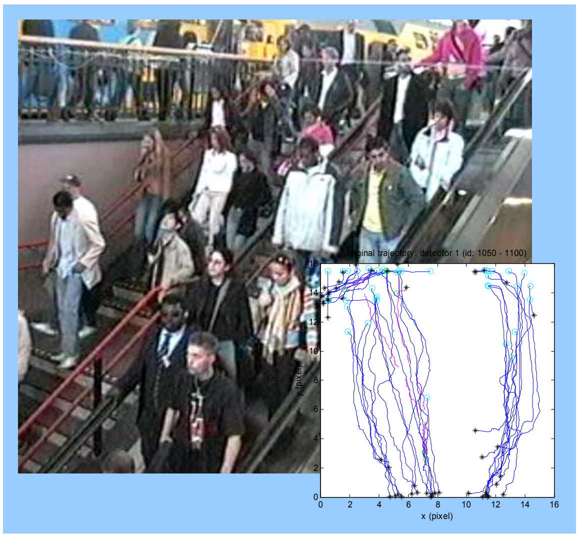
Pedestrian Walking and Choice Behavior on Stairways and Escalators in Public Transport Facilities



MASTER OF SCIENCE THESIS

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Information

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Preface

My first personal contact with "pedestrian flow" may be dated up to 2003, the year when I left my country to pursue my Master of Science degree in TU Delft. It was when I was browsing the web site of this department, the term, pedestrian flow, came to my eyes for the first time. "Pedestrian flow, it sounds interesting" I told to myself then.

The main stream education of traffic and transport still to a large extent focuses on motorized traffic. Relevant topics about the study of those on-foot travelers seldom appear on the official programme in school. By reviewing information on the web site, I find that although limited, there are still quite some researchers devoting their time and effort on pedestrian study. I am especially astonished with some of their brilliant ideas on modeling the behavior of pedestrians. The Normative Pedestrian Flow Behavior Theory by Hoogendoorn and the Social Force Model of Helbing open my eyes to the pedestrian study. Thus, by knowing the outstanding performance with respect to pedestrian researches of this department as well as to satisfy my personal curiosity about human behavior and enthusiasms on providing a better travel environment to those vulnerable travelers, I choose to study the walking and choice behavior of pedestrians in this thesis project.

However, to succeed on the tasks assigned for my thesis project, curiosity and enthusiasms do not help sometimes. Lots help is received from people surrounding me in the past seven months. First of all, I would like to acknowledge the crucial contributions of my thesis supervisor professor Piet Bovy for guiding me to explore the essence of my research questions. Secondly, I would like to express my greatest appreciation to my daily supervisor Winnie Daamen for her scientific support and patience. In addition, I would like to thank all members of my thesis committee for spending time reviewing my report and providing useful suggestions. All of your scientific and academic comments help me to strengthen my abilities in terms of academic researches.

The pedestrian observations conducted at the station of Den Haag Holland Spoort are the critical tasks of my research project. It would not be successful without the help from Kees and Peter. Thanks Frank. van den Heuvel and my friend Adam for providing knowledge about lens distortion and infrared technology. Thanks Hao for the company in the student office through the entire summer.

Last but not least, special thanks to my family and my friends Chia-Lin and Zin-An for their encouragement and unconditional support which give me comfort for countless moments of frustration.

Yu-Chen
Delft, October 12, 2005

Summary

This report studies walking and travel choice behavior of pedestrians concerning stairways and escalators in public transport facilities. With respect to walking behavior of pedestrians, we focus on deriving traffic characteristics such as free speeds and fundamental diagrams of pedestrian flows. Bi-linear models are hypothesized for the speed-density relationships of pedestrian traffic on stairways and escalators. In regard to travel choice behavior of pedestrians, two types of choice behavior are discussed: the first one considers the selection between available stairways and escalators to facilitate level changes; the second one concerns the choice between walking and standing on escalators.

To calibrate our hypothesized walking and choice models, observations were conducted in the NS intercity train station of Den Haag Holland Spoor on the 1st of June, 2005 (Wednesday) with a combined technique of infrared detectors and video cameras. 6 infrared detectors were installed to observe trajectories of individual pedestrians while 2 video cameras were used to observe personal characteristics such as gender and age of passengers. Observation data from these two sources will be jointed to allow analysis of pedestrian behavior taking into account their personal characteristics. The observations lasted for a period of 3.5 hours without interruption (15:40~19:10). However, no congestion had been observed.

Prior to utilizing the infrared and video data for analysis, some preparatory works had been performed. These preparatory works include:

- Convert infrared trajectory data from “pixel” to “cm”, which involves correction for both lens and perspective distortion;
- Match split trajectories within one field of view (infrared detector);
- Combine infrared trajectory data and personal characteristics read from video films;
- Correct (infrared) flow data based on video reading.

Our analysis of free speeds show that free speeds are influenced by directions of movement, types of infrastructure, and personal characteristics of pedestrians, namely, gender and age. The free speeds found on stairways are about 0.77 m/s and 0.68 m/s in the descending and the ascending direction respectively; those on escalators are about 0.88 m/s and 0.82 m/s in the descending and ascending direction respectively. Besides, in average, male passengers walk faster than female ones; Moreover, in general, free speeds decrease with age.

Our findings concerning the fundamental diagrams of pedestrian flows are quite limited due to the small variation of traffic conditions observed. During our observations, the highest flows observed on stairways are 0.86 P/ms and 0.18 P/ms in the descending and ascending direction respectively, while those on escalators are 0.93 P/ms and 0.67 P/ms in the descending and ascending direction respectively.

With respect to the choice behavior between stairways and escalators, binary logit models are applied for the model formulation. Based on the choice situations at the observation site, factors influencing the choice behavior may include travel time, physical effort, safety and comfort, personal characteristics of pedestrians, and vicinity. However, due to the incomplete travel information observed, simplified route networks are proposed for the analysis. In addition, only factors of travel time, physical effort, safety and comfort, and personal characteristic are considered in the utility functions. Our estimated results indicate a weak explanatory power of our hypothesized choice models. Possible explanations include the exclusion of influencing factors such as time pressure and vicinity, incomplete travel time information, possible bias caused by the algorithms applied for the estimation of alternative travel time.

In regard to the walk/stand choice behaviour on escalators, our study in this report is limited to the discussion about choice availability and influencing factors. The availability of the walk/stand choice may be determined by the distribution of standing passengers on escalators particularly those near to the entry. In addition, the main factors influencing this stand/walk choice on escalators may include physical effort, travel time and time pressure.

Finally, our investigation on pedestrian observations with infrared detectors shows that large amount of trajectory data can be observed and extracted automatically with existing program. Besides, our algorithms applied to correct trajectory data and the method used to join infrared and video data provide satisfactory results. Thus we conclude that the application of infrared detectors on pedestrian observations is promising. However, further studies should be performed to evaluate the accuracy of the detection outcomes and to develop algorithms to match trajectories across different fields of view to expand its possible application on pedestrian study.

Contents

1 Introduction

In addition to providing designated public transport services, the design of public transport facilities such as transfer stations and airport terminals needs to enable efficient, comfortable and safe flows of passengers. A well designed pedestrian environment will enhance not only the level of service perceived by its users but also the performance or efficiency of public transport systems. For instance, the dwelling times of public transport vehicles, which are dependent on the time required by passengers to board, alight and transit, could be shorted by providing an efficient pedestrian environment and be better estimated with more knowledge on pedestrian behavior to optimize system performances.

In spite of the advance in transport technologies in the past few decades, the design of public transport facilities still to a large extent relies on rules of thumb which are facing challenges from higher demands on efficiencies and increased complexities of functional designs of public transport systems. Some computer tools such as simulation models are developed to satisfy societal needs for qualitative and quantitative designs of public transport facilities. Those tools are established based on the current knowledge about pedestrian behavior which is in some aspects quite limited. Pedestrian movement in the vertical dimension is one of the examples.

In a multi-level public transport facility, passengers circulate in both horizontal and vertical dimensions. Pedestrian facilities such as lifts, ramps, stairways and escalators are normally used to facilitate level changes. Those vertical infrastructures are often bottlenecks of pedestrian traffic inside public transport facilities. Sufficient provision, proper location selection, and appropriate layouts of those vertical infrastructures are critical elements for designs of vertical circulations. Despite of its significance on the overall circulation of pedestrian traffic in multi-level public transport facilities, not many studies concerning those vertical infrastructures are available at present. Thus, the purpose of this thesis project is to gain insight into pedestrian behavior in the vertical dimension particularly those concerning stairways and escalators.

Pedestrian behavior can be divided into three levels, namely, the strategic level, the tactical level, and the operational level (Hoogendoorn & Bovy, 2004). At the strategic level, pedestrians decide the set of activities to be performed on the trip and the departure time; at the tactical level, short-term decisions such as activity scheduling, activity location selection, and route choices are made; at the operational level, they make instantaneous decisions about walking, queuing, performing activities, etc. Together with the prevailing traffic conditions, the decisions of travel choices at the tactical level serve as inputs for walking behavior at the operational level. Thus, we concern both the walking and choice behavior of pedestrians in this report. We aim at giving a contribution to the traffic flow theory as well as to the travel choice behavior theory of pedestrians.

With respect to walking behavior of pedestrians, we focus on deriving traffic characteristics such as free speeds and fundamental diagrams of pedestrian flows on stairways and escalators. Free speeds reveal pedestrians' desires on speeds when traveling in a specific environment or on a specific type of infrastructure. The fundamental speed-flow-density diagrams describe the dynamic features of pedestrian traffic in the macroscopic level.

In regard to travel choice behavior, we focus on the way passengers use stairways and escalators in public transport facilities. How do pedestrians make a choice among several available stairways and escalators to facilitate level changes? When traveling with escalators, what factors influence the travel behavior of passengers or their decisions on walking or standing on escalators?

This research is conducted in two stages. In the first stage, we focus on establishing conceptual models to describe walking and choice behavior of pedestrians concerning stairways and escalators. Those conceptual models are hypothesized based on existing empirical data and theories as well as our observations of real-life pedestrian behavior in public transport facilities. In the second stage, we conduct data observations with the technique of infrared detectors and video cameras for this project to calibrate and validate our hypothesized models.

The main contribution of this project is to gain insight into both walking and travel choice behavior of pedestrians in the vertical dimension. Besides, our findings can be used as inputs of pedestrian simulation models and the provision of guidelines or recommendations for the design of pedestrian environments. Moreover, our investigation on the infrared technology in terms of pedestrian observations provides a better understanding on the possibility as well as the limitation of utilizing low-cost infrared detectors to study pedestrian behavior of various kinds.

The remainder of this report is structured as follows. Following this introduction chapter, we give a review of existing literature concerning both walking and route choice behavior of pedestrians in chapter 2. This chapter aims at providing some empirical data as well as theoretical background about pedestrian behaviors of concerns. Chapter 3 and chapter 4 present the conceptual models hypothesized for walking and choice behavior of pedestrians respectively. Chapter 5 concerns the data observation conducted for this project in the NS intercity train station of Den Haag Holland Spoor. Chapter 6 discusses the preparatory works conducted prior to utilizing observation data to analyze walking and choice behavior of pedestrians. Chapter 7 and chapter 8 present results of our analysis with respect to walking and choice models respectively. Finally, in chapter 9 some conclusions and future research recommendations are given.

2 Literature Review

This chapter reviews existing literature concerning walking and route choice behavior of pedestrians. We aim at acquiring available knowledge and identifying blank spots in relation to our research questions. The results of this literature review will be used as starting points for the building of our conceptual walking and choice models discussed in the later chapter of this report.

The review is divided into two parts. The first part concerns walking behavior of pedestrians. We discuss human characteristics and capabilities related to pedestrian design, pedestrian flow theory, and empirical data. A basic understanding about human characteristics and capabilities related to pedestrian design is essential to study pedestrian behavior of various kinds. The pedestrian flow theory which discusses the fundamental speed-flow-density relationships of pedestrian flows provides theoretical background on modeling pedestrian walking behavior in the macroscopic level. Together with empirical data given in literature, the knowledge of pedestrian behavior in both individual and aggregated flow level provides guidelines to the formulation of our conceptual walking models on stairways and escalators. We elaborate those aspects in section 2.1.

The second part of the review considers pedestrian travel choice behavior. Since 1960s, in general, discrete choice models based on the principle of random utility maximization have been applied to predict choice behavior of travelers. Examples include for instance the choice of transport modes for travel to work and the choice of routes between origins and destinations. In this report we apply the same approach to formulate our hypothesized choice models. Thus, to ease our further discussion about modeling choice behavior in the remainder of this report, we give a presentation on the random utility maximization theory and binary logit models to provide some theoretical background. Following that we discuss some empirical data. We focus on factors influencing choice behavior of pedestrians in the vertical dimension. We discuss those in more details in section 2.2.

2.1 Pedestrian walking behavior

This section reviews pedestrian walking behavior given in literature. We discuss human characteristics related to pedestrian design, the theory of pedestrian flows, and empirical data.

2.1.1 Human characteristics and design for pedestrians

This subsection describes some human characteristics and capabilities related to pedestrian design. What is the physical size of a human body? What factors influence the spacing of people in public environment? What are the main features of human locomotion and their inferences on walking behavior? Answers to these questions will be given through our following discussion about the body ellipse, the body buffer zone, space zones in locomotion, and human locomotion.

The human body ellipse

The physical size of a human body determines lots dimensions in pedestrian environments. Examples include the width of a sidewalk and the size of a queuing area. The human body ellipse described by Fruin (1971a) represents the plan view of an average adult male body. This 18 by 24 inch (about 0.45 by 0.60 meter) body ellipse considers not only the body depth and shoulder breadth of an average male adult but also spatial allowance for the presence of personal articles, social conventions to avoid body contact with others and body sway. Although this body ellipse model provides a very simple way to visualize various situations involving confined pedestrians, its application is limited to high-density traffic conditions since the dynamic features of pedestrian flows such as the relationships between densities and speeds are not captured by this static model.

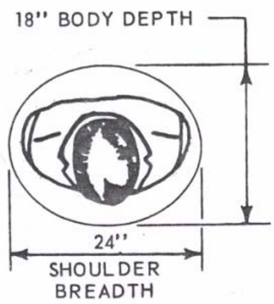


Figure 2.1
The human body ellipse described by Fruin (1971a)

The body buffer zone

Originating from psychological studies, the body buffer zone refers to the area around a human body which if intruded will cause anxiety. The concept of body buffer zone determines the inter-person spacing of pedestrians. When freedom of choice exists, pedestrian will adopt personal spacing that avoids physical contact with others, which may explain the step-and-slide maneuver taken by overtaking pedestrians. It is generally believed that personal and cultural differences among people affect the size of personal body buffer zones, and, consequently, the perception of space. The study by Hall (1966) reveals that many eastern societies accept closer spacing and a higher level of physical contact than that is tolerated by western communities. Besides, experiments on natural personal approach distances observed that participants of both genders select a smaller separation from female subjects than from male ones, which can be explained by the recognition of potential aggressiveness of male subjects (Fruin, 1971a)

Space zones in locomotion

According to Fruin (1971a), the space required for locomotion is composed of two parts: the pacing zone and the sensory zone (see Figure 2.2). The pacing zone refers to the area required for making a step forwards and for foot placement, while the sensory zone is required for sensory perception, and stimuli evaluation and reaction. We discuss factors influencing the sizes of the pacing and sensory zones with reference to the study by Fruin (1971a) in the following paragraphs.

The length of the pacing zone is influenced by factors such as physical size, age, gender, and speed of pedestrians as well as external influences such as terrain and traffic conditions. The physical size of pedestrians, which varies among individuals and in average differs between the two sexes, has direct influence on the step length. The influences of gender and age on walking locomotion find their support from the understanding of the effect of pelvic rotation on walking. It is known that for a given length of a stride, a greater pelvic rotation is required for female walkers due to their smaller range of hip movement. Besides, aging decreases the degree of pelvic rotation for both men and women, which leads to a reduction of step length, and consequently a smaller walking speed. Moreover, a linear relationship between step lengths and speeds is shown in literature. Finally, the pacing length is affected by the configuration of facilities (eg. the depth of treads) and available space for pacing or densities.

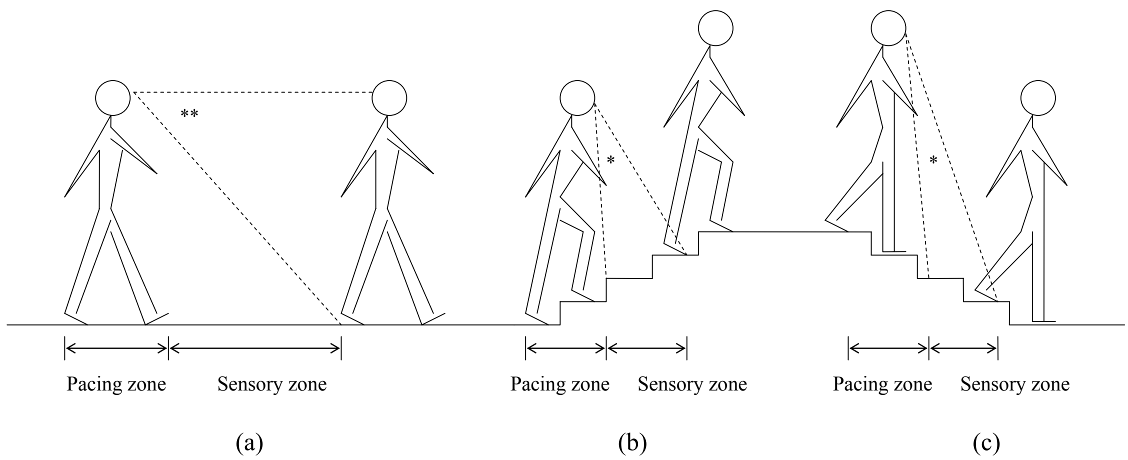


Figure 2.2
The space required for locomotion may be divided into the pacing zone, the area required for foot placement, and the sensory zone, the area required for sensory perception, stimuli evaluation, and reaction. (a) normal walking involves the use of the general visual angle ** (60-70 degrees) which is easier got hindered at dense conditions (b) when climbing the center of gravity is kept forward and greater energy is required to overcome the gravity (c) when decent the center of gravity is hold backward to avoid falling and greater concentration on controlling the shift of gravity is required; stair locomotion involves the use of the smaller acute cones of vision * (3-5 degrees) (Fruin, 1971a)

The sensory zone is determined by many human perceptual and psychological factors in particular the capacities of human vision and the responses towards stimuli or the so-called reaction time. Human vision has profound effects on locomotion with respect to the connected requirement on the judgments of speed, distance and direction of others. Observations of people with poor sight found that those people walk more slowly and negotiate stairs more cautiously. However, there are limitations of human vision. The human eye is capable of detecting very sharp details within a small cone-shaped range of only 3 to 5 degrees, which is used when caution is required, such as in stair locomotion or when boarding an escalator. In free-speed locomotion, pedestrians use the more general and comfortable visual angle of about 60 to 70 degrees, with a distance of about 2 m away from another person. However, if this distance is not available, such as in higher density traffic conditions or when facing restraints imposed by terrains, pedestrians experience hindered vision and tend to decrease walking speeds. Reaction time, the interval between the presentation of a stimulus and the response to it, plays roles in the human locomotion as well. Results of controlled studies of automobile breaking show that the eye-to-foot reaction time increases with age (Fruin, 1971a). This may explained the longer boarding time on escalator taken by the elderly.

Human locomotion

Biped walking is a unique skill of human beings and has evolved into a very energy-efficient means of locomotion. Despite of its efficiency and apparent ease, walking is indeed a complex mental and kinesthetic activity, which requires constant shifts in the center of gravity of human bodies for balancing, applications of muscle forces as support and propulsion, and adjustments of pacing length and timing for speed and direction control (Fruin 1971a).

In contrast with walking, stair climbing and descent is more restricted because of safety concerns and the restraints imposed by the configurations of stairs. In addition, energy consumption for stair climbing is about ten to fifteen times the energy needed for walking the equivalent horizontal distance, while surprisingly, only about one-third greater is required for descent (Fruin 1971a).

When climbing stairs the body's center of gravity is shifted forward, and the front leg is lifted and placed on the first step to support the body and to prevent it from falling forward. On the contrary, when descending, the center of gravity must be held backward to avoid falling, and the weight is carefully lowered to the supporting foot on the step below. Therefore, although less energy is required for descent, greater concentration is required for the control of gravity shifts.

The configurations of stair risers and treads have significant effects on stair locomotion. Instead of selecting a natural pacing distance, the width of the tread determines the step distance of a pedestrian. Faster walking is usually accomplished by increasing the stepping rate instead of distance because it is viewed as a dangerous and tiring action to take two stairs at once. In addition, sensory shifts occur on stairs due to the need to use the smaller and more acute cone of vision for more accurate foot placement and to avoid tripping. Moreover, stair locomotion requires larger flexion of knee and foot as well as higher muscle strength for the elongated load bearing stage. These increase difficulties of pedestrians with less favorable physical conditions on stairways.

2.1.2 Pedestrian flow theory

In traffic flow theory, the relation between the macroscopic traffic characteristics (flow, speed and density) is described as the fundamental relation given as follows (Daamen, 2004):

$$q = k \times u \tag{2.1}$$

where q is the flow, k is the density, and u is the speed.

When referring to pedestrian traffic, the flow (q) denotes the number of pedestrians passing a cross-section of a pedestrian facility in a unit of time. The customary unit for flow is P/ms (pedestrians per meter width per second). The density (k) is defined as the number of pedestrians present on an area at a given moment. The customary unit for density is P/m^2 (pedestrians per meter square). The speed (u) stands for the so-called space mean speed which is the average speed of pedestrians present on an area at a given moment (m/s).

It is noted that when applying to flows involving vertical movement such as those on stairways and on escalators, the speed is replaced by its horizontal components. Besides, the density refers to the number of pedestrians present on a unit vertical projected area in the horizontal plane at a given moment. In the remainder of this report, we use the term "speed" and "density" to denote "horizontal speed" and "density on the vertical projected horizontal plane" unless otherwise stated.

This fundamental relation is conventionally presented by the three interrelated fundamental diagrams: the flow-density, speed-density, and speed-flow diagram. It is noted that since these three diagrams give the same information, we can always deduce the other two from one. A typical hypothesized relationship between the flow and the density is given in Figure 2.3. We discuss this flow-density diagraph in more details below.

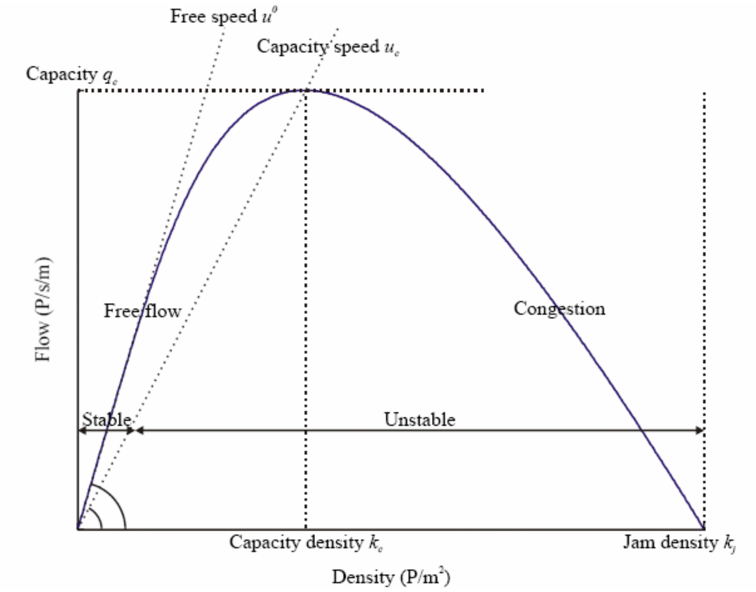


Figure 2.3
Hypothesized flow-density relation for pedestrian traffic (source from: Daamen 2004)

First, we explain some special points of the diagram given in Figure 2.3:

- Free speed (u^0) is the speed of a traffic stream under free flow conditions; it equals the slope of the function *q(k)* at the origin;
- Capacity (q_c) is the maximal flow or critical flow;
- Capacity density (k_c) is the density when the flow equals the capacity;
- Capacity speed (u_c) is the speed when the flow equals the capacity;
- Jam density (k_j) is the density at extremely crowded conditions or theoretically when both the speed and flow equal zero.

Sometimes we categorize traffic states into different regions. Based on the dynamic of disturbances or the stability of traffic states, we may divide traffic states into the "stable region" and the "unstable region". The stable region is characterized with a constant speed (u^0), while in the unstable region speeds decrease when densities increase. According to the traffic conditions or the level of service perceived, we may divide traffic states into the "free flow region" and the "congestion region". The free flow region refers to the part of the graph where densities are less that the capacity density ($k < k_c$), while the congestion region denotes the part with densities larger than the capacity density ($k > k_c$).

2.1.3 Empirical data of pedestrian walking behavior

Empirical studies of pedestrian walking behavior have been conducted by many researchers since 1960s, of which the findings provide significant insights into traffic characteristics of both individuals and aggregated flows. We focus on empirical data concerning traffic on stairways and escalators in this subsection. We discuss aspects of free speeds, speed-density relationships, and capacities of pedestrian facilities.

Free speeds

How fast do people walk? Quite a few studies have been conducted to measure free flow speeds of pedestrians, while different values were estimated for various countries. A comprehensive review by Daamen (2004) indicates that individual walking speeds in un-congested corridors, or the so-called free flow speeds, range from 1.08 m/s (Saudi-Arabia) to 1.6 m/s (UK and USA), and an estimated mean of 1.34 m/s could be representative.

Free speeds are affected by many factors. Based on the study of Weidmann (1993) we may divide those factors into three groups: pedestrian characteristics, movement conditions, and characteristics of infrastructure. We discuss these three groups of factors below.

Firstly, pedestrian characteristics include factors such as gender, age, physical size, health and fitness condition, cultural and racial background, and presence of luggage, etc. However, there seems to be some correlation between these personal factors. For instance, the physical size may be influenced by both gender and racial background of pedestrians. In addition, several studies indicate that it is not age but factors related to age, such as health and fitness conditions, which are determinant (Daamen, 2004). Secondly, movement conditions are defined by factors such as the trip purposes, time of the day, weather and ambient conditions, trip lengths, travel directions (ascending or descending), attractiveness of environment, and size of group. Finally, regarding infrastructure characteristics, influences of infrastructure types (eg. walkway, ramp, stairway or escalator), gradient, configurations of stair risers and treads, and surface conditions are identified in literature.

In this report, we concern walking behavior of commuting traffic involving vertical movement, of which the influence of gender and age of pedestrians, directions of movement, and infrastructure types and configurations on free speeds may be significant. We discuss these four factors in more details below.

- **Gender**

  The studies of normal walking patterns of men and women by Murray et al. (1964; 1970) have reported a larger step length of male walkers (79 cm) than female ones (66 cm) while a constant stepping rate was observed for the two sexes (117 step/min). The difference in the step length may be explained by the inherent physical differences of the two sexes. As we have discussed in section 2.2.1, the pacing length is influenced by the physical characteristics of pedestrians in particularly the physical size and pelvic rotations. The average smaller size and limited pelvic rotation of women result in an average smaller step length of female pedestrians. A later study by Fruin (1971a) has directly observed walking speeds of the two sexes on walkways. His results show that the average walking speeds of men and women are 1.37 m/s and 1.29 m/s respectively, which reveals an about 10% difference in walking speeds between the two sexes. When walking on stairways or escalators, although the pacing length is restrained by the tread configuration, the higher physical effort involved in stair locomotion may cause a reduction of pacing frequencies of female pedestrians. However, no empirical data concerning the walking patterns on stairways are found in literature.

- **Age**

  The study of Fruin (1971a) reported that the average walking speed of people of age 81-87 (1.09 m/s) is about 20% less than that of young adult of age 20-25 (1.39 m/s), which may be explained by the increase of physical inability and the decrease of pelvic rotation of the elderly. Aging can lead to several physical changes such as stiffening of connective tissue, decreased muscle strength, prolonged reaction times, decreased visual acuity, impaired vibratory sensation, and increased postural sway, all of which have negative impacts on efficient gait patterns (Trueblood and Rubenstein, 1990). In addition, studies also reveal that aging will decrease the degree of pelvic rotation, and, consequently a smaller step length (Fruin 1971a). Therefore, the old people are observed to walk with slower and smaller steps.

The influence of physical inability on walking speeds becomes more substantial on stairways or escalators because of the higher requirements on human energy, muscle strength, and postural stability involved in stair locomotion. Although several studies indicate that it is not age but other age related factors such as fitness level, cautiousness, and the possibility of having health problems that are determinant on walking behaviors (Daamen 2004), age is often used in the study of pedestrian traffic because of its ease on observations.

- **Direction**

  Walking speeds in the ascending direction are lower than those in the descending one because it requires more human energy on climbing stairs. In general, free walking speed is observed to be normally distributed. However, a bi-modality of distribution is observed by Fruin (1971a) for descending pedestrians, which infers the presence of two different groups of walkers, the fast and the slow walkers, in descent situations. The higher demands of concentration on placing foot and controlling balance in descent may differentiate pedestrians into these two noticeable groups.

- **Infrastructure types and configurations**

  The type and configuration of pedestrian infrastructure have large influences on walking locomotion. As we have discussed in subsection 2.1.1, compared with level walking, stair locomotion is more restricted due to constraints imposed by the configuration of stair risers and treads. Thus, instead of selecting a desired pacing length, the step length is limited by the depth of stair treads. Moreover, the higher requirement on energy consumption involved on stair locomotion limits the speeds attainable by average pedestrians. Finally, a lower walking speed is measured on stairways with larger risers and slopes because of the higher energy consumption involved (Fruin, 1971a).

Table 2.1 summarizes some free speeds measurements on different types of infrastructure which include walkways or passageways, stairways and escalators. To make it comparable, horizontal speeds of one-directional flows are given in the table. The data shows that speeds on walkways or passageways are higher than those involving vertical movement on stairways and escalators. In additions, speeds in the descending directions are higher that those in the ascending one. Moreover, lower speeds are observed on stairways with larger slopes and higher risers.

Table 2.1
Horizontal free-flow speeds of one-directional flows (unit: m/s)

Infrastructure Type	Fruin (1971a) Bus terminal (USA)	Daly et al. (1991) Metro station (UK)	Lam et al. (2000) Metro station (HK)
Walkway or Passageway	1.35	1.47	1.37
Stairway – up	0.51[a]-0.57[b]	0.59[c]	0.86[d]
Stairway – down	0.67[a]-0.77[b]	0.67[c]	0.97[d]
Escalator – up	-	0.84[c]	0.89[e]
Escalator – down	-	1.00[c]	1.05[e]

Note:
[a] indoor stairs with 17.8-cm risers, 28.8-cm treads, and 32-degree inclination
[b] outdoor stairs with 15.2-cm risers, 30.5-cm treads, and 27-degree inclination
[c] the dimensions of stairs are not available
[d] indoor stairs with 15.0-cm risers, 30.5-cm treads, and 26-degree inclination
[e] indoor escalators with 20.5-cm risers, 40.5-cm treads, and 27-degree inclination

Speed-density relationships

Various speed-density relationships have been reported for different pedestrian groups and various types of pedestrian infrastructures. Most of the studies assumed a linear relationship between the speed and the density (Fruin 1971b, Lam et al. 1995, Sarkar & Janardhan 1997). An exception is the double S-bended curves described by Weidmann (1993).

The linear speed-density model can be expressed as follows:

$$u = u^0[1 - \frac{k}{k_j}] \tag{2.2}$$

where u is the speed; u^0 denotes the free flow speed; k is the density; k_j is the jam density.

This linear model is justified by the observation that when densities increase, the space available for pacing is reduced, and, consequently, pedestrians lower their speeds to avoid brushing with others or to prevent repeated and sudden stoppages.

Now we discuss some empirical models concerning the speed-density relationship of pedestrian flows. Due to the lack of data on escalator traffic, only models on level surfaces and stairways are presented. We give those empirical models in Figure 2.4 and summarize the relationships and some import points in Table 2.2. To make a comparison of traffic behavior involving different types of terrain and various directions of movement, we divide those models into three groups: (1) level surface; (2) stairway-up; (3) stairway-down.

Two distinctive groups of models, which correspond to the two types of infrastructure concerned in this section, namely, level surfaces and stairways, can be easily recognized from the graph given in Figure 2.4. The upper group, which is characterized by higher free speeds (1.29-1.46 m/s), smaller jam densities (3.58-5.40 P/m^2), and steeper inclination, describes walking behavior on level surfaces (model type 1). In contrast, the lower group, which is noted with lower free speeds (0.56-0.69 m/s), larger jam density (5.40-7.37 P/m^2), and relative flat slopes, represents walking behavior on stairways (model type 2 & 3).

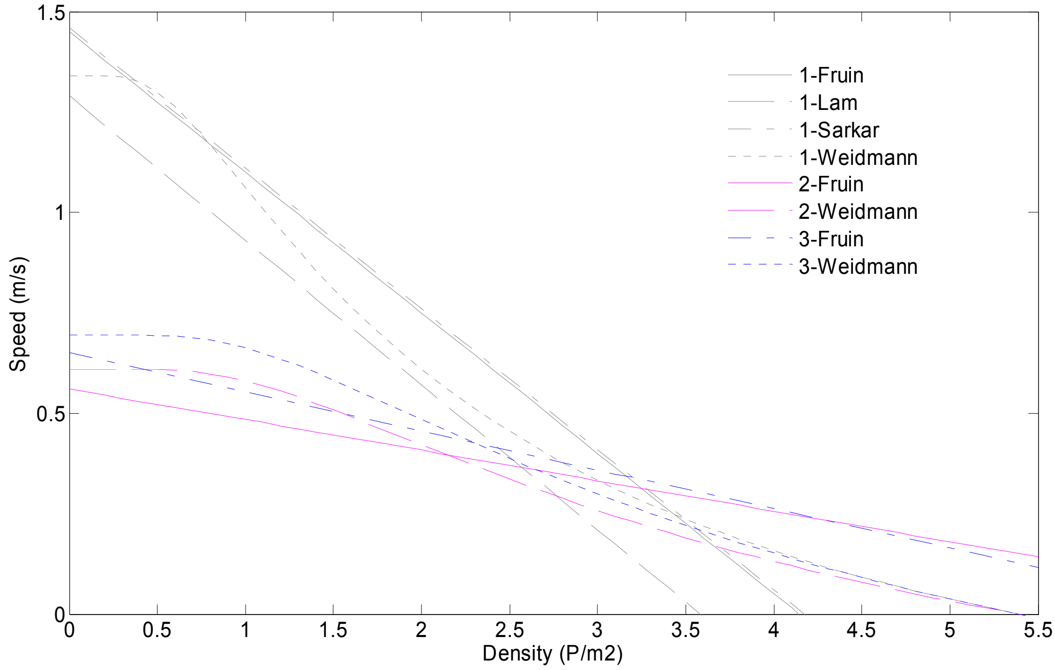


Figure 2.4
Empirical speed-density relationships for pedestrian traffic in literature (reference source from **Table 2.2**). Three types of models are given: (1) level surfaces (2) stairways - upward direction (3) stairways - downward direction.

Table 2.2
Empirical speed-density relationships for uni-directional pedestrian traffic flow in literature

Model Type	Source	Macroscopic traffic characteristics					
		Speed-density model	u^0	k_j	q_c	k_c	u_c
(1) Level surface	Fruin (1971a) Bus terminal, USA	$u = 1.43 - 0.35k$	1.43	4.09	1.47	2.04	0.72
(1) Level surface	Lam et al. (1995) HK indoor walkway	$u = 1.29 - 0.36k$	1.29	3.58	1.16	1.79	0.65
(1) Level surface	Sarkar & Janardhan (1997) transfer area, India	$u = 1.46 - 0.35k$	1.46	4.17	1.53	2.09	0.73
(1) Level surface	Weidmann (1993)	$u = 1.340[1 - e^{(-1.913\{\frac{1}{k}-\frac{1}{5.4}\})}]$	1.34	5.40	1.23	1.75	0.70
(2) Stairway – up	Fruin (1971a) Bus terminal, USA	$u = 0.56 - 0.076k$	0.56	7.37	1.03	3.68	0.28
(2) Stairway – up	Weidmann (1993)	$u = 0.610[1 - e^{(-3.722\{\frac{1}{k}-\frac{1}{5.4}\})}]$	0.61	5.40	0.85	2.23	0.38
(3) Stairway – down	Fruin (1971a) Bus terminal, USA	$u = 0.65 - 0.097k$	0.65	6.70	1.11	3.35	0.33
(3) Stairway – down	Weidmann (1993)	$u = 0.694[1 - e^{(-3.802\{\frac{1}{k}-\frac{1}{5.4}\})}]$	0.69	5.40	0.98	2.23	0.44

unit: k (P/m^2); u (m/s); q (P/ms)
u^0: free speed (m/s); q_c: capacity (P/m/s); k_c: capacity density (P/m^2); u_c: capacity speed (m/s); k_j: jam density (P/m^2)

We discuss the jam densities based on the findings from Fruin (1971b) and Weidmann (1993) below.

