Modelling Passenger Flows in Public Transport Facilities

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Modelling Passenger Flows in Public Transport Facilities

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Παντα Ρει *(everything flows)*

\- *Heraclites*

Preface

Until the early seventies of the last century, pedestrian traffic has hardly been subject of research. About that time, researchers started studying pedestrian behaviour more intensively, first by watching and deriving (simple) theories and models from what they observed. Only recently, when more advanced observation techniques became available, computers became faster and could handle larger and more complicated models, the number of available pedestrian models as well as their application scope and accuracy increased significantly.

Despite these developments, designers of public transport stations and other public facilities accommodating large pedestrian flows nowadays still use simple rules of thumb. Meeting the increasing needs of these designers for more advanced assessment tools was the impetus for my doctoral research to develop a dedicated simulation tool for modelling passenger flows in larger multi-modal public transport facilities. This new simulation tool does not only include walking behaviour as such, but covers as well the main behavioural dimensions in pedestrian behaviour in public accommodations, including route choice, performing activities, and boarding and alighting from public transport vehicles. For the validation of the modelled walking behaviour, I have performed innovative large-scale laboratory experiments involving large groups of subjects, who were assigned various walking tasks with respect to among other things walking direction and walking speed. In developing the new models, I did extensive observations of passenger behaviour on railway platforms in the city of Delft and route choice observations in the railway stations of the cities of Delft and Breda. A variety of case studies have shown the applicability of the new tool, given the name of SimPed. The alternations between the theoretical and practical activities of the dissertation research formed one of the attractive aspects of my work.

This doctoral research followed from a joint research endeavour by Delft University of Technology and Holland Railconsult. It is part of the research programme Seamless Multimodal Mobility (SMM), carried out within the Netherlands Research School for Transport, Infrastructure, and Logistics (TRAIL). This research programme studies all kinds of components of a multimodal transport system, such as travel demand modelling, design of multimodal transport networks, design of robust timetables, and operational control of line-bound public transport services.

Several years of dedicated research and hard work form the foundation of this thesis. I

am indebted to each from whom I have learned and who have contributed in many ways to this dissertation.

First of all, I wish to acknowledge the crucial contributions of my thesis supervisor professor Piet Bovy, supporting my research with admirable enthusiasm. Secondly, I would like to express my thanks and gratitude to my daily supervisor Serge Hoogendoorn for his scientific, mathematical, and personal support. Being always very critical, but at the same time prepared to help me finding solutions for seemingly inexplicable traffic phenomena. Their critical comments and many suggestions made this thesis more than I could have done by myself alone. In addition, I would like to thank all members of the promotion committee, taking the time to read this dissertation thesis and to provide very useful suggestions for improvement.

The design and implementation of the developed simulation tool SimPed were performed at my former employer Holland Railconsult, whereas the scientific research underlying the simulation tool leading to this thesis has been conducted at the Transport & Planning department of the faculty of Civil Engineering and Geosciences of the Delft University of Technology. I like to thank Sidney van de Stouwe formerly from Holland Railconsult for making this research possible at Holland Railconsult, as well as Patrick van Esch and Jack Kruijer for their efforts and dedication in developing the simulation tool and performing the first assignments (including the necessary work late at night and during the weekends). I would especially like to thank my former colleagues from the very beginning of this endeavour (of the department 'Processimulatie') for being a closely-knit group and making me realise there is more in life than just work, even at work.

I would equally like to thank my colleagues of the Transport & Planning department with whom I had many inspiring discussions especially during the last two years of my research. Despite the hard working needed, there was always time for a helping hand, an encouraging word, an interested question, or just a chat. I have had (and still have) a great time working with you!

Last but not least, special thanks go out to my family, being there for me when I needed them, for much more than just this piece of paper. I'd like to dedicate this thesis to them, since it would not have been possible without their continuous encouragement and support.

Winnie Daamen

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Notation

This section shows an overview of parameters (table 1), variables (tables 2), indices (table 3), superscripts (table 4), and sets of elements (table 5) used in this thesis.

The following notational conventions have been followed:

- Random variates are underlined ($\underline{X}$).
- Subscripts indicate the element the variable concerns (x_i).
- Superscripts indicate the type of variable (x^i), e.g. walking time on link a (T_a^{walk}).
- Calligraphic capitals indicate a set ($\mathcal{X}$).
- Expected value of a random variable ($E\left(\underline{X}\right)$).

Table 1: Overview of parameters

Symbol	Explanation
$\alpha, .., \delta, \zeta, .., \lambda$	parameters of the utility function
τ	route update interval
ξ	comfort parameter for an escalator
ξ^0	initial value of the escalator comfort parameter

Table 2: Overview of variables

Symbol	Explanation
A_i	occupied area by pedestrian i
A_a^{net}	net occupied walk area of link a
a_a	acceleration of lift a
C	capacity of a part of the pedestrian infrastructure
C^y	capacity of a layer in a pedestrian flow
C_r	alternative specific constant in disutility function of route r
ε_r	random utility of route r
f	floor where the lift may stop
f_i	floor where pedestrian i is waiting for the lift
$\underline{F}$	random variable indicating the floor of the lift
k	density
k_a	density on link a
l_a	length of link a
L_j	length of trajectory j
N^a	number of alighting pedestrians
N^{walk}	number of pedestrians walking on a link
$N^{service}$	number of pedestrians being served at an activity location
N^{wait}	number of pedestrians waiting to be served
N^{max}	maximum number of pedestrians on a link
P_m^{asc}	probability of a pedestrian choosing escalator m
	while moving in ascending direction
P_m^{desc}	probability of a pedestrian choosing escalator m
	while moving in descending direction
P_r	probability of choosing route r
q	pedestrian flow
T	time period
ΔT^l	difference in walking time between two alternative routes
T^a	alighting time at a public transport vehicle door
T^b	boarding time at a public transport vehicle door
$T^{a,avg}$	average alighting time per pedestrian
$T^{b,avg}$	average boarding time per pedestrian
T_a	total time spent on link a
T_a^{walk}	walking time on link a
$T_a^{service}$	service time on link a
T_a^{wait}	waiting time on link a
t_v^{sa}	scheduled arrival time of public transport vehicle v
U_r	utility of route r
u	speed
u_a	moving speed of link a

Table 2: Overview of variables (continued)

Symbol	Explanation
u^{avg}	speed of an average pedestrian
$u^{0,avg}$	free speed of an average pedestrian
v_i	speed of pedestrian i
v_i^0	free speed of pedestrian i
V_r	systematic utility component of route r
w_a^l	width of link a
w^{avg}	width of an average pedestrian
w^e	effective width of a bottleneck
w_i^p	shoulder width of pedestrian i
w^{max}	maximum shoulder width of a pedestrian
w^m	depth of an escalator step
x	longitudinal position of a cross section

Table 3: Overview of subscripts

Index	Element	Index	Element
a	level walkway	m	moving walkway
b	boarding door	p	passing element
c	activity	q	queue
f	floor	r	route
i	pedestrian	s	stairs
j	trajectory	t	time
l	lift	v	public transport vehicle

Table 4: Overview of superscripts

Symbol	Superscript	Symbol	Superscript
0	initial value	max	maximum
a	alighting	net	net
asc	ascending	o	obstacle
b	boarding	p	path progression
avg	average	$service$	being served
$desc$	descending	sa	scheduled arrival
e	effective	sp	service point
f	floor	t	transfer
$walk$	walking	$wait$	waiting
m	moving walkway	y	layer

Table 5: Overview of sets of elements

Symbol	**Set of elements**
$\mathcal{A}$	level walkways
$\mathcal{B}$	boarding infrastructure
$\mathcal{C}$	activities
$\mathcal{F}$	floor served by a lift
$\mathcal{L}$	lifts
$\mathcal{M}$	moving walkways
$\mathcal{P}$	passing infrastructure
$\mathcal{R}$	routes
$\mathcal{S}$	stairs

Chapter 1

Introduction

1.1 Research motivation

This thesis is about a computational tool specifically developed for supporting assessments of designs of public transport facilities and similar public spaces with intensive pedestrian flows. The research described does not only pay attention to walking, but covers multiple aspects of pedestrian behaviour, such as route choice, performing activities, and boarding and alighting from public transport vehicles.

Public transport facilities and public spaces are to a large extent designed by rules of thumb. However, because increasingly the available place for these public spaces is reduced, the efficiency and soundness of the design of such facilities are getting more and more emphasis. Planning and design processes of such public spaces require the support of quantitative information about the expected performance. With the help of a tool supplying such information, studies can be performed to predict the quality of the designed facility, both in a qualitative and quantitative sense.

Each designed facility is subject to all kinds of requirements depending on the conditions in the facility. In normal conditions, the designed public transport facility should function optimally, indicating that the space available is tuned to possibly occurring pedestrian flows. In a public transport facility, pedestrians do not only walk, but may also perform other activities, such as purchasing a ticket or visiting a shop. Of course, interaction with arriving and departing public transport services is essential in determining the quality of a transport station design. Therefore, processes such as boarding and alighting public transport vehicles need to be analysed as well. Occasionally, extreme conditions may occur, due to festivals, exhibitions but also due to calamities (fire or even terror attacks). These conditions do not only influence pedestrian walking behaviour, but also pedestrian decision making, such as the choice of a destination and the route to this destination. The aim of the analysis tool is thus to support assessment of a design with respect to its efficiency, its safety, and the quality of processes taking place in the design area.

Apart from being an aid in the design process, the assessment tool also has to satisfy requirements concerning the easy and effective handling of the tool and concerning the processes included as well. The tool handling is not only related to the user-friendliness of the tool, but also to the availability of visualisation of processes, in order to see what is going on in the designed public transport facility. In order to determine which processes have to be covered by the tool, one needs to identify direct and indirect users of the tool. Direct users assess designs and calculate required information, such as walking times, location and duration of congestion. The results of the assessment are used by several parties (indirect users), that is, designers use the output to improve their designs, evaluators compare designs and come up with a rating of these designs, and finally, decision makers decide on a final solution, among other things based on the results of the evaluation of the designs.

Since the number of relevant and complex processes of which detailed information is needed is manifold, a simulation tool is preferred instead of using analytical models. Preferably, the requested information is of a quantitative nature thereby enabling an objective comparison of different designs under a variety of conditions, which is one of the benefits of a simulation tool. A variety of different processes are required to be included, such as the walking behaviour of pedestrians, pedestrians performing activities, and the interaction of passengers with public transport vehicles. These are rather profound requirements which are not satisfied by existing tools. A new type of simulation tool is thus required, the development of which is subject of this thesis.

The development of such a computational tool consists of a practical part and a part concerning the tool functioning. For the practical part, a conceptual design of the tool is needed, whereas in-depth knowledge of processes is needed to describe the tool components. The conceptual design of the tool consists of the requirements concerning input, visualisation, and analysis of the results and a description of the implementation of the tool. The knowledge of processes, coming from literature and dedicated data collection, is transformed into models, of which the tool is composed.

1.2 Research objectives

The main research objective of this thesis is the development of a dedicated operational simulation tool to support designers of public transport facilities and other public spaces to optimise their designs.

In order to fulfil the main objective of the research, a number of derived objectives have been formulated:

- Specification of the functional and technical requirements of the simulation tool.
- Design of the tool set up in both functional and technical sense.
- Review of the existing state-of-the-art on (existing) simulation tools as well as relevant processes and identification of lacks in this knowledge.

- Performance of dedicated empirical observations to fill some of the identified blank spots.
- Specification of theories and related process models of all relevant processes.
- Verification of the process models separately and of the simulation tool.
- Validation of (a subset of) the components of the simulation tool.
- Demonstration of the practical value of the simulation tool by performing several case studies.

1.3 Research approach

The development of the operational simulation tool is divided into conceptual tool design, knowledge of processes, and testing of tool components. In establishing the tool and acquiring necessary knowledge a variety of research methods have been adopted, as shown in italics in figure 1.1.

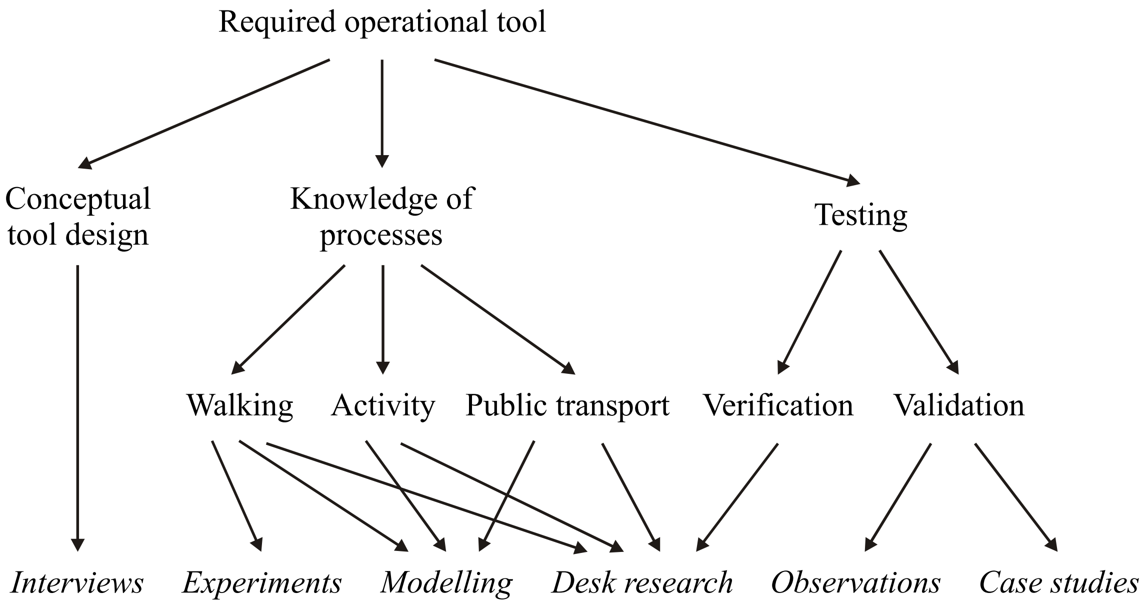


Figure 1.1: Derivation of the research methods

For gaining insight into the processes modelled by the tool, first, *desk research* has been performed to gather information from literature. This resulted in an overview of relevant existing empirical data, theories, and models of pedestrians in transfer stations, but also a list of blank spots, indicating relevant processes on which none or only little knowledge exists. Some of these blank spots have been filled in this research, while others have just been identified and will be subjects for future research.

Specific *data collection* for this thesis concerned pedestrian walking behaviour in general and pedestrian traffic flow characteristics in a transfer station in particular. In order to isolate the influence of different factors on pedestrian walking behaviour, *controlled walking experiments* have been carried out. These have been complemented by *observations* in transfer stations concerning boarding and alighting, walking times, and platform densities, using hand-held computers as well as concerning pedestrian route choice behaviour by the following of passengers ('stalking').

The conceptual tool design mainly concerned the computer science part of the tool design. The user-friendliness and visualisation and analysis abilities are important in this respect. One of the standard methods for developing an object-oriented application has been applied, the so-called *Unified Modelling Language* (Warmer & Kleppe 1999). The requirements for the tool have been collected by consulting existing *guidelines* with respect to the design of public transport facilities and *interviewing* designers, people involved in assessments and evaluations of designs, and decision makers.

