the facilities located at the study area of the pedestrian activity-simulation (PAS) model. Figure 3.4 shows the location of the crosswalk in the study area of the PAS model. This chosen signalized crosswalk is one of the busiest signalized intersections in Hong Kong congested urban areas. The physical characteristics such as length, width and signal cycle time of this selected crosswalk are illustrated in Figure 8.1. The length and width of the crosswalk are 18.2 meters and 14.5 meters respectively. The cycle length was 120 seconds. The pedestrian green and flashing green time were about 30 seconds and 13 seconds respectively. Moreover, the pedestrian red time was 77 seconds which included the all-red time (i.e. 2 seconds).

Physical Characteristics

Width = 14.5 meters
Length = 18.2 meters

Signal Cycle Time (seconds)

Pedestrian Green + Flashing Green = 43 seconds
Pedestrian Red = 77 seconds
Cycle Time = 120 seconds

Figure 8.1 Physical characteristics of the selected signalized crosswalk

For the pedestrian signal at the crosswalks in Hong Kong, the sequence is red, green, flashing green and red. When the pedestrian "steady red" signal (i.e. red stationary man) is illuminated, pedestrians should not cross or start to pass through the crosswalk. The pedestrian green signal (i.e. green walking man) when illuminated by a steady light indicates that pedestrians can traverse the crosswalk. When the green signal is illuminated by an intermittent light (i.e. flashing green man), it implies that i). pedestrians who are already on the crosswalk should speed up to completely pass through the facility before the pedestrian "steady red" signal is illuminated; and ii). pedestrians who are not on the crosswalk should not start to cross the facility.

8.2.2 Observational Survey

An observational survey was conducted on a typical Friday on November 2003 by using the video recording technique at the chosen signalized crosswalk. It was found from the passenger data provided by MTR Corporation Limited that the evening peak hour was the most congested period throughout a day for the Causeway Bay MTR Station. Thus, the evening peak hour 5:30 p.m. - 6:30 p.m. was chosen for conducting the observational survey. An hourly video record was taken from a tall building with a top view of the chosen crosswalk. A time-lapse photography technique, adopted in a number of previous studies (Cheung and Lam, 1997 & 1998; Lam et al., 2002 & 2003) was used to record the pedestrian movements on the chosen crosswalk. Before data extraction, a time code with a precision of 0.04 second was mapped onto the video images so as to enhance the measurement precision. A detailed description of the data extraction method can be found in Appendix D. An extracted image is also illustrated in Figure 8.1.

The chosen crosswalk was further divided into four main measurement sections and are illustrated in Figure 8.2, namely Waiting Area (N); Crosswalk Area (N); Crosswalk Area (S); and Waiting Area (S). Li et al. (2005) suggested that walking directions might influence the pedestrian delays. Therefore, pedestrians are divided into two categories: North Bound (NB) pedestrians, who encounter the west bound vehicle flow first; and South Bound (SB) pedestrians, who encounter the east bound vehicle flow first. There are 3 east bound traffic lanes but only one lane for west bound traffic. A tram-way is also located at the study area (see Figure 8.1 and Figure 8.2).

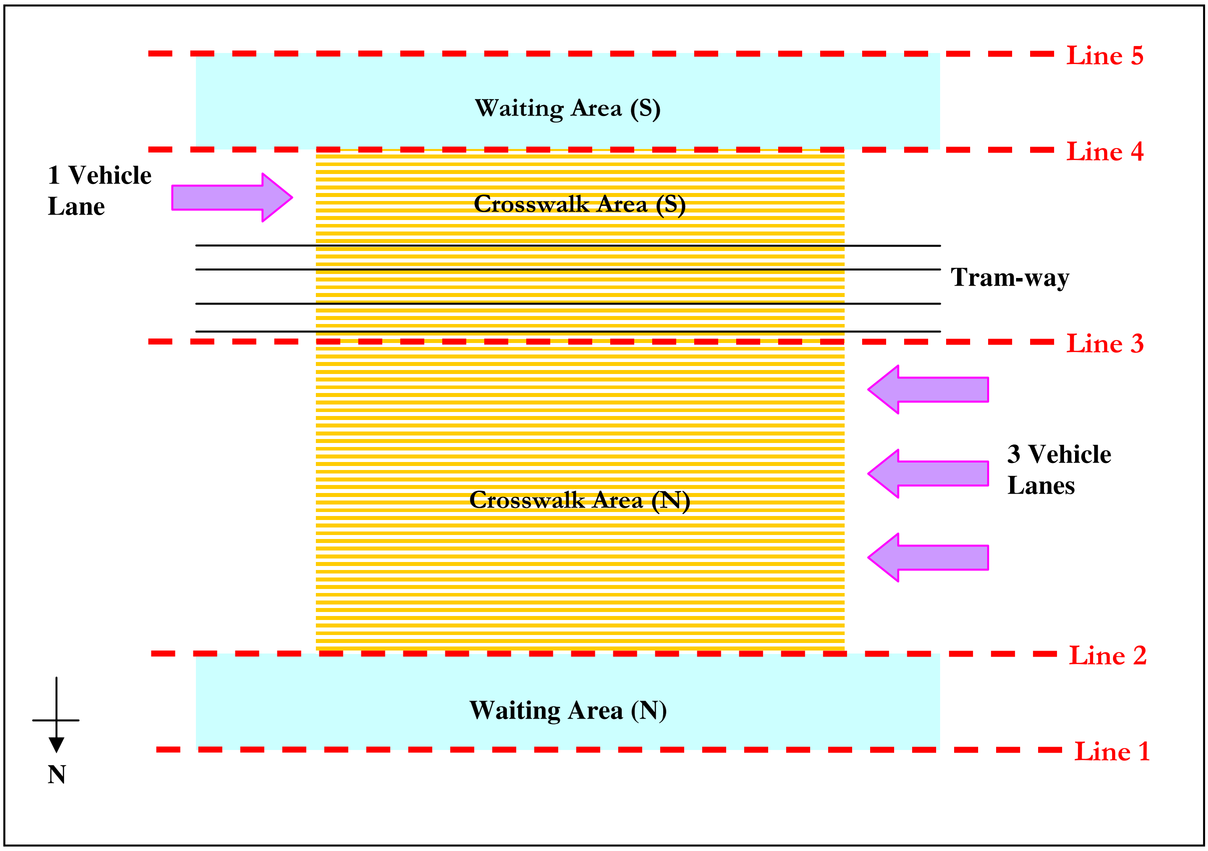


Figure 8.2 Layout of the chosen signalized crosswalk

The pedestrian arrival patterns for the both directions can also be extracted from the video records by counting pedestrians passing through Line 1 (for SB) and Line 5 (for NB) as shown in Figure 8.2. In addition, the arrival time, departure time and finishing time of each pedestrian can also be extracted from the video records. The time when a pedestrian arrive at the waiting area is defined as arrival time. The time when a pedestrian leave the waiting area and enter the crosswalk area is defined as departure time. Thus, the time when a pedestrian leave the crosswalk area is defined as finishing time. Take a SB pedestrian as an example. The time when s/he passed through Line 1 and Line 2 are defined as his/her arrival time and departure time respectively. Besides, finishing time is defined as the time that s/he passed through Line 4. In total, 656 SB pedestrians and 649 NB pedestrians were sampled.

Pedestrian delay is defined as the difference between his/her actual walking time and the ideal walking time. The ideal walking time was determined by measuring the average walking time when the pedestrian flow is very low (i.e. free-flow walking time). The observed ideal walking time for both SB and NB pedestrians were 13.4 seconds (i.e. 1.35 meters/second) and 14.4 seconds (i.e. 1.26 meters/second) respectively.

8.2.3 Pedestrian Simulation Model (PSM)

The objective of the new PSM for signalized crosswalks is to determine the average pedestrian delays and its variations. This PSM is also capable to estimate the variations of walking time, not only the average walking time. The layout of the chosen signalized crosswalk was firstly constructed by using the AutoCAD software. This layout is illustrated in Figure 8.2 and was incorporated into the PSM for graphical presentation.

The generalized walking time function for signalized crosswalks was incorporated into the PSM to estimate the pedestrian walking time and delays on the chosen crosswalk together with the walking speed variations. The detailed formulation of the GBPR function is discussed previously in Chapter 5. The total simulation time for the model is 60 minutes. Figure 8.3 shows the newly developed PSM for the selected signalized crosswalk. The blue dots represent the NB pedestrians, while the red dots represent the SB pedestrians. Each dot in Figure 8.3 illustrates an individual pedestrian movement within the study area.

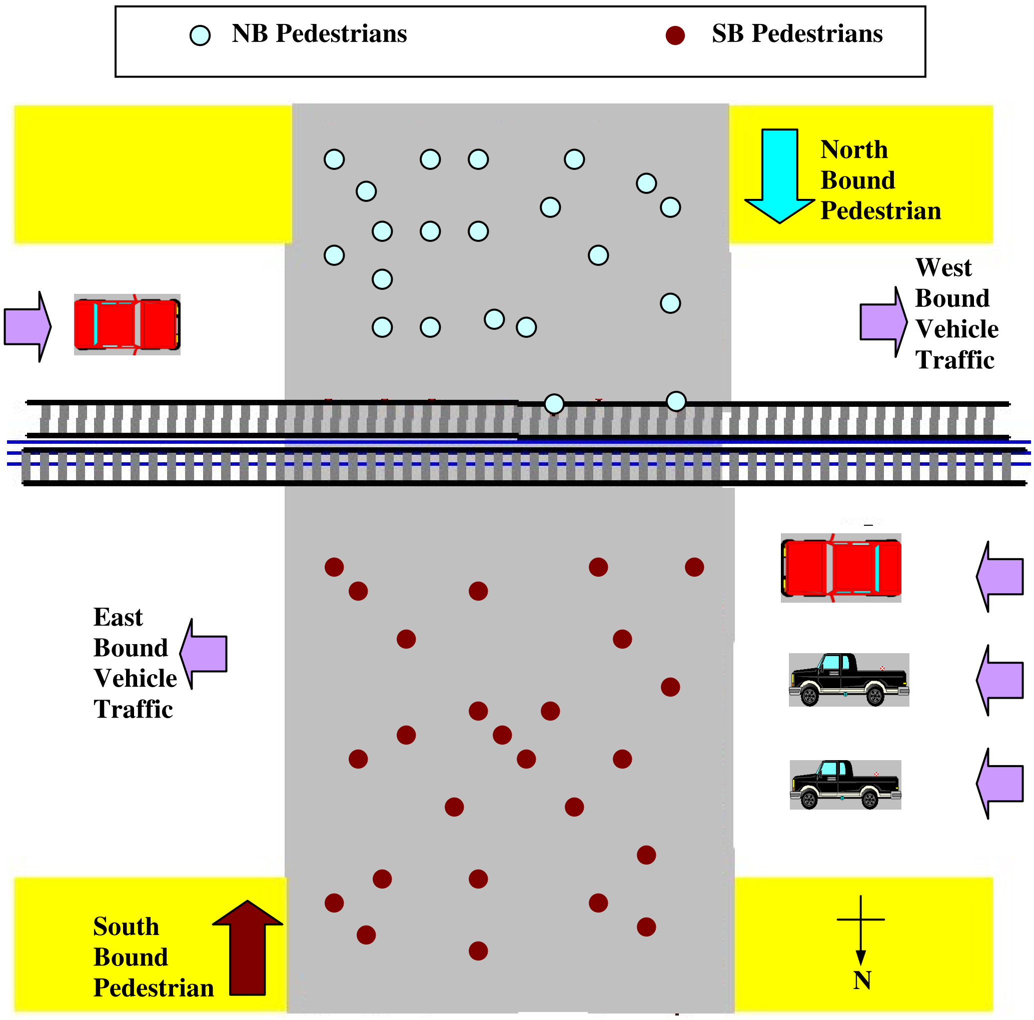


Figure 8.3 Pedestrian simulation model for signalized crosswalks

8.2.4 Model Formulation

Pedestrian flows are inherently more complex than vehicular flows as the bi-directional flow effects are considered in pedestrian movements. The objective of this study is to develop an intuitively and empirically appealing PSM for the signalized crosswalks. By incorporating the GBPR function calibrated in Chapter 5 and the walking speed variations investigated in Chapter 6, the new PSM can simulate the pedestrian movements and walking behaviors on the signalized crosswalks, particularly when the pedestrian flow approaches to crosswalk's capacity and pedestrians are facing heavy opposing flows.

Blue and Alder (2001) investigated the bi-directional pedestrian flows using cellular automata micro-simulation method. They proposed that there are three fundamental rules of the pedestrian movements that a bi-directional microscopic PSM should cater for:

- Side stepping - the desire of a pedestrian to "switch-lanes" move laterally to either enable increased velocity or avoid head-on conflicts;
- forward movement - the desired speed of the pedestrian and the placement of other persons in the immediate neighborhood; and
- Conflict mitigation - the manner in which pedestrians approaching each other from opposite directions manage to avoid a head-on collision or deadlock.

These pedestrian movements can be easily observed at a congested crosswalk. When the pedestrian flows on the crosswalk approach its capacity together with a heavy opposing flow, pedestrians have less freedom to choose their own walking speeds (forward movement). Then, they will try to avoid (or side stepping) from the opposing pedestrians so as to mitigate head-on conflicts (conflict mitigation).

Unlike the micro-simulation rules used in the cellular automata model, there are several built-in routing rules in the SERVICE MODEL package. They are common rules for pedestrian routes such as:

- "First Available" – pedestrians select the first location that has available capacity;
- "Most Available" – pedestrians select the location that has the most available capacity;
- "Random" – pedestrians select randomly among two or more available locations; and
- "Probabilistic" – pedestrians select the location based on the probability specified.

In reality, pedestrians usually try to minimize their walking time when walking on a crosswalk. They would like to select the first location that has available capacity. In view of this, the routing rule – "First Available" was selected and adopted in the PSM. This rule is the most realistic one to simulate the pedestrian walking behavior. This routing rule causes the first location (with available capacity) listed in a block of routes to be selected. Pedestrians can change lanes only when an adjacent location has available capacity. For the step forward movement, a minimum clearance distance of 0.5 meter is kept in the front so as to eliminate conflicts with the opposing pedestrians. If an empty location between two pedestrians is available, pedestrians who first enter the empty space has the occupancy right (as stated in the "First Available" rule) to be located in the empty space.

8.2.5 Pedestrian Stop/Cross Probability during Pedestrian Flashing Green Time

In Hong Kong, there are three phases of pedestrian signal: pedestrian green time, flashing green time and red time. Pedestrians are not allowed to walk through the crosswalks during pedestrian red time, but allowed to traverse during pedestrian green time. When the pedestrians arrive during flashing green time, they are also not allowed to enter the crosswalks. However, for those who were already on the crosswalks, they are forced to speed up until they can completely traverse the crosswalk for safety.

As mentioned in Section 8.2.2, the observational survey was carried out to record the pedestrian movements using video record technique. Data such the stop/cross probabilities when the pedestrians arrived during flashing green time can be extracted from the video records. The duration of the flashing green time is 13 seconds. The trade-off between stop and cross decision is about half of the duration of pedestrian flashing green time (i.e. 6 seconds) from the empirical data. It is found that majorities of the pedestrians will immediately traverse the crosswalk if they arrive during the first 7 seconds of flashing green time. However, it is worth noting that over 50% of pedestrians will not start to cross when they arrive during the last 6 seconds of flashing green time. Therefore, a time period of 6 seconds is selected for the stop/cross probability criteria. Two assumptions on the pedestrian stop/cross decision are made. Firstly, it is assumed that all pedestrians will traverse the crosswalk once they arrive during pedestrian green time. Another assumption is that all pedestrians arriving during pedestrian red phase will not traverse the crosswalk until the next pedestrian green phase.

8.2.6 Generalized Walking Time Function for Signalized Crosswalks

The relationship between pedestrian flow, walking time and flow ratio for signalized crosswalks is calibrated and briefly discussed in Chapter 5. The calibrated GBPR function for signalized crosswalks is then incorporated into the PSM. The purpose of the GBPR function is to estimate the walking time during the pedestrian green and flashing green phases on the signalized crosswalks ranging from free-flow to at-capacity flow conditions and from uni-directional to bi-directional flow conditions. The GBPR function for signalized crosswalks is given below:

$$GBPR\left(r,\frac{v}{C_{eff}}\right)=0.868+0.364\times(r)^{-0.418}\times\left(\frac{v}{C_{eff}}\right)^{2.280} \tag{8.1}$$

where:

$$C_{eff}=60.84+27.86r-0.22r^{2}-10.84r^{3} \tag{8.2}$$

r is the flow ratio $(0<r\le 1)$;

v is the two-way pedestrian flow (pedestrians/meter/minute);

C_{eff} is the fitted effective capacity (pedestrians/meter/minute) of the signalized crosswalk at flow ratio r; and

$GBPR\left(r,\frac{v}{C_{eff}}\right)$ is the unit walking time (seconds/meter) for pedestrians walking on a signalized crosswalk at flow v under flow ratio r during pedestrian green and flashing green phases.

This GBPR function for pedestrians can only estimate the average walking time under certain pedestrian flow conditions. However, the variations on walking time/speeds are not taken into account. In Chapter 6, the relationships between mean walking time and its standard deviation were proposed and calibrated with the observed data. The calibrated models for the relationships between mean walking time and standard deviation for the uni-directional and bi-directional pedestrian facilities are summarized as follows:

For uni-directional pedestrian facilities: $SD_t = 0.0929 \times \bar{t}^{\,1.2792}$ (8.3)

For bi-directional pedestrian facilities: $SD_t = 0.1028 \times \bar{t}^{\,1.5733} \times r^{0.0546}$ (8.4)

where SD_t is the standard deviation of the mean walking time; $\bar{t}$ is the mean walking time (seconds); and r is the flow ratio ($0 < r \leq 1$). Then, the GBPR function is then incorporated into the PSM so as to predict the average walking time under different flow conditions. Moreover, with the calibrated relationships between mean walking time and its variations, the PSM can provide a comparatively good estimation not only on average walking time but also on their variations.

8.3 MODEL VALIDATION

On a typical Saturday on 20 November 2004, an independent data set was collected at the chosen signalized crosswalk but in a different time period (during lunch time from noon to 1 p.m.). This new data set collected was used to validate the reliability of the simulation results given by the PSM. The simulation results were then compared with the observed data and derived as follows:

- Mean walking speed for each signal cycle
- Standard deviation of walking speed for each signal cycle

A goodness-of-fit test was carried out to determine the difference between the observed data and simulation results. This test was measured by the R^2 value.

The closer the value of R^2 to 1, the smaller the difference between the observed data and the simulation results.

8.3.1 Mean and Standard Deviation of Walking Speeds for Each Cycle

Figure 8.4 and Figure 8.5 show the observed mean and standard deviation of walking speeds versus results estimated by the PSM for the chosen crosswalk respectively. Y -axis represents the observed data at each cycle while X -axis represents the corresponding simulated by the PSM. In Figure 8.4 and Figure 8.5, the points located above the diagonal line indicate that the observed data are larger than estimated results (i.e. underestimated). Those points lie below the diagonal line indicate that the observed data are smaller than the estimated results (i.e. overestimated).

For the average pedestrian walking speeds, Figure 8.4 shows that the R^2 values for SB and NB pedestrians are 0.749 and 0.719 respectively. For the standard deviations of the average walking speeds, Figure 8.5 presents that the R^2 values for SB and NB pedestrians are 0.713 and 0.747 respectively. This can partially be explained by the fact that the observed walking speeds may decreased as a result of the heavy opposing flows. It is worth noting that the estimated average walking speeds is fitted with the observed. Similar results are found for standard deviation of the average walking speeds.

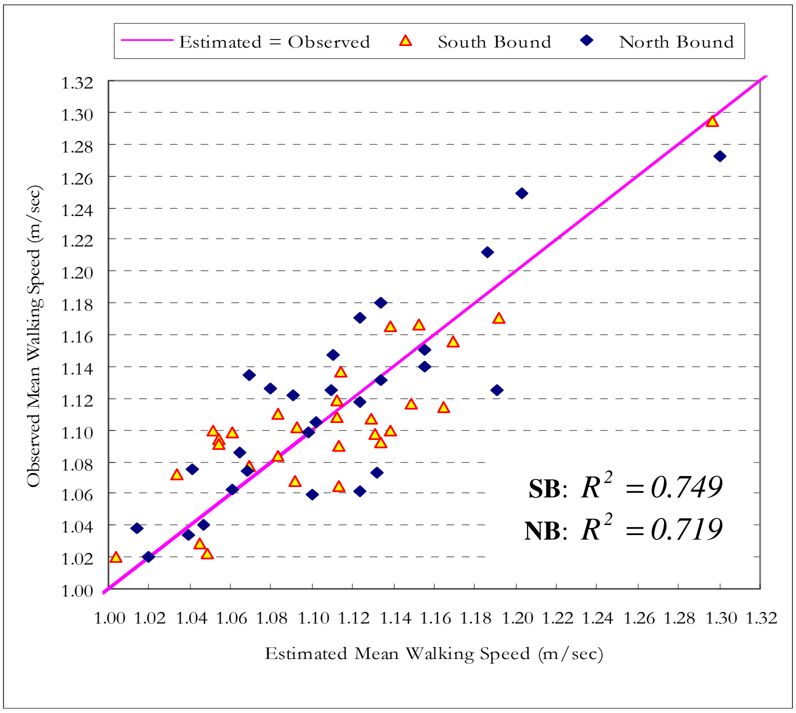


Figure 8.4 Observed vs estimated mean walking speeds

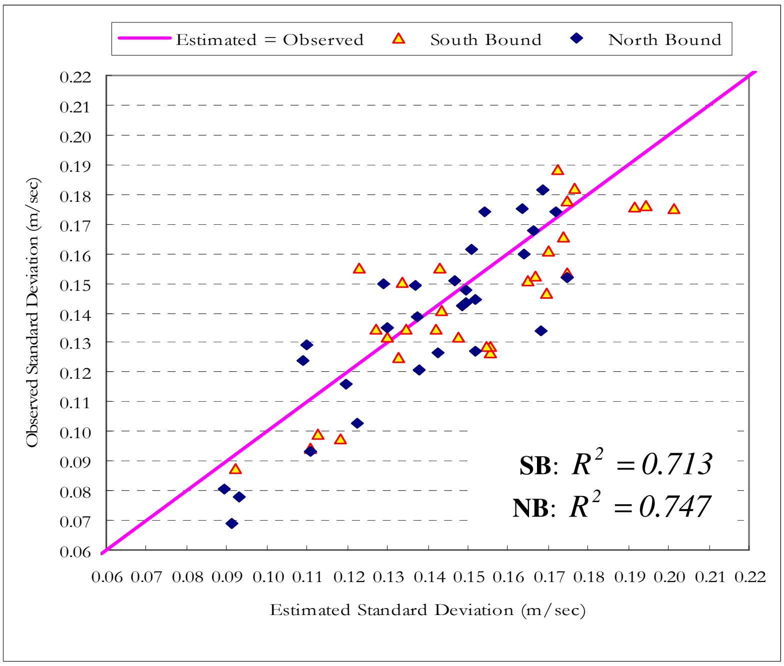


Figure 8.5 Observed vs estimated standard deviation of mean walking speeds

8.4 CASE STUDY

In Hong Kong, it is assumed in the current practice in the signalized intersection design that the pedestrian walking speed is 1.2 meters/second. This design speed is fixed regardless of the prevailing pedestrian flow conditions. In view of this assumption, it is considered that the current practice is over-simplified. Pedestrians may not have adequate time to completely traverse a signalized crossing, particularly when the opposing pedestrian flow is high and the pedestrian flows on the crosswalk approaches its capacity during pedestrian green and flashing green phases. Therefore, for pedestrian safety, the assessment/design of a signalized crosswalk should be based on its capacity with the consideration of the walking speeds under different flow ratios.

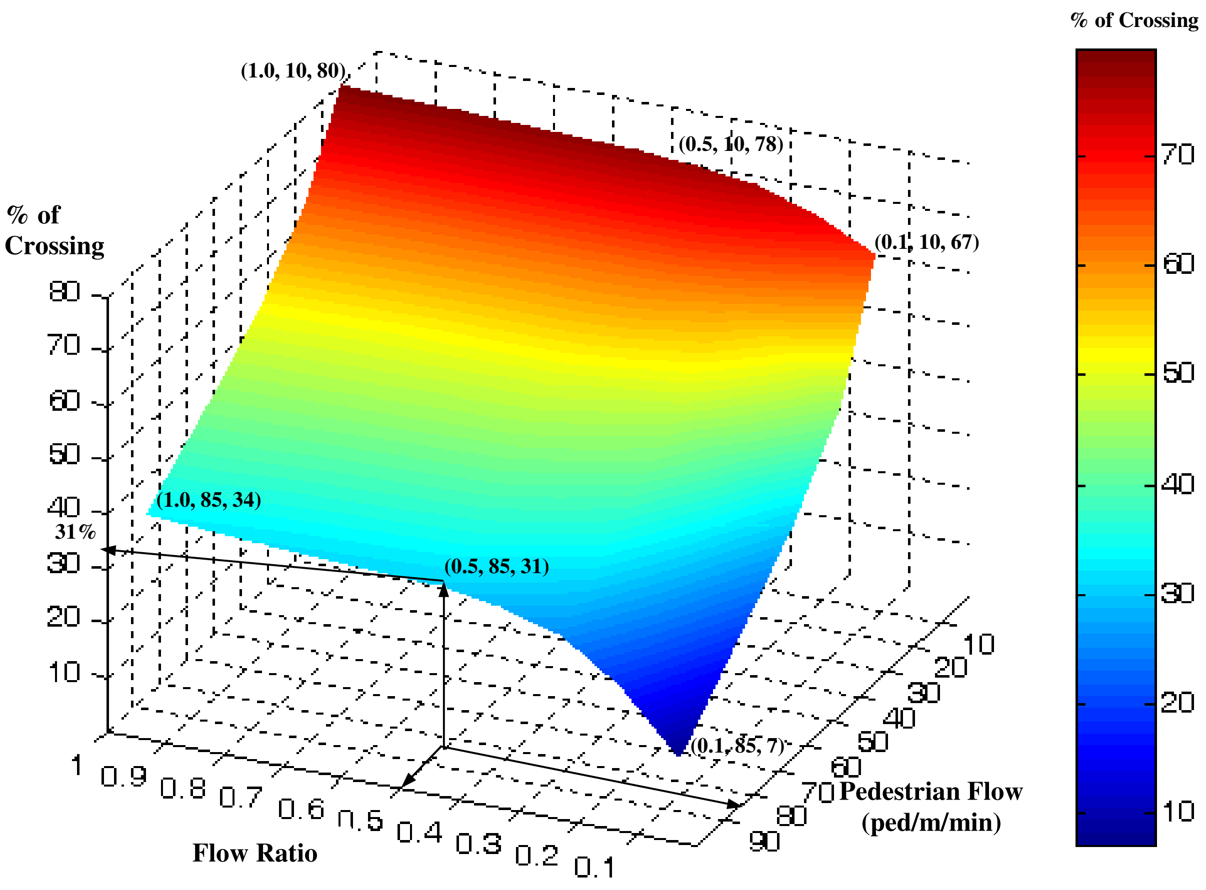
The purpose of this PSM is to estimate of pedestrian walking speeds over a wider range of flow conditions particularly when pedestrians encounter heavy opposing flows at the signalized crosswalks. This estimation can be conveniently obtained by the newly developed PSM than observations on on-site as the latter is costly. This PSM can also show the effects of changes in some factors while other factors are held constant.

8.4.1 The Bi-directional Pedestrian Flow Effects

This scenario is simulated by the PSM which considers different pedestrian flow demands together with different imbalance of directional pedestrian flows. The changes on the percentage of pedestrians crossing the crosswalk are investigated. The newly developed PSM can simulate pedestrian movements under different flow conditions ranging from the uni-directional to the imbalance directional split of pedestrian flow conditions.

Figure 8.6 illustrates the simulation results which show the impacts of pedestrian flow and flow ratio on the chance of crossing. It should be noted that the pedestrian signal sequence and time were fixed. Figure 8.6 shows that 80% pedestrians can completely traverse the crosswalk under the uni-directional flow condition (i.e. flow ratio = 1.0) when the pedestrian flows are low (i.e. 10 pedestrians/meter/minute). However, if the imbalance of directional split of pedestrian flows increases (i.e. until flow ratio = 0.1), a reduction on the possibility of completely crossing of about 13% will be obtained. The impacts of bi-directional pedestrian flows on the chance of crossing is small when the pedestrian flow on the crosswalk is also low.

If the pedestrian flow approaches to crosswalk capacity (i.e. 85 pedestrians/meter/minute), pedestrians will only have 34% possibility to completely pass through the crosswalk when flow ratio equals to 1.0. This percentage significantly reduces to 7% when the flow ratio decreases to 0.1. This reduction can be partially explained by the fact that pedestrians in the minor flow direction (i.e. 0 < flow ratio < 0.5) are unable to select their walking speeds due to the heavy opposing flows. Hence, their walking speeds decrease while the walking time increase as they are required weaving through the heavy oncoming pedestrians. Their possibility to completely traverse the crosswalk will be decreased.



(0.5, 85, 31) represents (flow ratio = 0.5, pedestrian flow = 85 ped/m/min, 31% chance of crossing)

Figure 8.6 Impacts of pedestrian flow and flow ratio on the chance of crossing

It is interesting to note in Figure 8.6 that the chance of crossing reduces from 80% to 34% as the pedestrian flows at the crosswalk are approaching its capacity under the uni-directional flow condition. This reduction is more significantly observed under the bi-directional flow condition. The possibility of pedestrians crossing reduces from 67% to 7% as the pedestrian flows increase from free-flow to at-capacity flow conditions.

It is observed that pedestrians in the minor-flow direction may not have adequate time to cross a signalized crosswalk particularly when these pedestrians are facing heavy opposing flow and the total pedestrian flows on the crosswalk are close to its capacity. This calls for a need to review the current design walking speed for signalized crosswalks. Findings show that the walking speed is not only dependent on the total pedestrian volume but also on the bi-directional flow effects. It is suggested that different design walking speeds corresponding to different bi-directional flow conditions should be considered for determining the duration of the pedestrian green time at signalized crosswalks.

8.4.2 Service Levels of Crosswalk

A new set of Level-of-Service (LOS) standards is developed for signalized crosswalks taking into account the bi-directional flow effects and is presented in Chapter 9. Five LOS standards are proposed ranging from LOS A (i.e. the best condition) to LOS E (i.e. the worst condition). These LOS standards were then used to examine the service levels of the chosen crosswalk and the results are shown in Figure 8.7.

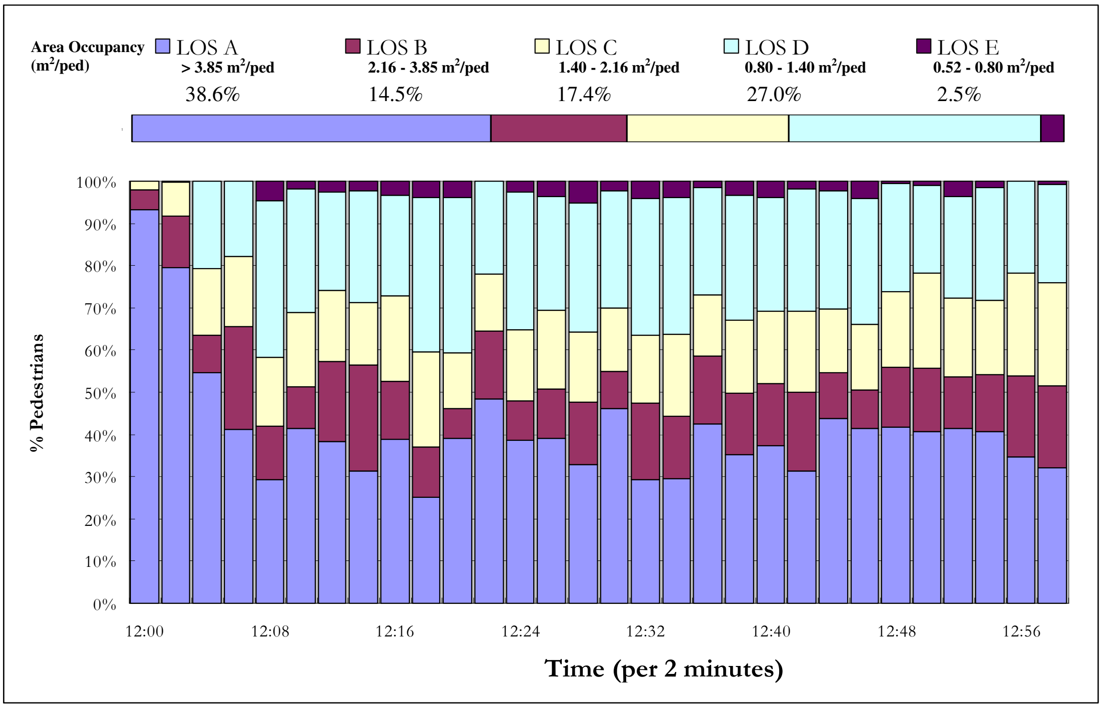


Figure 8.7 Pedestrian distribution by signal cycle

The simulation results illustrating the service levels of the chosen crosswalk are also summarized in Figure 8.7. It can be seen that 38.6% and 14.5% of pedestrians are walking on the crosswalk under LOS A and B respectively. 17.4% and 27.0% of pedestrians traverse the crosswalk under LOS C and D respectively. Only about 2.5% of pedestrians walk under LOS E which represented the situation that the pedestrian flow on the crosswalk is approaching its capacity. The findings can partially explained that pedestrians can freely choose their walking speeds (i.e. LOS A and LOS B) when they pass through the crosswalk during the start of pedestrian green time. This situation is no longer valid when they meet the oncoming pedestrian platoon. Therefore, large numbers of pedestrians are cumulated within the crosswalk (LOS C to LOS E).