- **Jam densities on level surfaces and on stairways**

  A major conceptual difference between the models of Fruin and Weidmann lies on their assumption about the way pedestrians use space. Fruin has estimated various jam densities for different flows (4.09 P/m^2, 7.37 P/m^2, and 6.70 P/m^2 for flows on level surfaces, ascending on stairways, and decending on stairways respectively) while a constant value (5.4 P/ m^2) is assumed by Weidmann. According to Fruin, pedestrians tolerate closer spacing on stairways than on level surfaces because of the restricted locomotion on stairways; besides stair climbing needs larger space than descent.

  With respect to jam densities on level surfaces, the value of 4.1 P/m^2 estimated by Fruin infers an area of about 0.24 m^2 available for individual pedestrians which approximately equals the size of the human body ellipse described in section 2.2.1; the value of 5.4 P/m^2 assumed by Weidmann describes a condition when body contacts among pedestrians is less likely avoidable since only an area of about 0.19 m^2 is available for individuals.

  However, the way people use space on stairways may be different from what they do on walkways because of the physical constrains caused by the configuration of stairways. For instance, the depth of treads regulates the spatial distribution of pedestrians in the longitudinal direction. That means the longitudinal spacing of pedestrians on stairways is restricted by the tread depth. Thus, the jam density on stairways is determined not only by the physical size of pedestrians but also the configuration of stairways. If we consider stairways with tread depths equal 30 cm, which is similar to the depth of human bodies (33 cm for fully clothes male laborers, Fruin 1971a), we have a situation similar to that described by Weidmann, of which a common value of jam density may exist for flows on walkways as well as on stairways.

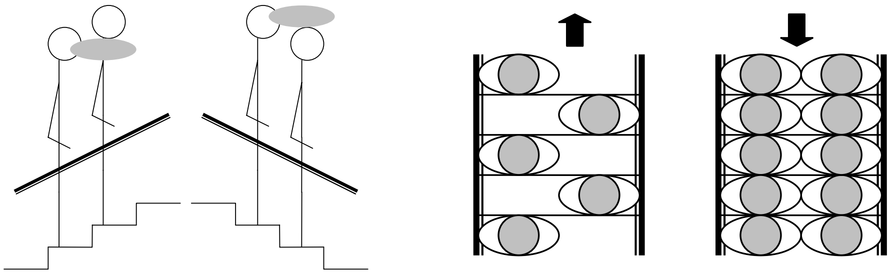
  In addition, we argue for a smaller jam density on stairways than on walkways due to the higher safety concerns on stairs. To protect their required space for keeping balance on stairways pedestrians may step on two treads instead of only one, which leads to a reduction of densities on stairways.

- **Jam densities of descending and ascending flows on stairways**

  With respect to jam densities on stairways, Fruin has observed a smaller value in the descending direction while a constant value is assumed by Weidmann in both directions. We discuss the way pedestrians use space in the vertical dimension based on the study by Davis & Dutta (2002) in the following paragraphs.

  Davis & Dutta have studied the capacity of escalators in London Underground stations. In their study, they describe the influence of the "facial ellipse" on the spatial distribution of standing passengers on ascending and descending escalators. This facial ellipse refers to the space in front of the face of a person which is highly valued by individuals. An intrusion on this facial ellipse will cause great discomfort and anxiety to the person since it may hinder the visibility and cause losses of personal space. Thus, they have observed that passengers stand closer on down escalators than on up ones since this facial ellipse is less possibly intruded in descending direction (see Figure 2.5).

  We assume that similar situations exist on stairways. Thus, when the density is approaching the jam density, where people are almost standing still on stairways, the requirement of a clear facial will lead to a lower jam density on ascending direction.



(a) ascend (b) descend (c) ascend (d) descend

Figure 2.5

It is observed that passengers stand closer on down escalators than on up one since their facial ellipse is less possibly intruded in descending direction (reference from Davis & Dutta 2002).

Capacity of pedestrian facilities

The capacity of pedestrian facilities is one of the most critical parameters related to pedestrian designs in public transport facilities. Daly et al. (1991) and Lam et al. (2000) have conducted thorough investigations on flow characteristics for different types of pedestrian facilities at metro stations in London and Hong Kong respectively. We summarize their findings about the capacity of passageways, stairways, and escalators in Table 2.3.

Table 2.3
Capacities of pedestrian facilities from literature (one-directional flow)

Infrastructure Type	unit	Daly et al. (1991)[1] MTR station (UK)	Lam et al. (2000)[2] MTR station (HK)
Passageway	P/m/min	86	92
Stairway (up)	P/m/min	62	70
Stairway (down)	P/m/min	68	80
Escalator (up)	P/esc/min	120	120
Escalator (down)	P/esc/min	120	120

Note:
[1] Facility dimensions of London Underground are not available
[2] Facility dimensions of HK MTR station are given as follows:
Escalators: riser height = 20.5 cm; tread depth = 40.5 cm; tread width = 100 cm
Stairways: riser height = 15.0 cm and tread depth = 30.5 cm

Common escalator capacity is found by these two studies. However, relative larger capacities of passageways and stairways are measured in the MTR station in HK. This is explained by the smaller physical size and the higher level of acceptance on closer spacing exhibited by Asian pedestrians (Lam et al. 2000).

Traditionally, the capacity of a walkway or stairway is calculated with the following formula:

$$C = C_u \times W_e \tag{2.3}$$

where C = capacity of a walkway or stairway; C_u = capacity per unit width of a walkway or stairway; and W_e = effective width of a walkway or stairway. The unit width capacity depends on pedestrian characteristics (eg. gender, age, trip purpose, walking direction), infrastructure characteristics (eg. grade and dimension of stairs), and movement conditions (eg. weather and temperature) (Hoogendoorn 2004). Due to the fact that pedestrians always keep some distance from the edge of the infrastructure, which means that some part of the infrastructure is not used by pedestrians, the actual capacity of a walkway or stairway is determined by the effective width rather than its total width. This so-called shy-away distance is determined by factors such as wall condition (eg. wall material), pedestrians' freedom of movement (eg. presence of obstacles and opposing flows), and density (Daamen 2004).

However, the study of Hoogendoorn & Daamen (2005) indicates that the capacity of a narrow bottleneck is not linear to its width but increases in a stepwise manner. Based on their concept of "dynamic layers", which describes following behavior of pedestrians in bottlenecks, following equation is proposed to determine the capacity (C) of a unidirectional bottleneck:

$$C = c_l \cdot \left\lfloor \frac{W_e}{d_{lane}} - \frac{w_{\max}}{d_{layer}} + 1 \right\rfloor \tag{2.4}$$

where c_l is the capacity per dynamic layer; $\lfloor x \rfloor$ denotes the smallest integer near x; W_e is the effective width of a bottleneck; w_{max} is the maximum shoulder width of a pedestrian; d_{layer} is the lateral distance between two dynamic layers.

The influence of inverse or cross-flow traffic conflicts on the capacity of a walkway has been studied by Navin & Wheeler (1969). Their findings show that opposing flows do not drastically reduce the capacity of a walkway. A minor traffic stream of 10% will cause an about 14.5% reduction on maximum flow. When the two opposing streams are almost equal in proportion (50:50), only a 4% reduction is observed. However, the situation on stairways will be different. Because of higher safety concerns, it is observed that pedestrians will have less side-stepping and bypassing maneuver on stairs. Thus, a minor opposing traffic flow can effectively cut stairway capacity in half, particularly on a narrow stairway (Fruin 1971a). It is noted that the influence of opposing traffic on pedestrian walking behavior is not discussed in this report.

2.2 Route choice behavior of pedestrians

This section reviews route choice behavior of pedestrian given in literature. We first give a presentation about the theory of random utility maximization and binary logit models to provide some theoretical background on modeling choice behavior of travelers. Following that, we present some empirical studies. However, due to limited literature available, we focus on discussing factors influencing pedestrian route choice behavior and the two empirical models concerning route choice in the vertical dimension by Cheung & Lam (1998) and Daamen et al. (2005). It is noted that no relevant data about the walk/stand choice behavior on escalators have been found in literature.

2.2.1 Random utility maximization theory

The study of pedestrian route choice behavior is normally based on the discrete choice theory with the concept of random utility maximization. It is assumed that a decision-maker (a pedestrian) always chooses the alternative (the route) with the highest subjective utility in a finite choice set. However, the utilities are not known with certainty to the analyst and are therefore treated as random variables. Four different sources of uncertainty are identified: unobserved alternative attributes, unobserved taste variations, measurement errors and imperfect information, and instrumental (or proxy) variables (Ben-Akiva, 1985).

Under the concept of random utility, for decision-maker n, the utility of alternative i is determined by the following expression:

$$U_{in} = V_{in} + \varepsilon_{in} \tag{2.5}$$

where U_{in} denotes the random utility; V_{in} is the systematic part of the utility which is known to the analyst (deterministic); ε_{in} is the stochastic part of the utility.

The systematic component V_{in} is a function of attributes attached to the alternative i and the decision maker n. Conventionally, it is specified as a function that is linear in the parameters given as follows:

$$V_{in} = \sum_k \beta_{nk} X_{ink} \tag{2.6}$$

where X_{ink} denotes the alternative-specific and individual-specific attributes; and β_{nk} is the parameter of attribute X_{ink} which reflects the preferences or taste of the decision maker.

In addition, the probability that alternative i is chosen by decision-maker n is equal to the probability that the utility of alternative i is larger than or equal to the utilities of other alternatives in the choice set C_n. This can be written as follows:

$$P(i|C_n) = P(U_{in} \geq U_{jn}, \forall j \in C_n) = P(V_{in} + \varepsilon_{in} \geq V_{jn} + \varepsilon_{jn}, \forall j \in C_n) \tag{2.7}$$

Finally, it is noted that the property and form of the resulting probabilistic choice model depends on assumptions about the distribution of the error terms.

2.2.2 Binary logit models

The binary logit model is a probabilistic choice model describing a specific choice situation when the choice set of a decision-maker contains exactly two alternatives. The model follows the concept of random utility maximization presented in the previous subsection (2.2.1), which means a decision maker selects an alternative that yields highest utility to him. Thus, according to equation (2.5), the utilities of these two alternatives can be expressed as follows:

$$U_{in} = V_{in} + \varepsilon_{in},\ i = 1, 2 \tag{2.8}$$

In addition, with regards to the distribution of the error terms in the utility function, it is assumed that the error terms are independently and identically Gumbel distributed. Under this assumption, given a choice set which contains two alternatives i and j, the probability of decision-maker n choosing alternative i is

$$P_n(i) = P(U_{in} \geq U_{jn}) = \frac{e^{V_{in}}}{e^{V_{in}} + e^{v_{jn}}} = \frac{1}{1 + e^{(V_{jn} - V_{in})}} \tag{2.9}$$

The probability of choosing alternative j is

$$P_n(j) = P(U_{jn} \geq U_{in}) = 1 - P_n(i) \tag{2.10}$$

It is noted from equation (2.9) that the choice probability of a binary logit model depends on the relative utility of the two alternatives (V_{jn}-V_{in}).

2.2.3 Empirical data of pedestrian route choice behavior

We discuss empirical data concerning route choice behavior of pedestrians. We focus on factors influencing the choice behavior and empirical models involving movement in the vertical dimension.

Influencing factors

Many factors influence the route choice behavior of pedestrians. A comprehensive review by Daamen (2004) has divided those factors into four categories: network characteristics (eg. overlapping of alternative routes), route characteristics (eg. distance, time, pleasantness, directness, crowdedness, safety, weather protection, noise and air pollution, and quality of walking surface), personal characteristics (eg. decision style), and trip characteristics (eg. trip purpose). However, with respect to route choice behavior in the vertical dimension, only the influence of travel time, travel distance and physical effort has been noted in literature (Daamen 2004). We discuss these factors below.

- **Travel time**

  Travelers always value travel time. Thus pedestrians prefer the route with the least travel time. The purpose of the trip plays a substantial role in determining to which extent factors such as travel time is perceived by pedestrians. Generally travel time is valued more highly by commuters than by tourists.

- **Physical effort**

  Walking consumes energy. To maximize travel comfort, pedestrians will choose the route involves the least physical effort. The amount of human energy involved in making a trip depends on the travel distance. The longer the travel distance the larger the demand on human energy. Besides, the physical effort is dependent on the types of terrain composed of the routes. For instance, stair locomotion involves higher energy consumption than level working. Thus the existence of stairways on a route may reduce its attractiveness to pedestrians particularly in the ascending direction. Moreover, it is noted that since walking involves not only the movement of extremes but also mental activities such as stimuli evaluation and reaction, the presence of opposing and conflicting traffic will increase the requirement of mental effort for concentration, and, consequently reduce the travel comfort.

Route choice between stairways and escalators

Cheung & Lam (1998) have studied route choice behavior of pedestrians in vertical dimension. They have applied a binary logit model to predict choices of pedestrians between a stairway and an escalator in HK MRT (Mass Rapid Transit) stations to change levels. In their model, they have considered the influences of travel time and physical effort on route choice behavior. According to their study, the choice probabilities of choosing escalators in descending and ascending directions are given as follows:

In the descending direction:

$$P_{esc} = \frac{1}{1+\exp(-3.1001-0.1745\Delta t)};\ R^2 = 0.8443 \tag{2.11}$$

In the ascending direction:

$$P_{esc} = \frac{1}{1+\exp(-5.3441-0.2073\Delta t)};\ R^2 = 0.8666 \tag{2.12}$$

where P_{esc} denotes the probability of choosing escalators, and Δt stands for travel time difference between stairways and escalators (Δt = travel time on stairways – travel time on escalators). Figure 2.6 illustrates these two models.

To ease the following discussion, we give below a standard format of a binary logit model.

$$P_{esc} = \frac{1}{1+\exp(\alpha+\beta\cdot\Delta t)} \tag{2.13}$$

where α denotes relative preferences between stairways and escalators, and β refers to utility costs of time.

The negative sign of α in equation (2.11) and (2.12) infers the relative attractiveness of escalators in both directions given all the other things equal. Besides, if there is no travel time difference between the two alternatives (Δt =0), about 96% of people choose escalators in descending direction while almost 100% pedestrians choose escalators in ascending direction. The extremely low preference on stairways is explained by the larger physical effort involved in stair locomotion. However, it is noted that still about 4% pedestrians choosing stairways in descending direction when the travel time is identical. This can be explained by the relatively low energy consumption involved in descent so that still few pedestrians use stairways when going downwards (Cheung & Lam 1998).

The negative sign of β in equation (2.11) and (2.12) indicates that travel time is viewed as disutility by pedestrians in both directions. When there is travel time difference between using stairways and escalators, pedestrians face a trade-off between physical effort and travel time involved in both alternatives. As we can seen from Figure 2.6, when travel time on stairways is less than that on escalators (Δt <0), the attractiveness of stairways increases, and some pedestrians shift their choices from escalators to stairways. In addition, the smaller absolute value of β in the descending direction indicates that pedestrians are more sensitive to relative delays on escalators when descent. For instance, about 85% of pedestrians use escalators when relative delays are up to 7.8 s in the descending direction while 17.4 s is acceptable for the ascending direction. This is explained by the fact that the physical effort involved in decent is less than that in climbing (Cheung & Lam 1998).

Although these two models show strong explanatory powers on the choice behavior, there are two aspects missing in their study. Firstly, the models consider only the influence of relative delays between the two alternative routes. Taking into account the limitation of human bodies, we argue for models concerning the total travel time since the perception towards the physical effort involved in a trip is dependent on the scale of time involved. That means people may behavior differently at situations involving a 1-minute climb and those with 10-minute climb. Secondly, the acceptance of physical effort and travel comfort may depend on personal characteristics of pedestrians. Thus we may expect different behaviors between the two sexes and among different age group. The extra burden from luggage may lower the acceptance level as well.

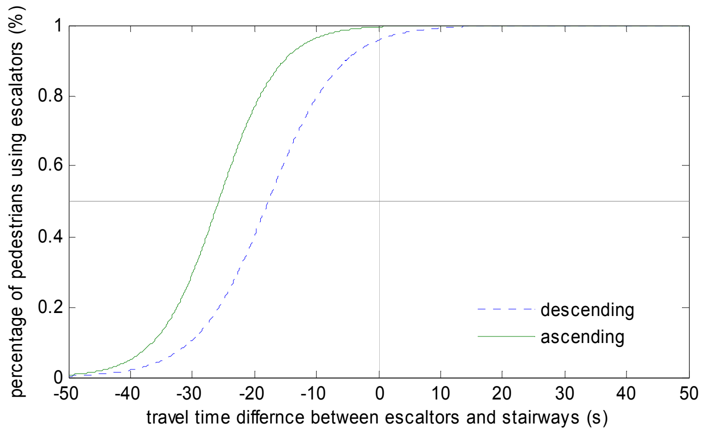


Figure 2.6
Empirical model concerning route choice behavior between a stairway and an escalator derived by Cheung & Lam (1998) at HK MTR stations

Route choice model concerning level changes

Daamen et al. (2005) have also studied the route choice behavior of passengers in public transport facilities. The main purpose of their study is to get insight into the influence of infrastructure types on route choice behavior in particular those bridging level changes such as stairways, escalators and ramps. In addition to walking time and physical effort involved in walking on different types of infrastructure, they considered the influence of route overlapping in their model. Therefore, a path-size logit model is adopted for the purpose. Based on the data collected with the method of stalking (or following pedestrians) in two Dutch railway stations, an estimated utility function is given as follows:

$$U_r = -0.130T_r^l - 0.242T_r^{st} - 0.167T_r^{esc} - 0.178T_r^{ramp} + 3.181PS_r + \varepsilon_r \text{; } R^2 = 0.76 \qquad (2.14)$$

where

U_r	= utility of taking route r
T_r^l	= walking time on a level part of the infrastructure being part of route r
T_r^{st}	= walking time on stairs in route r
T_r^{esc}	= walking time on escalators in route r
T_r^{ramp}	= walking time on ramps in route r
PS_r	= path size of route r
ε_r	= error term of route r

The first four variables (T_r^l, T_r^{st}, T_r^{esc}, T_r^{ramp}) concern travel time on different infrastructure elements and the associated parameters reflect the utility cost of time concerning each element. The negative signs of these parameters indicate that walking time is viewed as disutility to passengers and the shortest route in time is preferred. The values of those parameters indicate the preference or attractiveness of various types of infrastructure. Level surfaces, with the biggest parameter (-0.13), is more favorable than the other three types of infrastructure involving vertical movement. This could be explained not only by the higher physical effort involved in vertical movement, but also passengers' negative spatial perception towards level changes which increase the complexity and indirectness of routes. In terms of the design of public transport facilities, this indicates the less attractiveness of multi-level ones. With respects to the three types of vertical infrastructure (stairways, escalators, and ramps), it shows that escalators are the most preferable mode for vertical transport while stairways have the least attraction to passengers, which corresponds to the level of physical effort involved in walking on these vertical infrastructures (the higher the requirement on physical effort, the lower the attractiveness of the infrastructure).

The path size variable (PS_r) indicates the overlap factor of route r, and it is calculated by the following formula:

$$PS_r = \ln\left(\sum_{a \in r} \frac{l_a}{L_r} \cdot \frac{1}{N_a}\right) \tag{2.15}$$

where a is an index for an infrastructure element such as stairways, r is the route index, l_a is the length of element a, being a part of route r, and L_r is the total length of route r. N_a is the number of alternatives in the choice set of which element a is part of. The positive parameter of PS_r (+3.181) indicates that overlapping is treated as a kind of utility since it implies a higher degree of connection of the route with the entire network. A good connection to the network infers a higher possibility to change routes in case of congestion or accidents for instance.

2.3 Conclusions

This chapter reviews existing literature concerning walking and route choice behavior of pedestrians. With respect to walking behavior, we discuss human characteristics related to pedestrians design, the theory of pedestrian flows, and some empirical data in section 2.1.

A qualitative design of a pedestrian environment can never be achieved without a basic understanding about human characteristics and capabilities. The body ellipse model describes the plan view of an average pedestrian and provides a simple way to visualize situations involving confined pedestrians. The concept of body buffer zone determines the intra-person spacing of pedestrians in public environment. The space required for human locomotion is divided into the pacing zone and the sensory zone, which is influenced by factors such as personal characteristics of pedestrians (eg. physical size, gender, age, human vision, reaction time, etc.), terrains and speeds. The sizes of these two space zones describe dynamic feathers of pedestrian flows.

Compared with walking locomotion on level surfaces, stair locomotion is more restricted and stylized. Stair locomotion is characterized by restricted pacing distances, shifts of the body gravity, utilization of the acute cones of vision for foot placement, and higher energy consumption. With respect to moving directions on stairways, higher requirements on human energy and concentration for the control of gravity shifts reduce the average walking speeds in the ascending direction.

The fundamental relation of pedestrian flows given in equation (2.1) describes the relationships of macroscopic traffic characteristics: flow, speed, and density. In general, a liner relationship between the speed and the density is assumed for flows on level surfaces and on stairways (see Table 2.2). When densities increase, the available space for locomotion is decreased and pedestrians reduce their speeds for reasons of safety and comfort. It is noted that no studies concerning the fundamental relation of pedestrian flows on escalators are found in literature.

Free speeds are influenced by many factors. We discuss the influences of gender and age of pedestrians, directions of movement, and infrastructure types and configurations. In general, male pedestrians walk faster than females ones; walking speeds of adults decline with age; speeds on stairs are lower those on level surfaces; climbing speeds are smaller that those of descent.

With respect to jam densities on stairways, only the studies by Fruin (1971b) and Weidmann (1993) are found in literature. However, they have different perceptions toward the spatial usage of pedestrians on stairways. Fruin has estimated various jam densities for flows on level surfaces, ascending on stairways, and decending on stairways, while a constant value is assumed by Weidmann. Our discussion in subsection 2.1.3 indicates that the jam density is determined by the physical size of pedestrians as well as the tread depth of stairways. Taking into account the facial ellipse described by Davis & Dutta (2002), we argue for a smaller jam density in the ascending direction on stairways.

Section 2.2 gives a literature review on route choice behavior of pedestrians. The theory of random utility maximization and binary logit model presented in subsection 2.2.1 and 2.2.2 provide some theoretical background about modeling choice behaviors of travelers. The influences of travel time, travel distance, and physical effort on pedestrian route choice behavior in the vertical dimension have been found in literature. The two empirical models by Cheung & Lam (1998) and Daamen et al. (2005) consider the effects of relative delay and physical effort on route choices concerning level changes. However, we argue for models taking into account the absolute travel time as well as personal characteristics of pedestrians due to the concerns of human capabilities.

Through the literature review given in this chapter, we identify that the fundamental diagrams and the walk/stand choice behavior on escalators are blank spots to our research questions since no relevant studies are found in literature. Studies concerning walking on stairways and route choice behavior in the vertical dimension are also quite limited. However, together with the results of empirical studies, the existing theories concerning pedestrian flows and travel choice models are used as starting points for the building of our conceptual walking and choice models in this project.

3 Modeling Walking Behavior in the Vertical Dimension

This chapter presents models describing walking behavior of pedestrians on stairways and escalators inside public transport facilities. The stairway and escalator-related traffic processes may be divide into three stages: the approaching stage, the stage of level changes, and the exiting stage. These three stages concern behavior of approaching, utilizing, and exiting stairways or escalators respectively. We describe these three stages in section 3.1.

However, in this report, we mainly concern the macroscopic traffic characteristics in the stage involving vertical movement, which is the stage of level changes. We especially focus on the speed-density relationships of pedestrian flows on stairways and escalators. Based on the theoretical and empirical data presented in section 2.1, bi-linear models are adopted for the formulation of the speed-density relationships. We present these walking models concerning pedestrian flows on stairways and escalators in section 3.2 and section 3.3 respectively. We describe the concept behind this bi-linear format of speed-density relationship. Special points of the walking models such as the free speed and the jam or maximum density will be discussed in more details.

3.1 Traffic processes concerning level changes

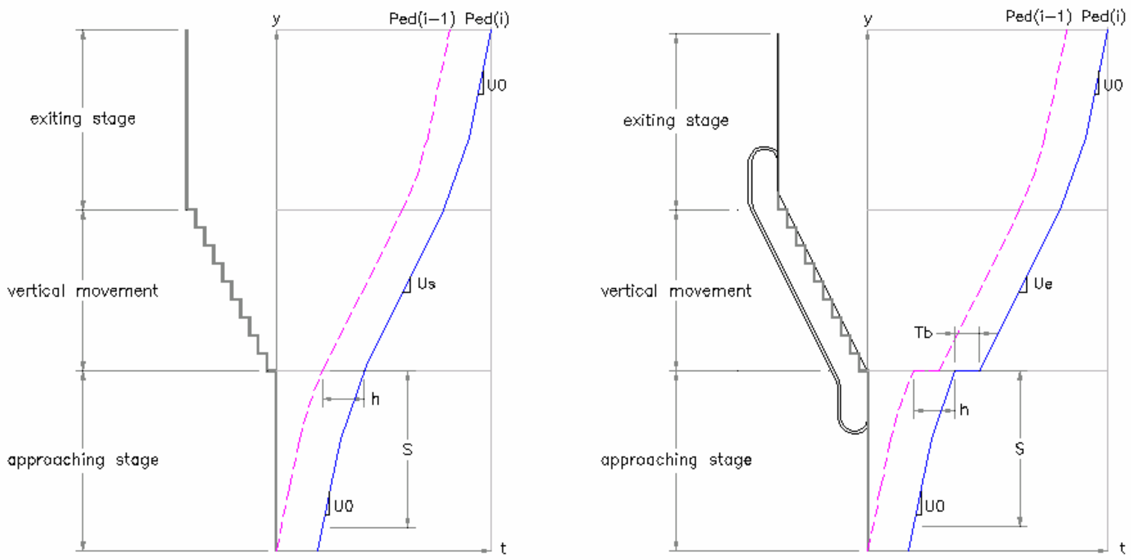
Based on our observations, we divide the stairway and escalator-related traffic process into three stages: the approaching stage, the stage of level changes, and the exiting stage (see Figure 3.1). The distinction is made to reflect the change of terrains as well as the variation of traffic behavior. We discuss traffic behavior in these three stages in the following paragraphs.

The first stage is the approaching stage, where pedestrians approach either a stairway or an escalator to facilitate level changes. In a typical public transport facility, the approaching terrains are mostly composed of horizontal elements such as platforms, passageways, and hallways. A prominent traffic behavior of this phase is queuing, which occurs particularly at dense traffic conditions. When a queue is formed in front of that vertical infrastructure, pedestrians will experience a certain amount of delay. Cheung & Lam (1998) have measured a lower speed on the walkways leading to escalators and stairways at metro stations in HK. The observed tendency towards decelerating at this stage may be explained by psychological influences resulting from expecting changes in terrains and locomotion as well as queues observed when approaching.

The second stage describes traffic behavior involving vertical movement to change levels. Based on the direction of movement, this stage considers either ascending or descending behavior. The most important microscopic traffic characteristics include speeds and headways. At light traffic conditions, pedestrians select their desired speeds, while the headways are mostly dependent on arrival processes of passengers. When the flow is high, less freedom on speed selection exists and pedestrians tend to keep a minimal headway between their predecessors for reasons of safety and comfort. It is noted that for passengers entering an escalator, the boarding behavior is characterized by a boarding time taken by individual passengers to get on the first moving step. However, this kind of boarding behavior is not noticeable on stairways since those steps are static.

The final stage concerns walking behavior after leaving those vertical facilities. When referring to pedestrian traffic in public transport facilities, typical terrains of this stage include platforms, passageways, and hallways. The transition between the second and this final stage is remarked by the change of terrains as well as an expected accelerating behavior of pedestrians.

In this report, we focus on pedestrian walking behavior concerning the stage of level changes. More details about both microscopic as well as macroscopic traffic behavior on stairways and escalators will be discussed in the remaining part of this chapter.



(a) (b)

Figure 3.1
(a) Stairway and (b) escalator-related traffic processes are divided into three stages: the approaching stage, the vertical movement stage, and the exiting stage. Ped(i) represents the space-time trajectory of an ascending pedestrian on either a stairway or an escalator while Ped(i-1) represents the trajectory of his predecessor. U_0 denotes his normal walking speed on level surfaces. His speed at the approaching stage may be lower than U_0 due to reasons such as delay caused by queues or his reflective behavior connected to expectation on terrain changes. The speed at the vertical movement stage (U_s or U_e) is determined by the characteristics of infrastructure involved. Contrary to the approaching stage, an accelerating behavior is expected in the exiting stage. Finally, a noticeable boarding time (T_b) is required to get on the escalator.

3.2 Walking model on stairways

The fundamental flow-speed-density given in equation (2.1) describes the macroscopic traffic characteristics of pedestrian flows. As we have mentioned in subsection 2.1.2, the three interrelated fundamental diagrams (flow-density, speed-density, and speed-flow diagram) can be derived if any one of them is known since they provide the same information. In this report, we focus on the speed-density relationship of pedestrian flows since the relation between the speed and the density is better known and can be formulated with a simple mathematical form. We discuss the relation between speeds and densities below.

People need space when walking. The space is needed for both pacing and sensory requirements. In comparison to level walking, stair locomotion demands less space due to the restricted locomotion on stairs. The pacing length of stair locomotion is restricted by the depth of treads which is generally about half of a normal pacing distance. In addition, the shifts of visual angle between the comfortable 60-70 degrees to the attentive 3-5 degrees characterized by stair users makes the size of sensing zones less significant to speeds on stairways. Thus, we assume that a smaller space is required for freely walking on stairways and pedestrian can maintain free walking at low certain low density conditions.

However, when densities increase, the space available for individual pedestrian may not be sufficient anymore for free walking. Thus increased densities imply not only a reduction of space available for pacing and sensing but also a higher possibility of being hindered by proceeding pedestrians. Hence pedestrians decrease their speeds for reasons of safety and comfort when densities increase. At extremely crowded situations, where densities equal jam densities, we assume pedestrians are confined in the flow and cannot proceed anymore.

Based on the above description, a bi-linear model is proposed to describe the speed-density relationship of pedestrian flows on stairways in both ascending and descending direction. The selection of this bi-linear format is due to their simplicity in forms as well as their capability on describing traffic behavior of concern. Some important feature of the models such as the free speeds and the jam densities will be discussed in more details. We present these bi-linear models with the following expressions:

$$u = u_0 \text{ if } k \le k_f \tag{3.1}$$

$$u = u_0[1 - \frac{(k - k_f)}{(k_j - k_f)}] \text{ if } k_f < k \le kj \tag{3.2}$$

where u is the speed of flows, u_0 is the free speed, k is the density, k_f is the maximum density when speeds equal the free speed, and k_j is the jam density.

It is noted that the models given in equation (3.1) and (3.2) are applied to flows in both descending and ascending direction. However, due to the different traffic characteristics between descending and ascending flows, the values of u_0 and k_j may be different. We illustrate our hypothesized speed-density models in Figure 3.2. We discuss the free speed and jam density of descending and ascending flows on stairways in the following paragraphs.

As we have discussed in section 2.1.3, free speeds are influenced by directions of movement. Empirical studies show that speeds in the ascending direction are lower than those in the descending one because of higher human energy involved in climbing stairs. Thus a lower free speed is assumed for ascending flows on escalators. In addition, taking into account the influence of “facial ellipse” on the spatial usage of pedestrians described by Davis & Dutta (see subsection 2.1.3), a smaller jam density is assumed for ascending flows on stairways.

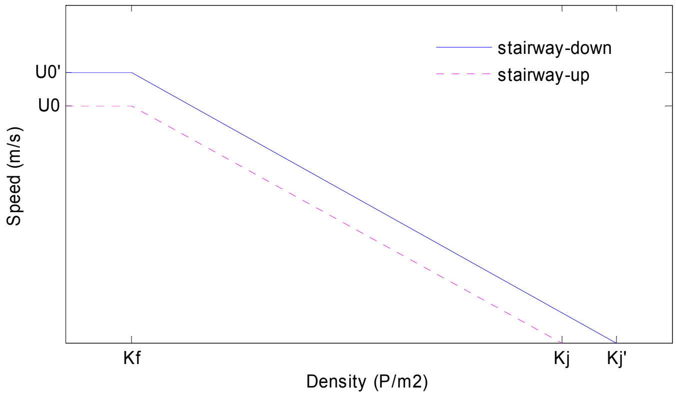


Figure 3.2
Hypothesized speed-density relationships for pedestrian flows on stairways: u_0 and $u_0^{'}$ denote the free speeds of ascending and descending flow respectively; k_j and $k_j^{'}$ stand for the jam densities in the ascending and descending direction respectively; k_f is the biggest density when speeds equal free speeds.

Finally, we discuss the influence of personal characteristics on the selection of speeds at free-flow situations on stairways. When the traffic is light, pedestrians are more freely on selecting their speeds in either up or down directions, and personal characteristics, namely gender and age, are more distinctive under this situation. However, when densities increase, individual walking behavior becomes more restricted due to the reduction of space available for pacing and sensing and, consequently, less freedom exists for choosing desired speeds. The influence of increased densities on speeds is more profound for fast walkers because they are more easily hindered by slower walkers on crowded stairways. Hence, the variation of speeds decreases when densities increase, which infers a more homogeneous flow at dense situations.

3.3 Walking model on escalators

Since no empirical data concerning the speed-density relationship of pedestrian flows on escalators is available, we discuss our hypothesized walking model on escalators based on understandings about stairways traffic and our real-life observations in this section. Taking into account the composition of standing and walking passengers on escalators, we discuss traffic characteristics of escalator flows by considering the following three situations:

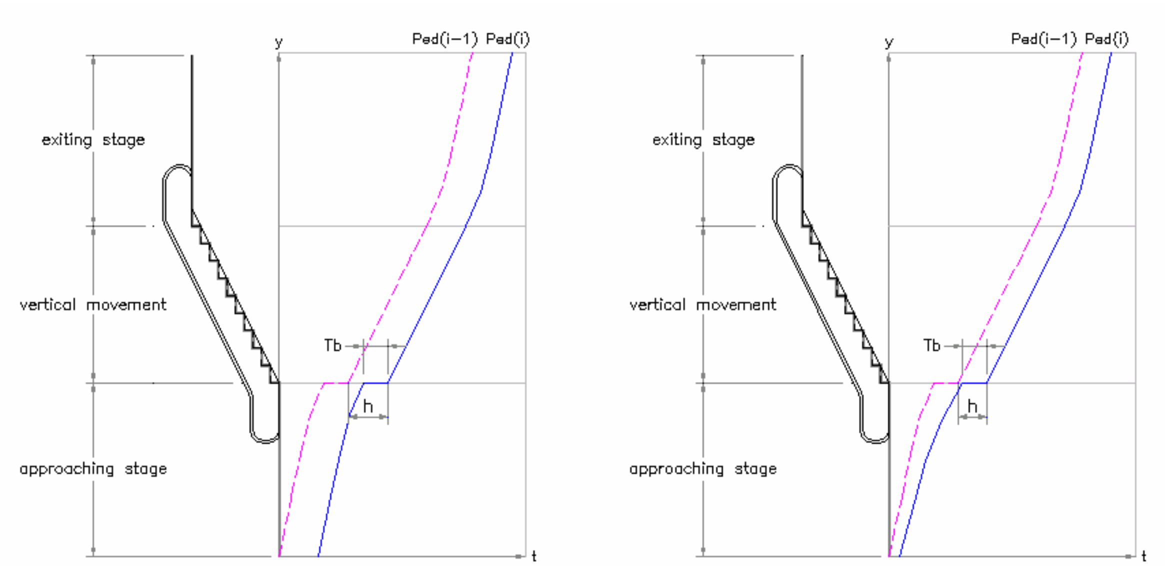
- Case I : with only standing passengers on escalators
- Case II : with only walking passengers on escalators
- Case III : with both standing and walking passengers on escalators

Case I : with only standing passengers

The situation where only standing passengers presenting on escalators generates the simplest traffic behavior of pedestrian flows. The speeds of passengers are synchronized with the operating speed of the escalator unit except at the entry and exit sections. Thus the flow is just in proportion to the density. Besides, at low density conditions the flow on escalators is dependent on the arrival process of passengers while at high flow situations it is determined by the distribution of boarding time (see Figure 3.3). Moreover, we replace the concept of jam densities by a concept of maximum densities since flows on escalators never stop (there is no traffic state of zero speed and zero flow on escalators).