In order to model all processes with similar accuracy, to reduce the complexity of the models and the simulation tool as a whole, and to increase maintainability, only a limited number of model types have been applied, in our case service queuing models and discrete choice models. Queuing models have been applied to all those processes that function as service systems, such as performance of activities, boarding and alighting from public transport vehicles, and passing joints, such as turnstiles and doors. Choice models have been adopted for all those decisions of pedestrians where a choice from a limited set of discrete options has to be made, for example to determine routes to destinations and locations where to perform activities. Walking behaviour modelling, in the end, has been based on traffic flow theory.

Testing of the simulation tool consisted of calibration, verification, and validation. In the calibration of the tool, parameters values have been set, which have been derived from literature and from the controlled experiments. For the verification, results of the simulation have been compared with manually calculated results to test whether the tool functions as required. For the validation, simulation data have been compared to observations in a transfer station (Delft, the Netherlands). Also, a number of case studies performed with the simulation tool have been used to fulfil a part of the testing, as the results of the simulation have to be explainable.

1.4 Thesis contributions

The main scientific contribution of the research described in this thesis is the integration of pedestrian choice models and queuing models describing various dimensions of pedestrian behaviour including walking, route choice, performance of activities, and interaction of passengers with public transport vehicles into a consistent framework. This has resulted in an operational simulation tool for modelling passenger flows, supporting design assessments of public transport facilities and public spaces with intensive pedestrian flows. A comprehensive validation of the simulation tool has been performed, based on experiments and observations.

In a state-of-the-art overview an in-depth account is given of existing knowledge on pedestrian behaviour as well as an overview of the blank spots. Data collection has been performed to fill in some of these blank spots. To our best knowledge, controlled experiments have been applied for the first time to gather data on pedestrian walking behaviour. In a laboratory environment, parameters influencing pedestrian walking behaviour have been investigated. Another contribution is the manual collection of data on pedestrian behaviour on a platform using hand-held computers. Cumulative flow curves (for the first time applied in pedestrian traffic flow analysis), describing observed densities on the platform (distributed over time and space) and corresponding levels-of-service have been used to compare with simulation results.

Especially from the experiments new theories and models have been derived. One of the most innovative elements was the finding that, contrary to existing capacity rules, capacity does not linearly increase with the width of a bottleneck, but rather step-wise. This is a consequence of layer-formation inside the bottleneck, causing the so-called ‘zipping effect’. Other remarkable findings were self-organisation of pedestrian flows, fundamental diagrams, hysteresis, and the spatial distribution of pedestrians depending on external conditions.

The simulation tool consists of a combination of microscopically and macroscopically modelled processes, indicating different levels of aggregation. A quasi-dynamic individual route choice model has been included, where pedestrians update their routes after fixed time intervals, while pedestrian flows are modelled macroscopically using a speed-density relation. One of the contributions of this research concerns the modelling of interpersonal differences, not only regarding pedestrian choice behaviour, but also in terms of walking behaviour as a result of different individual free speeds.

An innovative dedicated software architecture has been designed following an open and modular structure, in which each of the components may be tested separately. Both for the architecture and the separate models, the Unified Modelling Language has been applied, among other things to design dedicated object models.

1.5 Relevance of the research

The relevance of research results reported in this thesis can be categorised according to its scientific and practical relevance. Scientific relevance considers aspects such as controlled experiments, that contribute to the current state-of-the-art in data collection, theory development, and application of new methods and models. Practical relevance pertains to the value of this research for designers of public transfer facilities as well as those assessing and evaluating these designs.

Scientific relevance

A *state-of-the-art overview* has been compiled on pedestrian route choice behaviour and pedestrian walking behaviour. On both topics aspects related to empirical and experimental data, pedestrian behaviour theories and models, and modelling results have been discussed. This state-of-the-art overview also shows gaps in existing knowledge. To fill in some of these blank spots *new data* has been made available on (Dutch) pedestrian walking behaviour, pedestrian behaviour on train platforms, and pedestrian route choice behaviour in transfer stations.

To collect these aforementioned data, a number of new methods have been applied. Pedestrian walking behaviour has been observed by video cameras, while pedestrians were subjects in *controlled laboratory walking experiments*, where conditions with respect to walking directions and the presence of bottlenecks were changed in order to see the influences on pedestrian walking behaviour. This method is very suited to investigate the influence of one stimulus to different response variables (such as walking speeds and flows) and will be used for further research. The method has already been applied in other research areas and proved to be valuable in traffic research as well.

Observations on train platforms have been performed using hand-held computers. The interface of these computers was designed specifically for these observations, which makes it a powerful tool. One of the results of the observations were *cumulative (pedestrian) curves*, suited for a description of densities, average speeds, and pedestrian flows on (a part of) the platform. This method has originally been developed for car traffic, but this research proved it suitable for pedestrian traffic as well.

Since cross-sections in a pedestrian network are very wide and pedestrians are difficult to identify, route choice observations are hard to acquire by counting pedestrians on cross-sections. A method being formerly applied for bicycle traffic, namely *person following*, resulted in a sufficient and reliable data set. Such detailed information on pedestrian route choice behaviour is not yet available and the method is also applicable in other conditions and facilities.

Due to these new data new insights into the related processes have come up, which may be used for further theory development and derivation of new and better mathematical models. Amongst the interesting new insights were a *step-wise relationship between capacity and width of a bottleneck* and the *use of available space* in front of a bottleneck.

The integration of various pedestrian behaviour models into a single framework shows the possibility to cover multiple related behavioural dimensions. The *modular and open structure* of the tool provides opportunities to replace old models or to add new ones without completely adapting the software architecture and other modules.

Practical relevance

The research resulted in a validated operational simulation tool for modelling pedestrians in transfer stations and other public spaces. The simulation tool does not only include pedestrian walking behaviour, but also other relevant processes with respect to the behaviour of pedestrians in transfer stations. Using this tool, assessment studies may be performed to evaluate facility designs with respect to pedestrian comfort. Such an evaluation may show shortcomings or inefficiencies in the design, which may be improved already in an early stage of the total design process. As the simulation results give an objective and quantitative assessment of the design, simulation results may also be used as a criterion for the weighing of alternative designs, a justification of the costs related to the design, and as a means of communication with the public. Also the mentioned relationship between capacity and bottleneck width may be new input for the design process.

The three dimensional Virtual Reality model shows the spatial aspects of the designed facility and gives an indication of the crowd and comfort of the pedestrians, as it allows the user to 'walk around' in the facility.

The performed case studies show possible application areas of the tool as well as the potential form of the output used to evaluate a design. The case study of the ferry terminals in Vlissingen and Breskens indicates that the simulation tool is not restricted to transfer stations, but may be applied to ferry terminals as well.

1.6 Outline of the thesis

The research presented in this thesis may be split into three parts, namely concerning the conceptual design of the tool, the modelling aspects, and the observations and experiments respectively (see also figure 1.2).

First, the requirements of the tool are assembled, where most of the requirements originate from interviews with designers, evaluators, and decision makers. Requirements are set with respect to the handling of the tool, the processes to be included in the tool, and the desired output of the tool. An overview of these requirements is found in chapter 2. Requirements form the basis of the fundamental system specifications to determine the essential processes, which are to be included in the simulation tool. Chapter 5 analyses the functioning of pedestrian facilities and specifies essential elements and processes to be modelled. The way of implementation of these elements and processes in the tool is discussed in chapter 7, describing the dedicated object model and software architecture. This software architecture links different applications, concerning among other matters visualisation, input, and analysis of the simulation results.

As indicated in the research approach, a study of the literature (chapter 3) is not only intended to give an overview of existing knowledge concerning pedestrian behaviour in public facilities and in transfer stations in particular, but will also reveal blank spots in

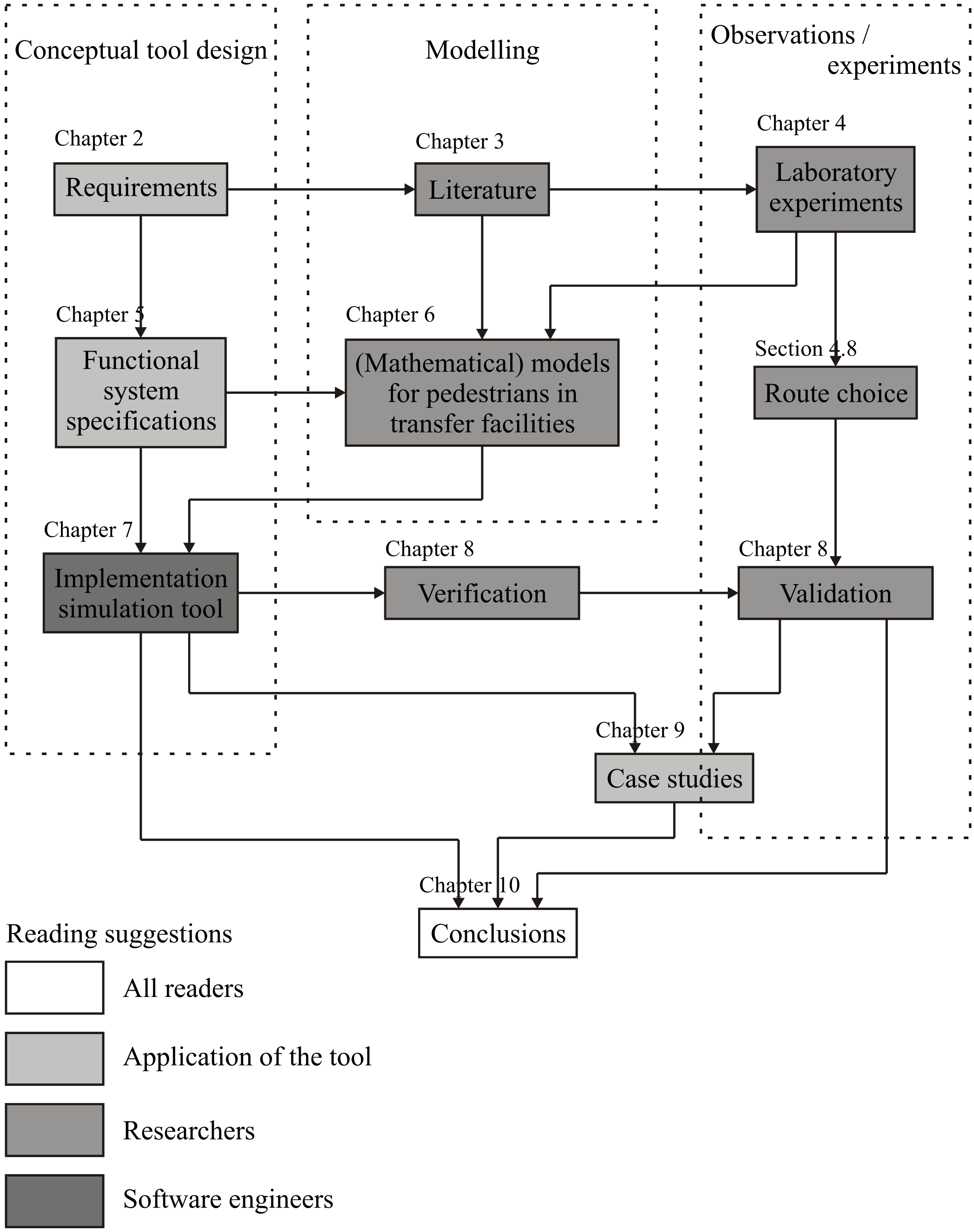


Figure 1.2: Overview of the thesis outline

this knowledge, such as the influence of free speed and walking direction on pedestrian walking behaviour. Some of these blank spots are filled in this research (chapters 4 and 8 and appendices B and E).

Based on the model descriptions assembled in chapter 5 and the collected knowledge on pedestrian behaviour in public facilities (chapter 4), mathematical models are derived to be included in the simulation tool (chapter 6). For each of the distinguished processes (activity location choice, route choice, walking, performing an activity, and boarding and alighting) a separate model is composed.

The third part of the thesis concerns new data collection, consisting of laboratory experiments and observations in Dutch railway stations. To fill some of the blank spots found in literature, controlled experiments are performed (chapter 4) in a laboratory environment. The resulting data are used to derive among other things speed-density relations for pedestrians, depending on walking direction and free speed distribution. For the validation of the simulation tool, simulation results are compared with observations from practice, collected in the railway station in Delft, the Netherlands (chapter 8).

The resulting operational simulation tool SimPed is used to perform a number of case studies (chapter 9) to show the applicability of the tool. Chapter 10 summarises findings and conclusions for the total research described in this thesis.

Chapter 2

User requirements of a pedestrian flow simulation tool

As indicated in section 1.2, the aim of the research described in this thesis is to develop an operational simulation tool to determine characteristics of pedestrian flows in multi-model public transport facilities, depending on infrastructure configuration and available transport services. The tool is an aid to quantify and to visualise effects of design choices on pedestrian flows through the facility. The simulation tool also has to serve the purpose of analysing effects of timetables and platform allocations of different transport modes (such as arrival and departure times of transport services at a station) on pedestrian flows in and through a pedestrian facility (congestion, transfer times, etc.).

Before describing the development of this tool, this chapter gives an overview of the user requirements of a pedestrian flow simulation tool. In order to structure the requirements, figure 2.1 shows the simulation tool as a black box and identifies the input and output in relation to the user objectives.

Figure 2.1 distinguishes different types of input and output:

- Input (section 2.1), consisting of facility design, passenger demand, and public transport services.
- Performance indicators (section 2.2).
- System requirements, separated into requirements concerning the graphical user interface (section 2.3.1) and other system requirements (section 2.3.2).
- Goals and objectives of the users, to be compared to the performance indicators. In case of a proper design, the proxies will correspond to the user objectives.

Different types of users of the simulation tool may be identified. Direct users are the operators of the tool who investigate designs of accommodations and calculate required information, such as walking times and locations and duration of congestion. The results

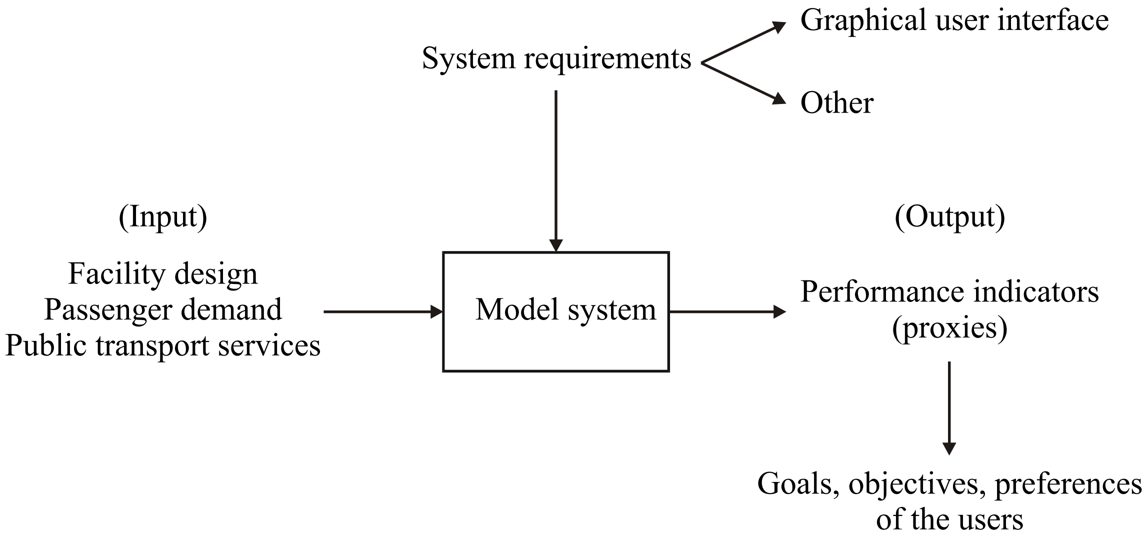


Figure 2.1: Types of user requirements for the simulation tool

of such an assessment are used by several parties (indirect users), which are among others the designers who use the output to improve their designs, evaluators who compare designs and come up with a rating of these designs, and finally, decision-makers who decide on a final design, among other things based on the results of the evaluation of the alternative designs. All types of users have their own objectives and, derived from these, their own requirements with respect to the input and output of the tool. Especially direct users will have requirements with respect to the graphical user interface of the tool.