8.4.3 Average Pedestrian Delays

This newly developed PSM can estimate the pedestrian flows, average pedestrian delays and its variation during each signal cycle. This advancement can be used as a practical tool for the traffic engineers so as to minimize the pedestrian delays under certain pedestrian flow conditions. Pedestrian flows and average delays during each signal cycle were simulated. Figure 8.8 illustrates the simulation results showing the average pedestrian delays together with pedestrian flows. It can be seen that the average delay is about 34 seconds which is about a half of the pedestrian red time (i.e. 77 seconds). The range of the average delay is from 30 seconds to 40 seconds.

Figure 8.9 illustrates the variation of pedestrian delays. The average delay and its standard deviation for each signal cycle (i.e. every 2 minutes) are shown in Figure 8.9. Variations of pedestrian delays is large when the average pedestrian delay is also high. It should be noted that the simulation error of the first and last 2 minutes of each run are large as initiation of the simulation run is required.

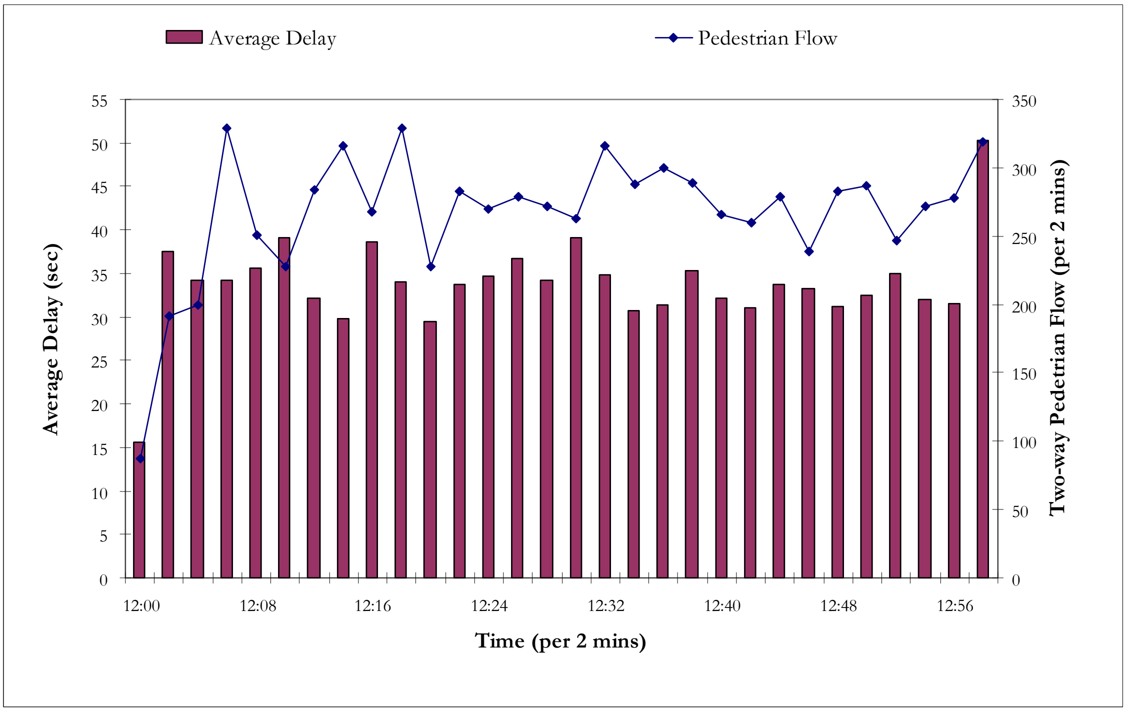


Figure 8.8 Total pedestrian delays by signal cycle

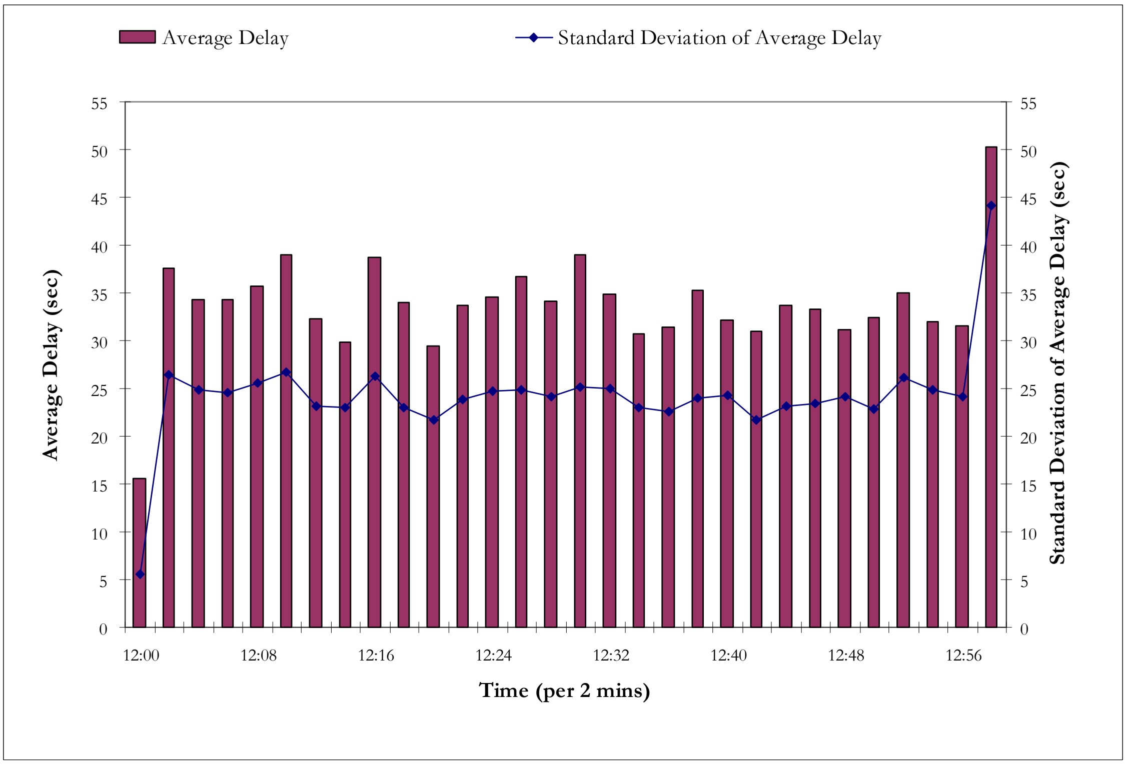


Figure 8.9 Standard deviation of average pedestrian delay by signal cycle

8.5 SUMMARY

The newly developed PSM is capable of simulating pedestrian movements with consideration of the bi-directional pedestrian flow effects so as to determine the duration of pedestrian signal time. This advancement in model technique can be used for the assessment of the effects of each measure/scenario being considered. Hence, the benefit of each scenario can be evaluated. Simulation results highlight the inability of the current design which does not account for the pedestrian flow volumes and the different bi-directional flow effects. The simulation results demonstrate that different design walking speeds for signalized crosswalks are required with consideration of the different bi-directional pedestrian flows. If the bi-directional flow effects were not accounted for in the design, pedestrians who entered the crosswalk facing heavy opposing flow under high flow conditions would not be able to complete their crossing before the end of the pedestrian flashing green time. Hence, safety of pedestrians is not ensured as they are leading to either risk crossing after the pedestrian flashing green phase or return and wait at the waiting area.

The development and calibration of the PSM are outlined. Validation by using an independent set of observed data was carried out. The validation results clearly show that the PSM is also effective in estimating the average walking speeds and the standard deviations. The developed PSM can then be extended to simulate pedestrian movements in a congested urban area taking into account the pedestrian activities. The level-of-service standards for signalized crosswalks taking into account the bi-directional pedestrian flow effects are discussed in Chapter 9.

9 A NEW SET OF LEVEL-OF-SERVICE STANDARDS FOR SIGNALIZED CROSSWALKS WITH BI-DIRECTIONAL PEDESTRIAN FLOWS

9.1 INTRODUCTION

The calibration and validation of the pedestrian simulation model (PSM) for signalized crosswalks are presented in Chapter 8. This chapter aims to describe a new set of level-of-service (LOS) standards for signalized crosswalks. These LOS standards explicitly take into account the bi-directional pedestrian flow effects. The service performances of the signalized crosswalks can be evaluated to enhance the design and planning of the crosswalk facilities. This chapter is an edited version of: Lee, J.Y.S., Goh, P.K. and Lam, W.H.K., 2005. New level-of-service standard for signalized crosswalks with bi-directional pedestrian flows. *Journal of Transportation Engineering,* (Special Issue: Calibration and Validation of Highway Capacity Manual Models), 131(12), 957-960.

Few studies have been conducted to explicitly account for the effects of bi-directional flows on pedestrian LOS or discussed its implications to signalized crosswalk design. This chapter proposes a new set of LOS standards for signalized crosswalks which explicitly takes the bi-directional flow effects into account. An interview survey technique which utilized pedestrian stated preferences was used to determine the respective congestion boundaries under different bi-directional flow conditions. The newly defined LOS boundaries are ranging from no effect (1.0 to 0.5 flow ratio) to a strong bi-directional pedestrian flow effect (0.5 to 0.1 flow ratio). The results are also compared against the local observed data. In addition, comparisons are made to highlight the differences between LOS boundaries determined for crosswalks against those for other facility types reported in the previous studies. It is believed that this is one of the first attempts that the effects of bi-directional pedestrian flows is explicitly accounted for in a LOS standard for pedestrian crosswalks.

In this chapter, there are 7 sections. In Section 9.1, an introduction of this chapter is presented. Motivation of this chapter is discussed in Section 9.2. The concept of the LOS standards for pedestrian facilities is described in Section 9.3. The study methodology is summarized in Section 9.4. Data analysis and results are discussed and presented in Section 9.5. Comparison is made in Section 9.6 between the perceived LOS standards for signalized crosswalks and the LOS standards determined in the previous studies for other facilities. Finally, a summary is presented in Section 9.7.

9.2 MOTIVATION

Two shortcomings are of particular interest in this chapter. The first is that the effects of bi-directional flows on pedestrian LOS are not explicitly accounted for in the LOS standard. The bi-directional pedestrian flows are a characteristic of pedestrian facilities, which operate in such a manner where flows of opposing direction make use of the same space for travel. The effects of bi-directional flows on pedestrian LOS are recognized in the Highway Capacity Manual (Transport Research Board, 2000) and the Quality of Service Handbook (State of Florida Department of Transportation, 2002) which state that a directional split of 90% versus 10% (flow ratio of 0.1) at high flow rates can result in capacity reductions of 15%. However, no specific recommendations were provided in the Highway Capacity Manual (Transport Research Board, 2000) to allow the analysis of the effects of bi-directional pedestrian flows effects on LOS under different flow ratios. Of particular importance is the impact on walking speeds and comfort of pedestrians of the bi-directional flows on those traveling in the minor flow direction (travel direction with fewer pedestrians). At the pedestrian signalized crosswalks, such impact results in longer crossing time for pedestrians as well as increased conflicts and accident risk for pedestrians. While several attempts have been made to quantify the effects of bi-directional flows on various pedestrian facilities (Lam et al., 2003; Lam et al., 2002), few studies have explicitly dealt with the effects of bi-directional flows on pedestrian LOS or discussed its implications to signalized crosswalk design. Photographs showing one of the heavily used signalized crosswalks in Hong Kong are presented in Figure 9.1 to illustrate the problem of the bi-directional flows and congestion in Hong Kong.

The effects of bi-directional flows are important since pedestrians who enter the crosswalk may not be able to complete the crossing before the end of the clearance interval.

The second is that the LOS used in the Highway Capacity Manual (Transport Research Board, 2000) is determined for pedestrian walkways using boundaries. While this is the common practice, it is hypothesized that the determination of the LOS boundaries based on facility type should be attempted due to the inherent differences in the characteristics of different pedestrian facilities.

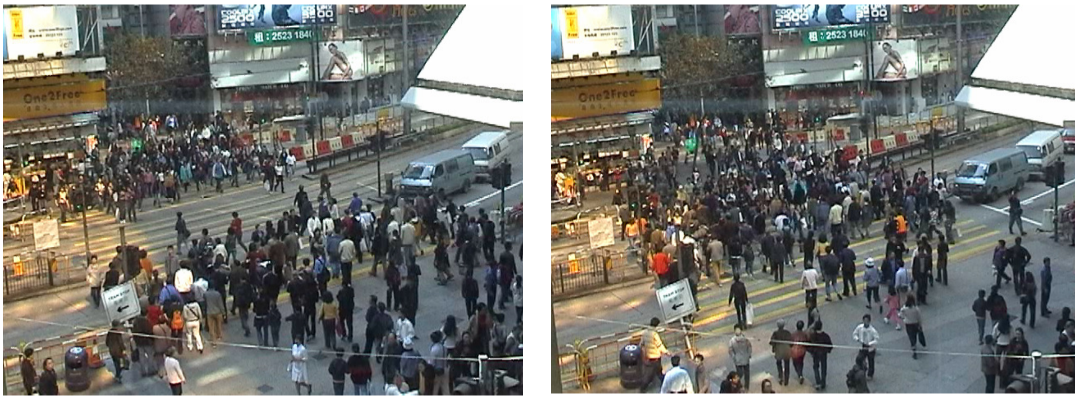


Figure 9.1 Photographs showing one of the heavily used signalized crosswalks in Hong Kong

9.3 DETERMINING QUALITY-OF-FLOW LOS AT PEDESTRIAN FACILITIES

The determination of LOS thresholds for pedestrian facilities is largely based on the use of subjective measures, which link the performance of pedestrian facilities to qualitative descriptions of pedestrian flows. This method is generally attributed to the method used by Fruin (1970), which are based on the use of pedestrian characteristics like walking speed, density/space and flow combined with a qualitative description on the status of pedestrian flow. This is usually achieved through the use of video capture and the subsequent extraction and derivation of pedestrian flow characteristics under different measures of congestion. A detailed description of this method can be found in the Highway Capacity Manual (Transport Research Board, 2000). In addition to the use of subjective LOS measures, some researchers have proposed alternative measures in determining the LOS performance measures over the years.

Some researchers have attempted to make use of objective measures to determine the LOS boundaries. For example, Polus et al. (1983), who studied sidewalks in Israel, fitted 3 regression equations to derive LOS boundaries corresponding to the LOS A to LOS D. A different approach was used by Mori and Tsukaguchi (1987) who combined theoretical arrival rate and overtaking functions to derive LOS boundaries under different sidewalk widths. Other researchers have proposed the use of attitudinal surveys to account for the perceived LOS as a measure of the effectiveness of pedestrian facilities (Seneviratne and Morrall, 1985b). The need for crosswalk-specific measures has also been recognized in Baltes and Chu (2002) who attempted to quantify pedestrians' perceived quality of service in crossing roads at signalized crossing locations. A variation of the attitudinal survey approach was used in Lam and Lee (2001) to derive a LOS standard for signalized pedestrian crosswalks in Hong Kong. Unlike previous methods used in determining LOS boundaries for pedestrians, Lam and Lee (2001) made use of photographs to obtain the pedestrian's perceived LOS boundaries using interview surveys. Implications of this approach are discussed in the following sections.

9.3.1 Determining Perceived LOS Boundaries

The concept of the perceived LOS boundaries employed in Lam and Lee (2001) is similar to that used in the stated preference surveys which require respondents to respond to a particular situation. The LOS boundary determined in this way is termed the perceived LOS boundary which is derived based on the pedestrians' perception of differentiating the subjective LOS boundary obtained from a direct observational measure.

The basic approach used a series of photographs depicting different levels of pedestrian flow and congestion. Respondents were then presented with a qualitative description of the quality of flow and asked to point out the photograph where they felt the qualitative description was no longer true. In effect, the respondents' choice represented the lower boundary for a particular LOS. The advantage of this method is that it allows the testing of hypothetical scenarios which may not be easily observed or replicated in the real-life situations. Sample photographs of the perceived LOS boundaries are described and presented in Figure 9.2.

From Figure 9.2, photographs corresponding to the upper and lower range of pedestrian area occupancies are used to determine the lower boundaries for each perceived LOS from A to E. A total of 6 photographs (see Appendix E) were presented to the respondents for each perceived LOS during the survey although the photographs in between the lower and upper ranges are not shown in Figure 9.2. Also presented in Figure 9.2 are the qualitative descriptions (see Fruin, 1970 and Henson, 2000) corresponding to each perceived LOS as well as the area occupancies derived from the choices made by the respondents.

The area occupancies are calculated from the photographs and matched with the corresponding flow volume and walking speed boundaries from the speed-flow profile (Lam et. al, 2002). This will then represent the pedestrian LOS for signalized crosswalks under flow ratio of 0.6. The lower boundary for area occupancy ranged from 3.85 meter^2/pedestrian for LOS A to 0.52 meter^2/pedestrian for LOS E. Likewise, the perceived LOS boundaries for flow volume are 20.6 pedestrians/meter/minute and 72.9 pedestrians/meter/minute for LOS A and E respectively.

The perceived LOS boundaries for walking speed are 75.4 meters/minute for LOS A and 37.7 meters/minute for LOS E. A final sample of 225 surveys was obtained in Lam and Lee (2001) which were then used to obtain the corresponding perceived LOS boundaries. A test was also conducted to ensure the stability of the survey results. Details of the determination of the perceived LOS boundaries using the survey methodology can be obtained in Lam and Lee (2001).

9.3.2 Comparison between the Perceived and Observed LOS Boundaries

In order to determine the differences between the perceived and subjective/observed LOS boundaries, an estimate of the subjective boundaries was attempted using observational data from signalized crosswalks in Hong Kong. Data from approximately 1500 observations collected at signalized crosswalks from shopping areas were used for this comparison (Additional details on data extraction can be found in Appendix D). A similar procedure to the method employed in the HCM (2000) was used to obtain the subjective LOS boundaries from observational data.

Figure 9.3 shows a plot of the walking speed versus the area occupancy data. The perceived LOS boundaries in vertical dotted lines and the observed LOS boundaries in solid vertical lines are also presented in Figure 9.3. The corresponding perceived and subjective LOS boundaries are superimposed onto the flow profile to illustrate the differences between the 2 LOS boundaries.

Lower Range **Upper Range**

Service Description

Level of Service A
Average Pedestrian Area Occupancy:
>= 3.85 meter^2/pedestrian
Average Flow Volume:
<= 20.58 pedestrians/meter/minute
Average Walking Speed:
>=75.40 meters/minute

Sufficient signalized crosswalk area is available for pedestrians to freely select their own walking speed and maneuver to avoid conflicts with other pedestrians

Level of Service B
Average Pedestrian Area Occupancy:
2.16 to 3.85 meter^2/pedestrian
Average Flow Volume:
20.58 to 34.55 pedestrians/meter/minute
Average Walking Speed:
73.48 to 75.40 meters/minute

Sufficient signalized crosswalk area is available for nearly all pedestrians to select their own walking speed, although reverse flows would cause minor conflicts

Level of Service C
Average Pedestrian Area Occupancy:
1.40 to 2.16 meter^2/pedestrian
Average Flow Volume:
34.55 to 48.86 pedestrians/meter/minute
Average Walking Speed:
66.38 to 73.48 meters/minute

Freedom to select walking speed and pass other pedestrians is restricted. Minor reverse flow would encounter some difficulties.

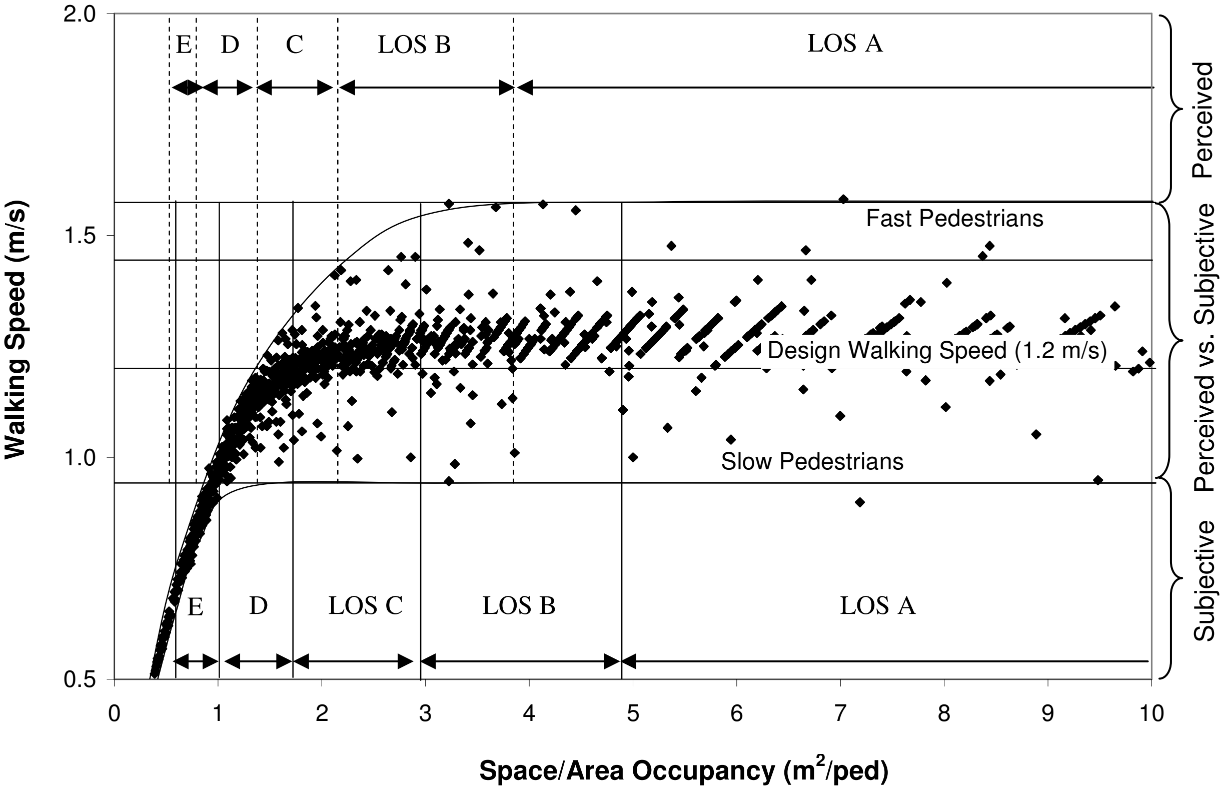
Level of Service D
Average Pedestrian Area Occupancy:
0.80 to 1.40 meter^2/pedestrian
Average Flow Volume:
48.86 to 63.52 pedestrians/meter/minute
Average Walking Speed:
50.56 to 66.38 meters/minute

The majority of pedestrians have their normal walking speed and maneuverability restricted. Pedestrians involved in reverse flow would be severely restricted.

Level of Service E
Average Pedestrian Area Occupancy:
0.52 to 0.80 meter^2/pedestrian
Average Flow Volume:
63.52 to 72.86 pedestrians/meter/minute
Average Walking Speed:
37.73 to 50.56 meters/minute

Virtually all pedestrians have their normal walking speed and maneuverability restricted. Pedestrians attempting reverse flow would experience extreme difficulty.

Figure 9.2 Sample of photographs to determine the congestion boundaries



LOS	Observation Description	Lower Boundary		
		Perceived (m^2/ped)	Observed (m^2/ped)	Difference (%)
A	Walking in checkerboard pattern	3.85	4.89	21%
B	Fast pedestrians able to reach chosen speed	2.16	2.96	27%
C	Normal walking speed	1.40	1.73	20%
D	Slow walkers forced to further slow down	0.80	1.02	22%
E	Shuffling gait	0.52	0.60	12%

Figure 9.3 Comparison between subjective and perceived LOS boundaries

From Figure 9.3, it can be seen that the perceived LOS boundaries are consistently lower than those of the observed LOS boundaries by 12-27% for pedestrians in Hong Kong. This is to be expected given the differences between the methodologies used in determining the LOS boundaries. Nevertheless, it is worth noting that the differences tend to be fairly consistent (with an average difference of 20%), suggesting that pedestrians tend to overestimate their ability to cross the crosswalks.

The subjective boundary for LOS A (pedestrians walking in checkerboard pattern) is found to occur when pedestrian area occupancy is close to 4.9 meter^2/pedestrian while the perceived LOS boundary is 3.85 meter^2/pedestrian. The subjective lower boundary of LOS B (walking speeds for fast pedestrians decreased) occurred after area occupancy of 3.0 meter^2/pedestrian as compared to 2.16 meter^2/pedestrian for the perceived LOS. For LOS C, pedestrian walking speed is found to drop below 1.2 meters/second at area occupancy of 1.7 meter^2/pedestrian, while walking speed for slow pedestrians is reduced at area occupancy lower than 1.0 meter^2/pedestrian (LOS D). The corresponding perceived LOS boundaries are 1.4 meter^2/pedestrian (LOS C) and 0.8 meter^2/pedestrian (LOS D) respectively. For the lower bound of LOS E, it is found that the shuffling walking movement of pedestrians occurred when walking speed is approximately 0.7 meter/second (space of 0.6 meter^2/pedestrian) as compared to 0.5 meter^2/pedestrian for the perceived LOS E.

9.3.3 Need for Bi-directional LOS Studies in Hong Kong

Hong Kong has a land area of 1,108 km^2 and a population of 7.009 million people in 2008. The territory is characterized by a combination of high density development and high population density which is one of the most congested cities in the world. It has already been reported in Goh and Lam (2004) that signalized pedestrian crosswalks in Hong Kong experience relatively high volumes of pedestrian flow that can impact the design walking speed of pedestrians. The Planning Department of Hong Kong has released a Public Consultation Report on pedestrian planning in 2002 in recognition of the need for future improvement of pedestrian travel. One of the issues raised is the need for LOS standards for pedestrian facilities in Hong Kong (Planning Department, 2001 & 2002).

In particular, pedestrians traveling in the minor flow direction may face an increase in the risk of accidents, discomfort due to conflict, and delays caused by the inability to select their walking speeds, especially under high flow volumes (Lam et al., 2002). In fact, Lam et. al (2002) highlighted the need to review the current Transport Planning and Design Manual (code of practice and design in Hong Kong) is necessary to ensure that adequate safety is provided for pedestrians for heavily used crossings, particularly when the bi-directional flow effects are considered. In spite of this, there is little literature to quantify the effects of bi-directional flow on pedestrian LOS at signalised crosswalks. In particular, the bi-directional flow effects may be significant at the mass transit stations during peak hours when both bi-directional and high pedestrian flows are prevalent.

9.3.4 Bi-directional Flows at Pedestrian Signalized Crosswalks

The problem of bi-directional pedestrian flows and its effects on pedestrian flow characteristics are gaining increasing recognition in pedestrian research. Unlike roadways where vehicle flow is separated by direction, pedestrian walkways tend to operate in a bi-direction as opposed to a uni-directional manner. This means that solutions derived from uni-directional flow's assumptions may not be able to properly describe the pedestrian flows under situations when bi-directional flow conditions are prevalent. Examples of some recent studies that investigated the effects of bi-directional pedestrian flows included the study by Blue and Adler (1999), where the bi-directional emergent fundamental pedestrian flows was simulated by using the cellular automata micro-simulation method. Daly et al. (1991) calibrated the pedestrian speed-flow relationships for walking facilities in London Underground stations and proposed effective capacities for different bi-directional flow distributions (or directional distributions of pedestrian flows). However, these proposed effective capacities have not been validated or supported by empirical data.

Empirical studies of the bi-directional pedestrian flow characteristics in a number of pedestrian facilities have also been conducted in Hong Kong, including Cheung and Lam (1997) for transit stations, Lam et al. (2003) for indoor walkways and Lam et al. (2002) for signalized crosswalks which have highlighted the important role played by the bi-directional flow effects on pedestrian flow characteristics. They investigated the relationships between the reduction of effective capacity on pedestrian facilities (under bi-directional flows) and the directional distribution of pedestrian flows. They also studied the effects of bi-directional pedestrian flows on the reduction of at-capacity walking speed. For signalized crosswalks, Lam et al. (2002) found that the effects of bi-directional pedestrian flows are particularly significant when the pedestrian flows are close to capacity and when the flow ratio approaches 0.1. In effect, both walking speed and effective capacity of the signalized crosswalk reduce with increasing imbalance of directional split of pedestrian flows. However, despite the progress made in quantifying the effects of bi-directional pedestrian flows in Hong Kong, practical difficulties remained in the determination of LOS boundaries from the observed data since it was often difficult to determine the subjective LOS boundaries under the bi-directional flow conditions. In view of these difficulties, the perceived LOS methodology was employed to determine the perceived LOS boundaries.

9.4 METHODOLOGY

The study made use of both observational and questionnaire data to investigate the effects of bi-directional pedestrian flows at signalized pedestrian crosswalks. The observational data were taken from Lam et al. (2002) in order to obtain information (such as pedestrian area occupancy, flow volume and walking speed) on the pedestrian flow characteristics under different flow conditions in Hong Kong shopping areas. The questionnaire data collected from the pedestrian state preference interview surveys were used to determine various congestion boundaries under different bi-directional flows.

9.4.1 Procedures of the Pedestrian State Preference Interview Survey

The survey methodology used in Lam and Lee (2001) was modified to evaluate the perceived LOS boundaries in this study. In order to minimize the effects of extraneous variables, the survey was conducted at the same study site as the one conducted by Lam and Lee (2001). The state preference survey was conducted on several weekday evenings (5:30 p.m. - 7:30 p.m.) which corresponded to peak pedestrian flows at the study site. Detail of the state preference survey can be found in Appendix E. The questionnaire used in the state preference survey is shown in Appendix F.

As mentioned in the previous section on the determination of perceived LOS boundaries, sample photographs depicting different area occupancies are displayed together with the qualitative description of LOS A to LOS E. Observational data from the paper by Lam et al. (2002) (which reported on the characteristics of bi-directional pedestrian flows at signalized crosswalks in Hong Kong) were used to determine the range of flow rates presented in each photograph for the different LOS and flow ratios. This may be the first attempt at quantifying the effects of bi-directional flows on LOS using a state preference survey methodology. However, 2 main modifications were made during the survey. The first modification was to ensure that respondents understood and provided the LOS boundaries under the bi-directional flows. The second was to reduce the range of the number of combinations of perceived LOS boundaries tested in the survey.

The first modification was made to ensure that respondents understood the implications of the bi-directional flow component and to measure their perceived responses. Several trials were made by asking the pedestrians to response to the various methods were investigated. All feedback obtained at this stage were used to improve the survey methodology. It was found that a survey which graphically illustrated the effect of congestion as well as the effects of bi-directional flows were most effective in helping respondents to understand the survey objective and method. It was found that showing a combination of photographs illustrating congestion level and the bi-directional flows before the survey helped to improve the understanding of respondents. A sample of the photographs employed during the survey is shown in Figure 9.4.

In Figure 9.4, the interviewer used 2 photographs (few pedestrians (top left) and many pedestrians (top right)) to explain to pedestrians on how photographs would be used to evaluate their own perceived effects of congestion on their behavior. Respondents were asked to consider the effect of other pedestrians on their walking speed, proximity to other pedestrians and level of conflict when answering the questions presented. The interviewer was instructed to continue when respondents indicated that they understood this part of the questionnaire.