The maximum density, which is determined by the tread depth of escalators and the spacing of passengers on it, refers the maximum number of standing passengers present per unit area at a given moment. However, the theoretical capacity of escalators claimed by manufactures can never be reached because of the phenomenon of empty steps observed on escalators (Fruin, 1971a). It is observed that there are always empty steps on escalators even at very congested situations. The phenomenon of empty steps occurs because some people just cannot board on escalator steps as quickly as possible or because they desire a more comfortable personal space on escalators.

With respect to influence of movement directions on flow characteristics, a higher maximum density and capacity are assumed for down escalators. We give our hypothesized fundamental diagrams of descending and ascending flows on escalators in Figure 3.4.



(a) light traffic conditions (b) saturated traffic conditions

Figure 3.3
At light traffic conditions (a), flows on escalators depend on arrival processes of pedestrians, while at saturated situations (b) boarding time becomes a determinant to flows or capacities of escalators.

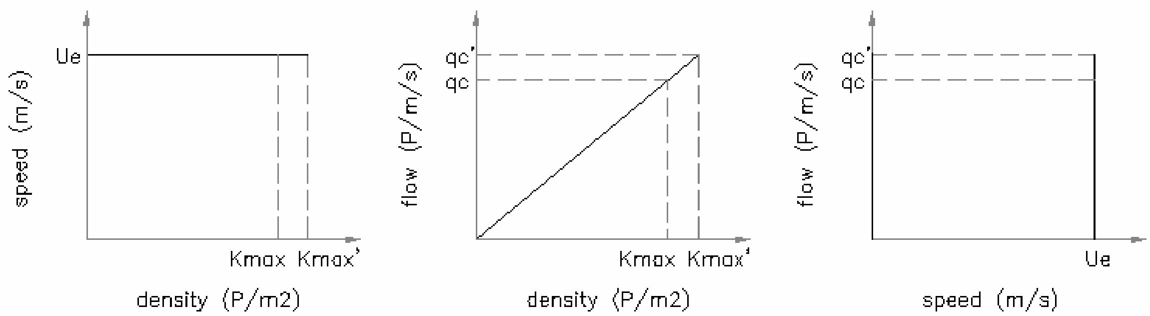


Figure 3.4
Fundamental diagrams of escalator flows only consisting of standing passengers: k_{max} and k'_{max} are the maximum density in the up and down direction; U_e equals to the operating speed of escalators; q_c and q_c' are capacities in the up and direction.

Case II: with only walking passengers

When all passengers walk on escalators, we get a traffic condition similar to that on stairways. Thus, following our discussion about stairway traffic in subsection 3.2, in this report, a bi-linear model is hypothesized for the associated speed-density relationship. However, two differences are pointed out here. One concerns the minimal speeds, which now equals the operating speed of escalators; the other one considers the concept of maximum densities on escalators (refer to Case I). Thus, the speed-density relationships are given by the following expressions:

$$u = u_0 \text{ if } k \le k_f \tag{3.3}$$

$$u = u_0[1 - \frac{(u_0 - u_e)}{u_0} \times \frac{(k - k_f)}{(k_{\max} - k_f)}] \text{ if } k_f < k \le k_{max} \tag{3.4}$$

where u is the speed of flows, u_0 is the free speed, u_e is the operating speed of escalators, k is the density, k_f is the biggest density when speeds equal the free speed, and k_j is the jam density. We describe these relationships graphically in Figure 3.5.

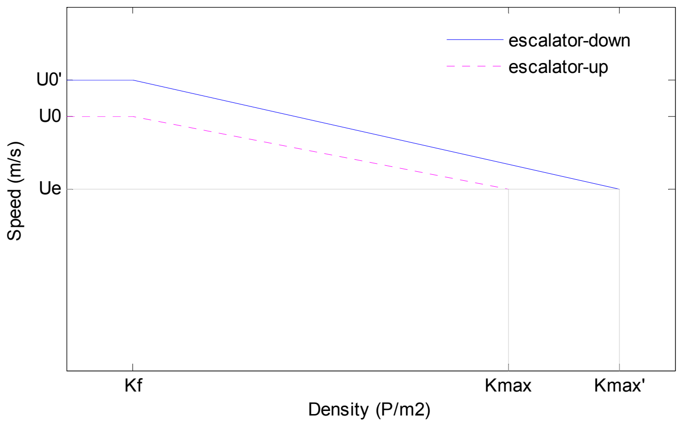


Figure 3.5
Hypothesized speed-density relationships of escalator flows only consisting of walking passengers: u_0 and u_0' denote the free speed of ascending and descending flow respectively; k_{max} and k_{max}' stand for the maximum densities on up and down escalators respectively; u_e denotes the operating speeds of escalators.

Case III: with both standing and walking passengers

When there are both standing and walking pedestrians on escalators, the traffic behavior will be rather unstable and unpredictable. In addition to travel speeds, the walking and standing passengers on escalators differ from their spatial requirement. When standing on escalators, the spacing of passenger is governed by the concept of body buffer zone and human body ellipse; when walking on escalators, the spacing or the distance headway is determined by the length of the pacing and the sensory zone.

To simplify the analysis, we consider only escalators with a width of 100 cm, which allows two passengers standing on the same tread. In addition, we consider a situation where pedestrians only stand on the right side and walk on the left side of the unit. Under these assumptions, the traffic behavior on the right lane and the left lane can be described by models hypothesized in Case I and Case II respectively. Thus, the maximum flow or capacity of the escalator (q_c) is simply the sum of the capacity measured at the standing side (q_c^s) and walking side (q_c^w).

$$q_c = q_c^s + q_c^w \tag{3.5}$$

However, it is noted that in this case, flows on the standing and walking side of the escalator are not only dependent on the arrival process and boarding time of passengers, but also influenced by the traffic demand of these two sides or the ratio of the number of passengers choosing the standing side to the number of people using the walking side. Therefore, even at saturated conditions, if only a small portion of people use the walking side, the available capacity will not be used efficiently regardless of high demand. The study by Davis & Dutta (2002) indicated that ratio of walking and standing passengers is influence by factors such as the rise, existence of other escalators, and accessibility.

According to our above discussion, the speed-density relationship on escalators may be presented by the graph given in Figure 3.6. The relationships derived for Case I and Case II form the lower and the upper boundaries of the diagram respectively. Thus, if we consider a situation when both standing and walking passengers present on escalators and no regulations about the escalator usage exist, the speed-density relationship of the traffic may be presented by the area between these two lower and upper boundaries.

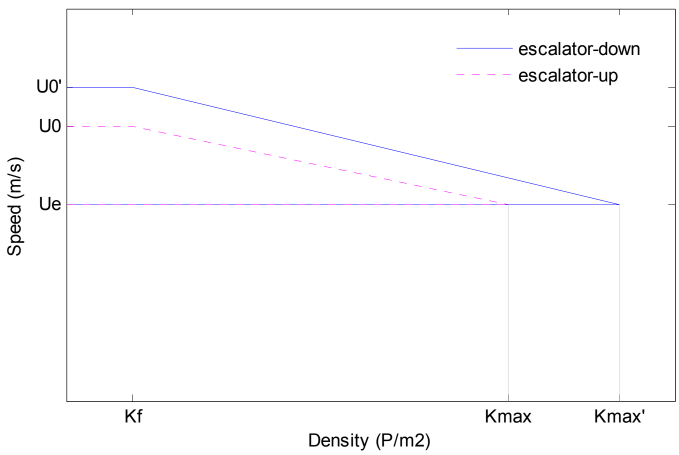


Figure 3.6
Hypothesized speed-density diagram of escalators flows. When concerning a situation when both standing and walking passengers present on escalators and no regulations about the escalator usage exist, the speed-density relationship of the traffic may be described by the area between the lower and upper boundaries derived from situations of Case I and Case II respectively.

4 Modeling Choice Behavior in the Vertical Dimension

This chapter presents models describing choice behavior of pedestrians involving movement in the vertical dimension. Although several different types of facilities such as ramps, lifts, stairways and escalators are commonly used to bridge level changes, in this report, we focus on the choice behavior only concerning stairways and escalators in public transport facilities.

Two types of choice behavior will be discussed in this chapter. The first one concerns route choices between stairways and escalators (the stairway/escalator choice model). We discuss how pedestrians make a choice from several available stairways and escalators to change levels. In this report, we apply the discrete choice theory with the concept of random utility maximization for the model formulation. We assume that a pedestrian always chooses the route with the highest subjective utility among several available alternatives. Based on the theories and empirical data presented in section 2.2, we focus on discussing the travel situations on stairways and escalators as well as factors influencing this stairway/escalator choice behavior in section 4.1.

The second one considers travel choices between walking and standing on escalators (the walk/stand choice model). The study of this walk/stand behavior on escalators is divided into two stages. In the first stage, the availability of choices is discussed; in the second stage, factors influencing this walk/stand choice behavior are identified. Since there are no relevant studies found in literature, the discussion is made based on our observations of real-life passenger behavior on escalators. We elaborate this walk/stand choice behavior in section 4.2.

4.1 Route choice between stairways and escalators

This section presents our hypothesized route choice models concerning making a choice between stairways and escalators to change levels. According to Bovy (1990), the choice situation consists of all possible routes between a given origin and a given destination. It defines the set of choices or alternatives considered by a traveler. With respect to the route choice behavior we are discussing in this section, the number of alternatives simply equals the quantity of vertical infrastructure available at the decision point. Besides, each alternative route is composed of exactly one element of infrastructure, which in our case is either a stairway or an escalator. So what makes these alternatives differ from each other to a pedestrian?

We discuss travel situations on stairways and escalator and factors influencing this stairway/escalator choice behavior in subsection 4.1.1 and 4.1.2 respectively.

4.1.1 Travel situations on stairways and on escalators

A pedestrian differs from a traveler of other transportation modes in the level of his physical involvement in realizing a trip. Traveling on foot requires both time and physical effort. Besides, being barely exposed to the traffic, a pedestrian has higher concerns about the safety and comfort on the trip, which means they are conflict-averse. Those features of pedestrians are determinant to their travel behavior.

Escalators are invented for the need of pedestrians. Conventionally installed with an inclination of about 30 degrees, escalators provide another means of traveling in the vertical dimension. The higher risers and deeper treads of escalator steps are designed to accommodate passengers standing on them. Unlike traditional stairways, escalators provide mechanical aids to change levels which are favorable to passengers with less physical fitness or with luggage. In addition, since those machines are operating in one direction (either up or down) at one time, they unify the direction of pedestrian flows. Thus in comparison with traveling on stairways, traveling on escalators require no effort on avoiding opposing traffic and relatively low levels of concentration for interacting with others or for boarding on the units. These enhance both the safety and comfort for traveling with escalators.

Normally, those escalators installed in public transport facilities are operating at a slope speed of 0.6 m/s or 0.75 m/s, which is equivalent to a horizontal speed of 0.52 m/s or 0.65 m/s respectively. According to Daly et al. (1991), (horizontal) free speeds of one-directional flows on stairways are about 0.59 m/s in the ascending direction and 0.67 m/s in the descending one. Thus, for an escalator operating at a slope speed of 0.75 m/s, the speeds on the escalator is in average larger than that on a stairway in particularly when traveling upwards. However, for escalators operating with a slope speed of 0.6 m/s, escalators may not be attractive to people with time pressures.

It is noted that up to now our discussion is limited on the situation when passengers only stand on escalators. However, this situation does not always hold in reality. Observations from real-life situations tell that people walk on escalators as well even though the size of escalator steps is not appropriate for human locomotion. Daly et al. (1991) have measured free walking speeds on escalators in London Underground stations. Their results show that the free speed on escalators is about 0.84 m/s in the up direction and 1.0 m/s in the down direction. Walking on escalators increases the travel speed, and, consequently reduces the travel time.

At low flow conditions passengers can almost freely decide on either to walk or stand on escalators. Thus, for passengers with or without time pressures, escalators dominate the choice situations by providing either comfort to those unhurried (standing) passengers or less travel time for those hurried (walking) ones. That is the situation we observe in reality: the coexistence of walking and standing pedestrian on escalators. Although still some people use stairways even when there is an empty escalator beside, those cases may be explained by factors such as habits, health concerns (take stair-walking as exercises), the approaching direction, groups, the presence of obstacles or conflicts near escalator entrance, or the randomness of human behavior.

However, when flows increase, the traveling situations change for both stairway and escalator users. The travel time on stairways increases with flows. The increased flow may cause more dramatic changes to traffic on escalators since the choice of walking on escalators may not exist anymore. Besides, the probability of getting blocked by standees on escalators increases with flows. Thus, at dense situations, passengers using escalators are also taking risks of been blocked, which may be highly concerned by passengers with time pressures. This may explain the observations that more people use stairways instead of escalators when flow increases. Depending on the operating speeds of escalators, passengers may face a trade-off between travel time and comfort on these two types of facilities.

4.1.2 Influencing factors of stairway/escalator choices

Based on our discussion about travel situations on stairways and escalators in the previous section, we find that many factors may influence the stairway/escalator choice behavior. According to the utility theory, the utility of an alternative is defined by attributes of the alterative and the decision maker. With respect to the stairway/escalator choice, the main alternative attributes may include the travel time and travel comfort. The main attributes of the decision maker, the pedestrian, may contain his gender, age, time pressure, habit, health concerns and travel conditions (eg. presence of luggage or travel in group). We discuss these influencing factors in more details in the following paragraphs.

With respect to pedestrian route choice behavior in the vertical dimension, only factors of travel time and physical effort have been identified in literature (see subsection 2.2.3). The relative delay and higher physical effort involved in making a trip via an alternative route will decrease its attractiveness to a pedestrian. However, based on our studies, we find that the choice behavior of pedestrian are far more complicated since quite some other factors play roles in the route choice behavior as well. In this section, we focus on the choice behavior concerning stairways and escalators to change levels. We give a summary about factors influencing this stairway/escalator choice behavior below. We discuss factors of travel times and time pressures, physical efforts, safety and comfort, personal characteristics, and vicinity.

- **Travel time and time pressure**

  Travelers always value the time spent on a trip. Thus pedestrians prefer the route with the least travel time. To which extent the travel time is perceived by pedestrians is mainly determined by the trip purpose or the time pressure facing by pedestrians. Normally, the travel time is more highly valued by commuters than tourists. In this report, we focus on pedestrians inside public transport facilities. However, our observations find that two groups of passengers exist in public transport facilities: passengers with time pressures and passengers without time pressures. Although we expect different route choice behavior between these two groups of passengers, we simply neglect this difference in this report since it is rather difficult to identify whether a pedestrian is with time pressure.

  However, taking into account human limitations, the perception towards the travel time may depend on the scale of time as well. Than mean the value of time of a 10-minute walk may be different from that of a 1-hour walk. Although pedestrians may increase their speeds to shorten their travel time, this requires extra human energy. Thus the choice behavior is influence by the relative delay as well as the total travel time of alternative routes.

- **Physical efforts**

  Walking consumes energy. Thus pedestrians prefer the route involving least physical effort. With respect to movement in the vertical dimension, the physical effort involved is determined by factors such as the configuration of infrastructure (slope and length), directions of movement (upwards or downwards), and the presence of luggage. Escalators provide chances for pedestrians to change levels without consuming energy, which is highly valued by pedestrians with poor physical fitness or with luggage.

- **Safety and comfort**

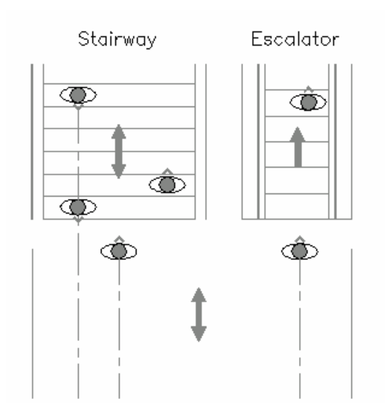
  Walking involves not only the movement of extremes but mental activities for interacting with others and the environment. External influences such as unfavorable terrains (eg. stairs) and the presence of conflicts (eg. opposing traffic) increase mental efforts required and consequently decrease travel comfort (see Figure 4.1). Escalators unify the movement direction of flows, and, consequently enhance travel safety and comfort. Finally, conflicting traffic on the approaching way leading to the facilities will decrease travel comfort as well.

- **Personal characteristics**

  The perception towards physical effort as well as safety and comfort may depend on personal characteristics such as gender, age or physical fitness, habit, and health concerns. In general, the female and the elderly are averse to physical effort and travel discomfort.

- **Vicinity**

  It is observed that pedestrians have higher inclination towards the nearest facilities. Thus based on their approaching direction, they may choose the first facility encountered on the way (see Figure 4.1).



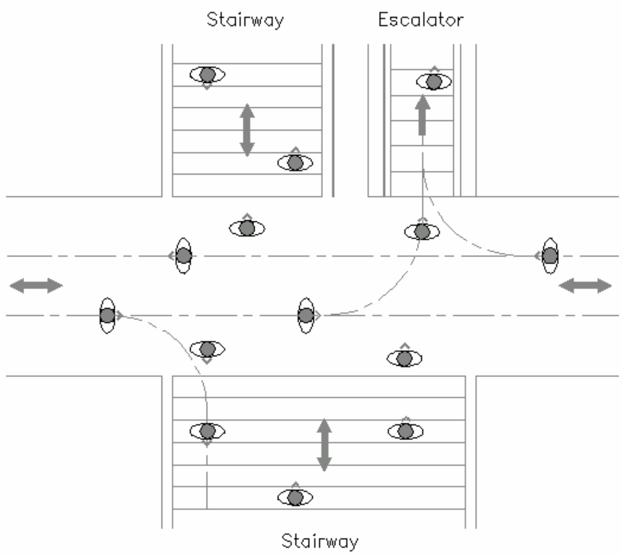


Figure 4.1
Examples of choice situations concerning level changes via stairways and escalators in public transport facilities.

Left: when flow directions are parallel to each other, factors such as travel time and comfort are determinant to the choice behavior

Right:
The choice behavior may influenced by the approaching direction of pedestrians. In addition, the presence of conflicting traffic on approach ways leading to those vertical facilities will reduce the directness to the vertical infrastructure and pedestrians will have to interact with traffic streams going in another direction. Those unavoidable interactions may increase the access time and comfort, and, consequently, affect the route choice behavior.

4.2 Walk/stand choice on escalators

This section discusses the walk/stand choice behavior of escalator passengers. It is noted that this choice dose not always available to a passenger. For instance, when the entire tread width is occupied by standing passengers the choice between walking and standing does not exist anymore. Thus we first discuss the availability of this walk/stand choice on escalators in subsection 4.2.1. Following that we analyze factors influencing this walk/stand choice behavior in subsection 4.2.2. Since no relevant studies are found in literature, the discussion is made based on our real-life observations.

4.2.1 Availability of walk/stand choices on escalators

Compared with car drivers, pedestrians get much higher freedom on making their travel choices. Their movement is neither confined by any predefined lanes nor do they need to concern regulations set by the authority. The usage of escalators may be an exception for pedestrians of some regions. For instance, passengers taking escalators in London Underground stations need to follow their stand-on-the-right rule.

In this report, we concern a situation with an unregulated escalator where people get their own freedom on deciding which side to walk or stand on the escalator. Thus, sometimes, passengers may find that their walking choices been deprived by standing passengers in front of them. Normally, under this situation, people just follow the behavior of their predecessors and stand on the escalators since no other choices exist.

The availability of this walk/stand choice may be determined by the distribution of standees on escalators in particular those present near the entry. In addition, it is influenced by the width and rise of the escalator. For a long escalator, the presence of standing passengers on the other end of the unit may have less an impact on the choice behavior.

4.2.2 Influencing factors

People ‘walk’ on stairways because it is the only way they can get themselves closer to their destinations. Therefore, we can say that it is the utility gained from reaching the destination that motivate people to walk on stairways. However, when using escalators, passengers have another choice. They can either walk or just stand on those moving steps and let the machine transport them to the other end of the unit. Both options will bring them to the same destination via the same infrastructure. So, why do people walk on escalators?

In subsection 4.1.1 we have discussed a situation of making a choice between one stairway and one escalator located parallel to each other to change levels. When the flow is low, the escalator seems to be the best choice for both unhurried and hurried passengers because of its ability on providing either comfort or speeds to its users. However, observations from real-life situations show that still some people use stairways when there is an empty escalator beside. Possible explanations include personal habits, health concerns, and the randomness of human behavior, etc.

According to the travel behavior on escalators, we may divide escalator passengers into three groups. The first group includes passengers with great concerns about physical effort involving in level changes.

People with poor physical fitness or with luggage may belong to this group. Normally they choose to stand on escalator steps after their boarding unless they are facing extremely high time pressures.

The second group considers passengers with time pressures. Those people use escalators instead of stairways because of the capability of speed enhancement on escalators. Thus, normally they are characterized by their continuous walking behavior on escalators. Even when facing blockages from standing passengers in front of them, they will try hard to by pass those standees to reach their destination as soon as possible. The possibility of being blocked on escalators increases with flows, thus most highly hurried passengers avoid escalators when flows are high.

The third group concerns passengers have neither time pressures nor physical disability. Those passengers may decide to stand or walk or exhibit shifting behavior between standing and walking on escalators. In addition, they may be characterized by their following behavior on escalators. That means when their predecessors decide to stand on escalators, they do not mind to follow them and stand on the units as well. Thus, their decision on choosing to walk or stand on escalators may be influenced by the behavior of their predecessors.

According to the above discussion, we summarize factors influencing choices between standing and walking on escalators as physical effort, travel time and time pressure, habits, health concerns, and randomness of human behavior. It is noted that those factors affect the choice behavior in both the ascending and the descending direction. However, most of the factors are not observable. Therefore, no further discussion about this walk/stand choice behavior on escalators will be given in the remainder of this report.

5 Data Collection

To calibrate and validate those walking and choice models hypothesized in chapter 3 and chapter 4, we require microscopic traffic data such as trajectories, personal characteristics, and choice decisions of individual pedestrians. Unfortunately, there is no such kind of data available at the time being when this project is conducted. Therefore, it becomes necessary to collect data for the need of this research project.

In this chapter, we discuss issues concerning the collection of microscopic pedestrian traffic data on stairways and escalators. In section 5.1, we give a literature review on methods been used to collect pedestrian traffic data. Taking into account factors such as the acquisition of data, the variation of traffic conditions, constraints of physical environments and observation techniques, and project duration, we decided to perform the observations at the NS intercity train station of Den Haag Holland Spoor with the technique of infrared detectors and video cameras. For details about the site selection, we refer to the Site Visit Report given in Appendix A of this report. We present the observation plan in section 5.2. Some statistical data of the observation are given in section 5.3. Finally, conclusions will be drawn in section 5.4.

5.1 Data collection methods

In general, two different types of approach could be applied for data collection. One is to generate required data through experiments in a laboratory where things can go in a well-controlled situation. In this case, the researcher determines the controlled and non-controlled variables based on the defined purpose of his experiments. The directness to the research questions makes it a very useful tool especially when the observing behavior is not or hardly occurs in practice. Hoogendoorn & Daamen (2002) have conducted innovative experiments with 60 participants involved to study pedestrian walking behavior of various kinds. These experiments are recorded with a video camera to keep all information for further study. However, this experimental approach may suffer from bias resulting from for instance population generalization of population as well as unrealistic behavior in experimental environments if special attention is not paid for the experiment set-up (such as the selection of participants).

The other possible approach is to gather data directly from real-life situations. In contrast to laboratory experiments, this approach allows the observation of real traffic behavior with a representative sample population if the observation period is carefully selected. However, since the observations are conducted in real situations, the researcher can hardly control some external factors such as flows. In addition, the conditions of the observing site (such as the layout of infrastructure) may have unexpected influences on the results.

This project concerns walking and route choice behavior of pedestrians on stairways and escalators in public transport facilities where the interaction of passengers with public transport system is significant. Because it is rather difficult to reproduce the situation in a designed laboratory, the data will then be collected from real-life observation. In this section, we focus on the techniques used for the observation. We start by giving a literature review on observation techniques in subsection 5.1.1. Then we proceed to assess their adequacy with respects to the purpose of our observation in subsection 5.1.2. Finally, conclusions will be given in subsection 5.1.3.

5.1.1 Literature review of observation techniques

The study of pedestrian behavior can be dated back to 1960s. Quite a few techniques have been applied for collecting pedestrian traffic data of various kinds. According to the overview given by Daamen (2004) with respect to data collecting techniques, promising techniques include manual counting, questionnaires, stalking, video, and infrared detectors. In the following sections, we will discuss these techniques in more details.

Manual counting

Manual counting is the primitive way of collecting traffic data of pedestrians. It can be easily applied for the observation of traffic data (such as flows and travel times) as well as personal characteristics. Although no specific device is required for the implementation, it is thought to be time-consuming and labor-intensive. Besides, the performance of manual counting deteriorates when flow increases since it is very difficult to keep good records at high flow situations. Thus, counting errors are neither avoidable nor measurable.

Questionnaires

Questionnaires are normally used for the study of route choice behavior of pedestrians. The biggest advantage of this method is that the researcher can get information such as alternative choices which are not explicit to the researcher. However, it may be difficult on getting proper information from commuters because of their typical hurries. Besides, only stated preference is collected which may be different from real behavior.

Stalking

By following pedestrians, the researcher can correctly record travel information such as origin, destination, and travel time, of the followed pedestrian on the journey. Contrary to the method of questionnaires, this stalking method observes only realized behavior and observable characteristics. In addition, it also suffers from large amount of time and labor involved for the observation.

Video

The utilization of video techniques seems to be ideal for the study of pedestrian behavior since every piece of traffic and travel information is recorded. The biggest advantage of using video techniques is that the recording or data extracting can be done later in laboratories. In addition, the film can be replayed. Thus, the precision of the data can be much higher in comparison to manual counting on site. However, there are some restrictions with respect to the installation of video cameras, of which important aspects include the location of fixing right above the observing area and constant lighting or ambient conditions.

Moreover, although software is available for extracting trajectory data from digital images, the detecting and tracking of pedestrians still need to be guided by an operator. That means the data extracting process is only semi-automatic and still largely relies on human intervention. Hoogendoorn et al. (2003) have developed algorithms to allow automatic detecting and tracking of pedestrian movement from video images. However, the algorithms rely on the colored hats worn by individual participants in their experiment which is not applicable to observation from real-life traffic. Therefore, the extracting of trajectory data from digital images is thought to be time-consuming.

Infrared detector

Armitage et al. (2003a) have extracted trajectory data of pedestrians with low-cost infrared detectors. The kind of detectors they used is normally installed to count people passing a predefined counting line. Their study indicates that large amounts of trajectory data can be extracted automatically from the detector. Besides, since those infrared devices detect temperature differences of objects in the coverage area, they can even function in complete darkness.

However, several limitations have been addressed as well. Firstly, the detectors are normally installed in a downwards looking manner, thus a fixing location right above the detecting area is required. Secondly, because of low cost, the image resolution is also quite low, which makes it impossible to recognize individuals from the image. Thus personal characteristics of pedestrians, namely gender and age, can not be observed with this kind of low-cost, low-resolution infrared detectors. Thirdly, the internal processors have difficulties on catching targets at the edges of the field of view, which may cause some artifacts at the edges of an image ("edge effects"). Finally, when several detectors are installed for instance in a line to expand the detecting area, there are still problems on matching trajectories across different fields of view. According to the study by Armitage et al. (2003b) only about 60% trajectories of two adjacent view fields are successfully matched. Problems of matching come from for instance installation errors as well as the edge effects mentioned above.

5.1.2 Assessment of observation techniques

In the previous subsection 5.1.1, we have discussed both advantages and disadvantages of the five observation techniques, namely, manual counting, questionnaires, stalking, video, and infrared detector. In this subsection, we will further assess their adequacy as the observation technique applied for the purpose of this project.

In this project, we focus on both walking and choice behavior of pedestrians. With respect to the walking behavior, the most important measurements include flows and individual travel time. As for the choice behavior, available choice sets and choice decisions are essential observations. Besides, we are interested in the influence of personal characteristics on these two types of choice behavior. Hence, the acquisition of the above-mentioned traffic and personal data is considered as the most important criterion to be met. Moreover, due to the limited research period, the time required for observation and data processing are another two factors considered for the determination of observation techniques. Thus, three criteria are set to assess the adequacy of each technique, which include:

- acquisition of traffic and personal data
- time constraints for site observation work
- time constraints for data processing

We summarize the assessment results in Table 5.1. Besides, more details will be discussed below.

With respect to the ability of data acquisition, only the method of manual counting and video technique can work independently to get all the required data. Methods of questionnaire and stalking have poor ability on acquiring traffic data which makes them unattractive in this project.

Although manual counting can get all required data, the precision of the counting results is of doubt. As we have discussed in subsection 5.1.1, it is thought to be neither practical nor feasible to rely solely on manual counting to get traffic and personal data due to the difficulties on observing crowded conditions. Besides, the high cost in terms of time and manpower for the site work also reduces its attractiveness. As for the time required for data processing, it depends on the auxiliary tools used for recording. However, generally the processing procedure could be quite time consuming as well.

Both infrared detectors and video cameras can be used to extract valuable trajectory data. Besides, software required for transforming original image data into numerical trajectory data is available, which will largely reduce the complexity on the processing procedures. All the above mentioned makes both infrared and video technique very attractive in this project.

However, none of these two techniques plays a dominant role. The time required on converting video image to numerical trajectory data still takes relatively longer time in comparison to infrared technique due to the demand of human intervention, while the infrared technique is not able to observe personal characteristics.

Table 5.1
Comparison of data collecting techniques

	observation technique				
criteria	manual counting	questionnaire	stalking	video	infrared detector
1. Data acquisition	+	−	−	+	0
flow	×			×	×
travel time	×		×	×	×
personal characteristics	×	×	×	×	
choice decision	×	×	×	×	×
2. Time for site work	−	−	−	+	+
3. Time for data processing	0/−	−	−	0/−	+

Note:
"+" means the technique is considered to be "good" in terms of the criteria concerned
"0" means the technique is considered to be "fair" in terms of the criteria concerned
"−" means the technique is considered to be "bad" in terms of the criteria concerned
"×" means the data can be observed from the technique concerned

5.1.3 Conclusions for data collection methods

According to our discussion in previous subsections 5.1.1 and 5.1.2, we propose a combined method involving both infrared and video technique for the observation. Infrared detectors will play the major role in the observation due to its simplicity and efficiency on extracting large amounts of trajectory data with existing software. Video cameras will then be installed to record personal characteristics to compensate the limitation of infrared detectors.

5.2 Observation set-up

To find out appropriate locations for the observation work, we have visited three NS train stations in the South Holland region which include the station of Rotterdam Centraal, Den Haag Centraal, and Den Haag Holland Spoor. Based on the capability of getting both the infrastructure-specific and site-specific data defined with respect to our research questions, we conclude in the Site Visit Report (see Appendix A) that the station of Den Haag Holland Spoor is the best location to perform the observation. The observation was finally conducted on the 1st of June, 2005 (Wednesday) using infrared detectors and video cameras. In order to get sufficient data in terms of sample size as well as the variation of flow conditions, the observation began at 15:40 and ended at 19:10 without interruption. The observation period contains the evening-peak-hours.

In the remainder of this section, we give a presentation of the observation setting on site and some technical data of the IRISYS infrared detectors used in this project.

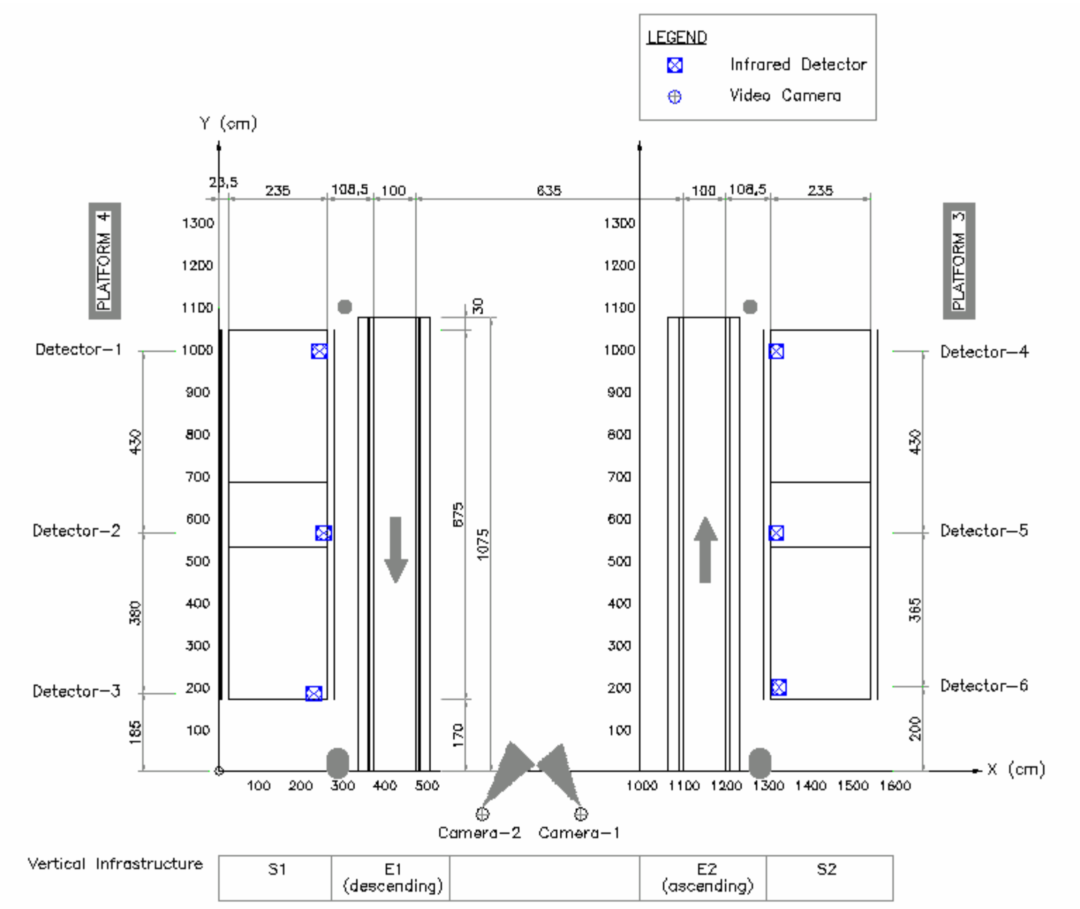
5.2.1 Site arrangement

The observation site at the intercity train station of Den Haag Holland Spoor situates two sets of vertical infrastructure (each consists of one stairway and one escalator) located parallel to each other (see Figure 5.1). These two sets of infrastructure, namely, S1/E1 and S2/E2, provide accesses to and from platform 4 and platform 3 respectively. The two stairways (S1/S2) serve bidirectional flows, while the two escalators are operating in either ascending (E2) or descending (E1) manner with a speed of about 0.6 m/s, which results in a horizontal projected speed of 0.52 m/s. More information about this site (such as the overview of the station and detail configurations of those facilities) is given in Appendix A of this report.

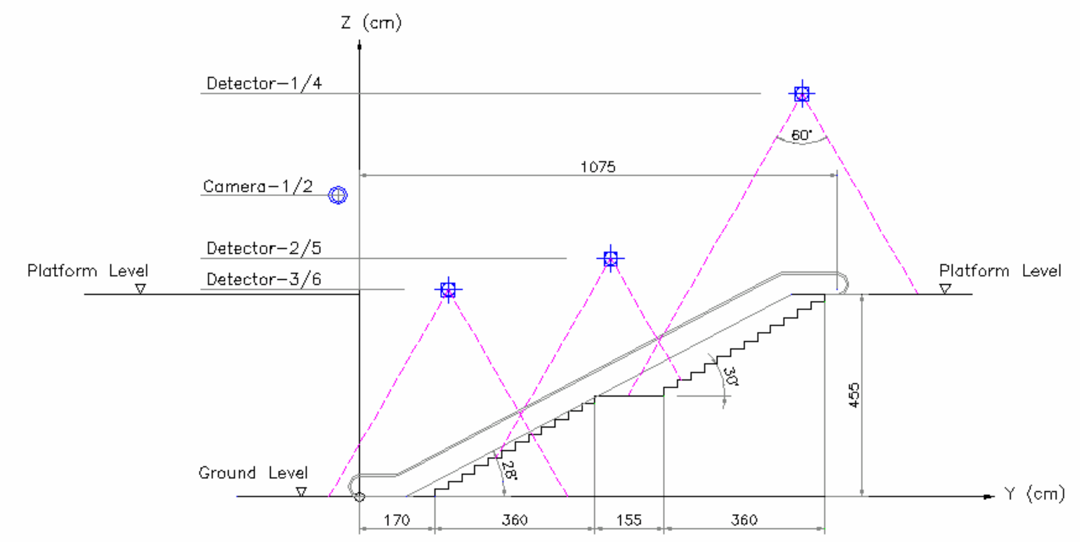
To minimize the disturbance on the operation of the station as well as to reduce the duration of site work, the observation is conducted simultaneously at these two sets of vertical infrastructure. Therefore, to cover the interested area, 6 infrared detectors (Detector-1~6) are installed above the two sets of vertical infrastructure either by means of auxiliary structural elements or cable attached to existing light post and handrails. In addition, 2 cameras (Camera-1 & 2) are installed opposite to the entrance of these vertical transport facilities at platform level. Due to the limited zooming capability, these 2 cameras only catch images of the upper part of facilities, which results similar coverage areas as that of detector 1 and detector 4 (see Figure 5.1).