Requirements have been collected by consulting existing guidelines for designing among other things public transfer stations (Van Gelderen 1999), (CROW 1998) and by interviews with designers and decision-makers as users of (output of) the tool. In the tool design documentation (Daamen 2002*b*) the Unified Modelling Language (Warmer & Kleppe 1999) has been applied, in which these requirements have been visualised by use-cases, describing the interaction between users and the system. For more information with respect of how to come to a simulation tool and to an extensive set of requirements, the reader is referred to (Behforooz & Hudson 1996), (Hughes & Cotterell 2002), (May 1990), (TRB 2002).

This chapter is confined to an overview of the requirements. Each type of requirement will be discussed in detail in the following sections, where all acquired information has been synthesised. This chapter concludes with a section on functionality of the tool as it is perceived by the user. This overview of processes will be a starting point for the identification of processes and elements in chapter 5.

2.1 Input

In figure 2.1 three categories of input have been distinguished, namely facility design, passenger demand, and public transport services.

The facility design contains the dimensions of the designed *facility layout*. Also, functions of different types of infrastructure are indicated (walkway, hallways, platforms, stairs, escalators, people movers), as well as locations of functions such as ticket offices, ticket machines, and shops, and locations and dimensions of obstacles (columns, dustbins, etc.).

Pedestrian demand includes an origin-destination table, describing origins and destinations of passengers, as well as the types of pedestrians, since each pedestrian type will probably have dedicated behaviour. Input of the planning and design stage is usually a predicted origin-destination table, describing the size and directions of the simulated pedestrian flows. This origin-destination table is therefore also used as input for the simulation tool. Changing this exogenous origin-destination table may initiate an assessment of the designed facility for different planning horizons or the occurrence of special events.

Input with respect to *public transport services* does not only consist of timetable data, but also includes service characteristics, platform allocation, and rolling stock characteristics.

Design parameters (i.e. policy levers and design options) are not explicit input of the simulation tool. These parameters are assumed to be part of the design process. The different designs resulting form this design process are input of the tool. The output generated by the simulation tool is again input for the design process. This feedback loop between both processes ends when the objectives of designers and decision-makers are satisfied.

2.2 Performance indicators

Assessments of designs of a public transport facility usually concern quantifiable *performance criteria* with respect to:

A. Accessibility. Not only the accessibility of specific parts of the infrastructure is important to determine for example attractive locations for shops, also bottlenecks in the designed facility have to be identified (those locations with limited or insufficient accessibility).

B. Pedestrian safety. Since people may be crushed to death in very dense crowds, especially in emergency conditions, all locations need to have a density level below a specified critical level. This critical level is determined by public transport managers or decision-makers. Nowadays, also aspects of personal security become more and more important, which are related to dark and scarcely used areas. These areas therefore also need to be identified.

C. Network capacity. What is the quality of the pedestrian infrastructure network, in which all types of infrastructure are connected? The simulation tool has to be able to indicate the influence of different demand patterns (varying in size, in time, and in locations of pedestrian origins and destinations) on the capacity.

D. Effects on travel times of passengers. Travel times of passengers in the facility may be affected by a number of factors, such as arrivals or departures of public transport vehicles, hindering waiting queues, and non-functioning or inaccessible parts of the infrastructure. Given probabilities of the occurrence of such a phenomenon, effects on travel times (consisting of both walking, waiting, and service times) have to be charted.

E. Availability and quality of facilities and services. These aspects are mainly related to waiting times of pedestrians. As indicated before, pedestrians might wait for a number of reasons. Waiting times for public transport vehicles (for either boarding or transferring passengers) give an indication of the quality of public transport services, whereas waiting times in front of activities are used to assess location and service quality of activities. A distinction has to be possible between the assessment of different types of activities.

F. Robustness and reliability. Robustness is an indication of the ability of the designed facility to handle emergencies, such as evacuation due to fire. The robustness indicates the time needed for the system to return to its normal conditions after a disruption. In a robust facility, a disruption in only causes minor delays. Reliability indicates the predictability of certain variables, i.e. walking times and waiting times. Not only the robustness of the facility as a whole needs to be indicated, also a judgement on the vulnerability of specific parts of the infrastructure (for example escalators and stairs) is required.

In order to quantify the above mentioned performance indicators, the following output needs to be generated by the simulation tool (these are so-called *proxies* for the criteria):

1. Walking times (distribution) of pedestrians walking from any origin to any destination in the infrastructure network, where an origin or destination is either an entry or exit point in the facility or a public transport service stop. Walking times may be summarised per group of passengers, where this group is either characterised by a physical identification (such as age, gender, or walking ability) or by a trip-related classification (such as boarding, alighting, and transferring passengers).

2. Waiting times (distribution), not only of boarding passengers until their vehicle arrives, but also of transferring passengers (including probable hidden waiting times) and of pedestrians waiting in queues before performing activities. Hidden waiting times concern times pedestrians use to perform activities instead of waiting on the platform.

3. Service times (distribution) of pedestrians. These service times indicate the quality of a type of activity, therefore grouped per type of activity and per location.

4. Available walking routes and corresponding walking times. The number of available walking routes indicates the robustness of the network and the vulnerability for bottlenecks.

5. Duration and location of congestion and number of pedestrians involved in order to detect bottlenecks and indicate their severeness.

6. Transfer characteristics, consisting of transfer times, number of transferring passengers, and percentage of passengers catching a transfer.

7. Planned and actual arrival and departure times of public transport vehicles.

Table 2.1 is a cross reference table between criteria (rows) and proxies (columns) in order to understand where the proxies come from and to make sure all criteria are covered.

Table 2.1: Cross reference table between criteria (rows) and proxies (columns)

	A	**B**	**C**	**D**	**E**	**F**
1	x	x	x	x		x
2	x		x	x	x	x
3				x	x	x
4			x	x		x
5	x	x	x	x	x	x
6			x	x		x
7				x		x

The design of a public transport facility needs not only be assessed under normal conditions, but also in extreme conditions (such as evacuation) or temporal conditions (for example during a reconstruction). Therefore, pedestrian behaviour (walking, route choice, etc.) in these conditions needs to be modelled in the simulation tool.

The planning horizon of designs may differ, that is, designs of new facilities have to be assessed for conditions occurring in a longer term (up to twenty to fifty years), whereas during a restructuring of a facility, the pedestrian comfort level is assessed in current conditions, but with reduced infrastructure. The simulation tool has to handle planning horizons from now to fifty years. Special attention needs to be paid to changes in the number of pedestrians generated, demand patterns varying over time, and the amount of infrastructure modelled (also in limited conditions).

The aim of the simulation tool is to be a support in all stages of the design process (from the early planning stage to a detailed design). In the early planning and design stages, the infrastructure is only roughly known, so the design is only assessed at an aggregate level. At the end of the design process, very detailed designs are available, thus the simulation tool has to use these details in order to assess designs conscientiously. The simulation tool therefore has to be able to anticipate on different scales of application by modelling processes in different levels of detail.

The results of the simulation tool will not only be used to assess designs of public transfer facilities, but also to develop new sets of guidelines for the use of public transport facilities and the development of new designs. Both input and output of the tool have to be tuned to this requirement.

The results of the simulation tool have to be reliable and accurate. Since the simulation tool will include various processes, it is important to mention that the tool is as accurate as its least accurate model. All models should therefore have a similar level of accuracy.

2.3 System requirements

As indicated before, the system requirements have been split up into requirements concerning the graphical user interface and the remaining requirements. Both types are discussed in the following sections.

2.3.1 Graphical user interface

The main requirement concerning the graphical user interface is user-friendliness, indicating that the interfaces of the applications are intuitive and understandable for designers and other users of the tool. Both a user-friendly interface for input and editing and a graphical and animated presentation of results are crucial. Another aspect concerning user-friendliness is the possibility of fast, easy, and unambiguous input of the infrastructure configuration, whereas adaptations of designs of existing public transport facilities (with respect to configuration, timetable, origin-destination data, and simulation parameters) may be carried out with only small additional effort. The input of the design configuration has to give a similar impression as the drawing tools currently used in the design process. Also, integration is preferred with databases containing descriptions of designs and existing facilities in order to facilitate the input process and to reduce the number of possible mistakes during the total input process. Finally, the tool has to provide default values for key parameters, which may be changed by the user when needed.

In order to verify outcomes of the simulations and to show designers and transport operators what happens during a simulation, a visualisation and animation of the various processes in the studied facility is desired. During recent years the role of animation films has increased significantly, partly due to the increase in computer calculation power. Animation films have become indispensable during the planning and design process. Important characteristics of a part of the infrastructure (for example stairs), need to be visualised using various colours, whereas more detailed information is available using dedicated online overviews. A preference is declared on the availability of a three dimensional animation, for example using virtual reality, to get a spatial impression of the sphere of the designed facility and the pedestrian flows present.

A specific analysis application is required generating standard output with 'a single press on a button'. Designers may produce these standard results themselves, whereas a computer expert is able to compose additional analyses and corresponding graphs and tables. The output of the simulation tool needs to be extensive and detailed on all occurring processes to be able to perform these dedicated analyses, so long as they are useful and add information.

Finally, the simulation tool has to be fairly insensitive to the size of the configuration and the number of pedestrians and transport vehicles present in order to keep the duration of a simulation study within reasonable limits. It is desired that the speed of the micro-simulation model be faster than real time.

2.3.2 Other system requirements

Since the simulation tool has to be used by designers and professionals assessing and evaluating designs, the simulation tool has to run on a PC (low-cost non-specialist computer) in a Windows environment, as this is the environment mainly used by these people. This leads to the requirement that interfaces of the simulation tool have to be Windows look-alike.

With respect to the programming of the simulation tool, we therefore need an object oriented modelling technique, whereas for the design of the simulation environment and the different applications the Unified Modelling Language (Warmer & Kleppe 1999) is required. In order to meet requirements with respect to maintainability and extendibility of the tool, it is desirable that the simulation tool has a modular structure. Also, other standard requirements in information technology design have to be met, but these requirements are outside the scope of this thesis (Behforooz & Hudson 1996), (Hughes & Cotterell 2002).

Since the simulation tool is designed in an organisational environment in which also other simulation tools are developed and maintained, the programming software has to fit in with the currently used software. As a result, for the simulation part of the tool, the software language MODSIM III (Compuware 2000) was chosen, whereas Visual C++ was used for supporting tools (such as input, animation, and archive).

2.4 Functionality of the tool

The functionality of the tool relates to the inside of the black box 'Model system' in figure 2.1. Requirements with regard to this functionality mainly concern identification of processes (by designers). These processes function as a start set of processes and elements to be modelled (see chapter 5). Relevant processes mentioned in relation to modelling passenger flows in public transport stations are:

- Horizontal and vertical movement of pedestrians on walkways, hallways, platforms, stairs, ramps, escalators, and in lifts. These processes do not only describe interactions between pedestrians and the infrastructure, but also interactions between pedestrians mutually and interactions of pedestrians with obstacles (such as dustbins) on the infrastructure.

- Pedestrians passing infrastructure connecting two areas in which a pedestrian may or may not experience delays. Examples of this type of infrastructure are doors, gates, and turnstiles.

- Waiting of pedestrians on platforms for public transport vehicles and in queues to perform activities. This waiting also involves the choice of a waiting location depending on the prevailing conditions, such as variation of densities over the area and functioning of public transport services.

- Boarding and alighting of passengers from all types of public transport vehicles stopping at the transfer facility. Clearly, the influence of public transport vehicle characteristics (such as height difference between the vehicle floor and the platform, and the gap between the door opening and the platform) on the boarding and alighting process has to be taken into account.

- Pedestrians performing all types of activities, for example ticket acquisition and validation, shopping, information provision, and service provision. Also, characteristics of activities (such as number of servers available and service times) depending on the arrival pattern of pedestrians are to be incorporated in the simulation tool.

- Pedestrian route choice and orientation within the transfer facility.

- Other modes in the facility, such as private modes (walking, biking).

Chapter 3

State-of-the-art of pedestrian flow theory

3.1 Introduction

The state-of-the-art in this chapter is an overview of existing literature aimed at both synthesising the available knowledge and identifying blank spots from the perspective of developing a simulation tool for pedestrians in transfer stations. This is why not only pedestrian behaviour concerning route choice and walking is described, but also the interaction of pedestrians with public transport vehicles.

Pedestrian behaviour is described at three levels: strategic level, tactical level, and operational level, as is described by Hoogendoorn et al. (2001) and CROW (1998). An overview of these decision levels is given in figure 3.1, as well as processes on and interactions between the different decision levels.

At the *strategic level*, travellers decide on which activities (as well as the activity order) they want to perform when they are in the station. While some of these activities are discretionary (buying a newspaper), others are mandatory (buying a ticket before accessing a train when a passenger does not yet possess one). Due to the fact that only few sources are available on activity choice set generation (Arentze & Timmermans 2004), (Helbing 1997), (Penn 2003), (Timmermans et al. 1992) and the fact that the strategic level is considered exogenous to the simulation model described in this thesis, the subject is not dealt with any further.