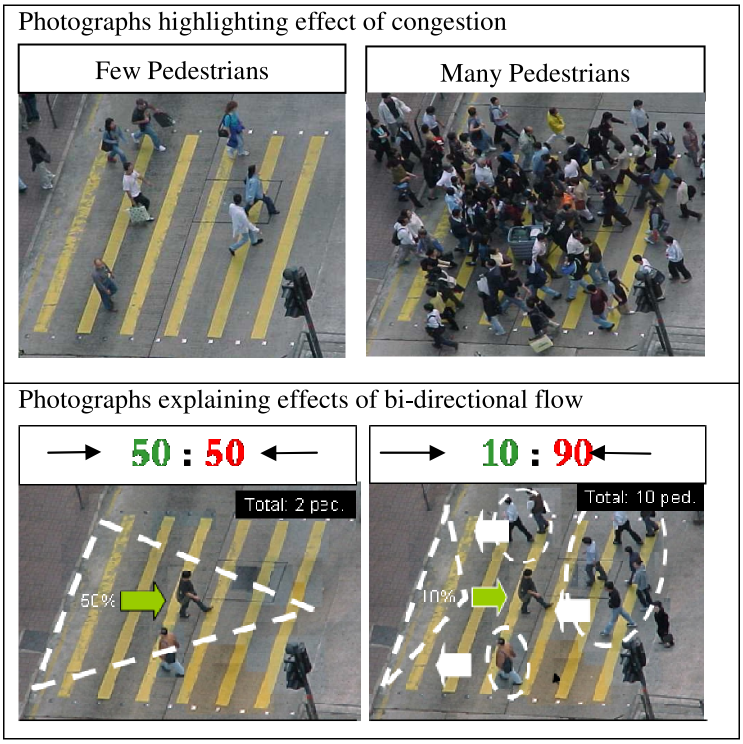


Figure 9.4 Photographs showing the effects of congestion and bi-directional flows

The respondents were then shown the second set of photographs which illustrated the bi-directional flow effects. In the second set of photographs, 2 pedestrians (50:50) can be seen in the first photograph (bottom left) and 10 pedestrians (10:90) can be seen in the second photograph (bottom right). The white triangles in the second set of photographs are used to illustrate the bi-directional flow effects. The size of the triangles are proportional to the flow ratio (Area of 50:50 flow ratio covers half the crosswalk while 10:90 flow ratio covers 10% of crosswalk). Variations of these photographs are used for different flow ratios during the survey. As in the previous case, interviewers proceeded with the survey after the respondents indicated that they understood the question.

The second modification deals with the length of the survey. Optimally, the survey should be conducted for each flow ratio from 1.0 to 0.1 for each perceived LOS from A to E. However, initial tests revealed that it was neither practical nor necessary to include all the different combinations of flow ratios. The reason is based upon findings by Lam et al. (2002) which found that the effects of bi-directional flows were small when the volume of pedestrian flow was small and when the flow ratio was greater or equal to 0.5. After testing, the cases corresponding to LOS A to E for flow ratios 1.0 and 0.6 (data from Lam and Lee, 2001) were included in the survey while only the cases for LOS C to E and flow ratios 0.5, 0.3 and 0.1 were designed. This was used in order to reduce the number of questions by obtaining only those cases where pedestrian flows were high (in this case, the survey included those corresponding to LOS C to E).

9.5 DATA ANALYSIS AND RESULTS

The final sample size in the study was 758 completed questionnaires from a signalized crosswalk located in a shopping area in Hong Kong. The survey data were normalized to account for variations in the respondent age (<20 years; 20-50 years; >50 years) and gender using the observed pedestrian proportion at the site.

Detail discussion on the data analysis can be found in Appendix E together with the variation in responses based on age, gender and etc. Nevertheless, it is worth noting that the survey and observed proportion was very similar, suggesting that sample bias was not particularly significant in the survey. In order to determine the lower congestion boundaries of each LOS, the respondents' choice of the perceived upper acceptance limit (or lower congestion boundary) for each perceived LOS (e.g. select 1 photograph from a set of 5 for each LOS) was used. The area occupancy boundary of each LOS standard for the survey sample could then be calculated as follows:

Area Occupancy Boundary of LOS *i*
$$M_i = \frac{\sum_{j=1}^{n} d_{ij} \times f_{ij}}{\sum_{j=1}^{n} f_{ij}} \tag{9.1}$$

where

d_{ij} = corresponding area occupancy of photo j of LOS *i*;

f_{ij} = corresponding frequency of pedestrian preference on photo j of LOS *i*; and

$\sum_{j=1}^{n} f_{ij}$ = total number of respondents.

9.5.1 Congestion Boundaries of LOS under Bi-directional Flow Condition

The analysis method for the questionnaire data collected from this survey is similar to those used in Lam and Lee (2001) and would not be repeated in detail here. The perceived area occupancy boundary of each LOS under different flow ratios is calculated using Equation 9.1, while the corresponding pedestrian flow and walking speed boundaries are determined from the speed-flow profile derived from the observational data (Lam et al., 2002). A summary of the survey results are presented in Table 9.1.

From Table 9.1, the perceived LOS under various flow ratios are presented together with the corresponding flow, area occupancy and walking speed under each respective perceived LOS. It can be observed that the perceived LOS boundaries for pedestrian flow under 0.5 flow ratio are 48.1 pedestrians/meter/minute, 62.7 pedestrians/meter/minute and 72.2 pedestrians/meter/minute for LOS C, D and E respectively while the perceived LOS boundaries for the 1.0 flow ratio are 49.1 pedestrians/meter/minute (LOS C), 63.7 pedestrians/meter/minute (LOS D) and 73.4 pedestrians/meter/minute (LOS E). It is worth noting that the area occupancy, corresponding pedestrian flow and walking speed for LOS A to E under flow ratio = 0.6 (Lam and Lee, 2001) are very close to those under flow ratio = 1.0. Likewise, the perceived LOS boundaries for flow ratio 0.5 at LOS C to E are similar to those for 1.0 and 0.6 flow ratios. It can therefore be concluded that, as observed in Lam et al. (2002), pedestrian LOS under situations when the flow ratio is greater than 0.5 will not significantly affect the bi-directional flows.

For flow ratio 0.1, it can be observed that the lower boundaries for pedestrian flow for LOS C to E are 41.8 pedestrians/meter/minute, 53.8 pedestrians/meter/minute and 62.2 pedestrians/meter/minute for LOS C, D and E respectively, while the lower boundaries for flow ratio 0.3 are in between flow ratios 0.1 and 0.5. It is worth noting that the area occupancy, corresponding pedestrian flow and walking speed under flow ratio = 0.1 are substantially different from those under flow ratio of 1.0 or 0.5. The differences between the pedestrian flow for LOS C, D and E are particularly large due to the combined influence of walking speed (slower walking speed) and area occupancy (greater conflict potential/poorer maneuverability) under the prevailing conditions. It can therefore be concluded that for pedestrians traveling in the minor flow direction (those pedestrians traveling in the direction with fewer pedestrians), the effects of bi-directional flows result in pedestrians experiencing a lower LOS when compared to those traveling in the major flow direction.

From Table 9.1, it can be seen that there are a number of missing categories for the LOS boundaries which have to be estimated. Two estimation results were required. The first is to estimate the LOS boundaries for LOS A and B for flow ratios 0.5, 0.3 and 0.1 (which were not collected in the survey) and the second is to interpolate the corresponding perceived LOS boundaries for the flow ratios in which survey data were not collected (e.g. for LOS under flow ratio 0.9). For the first estimate, the perceived boundaries for LOS A and B for flow ratios 0.5 to 0.1 (which were not included in the survey) was estimated from the observed data. This is possible because pedestrian walking behavior is not influenced by the effects of bi-directional flows as the pedestrian flow is very little. To do this, a proportion for flow ratio = 0.5 was applied by dividing the effective capacity of flow ratio = 0.5 (i.e. 77.1 pedestrians/meter/minute) and that of flow ratio = 1.0 (i.e. 78.5 pedestrians/meter/minute). Similar for estimating the pedestrian flow for LOS A and B for the flow ratio = 0.1, the calculation is based on dividing the effective capacity of flow ratio = 0.1 (i.e. 67.2 pedestrians/meter/minute) and that of flow ratio = 1.0 (i.e. 78.5 pedestrians/meter/minute).

Table 9.1 Summary of the survey results

Parameters		**Flow Ratio**				
		1.0	**0.6 ***	**0.5**	**0.3**	**0.1**
LOS A	**Flow Volume (ped/m/min)**	20.6	20.6	-	-	-
	Area Occupancy (m^2/ped)	3.83	3.85	-	-	-
	Walking Speed (m/min)	75.5	75.4	-	-	-
LOS B	**Flow Volume (ped/m/min)**	34.9	34.6	-	-	-
	Area Occupancy (m^2/ped)	2.17	2.16	-	-	-
	Walking Speed (m/min)	73.6	73.5	-	-	-
LOS C	**Flow Volume (ped/m/min)**	49.1	48.9	48.1	46.0	41.8
	Area Occupancy (m^2/ped)	1.37	1.40	1.40	1.47	1.59
	Walking Speed (m/min)	66.4	66.4	66.4	66.2	65.0
LOS D	**Flow Volume (ped/m/min)**	63.7	63.5	62.7	59.9	53.8
	Area Occupancy (m^2/ped)	0.80	0.80	0.81	0.83	0.89
	Walking Speed (m/min)	50.6	50.6	50.5	49.5	47.6
LOS E	**Flow Volume (ped/m/min)**	73.4	72.9	72.2	68.9	62.2
	Area Occupancy (m^2/ped)	0.51	0.52	0.52	0.52	0.53
	Walking Speed (m/min)	37.7	37.7	37.6	36.0	33.1
Effective Capacity (ped/m/min)**		78.5	78.0	77.1	73.7	67.2

Note: * Results from Lam and Lee (2001)
** Results from Lam et al. (2002)

For the second estimate, a number of regression models were used to interpolate the perceived LOS boundaries for different flow ratios. More specifically, linear regression models were used to interpolate the perceived LOS under flow ratios 0.9, 0.8 and 0.7 while quadratic regression models were used for estimating those for flow ratios 0.4 and 0.2. Therefore, in order to validate the interpolated LOS boundaries, an independent survey was conducted so as to collect the perceived LOS boundaries under flow ratios 0.2 and 0.8.

9.5.2 Validation on the Perceived LOS

The survey methodology used in the independent survey is similar to that mentioned in the Section 9.4.1 on the pedestrian interview survey procedure. The data analysis method for the survey results is also similar and would not be repeated in detail here. An independent set of perceived LOS (from LOS A to E) for flow ratios 0.2 and 0.8 was collected so as to validate the interpolated results. A comparison is presented in Table 9.2.

In Table 9.2, the interpolated LOS boundaries for flow ratios 0.2 and 0.8 are compared with the perceived LOS collected from the independent survey. Their percentage difference are calculated and also presented in Table 9.2. The differences tend to be fairly small (with a maximum difference of 3.4%). Therefore, this approach can successfully estimate the corresponding LOS boundaries for the flow ratios in which survey data was not collected. After validating the interpolating method, all the data were grouped together with those collected in the independent survey and then re-do the interpolation again so as to estimate a more realistic result.

9.5.3 Perceived LOS by Different LOS Criteria

In order to present the findings obtained in the study and the estimated data, graphical summaries of the perceived LOS boundaries by the different LOS criteria: pedestrian flow, area occupancy and walking speed presented in Table 9.1 are illustrated in this section. The order of presentation is as follows: First, the perceived LOS boundaries for pedestrian flow are presented in Figure 9.5, followed by the perceived LOS boundaries based on the area occupancy criterion in Figure 9.6. The LOS criterions using walking speed are presented in Figure 9.7. A discussion on the effects and differences of bi-directional flows are discussed in the subsequent section. Finally, a 3-dimensional graph are illustrated in Figure 9.8 so as to present the combined effects of pedestrian flow and its corresponding walking speed due to various flow ratios.

Table 9.2 Validation results

Ratio	LOS	Pedestrian Flow (pedestrians/meter/minute)			Area Occupancy (meter^2/pedestrian)			Walking Speed (meters/minute)		
		Interpolated	Independent Set	Difference (%)	Interpolated	Independent Set	Difference (%)	Interpolated	Independent Set	Difference (%)
0.8	A	20.59	20.61	0.10%	3.84	3.84	0.00%	75.46	75.40	0.08%
	B	34.71	34.75	0.12%	2.16	2.16	0.00%	73.53	73.52	0.01%
	C	48.97	49.06	0.18%	1.39	1.38	0.72%	66.40	66.40	0.00%
	D	63.63	63.70	0.11%	0.80	0.79	1.27%	50.58	50.59	0.02%
	E	73.14	73.27	0.18%	0.52	0.51	1.96%	37.73	37.72	0.03%
0.2	A	18.56	18.58	0.11%	4.26	4.12	3.40%	75.28	75.45	0.23%
	B	31.46	31.24	0.70%	2.41	2.39	0.84%	73.39	73.50	0.15%
	C	44.07	44.24	0.38%	1.52	1.49	2.01%	65.71	65.59	0.18%
	D	57.15	56.68	0.83%	0.86	0.86	0.00%	48.64	48.41	0.48%
	E	65.88	65.21	1.03%	0.52	0.53	1.89%	34.71	34.52	0.55%

Note: the percentage difference $(\%) = \frac{(\text{estimated} - \text{observed})}{\text{observed}} \times 100\%$

In Figure 9.5, it can be observed that the pedestrian flows of LOS A to E under uni-directional flow (or flow ratio = 1.0) are 20.6 pedestrians/meter/minute, 34.9 pedestrians/meter/minute, 49.1 pedestrians/meter/minute, 63.7 pedestrians/meter/minute and 73.4 pedestrians/meter/minute respectively. The corresponding pedestrian flows for flow ratio 0.1 are 17.6 pedestrians/meter/minute, 29.8 pedestrians/meter/minute, 41.8 pedestrians/meter/minute, 53.8 pedestrians/meter/minute and 62.2 pedestrians/meter/minute respectively. It can therefore be observed that there is a downward trend in the pedestrian flow boundaries due to the effects of bi-directional flows. These effects are negligible at flow ratios 1.0 to 0.5 but increase rapidly as the flow ratio falls below 0.5. It is also interesting to note that the pedestrian flow criterion is influenced by the combined effects of area occupancy and walking speed. The effects of bi-directional flows on the perceived area occupancies would now be presented in Figure 9.6 using a plot of area occupancy versus flow ratio.

Figure 9.6 shows that the area occupancies of LOS A to E under uni-directional flow (or flow ratio = 1.0) are 3.83 meter^2/pedestrian, 2.16 meter^2/pedestrian, 1.37 meter^2/pedestrian, 0.80 meter^2/pedestrian and 0.51 meter^2/pedestrian respectively. The corresponding area occupancies for flow ratio 0.1 are 4.47 meter^2/pedestrian, 2.52 meter^2/pedestrian, 1.59 meter^2/pedestrian, 0.89 meter^2/pedestrian and 0.53 meter^2/pedestrian respectively. In Figure 9.6, area occupancies increase as flow ratios decrease which may be a result of the increasingly difficulty to navigate the crosswalk under heavy opposing flows.

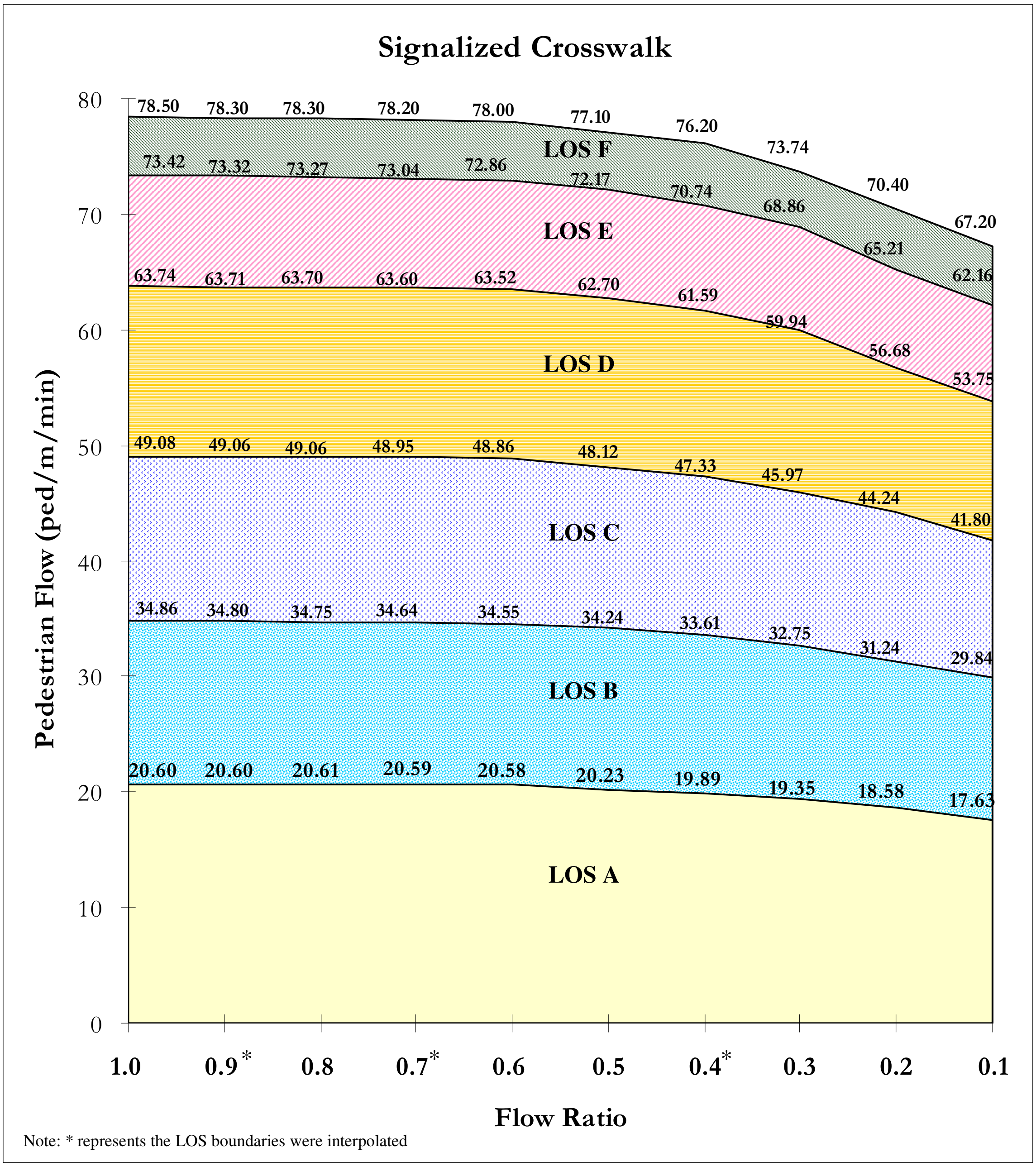


Figure 9.5 Perceived LOS boundaries by pedestrian flow under different flow ratios

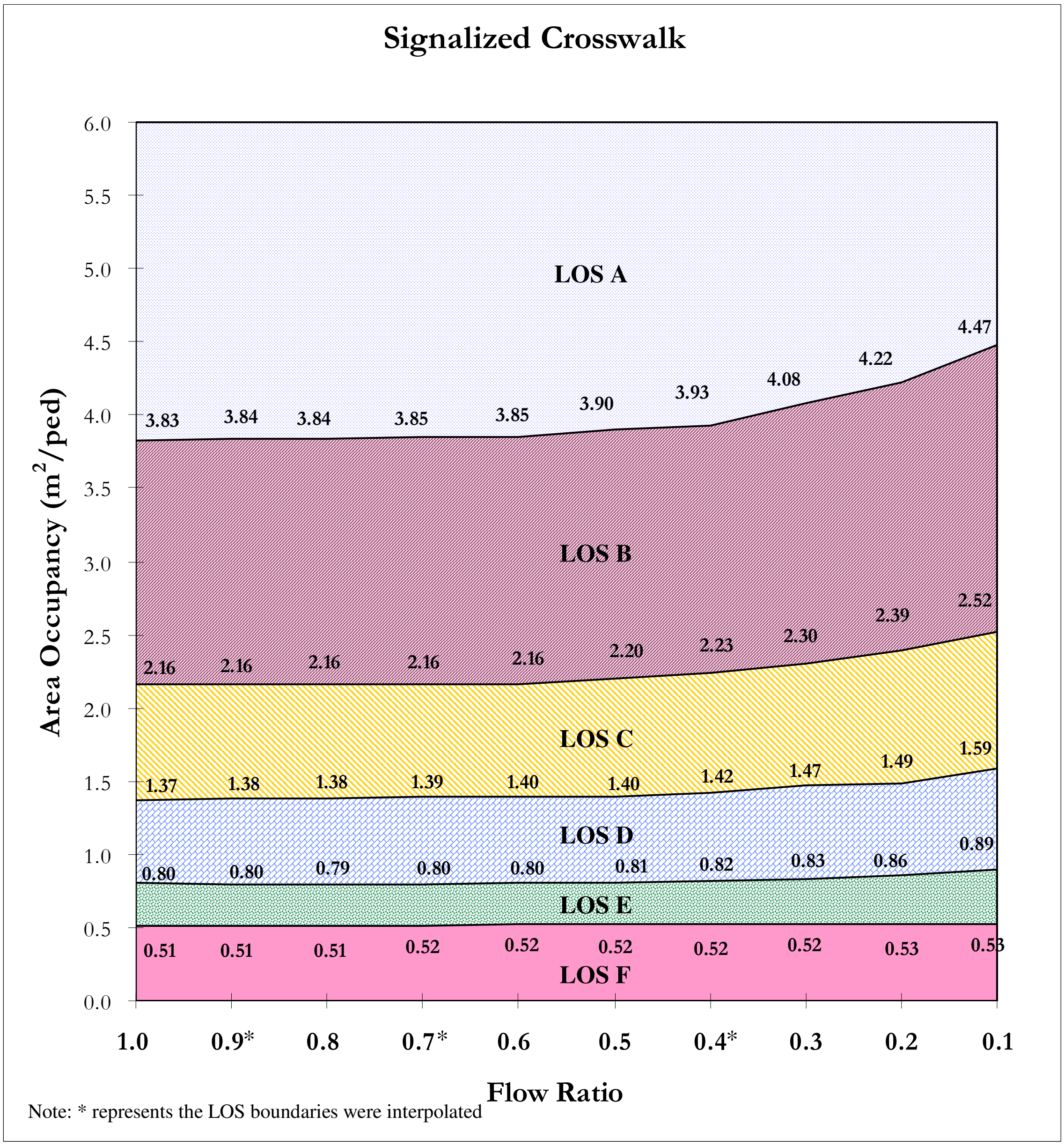


Figure 9.6 Perceived LOS boundaries by area occupancy under different flow ratios

In Figure 9.7, it can be observed that the walking speeds of LOS C to E under uni-directional flow (or flow ratio = 1.0) are 66.4 meters/minute, 50.6 meters/minute and 37.7 meters/minute respectively. The corresponding walking speeds for LOS C to E under flow ratio of 0.5 are close to those under flow ratio of 1.0. As mentioned before, the effects of bi-directional flows are not significant particularly when the pedestrian flow is low or at free-flow walking speed. Conversely, walking speed is sensitive to opposing flows as pedestrians are faced with increasing conflict and resistance due to the bi-directional flow effects. To present the effects of bi-directional flows on the pedestrian flows and its corresponding walking speeds, a 3-dimensional plot of pedestrian flow and walking speed against flow ratio is presented in Figure 9.8. In addition, the LOS boundaries corresponding to flow ratios (i.e. from 1.0 to 0.1) are also presented.

In Figure 9.8, walking speed is shown in vertical axis while the parameters for pedestrian flow and flow ratio are shown in horizontal axis. It can be observed that there is a downward trend under increasing pedestrian flow as the flow ratio decreased. When flow ratio equals to 1.0 (i.e. under uni-directional flow condition), the boundaries for the perceived LOS A are 75.5 meter/minute for walking speed with corresponding to 20.6 pedestrians/meter/minute for pedestrian flow. However, for LOS E, the walking speed boundary decreases to 37.7 meter/minute when the pedestrian flow increases to 73.4 pedestrians/meter/minute. When flow ratio equals to 0.1 (i.e. under heavy opposing flow condition), the walking speed boundary decreases from 75.4 meter/minute (for LOS A) to 33.1 meter/minute (for LOS E) with increasing the corresponding pedestrian flow from 17.6 pedestrians/meter/minute (for LOS A) to 62.2 pedestrians/meter/minute (for LOS E).

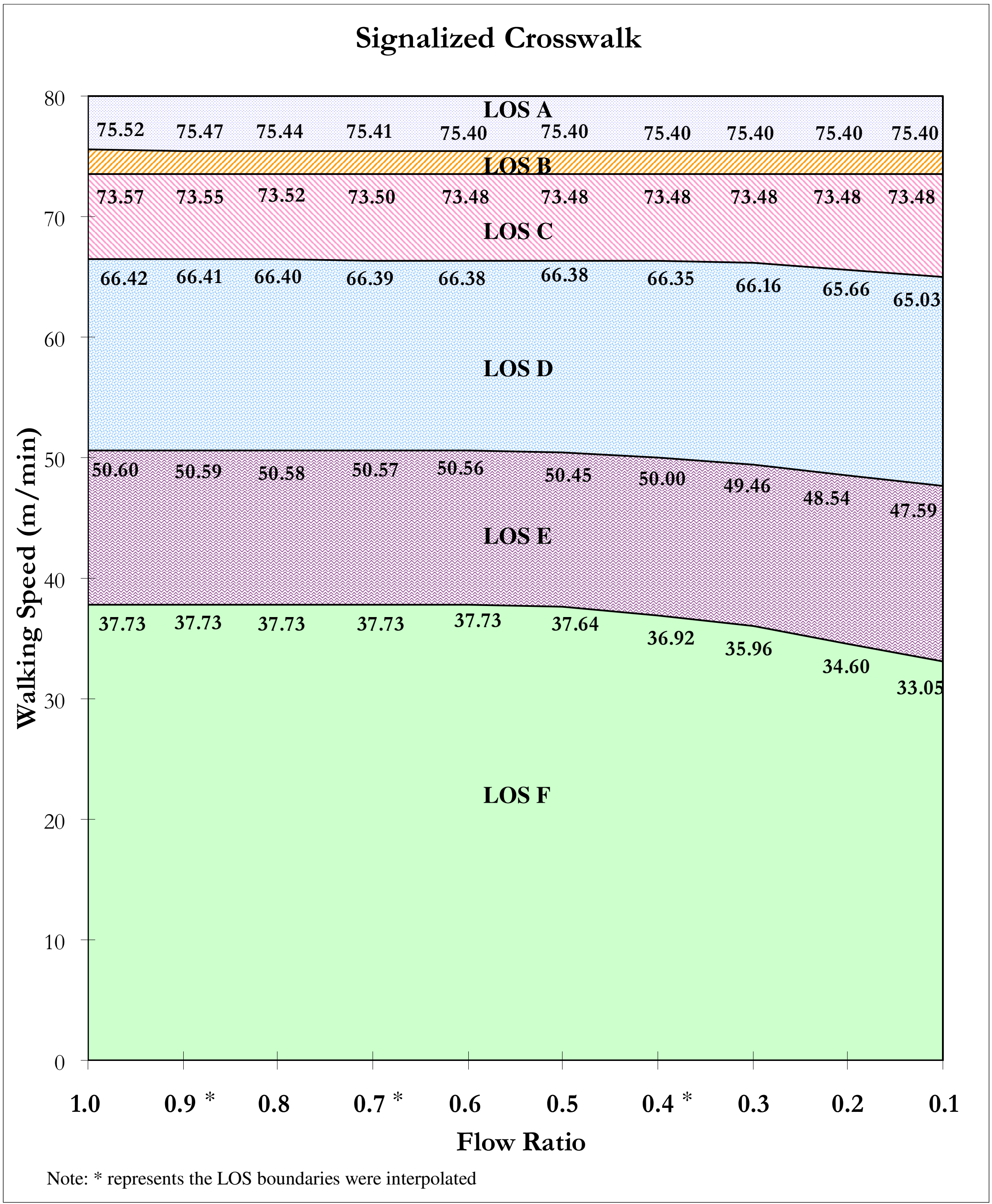


Figure 9.7 Perceived LOS boundaries by walking speed under different flow ratios

It is interesting to note that under congested condition, the acceptance levels of the pedestrians under uni-directional pedestrian flow (1.0 flow ratio) and heavy opposing flow condition (0.1 flow ratio) are different. It can be observed that the boundaries of perceived LOS E under 0.1 flow ratio are comparatively lower in both walking speed and pedestrian flow than those under 1.0 flow ratio (walking speed = 33.1 meter/minute vs 37.7 meter/minute and pedestrian flow = 62.2 pedestrians/meter/minute vs 73.4 pedestrians/meter/minute). This implies that pedestrians would accept lower walking speed and pedestrian flow when they are facing heavy opposing flow under congested condition than without. This may be partially explained by the "observed phenomenon" reported in Lam et al. (2003) that when the pedestrian flow in the opposing direction is heavy, pedestrians in the minor flow direction will then have less freedom to choose their walking speeds as it is not easy to bypass other pedestrians.

However, when compared with the boundaries for the perceived LOS A under uni-driectional flow condition to heavy opposing flow condition (i.e. flow ratio 1.0 against 0.1), the effects of bi-directional flows are comparatively very small when the pedestrian flow is low or at free-flow walking speed. When the number of pedestrians on a signalized crosswalk is very low, pedestrians walking in the direction with fewer pedestrians would face little opposing flow and have more freedom to choose their walking speeds and easily overtake other people on the crosswalk. Moreover, as mentioned before, these effects are not significant at flow ratios 1.0 to 0.5 but increases rapidly as the flow ratio falls below 0.5. It is worth noting that the walking speed criterion is influenced by the combined effects of pedestrian flow and directional distribution of pedestrian flow.

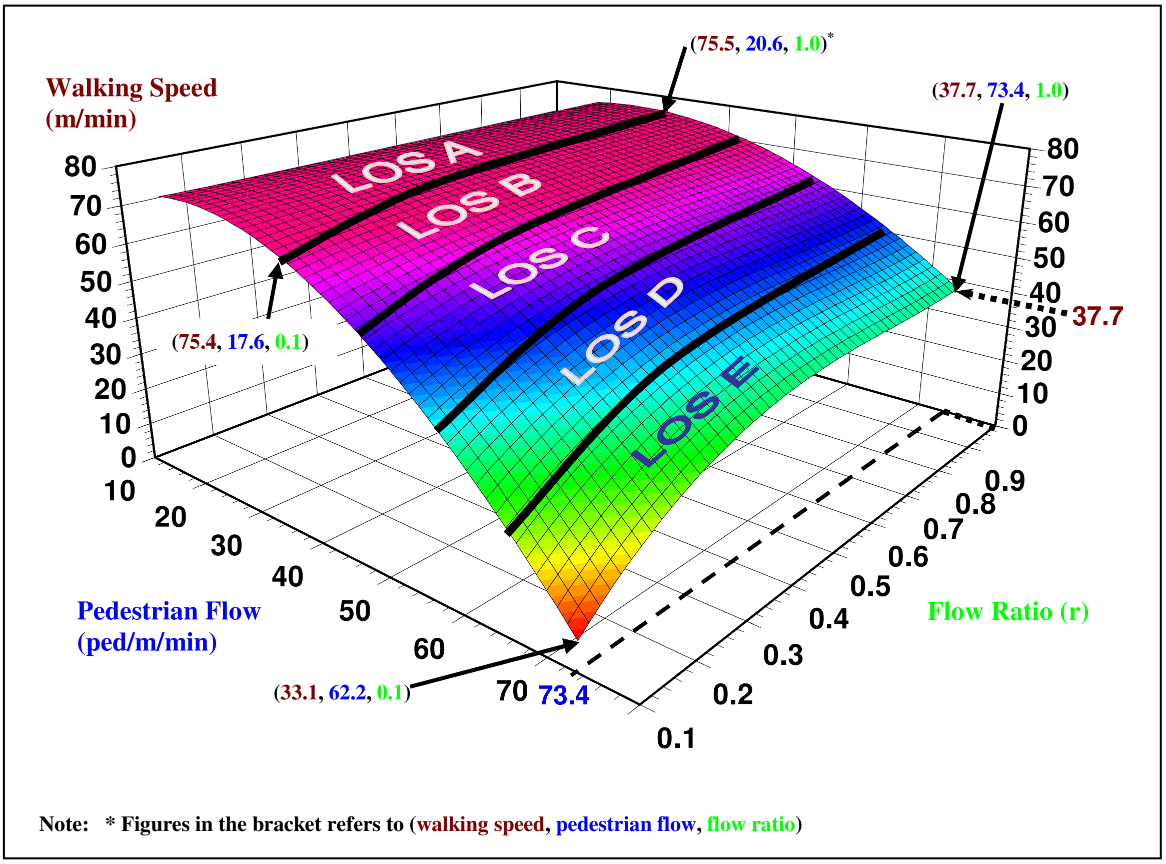


Figure 9.8 Three dimensional perceived LOS for signalized crosswalks with bi-directional pedestrian flows

9.6 COMPARISONS

The effects of bi-directional flows on the perceived LOS boundaries and how the effects change as the opposing flow increased are presented. A comparison is now made to highlight the perceived LOS standards proposed by Lam and Lee (2001) with the past LOS studies. It is worth noting that this comparison would be made between the LOS standards which do not explicitly incorporate the effects of bi-directional pedestrian flows. As mentioned in the introduction, this study is believed to be the first attempt that the effects of bi-directional pedestrian flows are explicitly accounted for in the LOS standards for pedestrian crosswalks. The perceived LOS boundaries for area occupancies are presented in Figure 9.9. In addition, LOS boundaries in the oversea studies are also included for comparison purposes.