Table 5.2
Position of infrared detectors installed for the observation

	S1/E1			S2/E2		
	Detector-1	Detector-2	Detector-3	Detector-4	Detector-5	Detector-6
x (cm)	240	250	227	1311	1311	1323
y (cm)	995	565	185	995	565	200
z (cm)	905	535	465	905	535	465



(a) plan view



(b) elevation view

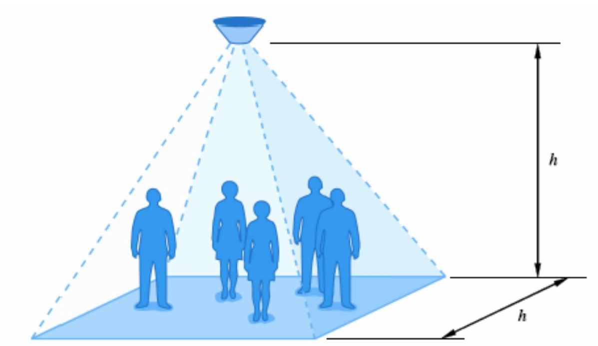
Figure 5.1
Site arrangement of observations: (a) plan view (b) elevation view of the observation setup at NS train station of Den Haag Holland Spoor. 6 infrared detectors and 2 video cameras are installed for the observations. Each detector and camera has its own coverage area as marked with dash lines. The setting allows overlapping of fields of view of the three detectors in line. (unit: cm)

5.2.2 IRISYS infrared detectors

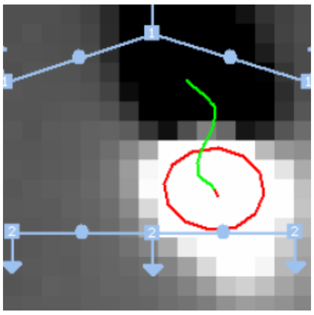
The infrared detectors used in this project are commercial products of the IRISYS People Counter Family manufactured by InfraRed Integrated SYStems Limited (www.irisys.co.uk). Those people counters detect the infrared radiation emitted by human bodies. The main elements of the infrared detector include imaging optics, sensor, and signal processing and interfacing electronics.

Normally those detectors are used in a downward looking manner with an unhindered view of the target area. The optical system contains germanium lens with a 60 degree filed of view which results in a square sensing area on the floor whose width is approximately equal to the mounting height. Mounting height ranges from 2.5-4.5 m can be accommodated with the standard lens. Besides, the image is read by a 16x16 sensor array, which results in a low-resolution image due to the relatively small number of sensor elements contained. It is noted that those sensors detects changes in temperature but not the absolute temperature. The frame rate of those detectors is about 30 fps (frequency per second).

(a)



(b)



(c)

Figure 5.2
IRISYS infrared detectors: (a) people counter with outdoor housing (b) the principle of operation may be visualized as being a square pyramid with a 60 degree apex, which results in a square sensing area on the floor whose width is approximately equal to the mounting height *h* (c) one pedestrian is seen as a hot spot (white areas) followed by a cold wake (black areas); the counter overlays an ellipse around the hot spot and tracks its movement
(source: photo (a) from www.irisys.co.uk (b) & (c) from Marco & Chan 2005)

5.3 Observation results

This section gives some statistical data of the observation results. We discuss traffic demand with respect to types of infrastructure (stairways and escalators) and directions of movement (descending and ascending) as well as personal characteristics (gender, age, and luggage) in subsection 5.3.1 and 5.3.2 respectively. It is noted that the results of infrastructure S1 and E1 are calculated with data observed by Detector-1, while those of S2 and E2 are measured with data observed by Detector-4.

5.3.1 Demand analysis based on infrastructure and direction of movement

We summarize the traffic demand of the four vertical infrastructures measured during our observation period (15:40 ~ 19:10) in Table 5.3. In total, 4819 numbers of pedestrians had been observed on those stairways and escalators. The large number (4819) shows the possibility of using infrared techniques to extract huge amounts of trajectory data of pedestrians automatically. Besides, the associated cumulative flow curves are given in Figure 5.3. We discuss the traffic conditions during our observation period below.

- Boarding demand (ascending) is about 50% higher than that of alighting (descending) one. It is noted that the observation is performed during the evening hours. Opposite demand patterns may be expected for the morning peak hours.

- Stairway S1 is mostly used by descending traffic (less than 1% in ascending direction) while S2 is more equally used by both ascending (44%) and descending (56%) one. Although there may be influence from opposing traffic on the traffic behavior on S2, observations from the video cameras show that the presence of opposing traffic only cause minor effects on the traffic on S2 since the situation mostly occurs at low flow conditions.

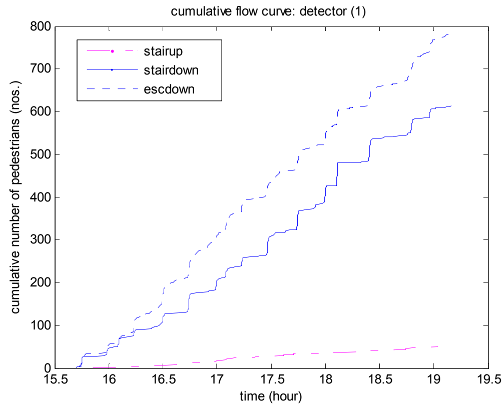
- About 30% more people use escalators when going downwards (E1/S1 = 1.28/1) while about 5 times more people use escalators when going upwards (E2/S2 = 6/1). The difference between the behavior in the descending and the ascending direction may be explained by the higher energy consumption involved in stair climbing.

- Demands on S1/E1 show tight interactions with the time table of trains. The alighting traffic is generated from arriving trains. Thus we observe arrivals of pedestrian platoons in front of those facilities. Those surges of traffic are characterized by high flows but relatively short durations. Observations show that a surge of passengers by an arriving train could be released in about 1 minute period. However, no congestion had been observed during our observation periods.

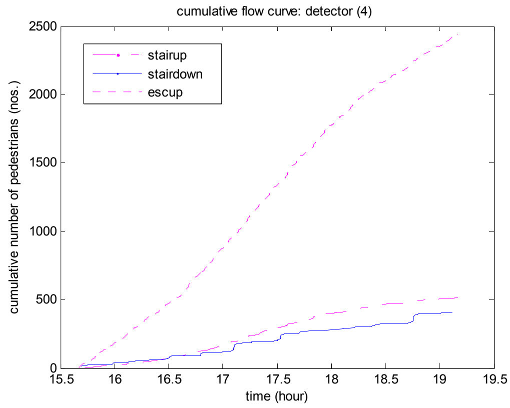
- The interaction between the traffic demand on S2/E2 and train schedule is not as noticeable as that of S1/E1 except that of descending (alighting) traffic on S2. This may be explained by the different natures of boarding and alighting traffic in public transport facilities. The arrival of alighting traffic is dependent on the time table of public transport vehicles, while that of boarding traffic is noted for its relatively higher randomness (The arrival of boarding traffic in public transport facilities relies on the nature of the time table of public transport vehicles. For systems with low frequencies, the arrival is dependent on the time table. As for those with higher frequencies, the arrival is more random.).

Table 5.3
Demand analysis based on infrastructure types and movement direction (data source: Detector-1 & Detector-4) (15:40 to 19:10)

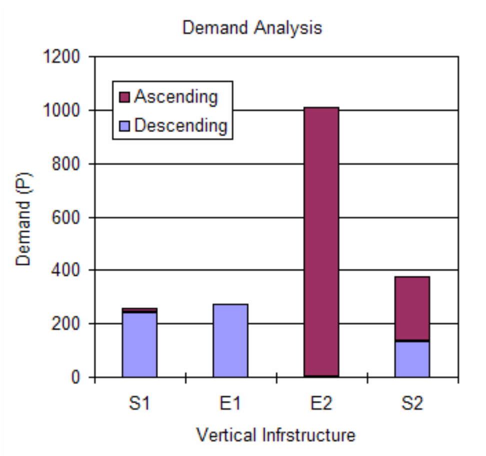
Direction of movement	Vertical Infrastructure				Total		
	S1	E1	E2	S2	Direction	Stairway	Escalator
Descending	614	784	-	514	1912	1128	784
Ascending	50	-	2449	408	2907	458	2449
Total observations by IR	1448		3371		4819	1586	3233

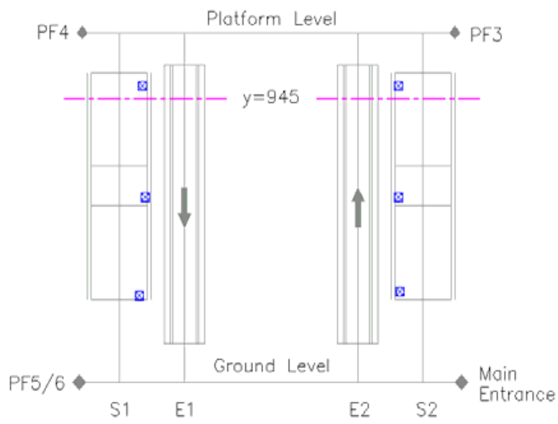


(a)



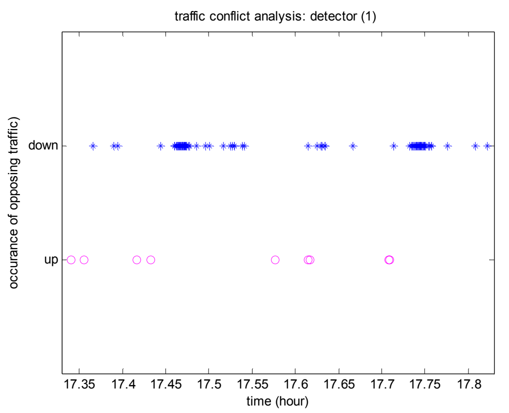
(b)



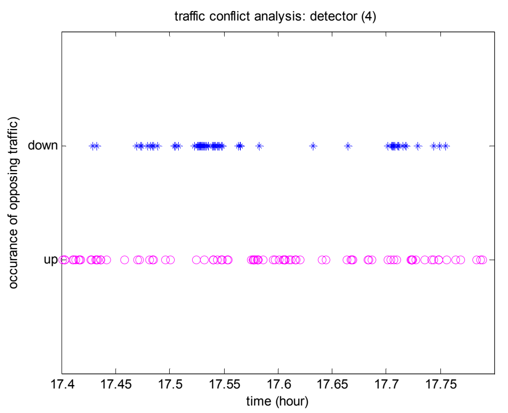


(c)

Figure 5.3
Traffic demands during the observation period from 15:40 to 17:10 (a) cumulative flow curves of infrastructure S1 and E1 (b) cumulative flow curves of infrastructure S2 and E2 (c) traffic demands based on infrastructure types and the direction of movement. Flows are counted at the location of about three steps down the platform level (y=945).



(a)



(b)

Figure 5.4
Opposing traffic (a) opposing traffic (up) on stairway S1 have no influence on the traffic behavior of the main stream (down) since they occur only at rather low flow conditions (b) the presence of opposing traffic on stairway

S2 may influence the traffic behavior on it; however, observations from video films show that the influence is minor. The behavior of bi-directional flows is not discussed in this report.

5.3.2 Choice analysis based on personal characteristics

Table 5.4 summarizes traffic demand based on the gender and age of passengers as well as the presence of luggage. It is noted that the demand is measured with the observation results of Camera-1 and Camera-2 for a period of one hour (17:00 and 18:00). In total 1917 pedestrians have been recognized during this period, among which 34% are in the descending direction, while 66% are in the ascending direction.

With respect to the composition of passengers, about 60% passengers are males while 40% passengers are females. In terms of the three age groups defined, the youth, the commuter, and the elderly are composed of 30%, 65%, and 5% of the population respectively. Finally, most of the passengers travel with only hand-carried baggage which causes no significant effects on their walking or route choice behavior. Less than 3% of the train passengers travel with luggage.

Table 5.4
Demand analysis based on personal characteristics (data source: Camera-1 & Camera-2) (17:00 ~ 18:00)

		Infrastructure				Total			
	Direction of movement	S1	E1	E2	S2	by direction		stairway	escalator
Gender	Descending	241	275	-	135	651		376	275
	Female	112	119	-	42	273	(41.9%)	154	119
	Male	129	156	-	93	378	(58.1%)	222	156
	Ascending	15	-	1011	240	1266		255	1011
	Female	5	-	469	80	554	(43.8%)	85	469
	Male	10	-	542	160	712	(56.2%)	170	542
Age	Descending	241	275	-	135	651		376	275
	Youth	92	57	-	47	196	(30.1%)	139	57
	Commuter	143	198	-	85	426	(65.4%)	228	198
	Elderly	6	20	-	3	29	(4.5%)	9	20
	Ascending	15	-	1011	240	1266		255	1011
	Youth	3	-	332	93	428	(33.8%)	96	332
	Commuter	11	-	633	144	788	(62.2%)	155	633
	Elderly	1	-	46	3	50	(4.0%)	4	46
luggage	Descending	241	275	-	135	651		376	275
	With luggage	4	14	-	1	19	(2.9%)	5	14
	Without luggage	237	261	-	134	632	(97.1%)	371	261
	Ascending	15	-	1011	240	1266		255	1011
	With luggage	0	-	32	0	32	(2.5%)	0	32
	Without luggage	15	-	979	240	1234	(97.5%)	255	979
	Total observations	**256**	**275**	**1011**	**375**	**1917**	**(100%)**	**631**	**1286**

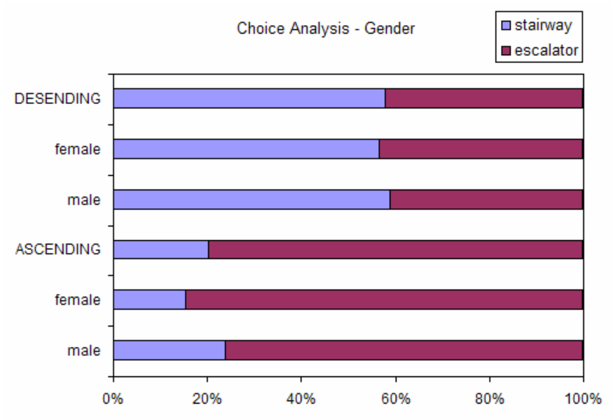


Figure 5.5
Choice analysis based on the gender of pedestrians.

Figure 5.5 gives results of choice analysis based on the gender of pedestrians. In the descending direction, the two sexes exhibit similar behavior. About 60% males and females use stairways when descent. In the ascending direction, preferences towards stairways decrease dramatically for both female and male passengers. In addition, a relative lower preference towards stairways is observed for the female (15%) than the male (24%) in ascending direction. This may be explained by the higher concerns about physical efforts of the female.

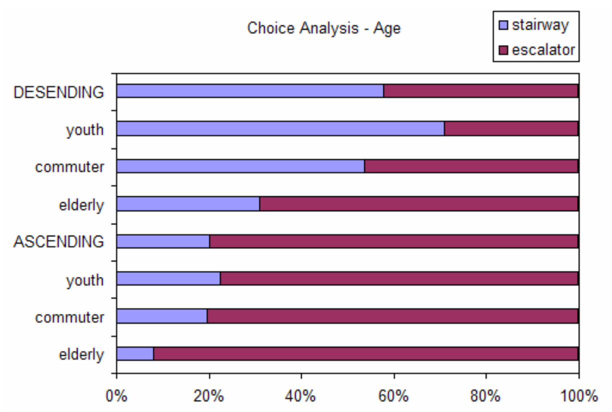


Figure 5.6
Choice analysis based on the age of pedestrians.

Figure 5.6 presents results of choice analysis based on the age of pedestrians. In the descending direction, different behaviors are observed among the three age groups. The youth show the higher acceptance on using stairways (71%) when decent. The lowest stairway usage by the elderly (31%) may be explained by the higher difficulty in keeping balance when going down stairs. In the ascending direction, the stairway demand decreases for the three age groups. Besides, the differences among the three age groups become smaller. Both the youth and commuters have about 20% usage rate of stairways, while that of the elderly is further decreased to less than 10%.

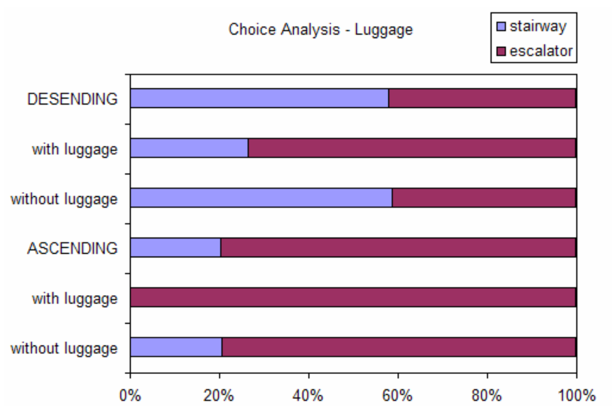


Figure 5.7
Choice analysis based on the traveling condition (with or without luggage)

Figure 5.7 gives results of choice analysis based on the presence of luggage when traveling. In the descending direction, 5 out of 19 people (26%) still find it acceptable to carry their luggage down stairways. However, our observations show that no one use stairways when ascending with luggage.

5.3.3 Conclusions of observation results

In total 4819 pedestrians had been observed during our observation period from 15:40 to 19:10, among which about one third is in the descending direction (alighting traffic) while the other two thirds are in the ascending direction (boarding traffic). The preference towards stairways and escalators are different in descending and ascending direction. About 30% more people use escalators when going downwards while more than 5 times people use escalators when going upwards. The difference between the behavior in descending and ascending direction may be explained by the higher energy consumption involved in stair climbing.

To study the influence of the gender and age of pedestrians and the presence of luggage on travel behavior in public transport facilities, 1917 passengers have been recognized for a period of one hour. The composition of the observed population is summarized as follows:

- About 60% of the station users are males while about 40% are females.
- The youth, the commuter, and the elderly are composed of 30%, 65%, and 5% of the population respectively.
- Most people travel with only hand-carried baggage; less than 3% of train passengers travel with heavy luggage.

Some findings about preferences towards escalators:

- In the descending direction, the two sexes exhibit similar preferences towards escalators. However, in ascending direction, female passengers (85%) show relative higher preference towards escalators than the males (76%).

- In the descending direction, the differences among the three age groups are noticeable. The youth show the highest acceptance on stairways (71%), while only 31% elderly passengers use stairways for decent. However, in the ascending direction, the differences among the three age groups reduce profoundly. Escalators are much more favorable for passengers of all ages in particularly the elderly.

- In the descending direction, about one third of passengers with luggage use stairways when descent. However, our observations show that no one use stairways when ascending with luggage.

The analysis about stairway and escalator usage with different passenger characteristics shows that all people concern the physical effort involved in stair climbing. Thus, in general stairways are considered as less favorable in the ascending direction. In particularly, the female, the elderly, and people with luggage show relative less preference towards stairways in the ascending direction.

With respect to the effectiveness of the observation set-up and the performance of infrared detectors in terms of observing individual trajectory data, we refer to chapter 6 for details.

6 Preparatory Works for Data Analysis

6.1 Introduction

In chapter 5 we have given a presentation about our observations of pedestrian behavior with infrared detectors and video cameras. The purpose of the observation is to gather microscopic traffic data (trajectory data) and personal characteristics at the selected station in order to calibrate and validate those walking and choice models hypothesized in chapter 3 and chapter 4.

The valuable trajectory data of individual pedestrians is extracted from the output of the six infrared detectors installed in our observation. The original output of the detectors is transformed into useful numerical data by means of an existing program developed by the Department of Transport & Planning, Delft University of Technology, of which the most important information includes:

- Moment of detecting (time);
- Identification numbers of detecting pedestrians (id);
- Position of targeted pedestrians at every detecting moment on the image plane (x, y).

Taking into account the technical characteristics of the detectors, we can rephrase the above-mentioned as follows: for every detected pedestrian, his x and y positions on the image plane will be recorded at a sub-pixel precision and written with a frequency of about 30 frames per second to the internal processors; in addition, each targeted pedestrian has given a unique identification number. As for the personal characteristics of pedestrians, the information is registered from the two video films taken during our observation.

However, after reviewing those original trajectory data and checking them in parallel with the video images, we found that those data have to be further corrected due to the following reasons:

- Projected trajectory data on the image plane is distorted (two types of distortions are identified, namely, lens distortion and perspective distortion);
- Variation of detecting area along the profile of the vertical infrastructure causes some trajectories dropped out from the image or leads to discontinuous detection of pedestrians at edges of the field of view;

- Difficulty of precise detecting on an inclined surface in particular at dense situations.

Therefore, some preparatory works needed to be performed to eliminate the negative effects resulting from the above-mentioned issues. Thus, prior to utilizing our observed infrared and video data for the analysis, some preparatory works have to be done. These preparatory works include:

- Correct distortion of trajectory data observed by infrared detectors;
- Match split trajectory within one field of view (infrared detector);
- Register personal characteristics from video images;
- Correct (infrared) flow data based on video reading.

The purpose of this chapter is to explain the necessity as well as to give some more details about these preparatory works.

We start by reviewing some plots of original trajectories observed by infrared detectors in section 6.1. The main purpose of the review is to get insight into the performance of these detectors in order to identify any possible factors that may influence the detection outcomes. In terms of detection precision, three main factors are identified, namely, distortion, discontinuous detection, and ineffective detection at high flow situations. We will discuss the causes as well as their influences on our analysis outcomes in this section. Then in section 6.2, we proceed to give a presentation about these preparatory works in the sequence of distortion correction, matching split trajectory, registration of personal characteristics, and correction for flow data.

It is noted that we limit our discussion on analyzing traffic behavior with data observed from a single detector. In order to use data across various fields of view to extend the trajectories, it is then necessary to match data read from different detectors and to couple trajectories of individual pedestrians across fields of view. However, this will not be discussed in this report.

6.2 Trajectory reviews

This section reviews some detection outcomes from the six infrared detectors installed during the observations. The purpose of the review is to examine the detection performance of individual detectors and the installation effectiveness. In regard to the detection performance, we focus on the ability of detecting, positioning, and tracking of targets. With respect to the installation effectiveness, we concern coverage areas of individual detectors. Regarding the layout of the observation site as well as the arrangement of these detectors, we refer to subsection 5.2.1 for details. It is noted that those trajectory plots given in this chapter contain only the travel paths of pedestrians in the horizontal plane (x-y plane). In addition, the original trajectory plots from infrared detectors are given in the unit of “pixel” in both x and y axis.

6.2.1 Examine the detection performance

The three plots given in Figure 6.1 provide clear profiles of a couple of trajectories observed by Detector-1 and Detector-2. To ease the discussion, we give information such as the direction of movement, status of detection (start or end points), and identification number of individual trajectories in the plots. We summarize here some of our observations:

- **Wobbly profiles**: The wobbly trajectory profiles reflect the sway of walking locomotion which characterizes the lateral displacement of the gravity centre of human bodies when walking.

- **Edge effects**: Some trajectories start or end at some distance away from the edges of an image area (eg. id = 1046), which infers a various detecting-effective-zone among pedestrians. This is explained by the so-called “edge effects” caused by the difficulty on catching targets at the edges of the field of view by the internal processors.

- **Distorted trajectory**: Although pedestrians can freely move in 3-dimension, the projected trajectories in particular those on escalators are supposed to be straight profiles parallel to the two sides of the escalator units. However, most of the profiles are noticed with certain degree of curvature as well as inclination, or, simply say that they are “distorted”.

- **Discontinuous detection**: The discontinuous detection is observed by noticing that some trajectories of various identification numbers are indeed belong to the same pedestrian. For instance, checking with video images, we find that trajectories of ID 1857, 1858, 1859, and 1860 belong to the same pedestrian. However, the entire trajectory is split into several parts. We also noted that this discontinuous detection is more severe for Detector-2 and Detector-5. This maybe caused by the observation setting. As we will discuss later in this section, the detecting area of these two detectors did not cover the entire width of stairways and escalators, which may lead to instable detection especially when pedestrians are moving close to the edge of these coverage areas.

- **Double counting**: Confirming with video images, we find that the two trajectories of ID 1855 and 1856 actually belong to the same pedestrian. The phenomenon of double detecting occurs for instance when pedestrians sway their arms. The enlarged body area is interpreted as multiple objects by the detectors due to the algorithm set for object detecting.

- **Lost counting**: On the contrary, when pedestrians walk rather close to each other, they may be considered as one sole target, which leads to a reduction of pedestrian counts. In this project, the detecting performance could be worsened due to the difficulty of precise detection on slope where the projected distance between pedestrians decreases when going down the slope (increased object distance). Comparing with video images shot by Camean-1 and Camera-2, we find that the effectiveness of detection is indeed weakened when the flow is high. A lost of about 30% observations is measured for a period of 30-second high flow states on stairways (only 24 out of 34 pedestrians are observed by Detector-1 during the period of 17:28:00 ~ 17:28:30). That means at dense traffic situations, not every object presenting in the view field of the detector can be correctly detected and tracked. Thus, it leads to errors on calculating flows or densities solely relying on the output data from infrared detectors.

- **Irrational behavior**: Some trajectories illustrate irrational behavior. For instance the trajectory of ID 877 infers that the pedestrian is jumping from the escalator E1 to the stairway S1. The possible explanation is that one descending pedestrian on the escalator E1 and one ascending pedestrian on the stairway S1 presented at the edge of the detection area at the same moment. Because of their close spacing they were viewed as one by the detector. After the descending pedestrian left the detection area, the detector kept tracking the ascending pedestrian and viewed it as an existing target.

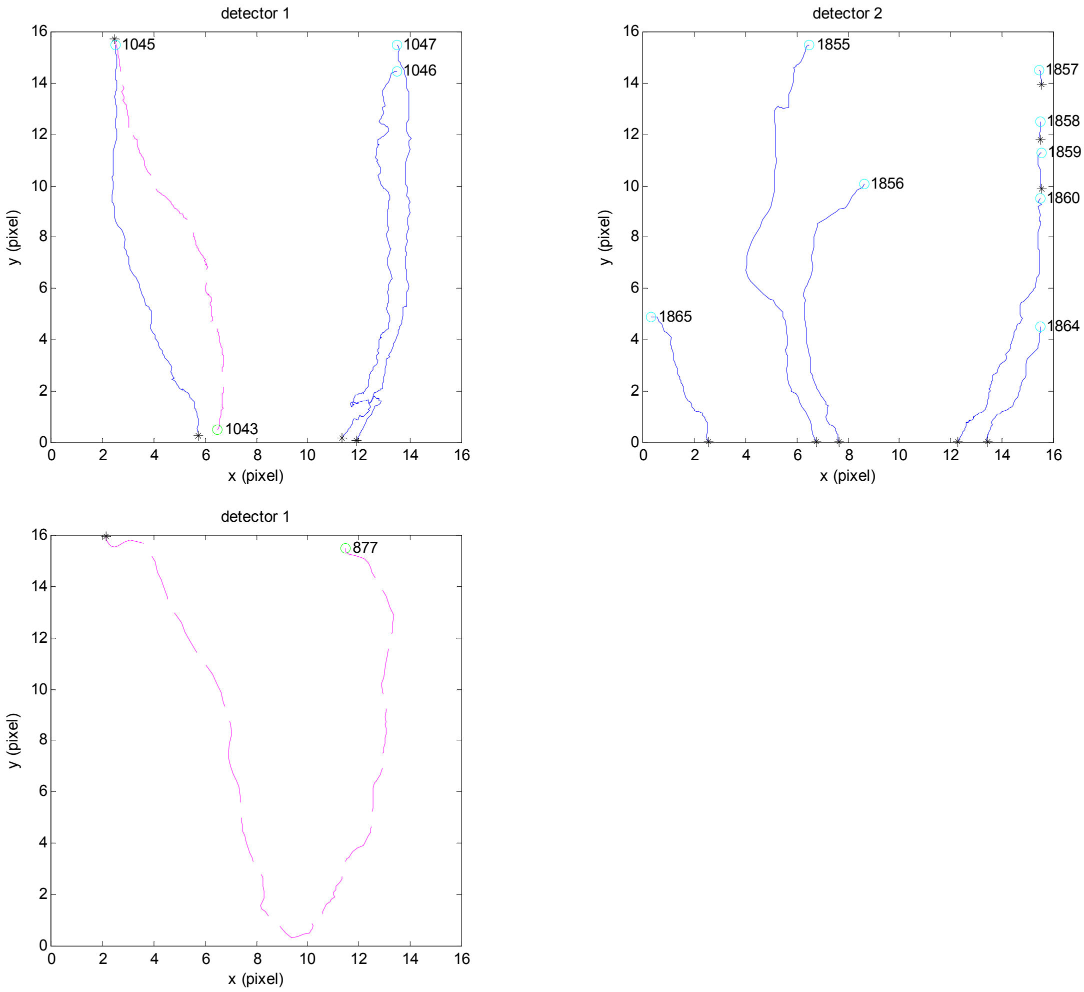


Figure 6.1
Plots of individual trajectories: The solid line represents descending trajectories while the dashed line represents ascending ones. Besides, the first and final detecting points of a specific target are indicated by the symbol "o" and "*" respectively. The figure shown beside the symbol "o" (eg. 1043) is the identification number of the trajectory.

6.2.2 Examine the installation effectiveness

Figure 6.2 shows trajectory plots of consecutive 50 pedestrians observed by the six installed detectors, which allows the recognition of the location and outlines of stairways and escalators from the images. We use those plots to check the adequacy of our observation set-up. Since these two sets of infrastructure (S1/E1 and S2/E2) as well as our observation set-up are symmetrical, we will discuss the detection results of the 6 detectors in pairs (eg. Detector-1 and Detector-4 will be discussed together).

Figure 6.2 (a) and (b) present cumulative plots from Detector-1 and Detector-4 respectively. The solid lines represents ascending trajectories (moving from $y = 0$ to $y = 16$) while the dashed lines represent descending ones. The detection areas of these two detectors contain two types of terrain: platforms ($y \approx 10$ to 12) and stairways or escalators ($y \approx 0$ to 10). A clear outline of the infrastructure can be observed. However, a slight curvature and inclination of trajectories are observed especially at the lower part of the images. Moreover, it is noted that the width of stairways (or the empty space between the stairway and escalator unit) becomes smaller when the y coordinates decrease (down the slope).

The usage of these infrastructures can also be observed from the plots. For instance, we can notice that the stairway leading to Platform 4 (by Detector-1) is mostly used by alighting traffic which are passengers leaving from platform (in descending direction); on the other hand, the stairway leading to Platform 3 (by Detector-4) is more equally utilized by both alighting and boarding traffic; this reflects the traffic demand during the observation period (evening peak).

Figure 6.2 (c) and (d) give plots from Detector-2 and Detector-5 respectively. These two detectors are installed at the middle of the infrastructure units and detect only traffic on them. Again, curvature, inclination and decreasing width of stairways are observed. Moreover, the detection area of these two detectors did not have a full converge over the entire width of the infrastructure. Therefore, some trajectories have been cut at the two sides of the images and we got only partial trajectory data of these pedestrians.

As for Detector-3 and Detector-6 (Figure 6.2 (c) and (d)), they also detect pedestrians on two types of terrain: stairways or escalators ($y \approx 6$ to 16) and passageways ($y \approx 0$ to 6). The detecting outcomes are quite similar to those of Detector-1 and Detector-4.

6.2.3 Conclusions of trajectory reviews

In subsections 6.2.1 and 6.2.2 some problems of infrared detections are discussed. Among those, we identify three major problems that will influence the outcomes of the analysis with respect to walking and choice behavior in this project. They are:

- Distorted trajectories which will introduce the measurement errors on calculating for instance speeds of pedestrians;
- Split trajectories resulted from discontinuous detection;
- Loss of traffic counts especially at dense conditions.

As for doubting detections as well as irrational trajectories, we neglect their influence on the analysis outcome because of the rareness of those special cases. In order to increase the precision and reliability on utilizing the technique of infrared detectors for the study of pedestrian behavior of various kinds, some necessary steps must be taken to eliminate or reduce the negative effects of these three mentioned problems. We discuss measures applied to overcome those problems in section 6.2.

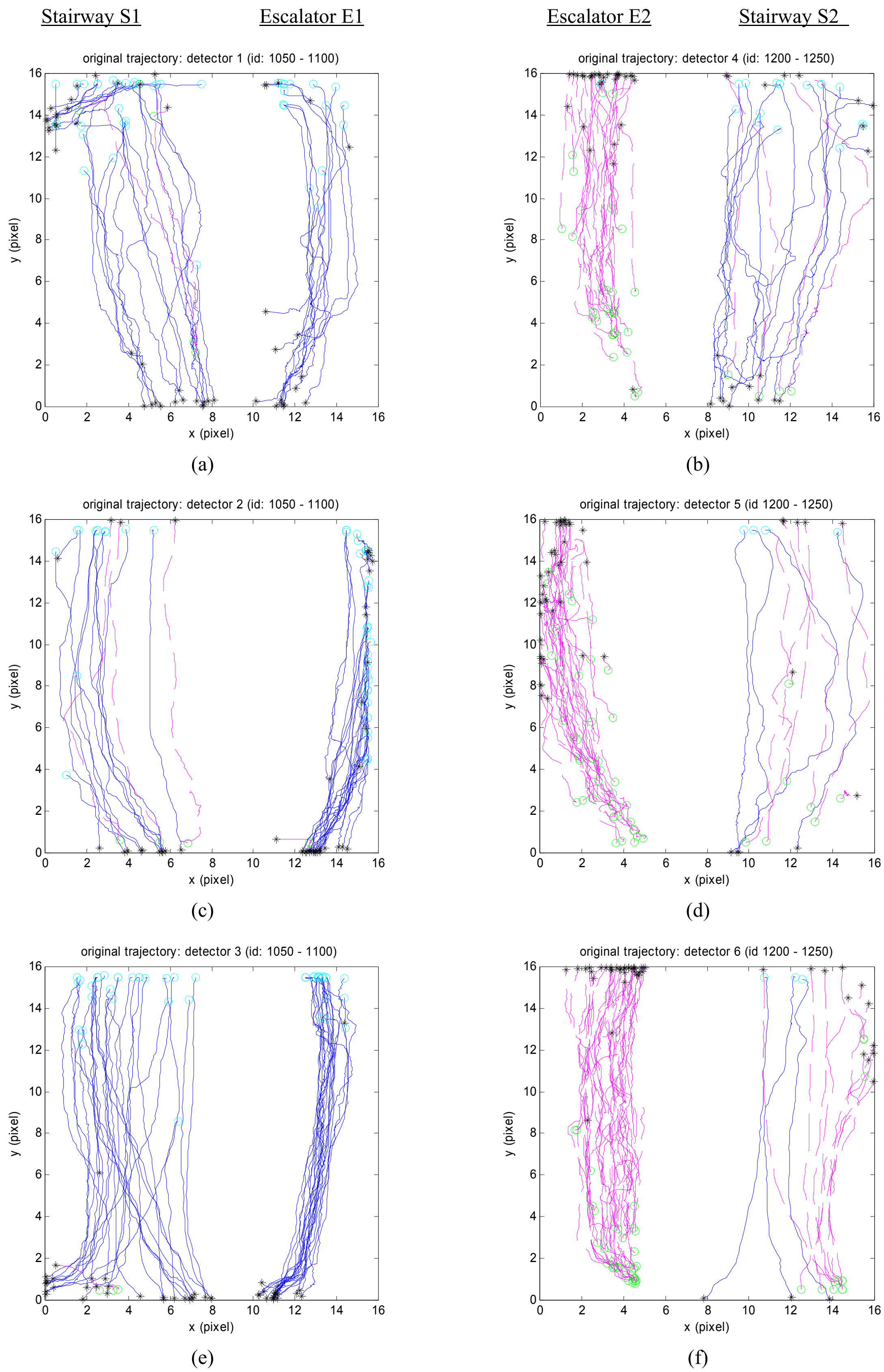


Figure 6.2
Cumulative plots of 50 pedestrians of Detector-1 to Detector-6. The solid lines represent descending trajectories while the dashed lines represent ascending ones.