The *tactical level* pertains to short-term decisions of pedestrians in the facility, given the choices made at the strategic level. On the strategic level, pedestrians have determined a list of activities they want to perform. The order in which pedestrians are going to perform these activities depends on prevailing conditions. Again, only a small literature exists on activity scheduling. Also, most of activity scheduling process is assumed exogenous as well in the simulation tool. However, the pedestrian may decide to skip one or more of

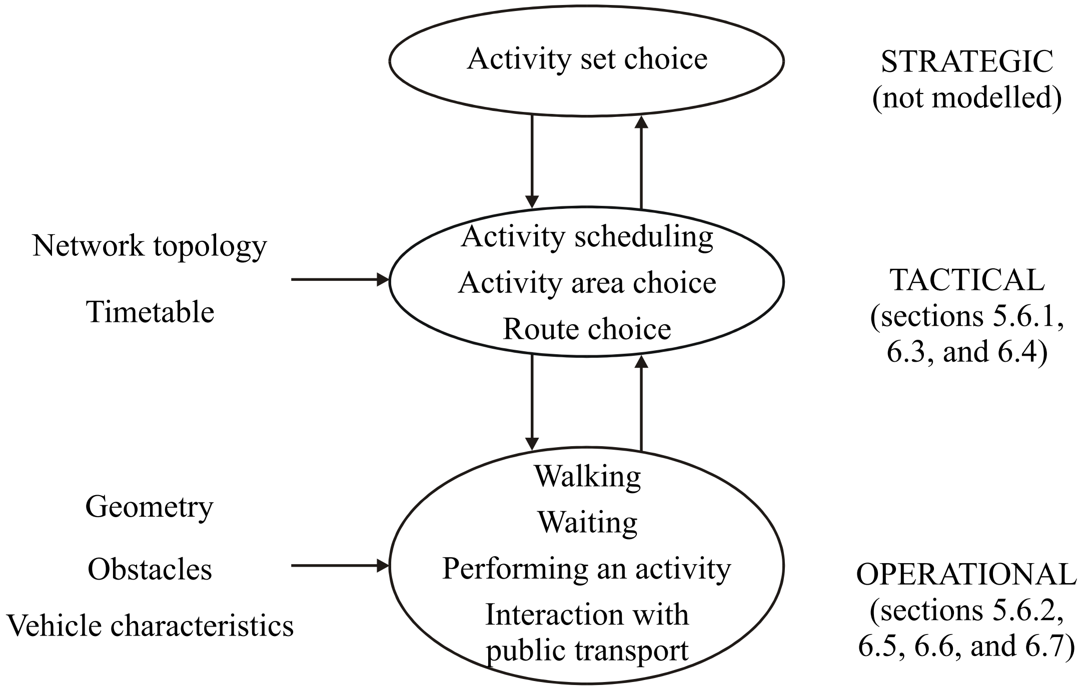


Figure 3.1: Levels in pedestrian behaviour, based on Hoogendoorn et al. (2001)

his activities due to time constraints. Therefore, no more details are given on this subject in this chapter (however, tactical level modelling is described in section 5.6.1).

Activities on the activity list may be performed at different locations. Activity area choice concerns the choice of optimal locations to perform an activity by individual pedestrians. Literature on the choice of activity locations in stations hardly exists. Some literature is found on related topics such as activity location choice in urban areas (Arentze & Timmermans 2004), (Borgers & Timmermans 1986*a*), (Helbing 1997), (Timmermans et al. 1992). This issue is considered as a blank spot and therefore not included in the remainder of this chapter (Hoogendoorn & Bovy 2004), but its modelling is described in section 6.3.

The last process at the tactical level is route choice between pedestrians' origins, possible intermediate destinations, and their final destinations. Route choice is a very important process in (pedestrian) flow simulation models, justifying why a lot of literature involves this theme. Route choice has been considered in a variety of research fields (such as psychology, geography, and traffic engineering). Traffic characteristics of route choice are discussed in section 3.2, whereas most psychological aspects (such as how pedestrians react on signing (CROW 1998), (Passini 1984)) are not incorporated.

At the *operational level*, pedestrians take instantaneous decisions for the immediate next time period, in line with the choices made at the tactical level. Most of the pedestrians' decisions on the operational level concern their walking behaviour, which is further elaborated in section 3.3.

Another process on the operational level is the interaction with public transport vehicles, which is one of the essential parts of a simulation model of pedestrians in transfer stations. Literature on this interaction is presented in section 3.4.

Also, decisions on waiting and performing an activity take place at the operational level. Fundamentals of waiting and performing activities are described in literature on queuing theory (Hillier & Lieberman 1995). However, traffic characteristics of these processes are not described extensively in literature (see for an exception (Gipps 1986)). This chapter will not go into detail into these two processes. Modelling aspects are described in section 6.6.

The state-of-the-art on pedestrian route choice behaviour revealed hardly any specific literature on route choice of pedestrians in public transport facilities and only a little literature on pedestrian route choice in general, whereas most of the literature deals with route choice principles for car traffic and multimodal traffic. Factors being identified as highly influencing pedestrian route choice were walking distance and, related to this, walking time. Most of the described pedestrian route choice theory and models were based on shortest path algorithms, whereas an alternative was found in utility maximisation, in which various criteria are applied.

Much literature has been found on pedestrian walking behaviour, although very few sources were dedicated to public transport facilities. Cultural influences on walking behaviour could be identified, as empirical data was collected all over the world. Also, influences of physical characteristics have been identified, which were significant for gender and age. Finally, pedestrian travel purpose and type of infrastructure influenced pedestrian walking behaviour. Pedestrian speeds varied significantly, due to different external conditions, but the average walking speed appeared to be 1.34 m/ s. Pedestrian traffic flow theory and models are similar to car traffic flow theory and models, but only limited studies exist in which fundamental diagrams are estimated. Also, mentioned influences such as age and type of infrastructure on this walking behaviour are not taken into account. This leads to a blank spot in identifying the influence of microscopic characteristics on macroscopic flow characteristics.

Figure 3.2 shows an overview of the amount of literature available as well as the identified blank spots. Processes have been distinguished on each of the decision levels (strategic, tactical, and operational). Furthermore, the aspects of the development cycle have been indicated (empirical data, theory, models, and modelling results) as well as the application area (general, with respect to pedestrians, and finally with respect to pedestrians in public transport facilities).

Summarising, this chapter describes the literature on route choice (section 3.2), pedestrian walking behaviour (section 3.3), and interactions between pedestrians and public transport vehicles (section 3.4). It concludes with an overview of the blank spots in knowledge on these processes (section 3.5).

The sections on route choice, walking behaviour, and interaction with public transport vehicles have a similar division into subsections, based on the development cycle of a

		Empirical data			Theory			Models			Modelling results		
		G	P	S	G	P	S	G	P	S	G	P	S
strategic	activity set choice		n.a.			n.a.			n.a.			n.a.	
tactical	route choice	1)	1)	1)	2)	2)	2)	3)	3)		4)	4)	
	activity area choice												
	activity scheduling												
operational	walking	5)	5)	5)	6)	6)		7)	7)	7)	8)	8)	
	waiting												
	performing an activity												
	interaction public transport	9)	9)	9)									

n.a. not applicable

With respect to:
- G General
- P Pedestrians
- S Pedestrians in public transport facilities

Blank spot

Little literature available

Much literature available

References to sections:
- 1) 3.2.1
- 2) 3.2.2
- 3) 3.2.3
- 4) 3.2.4
- 5) 3.3.1
- 6) 3.3.2
- 7) 3.3.3
- 8) 3.3.4
- 9) 3.4.1

Figure 3.2: Available literature for each of the mentioned subjects

simulation tool (empirical data, theory, models, and modelling results). Chapter 8 shows more details of this development cycle.

A separate state-of-the-art overview on data collection for walking behaviour is given in section 4.2

3.2 Route choice (tactical level)

This section discusses route choice for pedestrians in public transport facilities. Four aspects of route choice are described, namely empirical data, theory, mathematical models and modelling results. On some aspects only a little literature is available, thus to have at least a starting point in modelling route choice for pedestrians in transfer stations, literature on route choice with respect to pedestrians in other areas than public transport facilities (such as urban areas) as well as route choice with respect to other modes, such as car traffic and transit, is included as well.

3.2.1 Empirical data

A first distinction is made between route choice in the horizontal dimension (forwards) and in the vertical dimension (up and down). Factors influencing route choice in *horizontal* dimension may be divided into four categories:

- Network characteristics.
  - Number of routes available (Seneviratne & Morrall 1985*a*). One of the most important characteristics is overlap in routes.
- Route characteristics.
  - Distance (Ciolek 1978), (Guy 1987), (Helbing 1997), (Lausto & Murole 1974), (Seneviratne & Morrall 1985*a*), (Verlander & Heydecker 1997). Pedestrians appear to frequently choose the shortest route, although they are seldom aware that they are minimising distance as a primary strategy in route choice.
  - Time (Seneviratne & Morrall 1985*a*). Since pedestrians choose the route with the shortest length, this route often takes the least walking time. Reason for this is that congestion only occurs at specific areas, such as transport stations. For longer routes, pedestrians are less apt to choose not the shortest route in distance, as they have to supply their own energy.
  - Pleasantness or number of attractions along the route (Bovy & Stern 1990), (CROW 1998), (Seneviratne & Morrall 1985*a*). As routes become more attractive, walking time becomes a less important factor (CROW 1998).

- Directness (Ciolek 1978), (Helbing 1997). Directness is defined in relation with visibility, that is pedestrians walk straight towards a visible destination, unless they are hindered by obstacles, other pedestrians, or diverted by other attractions. Hill uses another definition of directness, in which route length and route complexity are combined (Hill 1982). However, route length is already included in the characteristic 'distance' and is therefore omitted from the aspect 'directness'.
- Crowdedness (Helbing 1997), (Seneviratne & Morrall 1985*a*). Even if the progress on a direct route is relatively slow (until approximately 3/4 of capacity flow is reached), still the choice for a longer route (in distance) is seldom made.
- Safety (Seneviratne & Morrall 1985*a*). Safety may be influenced by a number of factors (such as number of street crossings, size and speed of car traffic flows along the sidewalk, but also whether pedestrian and cycle traffic is mixed).
- Weather protection, noise, and air pollution (Bovy & Stern 1990), (Seneviratne & Morrall 1985*a*). These are all environmental influences of the chosen route, which are not evaluated as important factors influencing pedestrian route choice. Despite the availability of an elevated enclosed walkway system, hardly anybody chooses this route due to bad weather (Seneviratne & Morrall 1985*a*).
- Quality of the walking surface (Bovy & Stern 1990), (Helbing 1997). When a route is so unfavourable that large detours have to be made and the walking surface is of acceptable quality, pedestrians make their own paths, so-called 'stamped paths' (Helbing 1997).

• Person characteristics.

- Decision style (Bovy & Stern 1990), (Seneviratne & Morrall 1985*a*). Each pedestrian makes decisions based on a decision style, which may be different for the various types of decisions. Decision styles are based on herding behaviour, utility maximisation, and habitual behaviour (Avineri & Prashker 2003).
- Gender (Seneviratne & Morrall 1985*a*), (Verlander & Heydecker 1997). The choice of route appears to be not much different between the two sexes.
- Age (Seneviratne & Morrall 1985*a*), (Verlander & Heydecker 1997). The proportion of persons selecting a route according to a given factor changes marginally between the distinguished age groups.

• Trip characteristics.

- Purpose (Bovy & Stern 1990), (CROW 1998), (Seneviratne & Morrall 1985*a*), (Verlander & Heydecker 1997). The extent to which route attributes play a substantial role in route choice behaviour depends mainly on trip purpose (Bovy & Stern 1990), e.g. scenery is very important for recreational trips, but it plays no role for work-related walking trips.

Cross relations between items of these categories are identified, for example, the importance of the attributes depends on the trip motive of the pedestrian.

Considering the vertical dimension, pedestrians do not only consider walking time (including the delay in front of and on escalators and stairs) and walking distance, but also the effort involved in climbing a grade (with similar travel times, only few pedestrians choose stairs in ascending direction) (Cheung & Lam 1998).

3.2.2 Theory with respect to pedestrian route choice

Route choice is one of the processes that may be described by general choice theory, on which several handbooks have appeared (Bovy & Stern 1990), (Cascetta 2001), (Hensher & Button 2000), (Ortuzar & Willumsen 2001), (Ramming 2002). This section is therefore confined to the definition of some essential terms and a short overview of route choice theories related to pedestrians.

A *route* is described as a chain of consecutive nodes joined by links, connecting trip origin and destination (Bovy & Stern 1990). This definition fits in a discrete network, consisting of links and nodes. Pedestrians, however, are not restricted to a discrete network, but find their routes in a continuous space (Hoogendoorn & Bovy 2004). Routes may have overlap (sharing common links) and may cross each other, meaning that pedestrians from the same origin to the same destination using these routes impede each other.

A (route) *choice situation* refers to a trip from a given origin to a given destination between which multiple route alternatives exist. Three types of choice processes may be distinguished (Bovy & Stern 1990), namely simultaneous choice (choice of entire routes), sequential routes (choice of subroutes at decision points in the network), and hierarchical choice (similar to sequential choice, but choice behaviour depends upon previous choices). Quite distinct from any specification of the choice process is the phenomenon of adaptive route choice (Bovy & Stern 1990), (Stern & Sinuani-Stern 1989), where travellers make choices depending on changing conditions they encounter while they are on their way. A *choice set* is a group of alternatives, out of all possible routes between a given origin and a given destination from which travellers will make their choice.

In the literature, individual route choice is generally considered to follow user-optimality, indicating that each individual is assumed to decide on his own and to optimise his personal satisfaction. Each individual has his own perception of the (objective) situation, on which the pedestrian's personal decision is based. The decision process thus consists of two main parts, that is predicting the formation and composition of individuals' choice sets (choice set formation) and predicting the probability that an alternative belonging to an individuals' choice set will actually be chosen (choice modelling) (Arentze & Timmermans 2004).

Choice sets can be classified from a traveller's or a researcher's perspective and for an individual pedestrian or for a group of pedestrians (Hoogendoorn-Lanser & Van Nes 2004), see figure 3.3.

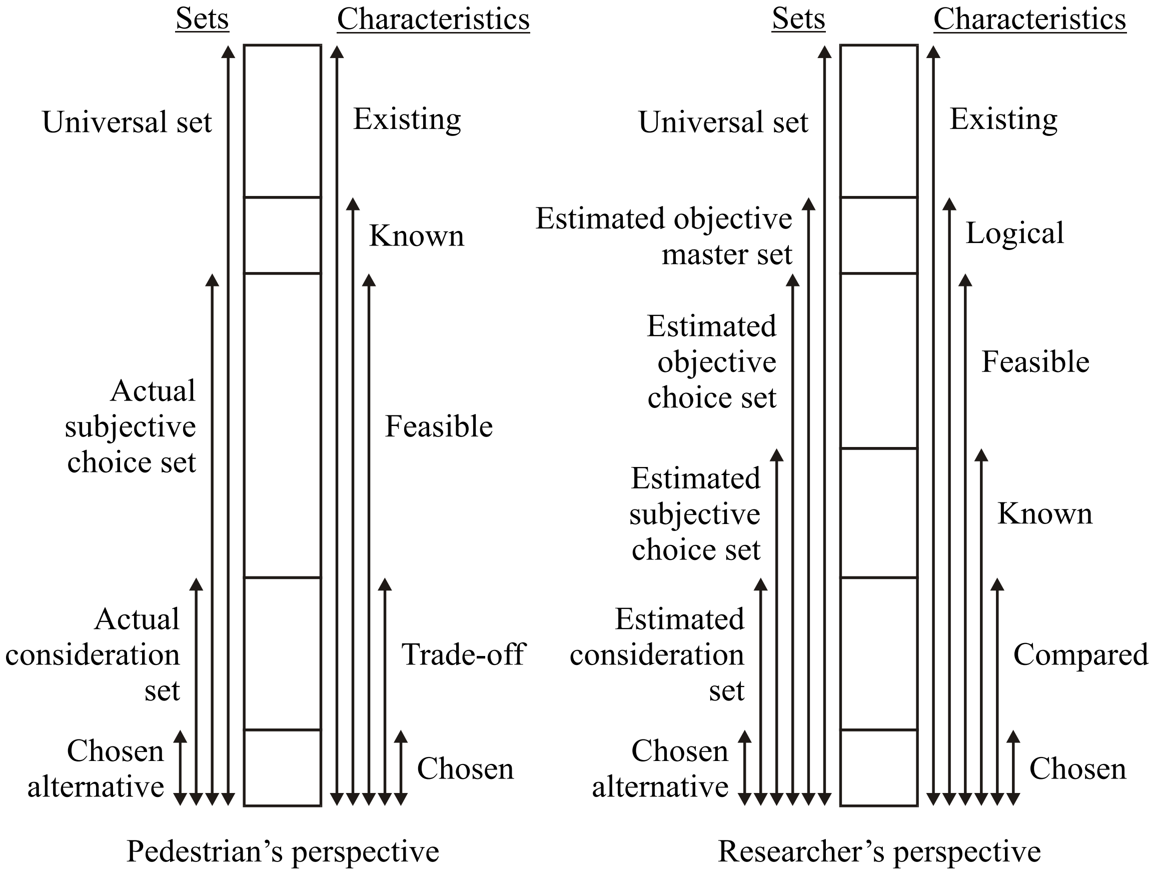


Figure 3.3: Hierarchy among route alternatives from the pedestrian's and the researcher's perspective (Hoogendoorn-Lanser & Van Nes 2004)

Choice set generation methods can be used to approach as closely as possible individuals' choice sets, resulting in estimated objective choice sets, estimated subjective choice sets, and estimated consideration sets (Hoogendoorn-Lanser & Van Nes 2004), (Ramming 2002).