From Figure 9.9, a comparison on the perceived LOS boundaries by area occupancy for signalized crosswalks in Hong Kong and those boundaries for walkways used in different countries are shown. When compared to LOS boundaries in other countries, it was found that the LOS boundaries for signalized crosswalks in Hong Kong are different from those proposed in the earlier studies. The perceived LOS boundaries are relatively similar to those proposed in Fruin (1987) and Gerilla et al. (1995) but are markedly different from those proposed by the Highway Capacity Manual (Transportation Research Board, 2000) and Tanaboriboon and Guyano (1989). These discrepancies can be attributed to the different study environment as well as in the various types of pedestrian facilities used in their study.

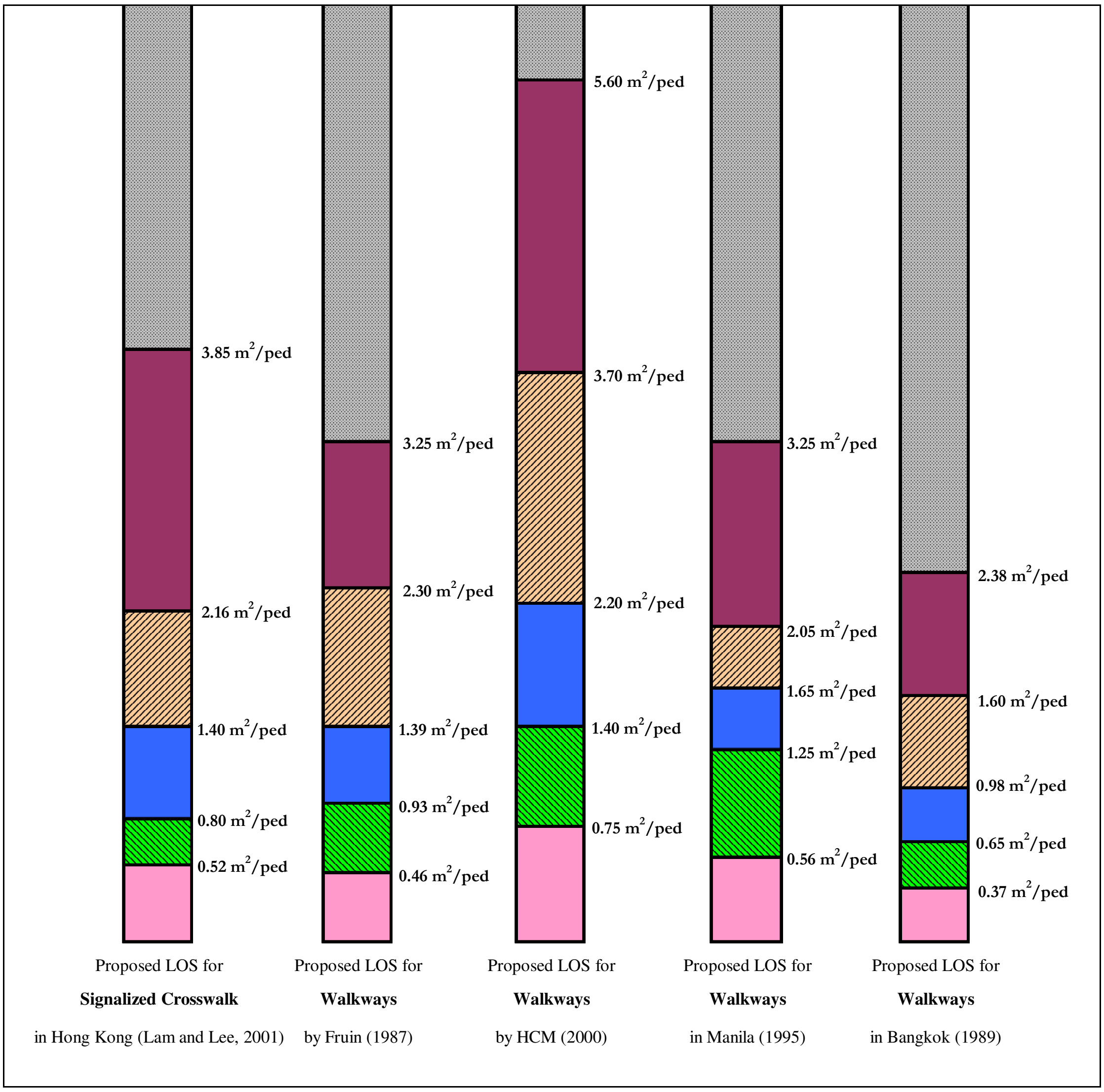


Figure 9.9 LOS boundaries by area occupancy used in different studies

9.7 SUMMARY

In this chapter, a method is proposed to provide a systematic framework that incorporates the bi-directional flow conditions within a single LOS scale. As demonstrated in the study, the congestion variable has been modified to allow the consideration of the bi-directional effects of pedestrian flows. A new set of LOS standards for signalized crosswalks with bi-directional pedestrian flows was derived based on pedestrian flow, area occupancy and walking speed. This study was taken reference to the findings from an observational study conducted in Hong Kong by Lam et al. (2002). As shown in the previous section, the use of a survey methodology to derive the area occupancies for the bi-directional flows is a feasible alternative. The differences in the LOS boundaries obtained using this method are averaged at 20% when compared to those boundaries obtained by the method proposed in the Highway Capacity Manual (Transportation Research Board, 2000).

The acceptance levels at congested condition of the pedestrian under uni-directional pedestrian flow (i.e. flow ratio = 1.0) and heavy opposing flow condition (i.e. flow ratio = 0.1) were found to be different. Pedestrians would accept lower in both walking speed and pedestrian flow when they are facing heavy opposing flows under at-capacity condition (LOS E) than the case without opposing flow. A comparison of the bi-directional LOS boundaries for different flow ratios showed that boundaries by pedestrian flow and their corresponding walking speeds were not significantly influenced by the bi-directional flow effects at low pedestrian flow volumes. However, as the volume of pedestrian flow increased, the effects of bi-directional flows became more significant, with pedestrians experiencing greater conflict as the flow ratio decreased. This supports the hypothesis that pedestrian LOS standards are negatively influenced by the bi-directional flows as well as the need to incorporate the bi-directional flow component in the pedestrian LOS standards. As discussed in Goh and Lam (2004) and Lam et al. (2002), the LOS at signalized crosswalks can influence the safety and design of pedestrian crosswalks.

The current design of crosswalk in Hong Kong is inability which does not account for the pedestrian flow volumes and different bi-directional flow effects. The simulation results of PSM in Chapter 8 demonstrate that different design walking speeds for signalized crosswalks are required with consideration of the different bi-directional pedestrian flows. Moreover, the newly proposed LOS standards show that pedestrians perceived differently when they are facing heavy opposing flows and under different flow conditions. If the bi-directional flow effects were not accounted for in the design, pedestrians who entered the crosswalk facing heavy opposing flows under high flow condition would not be able to complete their crossing before the end of the pedestrian flashing green time. Hence, safety of pedestrians is not ensured as they are leading to either risk crossing after the pedestrian flashing green or return and wait at the waiting area. Therefore, it is considered that the current design for signalized crosswalks is over simplified. Pedestrian flow, bi-directional flow effects and different LOS standards are required to consider in the design of the signalized crosswalks.

This is one of the first attempts that the effects of bi-directional pedestrian flows are explicitly accounted for in a set of LOS standards for pedestrian crosswalks. Similar studies should be carried out at different walking facilities so as to enhance the design and operation of the pedestrian facilities. A final conclusion of this thesis is summarized in Chapter 10 together with some recommendations for further studies.

10 CONCLUSION

Hong Kong has developed rapidly over the years evidenced by the increasing number of high-rise offices and residential buildings which leads to a dense concentration of people, many of whom need to be transported daily to different locations. Traffic generators, such as railway stations and bus stops, also put great pressure on pedestrian networks. Pedestrians need to walk to these traffic generators or public transportation modes from their origins such as their homes or offices.

In the Hong Kong Travel Characteristics Survey (2002), it was reported that over 6.8 millions walk-only trips were made on a daily basis by 2.76 millions of Hong Kong residents aged 3 or over. These figures implied that each resident may generate about 2.5 walk-only trips daily on an average. This places a huge demand on the pedestrian facilities particularly for those facilities that connect to the public transportation modes. In order to alleviate these adverse effects and subsequently improve the pedestrian circulation, new Pedestrian Schemes and/or new pedestrian facilities such as new railway exits are introduced in some of the congested urban areas in Hong Kong.

In practice, it is difficult to predict the changes of pedestrian origin-destination pattern due to the choices of different pedestrian activities and various responses of different personality types to the pedestrian network improvements. The reason is that different types of pedestrians (such as commuters and non-commuters) have different activity characteristics and preferences to their destinations and route choices particularly in the congested urban areas with mixed land uses. Their activity preferences will definitely influence the spatial distribution of the urban area and temporal distribution of the pedestrians on the streets. Therefore, pedestrian activity and destination choices in the congested urban areas should be well understood for planning and design of pedestrian facilities. Besides, to simulate the pedestrian activity behaviors, a microscopic pedestrian simulation model is necessary, which can be used to better assess the impacts of various improvement schemes for pedestrians.

10.1 KEY FINDINGS

The aim of this research was to model the pedestrian activity behaviors in the densely populated urban areas. The main contributions of this thesis were discussed in Section 1.3. The key findings of this research project are summarized as follows:

10.1.1 Development of Pedestrian Activity-Simulation (PAS) Model

A PAS model was newly developed, as presented in Chapter 3, to simulate the pedestrian movements in the congested urban areas with explicit emphasis on the pedestrian activity behaviors. A densely populated urban area in Hong Kong was chosen for case study as a part-time Pedestrian Scheme (i.e. pedestrian–only streets from 4 p.m. to the midnight during weekdays) has been implemented within the area during the peak period.

A large-scale survey was conducted at the chosen study area with the assistance of 70 surveyors on a typical Friday 5 August 2005. Two survey periods were chosen, an off-peak period from 2 p.m. to 4 p.m. (without Pedestrian Scheme implemented) and a peak period from 5 p.m. to 7 p.m. (with Pedestrian Scheme implemented). Two types of surveys were conducted simultaneously: (a) an observational survey; and (b) a tracking survey.

For the observational survey, twenty-two surveyors were sent to the major locations (i.e. origins and destinations). They were requested to count the total pedestrians crossing in both directions, over 15-minute intervals. Seven video cameras were set up on the 10th floor of a building to simultaneously record the complex and high pedestrian flow movements at the selected locations. With the use of manual location count and video recording techniques, the pedestrian trips generated from and attracted to each major location could be obtained.

From the data collected in the observational survey, it was found that the maximum pedestrian trips were observed during the time period from 6:30 p.m. to 6:45 p.m. Moreover, the total number of pedestrian trips observed in the study area was 80,643 trips during the peak period, which was much higher than that during the off-peak period (i.e. 51,387 trips). This finding could be partially explained by the fact that people in Hong Kong normally leave office after 6 p.m. They may go to a shopping area for some activities. They may go shopping after work particularly on Fridays. Thus, the pedestrian demand at 6:30 p.m. - 6:45 p.m. is the highest as compared with that in other time periods. Thus, a much higher pedestrian demand was observed during the peak period on Friday night in the congested urban area.

For the tracking survey in the study area, forty surveyors were allocated to several major locations found with high pedestrian flow from the pilot survey. They were required to trace the trajectories of the pedestrians by recording their trip information. It was found that the total trip duration of the majority of the pedestrians was less than 3 minutes on average. Over 90% of pedestrians were individuals or pairs. About 65% of the pedestrians were females. By using the tracking survey technique, the pedestrian activity and destination choice models could then be calibrated by using the tracking data collected.

The PAS model was developed with the necessary inputs, namely pedestrian activity and destination choice models (Chapter 4), generalized walking time functions for outdoor walkways and signalized crosswalks (Chapter 5), walking speed variations with the uni-directional and bi-directional pedestrian flow effects (Chapter 6) and time sliced pedestrian demand in terms of origin-destination matrices (Chapter 3). The newly developed PAS model for the congested urban area can also be used to estimate pedestrian flows and average walking time together with walking time variations particularly when pedestrians are facing heavy opposing flows. The newly developed PAS model for the congested urban areas can be used for assessments of the impacts of various improvement options on the pedestrian circulation movements.

10.1.2 Pedestrian Activity and Destination Choice Models

Studying pedestrian activity behaviors is of prime importance for the improvement of walking facilities in the congested urban areas. Pedestrian activity and destination choices were investigated and reported in Chapter 4. One of the densely populated urban areas in Hong Kong was selected for case study. It was found that a longer journey time of the indirect trips (i.e. pedestrian trips with activities performed) was observed than that of the direct trips (i.e. pedestrian trips without any activities performed). The average trip durations were 74 seconds and 343 seconds for direct and indirect trips respectively. The discrepancy on the average trip duration can be mainly explained by the activity durations of the pedestrians. When pedestrians perform shopping activities, their activity preferences can definitely influence the spatial distribution of the adjacent area. Besides, their shopping durations affect the temporal distribution of the pedestrians directly. If the pedestrian activity behaviors are not taken into account in the modeling of the pedestrian movements in the congested urban areas, the accuracy of the model results will be questionable. This finding supports the need of detailed investigation on the pedestrian activity behaviors.

The relationship between pedestrian travel demand and their choices of shopping activities was examined in this study. A modeling framework was newly proposed for estimating the pedestrian activity and destination choices using four decision models namely: staying or leaving choice, shopping choice, destination choice and shopping duration models. These four decision models were calibrated using the observed data gathered from the tracking and observational surveys to determine how various time components affected pedestrian decisions within the study area.

For the pedestrian staying or leaving choice model, relative and absolute time were the two important factors considered by the pedestrians. The calibrated results of the model showed that negative effects of both relative and absolute time were found. When the pedestrians stayed in the area for a long time (i.e. increment in relative time), they may get tired and uncomfortable at the outdoor area. Therefore, the chances for them to leave the area gradually become higher. Moreover, pedestrians will also leave the area when it is late at night (i.e. increment in absolute time).

Similar results were found for modeling the pedestrian shopping choices. Relative and absolute time were also the two important factors perceived by the pedestrians. The calibrated results demonstrated the positive effect of relative time component and the negative effect of absolute time component. Pedestrians would spend more time on shopping if it is not late at night. They may go for shopping after work at 5 p.m. or 6 p.m. Besides, with the increment of the shopping durations, the total trip durations of the pedestrians may probably be longer.

For modeling the destination choices of pedestrians, distance component was the main factor affecting their preferences. This component was quantified by the observed data. The calibrated results showed the negative effect of the distance component. Pedestrians search for the nearest destination exits to leave the area if they have no particular scheduled destinations (e.g. going to the underground railway station). The distance between the current location of the pedestrians and their preferred destination is assumed to be the shortest as compared to the other alternative destinations. Thus, with the increment in the walking distance to the destination, pedestrians may probably go to this destination with a lower probability.

The distribution of the shopping durations was also investigated in this study. A number of distributions were adopted to fit with the shopping duration data. It was found that the shopping duration data fitted with the exponential distribution. It was observed that majority of pedestrians used less than 5 minutes for shopping as these stores are mainly at street level with comparatively small floor areas. However, the observed maximum shopping duration can be up to 26 minutes. Pedestrians may stay in the store for a long time if they buy any thing or even use the fitting room. Thus, the shopping durations can vary and could be prolonged.

The consideration of the four newly calibrated decision models did lead to the improvements in the modeling of the pedestrian travel and activity behaviors in the congested urban areas. By introducing the activity-based approach, a new avenue of pedestrian demand analysis is offered for better planning of pedestrian facilities. Planners can also predict the pedestrian activity and destination choices so as to estimate the pedestrian origin-destination flow matrices and link flows more accurately in the densely populated urban areas.

10.1.3 Generalized Walking Time Functions

The walking speeds of pedestrians are of prime importance in modeling pedestrian movements and designing of pedestrian facilities in urban areas. In Chapter 5, the bi-directional pedestrian flow effects on free-flow walking speed, effective capacity and at-capacity walking speed on outdoor walkways and signalized crosswalks were investigated empirically. The generalized walking time (GBPR) functions of these two facilities were newly calibrated taking into account the bi-directional pedestrian flow effects.

Analyses conducted on the effects of bi-directional pedestrian flows on outdoor walkways and signalized crosswalks revealed that the effective capacities as well as the at-capacity walking speeds decreased with increasing imbalance of directional split of pedestrians. However, no significant impact of bi-directional flows was detected on the free-flow walking speeds. In particular, the bi-directional flow effects are particularly significant in the minor flow direction. Bi-directional pedestrian flow effects were also found to be more significant on outdoor walkways than at signalized crosswalks. The GBPR functions can estimate the walking speeds under various flow conditions ranging from free-flow to congested-flow (at-capacity) situations and different directional split of pedestrians ranging from the uni-directional flow condition to the bi-directional flow condition.

The proposed GBPR functions allow the bi-directional flows to be modeled yet retain the ability to represent the uni-directional flow effects (by setting the flow ratio r = 1). The proposed GBPR functions are expected to apply in the planning and design of pedestrian networks. It represents an evolutionary contribution to an active field of research and is a resource for those who are developing pedestrian models in practice. Findings derived from this research are expected to be directly applicable in Hong Kong or in other Asian Cities with similar pedestrian characteristics.

10.1.4 Walking Speed/Time Variations

The variation of walking speeds for pedestrians passing through a facility is known to be an important factor influencing pedestrian route choices. Therefore, the walking speed/time variations were studied (reported in Chapter 6) under uni-directional and bi-directional pedestrian flow conditions. The studied facilities, which included a uni-directional walkway and a bi-directional stairway, were selected for data collection and analysis. The variation in walking speed was due to sudden increase in pedestrian travel demand, different types of pedestrians and their walking behaviors such as elderly people or a family with several members may walk slower than the younger people.

Data were collected from the observational surveys to calibrate the relationship of mean walking time/speed and standard deviation under uni-directional and bi-directional pedestrian flow conditions. In addition, the distributions of walking time variations under congested and un-congested flow conditions were examined with consideration of the bi-directional flow effects. Therefore, large amount of observed data were required for examination of the relationship between mean walking time and standard deviation.

It was found that for the un-congested section, when the mean walking speed decreased, the walking speed variation also decreased under both uni-directional and bi-directional pedestrian flow conditions. In addition, the walking speed variation was smallest when pedestrian flow approached to capacity of the walking facility. However, in the congested section, when the mean walking speed decreased, the walking speed variation increased under both uni-directional and bi-directional pedestrian flow conditions.

Walking time data were empirically proved to fit with a normal distribution. It was also shown that the un-congested walking time data also fit with normal distribution while it would be better using a log-normal distribution to model the skewness observed for congested data. This study generally matched the findings from other previous studies but somewhat extended other findings especially the new proposed relationship between mean walking time and standard deviation taking into account the bi-directional flow effects. Models for walking speed variation were thus newly developed for the uni-directional and bi-directional pedestrian facilities.

10.1.5 Comparison of the Pedestrian Activity-Simulation Model and the Trip-based Simulation Model

In order to examine the reliability of the results given by the newly developed PAS model, an independent data set was observed and used to compare the simulation results with the observed data. Chapter 7 presented the comparison between the observed data and the results simulated by the newly developed PAS model and the traditional trip-based simulation model. It was found that the total trip durations simulated by the PAS model were closer to the observed data with minor underestimations about 4.3% on average. These errors in estimation were in relation to the lack of attention paid to some pedestrian characteristics in the PAS model such as group behaviors, walking behaviors of different types of pedestrians and different trip purposes of the pedestrians. However, if the traditional trip-based simulation model was used to simulate the pedestrian total trip durations, large underestimations were found with 17.8% on average. These serious underestimations can be explained by the fact that the pedestrian activity behaviors were not taken into account in the traditional trip-based simulation model. The comparison results confirmed that pedestrian activity behaviors are of prime importance to study for planning of walking facilities in the congested urban areas.

10.1.6 Pedestrian Simulation Model for Signalized Crosswalks

A new pedestrian simulation model (PSM) was firstly developed for signalized crosswalks as delineated in Chapter 8. This model is capable of estimating the variations of walking speed particularly on the effects of bi-directional pedestrian flows so as to determine the minimum required duration for pedestrian crossing. In Hong Kong, the current practice in signalized intersection design is assumed of a constant pedestrian walking speed (i.e. 1.2 meters/second). The pedestrian flow conditions on the signalized crosswalk are not heeded. Pedestrians may not have adequate time to cross a signalized crosswalk particularly when the opposing pedestrian flow is high and the pedestrian flows on the crosswalk are close to its full capacity. It is thus considered that for pedestrian safety, the assessment/design of a signalized crosswalk should not only be based on its capacity but also include the aspect of walking speed under different bi-directional flow ratios.

The GBPR function for signalized crosswalks and the walking speed variation function were incorporated in the PSM. These two functions were used to estimate the walking time on the crosswalk with particular emphasis on the walking speed variations due to the effects of bi-directional pedestrian flows. It was interesting to note that the negative impact of the bi-directional pedestrian flow effects was found on the chance of pedestrians crossing the signalized crosswalk completely within the same green phase. This implies that with the reduction on the bi-directional pedestrian flow effects (i.e. flow ratio from 0.1 to 1.0), the chance of pedestrians completely crossing do increase. Besides, the total pedestrian flows also had negative impact on the chance of pedestrians completely crossing within the same green phase. The chance for the pedestrians to completely traverse the crosswalks tended to increase when the total pedestrian flows on the crosswalk was lower.

Simulation results highlighted the limitation of the current design which does not account for the pedestrian flow volumes and different bi-directional flow effects. Evidence showed that the walking speed is not only dependent on the total pedestrian volume but also depends on the bi-directional flow ratios. The simulation results demonstrated that different designs based on walking speeds for signalized crosswalks are required as different bi-directional pedestrian flow effects should be considered for determining the duration of the pedestrian green time at signalized crosswalks. If the bi-directional flow effects were not accounted for in the design, pedestrians who entered the crosswalk facing heavy opposing flow under high flow conditions would not be able to complete their crossing before the end of the flashing green time at the pedestrian crossings. Hence, safety of pedestrians is not ensured as pedestrians are obliged either risk crossing or returning and waiting at the waiting area after the pedestrian signal has turned from flashing green to steady red. This calls for a need to review the current design with particular attention to walking speed for signalized crosswalks particularly in the congested urban areas with significant high pedestrian flows.

The calibrated PSM was validated using an independent data set so as to examine the reliability of the simulation results. The validation results showed that the new simulation model can provide an accurate evaluation on the changes of the walking speeds and their variations under different scenarios with particular emphasis on the effects of bi-directional pedestrian flows. The advancement of this simulation model can provide a tool to assess the effects of each improvement measure on signalized crosswalks and to evaluate the benefits of changes arising from these measures in practice.

10.1.7 Pedestrian Level-of-Service Standards for Signalized Crosswalks

A new set of pedestrian LOS standards for signalized crosswalks was derived based on pedestrian flow, area occupancy and walking speed (see Chapter 9 for details). These newly developed LOS standards, which can be used to assess the performance of the signalized crosswalks, explicitly take into account the bi-directional pedestrian flow effects. An interview survey technique which utilized the stated preferences of pedestrians was used to determine the respective congestion boundary for each service level. The LOS boundaries had been derived explicitly for different levels of bi-directional flows in terms of area occupancy, pedestrian flow and walking speed. The boundaries ranged from strong effect (0.1 to 0.5 flow ratios) on the minor flow direction to a mild effect (0.5 to 1.0 flow ratios) on the major flow direction. These results were complementary to those LOS standards for walkways reported in the previous studies (Fruin, 1987) which, unlike this study, did not account for the effects of bi-directional pedestrian flows.

For the congested condition, the acceptance levels under uni-directional pedestrian flow (1.0 flow ratio) and heavy opposing flow (0.1 flow ratio) conditions were found to be different. Pedestrians could accept lower walking speeds and pedestrian flows when they are facing heavy opposing flow under at-capacity condition (LOS E) in comparison with a case without opposing flow. A comparison of the bi-directional LOS for different flow ratios showed that pedestrian flow and their corresponding walking speeds were not significantly influenced by the bi-directional flow effects at the low pedestrian flow volume. However, as the volume of the pedestrian flow increased, the effects of bi-directional pedestrian flows became more significant, with pedestrians experiencing greater conflict as the flow ratio decreased. This supported the hypothesis that pedestrian LOS are negatively influenced by the bi-directional flows as well as the need to incorporate the bi-directional flow component in the pedestrian LOS.

This study is one of the attempts to explicitly examine the effects of bi-directional pedestrian flows on the LOS standards for pedestrian crosswalks. It is suggested that similar studies should be carried out at different walking facilities so as to enhance the design and operation of the pedestrian facilities. The observed findings and derived models from this research study on pedestrian activity behaviors can be used for assessing and evaluating various pedestrian improvement options in congested urban areas.

All the above mentioned results of this project will constitute an important contribution to an active field of research and a resource for those developing pedestrian models in practice.

10.2 IMPLICATIONS OF THIS STUDY

A PAS model for Hong Kong congested urban areas is newly proposed. This research appears to be the first devoted exclusively to the examination of relationships between pedestrian activity and travel demand in congested urban street environments in Hong Kong. The proposed PAS model demonstrates to provide deepen insights on the pedestrian walking and shopping behaviours in the spatial-temporal dimension at the street-level in Hong Kong congested urban areas.

This PAS model can assess the impacts of various traffic improvement schemes (such as pedestrian-only streets) implemented by the Government of Hong Kong Special Administrative Region in practice. The enhancements of the PAS model can be applied to assess the effects of a new entrance/exit of the underground railway station and to evaluate the benefits of each scenario practically. The PAS model also leads to an assessment of the impacts of pedestrian network improvements in Hong Kong so as to facilitate the planning of pedestrian facilities in Hong Kong.

Advantages of using the proposed PAS model are that the planners can predict the pedestrian activity and travel choices so as to estimate properly the pedestrian origin-destination matrices and link flows in congested urban areas. The advancement of the modeling techniques are particularly important in many large Asian cities like Hong Kong, with dense land uses and congested urban areas, where a large volume of pedestrian trips is made for different activities.

It is expected that the proposed PAS model and results will be highly useful in planning and design of pedestrian networks in Hong Kong, and can be applied to other Asian cities with similar pedestrian characteristics and land use patterns.

10.3 LIMITATIONS

Several limitations are observed after this study. They are listed as below:

- The calibrated pedestrian activity-destination choice models are simply relied on two time components: relative and absolute time. More explanatory and demographic factors are of interest to involve in the models as these factors/variables may influence both walking speed and propensity to shop. Including more variables could have led to a more powerful behaviorally based model that would be more amenable to different policy scenarios;

- The size of the chosen study area in this research is small as the length of the measurement section is about 150 meters. Based on the findings in Chapter 3, the total trip durations (including shopping activities at street-level) of the majority of the pedestrians was less than 3 minutes on average. It is also observed from the data that majority of the number of shops that pedestrians patronized is one only. Moreover, the size of the shops at street-level is small. The small area chosen in this study may be one of the reasons that the contribution of the proposed activity approach may be limited;
- The two time periods chosen in this research study are 2:00 p.m. - 4:00 p.m. of the off-peak period and 5:00 p.m. - 7:00 p.m. of the peak period respectively. The short time interval may also influence the effects of the activity approach proposed in this study;
- In the developed PAS model, it was assumed that the pedestrian origin-destination trip matrix was fixed and confined to single user class within the study area. In practice, it is difficult to predict the change of pedestrian origin-destination pattern due to various responses of different person types to pedestrian network improvements. It is because different types of pedestrians (such as commuters and non-commuters) have different activity characteristics and preferences to destinations and route choices particularly in Hong Kong congested urban areas with mixed land uses;
- The PAS model is developed to simulate the individual pedestrian movements. Based on the findings in Chapter 3, over 90% of pedestrians are

individuals or pairs. However, it can be easily to observe on-site that the movements of pairs are quite different to the individuals;

- The PAS model can simulate the pedestrian movements regardless the pedestrian characteristics such as gender, age and etc. It can be easily to observe on-site that the elderly may walk slower than the young people; and
- The developed PAS model can only simulate the pedestrian movements on street level. Pedestrian facilities connecting to the major entrances/exits of the traffic generators are also critical for pedestrian circulation within a congested urban area.

10.4 FURTHER RESEARCH

To overcome the above mentioned limitation, further research works on pedestrian studies are recommended in the following directions:

- The extension of pedestrian activity-simulation model to simulate the pedestrian movements
  - by multi-user classes such as person types for various activities in other urban areas with different land use development;
  - by pedestrian characteristics such as age, gender and etc;
  - for a longer period such as 24 hours;

- for a larger area involves pedestrian facilities connecting to the major entrances/exits of the traffic generators such as underground railway station;

➢ The development of pedestrian activity-simulation model for the other pedestrian-concentrated centre such as the Hong Kong International Airport Terminal;

➢ The investigation of the impacts of group behaviors on pedestrian movements.

➢ The development of Level-of-Service standards for various pedestrian facilities such as indoor and outdoor walkways.

Activity choice model should be calibrated with reference to a range of factors rather than just the shopping choice model. In this research, the pedestrian activity behaviors were investigated with four decision models, which were calibrated using the data collected from the tracking survey. These four models are staying or leaving choice, shopping choice, destination choice and shopping duration models. The shopping choice model is the pedestrian preference between going for shopping or not engaging in any shopping activities. However, this shopping choice model should ideally be further extended to account for a variety of choices including different activities not necessarily confined to shopping activity only. Further case studies are required for application of the developed models in other urban areas such as the central business districts in Hong Kong in order to investigate the transferability of the developed models and to model various types of pedestrian activities during day time in commercial areas.

Indeed a continuum approach to simulate pedestrian movements is of great worth as it can express the pedestrian movements in a more realistic manner. The PAS model developed in this research should be further extended to incorporate a continuum approach as the latter has recently been shown to be more appropriate for modeling pedestrian movements particularly when the pedestrian demand on the network is tremendous.

APPENDIX A PEDESTRIAN SCHEMES IN HONG KONG

Transport Department (TD) had implemented a number of Pedestrian Schemes (PS)* in highly congested urban areas in order to promote walking and to improve the overall pedestrian environment. Since year 2000, TD has been implementing these schemes in several areas, including Causeway Bay, Central, Wan Chai, Mong Kok, Tsim Sha Tsui, Jordan, Sham Shui Po, Stanley and Sheung Shui. There are three PS which include:

a) Full-time Pedestrian Street - vehicular access is restricted to emergency services only and pedestrians have absolute priority;

b) Part-time Pedestrian Street - vehicular access is not allowed in specific periods, typically between 4 p.m. and midnight. There is no on-street parking space. However, loading bays are provided for loading/unloading purpose; and

c) Traffic Calming Street - footpaths are normally widened and there are limited parking spaces for motorcycles and those with disabilities. Taxi and green minibus stands are also provided. There is no restriction to vehicular access. However, vehicles are slowed down through the use of traffic calming measures, such as narrower traffic lanes and speed tables etc.

* information about Pedestrian Schemes (PS) can be found in "Pedestrian Schemes for Hong Kong" from the Transport Department internet homepage

http://www.info.gov.hk/td/eng/transport/ped_index.html

Pedestrian Schemes at Causeway Bay

In Causeway Bay, there are substantial commercial, retail and other economic activities. Insufficient road space to accommodate both vehicular traffic and pedestrians may result in traffic accidents. In order to improve the environment and safety for pedestrians, TD has already implemented PS in the more crowded parts of Causeway Bay. Figure A.1 summarizes these implemented PS at Causeway Bay.