6.3 Data processing

This section describes steps performed as preparatory works for data analysis of walking and choice behavior in this project. It is noted that the data mentioned here refers to either observation data from infrared detectors or video images. Four steps are distinguished. They are:

- Correct distortion of trajectory data observed by infrared detectors;
- Match split trajectory within one field of view (infrared detector);
- Register personal characteristics from video images and incorporate them with trajectory data;
- Correct (infrared) flow data based on video reading.

In this section, we will discuss these four preparatory works in the sequence of distortion correction, matching split trajectory, registration of personal characteristics, and correction of flow data.

6.3.1 Distortion correction

Our reviews of the original trajectory data from infrared detectors in section 6.1 find that the data is suffering from certain degrees of distortion. Two possible sources of distortion are identified, namely: the lens distortion and the perspective distortion. We will describe those phenomenons and discuss measures taken for the correction in the following sections.

Lens distortion

Lens distortion, which results from imperfect design of an optical system, will cause a change in the shape of an image. It can be easily observed when an image contains vertical lines from objects that are vertical in reality (such as columns). On a distorted image, these straight lines will be seen as lines with certain degrees of curvature bending either towards or away from the centre of the image. The effect is more profound if those vertical lines are located close to the edges of the image, or more technically precise, when have larger off-axis distances. It is noted that the kind of distortion we have recognized from the infrared images is the so-called "barrel distortion", from which the distorted lines are noted as barrel shapes like those illustrated in Figure 6.3 (a).

In this report, we apply the following lens distortion model for the correction (Atksinson 1996):

$$r_u = r_d(1 + k_1 \cdot r_d^2) \tag{6.1}$$

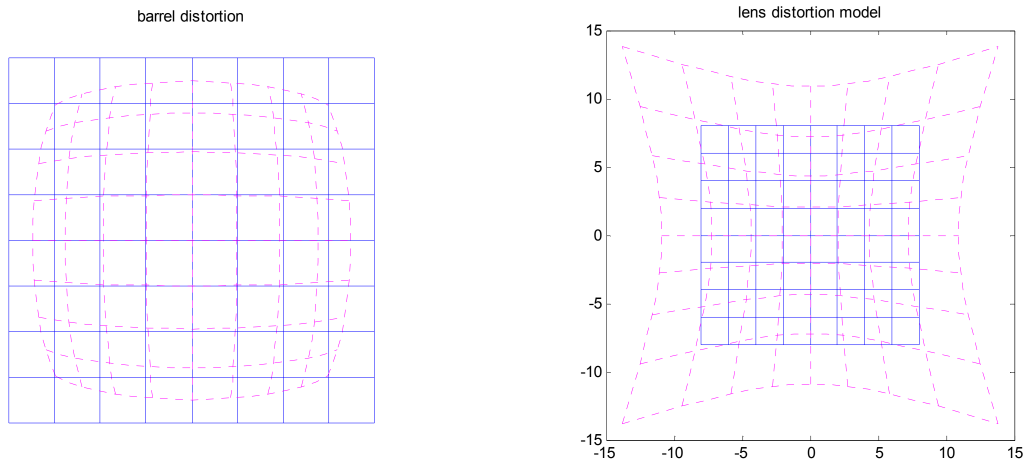
where r_u and r_d are the distance from the center of distortion (x_0, y_0) in the undistorted and distorted images respectively, and k_1 is the distortion parameter, which is specific to the lens. In this report, a value of 0.005662 is used for the k_1 in the formula.

To resample individual pixel, following algorithms are applied to transform distorted pixel data *(x_d, y_d)* into undistorted pixel data *(x_u, y_u)*:

$$r_d = \sqrt{(x_d - x_0)^2 + (y_d - y_o)^2} \tag{6.2}$$

$$x_u = (1 + k_1 r_d^2)(x_d - x_0) + x_0\,;\ y_u = (1 + k_1 r_d^2)(y_d - y_0) + y_0 \tag{6.3}$$

Figure 6.3 (b) illustrates the result of the implementation.



(a) (b)

Figure 6.3
Correction for lens distortion (a) Barrel distortion: the solid lines represent the original image while the dashed lines show the distorted one (b) Results of the correction algorithm: the solid lines represent original image while the dashed lines show the effect of applying the correction algorithm given in equation (6.1).

Perspective distortion

The perspective distortion concerns the effect of diminishing scale when measuring distance in space from a two-dimensional image. From a perspective point of view, it simply says that more distant objects are viewed as smaller than those near to viewers.

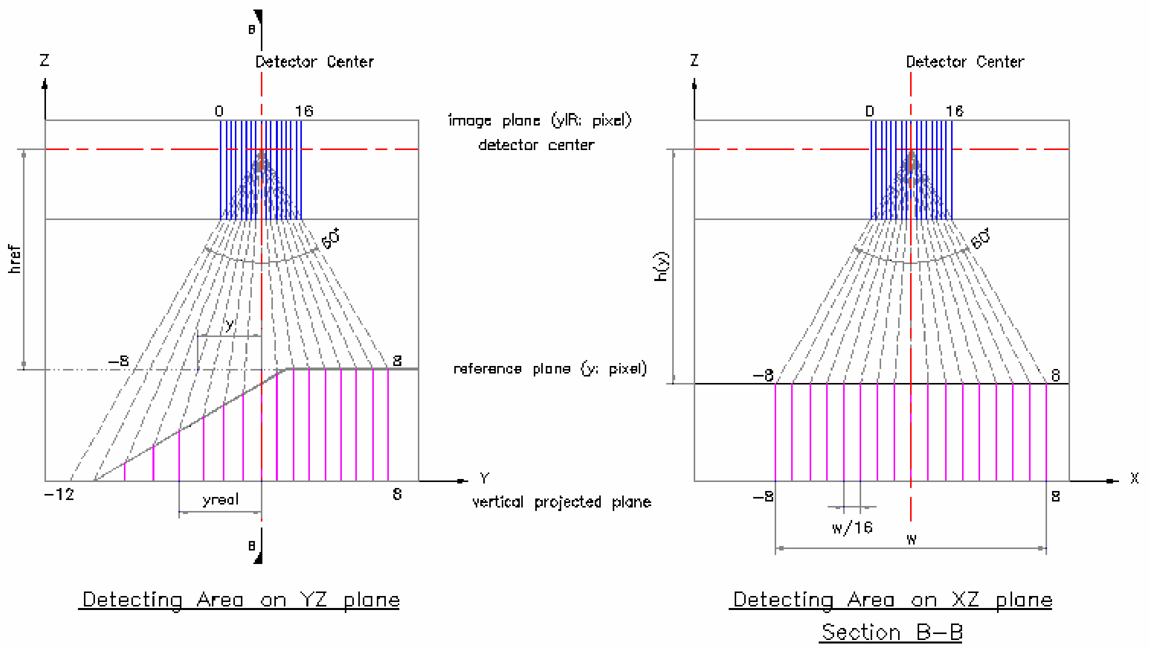


Figure 6.4
Correction for perspective distortion: (a) correction for y-coordinates (b) correction for x-coordinates. The correction is done by finding the relations between *y* on the reference plane and *yreal* on the vertical projected plane. The correction for the YZ plane is done with those relations given in Table 6.1.

In this project, regression relationships concerning the magnification factors between the reference plane and the vertical projected object plane are applied for the correction of the perspective distortion. We illustrate the concept in Figure 6.4.

According to the technical properties of those detectors used in this project, the image plane (of detectors) is composed of 16x16 sensor array distributed uniformly. The detectors are installed in a downwards looking manner with a field of view of 60 degrees. As shown in Figure 6.4, we assume that each element of the sensor array sees an equal angle of view, which results in various magnification factors along the profile of the infrastructure. Thus, to measure the real horizontal distance represented by each sensor element, we just need to find out the variation of the magnification factor along the infrastructure. It is noted that for each detector, the regression relationship is determined by the selection of a reference plane as well as the profile of the infrastructure within its coverage area. Thus, for each detector, there exists a specific relationship on the YZ plane. In addition, since the relation is determined by the profile of the infrastructure, it differs for stairways and for escalators as well. Finally, for the XZ plane, since the vertical projected object plane parallels to the reference plane, the pixels are uniformly distributed along the x axis.

Table 6.1 summarizes the relationships on the YZ plane found for the six detectors used in our observations. Figure 6.5 and Figure 6.6 give examples of the regression relationships found for stairways and escalators respectively.

Table 6.1
Algorithms apples for correcting perspective distortions on YZ plane

		zc	href	zref	Regression relationship between *yref* and *yreal*
		(cm)	(cm)	(cm)	
Stairways	Detector-1	995	450	545	$y \geq 1$: yreal = y $y < 1$: yreal = $-0.0584y^2 + 1.0614y$
	Detector-2	565	307.5	257.5	$y > 4$: yreal = $-0.018y^2 + 0.9559y + 0.5144$ $-2 \leq y \leq 4$: yreal =y $y < -2$: yreal = $-0.0819y^2 + 0.709y – 0.316$
	Detector-3	465	465	0	$y > -1$: yreal = $-0.0266y^2 + 0.9151y$ $y \leq -1$: yreal = y
	Detector-4	995	450	545	$y \geq 1$: yreal = y $y < 1$: yreal = $-0.0579y^2 + 1.0618y$
	Detector-5	565	307.5	257.5	$y > 4$: yreal = -0.019y2 + 0.994y + 0.3302 $-2 \leq y \leq 4$: yreal =y $y < -2$: yreal = $-0.0787y^2 + 0.744y – 0.2452$
	Detector-6	465	465	0	$y > -1$: yreal = $-0.028y^2 + 0.9095y$ $y \leq -1$: yreal = y
Escalators	Detector-1	995	450	545	$y \geq -1$: yreal = y; $y < -1$: yreal = $-0.0604y^2 + 0.9029y$
	Detector-2	565	307.5	257.5	yreal = $-0.039y^2 + 1.0163y$
	Detector-3	465	465	0	$y > -2$: yreal = $-0.0258y^2 + 0.8987y$ $y \leq -2$: yreal = y
	Detector-4	995	450	545	$y \geq -1$: yreal = y; $y < -1$: yreal = $-0.0604y^2 + 0.9029y$
	Detector-5	565	307.5	257.5	yreal = -0.039y2 + 1.0163y
	Detector-6	465	465	0	$y > -3$: yreal = $-0.0274y^2 + 0.8953y$ $y \leq -3$: yreal = y

Note:
zc = z coordinate of the detector center (cm);
href = vertical distance between the detector center to the reference plane (cm);
zref = z coordinate of reference plane = zc – href (cm);
y = yIR = pixel value from infrared detectors (pixel);
yreal = vertical projection of the object plane on the reference plane (pixel);
pixelL = distance per pixel at reference plane = (href / squr(3) * 2) /16 (cm).

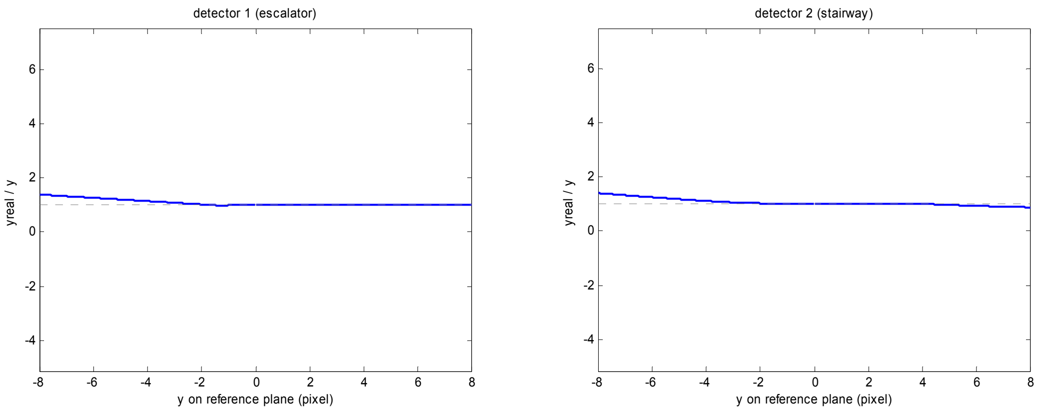


Figure 6.5
Examples of the relationships between *y* on the reference plane and *yreal* on the vertical projected plane: detector-1 and detector-2 on stairways (source from Table 6.1).

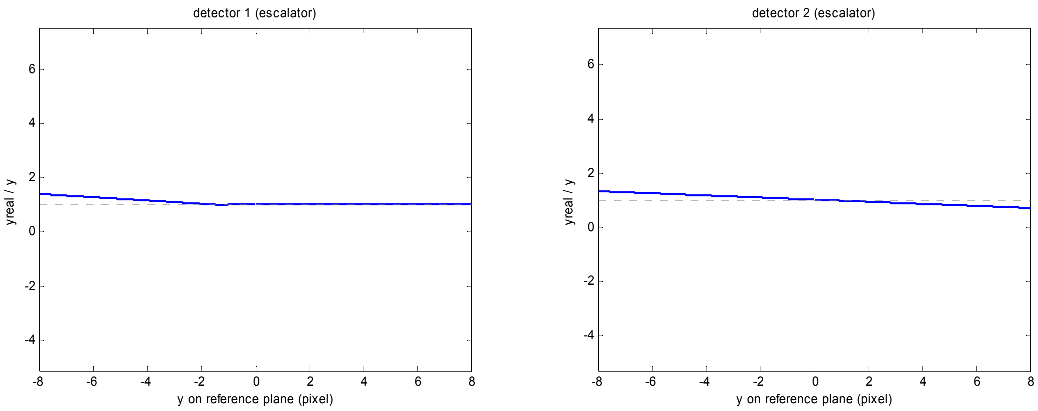


Figure 6.6
Examples of the relationships between *y* on the reference plane and *yreal* on the vertical projected plane: detector-1 and detector-2 on escalators (source from Table 6.1).

Evaluation of correction algorithms

To evaluate the results of the algorithms described in previous subsection B.2.1, we make a comparison between the original and corrected trajectory data. Figure 6.7 shows trajectory plots before and after the correction for lens distortion and perspective distortion applied for Detector-1 and Detector-2. The corrected results are noticeably positive with respect to the profiles of trajectories.

However, to further verify the precision of the correction, we compare the behavior observed from infrared data with the real images recorded by video cameras. A descriptive comparison is given in Table 6.2. It shows that the corrected trajectory reveals consistent behavior with the video images. Therefore, we conclude that the algorithms applied for the correction of both lens distortion as well as perspective distortion largely enhance the reliability of utilizing trajectory data extracted from infrared detectors to analyze pedestrian behavior of various kinds.

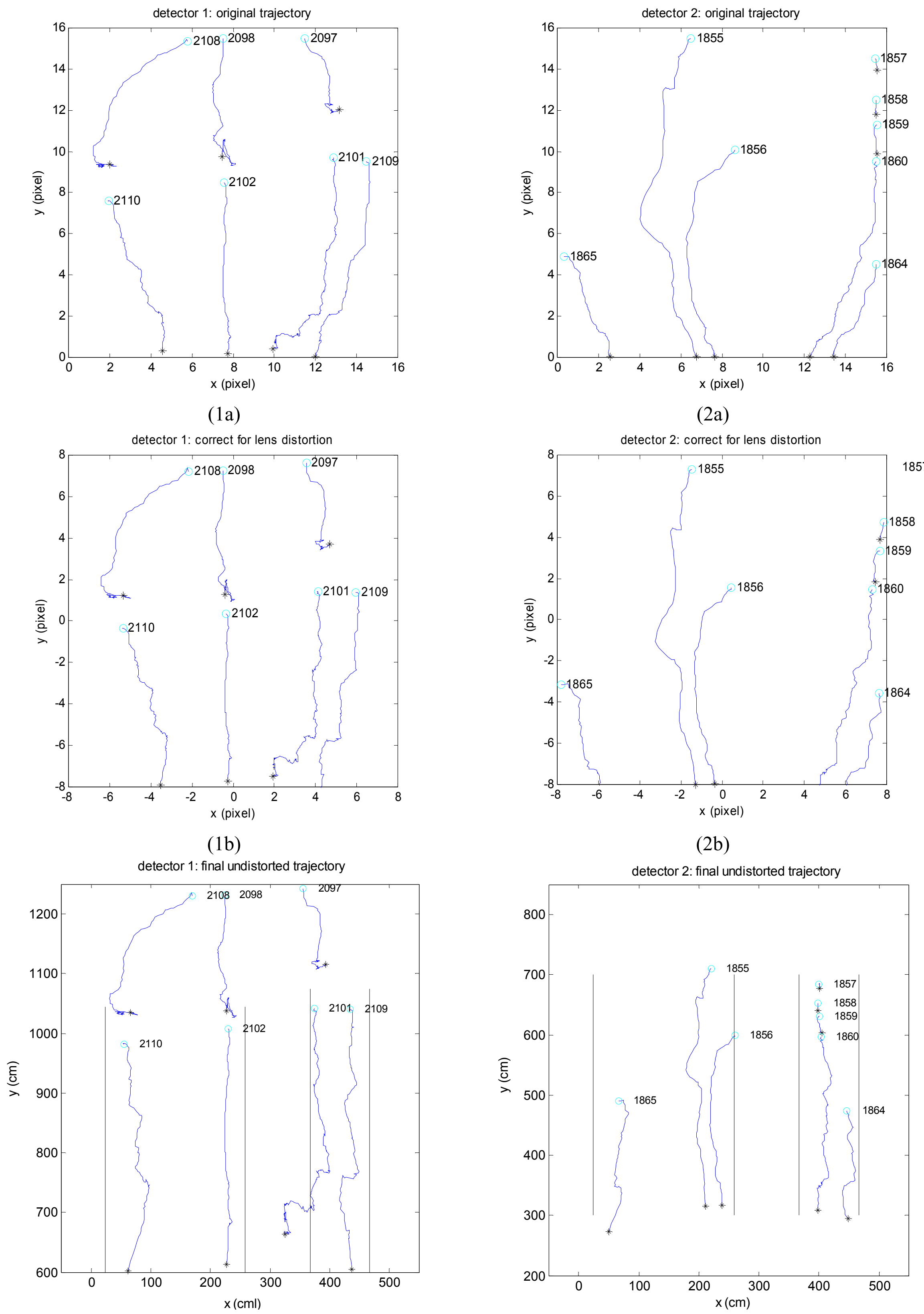


Figure 6.7
Plots of trajectories; (1a) & (2a): original plots; (1b) & (2b): plots after correcting for lens distortion; (1c) & (2c): plots after correcting for lens distortion and perspective distortion. Besides, the first and final detecting points of a specific target are indicated by the symbol “o” and “*” respectively.

Table 6.2
Descriptive comparison of pedestrian behavior observed between infrared detector and video images.

Corrected infrared trajectory data						Video data
time	id	name	x	y	Status*	Description of behavior observed from video
19:08:19	2097	A	392.99	1115.0	2	Pedestrian A stood in front of the escalator (LHS)
19:08:27	2101	A	374.46	1041.7	1	Pedestrian A stepped onto the first tread of the escalator
19:08:36	2101	A	324.80	663.47	2	Pedestrian A traveled downwards the escalator
19:08:21	2098	B	227.14	1037.5	2	Pedestrian B stood on the first stair down the platform level (RHS)
19:08:28	2102	B	229.04	1007.2	1	Pedestrian B started to walk down the stairway
19:08:34	2102	B	227.26	613.17	2	Pedestrian B traveled downwards the stairway
19:10:01	2108	C	65.49	1034.6	2	Pedestrian D stepped onto the first tread of the escalator
19:10:05	2110	C	55.26	982.3	1	Pedestrian C started to walk down the stairway
19:10:10	2110	C	62.14	602.5	2	Pedestrian C started to walk down the stairway
19:10:03	2109	D	433.99	1039.8	1	Pedestrian D stepped onto the first tread of the escalator
19:10:08	2109	D	437.04	605.0	2	Pedestrian D traveled downwards the escalator

* 1: start point; 2: end point

We give corrected results of the six infrared detectors in Figure 6.8 to Figure 6.10.

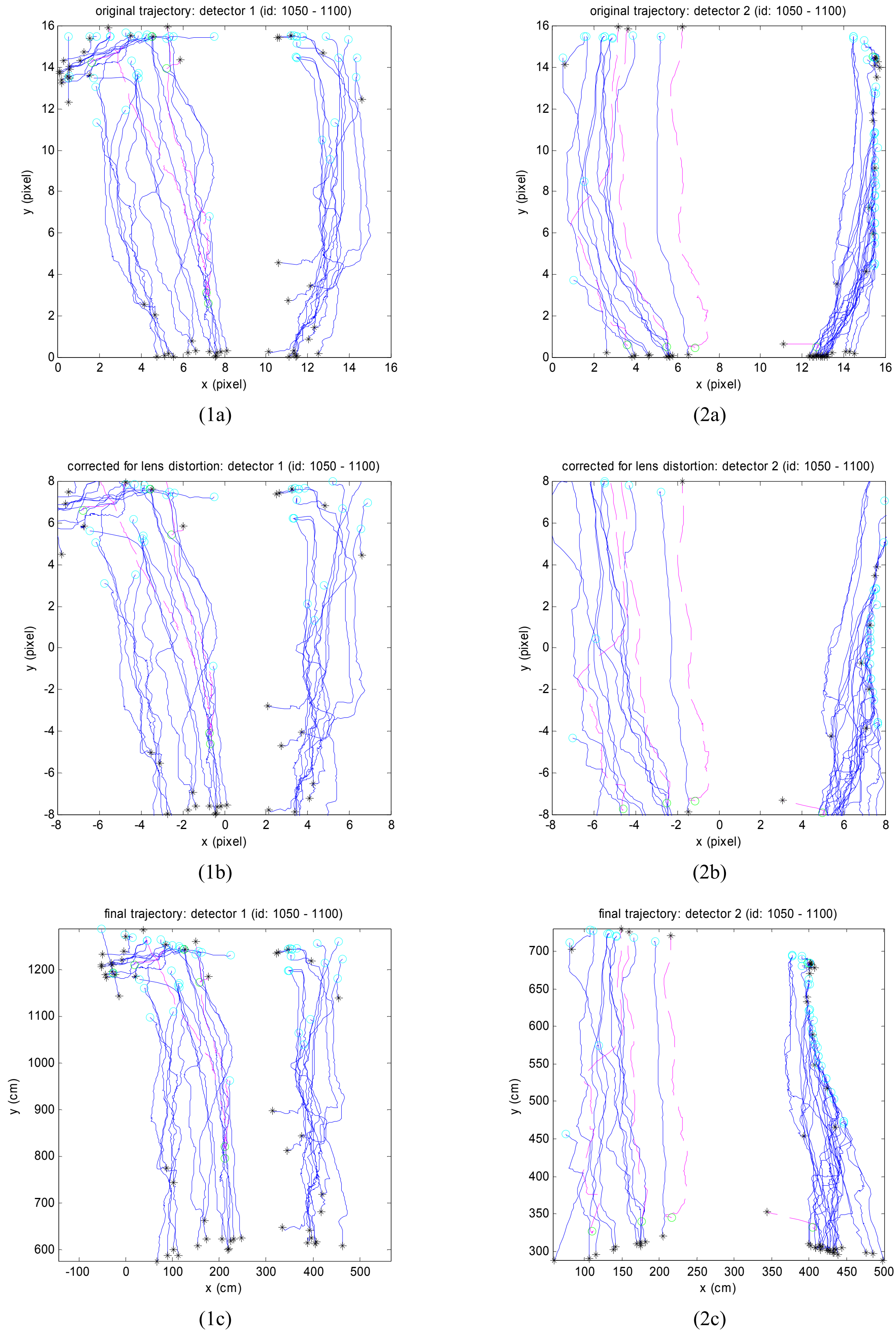


Figure 6.8
Trajectory plots for Detector-1 and Detetor-2. (1a) & (2a): original plots; (1b) & (2b): plots after correcting for lens distortion; (1c) & (2c): final trajectory plots.

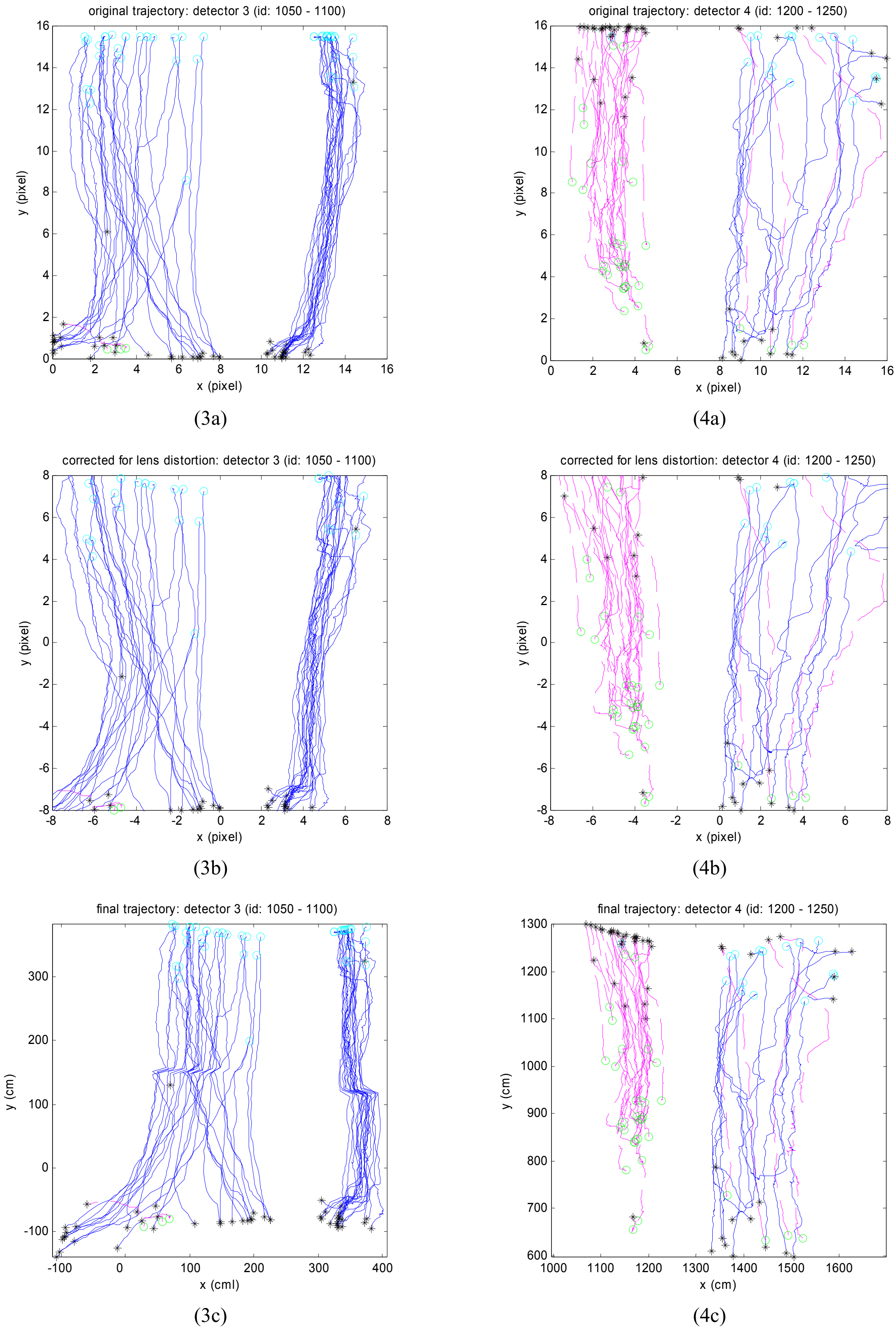
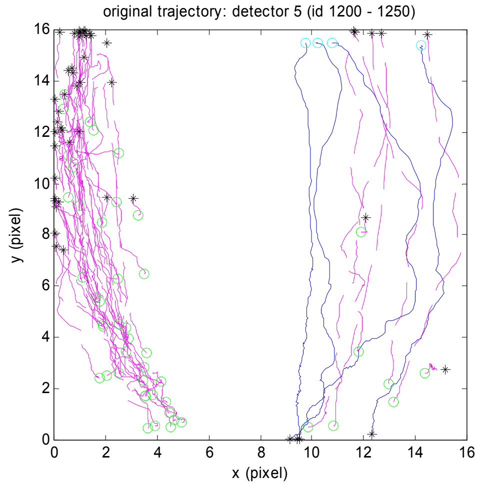
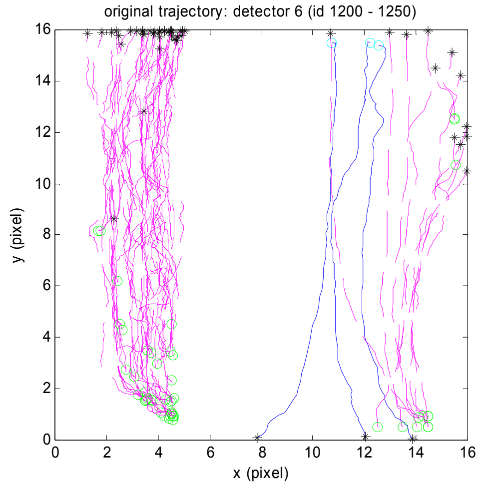


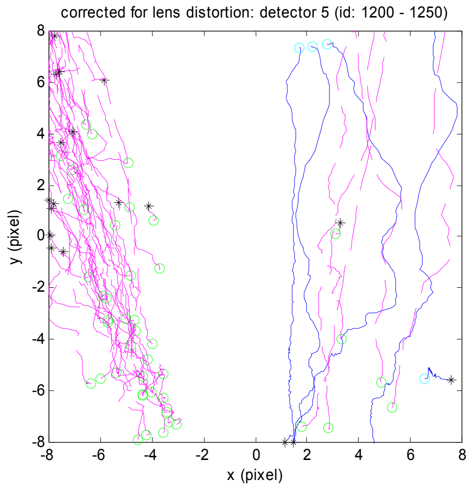
Figure 6.9
Trajectory plots for Detector-3 and Detetor-4. (3a) & (4a): original plots; (3b) & (4b): plots after correcting for lens distortion; (3c) & (4c): final trajectory plots.



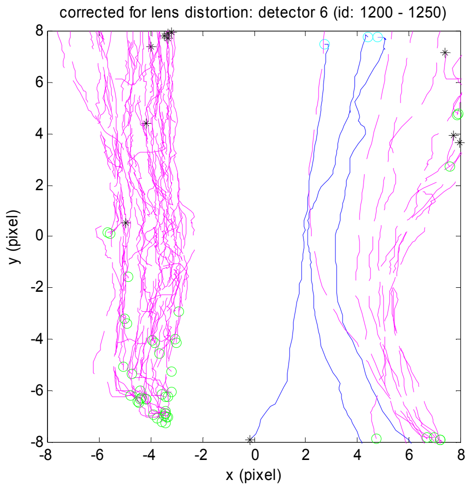
(5a)



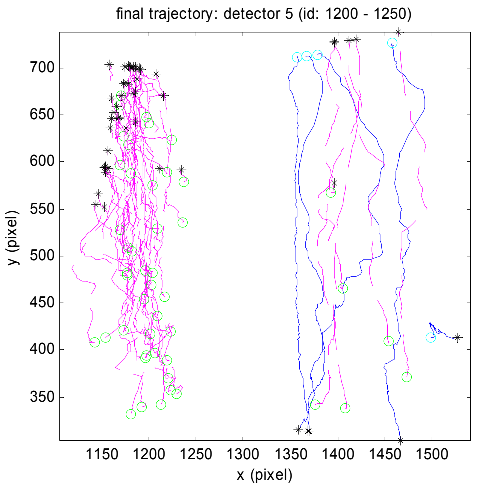
(6a)



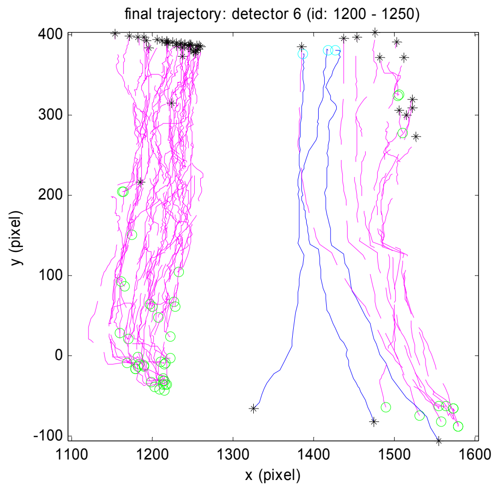
(5b)



(6b)



(5c)



(6c)

Figure 6.10
Trajectory plots for Detector-5 and Detetor-6. (5a) & (6a): original plots; (5b) & (6b): plots after correcting for lens distortion; (5c) & (6c): final trajectory plots.

6.3.2 Matching split trajectory

As we have observed in section 6.1.1, discontinuous detection has caused the split of a trajectory into several parts. In order to enhance the completeness of movement information of individual pedestrians, we need to search for those broken trajectories and combine them into a complete one. Four criteria in terms of time, x position, y position, and walking direction, are set as the conditions for matching. It is noted that there is no overlapping of those broken trajectories since one pedestrian can only present at one position at a specific time moment. Two trajectories are considered to be belonging to the same pedestrian, if and only if they satisfy all of the following conditions:

- The time difference (Δt) between the starting moment of one trajectory and the ending moment of another one is less than or equal to 1 second;
- The difference in x position (Δx) between the starting point of one trajectory and the ending point of another one is less than or equal to 50 cm;
- The difference in y position (Δy) between the starting point of one trajectory and the ending point of another one is less than or equal to 100 cm;
- The moving directions of these two trajectories are the same.

In the following paragraphs, we give some results of our matching with the data observed by Detector-1 and Detector-2. First, we will have a close look on the match results from our observation between 17:23 and 17:38 by Detector-1 to examine the performance of the algorithm. Then we summarize the outcomes of implementing with entire data set observed by Detector-1 and Detector-2 (15:40 ~ 17:10).

Sample data I: detector 1 (17:23 ~ 17:38)

During this 15-minute of observation, 187 trajectories are detected by Detector-1, while 3 pairs of trajectories are matched. It is noted that those 187 trajectories include pedestrians on platforms as well as those on stairways and escalators. Figure 6.11 shows the three pairs of trajectories found to be matched.

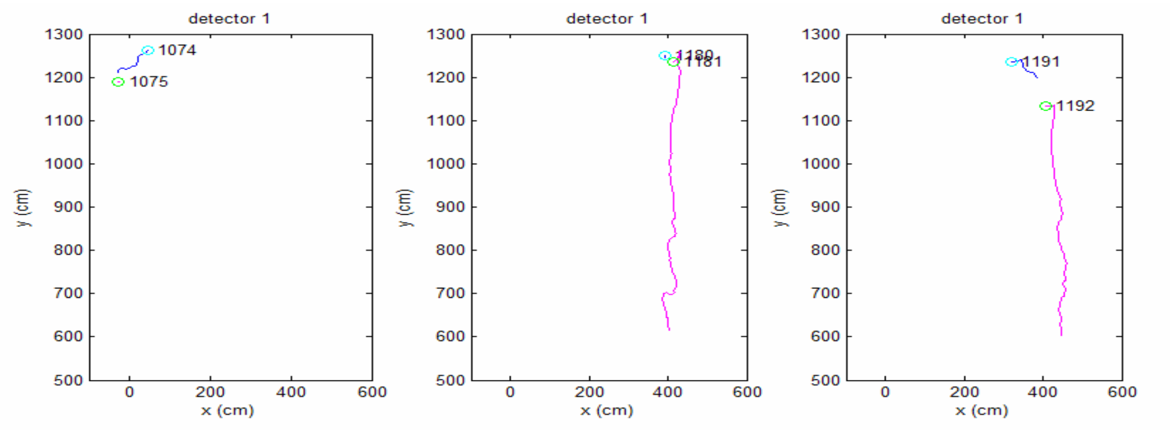


Figure 6.11

Results of matching split trajectories of Detector-1

Table 6.3
Results of matching split trajectories of Detector-1

Matched pair	Id-1	Id-2	Δt	Δx	Δy
1	1074	1075	0.04	27.489	-18.921
2	1180	1181	0.681	22.036	-79.025
3	1191	1192	0.2	22.491	-62.793

Sample data II: detector 1 (15:40 ~ 19:10)

The entire observation lasted for 3.5 hours. During this period, 2049 pieces of trajectory are observed by Detector 1, while 47 pairs are considered to as matched. It means that only about 0.2% of trajectories are suffering from discontinuous detection according to our algorithm. Some statistics data of these discontinuous trajectories is given in Table 6.4.