Although route selection strategies (also mentioned as decision styles), like most walking processes, are largely subconscious (Hill 1982), several researchers have formulated theories on this behaviour. These theories differ in behavioural assumptions underlying the various models (normative or 'pedestrian economicus', habitual, knowledge based, or production rules). One of these theories is *normative pedestrian behaviour theory* (Hoogendoorn & Bovy 2004). This theory differs from discrete choice theory in that an infinite number of routes is considered, in which the unit of analysis is not a link, but an infinitesimal part of the route. Also, the randomness in the theory pertains to the uncertainty in the route that can be realised, and finally the theory is designed to describe choice behaviour of individuals and is therefore not directly representative for groups of individuals. Hoogendoorn and Bovy model route and activity location choice simultaneously, where the disutility of a route depends on among other things travel distance or travel time between origin and destination, proximity of obstacles, route directness, level-of-service, and attractiveness.

Distance is not only an important factor on which route choice is based, it also influences the way pedestrians choose their routes. Different types of distance are therefore distinguished in literature. Khisty (1999) distinguishes between ‘perceived’ distance and ‘cognitive’ distance. Perceived distances are based on judgements about the proximity of objects that are seen on site, while cognitive distances (Lang 1987) are gathered from sources, such as sketches and pictures. People are not very accurate in estimating lengths of individual links, but are astonishingly good at judging relative distances between two or more links (Passini 1984), which is another reason to apply route length as decision variable. The literature does not mention notions of ‘actual distance’ and ‘relative times’.

3.2.3 Route choice models

This section describes different methods to generate route choice sets, followed by an overview of choice models used not only for pedestrian route choice, but also for route choice in other transport modes.

Choice set generation

The formation of choice sets can be supported by heuristics or deterministic choice set generation rules, by obtaining information directly from individuals (empirical data collection), or by random choice set generation (Ortuzar & Willumsen 2001). However, misspecification of choice sets seriously degrades the accuracy of models (Swait 2001), (Van der Waerden et al. 2004) and also the specification of choice sets may impact predicted choice probabilities (Ben-Akiva & Boccara 1995), (Chiang et al. 1999), (Roberts & Lattin 1991). Important characteristics of choice sets are size of the set mainly in terms of number of alternatives, composition of the set in terms of joint distribution of attributes and dominance, and spatial structure of the set, for example the degree of mutual overlap and crossing (Van der Waerden et al. 2004).

Table 3.1 shows an overview of methods for generating route choice sets.

Most choice set generation procedures are based on *shortest route* search (Borgers & Timmermans 1986*b*), (Bovy & Stern 1990). Shortest route algorithms happen to be very efficient to determine routes between two given points in networks of some size, whereas also the branch and bound algorithm has been applied (Hoogendoorn-Lanser et al. 2004).

Table 3.1: Methods to generate route choice sets

Type	**Procedure**
shortest routes	Ahuja et al. (1993) Dantzig (1967) Dial (1971) Dijkstra (1959)
k-shortest routes	Azevedo et al. (1993) Cascetta et al. (2002) Chabini & Ganugapati (2001) Phillips & Garcia-Diaz (1981) Verlander & Heydecker (1997) Weidmann (1989) Ziliaskopoulos (1994)
k-shortest with constraints	Van der Zijpp & Fiorenzo-Catalano (2002)
κ-dissimilar routes	Park & Rilett (1997) Scott et al. (1997) Verlander & Heydecker (1997)
combinatorial	Borgers & Timmermans (1986*b*) Arentze & Timmermans (2004)
essentially least cost	Antonisse et al. (1989) Hunt & Kornhauser (1997)
branch-and-bound	Hoogendoorn-Lanser et al. (2004) Friedrich et al. (2001)
labelling	Ben-Akiva et al. (1984)
simulation	Fiorenzo-Catalano et al. (2004) Sheffi & Powell (1982)
capacity restraint vine	Hofmann (2000)

The minimum criterion is mostly related to the traveller's choice criteria, such as minimum time and minimum distance. Using a shortest path algorithm implicitly assumes that the traveller being modelled is aware of all the links (and their costs) used by the algorithm. As the name already indicates the *k-shortest routes* method generates a complete route set of which the k shortest routes are included in the choice set.

Another method of generating choice sets is to identify in turn the routes that differ from the shortest in that they do not contain a certain number of links of it and are the shortest such routes. This is known as the *κ-dissimilar route* strategy, where κ denotes the number of links of the shortest route that were excluded.

Essentially-least-cost routes are indistinguishable due to varying traveller utility functions and inaccuracies implicit in measuring these utility functions. *Combinatorial* algorithms generate all possible routes combined with criteria to exclude unwanted routes.

The most recent developments are described by Fiorenzo-Catalano et al. (2004) and Ramming (2002). In the latter a utility function is used to generate a choice set in combination with *simulation*. For both the variables (perception of the user) and the parameters (personal weight of each variable) of the utility function, a distribution is composed. In a number of iterations simulation is used to calculate route utilities, where the route with the highest utility (or smallest disutility) is added to the choice set. This method is very flexible and the number of variables to be included in the utility function may be varied.

Choice models

Route choice models have been developed to predict flows (of pedestrians or other traffic participants) on links of a transportation network. Most models follow a decision-theoretical approach and are variants of discrete choice utility models. Table 3.2 gives an overview of route choice models. In the sequel, route choice models concerning pedestrians are elaborated upon in more detail.

Borgers & Timmermans (1986*a*) formulate a model for pedestrian route choice within city centres given pedestrian's destination. It is assumed that route choice is primarily influenced by the distance of the alternative links, leading to the following expression for the disutility U of route r:

$$U_r = \alpha L_r + \varepsilon_r \tag{3.1}$$

where L_r indicates the length of route r, α specifies the weight of this attribute, indicating the uncertainty of the model, and ε_r is the random error term.

Cheung & Lam (1998) adopt a logit model to model pedestrian choice between escalators and stairs in a station, in which the utility of an alternative U_r is described by:

$$U_r = V_r + \varepsilon_r \text{ with } V_r = C_r + \beta T_r^{walk} \tag{3.2}$$

Table 3.2: Overview of route choice models

Route choice models	**Type of model**	**Mode**
Ben-Akiva & Lerman (1985)	nested logit	car
Borgers & Timmermans (1986*a*)	multinomial logit	peds
Cascetta et al. (1997)	C-logit	car
Cascetta & Papola (2001)	implicit availability / perception logit	car
Cheung & Lam (1998)	bi-nomial logit	peds
Gipps (1986)	multinomial logit	peds
Hofmann (2000)	multinomial probit	peds
Hoogendoorn & Bovy (2004)	utility maximisation in continuous space	peds
Hoogendoorn-Lanser & Bovy (2004)	hierarchical nested logit	transit
Hoogendoorn-Lanser & Bovy (2004)	multi-nested generalised extreme value	transit
Hughes (2000)	utility maximisation in continuous space	peds
Ramming (2002)	path-size logit	car
Vovsha & Bekhor (1998)	cross-nested logit	car
Walker (2001)	logit kernel	car

where C_r is an alternative specific constant reflecting the relative disutility of facility r (stairs or escalator), T_r is the travel time along route r. Rewriting the resulting logit model leads to the following expressions:

$$P_m = \frac{\exp(V_m)}{\exp(V_m)+\exp(V_s)} = \frac{1}{1+\exp(V_s - V_m)};\ m \in \mathcal{M};\ s \in \mathcal{S} \tag{3.3}$$

$$V_s - V_m = \left\{C_s + \beta T_s^{walk}\right\} - \left\{C_m + \beta T_m^{walk}\right\} \tag{3.4}$$

$$= \alpha + \beta \Delta T;\ a \in \mathcal{A};\ m \in \mathcal{M};\ s \in \mathcal{S} \tag{3.5}$$

where α ($\alpha = C_s - C_m$) and β are parameters to be estimated. ΔT indicates the difference in travel time along the staircase and the escalator ($\Delta T = T_s^{walk} - T_m^{walk}$).

The route generation algorithm of the Gipps model has been based on observations (Ciolek 1978). Depending on the origin and destination and the physical layout, intermediate destinations (nodes) are generated. A pedestrian walks from his origin to his destination moves in straight lines from one node to another, and chooses the next node when he is within a short distance of his immediate destination. The choice is limited to those nodes that are visible from his present position and depends as well on the type of pedestrian making this choice. Gipps (1986) describes a number of algorithms to locate the intermediate destinations based on the physical layout of the facility.

Hofmann (2000) describes the Capacity Restraint Vine, evaluating all possible routes from anywhere to a particular destination, using a multinomial probit model. For route generation, the concept of path progressions has been introduced. A path progression is defined as two connecting network links, both on a possible path towards a particular destination. Let $P_p(a, b, D)$ be the path progression probability of moving from link a to link b to destination D and let $P_r(r, O, D)$ be the route probability for a route r from origin O to destination D then

$$P_r(r, O, D) = \prod_{a,b|a,b \in r,O,D} P_p(a, b, D) \tag{3.6}$$

Route choice is based on the stochastic user equilibrium theory. The decision vine solution is based on Dial (1971), Dijkstra (1959), andVan Vliet (1985).

Hoogendoorn & Bovy (2004) developed a model in which pedestrians schedule their activities, activity areas and the route between the activities simultaneously to maximise the predicted utility of their efforts and walking. The utility reflects a trade-off between the utility of completing an activity and the cost of walking towards the activity areas. These walking costs result from different factors, such as the travel time, discomfort of walking too close to obstacles and walls, and the stimulation of the environment. Uncertainty pertaining to the predictability of the future conditions is included by assuming that the predicted routes are realisations of random processes.

Hughes (2000) states that pedestrians have a common sense of the task (called potential) that they face to reach their common destination such that any two individuals at different locations having he same potential would see no advantage to either in changing places. There is no perceived advantage to a pedestrian of moving along a line of constant potential. Thus the motion of any pedestrian is in the direction perpendicular to the potential, i.e. in the direction for which the direction cosines are

$$\widehat{p}_x = \frac{-(\partial p/\partial x)}{\sqrt{(\partial p/\partial x)^2 + (\partial p/\partial y)^2}} \tag{3.7}$$

$$\widehat{p}_y = \frac{-(\partial p/\partial y)}{\sqrt{(\partial p/\partial x)^2 + (\partial p/\partial y)^2}} \tag{3.8}$$

where p is the potential. This statement is not appropriate to vehicular traffic but appears to be applicable to pedestrian flows where pedestrians can visually assess the situation.

3.2.4 Results for pedestrian route choice modelling

As indicated in the previous section, most route choice models are variants of discrete choice utility models. These models are often used to assess preferences by estimating weight parameters from data.

The probability of a pedestrian route choice model in the vertical dimension in both descending (P_m^{desc}) and ascending (P_m^{asc}) direction are given as follows (Cheung & Lam 1998):

$$P_m^{desc} = \frac{1}{1 + \exp(-3.10 - 0.17\Delta T)}; \; R^2 = 0.84 \tag{3.9}$$

$$P_m^{asc} = \frac{1}{1 + \exp(-5.34 - 0.21\Delta T)}; \; R^2 = 0.87 \tag{3.10}$$

in which ΔT is the difference in travel time between using the escalator or the staircase (in [s], see equation 3.3). The reliability of the estimated parameters is relatively high, due to the presence of only two alternatives. The constants (-3.10 in descending direction and -5.34 in ascending direction) indicate the relative disutility attached to the infrastructure (an escalator appears more comfortable than a staircase when travel times are similar; in descending direction 95.7% of the passengers use the escalator in these conditions, whereas 99.5% of the passengers use the escalator in ascending direction). This pair of formulae also indicates that pedestrians are more sensitive to relative delay on an ascending facility than on a descending facility (lower value of the weight for ΔT). For instance, 85% of pedestrians appears willing to use an escalator when the relative delay equals 7.8 s in the descending direction, but 17.4 s appears acceptable for the ascending direction. This is due to the fact that the effort in walking down a staircase is perceived to be less than that for walking up the staircase. However, these results have been collected in Hong Kong, Asia and it is questionable whether these results are valid for European situations.

Borgers & Timmermans (1986*a*) estimated their route choice model on observations as well, which resulted in the following utility function:

$$U_r = -0.04 L_r + \varepsilon_r \tag{3.11}$$

where L_r indicates the length of route r in metres. 52% of the observed routes have been predicted correctly by the model, which was a satisfactory result given the large number of alternatives.

3.2.5 Conclusions of the state-of-the-art on pedestrian route choice

This section gives the existing knowledge on factors influencing pedestrian route choice behaviour, of which travel time or travel distance appeared most important. However, none of the data with respect to horizontal route choice was collected in a public transport station, indicating that a detailed analysis of route choice factors in a transfer station remains a blank spot (Van de Reijt 2004), which will be dealt with in this research.

Most route choice models described in literature determine complete route alternatives from origin to destination, of which pedestrians will choose one. Consequences of sequential route choice and the influence of the distance between route choice points have not been included in literature. As conditions in transfer stations may change rapidly due to the arrival of trains, sequential route choice will be applied in the simulation tool to develop.

No literature is available on choice sets for pedestrians in public transport stations. However, most pedestrian route choice models are based on shortest route calculations. Therefore, the initial route choice model proposed in this thesis will be based on shortest routes in time. Based on the route choice data collected in transfer stations, we will try to develop an alternative route choice model, which might be included in the simulation tool after completion of this thesis.

Most route choice models use a logit model. Specific utility function specifications for pedestrians in public transport facilities have not been found in literature, except for one source describing a utility function in the vertical dimension. Most route choice models assume linear disutility functions. However, especially for slow traffic modes, this function is not likely to be linear, since when the walking distance surpasses a specific length, pedestrians will probably not choose this route any more. A logit model might be applied as well in the simulation tool, based on the mentioned development of a refined route choice model in transfer stations. However, in first instance an all-or-nothing assignment might by applied.