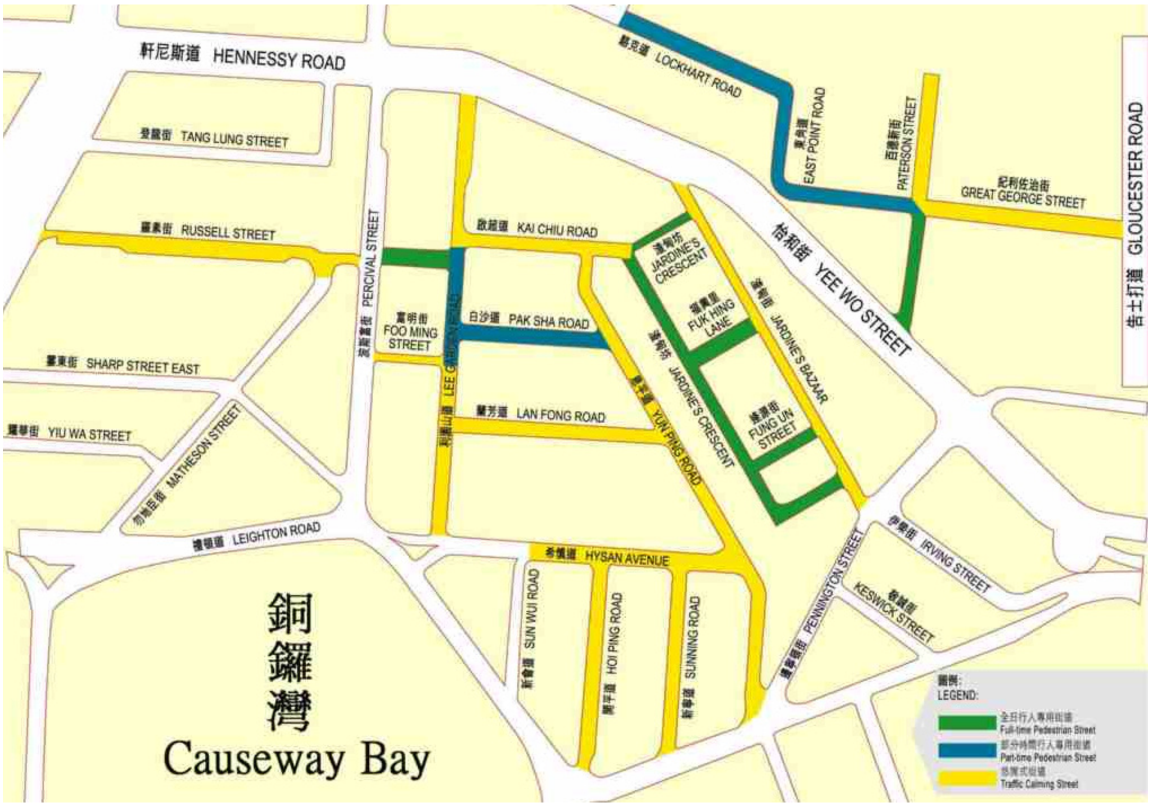


Figure A.1 Implemented pedestrian schemes in Hong Kong Causeway Bay

These PS include:

a) Full-time Pedestrian Street

- Jardine's Crescent (implemented since October 2000) – see Figure A.2
- Paterson Street (between Great George Street and Yee Wo Street) - implemented since June 2001
- Russell Street (between Lee Garden Road and Percival Street) - implemented since April 2000

Before (June 2000) ***After (March 2001)***

Figure A.2 Jardine's Crescent full-time pedestrian street – before and after

b) Part-time Pedestrian Street (operates between 4 p.m. and midnight on Monday to Friday and from noon to midnight on Saturdays, Sundays and Public Holidays)

- Lee Garden Road (between Kai Chiu Road and Pak Sha Road) - see Figure A.3
- Lockhart Road (between Cannon Street and Paterson Street)

- East Point Road
- Great George Street (between Cannon Road and Paterson Street)
- Pak Sha Road (trial since June 2004)

Before (June 2000) ***After (March 2001)***

Figure A.3 Lee Garden Road part-time pedestrian street – before and after

c) Traffic Calming Street

- Great George Street (between Paterson Street and Gloucester Road) – see Figure A.4
- Kai Chiu Road
- Foo Ming Street
- Lan Fong Road
- Lee Garden Road (between Foo Ming Street and Hysan Avenue)
- Russell Street Road (in front of Times Square)
- Yun Ping Road (between Kai Chiu Road and Hysan Avenue)

Before

After (November 2003)

Figure A.4 Great George Street traffic calming street – before and after

APPENDIX B PEDESTRIAN PRIORITY ZONE IN CAUSEWAY BAY

Planning Department (PD) has proposed to implement a Pedestrian Priority Zone (PPZ)* in Causeway Bay so as to give the priority of the use of road space to pedestrians. In Hong Kong, Causeway Bay is one of the most popular shopping districts which is flocked with crowds of people and heavy traffic throughout the day as shown in Figure B.1. The new proposed PPZ in Causeway Bay is bounded for the area by Gloucester Road, Leighton Road and Canal Road East as shown in Figure B.2.

Figure B.1 Causeway Bay

---

* information about Pedestrian Priority Zone (PPZ) can be found in "Pedestrian Plan for Causeway Bay - Technical Note" from the Planning Department internet homepage

http://www.info.gov.hk/planning/index_e.htm

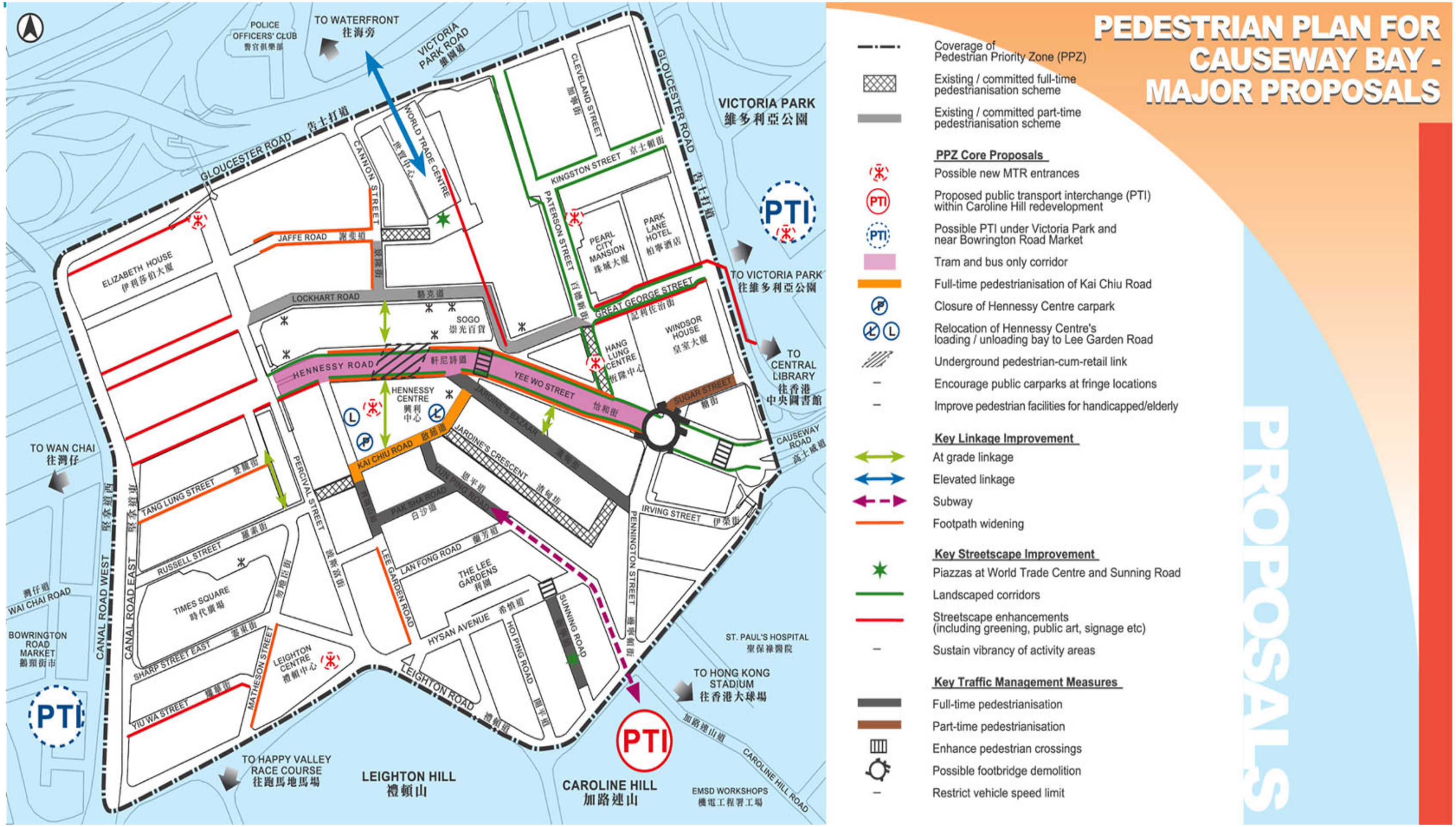


Figure B.2 Proposed pedestrian priority zone at Causeway Bay

The core proposals of the PPZ involve:

a) Proposed public transport interchange (PTI) within Caroline Hill redevelopment – includes redevelopment of the existing Electrical and Mechanical Services Department workshops and adjoining Government sites to cater for franchised buses, Green Mini Buses (GMB) and taxis;

b) Possible PTI under Victoria Park and near Bowrington Road Market – the Victoria Park PTI located on the eastern side of Causeway Bay could be used to curtail the bus routes coming from the east and truncate cross-harbour routes. This PTI also could be used to accommodate all types of public transport services terminus, passenger setting down and picking up bays and public car park spaces. The Bowrington Road Market PTI located to the west of Causeway Bay could be used to curtail buses and GMBs coming from the Southern District;

c) Six possible new MTR entrances – to enhance access to the railway and reduce reliance on cars. The new entrances (see Figure B.2) would also provide an alternative weather protected route for movements in Causeway Bay;

   - New entrance at the basement of the Leighton Centre;
   - New entrance at Hennessy Centre at Lee Garden Road;
   - New entrance outside Hang Lung Centre at Paterson Street;
   - New entrance at the junction of Paterson Street/Kingston Street;

- New entrance at the junction of Percival Street/Gloucester Road; and
- New entrance at the long term possible PTI at Victoria Park.

d) Tram and bus only corridor – convert the section of Hennessy Road/Yee Wo Street (Percival Street to Pennington Street) into a "Tram and bus only corridor" as shown in Figure B.3. With traffic diversion and bus restructuring, a tram lane plus one traffic lane for buses would be maintained along this section in both directions to minimal public transport services;

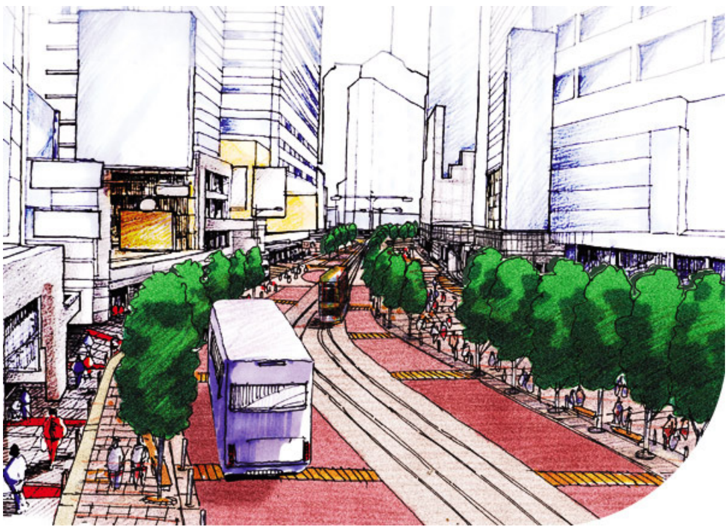


Figure B.3 Proposed tram and bus only corridor at Hennessy Road in Causeway Bay

e) Full-time pedestrianisation of Kai Chiu Road – Kai Chiu Road (see Figure B.4) is the main pedestrian corridor from Sogo to Times Square, two key pedestrian attractors in Causeway Bay. At peak time, pedestrian flows (two directions) reach 13,000 persons/hour;

Before **After**

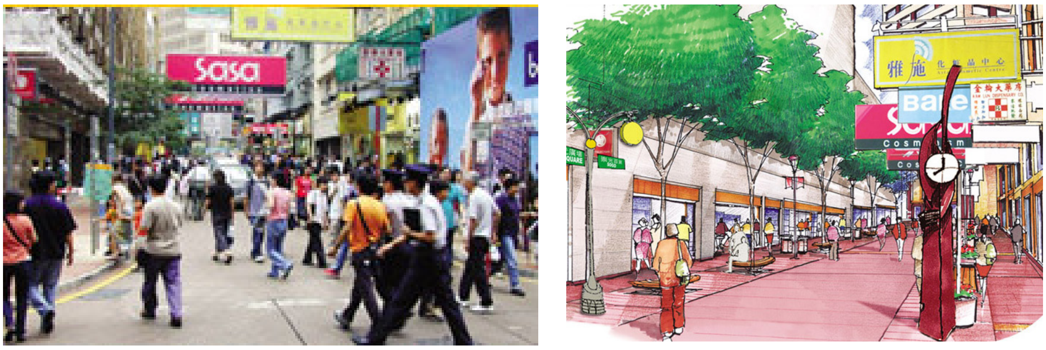


Figure B.4 Kai Chiu Road full-time pedestrian street – before and after

f) Closure of Hennessy Centre carpark – as proposed to pedestrianise Kai Chiu Road on a full-time basis, this would require the closure of the carpark at Hennessy Centre;

g) Relocation of Hennessy Centre's loading/unloading bay to Lee Garden Road – as proposed to pedestrianise at Kai Chiu Road on a full-time basis and the closure of Hennessy Centre carpark, this would also require the relocation of Hennessy Centre's loading/unloading bay to Lee Garden Road; and

h) Underground pedestrian-cum-retail link – preferably to connect Hennessy Centre, Sogo and the MTR Stations as Figure B.5. This link will relieve the congestion and integrate the existing retail facilities on the both sides of Hennessy Road.

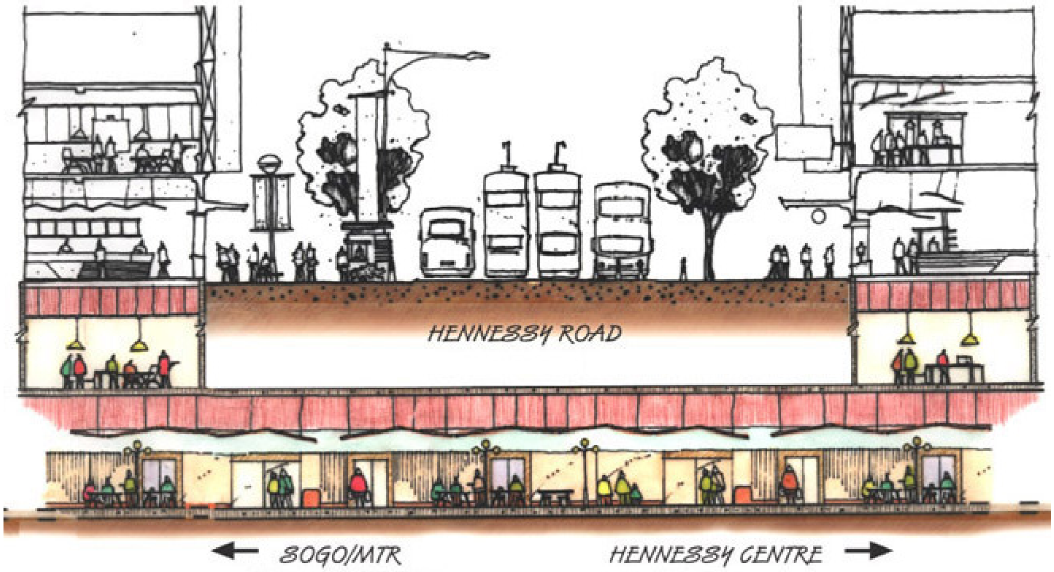


Figure B.5 Proposed underground pedestrian-cum-retail link across Hennessy Road

APPENDIX C TRACKING SURVEY

On Friday 5 August 2005, a large-scale survey was conducted at the Causeway Bay study area with the assistance of 70 surveyors. The study area is illustrated in Figure C.1. Two survey periods were chosen, an off-peak period from 14:00 to 16:00 (without PS) and a peak period from 17:00 to 19:00 (with PS). The selection of the survey period was based on the historical passenger data of Causeway Bay Mass Transit Railway (MTR) station provided by the MTR Corporation Limited. It was found that the evening peak period (i.e. 17:00-19:00) was the most congested.

Tracking Survey

Before the commencement of the surveys, a briefing session was given to the surveyors on the same date of the tracking survey (see Figure C.2). The purpose of the briefing session is to provide training to each of the surveyor before they conducted the survey.

Seventy surveyors were divided into 6 tracking groups and 2 observational groups. About eight to nine surveyors were assigned in each group. Four tracking groups were allocated with a fixed starting point while the other 2 were free for tracking the pedestrians. Figure C.3 illustrated the locations of the starting point that surveyors were assigned. High pedestrian flows were observed during pilot surveys at several major locations such as the entrances/exits of department store, the entrances/exits of MTR station and etc.

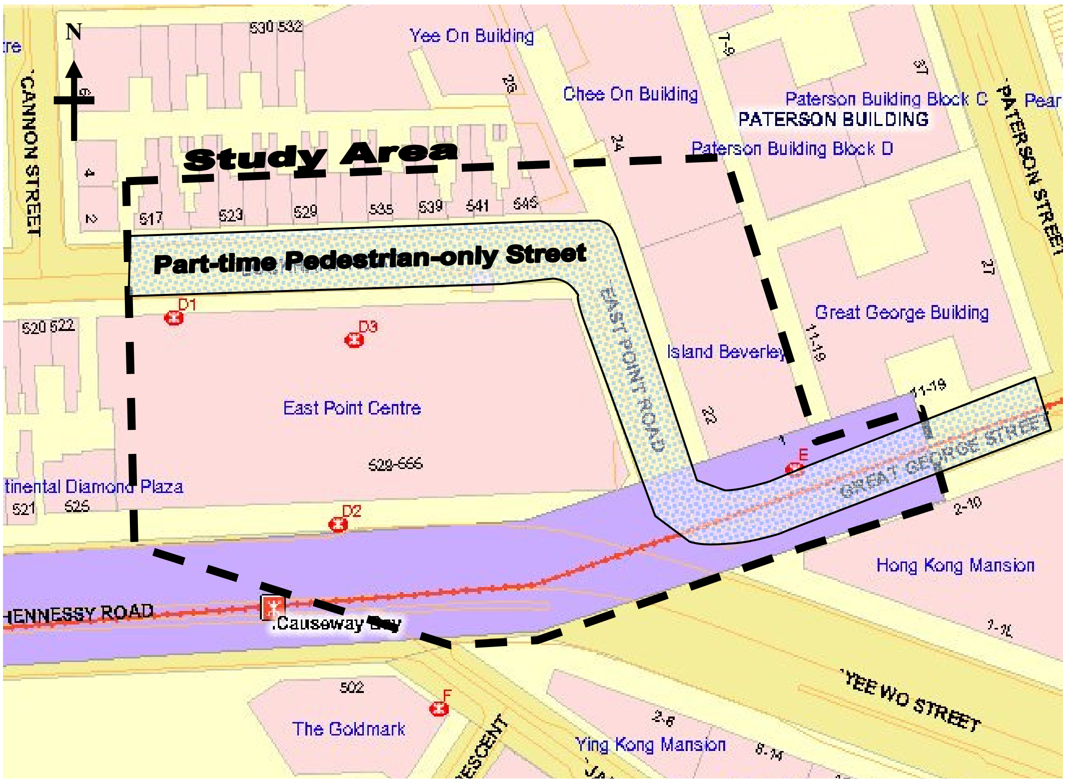


Figure C.1 The study area

Figure C.2 Briefing session on Friday 5 August 2005

Therefore, to ensure adequate data collected from the boundary location with high pedestrian flows, surveyors of four groups were allocated with fixed starting point. Surveyors were required to follow the sampled pedestrians to record their actual walking paths on a given map. A stopwatch and sixty maps were given to each surveyor for recording purposes. They were requested to follow a sample pedestrian or a group of pedestrians who is/are walking within the study area. They were also required to record the following data on the maps: time at origin, origin location, time at destination, destination location, walking path of the sample pedestrian(s), time when sample pedestrian(s) enter or exit the shop(s), party size and gender. By using the tracking survey technique, the patterns of pedestrian origin and destination trip matrices for both periods can be determined.

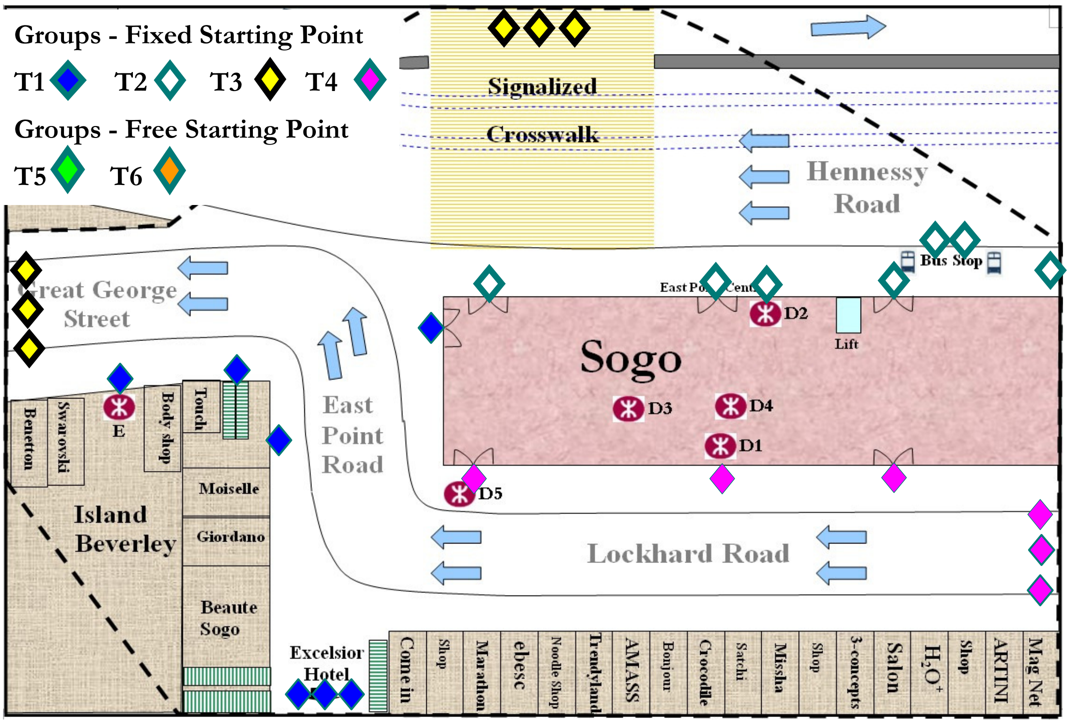


Figure C.3 Locations of the starting points

It should be noted that the synchronization of the surveyors' stopwatches was of prime importance. Moreover, surveyors were advised to keep a distance to the sampled pedestrians as the walking behavior may be varied if the sampled pedestrians knew they were being tracked. In order to ensure the quality of the data collected by the surveyors, a supervisor was assigned to each group. Supervisors were required to supervise their group members during the survey. They were also requested to follow each of their group members and check their data during survey.

Observational Survey

Twenty-two surveyors were assigned two observational groups for the location count and video recording. One group was designated to the major locations and the locations were shown in Figure C.4. A stopwatch and two tally counters were given to each surveyor for the measurement purposes. They were requested to count the total pedestrians crossing in both directions, over 15-minute intervals. Surveyors of one observational group were allocated for video recoding. Seven video cameras were set up at 10 floor of a building simultaneously to record the complex and high pedestrian flow movements at some selected locations. The locations were shown in Figure C.4. This can be minimized the measurement error of surveyors. The videotapes recorded on-site were then further processed by mapping a time code on the video records before data extraction. The time code is encoded in 25 frames per second. Therefore, a precision level of 0.04 second can be achieved. Therefore, the total numbers of pedestrians crossing the selected locations in 15-minute intervals can be extracted in the laboratory from the video records. Screenline counts were taken in two major locations to gather sufficient data for calibration of pedestrian OD trip matrices. By using location count and video recording techniques, the walking trips generated from and attracted to each major location can be determined.

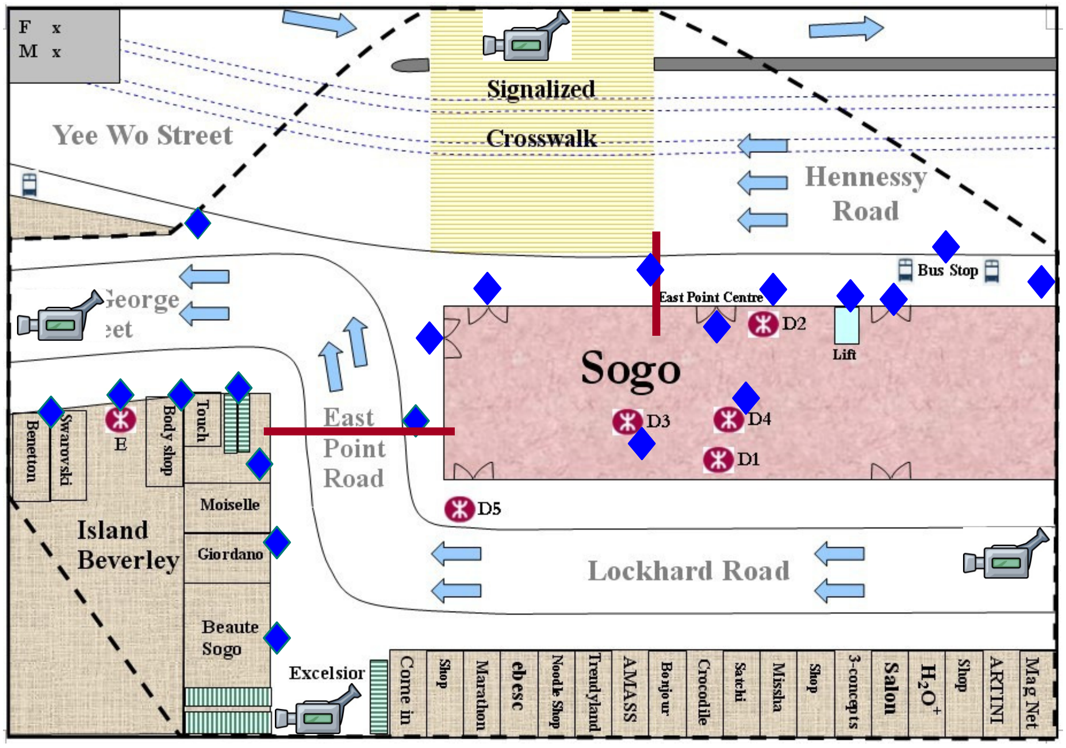


Figure C.4 Locations of the surveyors for the observational survey

Data Analysis by Demographic Factors

Based on the data collected from the tracking survey, preliminary analysis had been carried out to determine whether there was any variation in the analysis based on different sub-samples of the survey (e.g. gender, party size, etc.). The observed gender distributions from the data collected on-site is illustrated in Figure C.5.

In Figure C.5, the gender distribution is divergent. At each period, on average, about 60% of pedestrians who passed through the study area are female and 40% of them of male. The gender distributions by time periods are quite close. This can be partially explained by the fact that the chosen study area – Causeway Bay is a congested urban area with mixed land uses (i.e. commercial and shopping). Many female are attracted to the study area for shopping.

Figure C.6 shows the distribution by party size. Majorities of the pedestrians attracted to the study area are an individual or a pair. At each time period, on average, it should be noted that no significant difference can be observed from the walking trip distribution by party size except those for pair. The observed frequency of pair during peak period is much more than that during off-peak period. This can be partially explained that during peak period, couples are attracted to the study area for entertainment.

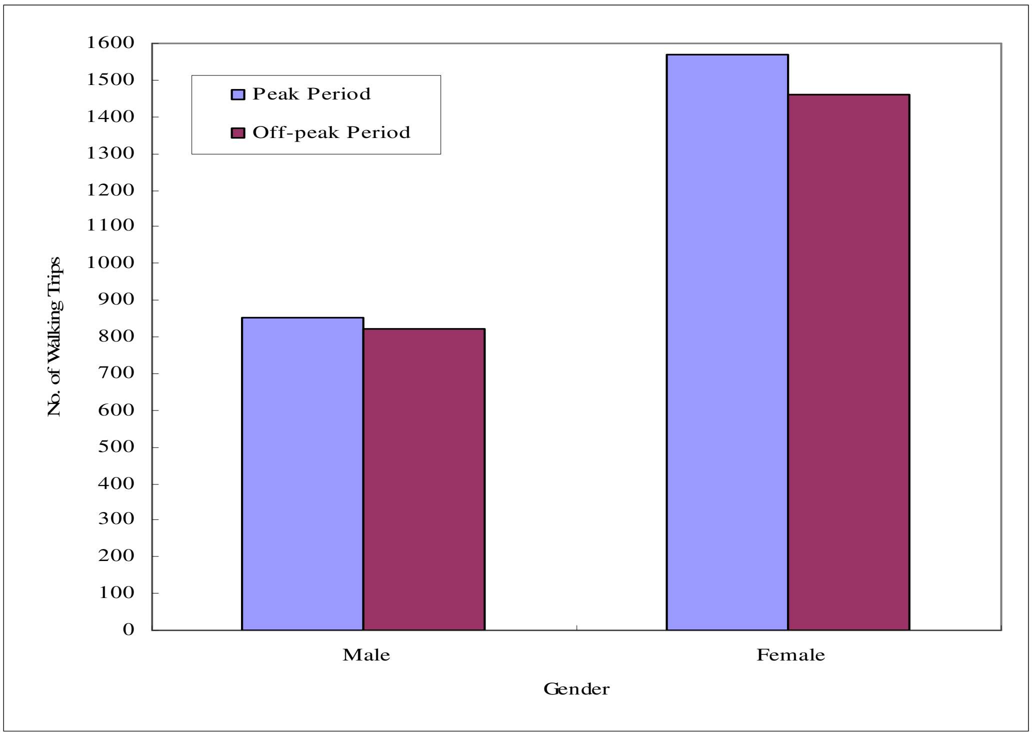


Figure C.5 Observed gender distribution

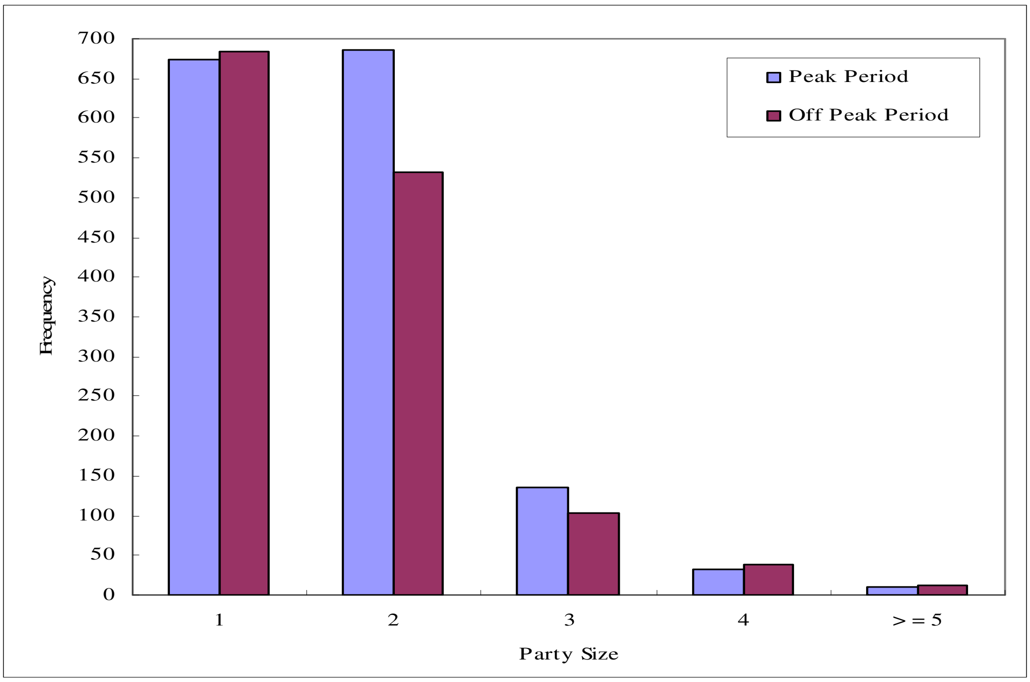


Figure C.6 Observed distribution by party size

Explanatory Factors

The pedestrian activity-destination choice models were developed in Chapter 4 based on two time parameters i.e. relative and absolute time. The choice of the parameters was based on the research works reviewed before the calibration of the models. After the revision of the relevant research works, it would have been interesting to include various other variables such as personal characteristics in the model. Therefore, a number of explanatory factors had been considered and tested during calibration of the pedestrian activity-destination choice models. These factors are summarized as follows:

- Total trip duration
- Walking distance, time & speed
- Origin & destination
- Time at the origin
- Party size
- Gender
- Time period
- The implementation of pedestrian scheme (level of crowding)
- Activity types & activity duration
- Type of shops
- No. of stops
- Floor area of the shops

- Shopping at street level
- Buying goods

The above mentioned explanatory factors are summarized from a number of relevant models that had been reviewed. These relevant models are summarized in the Table C.1. Including some explanatory factors (i.e. the degree of crowding and type of shops) in the models could have led to a more powerful behaviorally based model that would be more amenable to different policy scenarios. Therefore, the above explanatory factors summarized from the literature review had been considered during the calibration process. A number of models for staying or leaving choice, destination choice and shopping choice is calibrated and summarized in the Table C.2, Table C.3 and Table C.4 respectively. However, the effects of the explanatory factors to the models are insignificant. This may be partially explained by the size of study area and study periods.