Table 6.4
Statistical data of split trajectories found by our algorithms: Sample Data II

	Δt (s)	|Δx| (cm)	|Δy| (cm)
Average	0.23	21.44	38.83
Standard deviation	0.20	13.30	29.42
Min.	0.03	2.20	0.08
Max.	0.69	47.76	95.99

Sample data III: detector 2 (15:40 ~ 19:10)

The result from detector 2 shows that 1798 trajectories are observed during the entire observation period, while 250 pairs (about 1.4 %) are considered as matched. Some statistics data of these discontinuous trajectories is given in Table 6.5.

Table 6.5
Statistical data of split trajectories found by our algorithms: Sample Data III

	Δt (s)	|Δx| (cm)	|Δy| (cm)
average	0.28	7.97	31.44
standard deviation	0.27	8.14	21.86
min	0.03	0.05	0.90
max	0.99	39.44	92.37

Therefore, we can conclude that the discontinuous detection is not serious. The results from detector 1 and detector 4 show that less than 1.5 % of trajectories are split into parts. Those split data may result from too low speeds of pedestrians or hindrance by obstacles in the observing area such as light posts.

6.3.3 Registration of personal characteristics

Beside the trajectory data from infrared detectors, we also use the video images to register personal characteristics (gender, age, and luggage) of individual pedestrians. Those personal characteristics will be combined with the trajectory data in order to study the influence of these personal characteristics on the travel behavior of pedestrians. Therefore, we will present how the infrared and video data are integrated in this subsection.

To integrate personal information with trajectory data, we have to compare data from these two sources. This is simply done by checking the passage time and x position of every pedestrian at a specific cross-section from both sources. In this project, we select the location of about 3 steps down the platform level (y = 945) as the checking line. The registering work is then carried out by comparing the passage information (passage times and x positions) as shown in Figure 6.12 with video images. The information recorded for each pedestrian includes gender, age group, with or without luggage, and stand/walk choice on escalators. The choice between stairways and escalators is determined by the location of the pedestrian observed by detectors.

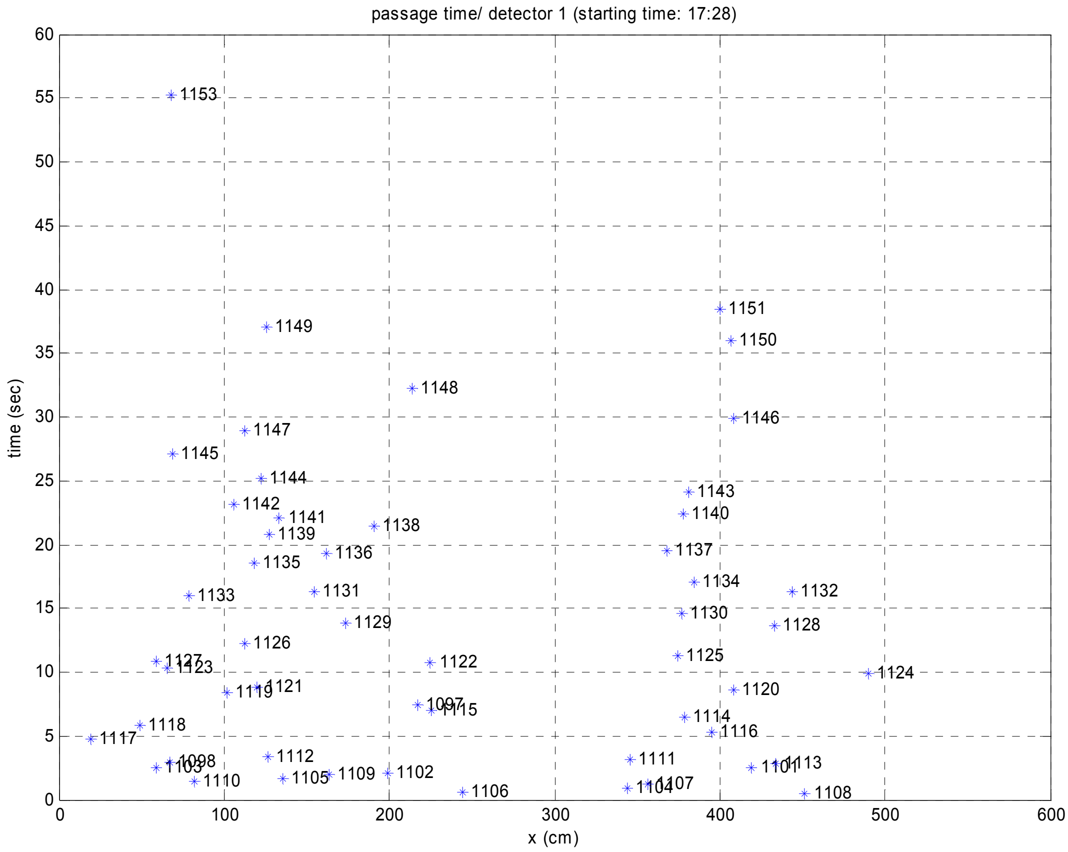


Figure 6.12
Plots of passage time and x position measured at about 3 steps down the platform level (y = 945) used to register personal characteristics of pedestrians.

6.3.4 Correction for flow data

When working on the registration of personal characteristics with video images, we found that there is discrepancy between traffic flows observed by infrared detectors and those counting from the video image. Some pedestrians are not detected by the infrared detectors, thus we do not have their trajectory data in our database. Since the video records the reality, we use it to verify the outcome of infrared detection.

Table 6.6 gives traffic counts of a period of 15 minutes (17:23~17:38) from both sources (Detector-1 and Camera-1). The data shows that only 87% of pedestrians are successfully detected by infrared detectors. Besides, the rate decreases to 80% when we focus on the 1 minute (17:27~17:28) of high flow period. This causes errors when measuring flows especially in high flow periods. Thus, to reduce the negative influence on traffic analysis, we correct this discrepancy by adding those missing observations back to our database. However, it is noted that the correction is only done for the flow data. Other traffic properties such as speeds are calculated only with trajectory data observed by infrared detectors.

Table 6.6
Traffic counts of a period of 15 minutes (17:23~17:38) from Detector-1 and Camera-1.

Time period	Source	Flow groups				Total	
		Stair-up	Stair-down	Esc-up	Esc-down		
17:23 - 17:38	Camera 1	5	72	0	68	145	(100%)
	detector 1	5	59	0	62	126	(87%)
17:27 - 17:28	Camera 1	0	54	0	36	90	(100%)
	detector 1	0	42	0	30	72	(80%)

6.3.5 Conclusions for data processing

In subsection 6.3.1 to 6.3.4, we describe algorithms applied to process traffic data observed by infrared detectors and video cameras. Four steps are defined: distortion correction, matching split trajectory, registration of personal characteristics, and correction of flow data. The results of the correction for both lens and perspective distortion give quite satisfactory outcomes (see Figure 6.8, Figure 6.9 and Figure 6.10). Exceptions are the corrections for detector-3 and detector-6 which show some systematic mistakes of the correction algorithms. The results of trajectories matching within one field of view indicate that the problem of discontinuous detection is not serious. Less than 2% trajectories are split into parts. The coupling of personal characteristics and trajectory data becomes rather difficult at dense traffic conditions. The short durations of high flows observed at our observation site makes it necessary to correct flow data based on video reading.

7 Data Analysis for Walking Behavior in the Vertical Dimension

This chapter presents our findings concerning pedestrian walking behavior in the vertical dimension. We focus on the free speeds and fundamental diagrams of various pedestrian flows. In this report, the estimation of free speed distributions is done with the product limit method which uses censored observations for the estimation. We give our results of free speed estimations concerning infrastructure type, directions of movement, gender and age in section 7.1. We then present the fundamental diagrams derived for the pedestrian flows on stairways and escalators in section 7.2. Due to the small variation of traffic conditions observed, the flow-speed-density measurements are limited at low flow conditions. Although no significant relationships are observed, hypothesized fundamental diagrams are given based on our hypothesized model presented in section 3.2 and empirical data given in subsection 2.1.3.

7.1 Free speeds in the vertical dimension

This section presents our findings about free speeds on stairways and on escalators. The estimation of free speed distributions is done by the project limit method with censored observations. We first give a review on the method. Then we discuss results of free speeds on stairways and escalators as well as the influences of gender and age on them.

7.1.1 Product limit method

This section discusses the distribution of free-flow speeds of pedestrians. In this report, the product-limit method (PLM) is used to determine the distribution of free speeds of various pedestrian flows. The most important feature of PLM is the use of “censored observations” in the estimation. Observations are called “censored observations” if they contain only partial information to observers. Thus with respect to the estimation of free speed distributions, we divide speed observations into two groups: constrained speeds and free (or non-constrained) speeds. Observations of constrained speeds are coded as censored observations since they fail on giving complete information about free speeds of those constrained walkers (followers); however, they still provide information such as that free speeds of those followers are higher than those measured values. Thus, the exclusion of those censored observations may lead to an error of underestimation since fast walkers have higher probabilities to be constrained by slower ones.

To apply PLM for the estimation of free-speed distributions, an explicit division of speed observations is needed. Criteria such as time headway, a combination of time headway and relative speed, and distance headway may be used to for the division (Daamen 2004). In this report, time headway is used to perform the separation between constrained and non-constrained speeds because of its capability of reflecting the space available for walking locomotion by taking speeds into account. We assume that a minimal time-headway (h*) exists so that pedestrians traveling under the condition of having their time headway larger than this minimal value are all free walkers. Taking into account the speed and space required for unconstrained locomotion on stairways and escalators, a minimal headway of 2 seconds is assumed in this report (h* = 2 s). Thus, two conditions are distinguished:

- $\delta = 0$: uncensored observations or measurements of free speeds if time headway > 2 seconds
- $\delta = 1$: censored observations or measurements of constrained speeds if time headway $\leq$ 2 seconds

Now we discuss the application of maximum likelihood method for the estimation of free speed distributions. Let $f(v_0)$ and $S(v_0)$ denote the probability density function and the survival function of free speeds (v_0) respectively. The maximum likelihood (L) of a sample set of free speed observations $\{v_i\}$ is determined by the following expression:

$$L = \prod_{i=1}^{n} f(v_i)^{1-\delta_i} S(v_i)^{\delta_i} \tag{7.1}$$

where $f(v_i)$ is the probability of free speeds equal v_i or denoted as $Pr(v_0 = v_i)$; $S(v_i)$ is defined as the probability that free speeds are larger than or equal any specific speed v_i or denoted as $Pr(v_0 \geq v_i)$.

In this report, we apply the method of Kaplan & Meier to determine a non-parametric estimate of the survival function. The non-parametric estimate of the survival function of free speeds is determined by the following equation (Hoogendoorn 2005):

$$S(v_i) = \prod_{j=1}^{m} \left(\frac{n-j}{n-j+1}\right)^{\delta_j} \tag{7.2}$$

where m equals the number of speed observations that are smaller then or equal v_i (i.e. $v_j \leq v_i$, j = 1,2,… m); n is the total number of observations.

It is noted that for the calculation of time headways, we adopt the concept of "dynamic layers" presented by Hoogendoorn & Daamen (2005). The concept of dynamic layers is used to describe following behavior of pedestrians in bottlenecks. In their study, a distance of about 45 cm is found for the width of overlapping layers observed at 1.0 m wide bottlenecks. In this report, we use 50 cm as the width of a dynamic layer to reflect the larger lateral displacement connected to stair locomotion.

7.1.2 Results of free speed estimations on stairways and escalators

Figure 7.1 to Figure 7.4 give results of free speed estimations calculated with only unconstrained (free) observations as well as those estimated with Product Limit Method for both ascending and descending flows on stairways and escalators. It is noted that those distributions are estimated only with stairway speed observations larger than 0.25 m/s and escalator speed observations larger than 0.5 m/s. We summarize the results in Table 7.1.

Table 7.1
Summary of the mean and standard deviation (stdv.) of (horizontal) free speed distributions calculated with only non-constrained (free) observations and total (all) observation by PLM.

Source	infrastructure	Direction	#observation		Non-constrained estimation		PLM	
Detector			free	all	mean	stdv.	mean	stdv.
1	Stairway	Descending	523	590	0.741	0.220	0.766	0.238
4	Stairway	Ascending	473	488	0.661	0.327	0.675	0.341
1	Escalator	Descending	606	706	0.838	0.322	0.883	0.346
4	Escalator	Ascending	1958	2207	0.790	0.274	0.817	0.292

According to Table 7.1, speeds in the descending direction are about 10% higher than those in the ascending direction on both stairways and escalators. In addition, speeds on escalators are higher than those on stairways. Finally, higher values of free speeds are measured with PLM than with non-constrained estimations because of the use of censored observations for the estimation.

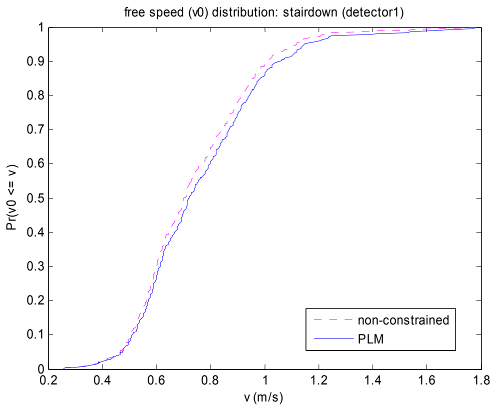


Figure 7.1
Free speed distribution of descending pedestrians on stairways (by Detector-1)

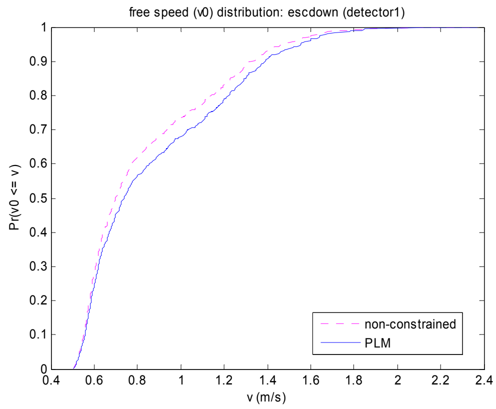


Figure 7.2
Free speed distribution of descending pedestrians on escalators (by Detector-1)

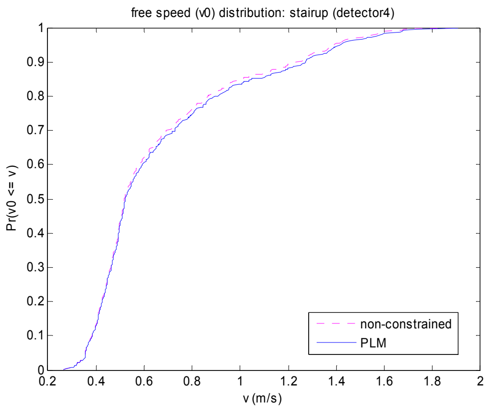


Figure 7.3
Free speed distribution of ascending pedestrians on stairways (by Detector-4)

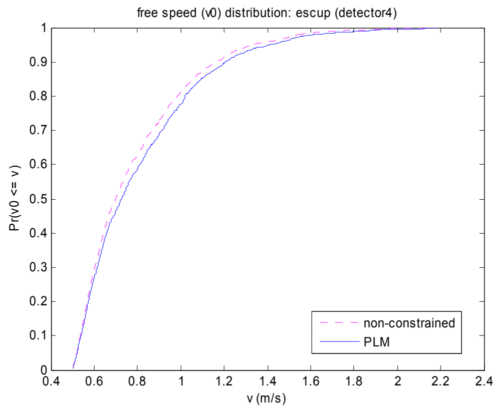


Figure 7.4
Free speed distribution of ascending pedestrians on escalators (by Detector-4)

7.1.3 Influence of gender on free speeds

We summarize the results about free speeds of female and male pedestrians on stairways and escalators in Table 7.2. In general, male pedestrians exhibit higher speeds than female pedestrians on stairways and escalators.

Table 7.2
Summary of the mean and standard deviation (stdv.) of free speed distributions calculated with only non-constrained (free) observations and total observation by PLM.

Infrastructure	Direction	Gender	#observation		Non-constrained estimation		PLM	
			free	all	mean	stdv.	mean	stdv.
Stairway	Descending	Female	121	132	0.696	0.189	0.712	0.195
		Male	236	271	0.777	0.227	0.810	0.251
	Ascending	Female	71	72	0.530	0.183	0.540	0.198
		Male	134	137	0.688	0.354	0.688	0.359
Escalator	Descending	Female	93	103	0.827	0.312	0.854	0.319
		Male	301	336	0.864	0.335	0.901	0.353
	Ascending	Female	144	158	0.849	0.310	0.875	0.318
		Male	171	189	0.884	0.306	0.922	0.330

7.1.4 Influence of age on free speeds

We summarize the results about free speeds of the three age groups (youth, commuter, and elderly) on stairways and escalators in Table 7.3. In general, free speeds decrease with ages. An exception is the result found for ascending pedestrians on stairways. The measured free speed of the elderly is higher than that of the commuter. It shows that some elderly people could be still quite physically fit. However, this result could be biased due to the few observations of elderly passengers.

Table 7.3
Summary of the mean and standard deviation (stdv.) of free speed distributions calculated with only non-constrained (free) observations and total observation by PLM.

Infrastructure	Direction	Gender	#observation		Non-constrained estimation		PLM	
			free	all	mean	stdv.	mean	stdv.
Stairway	Descending	Youth	96	110	0.800	0.267	0.837	0.283
		Commuter	253	283	0.733	0.194	0.756	0.214
		Elderly	8	10	0.655	0.169	0.666	0.159
	Ascending	Youth	69	72	0.673	0.340	0.676	0.356
		Commuter	132	133	0.612	0.300	0.614	0.300
		Elderly	4	4	0.672	0.369	n/a	n/a
Escalator	Descending	Youth	57	63	0.900	0.354	0.934	0.371
		Commuter	323	361	0.855	0.328	0.889	0.344
		Elderly	19	23	0.739	0.225	0.771	0.233
	Ascending	Youth	92	105	0.945	0.343	0.988	0.365
		Commuter	199	218	0.849	0.292	0.877	0.302
		Elderly	24	24	0.729	0.209	n/a	n/a

7.1.5 Conclusions of free speeds in the vertical dimension

We give results of free speed estimation of pedestrian flows on stairways and escalators in Table 7.1. In general, speeds in the descending direction are higher than those in the ascending direction on both stairways and escalators. A difference of about 10% is measured from our observation data. Moreover, higher speeds are observed on escalators than on stairways in both directions.

Table 7.2 and Table 7.3 give results of free speeds based on the gender and age of pedestrians. The two sexes exhibit different walking behavior on both stairways and escalators and in both ascending and descending direction. In general, the free speeds of females are lower that those of males. With respect to the influence of age on walking behavior, our results show that in general, free speeds decrease with ages. An exception is the result found for ascending pedestrians on stairways. However, the result could be biased due to the few observations of ascending elderly passengers on stairways.

7.2 Fundamental diagrams in the vertical dimension

In this section, we derive the fundamental relationships of the four pedestrian flows by means of cumulative flow plots. The reason of using this cumulative flow approach instead of directly measuring density is because multiple traffic states may exist on an element of a pedestrian facility at a time instant (Daamen 2004) especially when the demand fluctuation is big and the duration of a certain state is relatively short. That is the case in our observation. We did not really observe congestion during the observation period. Besides, we also noted that the crowded conditions exist mainly at the upper part of the stairways and last only for short periods of time. Therefore, if we simply divide the number of pedestrian present at a time instant by the effective area of the stairway, we are actually measuring an average density on the entire infrastructure which does not have much connection to the speeds measured at the counting cross-section.

We illustrate the approach of cumulative flow explicitly in Figure 7.5. The cumulative flow of each pedestrian group is counted at a specified cross-section *y*. Speeds of pedestrians passing that cross-section are measured as well. Thus, the average flow measured at the cross-section during time period (t_1,t_2) is calculated by the following formula:

$$q(y,\Delta t)=\frac{N(y,t_2)-N(y,t_1)}{(t_2-t_1)\times W_e} \tag{7.3}$$

where $q(y,\Delta t)$ denotes the number of pedestrians passing cross-section y within time interval Δt ($\Delta t = t_2 - t_1$); $N(y,t)$ is the cumulative flow at cross-section y and time moment t ($t = t_1$ or t_2); W_e = effective width of pedestrian infrastructure. In this report, an effective width of 1.85 m and 1.00 m is assumed for stairways and escalators respectively.

In addition, according to the fundamental relationship of flow, density and speed given in equation (2.1), the density at location y and time instant t can be calculated with the following expression:

$$k(y,t)=\frac{q(y,t)}{u(y,t)} \tag{7.4}$$

In this report, the aggregation of flow data is done in two phases. At the first phase, we aggregate flow data with a 5-second interval. The purpose of this is to enable correcting of flow data to eliminate the discrepancy between the flow data observed by infrared detectors and pedestrian counting from video reading (see section 6.2). Based on the video information, we manually correct the flow data measured by infrared detectors on the basis of 5-second intervals. The 5-second interval is selected due to the short high-flow periods occurred during our observation.

At the second phase, we further aggregate the flow data by considering a more appropriate sample size (number of observations) due to statistical concerns. In this report, we use 10 observations (pedestrians) as the minimal size of samples. It is noted that since the flow data has been aggregated in the previous stage, our method will result in a calculation of the flow, speed and density based on varied time periods as well as varied sample sizes.

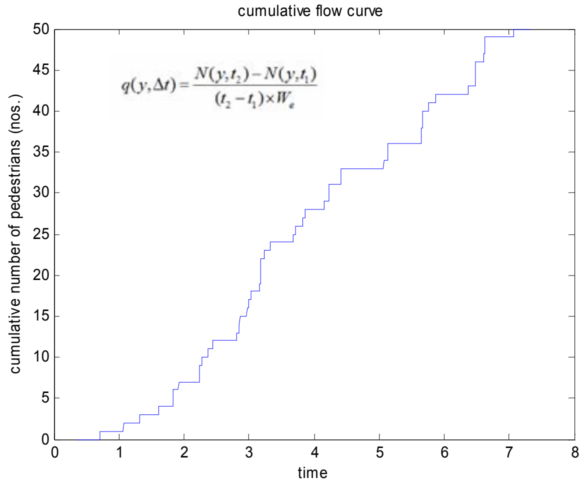


Figure 7.5
Cumulative flow approach for derivation of fundamental relationships of pedestrian flows at a cross section *y*

7.2.1 Fundamental diagrams of stairway flows

This subsection presents results of speed-flow-density measurements calculated for stairway traffic. It is noted that the counting cross-section is located at about three steps down the platform level (y = 945). Besides, only speed observations larger than 0.25 m/s are used for the speed calculation.

Descending direction on stairways

Figure 7.6 gives results of the speed-flow-density measurements calculated with the descending traffic observed on stairway S1 (16:30 ~ 19:10). The results show that quite limited traffic conditions had been observed. The biggest density observed is only about 1.3 P/m^2. In spite of the limited data, we can still observe decreasing speeds when densities increase. The linear relationship between speeds and densities become more noticeable when densities are larger than about 0.6 P/m^2. In addition, smaller spreads of data are observed at larger density conditions which may infer that the variation of speeds decreases when densities increase.

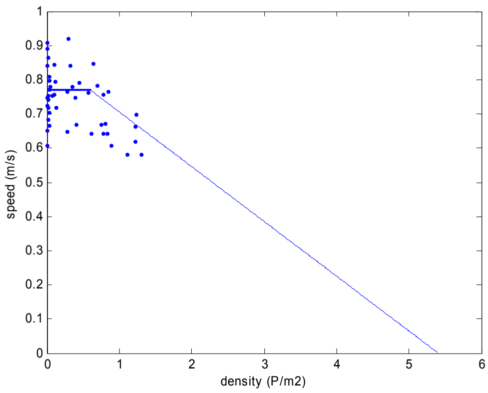
Although our observations fail on providing sufficient information about the entire fundamental diagrams on stairways, we still try to construct the possible fundamental relationships based on our hypothesized speed-density models given in section 3.2 (see Figure 3.2) and the empirical data discussed in section 2.1.3. Following are some assumptions made:

- Free speed (u_0) = 0.77 m/s (see Table 7.1);
- Biggest density when speeds equal free speeds (k_f) = 0.6 P/m^2;
- Jam density (kj) = 5.4 P/m^2 (Weidmann, 1993);
- Capacity density (k_c) = 2.23 P/m^2 (Weidmann, 1993).

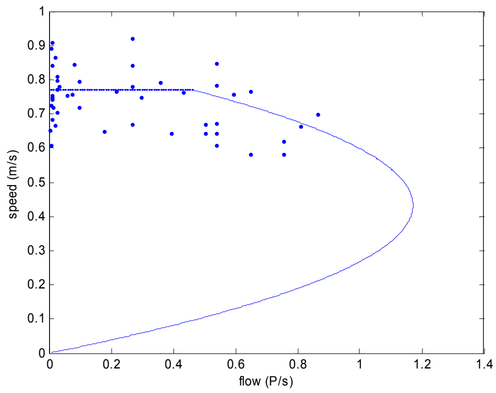
Thus, the possible speed-density relationships are given as follows:

$$u = 0.77 \qquad \text{if } k \le 0.6$$
$$u = 0.77(1.125 - 0.208k) \qquad \text{if } 0.6 < k \le 5.4$$

where u is the speed of flows (m/s) , k is the density (P/m^2). Consequently, the capacity speed (u_c) is 0.51 m/s; capacity (q_c) = 1.14 P/m/s. We give those hypothesized relationships in Figure 7.6 as well.



(a)



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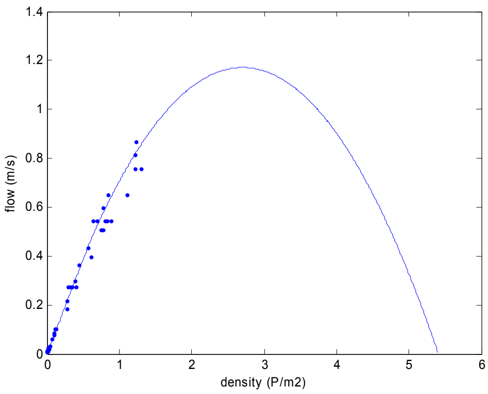


(c)

Figure 7.6
Speed-flow-density measurements and hypothesized fundamental diagrams of descending traffic on stairways (a) speed-density diagram (b) speed-flow diagram (c) flow-density diagram

Ascending direction on stairways

Figure 7.7 gives results of the speed-flow-density measurements calculated with the ascending traffic observed on stairway S2 (17:00~18:00). The results show that very limited traffic conditions had been observed. The biggest density observed is only about 0.18 P/m^2. Thus, no noticeable relations between speeds and densities are observed.

Still, we try to construct the possible fundamental relationships based on our hypothesized speed-density models given in section 3.2 (see Figure 3.2) and the empirical data discussed in section 2.1.3. Following are some assumptions made:

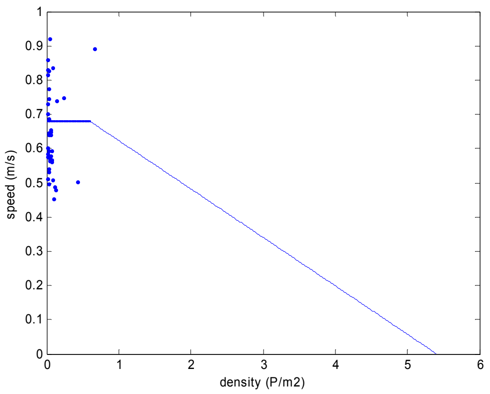
- Free speed (u_0) = 0.68 m/s (see Table 7.1);
- Biggest density when speeds equal free speeds (k_f) = 0.6 P/m^2;
- Jam density (kj) = 5.4 P/m^2 (Weidmann, 1993);
- Capacity density (k_c) = 2.23 P/m^2 (Weidmann, 1993).

It is noted that although we argue for a smaller jam density in the ascending (see subsection 2.1.3), we adopt the constant value given by Weidmann (1993) due to lack of evidence.

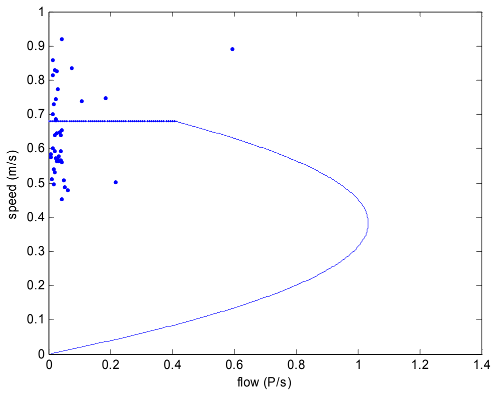
Thus, the possible speed-density relationships are given as follows:

$$u = 0.68 \qquad \text{if } k \le 0.6$$
$$u = 0.68(1.125 - 0.208k) \qquad \text{if } 0.6 < k \le 5.4$$

where u is the speed of flows (m/s) , k is the density (P/m^2). Consequently, the capacity speed (u_c) is 0.45 m/s; capacity (q_c) = 1.00 P/m/s. We give those hypothesized relationships in Figure 7.7 as well.



(a)



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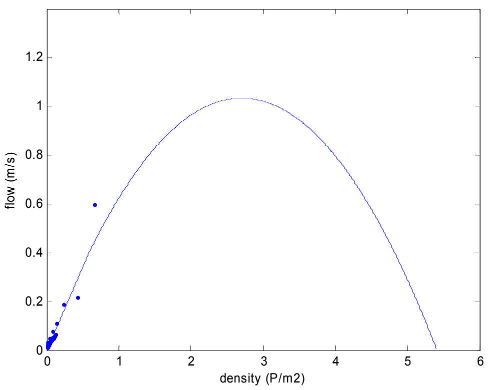


(c)

Figure 7.7
Speed-flow-density measurements and hypothesized fundamental diagrams of ascending traffic on stairways (a) speed-density diagram (b) speed-flow diagram (c) flow-density diagram

7.2.2 Fundamental diagrams of escalator flows

This subsection presents results of speed-flow-density measurements calculated for escalator traffic. It is noted that the counting cross-section is located at about three steps down the platform level (y = 945). Besides, only speed observations larger than 0.5 m/s are used for the speed calculation.

Descending direction on escalators

Figure 7.8 gives results of the speed-flow-density measurements calculated with the traffic observed on escalator E1 (16:30~19:10). The results show that quite limited traffic conditions had been observed. The biggest density measured is only about 1.06 P/m^2. The highest flow measured is only 0.93 P/m/s (56 P/m/min) which is less than 50% of the capacity value (120 P/m/min) observed by Daly et al. (1991) at London Underground stations.

Although not significant, the speed-density measurements given in Figure 7.8 (a) show that speeds decrease when densities increase. In addition, smaller spreads of data are observed at higher density conditions which may infer that the variation of speeds decreases when densities increase. Moreover, a lower boundary of speeds (about 0.6 m/s), which reflect the operating speed of escalators, can be observed. However, the value is higher than the actual horizontal operating speeds of escalators, which is about 0.52 m/s in our case. A possible explanation is because we consider only speed observations larger than 0.5 m/s for the analysis, thus the results may be overestimated due to measurement errors from our observation and data calibration.

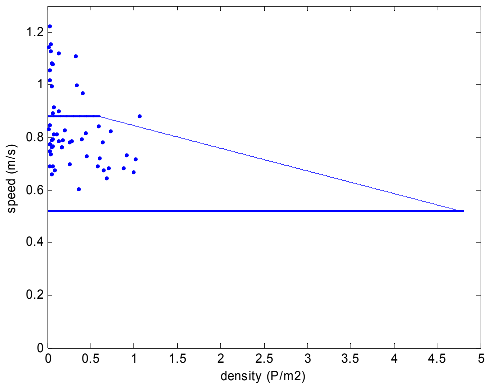
Although our observations fail on providing sufficient information about the entire fundamental diagrams, we still try to construct the possible fundamental relationships based on our hypothesized speed-density models given in section 3.3 (see Figure 3.2) and our real-life observations. Following are some assumptions made:

- Free speed (u_0) = 0.88 m/s (see Table 7.1);
- Horizontal operating speeds of escalators (u_e) = 0.52 m/s;
- Biggest density when speeds equal free speeds (k_f) = 0.6 P/m^2;
- Maximum density (k_{max}) = 4.8 P/m^2 (5 passengers / 3 escalator treads);
- Capacity density (k_c) = 1.90 P/m^2.

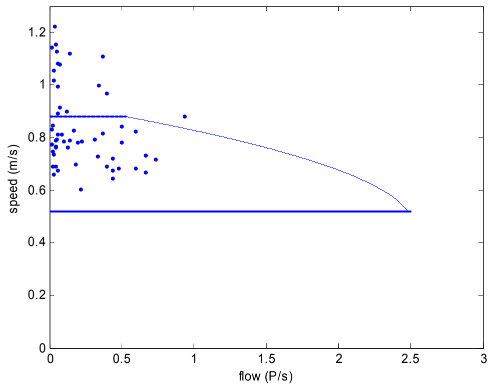
Thus, the possible speed-density relationships are given as follows:

$$
\begin{array}{ll}
u = 0.88 & \text{if } k \leq 0.6 \\
u = 0.88(1.06 - 0.1k) & \text{if } 0.6 < k \leq 4.8
\end{array}
$$

where u is the speed of flows (m/s) , k is the density (P/m^2). Consequently, the capacity speed (u_c) is 0.77 m/s; capacity (q_c) = 1.5 P/m/s. We give those hypothesized relationships in Figure 7.8 as well.



(a)



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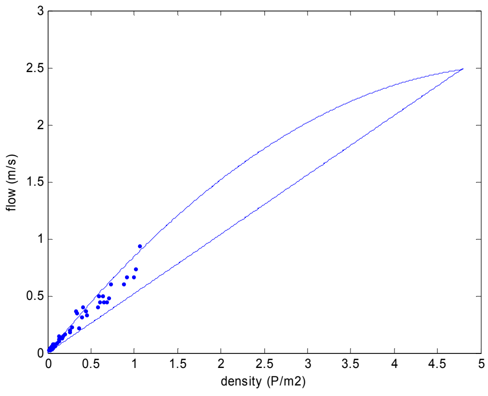


(c)

Figure 7.8
Speed-flow-density measurements and hypothesized fundamental diagrams of descending traffic on escalators (a) speed-density diagram (b) speed-flow diagram (c) flow-density diagram

Ascending direction on escalators

Figure 7.9 gives results of the speed-flow-density measurements calculated with the traffic observed on escalator E1 (17:00~18:00). The results show that quite limited traffic conditions had been observed. The biggest density measured is only about 1.08 P/m^2. The highest flow measured is only 0.67 P/m/s (40 P/m/min) which is only one third of the capacity value (120 P/m/min) observed by Daly et al. (1991) at London Underground stations.

The speed-density diagram given in Figure 7.9 (a) shows that speeds decrease when densities increase. In addition, larger spreads of data is observed at low density conditions. The variation of speeds decreases when densities increase. Moreover, a lower boundary of speeds (about 0.6 m/s) can be observed as what we have discussed for descending traffic on escalators in the previous section.

Although our observations fail on providing sufficient information about the entire fundamental diagrams, we still try to construct the possible fundamental relationships based on our hypothesized speed-density models given in section 3.3 (see Figure 3.2) and our real-life observations. Following are some assumptions made:

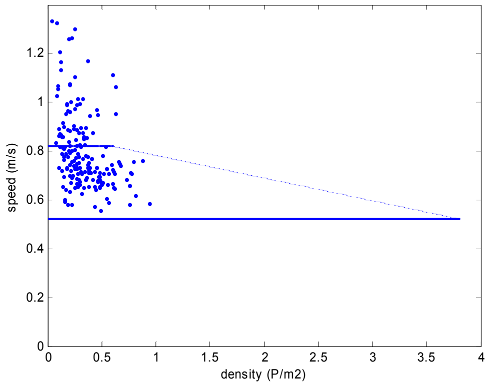
- Free speed (u_0) = 0.82 m/s (see Table 7.1);
- Horizontal operating speeds of escalators (u_e) = 0.52 m/s;
- Biggest density when speeds equal free speeds (k_f) = 0.6 P/m^2;
- Maximum density (k_{max}) =3.8 P/m^2 (4 passengers / 3 escalator tread);
- Capacity density (k_c) = 1.90 P/m^2.