3.3 Walking behaviour

This section describes empirical data, theories, models, and modelling results with respect to walking behaviour. However, first an overview is given of the process of walking, followed by definitions of frequently used terms describing microscopic and macroscopic walking characteristics.

The process of walking may be described on submicroscopic level as 'leg movement'. This leg movement can be characterised as an oscillating movement, in which the walking speed depends on the own frequency of the leg (about 2 Hz). The walking speed can be increased by a lengthening of the step, an increase of the step frequency, or both (Weidmann 1993).

Now, the main microscopic and macroscopic variables describing pedestrian traffic are defined. Main microscopic variables are trajectories and time headways, whereas main macroscopic variables are flow, density, and speed.

A *trajectory* is a graphical representation of walked path over time. Trajectories provide an intuitive, clear, and complete summary of pedestrian motion in the walking direction of the pedestrian. Since pedestrians have freedom to move in two dimensions in a horizontal area, the graphical representation of pedestrian trajectories in both longitudinal and lateral direction is complicated. Therefore, we use snapshots aggregated over a longer time period (see figure 4.20).

A *time headway* of a pedestrian is defined as the period (usually in seconds) between the passing moments of the preceding pedestrian and the pedestrian considered (see figure 4.21).

The traffic *flow* is the number of pedestrians passing a cross-section of an area in a unit of time (usually per second). The flow may be measured per metre width or for the total width of the cross-section. Flow is usually expressed in P/ m s.

The *density* of a traffic flow is the number of pedestrians present on an area at a given moment. Just like the flow, the density can refer to a total area or a strip of 1 m wide. The customary unit for density is P/m^2.

Speed indicates the mean speed of pedestrians, which may be averaged over time ('local mean speed' of pedestrians passing a cross-section during a certain period of time) or over space ('instantaneous mean speed' of pedestrians that are present on an area at a given moment).

A *cumulative plot* of pedestrians represents the number of pedestrians that has passed a cross section from an arbitrary starting moment (see figure 4.8). Since cumulative plots are very convenient to calculate flows and local mean speeds, they have been used several times in this thesis.

Considering a pedestrian traffic flow in a stationary and homogeneous 'state', the following relation (referred to as the *fundamental relation*) is valid for all types of flows:

$$q = ku \tag{3.12}$$

where q is the flow (in P/ m s), k is the density (in P/ m^2), and u is the average walking speed (in m/ s). The graphical representation of the relations between the macroscopic characteristics of a flow are called 'fundamental diagram(s)'. Three are in use, namely flow - density $q = q(k)$, speed - density $u = u(k)$, and speed - flow $u = u(q)$. These three relations represent the same information so that from one relation the other two may be deduced. Figure 3.4 shows the flow-density relation for pedestrian traffic, in which some special points are indicated.

Special points of the diagram are:

- Free speed u^0. This is the mean speed if $q = 0$ P/ m s and $k = 0$ P/ m^2; it equals the slope of the function $q(k)$ at the origin.
- Capacity q_c. This is the maximal flow, also called critical flow. Due to the relation between density and speed, the maximum flow is not achieved at the maximum walking speed.
- Capacity density or critical density k_c. This is the density if $q = q_c$.
- Capacity speed u_c. This is the mean speed if $q = q_c$.
- Jam density k_j. This is the density if $u = 0$ m/ s and $q = 0$ P/ m s.

The part of $q(k)$ with a constant speed is called the 'stable region'. As soon as speed decreases with increasing density, one enters the 'unstable region'. The region in which densities are greater than the capacity density is called 'congestion region', whereas the region with densities lower than capacity is called 'free flow region'.

Table 3.3 summarises characteristics of three flow conditions, that is unimpeded flow, capacity, and jammed flow, as found by various researchers.

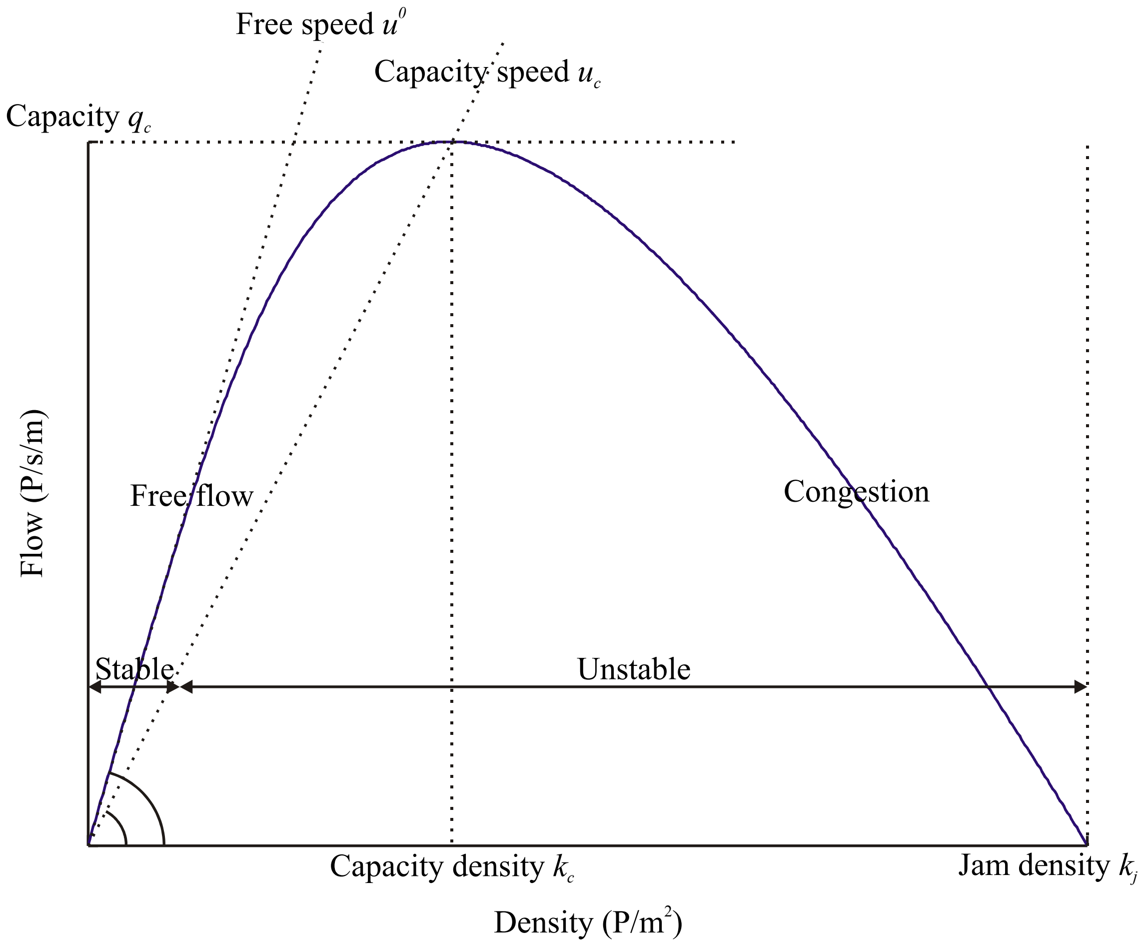


Figure 3.4: Flow-density relation for pedestrian traffic

Table 3.3: Characteristics of unimpeded, capacity, and jammed pedestrian flows derived for level walkways

Source	**Unimpeded**	**Capacity**	**Jammed**
AlGadhi et al. (2001)			$k_j > 7.0$
Fruin (1971*b*)	$k < 0.5$		$k_j > 5.0$
O'Flaherty & Parkinson (1972)	$k < 0.6$	$q_c = 1.29$ $u_c = 0.68$ $k_c = 1.89$	
Pauls (1987)	$k < 0.5$		$k_j = 4.0 - 5.0$
Pushkarev & Zupan (1975*b*)		$q_c = 1.67$ $u_c = 1.11$ $k_c = 1.5$	$k_j = 2.5 - 5.0$
Sarkar & Janardhan (1997)		$q_c = 1.53$ $u_c = 0.74$ $k_c = 2.1$	$k_j > 4.2$
Virkler & Elayadath (1994)		$q_c = 1.03 - 1.2$ $u_c = 0.75 - 0.82$ $k_c = 1.3 - 1.8$	
Weidmann (1993)	$k < 0.5$	$q_c = 1.23$ $u_c = 0.7$ $k_c = 1.75$	$k_j > 5.4$
Units: k [$\mathrm{P/m^2}$]; u [$\mathrm{m/s}$]; q [$\mathrm{P/m\,s}$]			

Jam density appears to be between 4.0 and 5.5 $\mathrm{P/m^2}$, whereas only AlGadhi et al. (2001) show a significantly higher jam density which is inherent to the conditions in which the density has been measured, namely during a yearly stone throwing ritual by pilgrims in Makkah, Saudi Arabia, where pedestrians do not have the intention to walk, but are waiting until it is their turn.

Flows appear to be unimpeded when the density is lower than 0.5 $\mathrm{P/m^2}$.

Capacity flows are found between 1.1 and 1.67 $\mathrm{P/m\,s}$. The range in capacities is due to walking conditions, low capacities are found after a football match, whereas high capacities are found in transfer stations. Observed speeds and densities correspond to the conditions and are similar.

3.3.1 Empirical data

This subsection first gives an overview of empirical data with respect to both macroscopic and microscopic characteristics of pedestrian traffic flows. The first part of this subsection deals with mean speed, flow, and density as macroscopic variables. In the second part conditions influencing the fundamental diagrams are described, such as age, gender, and type of walking infrastructure.

Macroscopic characteristics of traffic flow

Speed Table 3.4 shows an overview of measured average free flow walking speeds in literature.

The speed of individuals appears to follow a normal distribution, with an estimated mean of 1.34 $\mathrm{m/s}$ and a standard deviation of 0.37 $\mathrm{m/s}$, being calculated as a mean of table 3.4 using the co-efficient of variance. Weidmann (1993) also found a mean speed of 1.34 $\mathrm{m/s}$, with speeds varying between 0.97 $\mathrm{m/s}$ and 1.65 $\mathrm{m/s}$ (against 1.08 $\mathrm{m/s}$ and 1.6 $\mathrm{m/s}$ respectively in table 3.4). Under specific circumstances, the normal distribution can have a positive skewness. The median speed, considered to be more representative than the average speed, was 1.2 $\mathrm{m/s}$ (Fruin 1971*b*).

As density increases, various factors influencing free walking speed have a much smaller effect on walking speeds of individual pedestrians (Mitchell & Smith 2001). Also, the variability of the walking speeds appears to decrease.

Flow In multi-directional flows, the flow is two-dimensional, that is $\vec{q} = (q_1, q_2)$ describes the flow q_1 in the longitudinal direction and flow q_2 in the lateral direction. The respective elements of the flow vector can be determined by considering lines perpendicular to the direction of the considered element of the flow vector.

Table 3.4: Observed walking speeds in uncongested corridors

Source	Mean speed (m/s)	Standard deviation (m/s)	Location
CROW (1998)	1.4		the Netherlands
Daly et al. (1991)	1.47		United Kingdom
FHWA (1988)	1.2		United States
Fruin (1971*b*)	1.4	0.15	United States
Hankin & Wright (1958)	1.6		United Kingdom
Henderson (1971)	1.44	0.23	Australia
Hoel (1968)	1.50	0.20	United States
Institute of Transportation Engineers (1969)	1.2		United States
Knoflacher (1995)	1.45		Austria
Koushki (1988)	1.08		Saudi-Arabia
Lam et al. (1995)	1.19	0.26	Hong Kong
Morrall et al. (1991)	1.25		Sri Lanka
	1.4		Canada
Navin & Wheeler (1969)	1.32		United States
O'Flaherty & Parkinson (1972)	1.32	1.0	United Kingdom
Older (1968)	1.30	0.3	United Kingdom
Pauls (1987)	1.25		United States
Roddin (1981)	1.6		United States
Sarkar & Janardhan (1997)	1.46	0.63	India
Sleight (1972)	1.37		United States
Tanariboon et al. (1986)	1.23		Singapore
Tanariboon & Guyano (1991)	1.22		Thailand
Tregenza (1976)	1.31	0.30	United Kingdom
Virkler & Elayadath (1994)	1.22		United States
Young (1999)	1.38	0.27	United States
Estimated overall average	1.34	0.37	

Density Pedestrians can choose their preferred walking speed at low pedestrian volume, but both flow and speeds decline under crowded conditions (BGC 1998). Pedestrians are willing to accept higher densities than they normally would if this leads to a positive incentive. Muramatsu et al. (1999) found that the jamming density does not depend on the size of the area in which the congestion occurs.

The minimum surface of an average pedestrians (without bulky clothes and baggage) is about 0.085 m^2. As pedestrian forms are taken as ellipses, they can not fill completely a specific area, which leads to a pedestrian surface of 0.11 m^2, which is lower than the observed value of 0.15 m^2, leading to a maximum density of 6.7 P/m^2. In practice, a density between 2.0 and 2.9 P/m^2 is achieved for waiting pedestrians (Weidmann 1993).

Pushkarev & Zupan (1975*a*) noted that pedestrians prefer a body buffer zone space of 0.27-0.84 m^2, where also space needed to make a step is included. Virkler & Elayadath (1994) report an optimum density of 1.3-1.8 P/m^2. Physical contacts may be avoided at densities of 3.0-3.5 P/m^2 (Weidmann 1993).

Microscopic characteristics

Basic traffic characteristics depend on individual pedestrians and external conditions. Figure 3.5 describes the influences of these factors on the fundamental flow-density diagram with arrows. The considered aspects are age, culture, gender, shy away distance, temperature, travel purpose, type of infrastructure, and walking direction. Sources used are (Carstens & Ring 1970), (Fruin 1971*b*), (Helbing 1997), (Knoflacher 1987), (Knoflacher 1995), (Molen et al. 1972), (Older 1968), (Polus et al. 1983), (Seneviratne & Morrall 1985*b*), (Tregenza 1976), (Weidmann 1993), (Willis et al. 2000). In the following, each of the factors is discussed in more detail.

Age Age is often used to indicate speeds of pedestrians. However, several studies indicate that not age, but factors related to age are determinant, such as:

- Fitness level (Cunningham et al. 1986), (Imms & Edholm 1981); walking speed decreases with decreasing mobility level.
- Cautiousness (Wilson & Grayson 1980); walking speed decreases with increasing cautiousness
- Other problems (Coffin & Morrall 1992); the more problems, the more walking speed decreases.