The size of the chosen study area in this research is small as the length of the measurement section of the chosen study area is about 150 meters. Based on the findings in Chapter 3, the total trip durations (including shopping activities at street-level) of the majority of the pedestrians was less than 3 minutes on average. It is also observed from the data that majority of the number of shops that pedestrians patronized is one only. Moreover, the size of the shops at the street-level is small. The probability that pedestrians will stay long in the street-level shops is low. The total trip durations of pedestrians will have a high chance to be short. This causes the minimal effect of pedestrian activity duration on the total trip duration. Thus, the small area chosen in this study may be one of the reasons that the contribution of the proposed activity approach may be limited.

The two time periods chosen in this research study are 2:00 p.m. - 4:00 p.m. of the off-peak period and 5:00 p.m. - 7:00 p.m. of the peak period respectively. The short time interval may also influence the effects of the activity approach proposed in this study.

Table C.1 Literature review on explanatory factors

Explanatory factors	Zhang et al. (2004)	Lam and Yin (2001)	Srinivasan and Bhat (2005)	Hoogendoorn and Bovy (2004)	Borgers and Timmermans (1986)	Timmermans et al. (1992)	Arentze et al.(2005)
Actual travel time	✓	✓		✓			
Walking distance				✓	✓	✓	
Activity duration			working duration				
Floor area	✓	✓			✓	for clothing only	
Open hours of shopping center	✓						
Annual sale of shopping mall		✓					
Departure time		✓					
Day of week			✓				
No. of stops			□		✓		
Multi-proposes trips						□	✓
Age			✓				
Gender			✓				

Table C.2 Explanatory factors considered in staying or leaving choice model

Model	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Pseudo-R^2	0.0001	0.4956	0.4955	0.4955	0.4955	0.5953	0.5895	0.5928	0.4959	0.4956	0.5928
Explanatory factors included in the model											
Constant	-126.81	-1.58	-2.41	-1.58	-1.53	-18.04	-3.05*	-2.13*	0.50	-3.29*	-3.19*
Relative time	-0.0013	-0.020*	-0.13	-0.13	-0.020*	-0.0052	-0.015*	-0.016*	-0.020*	-0.020*	-0.016*
Absolute time	-0.00039	0.00031	-0.0055	-0.005	0.31	-0.0002	0.12	0.22*	0.0008	-	-
Party size	-0.26	-	-	-	0.034	-	-	-	-	-	-
Pedestrian scheme	-	-0.18	-	-0.18	-0.18	-	-	-	-	-	-
Time period (15 mins)	-	-	-	-	-	-	-	-	-0.075	0.018	0.026*
Time at origin	-	-	0.0056	0.0056	-	-	-	-	-	-	-
Shopping or not	-	-	-	-	-	-	-	-	-	-	-13.01
Shopping time	-	-	-	-	-	-9.28*	-13.30	-13.41	-	-	-
Crossing time	-	-	-	-	-	-9.85	-	-	-	-	-
Waiting time	-	-	-	-	-	-19.19	-14.66	-	-	-	-

Model	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Pseudo-R^2	0.5896	0.5782	0.5758	0.4954	0.4955	0.4955	0.4963	0.4966	0.3170	0.4968	0.4968
Explanatory factors included in the model											
Constant	-3.51*	-3.71*	-4.10*	-3.30*	-3.35*	-3.24*	-10.09*	-12.1*	-4.1*	-2.44*	-3.27*
Relative time	-0.015*	-0.020*	-0.021*	-0.020*	-0.20*	-0.020*	-0.0063	-0.004	-0.014*	-0.20*	-0.020*
Party size	-	-	-	-	-	0.034	-	-0.91	-0.07	-	-
Pedestrian scheme	-	-	-	0.034	0.16	-	-	-	-	-	-
Time period (15 mins)	0.015	0.008	0.016	0.015	-	0.018	-0.16	-0.09	0.022*	-	-
Time period (5 mins)	-	-	-	-	-	-	-	-	-	-	0.007*
Time at origin	-	-	-	-	-	-	-	-	-	0.17*	-
Shopping or not	-13.01	-	-	-	-	-	-13.1	-12.2	-13.0	-	-
Cross or not	-	-	-27.74	-	-	-	-26.8	-25.9	-29.3	-	-
Wait or not	-14.58	-13.80	-	-	-	-	-13.8	-13.3	-	-	-

* Figures are statistically significant at 0.10 level.

Table C.3 Explanatory factors considered in destination choice model

	Model					
	1	**2**	**3**	**4**	**5**	**6**
Pseudo-R^2	0.512	0.198	0.056	0.520	0.521	0.522
Explanatory factors included in the model						
Relative time	0.11*	14.7	19.1	0.12	-	-
Absolute time	0.0012	0.21	-6.4	-	-	0.0013
Shop or not	0.0000	-	-	-	-	-
Distance to destination	-0.0066	-14.6	-	-	0.007	-
Origin	-0.0000	-	-	-	-	-
Constant to the destination	2.19*	1234.1	570.5	0.87	0.21	0.79

* Figures are statistically significant at 0.05 level.

Table C.4 Explanatory factors considered in shopping choice model

	Model					
	1	**2**	**3**	**4**	**5**	**6**
Pseudo-R^2	0.159	0.160	0.159	0.160	0.160	0.160
Explanatory factors included in the model						
Constant	236.47*	238.71*	234.0*	236.0*	241.5*	239.8*
Relative time	0.82*	0.82*	0.82*	0.82*	0.82*	0.82*
Floor Size	-	-0.0006	-	-0.0006	-	-0.0008
Peak/Off Peak	-	-	4.54	5.02	-	4.5
Clothes	-	-	-	-	-91.1	-91.2
Restaurant	-	-	-	-	-27.8	-28.0
Cosmetic	-	-	-	-	-3.8	-4.8
Mall	-	-	-	-	-23.7	56.9
Others	-	-	-	-	-7.5	-8.2

* Figures are statistically significant at 0.05 level.

APPENDIX D OBSERVATIONAL SURVEY

During the observational survey, data was collected using two different measurement methods. They are video recording technique and manual counting method. The method used for data collection is based on the congestion level of the study facility.

For manual counting method, surveyors are assigned to the selected location to count the number of pedestrians passing through the location on-site. A stopwatch and two tally counters were given to each surveyor for measurement purposes. They were requested to count the total pedestrians crossing in both directions, over a time interval. Data collected by this method is costly and labour intensive as a large number of surveyors is required.

For video recording technique, a time-lapse photography technique was adopted. This technique was employed by Cheung (1998) to gather the data for various pedestrian facilities at selected stations for analysis. It has been effectively used for many traffic studies particularly when detail investigation is required. Time-lapse photography has a number of significant advantages. Cheung (1998) had briefly discussed these advantages.

Permanent record can be referred again to obtain additional data. This technique can minimize the measurement errors on-site when the pedestrian flows are heavy and complex. The camera used was a hand-held type video camera. A lightweight tripod was used to support the camera in order to obtain a stable image during data collection. Reference marks by tapes were made on the ground to identify the measurement section.

The choice of the selected locations for observational survey was depended on the crowding condition of the chosen facility. It should be noted that adequate data has to be collected at different flow conditions ranging from free-flow to congested situations. The data to be collected using the observational survey is listed as follow:

1. Pedestrian flows of the chosen facility in two directions (Chapters 3, 4, 5, 6, 7 and 8);
2. Walking time of pedestrian traverse the selected facility (Chapters 5, 6, 7 and 8); and
3. Photographs for illustrating the congestion level of the selected facility (Chapter 9).

As the angle of view of the camera image is limited, therefore, two or more cameras were required to collect the data in some case. The cameras were set in an ideal position of the selected facility. Synchronization of the system time of the cameras is of prime importance before the commencement of the video recording survey. This can provide a same basis for subsequent process and analysis. Data analysis was carried out in the laboratory to extract the required data from the video records.

Data Extraction from the Video Records

Data were extracted from the video records and stored in a computer file. The videotapes recorded on-site were further processed by mapping a time code on the video records before the data extraction. The time code is encoded in 25 frames per second. Therefore, a precision level of 0.04 second can be achieved. A real-time video capture board and a movie-editing package (i.e. Video Studio 7) were used. Therefore, the video records can be displayed on a computer monitor. A sample of the screen dump is illustrated in Figure D.1.

The data extraction was carried out in a semi-automatic process with assistantship of a computer program. This computer program was used as a counting device for data extraction. The system clock of the computer was firstly synchronized with the time code mapped on the video records. Figure D.2 shows a sample of a pedestrian passing through the measurement section of the selected facility. For the pedestrian flow count, the number of pedestrians and the corresponding elapsed time were recorded when the pedestrians passing through the middle line of the pre-determined area of the selected facility. These comprised a flow profile database. Table D.1 shows a sample of flow profile database extracted by using the data extraction program.

Figure D.1 Data extraction by using a video capture program

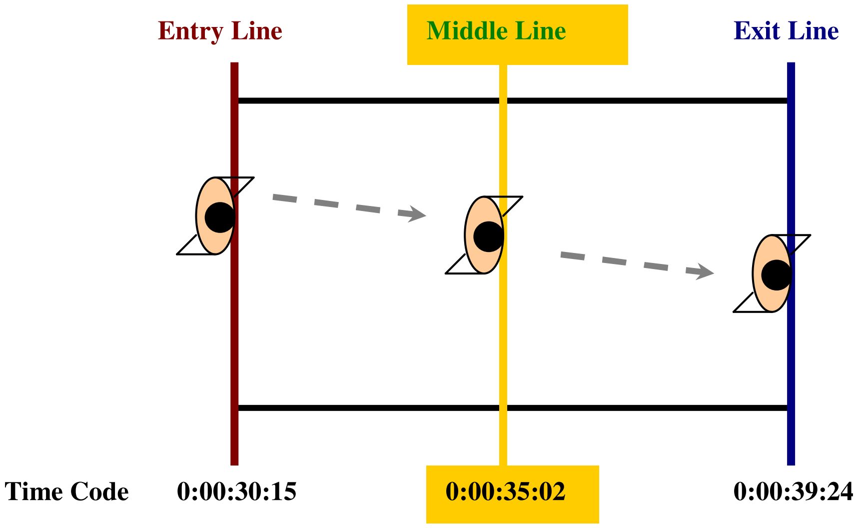


Figure D.2 A sample of a pedestrian passes through the measurement section

For the walking time measurement, a sampling technique was used to collect the walking time at a statistical significant level since it is costly to record all the samples for the survey period. A pedestrian was chosen at 2-second intervals to collect the walking time (Cheung, 1998). The corresponding walking time for a pedestrian to traverse a facility was obtained by considering the entry and exit time of the chosen pedestrian across a measurement section of the selected facility.

Table D.1 A sample of flow profile database

The start time = 0:00:00:00	
rec_no	**hur:min:sec:frame'0-24'**
0001	0:00:01:23
0002	0:00:02:22
0003	0:00:03:01
0004	0:00:03:22
0005	0:00:04:07
0006	0:00:04:09
0007	0:00:05:09
0008	0:00:06:05
0009	0:00:06:09
0010	0:00:06:21
0011	0:00:07:11
0012	0:00:09:11
0013	0:00:09:15
0014	0:00:10:09
0015	0:00:10:24
0016	0:00:11:03
0017	0:00:11:09
0018	0:00:12:13
0019	0:00:13:07
0020	0:00:13:11

It can be seen from Figure D.2, the entry time of this chosen pedestrian is 30 seconds and 15 frames, while the exit time of the chosen pedestrian is 39 seconds and 24 frames. The walking time of this pedestrian is found to be 9.36 seconds as there are 25 frames per second. The corresponding pedestrian flow during this particular time interval can be obtained from the flow profile database by knowing the time of the chosen pedestrian passing through the middle line of the measurement section of the chosen facility. The methodology of matching the walking time with corresponding pedestrian flow is discussed in the following.

Data Analysis

The analysis method of the data extracted from the video records is presented in this section. Three computer programs are written for analysis of the data extracted from the video records so as to compile three types of data such as pedestrian flows, walking time and their corresponding pedestrian flows.

These programs were written using Visual Basic Application (VBA) programming language which is a combination of the programming language - Visual Basic and the database analysis program Microsoft Excel. The extracted data can then be used to calibrate a generalized walking time function which is newly proposed to find the relationship of the walking time against the pedestrian flow and flow ratio. Note that flow ratio is the ratio of one-way pedestrian flow over the total pedestrian flows (two-way).

The 1^{st} computer program was written to generate the pedestrian flow for each minute interval from the flow profile database. The pedestrian flow can then be generated from the 0^{th} second to the 60^{th} second – the 1^{st} minute flow; from the 1^{st} second to the 61^{st} second – the 2^{nd} minute flow and so on. This procedure continues to the last second of the surveyed interval by shifting one second on each occasion. This procedure is shown graphically in Figure D.3. The survey is carried out in a total of N seconds. Therefore, N-59 samples of minute flows can be extracted from the flow profile. Thus, the number of pedestrians passing through the facility for each minute can be compiled.

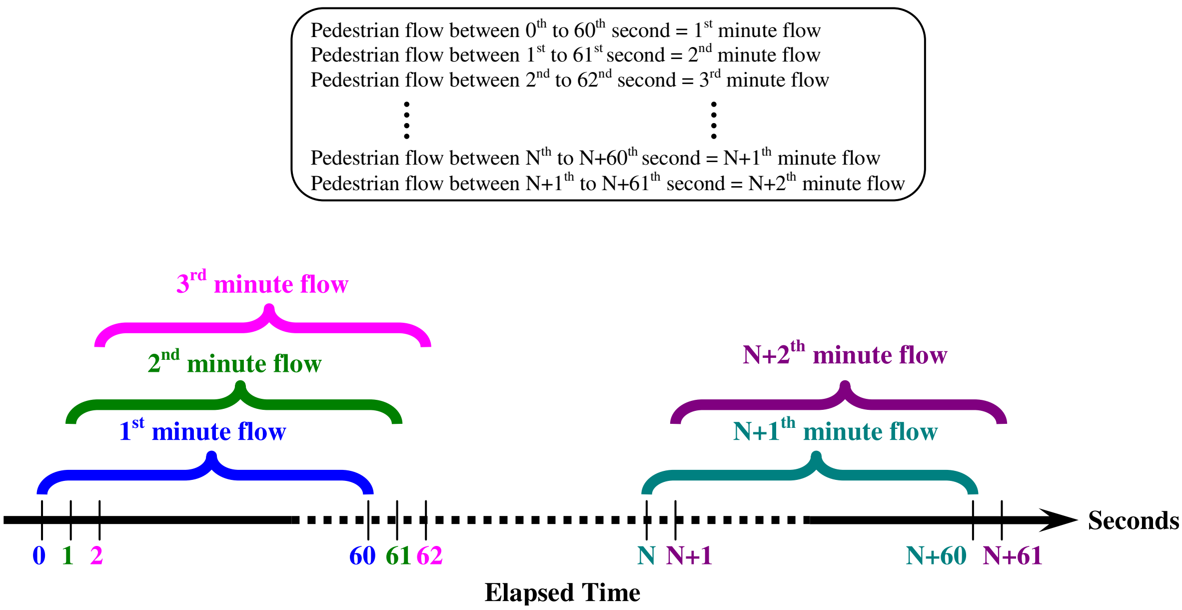
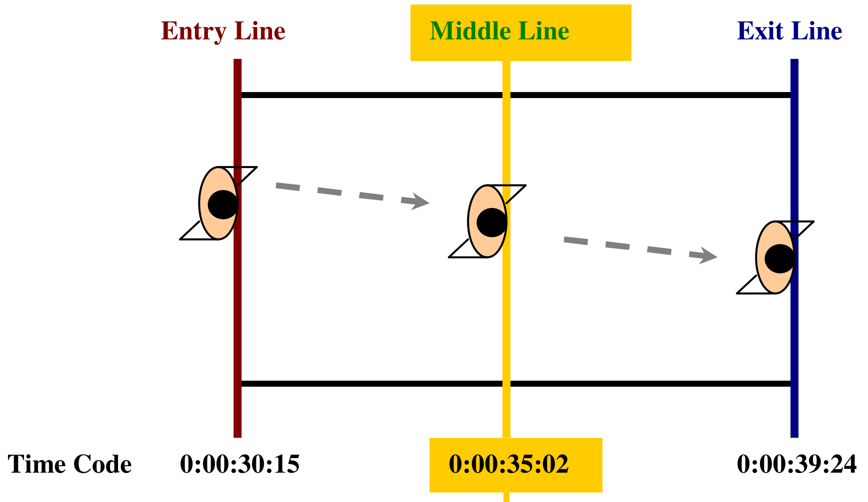


Figure D.3 Measurement of the pedestrian flows

As mentioned, the elapsed time of the chosen pedestrians entry and exit the measurement section can be extracted from the videotapes by using the data extraction program. Therefore, the 2nd computer program was written to derive the walking time for each chosen pedestrian automatically. The pedestrian flow can be obtained from the flow profile database mentioned by knowing the time of a chosen pedestrian passing through the middle line of the selected section of a pedestrian facility. This procedure is described graphically in Figure D.4. The third computer program was written to select the corresponding pedestrian flow from the flow profile database for the chosen pedestrian.

Figure D.4 shows the path of the chosen pedestrian passing through the selected measurement section of a pedestrian facility. The walking time for the particular pedestrian to cross the selected section can be calculated once his/her entry and exit time are known. The pedestrian flow at that particular time interval can be obtained from the flow profile database automatically. The walking time of the chosen pedestrian can be determined when he/she passes through the selected measurement section of a pedestrian facility with corresponding pedestrian flow.



Elapsed Time	Pedestrian Flow
31	50
32	57
33	53
34	51
35	**61**
⋮	⋮
N+29	38
N+30	41

Pedestrian flow profile database

Figure D.4 Measurement of the walking time of the chosen pedestrians and their corresponding pedestrian flows

APPENDIX E STATE PREFERENCE INTERVIEW SURVEY

For the development of the level of service (LOS) standards, the selected pedestrian facility is a crosswalk, which is indicated in Chapter 9. This crosswalk is one of the most congested crosswalks in Hong Kong urban areas. Photographs were taken from the selected crosswalk before the state preference interview survey was carried out. The photographs are taken to present the pedestrian flow conditions at each level of service. Therefore, pedestrians can determine the LOS standards of each level by choosing the photo.

The survey methodology was used to evaluate the qualitative and quantitative factors in the study. The survey is divided into 2 components; the first component is used to obtain the pedestrian rankings of the relative importance of different factors and the second component is used to obtain the congestion boundaries of the pedestrian LOS.

Respondents were asked to indicate the degree of importance of each of the factors listed on the questionnaire during the survey. The degree of importance of each factor is divided into five levels, which are 'Not Important', 'Less Important', 'General', 'Important' and 'Very Important'. The factor "congestion level" was further divided into 6 levels (corresponding to LOS A, B, C, D, E and F) to assess the pedestrian response to the various congestion levels, which formed the second component of the state preference interview survey. The concept of the perceived LOS boundaries employed in Lam and Lee (2001) is similar to those used in the stated preference interview surveys which ask respondents to state their response to a particular situation. The LOS boundary determined in this way is termed the perceived LOS boundary since it is determined based on the pedestrians' perception to differentiate from the subjective LOS boundary obtained from a direct observational measure. The basic approach used a series of photographs depicting different levels of pedestrian flow and congestion. Respondents were then presented with a qualitative description of the quality of flow (similar to those proposed by Fruin, 1970) and asked to state the photograph where they felt the qualitative description was no longer true. In effect, the respondents' choice represented the lower boundary for a particular LOS.

State Preference Interview Survey – 1st Pilot Survey

The 1st pilot survey was carried out on a typical Monday 5 Jan 2004 to determine the number of important factors needed to involve in the questionnaire. Eighteen qualitative factors are firstly proposed by taking reference from the qualitative factors defined by Henson (2000) for pedestrian signalized crosswalks and by Sarker (1993) for pedestrian facilities. These factors are length of crosswalk, air quality, presence of fencing, solitary location, congestion level, pedestrian waiting time for crossing, presence of trees/shrubs, footbridge or subway provided, habituate to use, time for crossing carriageway, width of crosswalk, noise quality, size of stagger block/mid-block, lighting in crosswalk, walking distance to crosswalk, degree of weather protection, surface condition of crosswalk and green time for pedestrian signal.

Thirty respondents were asked to indicate the level of importance of each of the eighteen factors on the questionnaire during the 1st pilot survey. Five levels of importance were set from "Not Important" to "Very Important". After the 1st pilot survey was carried out, eight most important factors were sorted out based on the perception and suggestion of the respondents. They are pedestrian red time (waiting time), pedestrian green time (crossing time), length of crosswalk, presence of countdown device, trip purpose, pedestrians (surrounding) cross the crosswalk, number of pedestrians in the same direction and number of pedestrians in the opposing direction.

State Preference Interview Survey – 2nd Pilot Survey

The 2nd pilot survey was carried out on a typical Friday 9 Jan 2004 to determine the hypothetical scenarios needed to involve in the questionnaire. It was found in Lam and Lee (2001) and Lam et al. (2002) that walking speeds are not affected by the pedestrian flow in the oncoming crowd when the pedestrian flow on the facility is low. Therefore, several hypothetical scenarios were set with different congestion levels and flow ratios in the questionnaire for the 2nd pilot survey.

A series of photographs was shown to the respondents depicting different levels of pedestrian flow and congestion for each scenario. Thirty respondents were then presented with a qualitative description of the quality of flow (similar to those proposed by Fruin, 1987) and asked to differentiate the photograph where they felt the qualitative description was no longer true.

It was found that some scenarios can be eliminated as the results of these scenarios can be interpolated. For example: when the LOS standards under flow ratio 0.1 and 0.3 are revealed from the respondents' perception. Then, the LOS standards under flow ratio 0.2 can be interpolated by those under flow ratios 0.1 and 0.3. Therefore, hypothetical scenarios for asking the LOS standards under flow ratio 0.2 can be eliminated.

After the 2nd pilot survey was carried out, four flow ratios (i.e. 0.1, 0.3, 0.5 and 1.0) were selected to investigate in the main survey. Three hypothetical scenarios were set for each flow ratio of 0.1, 0.3 and 0.5 while five were set for flow ratio 1.0. Six photographs were shown to the respondents depicting different congestion levels for each scenario. An independent set of data was collected so as to validate the calibration results of the LOS standards. Five hypothetical scenarios were set for each flow ratio of 0.2 and 0.8 for validation.

State Preference Interview Survey – Main Survey

The purpose of conducting the main survey is to gain the pedestrian perceptions on the crosswalks. In order to determine the LOS standards from the responses of the pedestrians, main surveys were scheduled to be carried out. The survey schedule is shown in Table E.1. Pedestrians were asked to interview after they traversed the crosswalk. In total, 758 pedestrians were successfully interviewed and asked for their responses on various questions listed on the questionnaire.

Table E.1 Survey Schedules

Date	Time Period	No. of Pedestrians Interviewed	Flow Ratio illustrated in the Photos
15 Jan 2004 (Thu) 29 Jan 2004 (Thu)	10:00-18:00	131	0.1
28 Jan 2004 (Wed)	10:00-18:00	100	0.3
14 Jan 2004 (Wed)	10:00-18:00	122	0.5
1 Dec 1999 (Wed) 8 Dec 1999 (Wed) 15 Dec 1999 (Wed) 22 Dec 1999 (Wed)	10:00-18:00	225	0.6
14 Jan 2004 (Wed) 18 Feb 2004 (Wed)	10:00-18:00 14:00-19:00	100	1.0
17 Feb 2004 (Tue)	14:00-19:00	40	0.2
16 Feb 2004 (Mon) 19 Feb 2004 (Thu)	14:00-19:00	40	0.8

The questionnaire used in the main survey is shown in Appendix F. It includes the following three parts:

Part 1: Levels of importance of factors. Pedestrians were asked to rate the levels of importance of the factors affecting their crossing decision. Six important factors were identified from the various pilot surveys. These factors are pedestrian red time (waiting time), pedestrian green time (crossing time), length of crosswalk, presence of countdown device, number of pedestrians in the same direction and number of pedestrians in the opposing direction.

Part 2: Upper acceptance limit of congestion levels. Several hypothetical scenarios were set with different congestion levels and flow ratios. A series of photographs was shown to the respondents depicting different levels of pedestrian flow and congestion for each scenario. Respondents were then presented with a qualitative description of the quality of flow and asked to differentiate the photograph where they felt the qualitative description was no longer true. Therefore, the upper acceptance limit for a particular LOS was revealed from the respondents' responses.

Part 3: Personal information. Demographic information, such as gender, age group and income range, was requested. Respondents were also asked to report if they will use the carriageway nearby while the pedestrian signal light is red.

State Preference Interview Survey – Data Analysis

Based on the data collected from the state preference interview survey, preliminary analysis had been carried out to determine whether there was any variation in the calculation of Equation 9.1 based on different sub-samples of the survey (e.g. gender, age, etc.). The observed age distributions from the data collected on-site is illustrated in Figure E.1.

In Figure E.1 and Table E.2, the distribution age is divergent. At each 15-minute period, on average, majorities of pedestrians (i.e. over 90%) passed through the study area with their age 20 to 50 years old. Only about 5% of the pedestrians are younger than 20 years old and older than 50 years old. This can be partially explained by the fact that the chosen signalized crosswalk is located at a congested urban area with mixed land uses (i.e. commercial and shopping). Therefore, the survey data were normalized to account for the variations in the respondent age (<20 years; 20-50 years; >50 years) and gender using the observed pedestrian proportion at the site.

Figure E.2 shows that the distribution of male and female is fairly close. At each 15-minute period, on average, there is about 54% of male and 46 % of female in the study area. The difference is about 8% only. Moreover, Table E.3 shows the perceived upper acceptance limits of each LOS by gender. It should be noted that no significant difference can be observed from the upper acceptance limits perceived by the male and female respondents.

Table E.2 Observed age and gender distribution

Statistics in 15min Intervals			Count by Age and Gender			% by Age and Gender		
Start time	**End time**	**Gender**	**<20**	**20-50**	**>50**	**<20**	**20-50**	**>50**
		Male	24	552	55	2%	50%	5%
17:30	17:45	Female	25	423	27	2%	38%	3%
		Total	49	975	82	4%	**88%**	8%
		Male	31	491	50	3%	46%	5%
17:45	18:00	Female	25	449	21	2%	42%	2%
		Total	56	940	71	5%	**88%**	7%
		Male	39	614	49	3%	45%	4%
18:00	18:15	Female	11	645	17	1%	46%	1%
		Total	50	1259	66	4%	**91%**	5%
		Male	34	696	51	2%	46%	3%
18:15	18:30	Female	32	669	21	2%	46%	1%
		Total	66	1365	72	4%	**92%**	4%
		Male	27	684	52	2%	47%	4%
18:30	18:45	Female	17	664	7	1%	46%	0%
		Total	44	1348	59	3%	**93%**	4%
		Male	8	562	28	1%	49%	2%
18:45	19:00	Female	14	518	7	1%	46%	1%
		Total	22	1080	35	2%	**95%**	3%

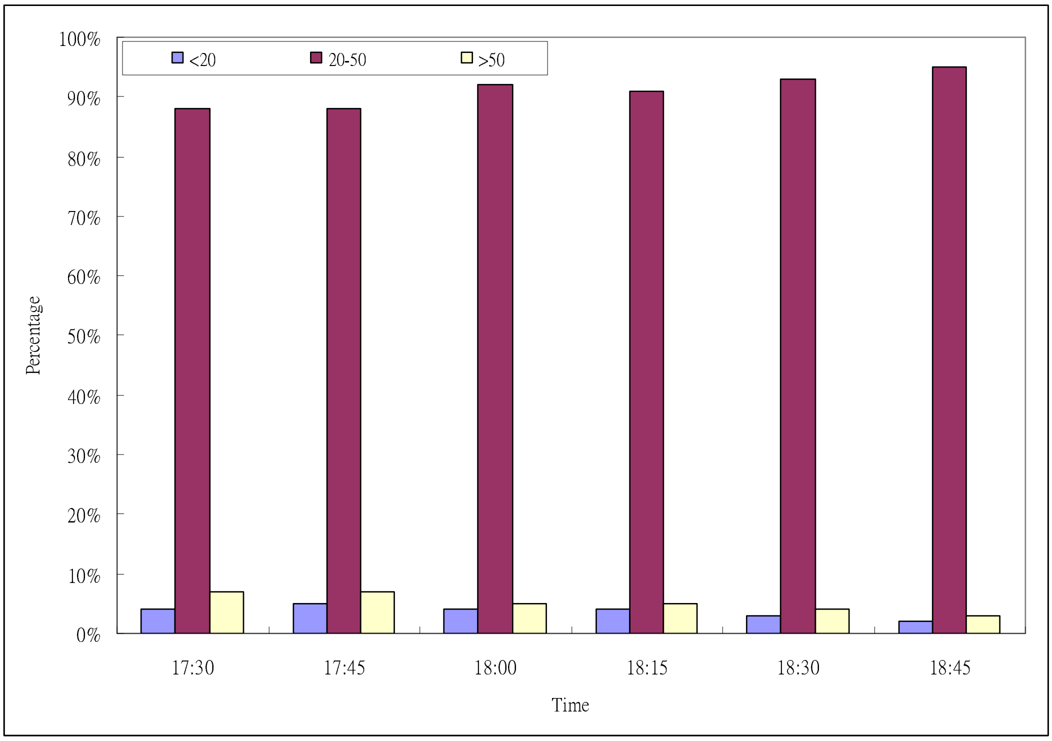


Figure E.1 Observed age distribution

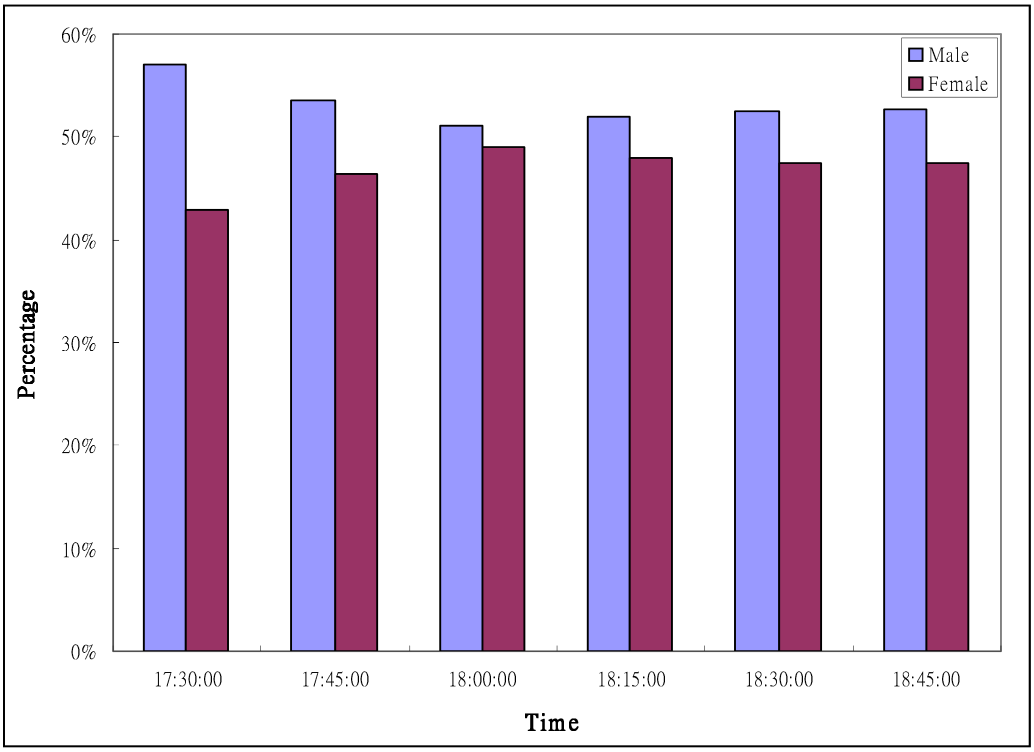


Figure E.2 Observed gender distribution

Table E.3 Upper acceptance limits by gender

Flow (ped/m/min)	Flow Ratio 1.0		0.5		0.3		0.1	
	Female	Male	Female	Male	Female	Male	Female	Male
LOS A	20.3	20.8						
LOS B	34.1	35.6						
LOS C	48.9	49.2	48.1	49.2	46.6	45.3	41.6	41.9
LOS D	63.8	63.7	62.7	62.9	59.8	60.0	54.0	53.6
LOS E	73.8	73.1	72.3	73.0	69.2	68.6	62.4	62.0

Area Occupancy (m^2/ped)	Flow Ratio 1.0		0.5		0.3		0.1	
	Female	Male	Female	Male	Female	Male	Female	Male
LOS A	3.92	3.73						
LOS B	2.22	2.11						
LOS C	1.48	1.46	1.42	1.40	1.44	1.41	1.40	1.38
LOS D	0.82	0.80	0.81	0.81	0.83	0.82	0.88	0.79
LOS E	0.54	0.52	0.53	0.52	0.51	0.53	0.52	0.52

Walking Speed (m/min)	Flow Ratio 1.0		0.5		0.3		0.1	
	Female	Male	Female	Male	Female	Male	Female	Male
LOS A	75.3	75.5						
LOS B	73.8	74.0						
LOS C	66.5	66.7	66.4	66.6	65.5	66.8	65.2	64.9
LOS D	50.6	50.9	50.5	50.8	49.6	49.3	47.2	47.9
LOS E	37.3	38.2	37.4	37.7	35.5	36.4	32.7	33.3

APPENDIX F QUESTIONNAIRE FOR STATE PREFERENCE INTERVIEW SURVEY

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

QUESTIONNAIRE – PEDESTRIAN PERCEPTION AT CROSSWALKS

Part 1: Point out the importance of each factor.