Thus, the possible speed-density relationships are given as follows:

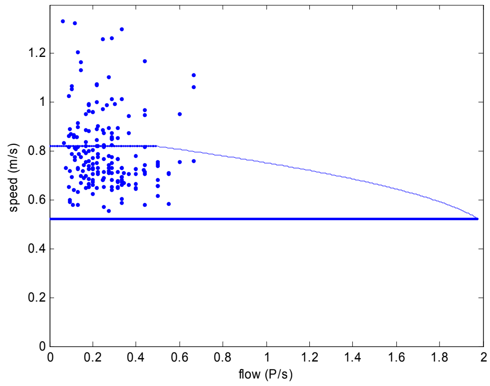
$$u = 0.82 \qquad \text{if } k \leq 0.6$$
$$u = 0.82(1.07 - 0.12k) \qquad \text{if } 0.6 < k < 3.8$$

where u is the speed of flows (m/s) , k is the density (P/m^2).

Consequently, the capacity speed (u_c) is 0.69 m/s; capacity (q_c) = 1.31 P/m/s. We give those hypothesized relationships in Figure 7.9 as well.



(a)



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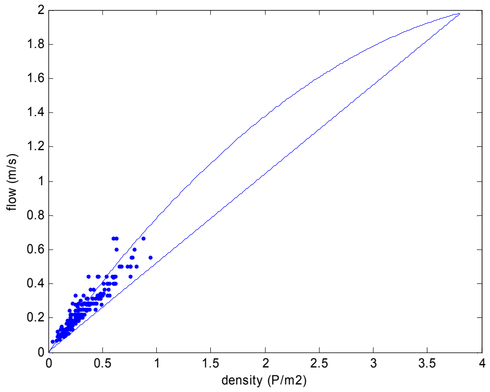

(c)

Figure 7.9
Speed-flow-density measurements and hypothesized fundamental diagrams of ascending traffic on escalators (a) speed-density diagram (b) speed-flow diagram (c) flow-density diagram

7.2.3 Conclusions of fundamental relationships in the vertical dimension

Because of the small variation of traffic conditions observed, our findings about the fundamental diagrams of pedestrian flows are quite limited. The highest flows observed on stairways are 0.86 P/ms and 0.18 P/ms in the descending and ascending direction respectively, while those on escalators are 0.93 P/ms and 0.67 P/ms in the descending and ascending direction respectively. Thus, our observations only provide traffic measurements at low flow conditions.

Although no significant relationships are observed, hypothesized fundamental diagrams are derived based on our hypothesized walking model presented in section 3.2 as well as empirical data discussed in subsection 2.1.3. We present our flow-speed-density measurements and those hypothesized fundamental diagrams in Figure 7.6 to Figure 7.9.

8 Data Analysis for Choice Behavior in the Vertical Dimension

This chapter presents our analysis results concerning route choices between stairways and escalators to change levels. Based on our discussion in section 4.1 and the conditions of our observation site, we start by formulating the choice situations and identifying influencing factors of the investigated choice behavior in section 8.1. However, due to incomplete travel information observed, two simplified choice networks are proposed in this report. In addition, only factors of travel time, physical effort, safety and comfort, and personal characteristic are considered in the utility functions formulated in section 8.2. The calculation of travel time is discussed in section 8.3. The model calibration is performed with the software BIOGEME. The estimated results are given in section 8.4. Finally, conclusions are drawn in section 8.5.

It is noted that the results presented in this chapter are derived only with data observed by Detector-1, Detector-4, Camera-1, and Camera-2.

8.1 Choice situations at the observation site

This section discusses choice situations facing by individual pedestrians at our observation site. The flows of pedestrians may be formulated with a 4x4 OD-matrix whose origins and destinations include Main Entrance (ME), platform 3 (PF3), platform 4 (PF4), and platform 5 and 6 (PF5/6). Figure 8.1 illustrates the route network with a link-and-node representation. Since escalators are operating in a specific direction, related links, link no. 7~9 and 12~14, are defined as unidirectional links in the network.

We focus on choice behavior in the vertical dimension, thus only OD pairs involving level changes will be discussed in the remainder of this report. Besides, taking into account the influence of movement directions, we make a distinction between choice situations concerning upward movement and those involving downward movement. For both upward and downward directions, 4 choice situations are identified (see Figure 8.4 and Figure 8.2). We discuss choice situations and factors influencing the route choice behavior in the descending and the ascending direction in subsection 8.1.1 and 8.1.2 respectively.

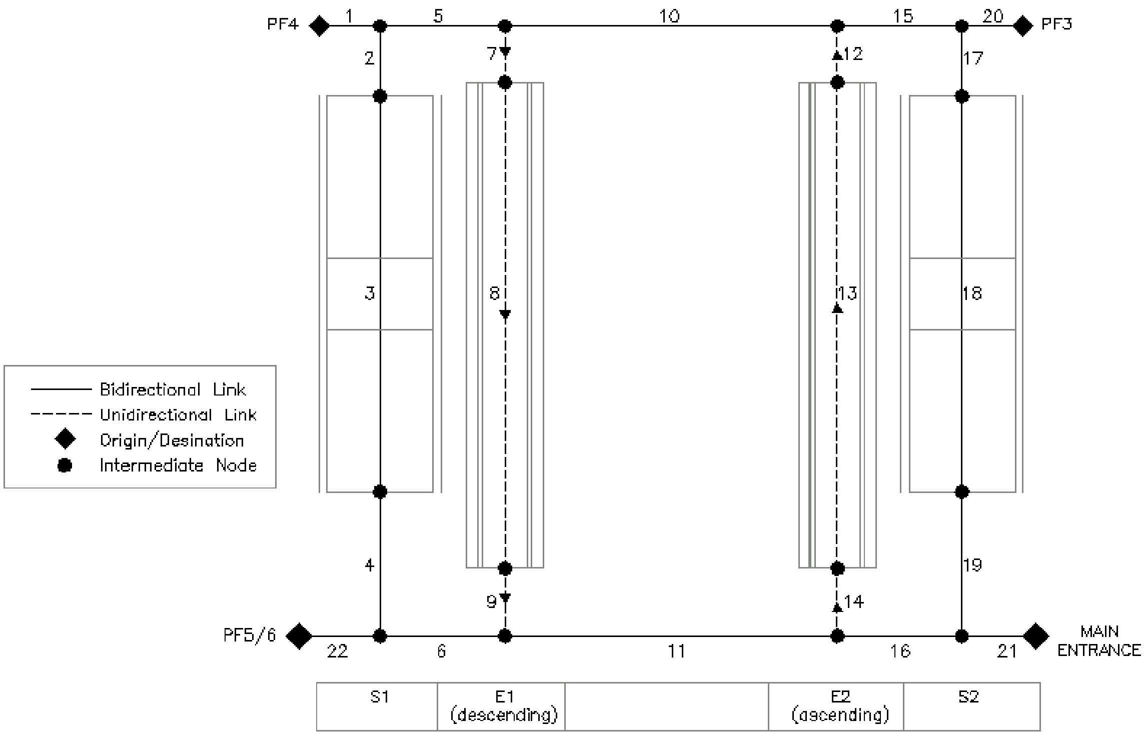

Figure 8.1
The route choice network at the observation site may be formulated with a 4x4 OD matrix

It is noted that based on our discussion in subsection 4.1.1, factors influencing route choice behavior in the vertical dimension may include the travel time and time pressures, physical effort, safety and comfort, personal characteristics, and vicinity. However due to the lack of information concerning time pressures facing by individual pedestrians, we neglect its possible influence on the choice behavior in this report.

8.1.1 Choice situations in the descending direction

Figure 8.2 gives the 4 choice situations concerning movement in the descending direction. We discuss these 4 choice situations and factors influencing the choice behavior below.

- **Choice situation 1**: For pedestrians traveling from PF3 to ME, two alternatives are considered: R11 and R12. Since these two alternatives differ in route lengths and compositions of terrains, influencing factors may include travel time, physical effort, safety and comfort, and personal characteristics.

- **Choice situation 2**: For pedestrians traveling from PF3 to PF5/6, three alternatives are considered: R21, R22, and R23. Although alternative R21 and R23 are identical in terms of route attributes (lengths and terrain compositions), the vicinity of the vertical facilities may have influence on the choice behavior. Besides, the involvement of either stairways or escalators in each alternative, results in different energy requirement between the alternatives. Thus, influencing factors may include travel time, physical effort, safety and comfort, personal characteristics, and vicinity. Finally, the overlapping of R32 and R33 may play roles as well.

- **Choice situation 3**: For pedestrians traveling from PF4 to ME, three alternatives are considered: R31, R32, and R33. The choice situation concerned here is very similar to that of choice situation 2, thus factors such as travel time, physical effort, safety and comfort, personal characteristics, and vicinity may affect the choice behavior.

- **Choice situation 4**: For pedestrians traveling from PF4 to PF5/6, two alternatives are considered, R41 and R42. Similar to choice situation 1, factors may include travel time, physical effort, safety and comfort, and personal characteristics.

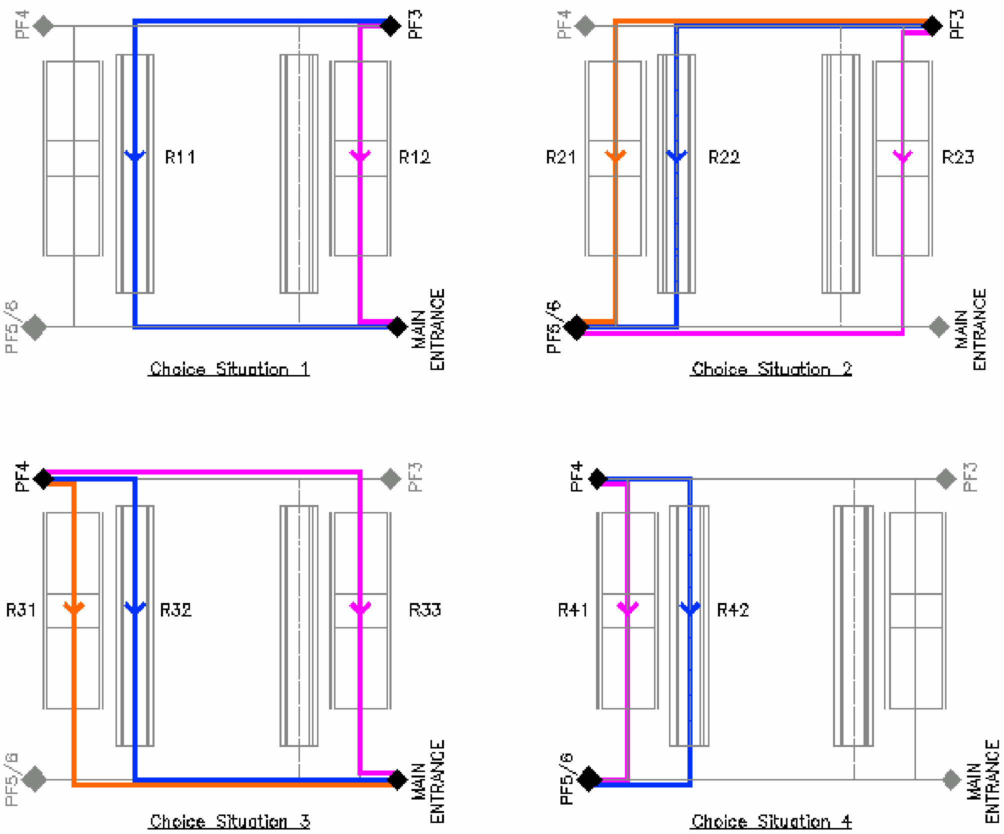

Figure 8.2
Choice situations of descending flows at the observation site: influencing factors of each choice situation are (1) travel time, physical effort, and safety and comfort; (2) travel time, physical effort, safety and comfort, vicinity, and route overlapping; (3) travel time, physical effort, safety and comfort, and vicinity ; (4) travel time, physical effort, and safety and comfort.

However, our observation set-up did not allow the observation of the complete travel behavior in the network. Those infrared detectors and video cameras used in the observations observed only travel behavior on those vertical infrastructures (vertical links). Because of lacking travel data on those horizontal links, we can identify neither the origin nor the destination of observed passengers. Thus, based on the available information, we focus in this report the choice behavior concerning adjacent stairways and escalators. Therefore, a simplified choice network is proposed. We give this simplified descending choice situation in Figure 8.3. We specify the descending choice situation as follows:

The simplified descending route choice situation

- pedestrians make a choice between Alt-S (via stairway S1) and Alt-E (via escalator E1) when moving downwards; therefore, the choice situation is composed of two alternatives;
- alternative Alt-S is composed of link-1 and link-2 while Alt-E consists of only link-3;

- factors influencing the choice behavior include travel time, physical effort, safety and comfort, and personal characteristics;
- these two alternatives are available to every observed pedestrian since they were always accessible during our observations.

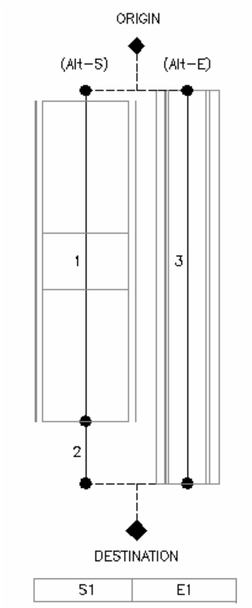

Figure 8.3
The simplified descending choice network concerning adjacent stairways and escalators proposed in this report

We summarize link attributes of this simplified network in Table 8.1.

Table 8.1
Link attributes of the simplified descending route choice networks given in Figure 8.3

Link no.	Link length (m)	Infrastructure	Movement characteristics
1	8.75	Stairway	Horizontal + Vertical
2	1.70	Passageway	Horizontal
3	10.75	Escalator	Horizontal + Vertical

8.1.2 Choice situations in the ascending direction

Figure 8.4 gives the 4 choice situations concerning movement in the ascending direction. We discuss these 4 choice situations and factors influencing the choice behavior below.

- **Choice situation 5**: For pedestrians traveling from ME to PF3, two alternatives are considered: R51 and R52. Influencing factors may include the travel time, physical effort, safety and comfort, and personal characteristics.

- **Choice situation 6**: For pedestrians traveling from ME to PF4, three alternatives are considered: R R62, and R63. Influencing factors may include the travel time, physical effort, safety and comfort, personal characteristics, and vicinity.

- **Choice situation 7**: For pedestrians traveling from PF5/6 to PF3, three alternatives are considered: R71, R72, and R73. Factors such as the travel time, physical effort, safety and comfort, personal characteristics, vicinity, and overlapping may affect the choice behavior.

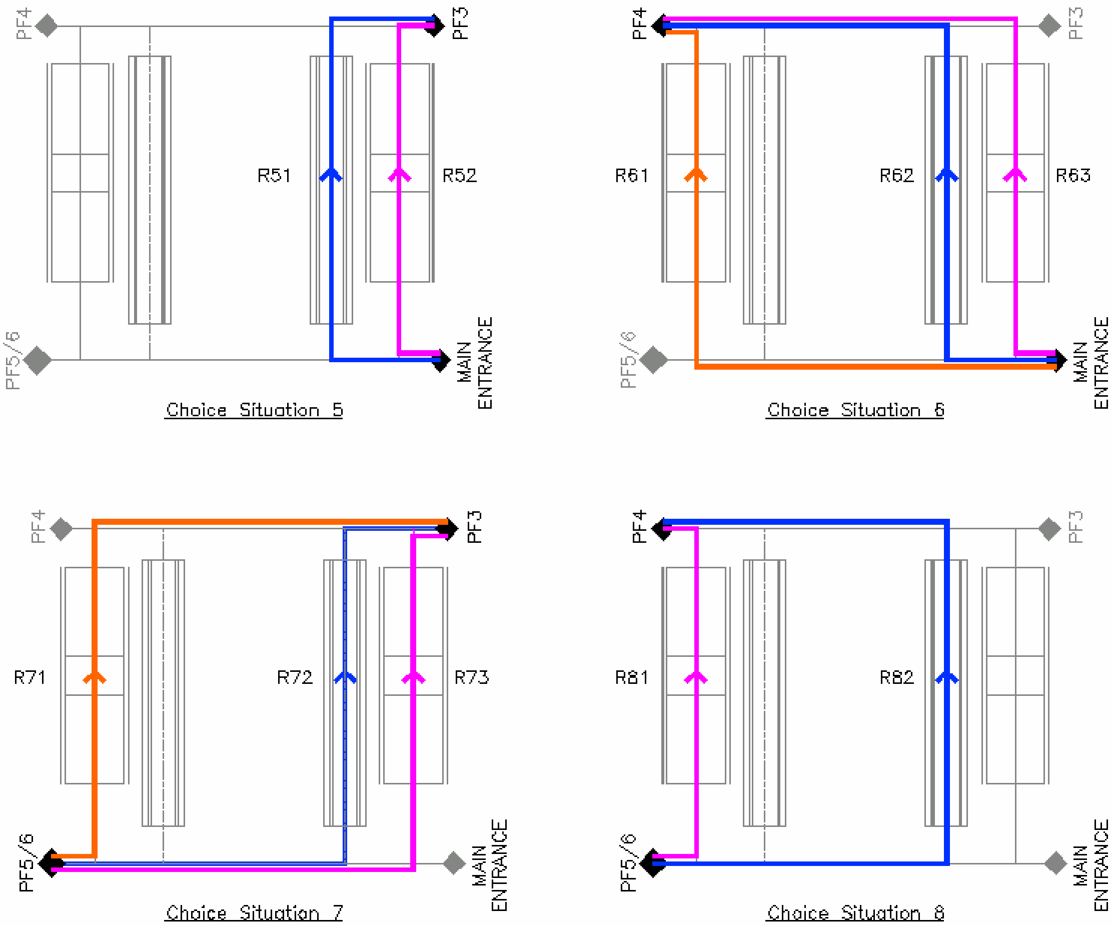

Figure 8.4
Choice situations of ascending flows at the observation site: influencing factors of each choice situation are (1) travel time, physical effort, and safety and comfort; (2) travel time, physical effort, safety and comfort, and vicinity; (3) travel time, physical effort, safety and comfort, vicinity, and route overlapping ; (4) travel time, physical effort, and safety and comfort.

- **Choice situation 8**: For pedestrians traveling from PF5/6 to PF4, two alternatives are considered: R81 and R82; influencing factors may include the travel time, physical effort, safety and comfort, and personal characteristics.

Due to the incomplete travel data observed (refer to subsection 8.1.1), we focus in this report the ascending choice behavior involving adjacent stairways and escalators. Therefore, a simplified choice network is proposed in this report. We illustrate this simplified ascending choice situation in Figure 8.5. The descending choice situation is specified as follows:

The simplified ascending route choice situation

- pedestrians make a choice between Alt-S' (via stairway S2) and Alt-E' (via escalator E2) when moving upwards; therefore, the choice situation is composed of two alternatives;
- alternative Alt-S' is composed of link-1' and link-2' while Alt-E' consists of only link-3';
- factors influencing the choice behavior include travel time, physical effort, safety and comfort, and personal characteristics;
- these two alternatives are available to every observed pedestrian since they were always accessible during our observations.

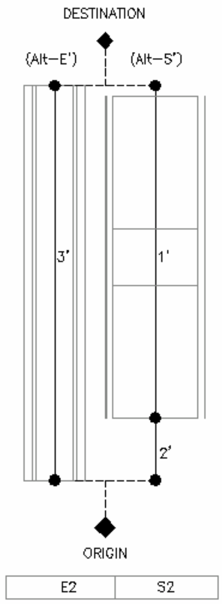

Figure 8.5
The simplified ascending choice network concerning adjacent stairways and escalators proposed in this report

We summarize link attributes of this simplified route choice network in Table 8.2.

Table 8.2
Link attributes of route choice networks given in Figure 8.5.

Link no.	Link length (m)	Infrastructure	Movement characteristics
1’	8.75	Stairway	Horizontal + Vertical
2’	1.70	Passageway	Horizontal
3’	10.75	Escalator	Horizontal + Vertical

8.2 Relative utilities of the simplified route choice models

In section 8.1, two simplified choice situations are specified for route choices between stairways and escalators at our observation site. In the descending situation, two alternatives are concerned: Alt-S and Alt-E (see Figure 8.3); in the ascending situation, also two alternatives are considered: Alt-S’ and Alt-E’ (see Figure 8.5). Since both choice situations contain two alternatives, we adopt the format of binary logit models for the model formulation. Thus, according to equation (2.9), the probability of choosing stairways (Alt-S or Alt-S’) is determined by the following expression:

$$P_{stair} = \frac{1}{1+\exp(V_{esc} - V_{stair})} = \frac{1}{1+\exp X} \tag{8.1}$$

where P_{stair} denotes the probability of pedestrians choosing stairways, V_{stair} and V_{esc} denote the deterministic components of the utility of alternative Alt-S/Alt-S’ and Alt-E/Alt-E’ respectively, and X is the relative utility of choosing escalators.

In addition, the probability of choosing escalators (Alt-E or Alt-E’) can be calculated with the following expression:

$$P_{esc} = 1 - P_{stair} \tag{8.2}$$

where P_{esc} denotes the probability of pedestrians choosing escalators.

Moreover, the formulation of the relative utility X is determined by those influencing factors identified in section 8.1, which include travel time, physical effort, safety and comfort, and personal characteristics. Since common variables are identified for the route choice behavior in both directions, we make no distinction between ascending and descending models in this section. In addition, the alternative of choosing stairways (Alt-S or Alt-S') is considered as the reference alternative whose alternative specific constant equals zero.

Since only the travel time and personal characteristics are observed measurements in our observations, we explicitly consider their influence on the route choice behavior in this report. In addition, a model concerns only preferences towards escalators is used as a reference model. We discuss the relative utilities X of different model formations in the following sections.

C0: Preference

This model concerns pedestrians' preferences towards escalators. The relative utility of using escalators equals the relative alternative specific constant β_0.

$$X = \beta_0 \tag{C0}$$

C1 – C2: Travel Time

Now we consider the influence of travel time on the route choice behavior. We consider the effects of relative delays and human limitations on the choice behavior (see subsection 4.1.2). When only relative delays are concerned, the travel time may be specified as a linear variable.

$$X = \beta_0 + \beta_1 \cdot (T_{esc} - T_{stair}) \tag{C1}$$

weher T_{esc} and T_{stair} refer the travel time on escalators and on stairways respectively; β_0 is the alternative-specific constant of choosing escalators; β_1 reflects the utility cost of time.

When both relative delays and human limitations are concerned, the travel time may be specified as an exponential variable. The travel time has exponential effects on the utility of an alternative.

$$X = \beta_0 + \beta_1 \cdot [\exp(T_{esc}) - \exp(T_{stair})] \tag{C2}$$

C3 – C5: Travel Time and Personal Characteristics

Now we discuss the influence of personal characteristics on the route choice behavior. We study the influence of gender (C3-C4), age (C5-C7), and presence of luggage (C8-C9) separately. These models contain three dummy variables: *Female, Elderly*, and *Luggage*.

$$X = Female \cdot \beta_0^{female} + Female \cdot \beta_1^{female} \cdot (T_{esc}^{female} - T_{stair}^{female}) + (1 - Female) \cdot \beta_0^{male} + (1 - Female) \cdot \beta_1^{male} \cdot (T_{esc}^{male} - T_{stair}^{male}) \tag{C3}$$

$$X = Elderly \cdot \beta_0^{elderly} + Elderly \cdot \beta_1^{elderly} \cdot (T_{esc}^{elderly} - T_{stair}^{elderly}) + (1 - Elderly) \cdot \beta_0^{notelderly} + (1 - Elderly) \cdot \beta_1^{notelderly} \cdot (T_{esc}^{notelderly} - T_{stair}^{notelderly}) \tag{C4}$$

$$X = Luggage \cdot \beta_0^{luggage} + Luggage \cdot \beta_1^{luggage} \cdot (T_{esc}^{luggage} - T_{stair}^{luggage}) + (1 - Luggage) \cdot \beta_0^{noluggage} + (1 - Luggage) \cdot \beta_1^{noluggage} \cdot (T_{esc}^{noluggage} - T_{stair}^{noluggage}) \tag{C5}$$

where

T^k_{esc}, T^k_{stairc} = travel time of pedestrian group k on escalators and stairways (k = *female*, *male*, *elderly*, *notelderly*, *luggage*, or *noluggage* if female, male, elderly, not elderly, with luggage, or without luggage);
Female = 1 if female pedestrians; otherwise 0;
Elderly = 1 if elderly pedestrians; otherwise 0;
Luggage = 1 if pedestrians with luggage; otherwise 0;
β^k_0 = relative alternative-specific constant of escalators of pedestrian group k, which reflects the relative preference for escalators if being pedestrian group k;
β^k_1 = parameter which denote the utility cost of time perceived by pedestrian group k.

8.3 Travel time calculations

This section describes algorithms applied for the calculation of travel time in those relative utility functions (C1-C5) specified in section 8.2. We discuss the calculation of travel time on the chosen route and the alternative route separately.

8.3.1 Travel time on the chosen route

The travel time on the route taken by a pedestrian can be measured directly from the observation data with the following equations.

In the descending direction:

T_{stair} = Travel time of Alt-S = travel time on link 1 + travel time on link 2 (8.3)

T_{esc} = Travel time of Alt-E = travel time on link 3 (8.4)

In the ascending direction:

Tstair = Travel time of Alt-S’ = travel time on link 1’ + travel time on link 2’ (8.5)

Tesc = Travel time of Alt-E’ = travel time on link 3’ (8.6)

However, in this report, the route choice behavior is analyzed simply with trajectory data observed by Detector-1 and Detector-4 whose coverage areas contain only about one third of the entire routes. It means that the realized travel time cannot be calculated directly from our observation data. Thus some assumptions are made. First, we assume a constant speed on the route. Hence the travel time of a pedestrian on link 1, 3, 1’ and 3’ is calculated with his speed measured from Dector-1 and Detector-4.

Secondly, due to the lack of information on link 2 and 2', an average speed of 1.34 m/s (Weidmann 1993) is assumed for speeds on level surfaces. We summarize the algorithms used to calculate link travel time of the chosen route in Table 8.3.

Table 8.3
Calculation of travel time on the chosen route

Link no.	Link length (m)	Travel speed (m/s)	Link travel time (s)	Link no.
1	9.05	Observation by IR (u_s)	9.05 / u_s	1'
2	1.70	1.34	1.70 / 1.34	2'
3	10.75	Observation by IR (u_e)	10.75 / u_e	3'

8.3.2 Travel time on the alternative route

The travel time on the alternative route may be estimated with information known about the prevailing traffic condition at the time when a choice decision is made. We assume that pedestrians make an estimation based on the prevailing traffic conditions observed when approaching the decision point. Among the three macroscopic traffic characteristics (flow, speed, and density), the density which can be easily observed from a glance is regarded as an important piece of information used by pedestrians to estimate the required travel time. Thus, theoretically the alternative link travel time may be estimated from a known speed-density relationship associated with the terrain involved. If we know the densities on the alternative links when the decision is made, we can estimate the speeds from the speed-density relationships, and, consequently the expected travel time.

However, the application of this approach concerning speed-density relationships for the calculation of alternative travel time may be valid only at situations when a constant traffic state exists on the links of concern. Otherwise, the variation of densities or the density distribution on the links should be taken into account as well. We discuss the influence of density distributions on the link travel time with cases given in Figure 8.6.

Figure 8.6 shows four cases with a constant density (5 P/esc) but various distributions of passengers on an escalator. Case (a) describes a situation when only walking passengers uniformly present on an escalator. In this case, the expected travel time may be estimated with the speed-density relationship. Case (b) depicts a situation when pedestrians distributed only at one side of the escalator. In this case, a pedestrian can freely choose either to walk or stand on the escalators. Thus the travel speed may equal the free speed of the pedestrian or the escalator operating speed. Case (c) concerns a situation when passengers present only on the upper part of an escalator. Under this situation, those presenting passengers may have less an impact on the travel speed of the pedestrian. The pedestrian may freely choose either to walk or stand on it, which leads to a similar situation as case (b) in terms of the travel speed. On the contrary, case (d) considers a situation when existing passengers concentrate at the lower part of an escalator in particular near the entry. In this case, the travel speed is dependent on the behavior of those existing passengers. Thus, the travel speed could be either the operating speed of the escalator (if those existing passengers choose to stand on the escalator) or the following speed of the pedestrian (if those existing passengers choose to walk on the escalator).

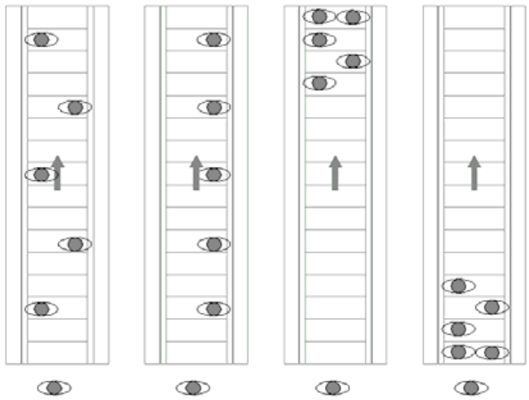

Figure 8.6
Distribution of pedestrians on escalators and their inferences on travel time estimation

In this project, we simply use the average travel time measured on the alternative route during the period when a pedestrian is traveling on his chosen route as an estimate of his alternative travel time. The average travel time measured on the alternative route is determined by the realized travel time of pedestrians taking the alternative route during the time period of concern. However, when no pedestrians choose the alternative route during the time period of concern, we use the following average speed data found in this project (see Table 7.1) as the estimated travel speed on the alternative route.

- Average descending speeds on stairways 0.77 m/s
- Average ascending speeds on stairways 0.68 m/s
- Average descending speeds on escalators 0.88 m/s
- Average ascending speeds on escalators 0.82 m/s

Together with our assumption about a speed of 1.34 m/s on horizontal elements (see subsection 8.3.1), the average travel time of each alternative is given as follows:

- Average descending travel time on stairways 13.0 m/s
- Average ascending travel time on stairways 14.8 m/s
- Average descending travel time on escalators 12.2 m/s
- Average ascending travel time on escalators 13.1 m/s

Finally, it is noted that when personal characteristics are concerned, such as the choice models C3-C5 specified in section 8.2, the estimation of the alternative travel time is done following the concept we have discussed in the previous paragraph. That mean, the influence of personal characteristics on the alternative travel time is not taken into account in this report.

8.4 Estimated results of relative utility functions

This section presents our estimated results of the choice models C1 to C3 given in section 8.2. The estimation is done with the software BIOGEME. Models C4 and C5 are not calibrated because of small sample sizes available. We present the estimated relative utility functions and discuss their inferences on the stairway/escalator choice behavior in both descending and ascending direction.

Figure 8.7 and Figure 8.8 show the realized travel time on the chosen route and the estimated travel time on the alternative route considered by individual pedestrians when making the route choice decision in the descending and ascending direction respectively. They show a quite wide spread of travel time differences between the two alternative choices.

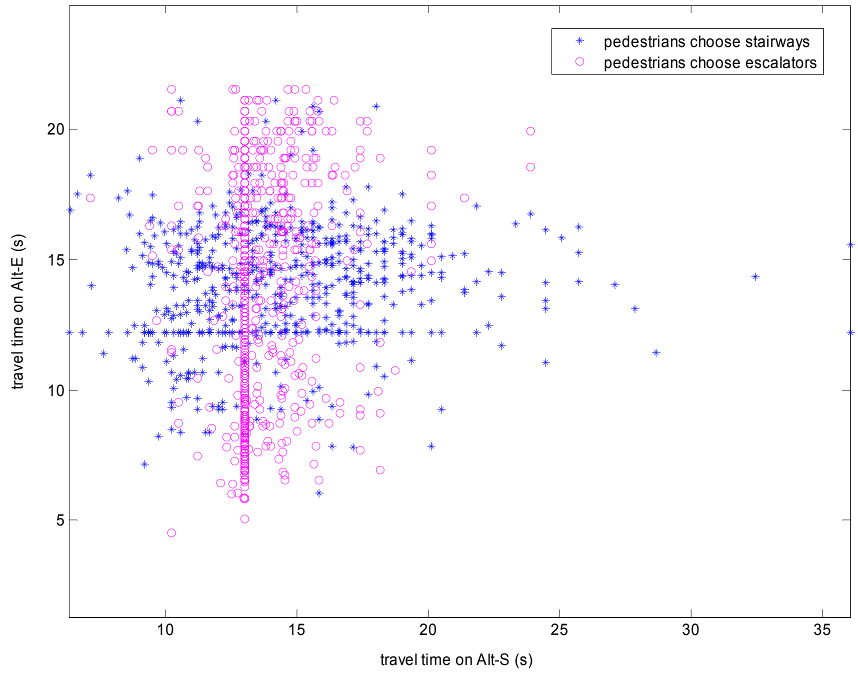

Figure 8.7
Travel time difference in the descending direction (Alt-S and Alt-E)

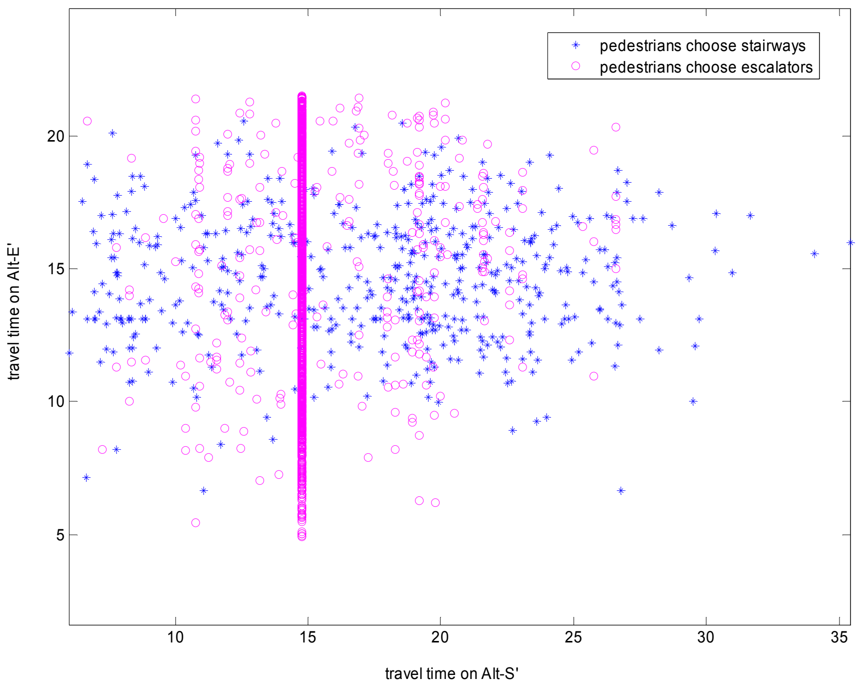

Figure 8.8
Travel time difference in the ascending direction (Alt-S’ and Alt-E’)

We discuss the estimated relative utility of choosing escalators (X) from BIOGEME below. We summarize the results with some statistical data in Table 8.4 and Table 8.5.

C0: Preference

In the descending direction:

$$X = 0.174;\ R^2 = 0.005$$

In the ascending direction:

$$X = 1.502;\ R^2 = 0.315$$

where X denotes the relative utility of choosing escalators. The positive relative utilities show that escalators are preferred by pedestrians in both the descending and ascending direction. Besides, the larger value in the ascending direction indicates a higher preference of escalators in the ascending direction. However, the R^2 of those two models are quite low which infer the weak explanatory power of the models.

C1: Travel Time (linear)

In the descending direction:

$$X = 0.203 - 0.03(T_{esc} - T_{stair})\ ;\ R^2 = 0.011$$

In the ascending direction:

$$X = 1.50 + 0.009(T_{esc} - T_{stair})\ ;\ R^2 = 0.318$$

where T_{stair} and T_{esc} denote the travel time (in second) on stairways (Alt-S or Alt-S') and escalators (Alt-E or Alt-E') respectively.

The result in the descending direction shows that escalators (Alt-E) have relative higher preference than stairways (Alt-S). Besides, the travel time is considered as disutility to pedestrians. The utility cost of time for descent is -0.03 utility/s. Similarly, escalators are preferred in the ascending direction. Surprisingly, the travel time is considered as utility to travelers. The utility cost of time for climbing equals +0.009 utility/s. However, the R^2 of those two models are quite low.