One problem concerns the measurability of the characteristics, that is age may be observed relatively easy, whereas fitness level or cautiousness can not be observed directly. Tendency is that people live longer these days, so more and more elderly pedestrians are part of daily life, including walking (Weidmann 1993). Especially in the first 20 years,

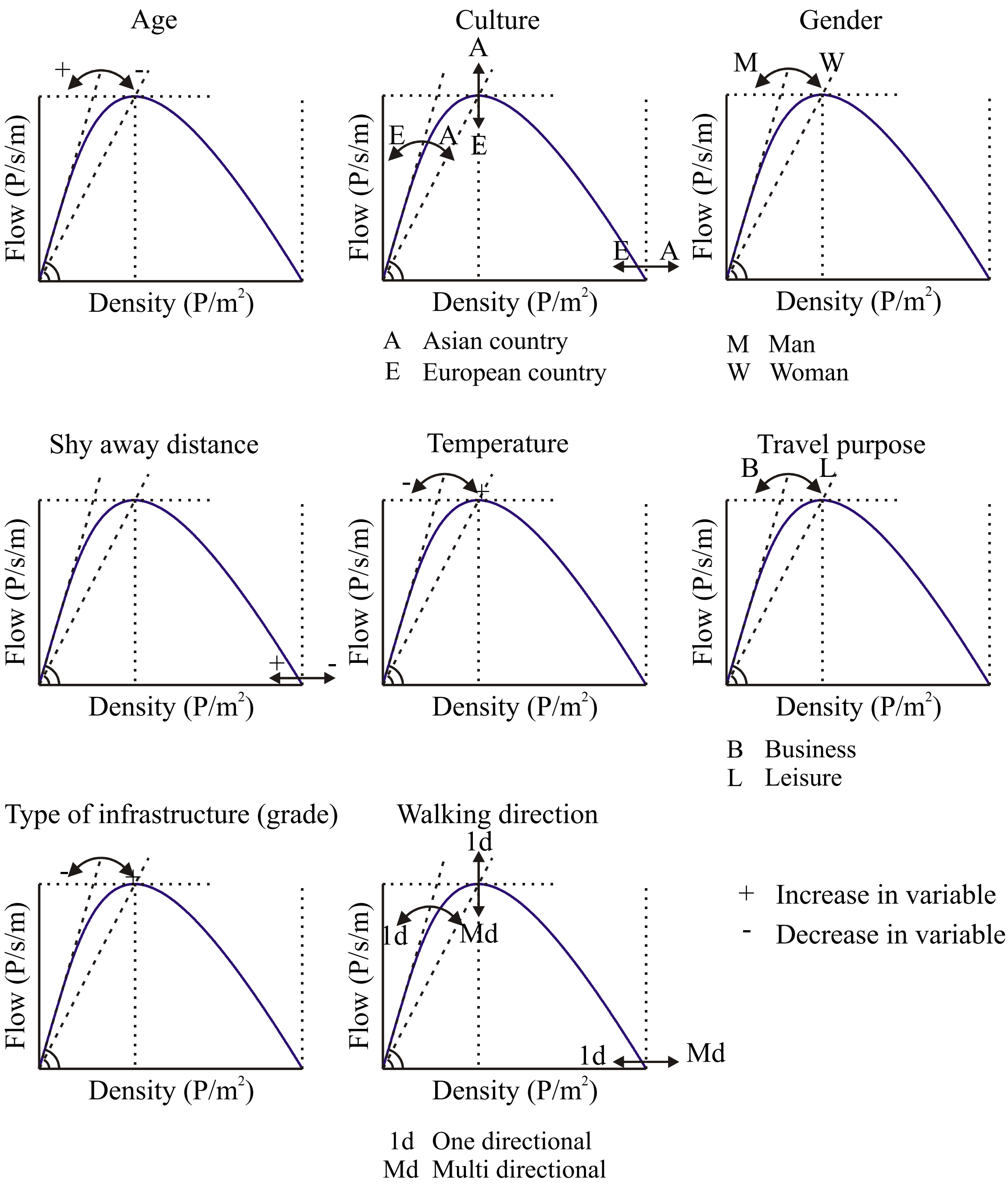


Figure 3.5: Influencing of individual pedestrian characteristics and external conditions on the fundamental diagram, based on various sources

the physical abilities of a person increase rapidly, namely from 40% to 100% of the final abilities (Weidmann 1993).

The walking speed for the 18 to 60 age group is significantly higher than that of the over 60 age group (Bowman & Vecellio 1984). Several studies (Coffin & Morrall 1992), (Dahlstedt undated), (Fruin 1971*b*), (ITE Committee 4A-6 undated), (Tanariboon et al. 1986), (Wilson & Grayson 1980) report speeds between 0.6 and 1.2 m/ s, with an average of 1.06 m/ s and a larger variance than for adults. Tanariboon et al. (Tanariboon et al. 1986) found that young pedestrians (secondary school children) had a mean walking speed comparable with the adult's speed. However, children (age $<$12 years) have a much smaller walking speed (Knoflacher 1987), (Weidmann 1993).

Cultural and racial differences Most studies have been performed in Northern America, Europe and Asian countries. Walking behaviour in Northern America and Europe appears to be similar, whereas walking behaviour in the Asian countries is significantly deviant. This is mainly caused by the body buffer zone space, including pedestrian size (Asian pedestrians are much smaller than in western countries) and culture (Asian pedestrians maintain smaller inter-pedestrian distances) (Tanariboon et al. 1986).

Table 3.4 shows the speeds found in different studies, including the study location. From this table, average speeds are determined, leading to an average speed in European studies of 1.41 m/ s, 1.35 m/ s in studies in the United States, 1.44 m/ s in an Australian study and in Asian studies 1.24 m/ s.

Maximum flow rates in Asian countries (Lam et al. 1995), (Sarkar & Janardhan 1997), (Tanariboon et al. 1986) vary between 1.48 P/ m s and 1.53 P/ m s. These values clearly exceed those found for American and European facilities (capacity flows range between 1.0 and 1.29 P/ m s (O'Flaherty & Parkinson 1972), (Virkler & Elayadath 1994), (Weidmann 1993)), caused by a smaller Asian body buffer zone space (Tanariboon & Guyano 1989), but this is partly undone by the lower walking speeds.

Gender Men's walking speed is about 10.9% higher than the walking speed of women. Weidmann (1993) found a mean walking speed of 1.41 m/ s for men and 1.27 m/ s for women, whereas Hoel (1968) observed a mean speed for men of 1.55 m/ s and for women of 1.45 m/ s in the Central Business District of Pittsburgh (United States). The fact that Hoel found higher speeds than Weidmann may be caused by the different trip purposes of the pedestrians, e.g. commuters versus mixed flows. The walking speed difference between men and women may be the result of the physical characteristics of men and women, which may result in larger step lengths and higher step frequencies for men.

No literature is available on walking speeds for pedestrian groups, i.e. when men and women walk together.

Shy away distance Pedestrians keep a minimum distance to walls (so-called shy away distance), depending on wall condition and freedom of movement of pedestrians. Table 3.5 shows the varying shy away distances as found in the literature. This shy away distance has to be taken into account in determining the density.

Table 3.5: Shy away distances of pedestrians (in cm)

Criterion	Distance	Source
Concrete walls	30-45	CROW (1998)
	45	De Neufville & Grillot (1982)
	15	Pauls (1987)
	40	Van Soeren (1996)
	25	Weidmann (1993)
Metal walls	20	Weidmann (1993)
Obstacles	40	Van Soeren (1996)
	10	Weidmann (1993)
Opposite flows	60	De Neufville & Grillot (1982)
Pedestrians	27.5	Knoflacher (1987)
Platform edges	80	Van Soeren (1996)

Temperature Temperature influences the pedestrian speed significantly. At 25°C the speed is only 92% of the average speed, whereas the speed increases to about 109% at a temperature of 0°C (Weidmann 1993). According to Weidmann, the average speed is 100% at a temperature of 15°C, which is similar to the yearly average temperature in the Netherlands. Influence of temperature on walking speeds are therefore not into account in this research any further.

Travel purpose The walking speed also depends on the travel purpose of the pedestrian. Pedestrians travelling for business have the highest walking speed (1.45-1.61 m/ s), followed by commuters (1.34-1.49 m/ s), shoppers (1.04-1.16 m/ s) and pedestrians walking in leisure (0.99-1.10 m/ s). A free walking speed for commuters of 1.5 m/ s and for students of 1.75 m/ s has been found in Roddin (1981), whereas actual walking speeds in a study described in Imms & Edholm (1981) range from 0.40 m/ s for housebound subjects to 0.93 m/ s for subjects with unlimited outdoor activity. Testing was however conducted indoors, which may have influenced walking speeds.

In pedestrian flows with different travel purposes, the variation in walking speeds increases (up to 0.5 - 1.0 m/ s (O'Flaherty & Parkinson 1972)).

Type of infrastructure Different types of walking infrastructure may be distinguished. In a public transport facility, the apparent types of infrastructure are walkways, concourses, hallways, stairs, escalators, doors and turnstiles (Van der Spek 2003). In the urban environment (also the forecourt of a station), intersections and crossings appear. Physical changes in streets, highways, and vehicles may alter conditions for pedestrians, but walking speeds remain relatively the same (Institute of Transportation Engineers 1969). Studies of street crossing speeds display slightly different results, because oncoming vehicles and impending signal change prompt non-disabled pedestrians to move faster. Pedestrians are more sensitive to relative delays when using the vertical pedestrian facilities in the descending direction than in the ascending direction, due to the fact that the effort in walking downwards is perceived to be less than that for walking upwards (Cheung & Lam 1998).

Free flow speeds for the walkways leading to escalators and stairs are smaller than those on general walkways. This can be explained by the fact that pedestrians normally decelerate when walking towards the approach to an escalator or stairs (Cheung & Lam 1998). The length of stairs significantly influences the walking speed (the longer the staircase, the lower the walking speed).

The horizontal speed on slopes depends heavily on the gradient and varies between 1.19 m/s and 1.66 m/s in ascending direction (Institute of Transportation Engineers 1969). At declines, the horizontal speed increases slightly to 1.41 - 1.51 m/s (Institute of Transportation Engineers 1969). On stairs, ascending speeds are measured between 0.61 m/s and 0.9 m/s (Pauls 1987), (Weidmann 1993), but for walking downwards on stairs, the speed decreases to 0.70 m/s (Weidmann 1993). Ladetto et al. (2000) found that pedestrians only slowed down (-15.3%) in very steep uphill sections ($>$ 10% incline).

Surprisingly, several studies show that capacity does not differ much between walking down and up stairs (Løvas 1994), although the Institute of Traffic Engineers reports a capacity of 0.91 P/ms in ascending direction and 1.07 P/ms in descending direction (Institute of Transportation Engineers 1969), which are somewhat higher than the capacities observed by Fruin (1971*b*) (0.85 P/ms respectively 0.98 P/ms).

Speeds on stairs do not decrease as fast as on level infrastructure beneath densities of 1.0 P/m^2 (Weidmann 1993). The optimal pedestrian density on stairs is, both in upwards as in downwards direction, 2.2 P/m^2. The density may not be higher than 3.0 P/m^2 (Predtetschenski & Milinski 1971).

In panic situations the flow through a door is not regular, due to the formation of arches, when pedestrians block each other and thus prevent anyone passing through the door (Peschl 1971). In passing a door, the probability for arches to occur is always present, but depends on the width of the door and the measure of panic. Capacities have been measured for different types of standard turnstiles and vary between 0.17 P/s (for a coin operated turnstile) and 1.0 P/s for a turnstile with free admission.

Walking direction Unidirectional flow is associated with a lower collision probability. Nevertheless, empirical results show any important difference between the flow characteristics of these types of flows (Fruin 1971*b*).

Two-directional flows cause a decrease of pedestrian flow (4% in a direction distribution of 50%/50% and 14.5% at 90%/10%) (Navin & Wheeler 1969) (Weidmann 1993). The smaller flow causes a more than proportional spatial use (BGC 1998). For a given density, as counterflows increase, capacity losses decrease and total flow therefore increases (Navin & Wheeler 1969).

A crossflow is a pedestrian flow that is roughly perpendicular to and crosses another pedestrian stream. In general, one refers to the smaller of the two flows as the crossflow. A major flow does not undergo a significant change up to a pedestrian density of about 0.8 to 1.0 $\mathrm{P/m^2}$ (Khisty 1982). The minor flow begins to change when densities approach 0.7 to 0.8 $\mathrm{P/m^2}$. Minor flow speeds appear to be higher than major flow speeds because pedestrians in the former group must act aggressively to cross the major flow. The two flows hardly mix, for members of the minor flow simply wait for gaps in the major flow and then accelerate quickly through the heavier stream. Finally, when major flow levels reach 1.0 $\mathrm{P/m^2}$, the minor flow reduces dramatically and queues are formed.

In terminal areas without cross-directional flow, free-flow speeds are generally achieved when the density is less than 0.43 $\mathrm{P/m^2}$. When cross-directional flow or standing pedestrians exist, the impedance to free-flow walking increases, leading to a density less than 0.31 $\mathrm{P/m^2}$ (Fruin 1971*b*).

3.3.2 Theory of pedestrian walking behaviour

Many studies about walking speed have considered the density to be the only significant factor influencing the walking speed of an individual pedestrian (Løvas 1994). Most of these studies reported a linear relation between speed and density, according to the following form:

$$u = u^0 - \alpha k; \;\; \alpha > 0 \tag{3.13}$$

where u^0 represents the theoretical speed attained by a traffic stream under conditions of completely free flow (free speed). The linearity of the speed-density relation has long been questioned for both vehicular (TRB 1965) and pedestrian flows (Pushkarev & Zupan 1975*b*). Theory behind this form of the speed-density relation is that pedestrians have to shorten their steps when they have only few space available. This leads to a lower walking speed (speed is a function of step length and step frequency). Also, swaying movements, indicating occupied area in lateral direction, reduce at lower speeds.

Hughes (2000) argues that despite popular belief the motion of a crowd is governed by well-defined rules of behaviour. These rules imply a set of coupled, non-linear, partial differential equations for the density, in other words the ‘conservation of pedestrians’, and velocity potential for each type of pedestrian in the crowd. As may be expected, the solution of these equations differs in free flow regime and in congestion regime for different space regions with the possibility of a shock wave separating the regions. Less predictable is the remarkable finding that these coupled, non-linear, time dependent equations are conformably mappable, which enables solutions to be obtained easily for both free and congested flows.

To determine the capacity of an escalator C_a, Grabe & Meyer (1970) suggested the following relation:

$$C_a = \frac{N^{st} \cdot u_a}{w^m}; \ a \in \mathcal{M} \tag{3.14}$$

where N^{st} indicates the number of pedestrians per step, u_a the speed of the escalator a (in m/s) and w^m the depth of the escalator steps (in cm). This relation does not take into account the influence of pedestrians walking on the escalator.

The speed/velocity distribution function of pedestrian flows may also be described with Maxwell-Boltzman theory, applied in the gaseous phase (Henderson 1971). Good agreement is obtained, except for a significant deviation near the frequency mode of the distribution, due to gender inhomogeneity (see section 3.3.4).

Helbing & Molnar (1997) have studied pedestrian crowds as self-organised phenomena. The motion of the organisms is usually controlled by interactions with other organisms in their neighbourhood, while randomness plays an important role as well (Vicsek et al. 1999). This is one of the explanations of phenomena dedicated to pedestrian traffic, such as lane formation.

3.3.3 Models describing pedestrian walking behaviour

This subsection starts with a discussion of relationships found with respect to the fundamental diagram. Then, some details are given on existing pedestrian (simulation) models, in which the need for a new specific simulation tool to model pedestrians in transfer stations is expressed.