Factors affecting your crossing decision Please "✓" 1 box	Not Important 1	2	General 3	4	Very Important 5
1. Waiting time to cross	☐	☐	☐	☐	☐
2. Green crossing time	☐	☐	☐	☐	☐
3. Length of crosswalk	☐	☐	☐	☐	☐
4. Presence of countdown device	☐	☐	☐	☐	☐
5. No. of pedestrians (same direction)	☐	☐	☐	☐	☐
6. No. of pedestrians (opposite direction)	☐	☐	☐	☐	☐

Part 2: Match Description Keywords to photographs in PowerPoint.

	Description Keywords	Same Direction Flow %	"✓" Photograph with closest match 1	2	3	4	5
Case A	1. Walk without stopping 2. Difficult to overtaking 3. May have conflict when crossing	50%	☐	☐	☐	☐	☐
		10%	☐	☐	☐	☐	☐
Case B	1. May stop momentarily 2. Very difficult to overtake 3. A few conflicts when crossing	50%	☐	☐	☐	☐	☐
		10%	☐	☐	☐	☐	☐
Case C	1. Frequently stop and wait 2. Cannot overtake 3. Many conflicts when crossing	50%	☐	☐	☐	☐	☐
		10%	☐	☐	☐	☐	☐

Part 3: Please Tell Us about Yourself

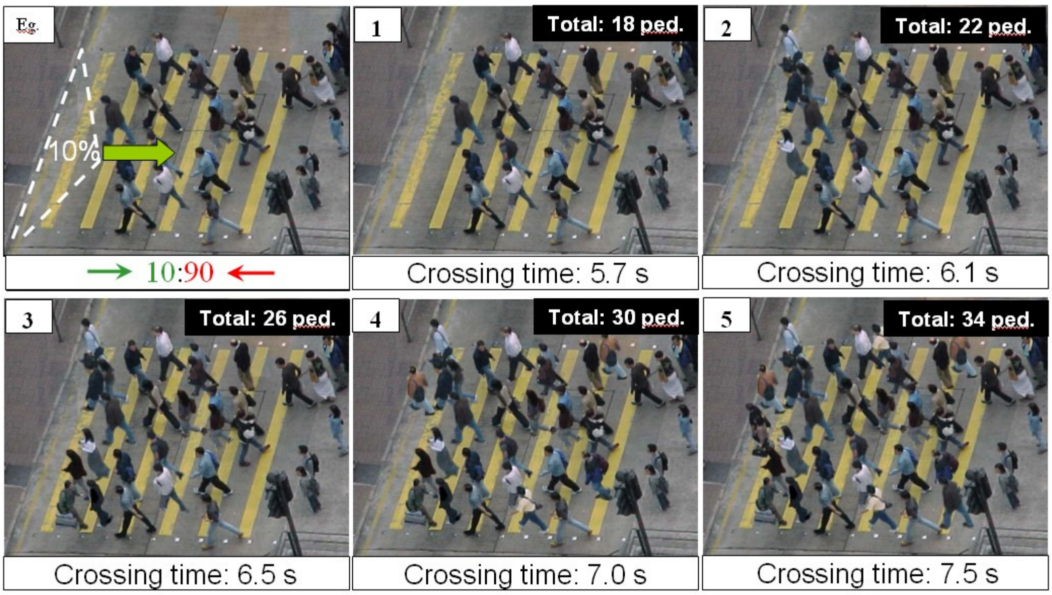
Gender: Male ☐ Female ☐ Age Group: < 20 ☐ 20-24 ☐ 25-39 ☐ 40-49 ☐ 50-59 ☐ >60 ☐

Will you cross the carriageway while the pedestrian signal light is red? Yes ☐ No ☐

Monthly income range:
<$3000 ☐ $3-$5000 ☐ $6-$9000 ☐ $10-$14000 ☐ $15-$19000 ☐ $20-$24000 ☐ $25-$34000 ☐ >$35000 ☐

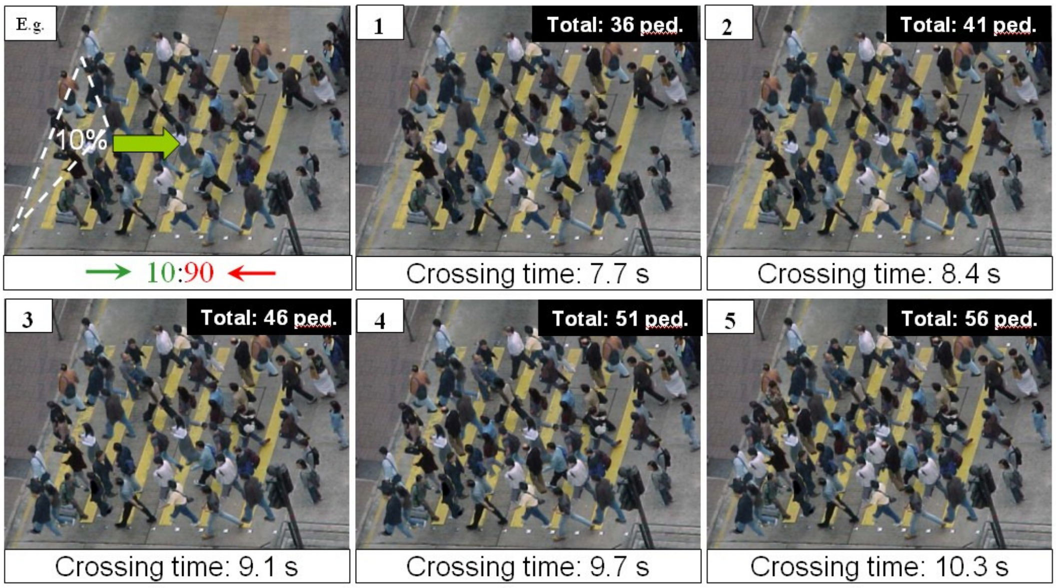
Case A - 10:90

1) Walk **without** stopping 不需要停步
2) **Difficult** to overtake 困難地繞過其他人
3) **May have** conflict when crossing 可能與其他人碰撞



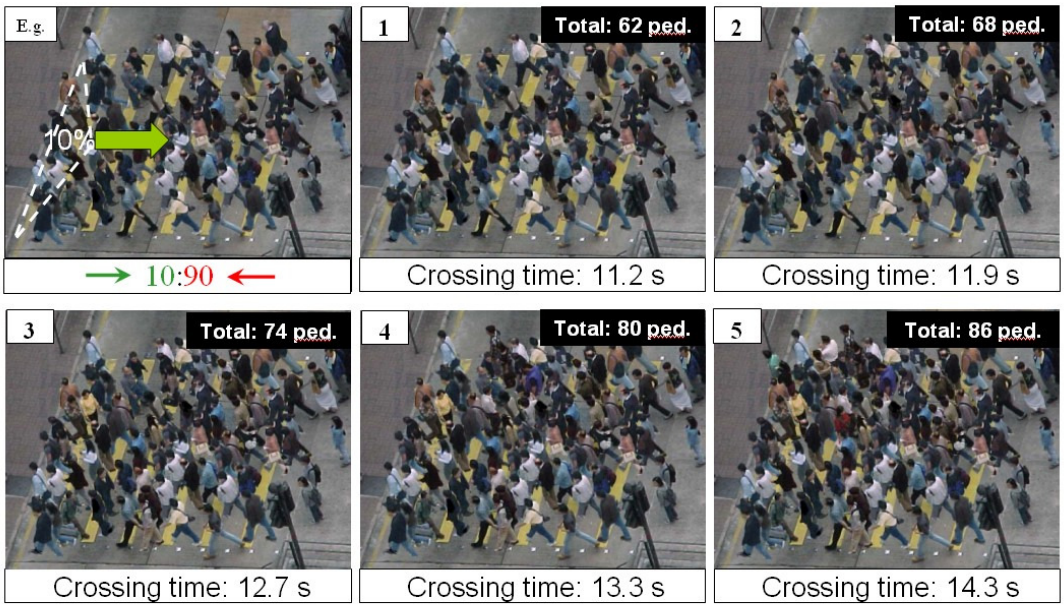
Case B - 10:90

1) May stop **momentarily**有時需要停步
2) **Very difficult** to overtake 很困難地繞過其他人
3) **Few** conflicts when crossing 與其他人有少許碰撞



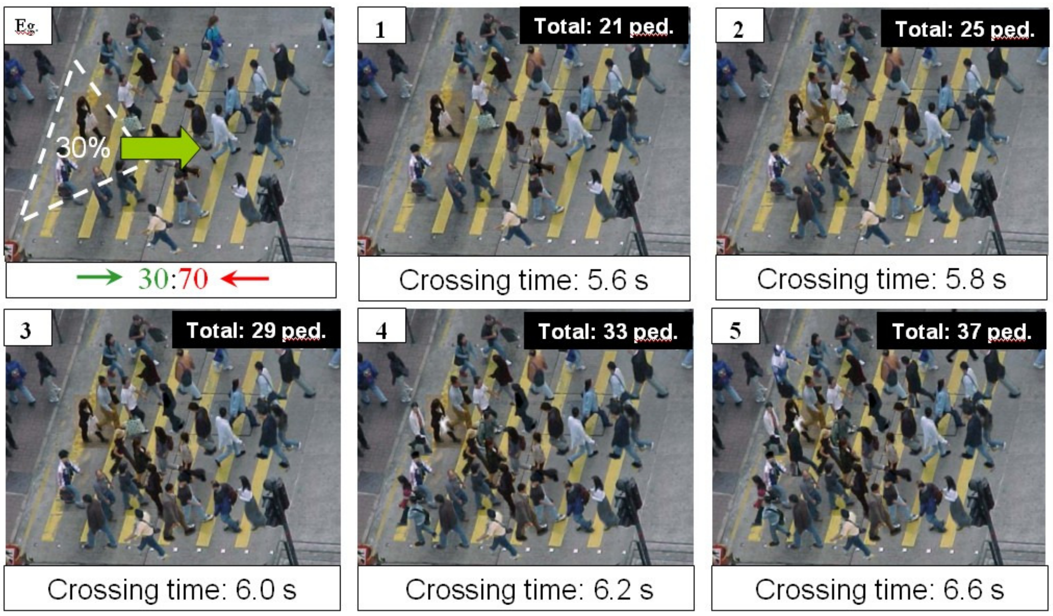
Case C - 10:90

1) **Frequently** stop and wait 經常需要停步及等候
2) **Cannot** overtake 不可能繞過其他人
3) **Many** conflicts when crossing 經常與其他人碰撞



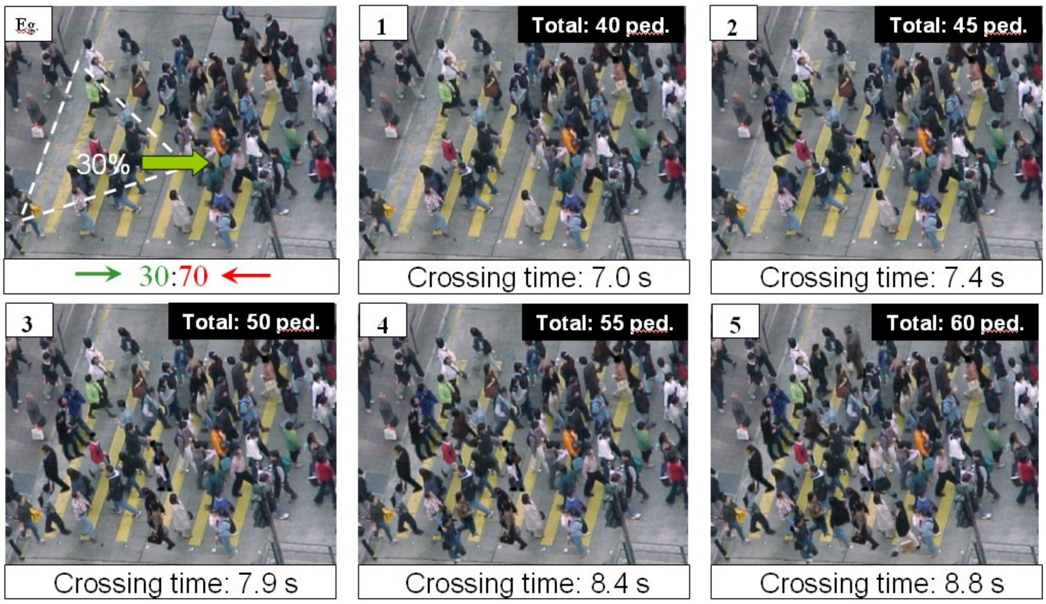
Case A - 30:70

1) Walk **without** stopping 不需要停步
2) **Difficult** to overtake 困難地繞過其他人
3) **May have** conflict when crossing 可能與其他人碰撞



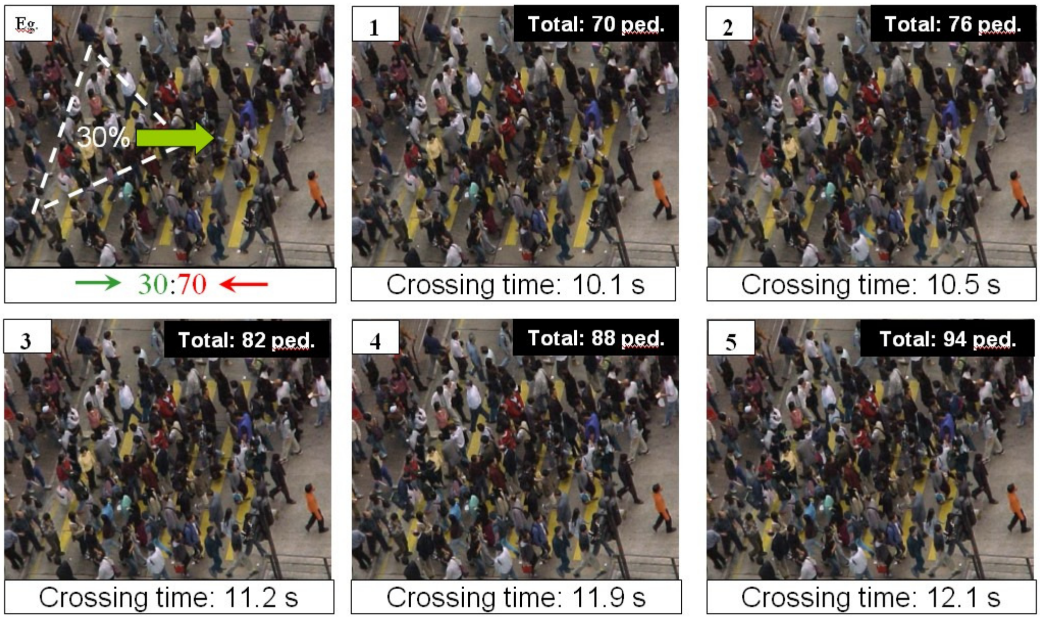
Case B - 30:70

1) May stop **momentarily**有時需要停步
2) **Very difficult** to overtake 很困難地繞過其他人
3) **Few** conflicts when crossing 與其他人有少許碰撞



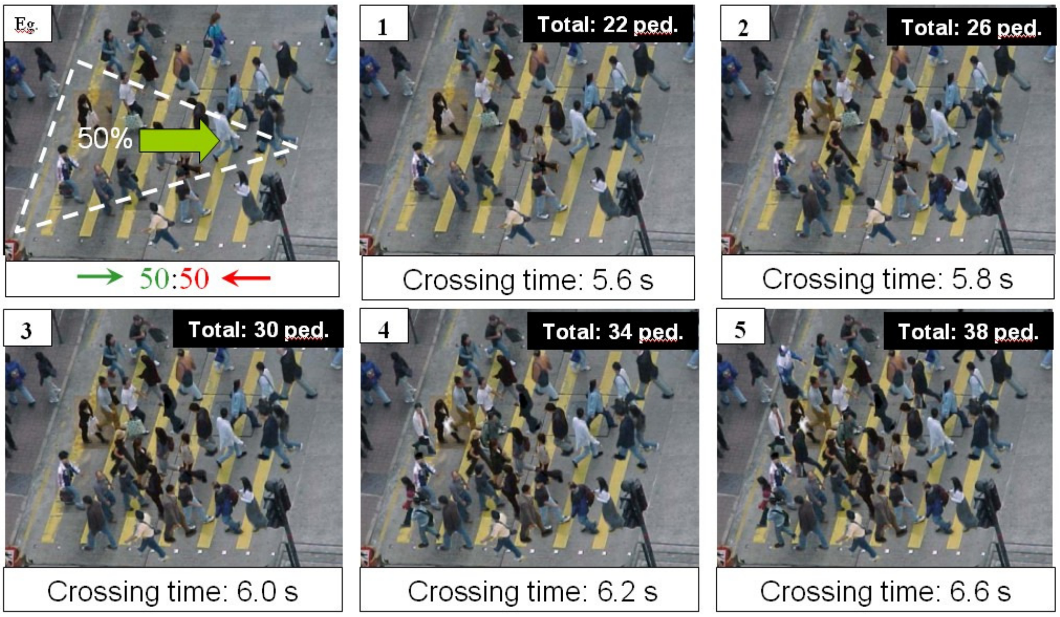
Case C - 30:70

1) **Frequently** stop and wait 經常需要停步及等候
2) **Cannot** overtake 不可能繞過其他人
3) **Many** conflicts when crossing 經常與其他人碰撞



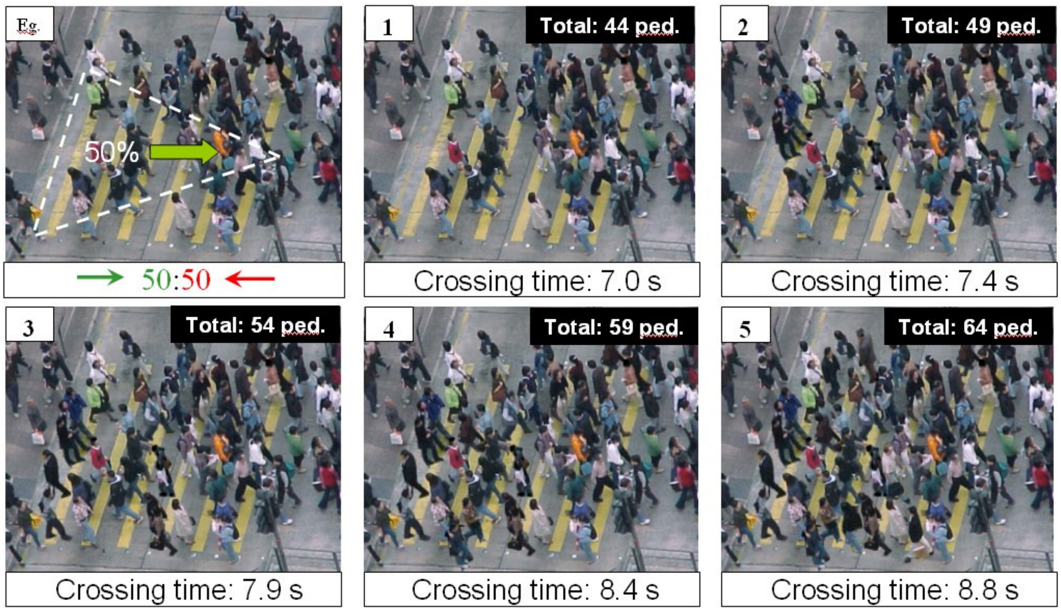
Case A - 50:50

1) Walk **without** stopping 不需要停步
2) **Difficult** to overtake 困難地繞過其他人
3) **May have** conflict when crossing 可能與其他人碰撞



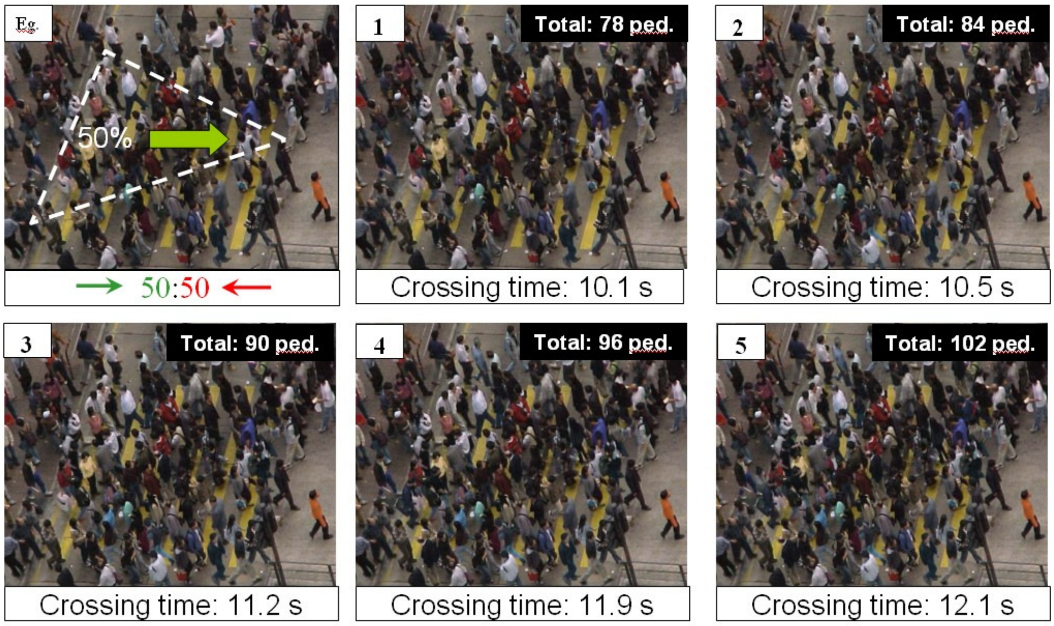
Case B - 50:50

1) May stop **momentarily**有時需要停步
2) **Very difficult** to overtake 很困難地繞過其他人
3) **Few** conflicts when crossing 與其他人有少許碰撞



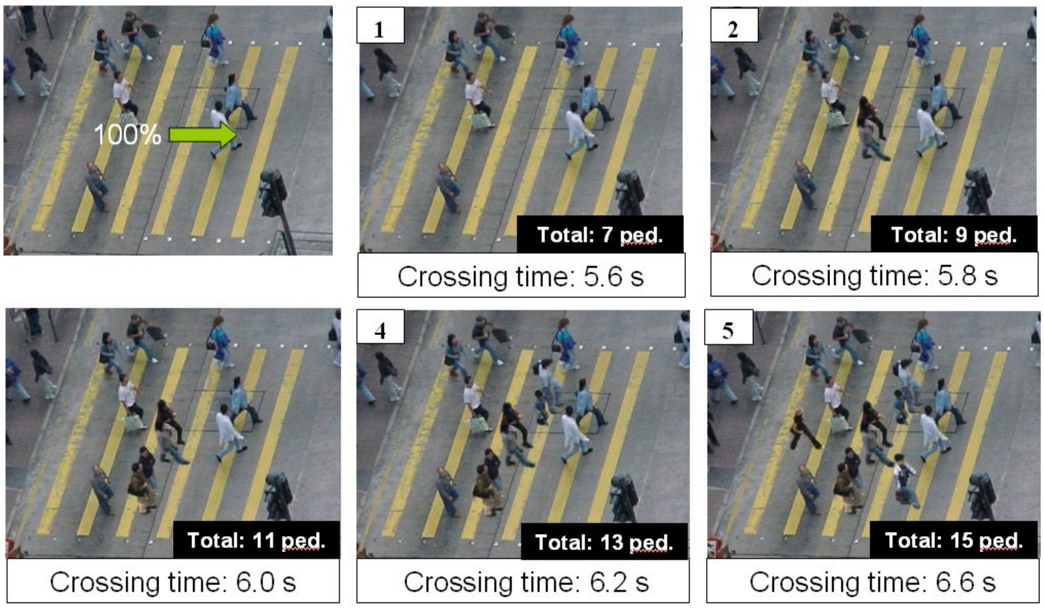
Case C - 50:50

1) **Frequently** stop and wait 經常需要停步及等候
2) **Cannot** overtake 不可能繞過其他人
3) **Many** conflicts when crossing 經常與其他人碰撞



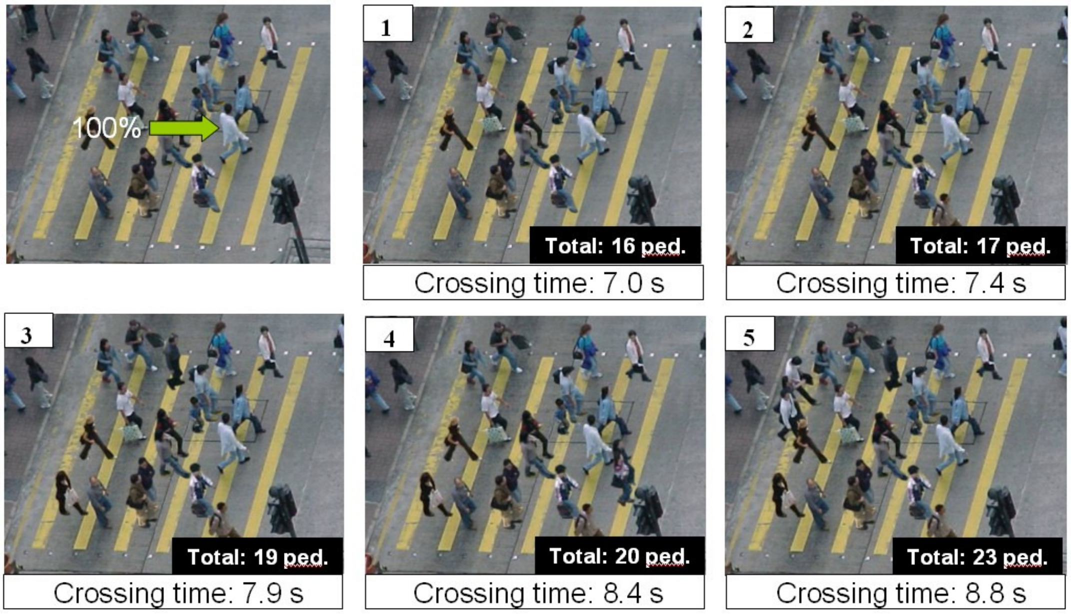
Case A

1) **Free** to chose walking speed 步行速度隨意選擇
2) **No problem** overtaking很容易繞過其他人
3) No conflict when crossing 不會與其他人有碰撞



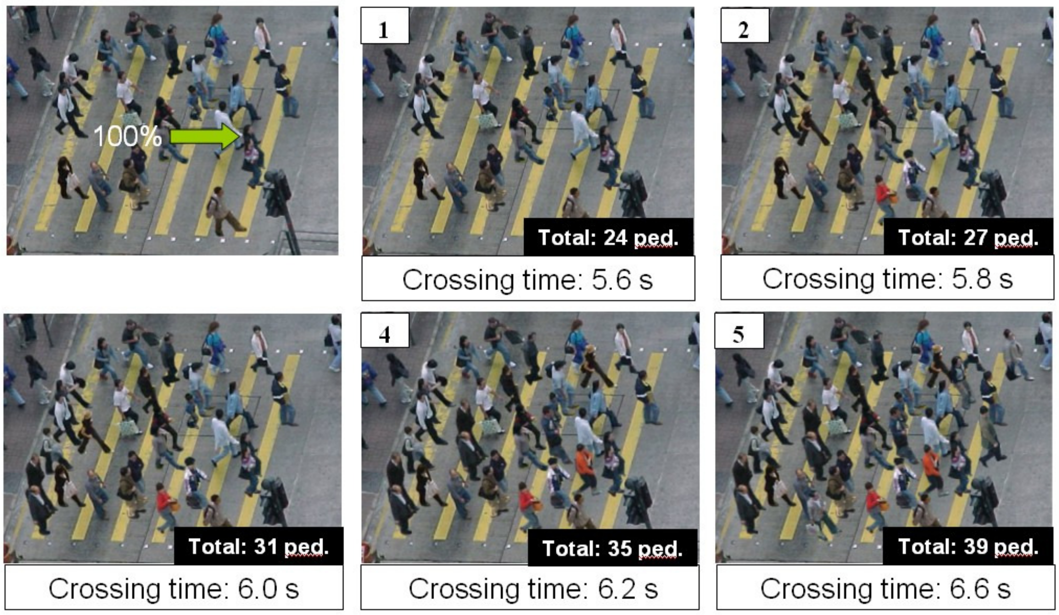
Case B

1) **Slight** restriction of walking speed 步行速度有少許限制
2) **Easy** to overtake 容易繞過其他人
3) No conflicts when crossing不會與其他人有碰撞



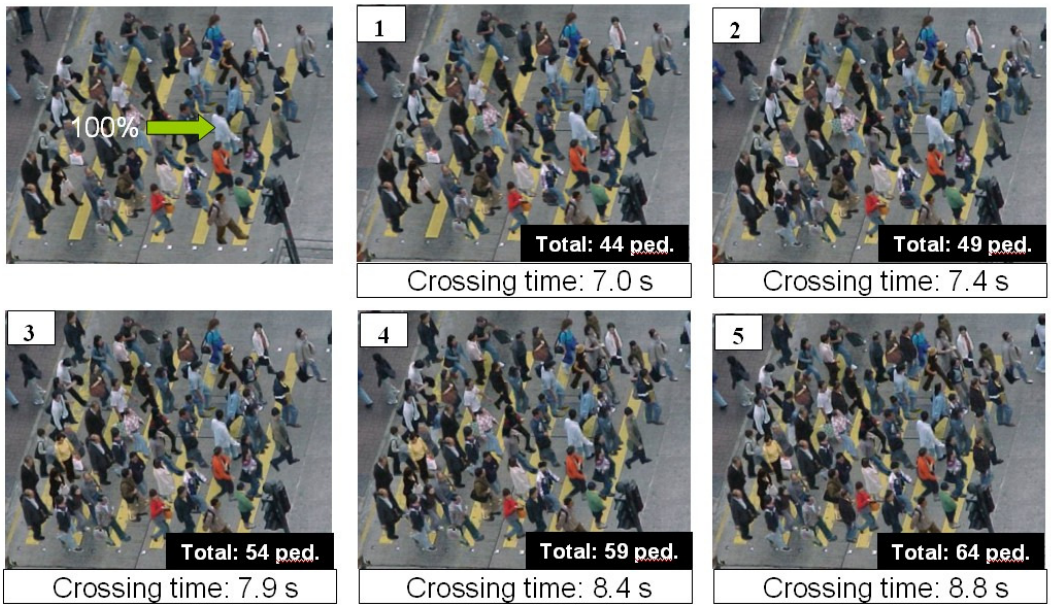
Case C

1) Walking speed **restricted** 步行速度受限制
2) **Difficult** to overtake 困難地繞過其他人
3) **May have** conflict when crossing 有可能與其他人碰撞