C2: Travel Time (exponential)

The estimated relative utility of choosing escalators (X) is given as follows:

In the descending direction:

$$X = 0.204 - 1.29 \cdot [\exp(T_{esc}) - \exp(T_{stair})]\ ;\ R^2 = 0.01$$

In the ascending direction:

$$X = 1.50 - 0.007 \cdot [\exp(T_{esc}) - \exp(T_{stair})]\ ;\ R^2 = 0.316$$

It is noted that the travel time in these relative utility functions are given in minute. The results are very similar to those for model C1. Escalators are preferred in both descending and ascending direction when there is no travel time difference on alternative routes. The utility costs of time are -1.29 utility/min and -0.006 utility/min in the descending and ascending direction respectively. Travel time is considered as disutility for pedestrians in both directions. However, the R^2 of those two models are quite low.

C3: Travel Time and Gender

In the descending direction:

Female: $X = -0.271 + 0.007(T_{esc} - T_{stair})$; $R^2 = 0.013$

Male: $X = +0.370 - 0.07(T_{esc} - T_{stair})$; $R^2 = 0.042$

In the ascending direction:

Female: $X = +0.806 + 0.004(T_{esc} - T_{stair})$; $R^2 = 0.108$

Male: $X = +0.344 - 0.004(T_{esc} - T_{stair})$; $R^2 = 0.023$

The extremely values of R^2 make it difficult to get any inference from these estimated outcomes.

The results given in Table 8.4 and Table 8.5 show that our hypothesized choice models have very weak explanatory power on the choice behavior between stairways and escalators. Possible explanations are given as follows:

- Influences of time pressures are not taken into account: two types of passengers, hurried and unhurried travelers, coexist in public transport facilities. For these two groups of passengers they have quite difference perception towards travel time and travel comfort. However, in this report, we make no distinction between these two groups of pedestrians because of lacks of information.

- Incomplete travel time information: only travel times on the vertical links are considered in the utility function; the influence of queuing in front of those facilities are not taken into account.

- Biased alternative travel time: based on section 8.3, the alternative travel time perceived by a pedestrian is estimated with the average travel time observed on the alternative route during his real traveling period. However, the approach does not consider the influence of sample sizes on the estimation. Thus at low flow situations, the estimated alternative travel time may be biased due to small sample sizes.

- Exclusion of other influencing factors: due to lack of complete travel information, the analysis is done based on simplified choice situations. The simplification excludes some important factors that may influence the choice behavior as well. The factor of vicinity is one of the examples.

Table 8.4
Parameters and statistical data from BIOGEME for the route choice model C0, C1, and C2

	Choice model type					
	C0		C1		C2	
	descending	ascending	descending	ascending	descending	ascending
Sample size	1303	2701	1303	2701	1303	2701
Parameter						
ASC	+0.174	+1.502	+0.203	+1.501	+0.204	+1.500
t-test	*+3.13*	*+30.13*	*+3.58*	*+30.03*	*+3.60*	*+30.01*
Utility cost of time			-0.03 utility/s	+0.009 utility/s	-1.290 utility/min	-0.007 utility/min
t-test			*-3.05*	*+2.57*	*-2.99*	*-0.671*
Statistical data						
Rho-square	0.005	0.315	0.011	0.318	0.010	0.316
Null log-likelihood	-903.17	-1872.19	-903.17	-1872.19	-903.17	-1872.19
Init log-likelihood	-903.17	-1872.19	-903.17	-1872.19	-903.17	-1872.19
Final log-likelihood	-898.27	-1282.02	-893.50	-1277.26	-893.67	-1281.49
Likelihood ratio test	9.81	1180.35	19.33	1189.85	19.00	1181.40

Table 8.5
Parameters and statistical data from BIOGEME for the route choice model C3

	Choice model type			
	C3-Female		C3-Male	
	descending	ascending	descending	ascending
Sample size	240	229	593	322
Parameter				
ASC	-0.271	+0.806	+0.370	+0.344
t-test	*-2.07*	*+5.62*	*+4.27*	*+3.03*
Utility cost of time	+0.007 utility/s	+0.004 utility/s	-0.070 utility/s	-0.004 utility/s
t-test	*+0.31*	*+0.60*	*-4.44*	*-0.75*
Statistical data				
Rho-square	0.013	0.108	0.042	0.023
Null log-likelihood	-166.36	-158.73	-411.04	-223.19
Init log-likelihood	-166.36	-158.73	-411.04	-223.19
Final log-likelihood	-164.17	-141.60	-393.90	-217.92
Likelihood ratio test	4.3729	34.265	34.27	10.55

8.5 Conclusions for route choice between stairways and escalators

Two simplified route choice networks (see Figure 8.3 and Figure 8.4) are proposed for the study of choice behavior between stairways and escalators due to lack of complete travel information. We formulate the choice models with the forms of binary logit model since only two alternatives are considered by each pedestrian. Factors taken into account include the travel time, physical effort, personal characteristics (gender and age), and the presence of luggage. The model calibration is performed with the software BIOGEME. The estimated results are summarized in Table 8.4 and Table 8.5. The relatively low value of R^2 infers the weak prediction power of our hypothesized models on the choice behavior between stairways and escalators. Possible explanations include: the exclusion of influencing factors such as time pressures and vicinity, incomplete travel time information, possible bias caused by the algorithms applied for the estimation of alternative travel time.

9 Conclusions and Future Research Recommendations

In this report, we study both the walking and choice behavior of pedestrians on stairways and escalators in public transport facilities. The literature review given in chapter 2 indicates two blank spots of our research questions. One is the fundamental diagrams of escalator traffic; the other one is the walk/stand choice behavior on escalators. Besides, relevant studies about walking and route choice behavior in the vertical dimension are quite limited. Based on the existing theories and knowledge on pedestrian behavior as well as the available empirical data, we discuss our hypothesized walking and choice models in chapter 3 and chapter 4 respectively.

With respect to the speed-density relationship on stairways, bi-linear models are adopted in this report. In addition, a higher free speed and a larger jam density is assumed for flows in the descending direction (see Figure 3.2). In regard to the speed-density relationship on escalators, at situations where passengers can freely choose where and whether to walk and stand on the escalator, the speed-density diagram is presented by an area instead of a curve (see Figure 3.6). To apply the random utility theory to study the stairway/escalator choices, we identify influencing factors as travel times and time pressures, physical efforts, safety and comfort, personal characteristics, and vicinity. However, our discussion about the walk/stand choice behavior on escalators is limited to the choice availability and influencing factors due to unobservable factors (such as time pressure) identified.

A combined technique with infrared detectors and video cameras are applied for the pedestrian observations in this project. The observations aim on collecting both trajectory and personal data of individual pedestrians. We discuss our observation arrangement and results in chapter 5. Among the four data processing tasks defined in chapter 6, the correction of trajectory distortion has the largest influence on our analysis results. Our distortion correction algorithms provide satisfactory results (see Figure 6.8, Figure 6.9, and Figure 6.10). The discontinuous detection of individual pedestrian has less an impact on the detection outcome since less than 2% trajectories are identified as split ones based on our applied algorithms. The coupling of infrared trajectory data and video data allow the study of the influences of personal characteristics on pedestrian behavior. Our findings about free speeds of different pedestrian groups indicate that the approach applied in this project produce reasonable outcomes. However, the difficulty in matching data increases with flows. The correction of flow data based on video reading becomes necessary in this project due to the short duration of high flows at our observation site.

Our analysis of free speeds in chapter 7 shows that free speeds are influenced by directions of movement, types of infrastructure, and personal characteristics of pedestrians (see Table 7.1, Table 7.2, andTable 7.3). In general, free speeds on escalators are larger than those on stairways; descending speeds are faster than climbing ones; male pedestrians walk faster than female ones; free speeds decrease with age.

Our finding about fundamental diagrams on stairways and escalators are limited due to the small variation of traffic conditions observed on site. Based on the empirical data given in section 2.1 and our conceptual walking models presented in section 3.1, hypothesized fundamental diagrams for descending and ascending flows are given in Figure 7.6, Figure 7.7, Figure 7.8, and Figure 7.9.

The relatively low value of R^2 of our estimated choice models given in chapter 8 infers a weak explanatory power of our hypothesized models on the choice behavior between stairways and escalators (see Table 8.4 and Table 8.5). Possible explanations include the exclusion of influencing factors such as time pressures and vicinity, incomplete travel time information, and possible bias caused by the algorithms applied for the estimation of alternative travel time.

To further improve the outcomes of the walking and route choice models discussed in this report, some suggestions are given as follows:

- With respect to the fundamental diagrams on stairways, improvement could be done by searching for another location to conduct pedestrian observations; the site should allow the observation of a large variation of traffic conditions; the metro stations in Rotterdam could be promising sites.
- In regard to traffic characteristics on escalators, future researches may just focus on finding the capacities of escalators since no specific fundamental diagrams exists on escalators. As for the walk/stand ratio on escalators, it may be significant only at situations where walk/stand lanes are regulated by the authority (such as London Underground stations).
- Pedestrian route choice behavior is very sensitive to the conditions of pedestrian environments involved. Depending on their approaching direction, the factor of vicinity may play roles on their choice behavior. The attractiveness of environments could have influence on their choice behavior as well.
- Our investigation on pedestrian observation with infrared detectors shows that large amount of trajectory data can be automatically extracted with the existing program. However, in this report, the precision of the detection outcome is not verified. Besides, the data analysis is performed based on trajectory data observed from single detector. Thus to further explore the possibility of utilizing infrared detectors on pedestrian study, future studies could focus on increasing the precision of distortion correction as well as on finding algorithms to match trajectory data across various fields of view.

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Appendix A Site visit report

A.1 Introduction

"Site-visit" is one defined task in this thesis project. The main purposes of visiting public transport facilities are to gain insight into real-life pedestrian behavior, to see which kinds of solutions for vertical transport of passengers are adopted in practice, and to search for suitable sites for traffic data collection. The objective of this report is to present the results of site visits at three train stations: Den Haag Holland Spoor, Den Haag Centraal, and Rotterdam Centraal. In this report we focus on the design solutions applied in these three stations and their adequacy for the site collection works.

Before going out for the visits on site, some desk review is carried out by browsing the website of the Netherlands Railways (www.ns.nl). General information such as infrastructure layout of a station is available for most of the train stations in the Netherlands which helps to identify stations with the vertical infrastructure of interest. Basically, train stations in the Netherlands have quite simple layouts in which vertical infrastructures such as ramps, stairways, escalators, and lifts are used to facilitate level changes. However, we consider only stairways and escalators in the remaining part of this report.

In terms of the configuration of stairways and escalators, the following stations are identified as promising sites: Den Haag Centraal, Den Haag Holland Spoor, Rotterdam Centraal, Leiden Centraal, Amsterdam Centraal, Utrecht Centraal and Eindhoven. Taking into account the geographic location and vertical infrastructure layouts, site visits are only carried out in three stations in the South Holland region: Den Haag Holland Spoor, Den Haag Centraal, and Rotterdam Centraal.

Section A.2 gives a presentation of the three visited stations in the sequence of Den Haag Holland Spoor, Den Haag Centraal, and Rotterdam Centraal. We describe the layouts and physical dimensions of vertical infrastructure, passenger flows, and choice situations faced by a pedestrian (choice between different vertical infrastructures). In section A.3, we consider the adequacy of individual sites in terms of data collection. We give a summary of data needed to be collected through the observation and evaluate the qualification of each station. Finally, conclusions will be drawn in section A.4.

A.2 Station and Vertical Infrastructure

This section describes the layout and physical dimensions of vertical infrastructures, related flows of passengers, and choice situations connected with stairways and escalators at three train stations, namely Den Haag Holland Spoor, Den Haag Centraal, and Rotterdam Centraal.

A.2.1 Den Haag Holland Spoor (HS)

The train station of Den Haag HS is a transit station located in the city of Den Haag. Other public transport systems such as tram lines and bus services are available just outside the station building. The station building is a two-layer structure composed of the ground level and the platform level. The vertical difference between these two layers is about 4.5 m, and vertical infrastructure such as stairways, escalators and lifts are equipped to provide access for passengers to move between these two levels. A general layout of the station is given in Fig. A-1 in which two promising sites (A and B) for traffic data collection work are identified.

Fig. A-1
Station Den Haag HS – general layout (source: www.ns.nl)

Vertical Infrastructure Layouts and Dimensions

The arrangement of vertical infrastructures at sites A and B are shown with some more details in Fig. A-2. Sites A and B are situated at the same side of the main passageway inside the station where the vertical infrastructures provide access to platform 4 and platform 3. Site A is composed of a stairway (S2) and an ascending escalator (E2). In contrast, site B has a stairway (S1) combined with a descending escalator (E1). Theoretically the infrastructures at site A (S2, E2) and site B (S1, E1) are designed mainly to accommodate pedestrian traffic going to and from platform 4 and platform 3 respectively. However, since no physical separation of these two pedestrian flows at either end of the vertical infrastructure exists, pedestrians indeed have free access to the infrastructure at both sites. Some physical dimensions of the vertical infrastructures are given in Tab. A-1.

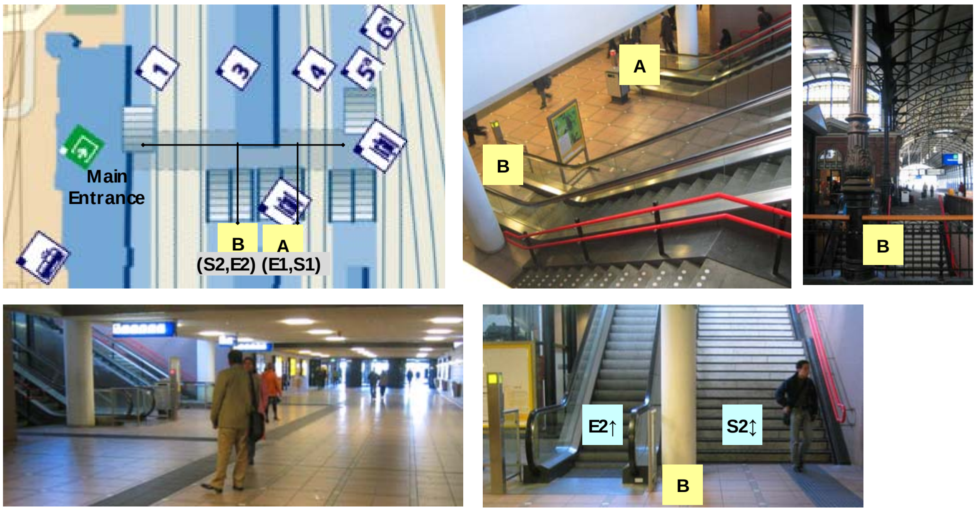

Fig. A-2
Vertical infrastructures sites A and B in Den Haag HS station

Tab. A-1
Dimensions of infrastructure in Den Haag HS station

Site	Infrastructure ID	direction	Overall dimension rise (m)	slope	Tread riser (mm)	depth (mm)	width[1] (mm)	Escalator speed[2] (m/s)
A	S1	Two-way	4.55	28	175	300	2350	
	E1	Down	4.55	30	200	350	1000	0.6
B	S2	Two-way	4.55	28	175	300	2350	
	E2	Up	4.55	30	200	350	1000	0.6

[1] the width of an escalator or a stairway refers to the total tread width
[2] the escalator operating speed needs to be confirmed with station staff

Passenger Flow

Here we discuss the flow of boarding and alighting traffic at site A and site B. Boarding passengers enter the station from the main entrance and then walk via the main passageway towards their final destination (either platform 3 or platform 4). They ascend to the platform level by means of vertical infrastructures S1, E1, or S2. Alighting traffic descends from the platform level to the ground level via vertical infrastructures S1, E2, or S2 and then exits the station from the main entrance. The wide landing areas at either end of the infrastructure largely reduce possible conflicts of various pedestrian flows.

Choice Situation

With respect to the choice behavior between stairways and escalators, two choice situations of interest are identified in the station of Den Haag HS:

- At site A, descending pedestrians make a choice between a stairway and an escalator located adjacent to each other. (choice situation 1)
- At site B, ascending pedestrians make a choice between a stairway and an escalator located adjacent to each other. (choice situation 2)

A.2.2 Den Haag Centraal

The train station of Den Haag Centraal is a terminal station located in the city of Den Haag. Other public transport systems such as trams and buses are available above or outside the station building. A general layout of the station is given in Fig. A-3.

The station building is basically a two-layer structure. However, unlike the one in Den Haag HS, platforms for trains are located at ground level, while the second layer is used by tram and bus services. The total vertical difference between these two layers is about 7 m, for which stairways and escalators are installed to transport passengers between these two levels. Promising sites (A, B, C, and D) are indicated in Fig. A-3. More details of the vertical infrastructure will be given in the following sections.

Fig. A-3
Station Den Haag Centraal – general layout (source: www.ns.nl)

Vertical Infrastructure Layouts and Dimensions

The arrangement of vertical infrastructures at sites A, B, C, and D are shown with some more details in Fig. A-4. Site A is composed of one stairway (S1), one descending escalator (E1), and one ascending escalator (E2). Sites B and C both consist of one stairway (S3/S4) and one ascending escalator (E3/E4), providing access to the platforms of tram lines. Similar to site A, site D includes also a stairway (S5) and two escalators serving downwards (E5) and upwards (E6), offering access to bus services. Some physical dimensions of these vertical infrastructures are given in Tab. A-2.

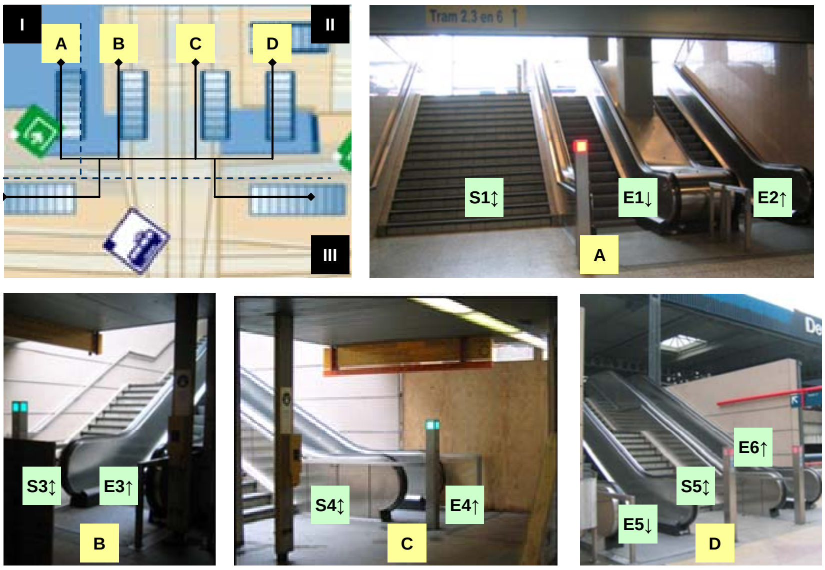

Fig. A-4
vertical infrastructures sites A, B, C, and D in Den Haag Centraal station

Tab. A-2
Dimensions of infrastructure in Den Haag Centraal station

Site	Infrastructure ID	Infrastructure direction	Overall dimension rise (m)	Overall dimension slope	Tread riser (mm)	Tread depth (mm)	Tread width[1] (mm)	Stairway step (nos.)	Escalator speed[2] (m/s)
A	S1	Two-way	2.8	27	175	345	3000	16	
	E1	Down	2.8	30	200	400	1005		0.6
	E2	Up	2.8	30	200	400	1005		0.6
B	S3	Two-way	4.2	27	175	345	2500	24	
	E3	Up	4.2	30	200	400	1005		0.6
C	S4	Two-way	4.2	27	175	345	2500	24	
	E4	Up	4.2	30	200	400	1005		0.6
D	S5	Two-way	4.2	27	175	345	2500	24	
	E5	Down	4.2	30	200	400	1005		0.6
	E6	Up	4.2	30	200	400	1005		0.6

[1] the width of an escalator or a stairway refers to the total tread width
[2] the escalator operating speed needs to be confirmed with station staff

Passenger Flow

The infrastructure shown in Fig. A-4 connects three different pedestrian spaces: (I) the concourse of the train station, (II) the platforms of tram lines and bus stops, and (III) the space outside the station building. It is noted that the infrastructure at site A is mainly used by passengers going between the concourse and platforms of tram and bus. Infrastructures at sites B and C are only used by tram passengers, the traffic demand of which, in particular the alighting one, is highly related to the time table of tram lines. The sudden surge of passengers from a tram will lead to a higher flow in the descending direction. Infrastructure at site D is used by bus passengers, most of whom approaching either from the concourse or from outside the station building.

Choice Situation

With respect to the choice behavior between stairways and escalators, three choice situations are identified in the station of Den Haag Centraal:

- At sites B, C, and D, ascending pedestrians make a choice between a stairway and an escalator located adjacent to each other. (choice situation 1)
- At sites A and D, descending pedestrians make a choice between a stairway and an escalator located adjacent to each other. (choice situation 2)
- At site A, ascending pedestrians make a choice between a stairway and an escalator separated by a descending escalator. (choice situation 3)

A.2.3 Rotterdam Centraal

The train station of Rotterdam Centraal is a transit station located in the city of Rotterdam. Other public transport systems such as metro, tram and bus services are available underneath or outside the station building. A general layout of the station is given in Fig. A-5.

The station structure can be divided into the ground level and the platform level. The vertical difference between these two levels is about 4 m for which vertical infrastructures such as stairways, escalators and lifts are equipped to provide access for passengers to move between these two levels. Basically, only one design arrangement of vertical infrastructure is adopted in this station. Therefore, only one promising site (A) is identified of which more details will be described in the following sections.

Fig. A-5
Station Rotterdam Centraal – general layout (source: www.ns.nl)

Vertical Infrastructure Layouts and Dimensions

The arrangement of vertical infrastructure at site A is shown with some more details in Fig. A-6. The site is composed of two stairways (S1 & S2) and one ascending escalator (E1). However it is noted that these infrastructures are located at opposite sides of the main corridor. Although they provide access to the same platforms, difference on the final destination is noted. Some physical dimensions of these facilities are given in Tab. A-3.

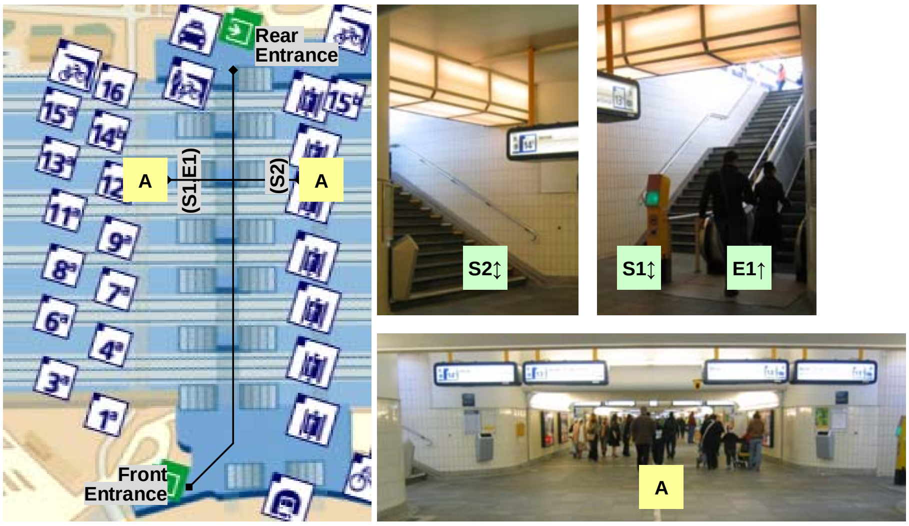

Fig. A-6
Vertical infrastructure site A in Rotterdam Centraal station

Tab. A-3
Dimensions of infrastructure in Rotterdam Centraal station

Site	Infrastructure		Overall dimension		Tread			Stairway	Escalator
	ID	direction	rise (m)	slope	riser (mm)	depth (mm)	width[1] (mm)	step number	speed[2] (m/s)
A	S1	Two-way	3.9		150	335	2500	26	
	E1	Up	3.9	30	200	400	1000		0.6
	S2	Two-way	3.9		150	335	3500	26	

[1] the width of an escalator or a stairway refers to the total tread width
[2] the escalator operating speed needs to be confirmed with station staff

Passenger Flow

The sole passageway inside Rotterdam Centraal simplifies the flow of passengers using vertical infrastructure at site A. The boarding passengers enter the station from either the front or the rear entrance shown inFig. A-6. Then they walk through the main passageway and reach their final destination by means of S1, E1 or S2. As for the alighting traffic, passengers leave the platform via S1 or S2 and finally exit the station from either the front or the rear entrance.

Choice Situation

With respect to the choice behavior between stairways and escalators, only one choice situation is identified at the station of Rotterdam Centraal:

- At site A, ascending pedestrians make a choice between 2 stairways and an escalator located at two sides of the passageway (three alternatives). (choice situation 4)

A.3 Site Selection

A.3.1 Criterion for site selection

With respect to the adequacy of sites for data collecting work, we identify below the most important aspects to be taken into consideration. These are: availability of required data and physical requirement of data collecting technique. We discuss these aspects in more details in the following sections.

Availability of Required Data

Since we solely rely on site observations to calibrate and validate the hypothesized models, it is then of utmost importance to get all necessary data on site. Fig. A-7 summarizes the required observations for the walking and route choice models hypothesized in this project.

This thesis project studies pedestrians' walking and route choice behaviors on stairways and escalators in public transport facilities. With respect to walking behavior, three models are distinguished: a walking model on stairways, a walking model on escalators, and a walk/stand choice model on escalators. As for route choice behavior between stairways and escalators, a choice model is hypothesized for a specific choice situation. Note that for these walking and route choice models, variables taken into account are common to both ascending and descending directions. However, separate observations should be conducted for both walking directions for parameter estimation.

For the walking models on stairways and escalators, we concern macroscopic traffic characteristics of pedestrian flows and the influence of personal characteristics. To calibrate and validate our hypothesized models, measurements of traffic flow, travel time, density distribution, and personal characteristics (eg. age and gender) will be obtained from the site data collecting work. In addition, special attention is paid to the boarding behavior on escalators. As for the walk/stand choice model on escalators, we focus on the influence of travel time and pedestrian characteristics on the choice behavior. In addition, the distribution of density on escalators is used to determine if the choice alternatives (walk and stand) are available for escalator passengers at certain moment. Therefore, the required measurements include the choice decision (walk or stand on escalators), travel time, pedestrian characteristics (eg. age, gender and presence of luggage), and density distribution on escalators.

With regards to the route choice model concerning vertical movement, we consider the influence of travel time and pedestrian characteristics on the choice behavior under the specified choice situation. Hence, the required measurements include the choice decision (use stairways or escalators), travel time, pedestrian characteristics (eg. age, gender and presence of luggage), and density distribution on escalators.

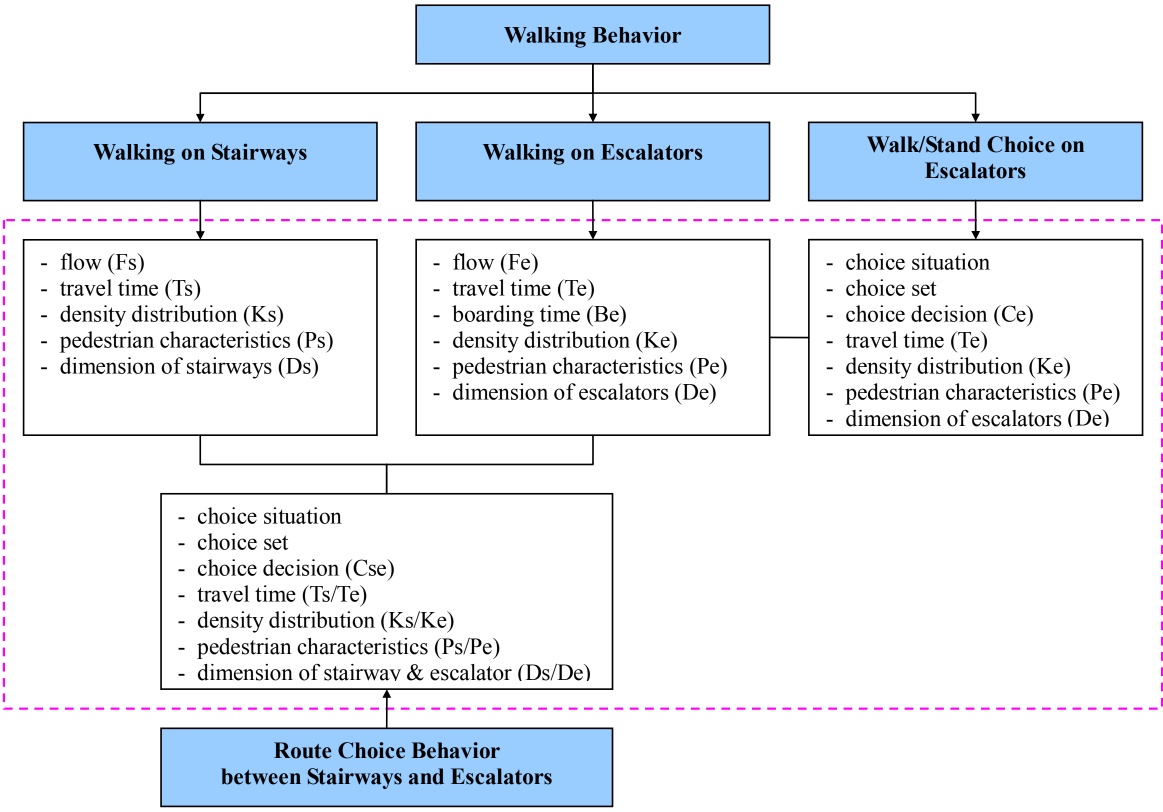

Fig. A-7
Data structure for the study of walking and route choice behaviors

Physical Requirement of Data Collecting Technique

The physical environment on site may cause restriction on applying certain data collecting technique. One example is the requirement of visibility of traffic conditions for observers when manual counting method is applied for data collecting. To avoid repetition, we discuss issues about data collecting technique in Chapter 5 of the main report.

A.3.2 Site assessment

This section analyzes the adequacy of those vertical infrastructure sites described under section A.2 to. According to the discussion of the three main concerns of data collecting site in previous section, we assess the adequacy of those promising sites based on the availability of required traffic data in the following paragraphs.

The required observation data is summarized and given in Tab. A-4. It is noted that most of the traffic data is infrastructure-specific, which means only the presence of infrastructure (stairway or escalator) matters. Examples are flow, travel time, density distribution, dimension of infrastructure, etc. Some data is site-specific, and it depends on local characteristics such as infrastructure layouts on site. Examples include choice situation and choice set for the route choice behavior between stairways and escalators. As for pedestrian characteristics, it causes no restriction on site selection in this project. Therefore, the assessment will be done based on the availability of infrastructure-specific and site-specific data.

For infrastructure-specific data, we make a distinction between stairways and escalators. In addition, directions are also considered. As for site-specific data, various choice situations are specified and viewed as different types of data. The result is given in Tab. A-4.

Tab. A-4
Site assessment based on data acquisition

Data Description			Den Haag HS	Den Haag HS	Den Haag Cent.	Den Haag Cent.	Den Haag Cent.	Den Haag Cent.	R'm Cent.
			A	B	A	B	C	D	A
Infra.-specific	Stairway	Up	×	×	×	×	×	×	×
Infra.-specific	Stairway	Down	×	×	×	×	×	×	×
Infra.-specific	Escalator	Up	×		×	×	×	×	×
Infra.-specific	Escalator	Down		×	×			×	
Site-specific	Choice (1)[1]: S-E	Up	×			×	×	×	
Site-specific	Choice (2)[2]: S-E	Down		×	×			×	
Site-specific	Choice (3)[3]: S-E	Up			×				
Site-specific	Choice (4)[4]: E-S-E	Up							×

Note:
"×" means the data is observable
[1] Choice (1): ascending pedestrians make a choice between a stairway and an escalator located adjacent to each other
[2] Choice (2): descending pedestrians make a choice between a stairway and an escalator located adjacent to each other
[3] Choice (3): ascending pedestrians make a choice between a stairway and an escalator separated by a descending escalator
[4] Choice (4): ascending pedestrians make a choice between 2 stairways and an escalator located at two opposing sides of the passageway

There are some further remarks about the data given in Tab. A-4:

Because sites A and B at Den Haag HS are very close to each other, we consider them as a single site in the remaining part of this report and we will denote this site as "site (A+B) at Den Haag HS".

Due to the construction works at site B and C at Den Haag Central station at mean time, we remove them from the discussion list in the remaining part of this report.

With respect to route choice behavior between stairways and escalators, Choices (1) and (2) are viewed as basic types because of the simplicity of the choice situation provided. As for Choices (3) and (4), the choice behavior is rather complicated due to the existence of a third infrastructure and other spatial factors. Therefore, higher priority is given to choice situations of type (1) and (2).

Based on the availability of data discussed in Tab. A-4, the adequacy of location is ranked as follows (from high to low preference):

- site (A+B) at Den Haag HS & site D at Den Haag Centraal
- site A at Den Haag Centraal
- site A at Rotterdam Centraal

However, since site D in Hen Haag Centraal is located outdoor, we are concerned that weather conditions might influence the collecting work and, consequently, the result. Besides, the shared stairway for both ascending and descending traffic might cause difficulty on getting proper data within scheduled time. Therefore, the site (A+B) at Den Haag HS is marked as the best location for data collecting work in this project. Site A at Den Haag Centraal and Rotterdam Centraal provide opportunities for further study of choice behavior between stairways and escalators of different kinds.

A.4 Conclusions

In this report, the results of site visits at three train stations: Den Haag Holland Spoor, Den Haag Centraal, and Rotterdam Centraal, are presented. Some similarities are found among these three stations. All of them have a two-layer structure, and the vertical circulation between the ground level and the platform level is realized by means of vertical infrastructures such as stairways, escalators, and lifts. In this report, we are only concerned about pedestrian traffic on stairways and escalators, so details of lifts are not discussed.

In section A.1 to section A.3, we discuss the layout and dimensions of vertical infrastructures, passenger flows, and choice situation concerning stairways and escalators in these three stations. The level difference of these three stations varies between 4 and 7 meter, which is viewed as an acceptable rise for using stairways to facilitate vertical movement with respect to physical effort involved. In addition, the flexibility of stairways in terms of capacity and flow directions make stairways more attractive than an escalator in terms of the design of vertical circulation of passengers. Therefore, a single stairway provides the simplest solution for vertical movement in public transport facilities.

However, if the level of comfort perceived by pedestrians is taken into account, we observe that a combination of a wide stairway and an ascending escalator is one popular solution for vertical circulation inside pubic transport facilities. Examples are site A in Den Haag HS (Fig. A-2) and site B and C in Den Haag Centraal station (Fig. A-4). The wide stairway is capable of accommodating a sudden surge of passengers from a train and opposing traffic flows, and the ascending escalator offers passengers an alternative for a more comfortable upward movement.

If there is enough space, a descending escalator is sometimes added to ease downward locomotion in particular for passengers with physical difficulty or heavy luggage. Examples include site A and site D in Den Haag Centraal station (Fig. A-4). The most efficient solution to heavy passenger flow is the case of site (A+B) in Den Haag HS (Fig. A-2). Although located separately, the two wide stairways, and the ascending and descending escalators actually function as a whole because of their spatial proximity and free access for passengers. The infrastructure is shared by different passenger flows (up/down to platform 3 and platform 4), and the special arrangement enhances the flexibility and efficiency of vertical circulation.

Different arrangements of vertical infrastructure result in various choice situations (choice between different infrastructures) facing by pedestrians. Four different choice situations are identified in these three visited stations, being:

- Choice situation 1 : ascending pedestrians make a choice between a stairway and an escalator located adjacent to each other
- Choice situation 2 : descending pedestrians make a choice between a stairway and an escalator located adjacent to each other
- Choice situation 3 : ascending pedestrians make a choice between a stairway and an escalator separated by a descending escalator
- Choice situation 4 : ascending pedestrians make a choice between two stairways and an escalator located at opposing sides of the passageway

In situations 1 to 3, only two choice alternatives are available, whereas in situation 4 three alternatives are present. Situations 1, 3, and 4 all refer to the ascending movement, whereas only situation 2 covers the descending movement.

We discuss the adequacy of sites for data collecting work in section A.3.1 where three important aspects are identified as: availability of required data, variation in traffic conditions, and physical requirement of data collecting technique. The required observation data for the study of walking and route choice behaviors is given in Fig. A-7, while the variation in traffic conditions and physical requirement of data collecting technique will be discussed in more details under “Data Collecting Plan” and Chapter 5 of the main report.

We analyze the adequacy of those promising sites in section A.3.2. The criteria used for the assessment is the availability of both infrastructure-specific and site-specific data. According to the results of the assessment given in Tab. A-4 and environmental concerns, site (A+B) at Den Haag HS is assessed as the best location for data collecting work in this project.