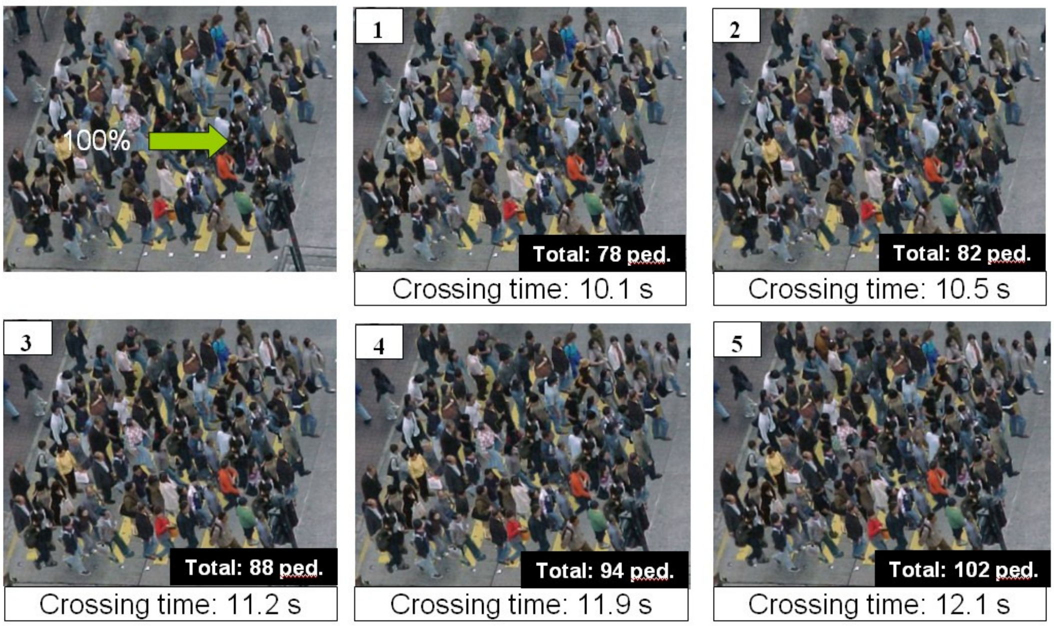
Case D

1) May stop **momentarily**有時需要停步
2) **Very difficult** to overtake 很困難地繞過其他人
3) **Few** conflicts when crossing 與其他人有少許碰撞



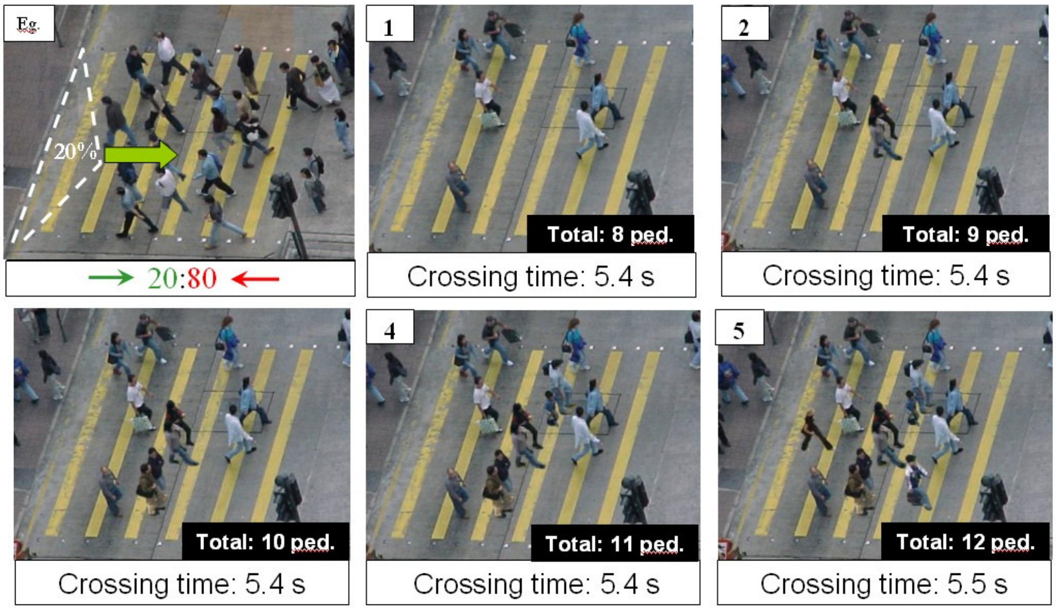
Case E

1) **Frequent** stopping and waiting 經常需要停步及等候
2) **Cannot** overtake 不可能繞過其他人
3) **Many** conflicts when crossing 經常與其他人碰撞



Case A - 20:80

1) **Free** to chose walking speed 步行速度隨意選擇
2) **No problem** overtaking很容易繞過其他人
3) No conflict when crossing 不會與其他人有碰撞



Case B - 20:80

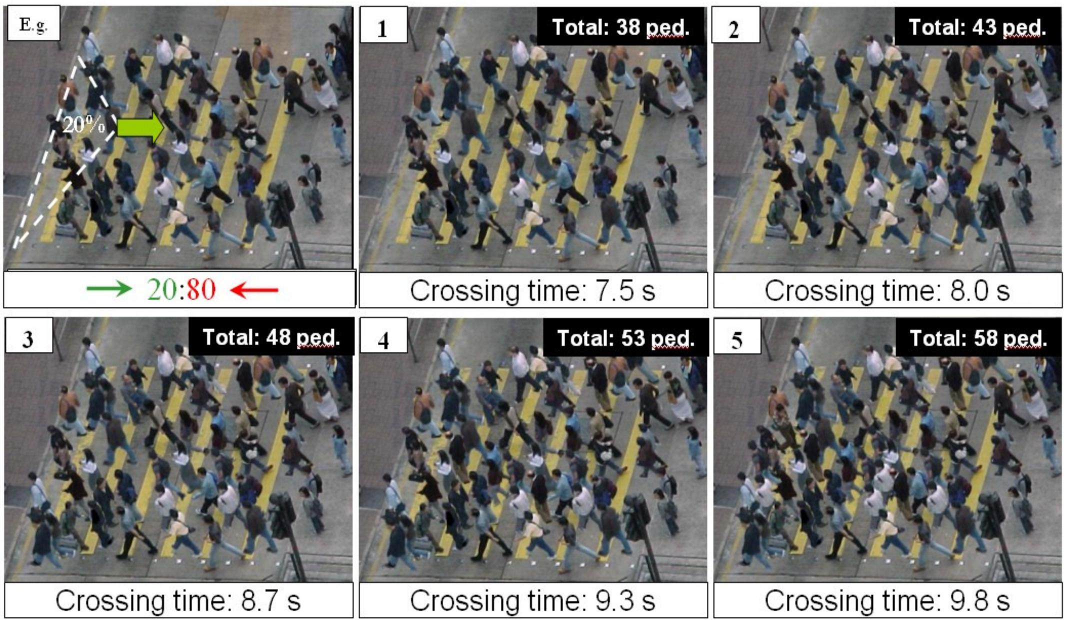
1) **Slight** restriction of walking speed 步行速度有少許限制
2) **Easy** to overtake 容易繞過其他人
3) No conflicts when crossing不會與其他人有碰撞

Case C - 20:80

1) Walk **without** stopping 不需要停步
2) **Difficult** to overtake 困難地繞過其他人
3) **May have** conflict when crossing 可能與其他人碰撞

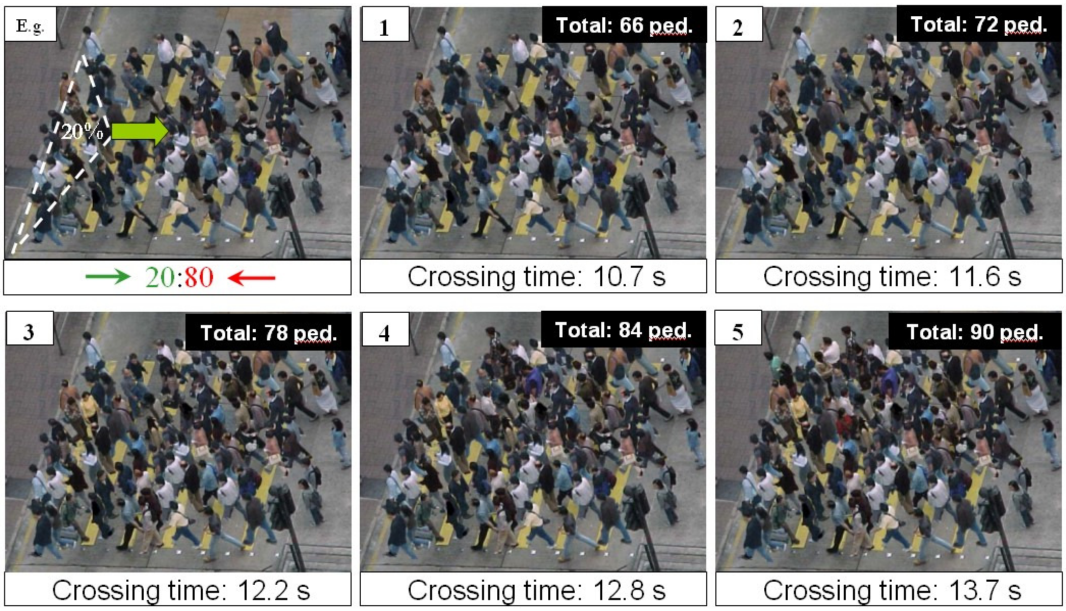
Case D - 20:80

1) May stop **momentarily** 有時需要停步
2) **Very difficult** to overtake 很困難地繞過其他人
3) **Few** conflicts when crossing 與其他人有少許碰撞



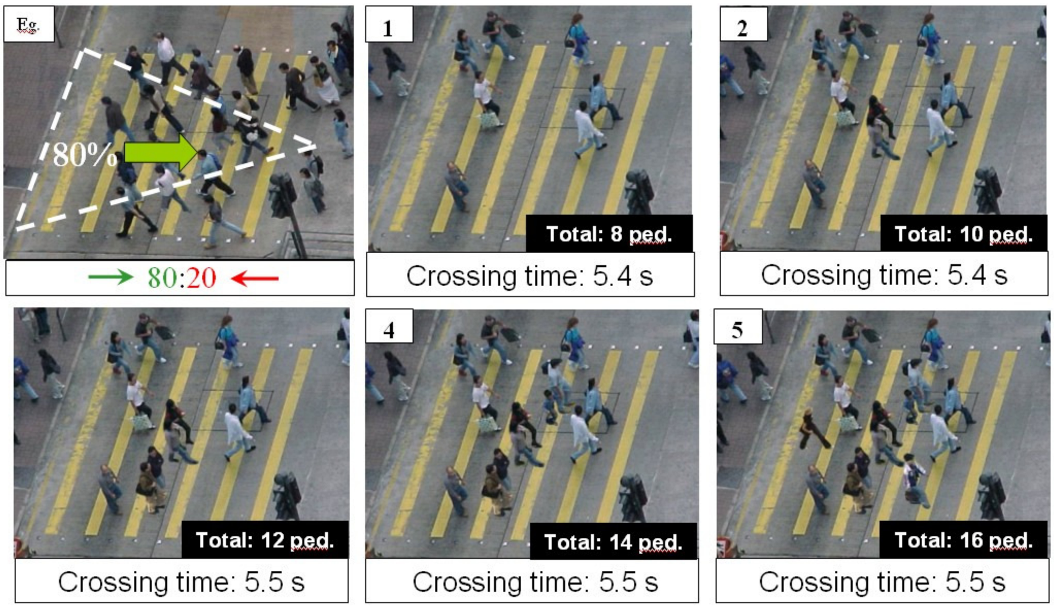
Case E - 20:80

1) **Frequently** stop and wait 經常需要停步及等候
2) **Cannot** overtake 不可能繞過其他人
3) **Many** conflicts when crossing 經常與其他人碰撞



Case A - 80:20

1) **Free** to chose walking speed 步行速度隨意選擇
2) **No problem** overtaking很容易繞過其他人
3) No conflict when crossing 不會與其他人有碰撞

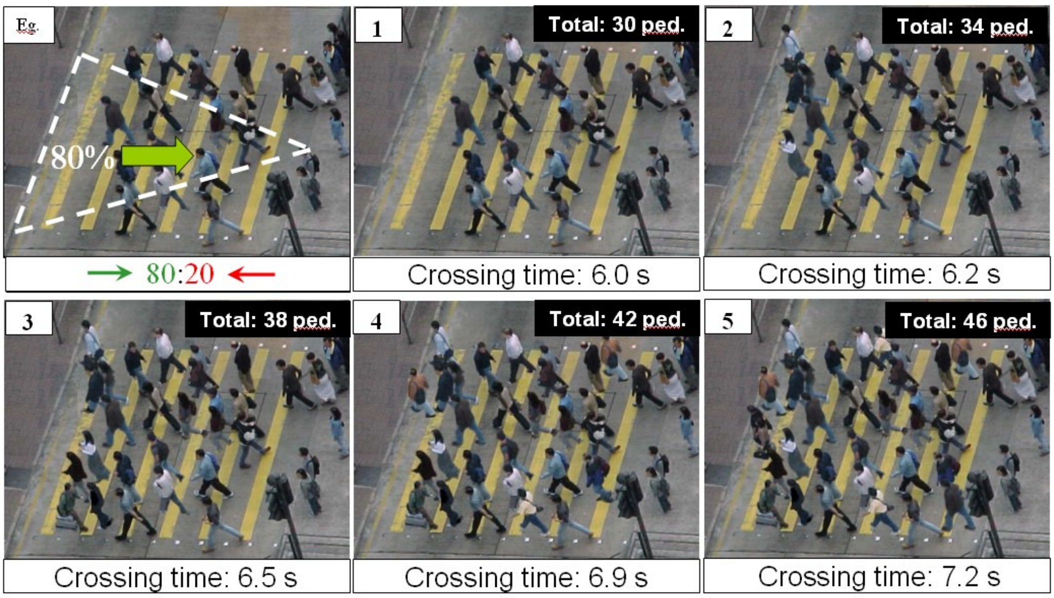


Case B - 80:20

1) **Slight** restriction of walking speed 步行速度有少許限制
2) **Easy** to overtake 容易繞過其他人
3) No conflicts when crossing不會與其他人有碰撞

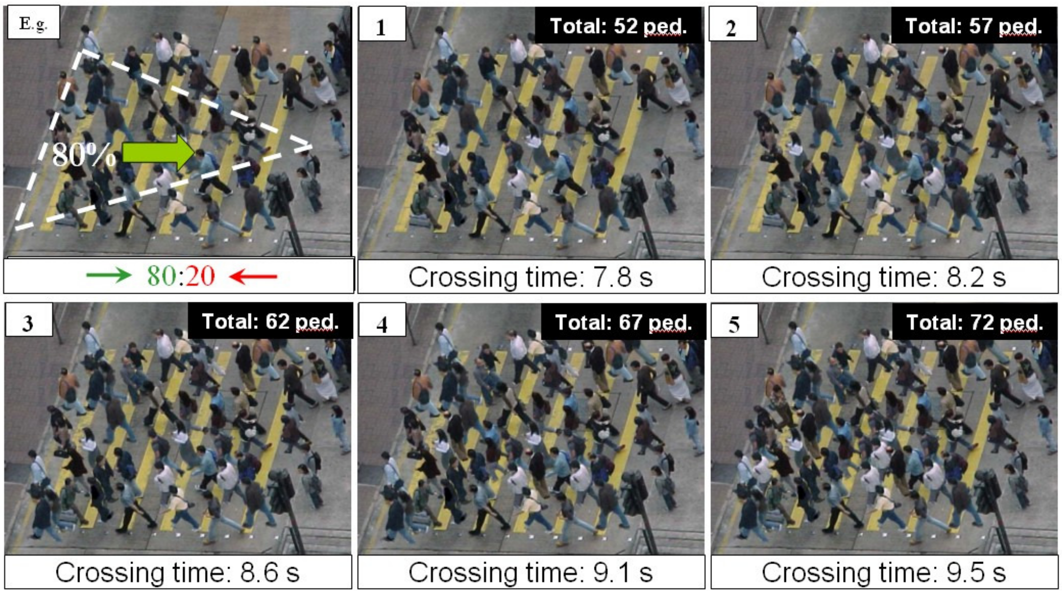
Case C - 80:20

1) Walk **without** stopping 不需要停步
2) **Difficult** to overtake 困難地繞過其他人
3) **May have** conflict when crossing 可能與其他人碰撞



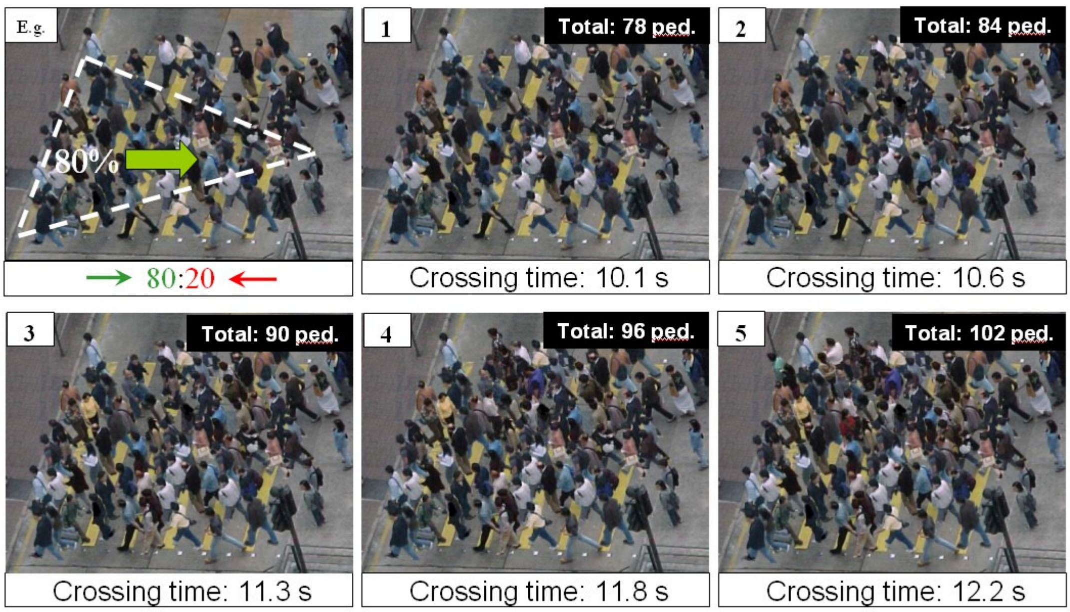
Case D - 80:20

1) May stop **momentarily** 有時需要停步
2) **Very difficult** to overtake 很困難地繞過其他人
3) **Few** conflicts when crossing 與其他人有少許碰撞



Case E - 80:20

1) **Frequently** stop and wait 經常需要停步及等候
2) **Cannot** overtake 不可能繞過其他人
3) **Many** conflicts when crossing 經常與其他人碰撞



REFERENCES

Arentze, T.A., Oppewal H. and Timmermans, H.J.P., 2005. A multipurpose shopping trip model to assess retail agglomeration effects. *Journal of Marketing Research*, 42 (1), 109-115.

Asano, M., Sumalee, A., Kuwahara, M. and Tanaka, S., 2007. Dynamic cell transmission-based pedestrian model with multidirectional flows and strategic route choices. *Transportation Research Record,* 2039, 42-49.

Baltes, M.R. and Chu, X., 2002. Pedestrian level of Service for midblock street crossings. *Transportation Research Record,* 1818, 125-133.

Blue, V.J., Adler, J.L., 1999. Bi-directional emergent fundamental pedestrian flows from cellular automata microsimulation. *Transportation and Traffic Theory*, 235-254.

Blue, V.J. and Adler, J.L., 2001. Cellular automata microsimulation for modeling bi-directional pedestrian walkways. *Transportation Research B,* 35, 293-312.

Borgers, A. and Timmermans, H.J.P., 1986a. A model of pedestrian route choice and demand for retail facilities within inner-city shopping area. *Journal of Geographical Analysis*, 18(2), 115-128.

Borgers, A. and Timmermans, H.J.P., 1986b. City center entry points, store location patterns and pedestrian route choice behavior: a microlevel simulation model. *Socio-Economic Planning Sciences*, 20, 25-31.

Borgers, A. and Timmermans, H.J.P., 2004. Simulating pedestrian route choice behavior in urban retail environments. *Proceedings of the 5th International Conference on Walking in the 21st Century.*

Buckman, L.T. and Leather, J. A., 1994. Modeling station congestion the PEDROUTE way. *Traffic Engineering and Control*, 35, 373-377.

Bureau of Public Roads, 1964. *Traffic Assignment Manual.* Washington D. C.: U.S. Department of Commerce.

Cheung C.Y., 1998. *Pedestrian Flow Characteristics in the Hong Kong Mass Transit Railway Stations.* Thesis (Mphil). The Hong Kong Polytechnic University.

Cheung, C.Y. and Lam, W.H.K., 1997. A study of the bi-directional pedestrian flow characteristics in Hong Kong Mass Transit Railway stations. *Journal of the Eastern Asia Society for Transportation Studies,* 2, 1607-1619.

Cheung C.Y. and Lam, W.H.K., 1998. Pedestrian route choices between escalator and stairway in Mass Transit Railway stations. *Journal of Transportation Engineering,* 124, 277-285.

Daamen, W., 2004. *Modelling Passenger Flows in Public Transport Facilities.* Thesis (PhD). Delft University of Technology.

Daamen, W. and Hoogendoorn S., 2007. Flow-density relations for pedestrian traffic. *Traffic and Granular Flow 05*, 315-322.

Daly, P.N., McGrath, F. and Annesley, T.J., 1991. Pedestrian speed/flow relationships for underground stations. *Traffic Engineering and Control*, 32, 75-78.

Desyllas, J., Duxbury, E., Ward, J. and Smith, A., 2003. Pedestrian demand modelling of large cities: an applied example from London. *Proceedings of the 8th International Conference on Computers in Urban Planning and Urban Management, Sendai, Japan*.

Fruin, J.J., 1987. *Pedestrian: Planning and Design*. New York: Elevator World.

Fruin, J.J., 1970. *Designing for Pedestrians: A Level of Service Concept*. New York: Ann Arbor Mich.

Goh, P.K. and Lam, W.H.K., 2004. Pedestrian flows and walking speed: a problem at signalized crosswalks, *Institute of Transportation Engineers Journal,* 74, 28-33.

Greene, W.H., 2003. *LIMDEP – Nlogit version 3.0: reference guide*. New York: Econometric Software Inc.

Griffiths, J.D., Hunt, J.G. and Marlow, M., 1984a. Delays at pedestrian crossings: 1. Site observations and the interpretation of data. *Traffic Engineering and Control,* 25, 355–371.

Griffiths, J.D., Hunt, J.G. and Marlow, M., 1984b. Delays at pedestrian crossings: 2. The development and validation of a simulation model of a zebra crossing. *Traffic Engineering and Control,* 25, 505–509.

Griffiths, J.D., Hunt, J.G. and Marlow, M., 1984c. Delays at pedestrian crossings: 3. The development and validation of a simulation model of a pelican crossing. *Traffic Engineering and Control,* 25, 611–616.

Griffiths, J.D., Hunt, J.G. and Marlow, M., 1985. Delays at pedestrian crossings: 4. Mathematical models. *Traffic Engineering and Control,* 26, 277–282.

Gerilla, G. P., Hokao, K. and Takeyama, Y., 1995. Proposed level of service standards for walkways in Metro Manila. *Journal of the Eastern Asia Society for Transportation Studies*, 1, 1041-1060.

Halcrow Fox and Associates, 1994. *User Guide to PEDROUTE 3.15*. London: Halcrow Fox.

Helbing, D., Buzna, L., Johansson, A. and Werner, T. 2005. Self-organized pedestrian crowd dynamics: experiments, simulations, and design solutions. *Transportation Science*, 39(1), 1-24.

Henson, C., 2000. Levels of service for pedestrians. *Institute of Transportation Engineers Journal*, 70(9), 26-30.

Herman, R. and Lam, T., 1974. Trip characteristics of journeys to and from work. *Proceedings 6th International Symposium on Transportation and Traffic Theory*, 57-85.

Hoogendoorn, S.P. and Bovy, P.H.L., 2004. Pedestrian route-choice and activity scheduling theory and models. *Transportation Research B*, 38, 169-190.

Hoogendoorn, S.P., Bovy, P.H.L. and Daamen, W., 2003. Walking infrastructure design assessment by continuous space dynamic assignment modeling. *Journal of Advanced Transportation*, 38(1), 69-92.

Jiang, R. and Wu, Q.S., 2007. Pedestrian behaviors in a lattice gas model with large maximum velocity. *Physica A-Statistical Mechanics and Its Applications,* 373, 683-693.

Khisty, C.J., 1994. Evaluation of pedestrian facilities: beyond the level-of-service concept. *Transportation Research Record,* 1438, 45-50.

Landis, B.W., Vattikuti, V.R., Ottenberg, R.M., McLeod, D.S. and Guttenplan, M., 2001. Modeling the roadside walking environment: pedestrian level of service. *Transportation Research Record,* 1773, 82-88.

Lam, W.H.K. and Cheung, C.Y., 1999. Pedestrian travel time function for the Hong Kong underground stations-calibration and validation. *Transactions*, 5, 39-45.

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. and Lee, J.Y.S., 2001. A study of levels of service for signalized crosswalk in Hong Kong urban areas. *Journal of the Eastern Asia Society for Transportation Studies,* 4(1), 27-40.

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

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, 169-192.

Lam, W.H.K., Morrall, J.F. and Ho, H., 1995. Pedestrian flow characteristics in Hong Kong. *Transportation Research Record,* 1487, 56-62.

Lam, W.H.K. and Yin. Y., 2001. An activity-based time-dependent traffic assignment model. *Transportation Research B*, 35, 549-574.

Lee, J.Y.S., 2002. *Development of Pedestrian Simulation-Assignment Models for Hong Kong Mass Transit Railway Stations*. Thesis (MPhil), The Hong Kong Polytechnic University.

Lee, J.Y.S., Goh, P.K. and Lam, W.H.K., 2005. New level-of-service standard for signalized crosswalks with bi-directional pedestrian flows. *Journal of Transportation Engineering,* 131(12), 957-960.

Lee, J.Y.S. and Lam, W.H.K., 2005. A study of pedestrian movements in Hong Kong urban area with and without pedestrianisation scheme. *Proceedings of the 10th International Conference of the Hong Kong Society for Transportation Studies*, 490-499.

Li, Q., Wang, Z., Yang, J. and Wang, J., 2005. Pedestrian delay estimation at signalized intersections in developing cities. *Transportation Research A*, 39, 61-73.

Mass Transit Railway Corporation Limited, 1998. *Comparison of the simulation package.* Hong Kong: The Hong Kong Mass Transit Railway Corporation Limited.

Mori, M. and Tsukaguchi, H., 1987. New method for evaluation of level of service in pedestrian facilities. *Transportation Research A*, 21(3), 223-234.

Morrall, J.F., Ratnayaka, L.L. and Seneviratne, P.N., 1991. Comparison of central business district pedestrian characteristics in Canada and Sri Lanka. *Transportation Research Record,* 1294, 56-62.

Moussaid, M., Helbing, D., Garnier, S., Johansson, A., Combe, M. and Theraulaz, G., 2009. Experimental study of the behavioural mechanisms underlying self-organization in human crowds. *Proceedings of the Royal Society B: Biological Sciences*, 276(1668), 2755-2762.

Norusis, M.J., 1994. *SPSS Advance Statistics 6.1*. Chicago: IL.

Oeding, D., 1963. Traffic loads and dimensions of walkways and other pedestrian circulation facilities. *Strassembau and Strassenverkehrstechnik*, 22.

Older, S.J., 1968. Movement of pedestrians on footways in shopping streets. *Traffic Engineering and Control*, 10, 160-163.

Planning Department, 2001. *The Hong Kong Planning Standards and Guidelines - Chapter 8: Internal Transport Facilities.* Hong Kong: The Hong Kong Special Administrative Region Government.

Planning Department, 2002. *Study on Planning for Pedestrians: First Stage Public Consultation Report.* Hong Kong: The Hong Kong Special Administrative Region Government.

Polus, A., Schofer, J. and Ushpiz, A., 1983. Pedestrian flow and level of service. *Journal of Transportation Engineering*, 109(1), 46-56.

Promodel Corporation, 2004. *Simulation using Promodel,* New York: McGraw Hill.

Pushkarev, B. and Zupan, J.M., 1975. *Urban Space for Pedestrians.* London: The MIT Press.

Richardson, A.J. and Taylor, M.A.P., 1978. Travel time variability on commuters journeys. *High Speed Ground Transportation Journal,* 12(1), 77-99.

Sandahl, J. and Percivall, M., 1972. A pedestrian traffic model for town centers. *Traffic Quarterly*, 26, 359-372.

Sarkar, S., 1993. Determination of service levels for pedestrians, with European examples. *Transportation Research Record,* 1405, 35-42.

Seneviratne, P.N. and Morrall, J.F., 1985a. Analysis of factors affecting the choice of route of pedestrians. *Transportation Planning and Technology,* 10, 147-159.

Seneviratne, P. N. and Morrall, J.F., 1985b. Level of service on pedestrian facilities. *Transportation Quarterly*, 39(1), 109-123.

Seyfried, A., Steffen, B. and Lippert, T., 2006. Basics of modelling the pedestrian flow. *Physica A: Statistical Mechanics and its Applications,* 368(1), 232-238.

Smeed, R. J. and Jeffcoate, G.O., 1971. The variability of car journey times on a particular route. *Traffic Engineering and Control,* 13(6), 238-243.

Song, W.G., Xu,. X, Wang, B.H. and Ni, S.J., 2006. Simulation of evacuation processes using a multi-grid model for pedestrian dynamics. *Physica A*, 363, 492-500.

Srinivasan, S. and Bhat, C.R., 2005. Modeling household interactions in daily in-home and out-of-home maintenance activity participation. *Transportation*, 32, 523-544.

State of Florida Department of Transportation, 2002. *Quality of Service Handbook.* U.S.A.: State of Florida Department of Transportation.

Sterman, B.P. and Schofer, J.L., 1976. Factors affecting reliability of urban bus services. *Journal of Transportation Engineering, 102*, TE1.

Tanaboriboon, Y. and Guyano, J.A., 1989. Level-of-service standards for pedestrian facilities in Bangkok: a case study. *Institute of Transportation Engineers Journal*, 59(11), 39-41.

Tanaboriboon, Y. and Guyano, J.A., 1991. Analysis of pedestrian movements in Bangkok. *Transportation Research Record*, 1294. 56-62.

Tanaboriboon, Y., Hwa, S.S. and Chor, C.H., 1986. Pedestrian characteristics study in Singapore. *Journal of Transportation Engineering,* 112(3), 229-235.

Taylor, M.A.P., 1982. Travel time variability-the case of two public modes. *Transportation Science*, 16(4), 507-521.

Timmermans, H.J.P., Borgers, A. and Waerden, P.V.D., 1992. Choice experiments versus revealed choice models: a before-after study of consumer spatial shopping behavior. *Journal of Professional Geographer*, 44(4), 406-416.

Transport Department, 2002. *Travel Characteristics Survey 2002*. Hong Kong: The Hong Kong Special Administrative Region Government. http://www.info.gov.hk/isd/tvapi/tdsurvey/english/text.htm.

Transport and Traffic Survey Division, 1985. *Data Record No. 393: Model for Pedestrian Movement-Literature Review*. Hong Kong: The Hong Kong Special Administrative Region Government.

Transportation Research Board, 2000. *Highway Capacity Manual*. Washington, D.C.: National Research Council.

Turner, J.K. and Wradrop, J.G., 1951. The variation of journey times in Central London. *London Road Research Laboratory Note*. RN/1511/JKT.JGW.

Turner, R. P., Jones, M. A. and Weston, J. G., 1991. Improving passenger infrastructure design: modelling pedestrian movement. *Transportation Planning Systems*, 1, 113-124.

Van Vliet, D. and Hall, M., 1986. *SATURN Documentation (Version 7.1) – A User's Guide Manual.* United Kingdom: University of Leeds.

Verlander, N.Q. and Heydecker, B.G., 1997. Pedestrian route choice: an empirical study. *The 25th PTRC European Transport Forum*, London PTRC Education and Research Services Ltd, 39-49.

Weng, W.G., Yuan, H.Y. and FAN, W.C., 2007. Experimental validation of motor schema-based cellular automaton model for pedestrian dynamics. *International Journal of Modern Physics C,* 18(6), 927-936.

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

Yu, Y.F. and Song, W.G., 2007. Cellular automaton simulation of pedestrian counter flow considering the surrounding environment. *Physical Review E*, 75(4).

Zhu, W., 2008. *Bounded Rationality and Spatio-Temporal Pedestrian Shopping Behavior*. Thesis (PhD), Eindhoven University of Technology.

Zhang, J., Timmermans, H.J.P., Borgers, A. and Wang, D., 2004. Modeling traveler choice behavior using the concepts of relative utility and relative interest. *Transportation Research B*, 38, 215-234.