Fundamental diagram

An overview of empirical relations established between speed, flow, and density are given in table 3.6 and figure 3.6. Most of the models use a linear speed-density relation, whereas Weidmann (1993) uses a double S-bended curve especially derived for pedestrian traffic. Virkler & Elayadath (1994) adopt a two regime model. Free walking speeds vary between 1.23 m/s and 1.5 m/s, while Virkler & Elayadath (1994) find much lower walking speeds. This is due to the external conditions: they observed a location after a football match, where pedestrians did not have an incentive to hurry, whereas Sarkar & Janardhan (1997) and Fruin (1971*a*) did observations in transportation terminals.The jam density measured by Older (1968) and Sarkar & Janardhan (1997) is significantly lower than the other jam densities, whereas the relation estimated by Virkler & Elayadath (1994) implies a jam density of infinity. In the middle of the density range (1.5 P/m^2 - 3 P/m^2) there is not much difference between the relations.

AlGadhi et al. (2001) and Cheah (1990) provide exponential walking speed models for bi- and multi-directional flows, not included in table 3.6.

An overview of some of the aforementioned speed-density relations is shown in figure 3.6. Exceptionally, not the estimated Fruin-relation has been depicted, but his observed data.

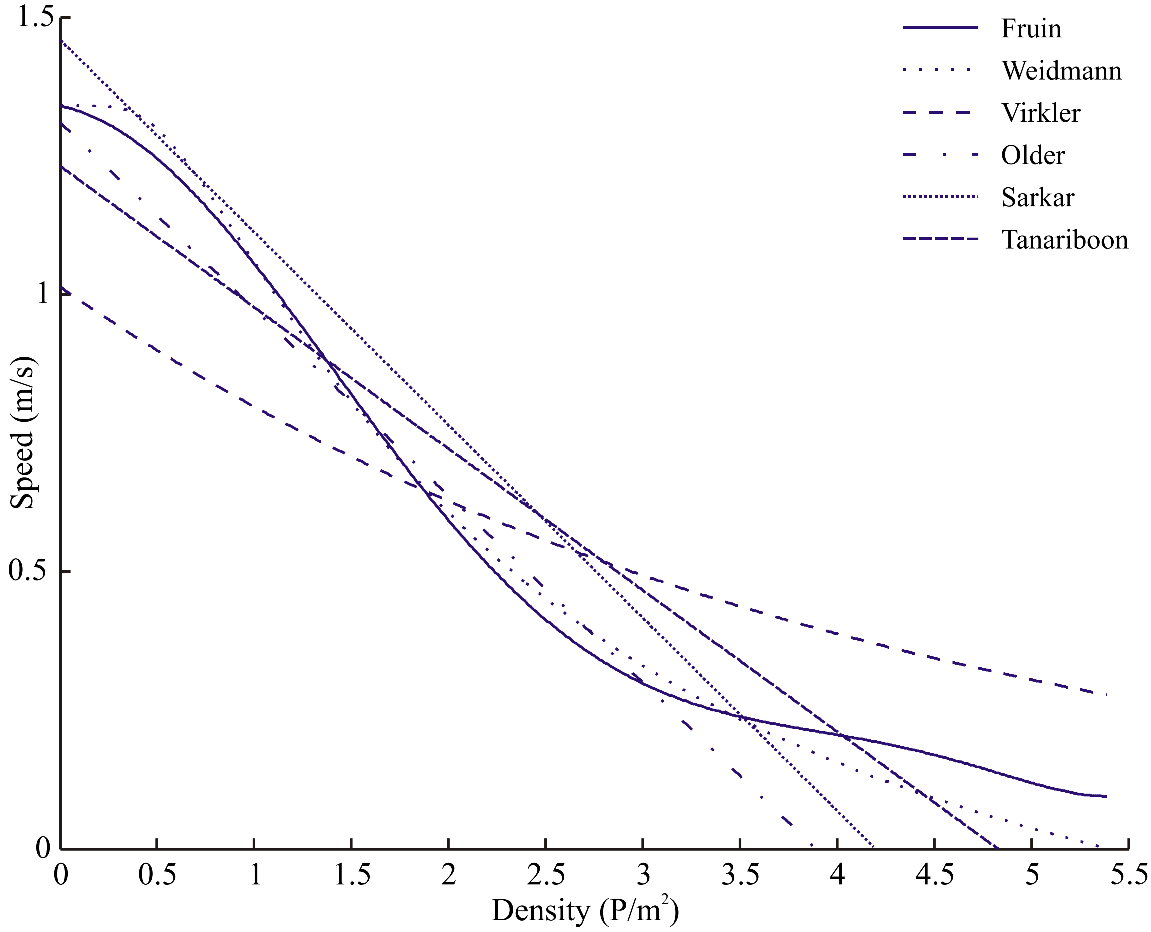


Figure 3.6: Speed-density relations from literature

Traffic flow (simulation) models

Traffic flow models may be categorised according to the following properties (based on Helbing (1997), Hoogendoorn & Bovy (2001), Klüpfel (2003), Teknomo (2002)):

- Type of modelling approach. Each of these models is discussed in more detail in the following.
  - Cellular Automata and particle hopping models.
  - Microscopic simulation models.

Table 3.6: Overview of proposed relations between speed, flow, and density for one-directional pedestrian traffic flows

Source	**Relation**
Fruin (1971*a*) Peak-hour flows at large commuter bus terminal	$u = 1.43 - 0.35k$ $q = 1.43k - 0.35k^2$ $q = 4.08u - 2.86u^2$
Lam et al. (1995) Indoor walkway in Hong Kong	$u = 1.29 - 0.36k$ $q = 1.29k - 0.36k^2$ $q = 3.58u - 2.78u^2$
Navin & Wheeler (1969) University of Missouri campus and Stephen's college	$u = 2.13 - 0.79k$ $q = 2.13k - 0.79k^2$ $q = 2.70u - 1.27u^2$
Older (1968) Shopping streets	$u = 1.31 - 0.34k$ $q = 1.32k - 0.34k^2$ $q = 3.85u - 2.94u^2$
Pauls (1987) Stairs in total evacuations of tall office buildings	$u = 1.26 - 0.33k$ $q = 1.26k - 0.33k^2$ $q = 3.82u - 3.03u^2$
Polus et al. (1983) Sidewalks in central business district Haifa, Israel	$u = 1.31 - 0.27k$ $q = 1.31k - 0.27k^2$ $q = 4.94u - 3.76u^2$
Sarkar & Janardhan (1997) Calcutta Metropolitan transfer area	$u = 1.46 - 0.35k$ $q = 1.46k - 0.35k^2$ $q = 4.17u - 2.86u^2$
Tanariboon et al. (1986) Singapore	$u = 1.23 - 0.26k$ $q = 1.23k - 0.26k^2$ $q = 4.73u - 3.85u^2$
Virkler & Elayadath (1994) After University of Missouri football games	$k < 1.07\ \mathrm{P/m^2}$ $\quad$ $k > 1.07\ \mathrm{P/m^2}$ $u = 1.01 \exp\left(\frac{-k}{4.17}\right)$ $\quad$ $u = 0.61 \ln\left(\frac{4.32}{k}\right)$ $q = 4.17v \ln\left(\frac{1.01}{u}\right)$ $\quad$ $q = 4.32v \exp\left(\frac{-u}{0.61}\right)$ $q = 1.01k \exp\left(\frac{-k}{4.17}\right)$ $\quad$ $q = 0.61k \ln\left(\frac{4.32}{k}\right)$
Weidmann (1993) Kladek-formula with double S-form	$u(k) = 1.34\left[1 - \exp\left(-1.913\left(\frac{1}{k} - \frac{1}{k_{jam}}\right)\right)\right]$
Units: k [$\mathrm{P/m^2}$]; u [$\mathrm{m/s}$]; q [$\mathrm{P/m\,s}$]	

  - Queuing models.
  - Gas-kinetic models.
  - Continuum models.

- Traffic representation. Traffic may be represented by individual pedestrians or by aggregate traffic flow.

- Type of behavioural rules. The type of behavioural rules is independent of the traffic representation, which is different from what is assumed in the usual division into microscopic, mesoscopic and macroscopic models (Bourrel & Lesort 2003). Behavioural rules may be either individual or collective.

- Scale of the independent variables. A natural classification is the time-scale, of which two types are distinguished, namely continuous and discrete. Other characteristics may also be described by either continuous or discrete variables (e.g. position, velocity, and desired velocity). Mixed models have also been proposed.

- Uncertainty in the process. In this respect, deterministic and stochastic models are distinguished. The former models have no random variables, implying that all actors in the model are defined by exact relationships. Stochastic models incorporate processes that include random variables.

- Operationalisation. With respect to the operationalisation criterion, models can be operationalised either as analytical solutions of sets of equations or as a simulation model.

- Area of application. Application areas are for example urban environment, general or stations.

Table 3.7 gives an overview of existing pedestrian walking models.

Cellular Automata and particle hopping models Cellular automata (CA) are simulation models in which both time and space are 'coarse grained', that is, discrete (Wolfram 1986). CA rules can be programmed so that they perform particle transport, enabling individual particles to be followed through the system. When one relaxes the requirement of the update to be parallel, one can still have particle hopping models, but they are no longer CA (Nagel 1998). From a theoretical perspective these particle hopping models can generate the same range of phenomena that the corresponding fluid-dynamical models generate, with the added advantage that one has access to individual particles. This implies that in general very simple microscopic models (not necessarily restricted to cells) can be powerful and may turn out to be sufficient for many large-scale questions. CA models aim to combine advantages of complex micro-simulation models, while remaining computationally efficient and are thus able to simulate large networks with large pedestrian flows. However, the behavioural rules of the CA models lack intuitive appeal

Table 3.7: Overview of published pedestrian walking models

Name of the model and source	type	repr.	rules	scale	rc	act	area
Aeneas (Petersen et al. (2003))	mi	pe	in	di	-	-	ev
AlGadhi et al. (2001)	mi	fl	col	di	0	0	de
Amanda (Dijkstra et al. (2002))	ca	pe	in	di	+	+	ue
Blue & Adler (2000)	ca	pe	in	di	-	-	ge
Burstedde et al. (2001)	ca	pe	in	di	-	-	ge
Di Gangi et al. (2003)	qu	fl	col	di	+	-	ev
Gordge & Veldsman (1998)	mi	fl	col	di	+	+	st
Helbing (1992)	gk	fl	in	con	-	-	ge
Helbing & Molnar (1995)	mi	pe	in	con	0	-	ge
Jiang (1999)	mi	pe	in	di	+	+	ur
Legion (Still (2000))	mi	pe	in	con	-	+	ge
Løvas (1994)	qu	pe	col	di	+	-	ge
Mipsim (Hoogendoorn & Bovy (2000))	gk	fl	in	di	-	-	ge
Nomad (Hoogendoorn & Bovy (2004))	mi	pe	in	con	++	+	ge
Paxport (Birchall et al. (1994))	co	fl	col	di	0	+	ai
Pedflow (Willis et al. (2001))	mi	pe	in	di	+	-	ur
PedGo (Klüpfel & Meyer-König (2003))	ca	pe	in	di	0	-	ge
Pedroute (Maw & Dix (1990))	co	fl	col	di	0	-	st
Penn (2003)	mi	pe	in	con	+	-	ge
Steps	mi	pe	in	con	+	+	ge
Streets (Schelhorn et al. (1999))	mi	pe	in	di	+	+	ur
Tajima & Nagatani (2001)	ca	pe	in	di	-	-	ge
Teknomo (2002)	mi	pe	in	con	-	-	ge
Yuhaski & Smith (1989)	qu	pe	col	di	-	-	ge

Type of model (type): **C**ellular **A**utomata, **mi**cro simulation, **qu**euing, **g**as **k**inetic, **co**ntinuum
Representation (repr.): aggregate **fl**ow, individual **pe**destrian
Type of behavioural rules (rules): **col**lective, **in**dividual
Scale: **con**tinuous, **di**screte
Route choice (rc): from non-existing to detailed
Activity performance (ac)
Application area (area): **st**ation, **ai**rport, **bu**ilding, **ur**ban, **ge**neral, **de**dicated, **ev**acuation

and their exact mechanisms are not easily interpretable (Hoogendoorn & Bovy 2001). The challenge of CA modelling therefore is to find the set of rules that would validly generate these seemingly chaotic emergent patterns in pedestrian movement (Dijkstra et al. 2002).

CA models describe the infrastructure as a lattice of cells of equal size. A CA model describes in a discrete way the movements of pedestrians from cell to cell. The size of the cells are chosen such that a pedestrian walking with a velocity equal to one moves to the next downstream cell during one time step. Given, at time t, configuration $C(t)$ of N particles on a lattice of size L. Each particle will be moved forward if, in the configuration $C(t)$, the site ahead is empty. Instead of picking one particle, moving it, picking the next particle, moving it, and so forth, all particles are treated simultaneously or in parallel. Let $v(i,t)$ be the number of sites particle number i has been moved in the last time step. The update now consists of two steps (Nagel 1998):

1. Velocity update and lane changing step. For each particle, find gap equals the number of empty sites ahead. The determination of the velocity can be either deterministic or stochastic (Brilon & Wu 1998).

2. Movement step. Move each particle according to its velocity.

A number of Cellular Automata models have been developed for pedestrian flows, each of which improves the original CA model (Blue & Adler 1998), (Blue & Adler 1999), (Blue & Adler 2000), (Blue & Adler 2001), (Burstedde, Klauck, Schadschneider & Zittartz 2001), (Burstedde, Kirchner, Klauck, Schadschneider & Zittartz 2001), (Dijkstra et al. 2001), (Dijkstra et al. 2002), (Fukui & Ishibashi 1999*b*), (Fukui & Ishibashi 1999*a*), (Kirchner et al. 2003), (Klüpfel & Meyer-König 2003), (Schadschneider 2001).

Microscopic simulation models The availability of fast computers has resulted in an increasing interest in complex micro-simulation models (Hoogendoorn 1999). These models distinguish and trace the time-space behaviour of individual pedestrians. Pedestrian behaviour is generally described by a set of rules defining pedestrian behaviour in specific situations on specific aspects (such as route choice and walking). From pedestrian behaviour and characteristics, position, speed, and walking direction of the pedestrian are recalculated for each time step.

A large number of microscopic simulation models have been developed, examples of which are Legion (Still 2000), Nomad (Hoogendoorn & Bovy 2004), Pedflow (Willis et al. 2001), the social forces model (Helbing & Molnar 1995), and Streets (Schelhorn et al. 1999).

Queuing models Queuing models describe how pedestrians move from one node of the network (mostly a room) to another (Helbing 1997), where each pedestrian is treated as a separate flow object, interacting with the other objects (Løvas 1994). Random waiting times are incurred on the network links (generally doors), due to queues building up when pedestrian traffic demand is larger than the door capacity.

Queuing models are based on the following assumptions (Løvas 1994):

- Any pedestrian facility can be modelled as a network of walkway sections.
- Pedestrian flow in this network can be modelled as a queuing network process, where each pedestrian is treated as a separate flow object, interacting with the other objects.

These models have been used mostly to describe pedestrian evacuation behaviour from buildings (Løvas 1994), (Yuhaski & Smith 1989).

Gas-kinetic flow models Instead of describing the traffic dynamics of individual pedestrians, gas-kinetic traffic flow models describe the dynamics of the velocity distribution functions of pedestrians in the traffic flow. Gas-kinetic models describe the dynamics of the reduced phase-space density (Hoogendoorn 1999), the concept of which is borrowed from statistical physics. The phase-space density can be considered as a mesoscopic generalisation of the macroscopic traffic density. The reduce phase-space density reflects the velocity distribution function of a single-vehicle. Dynamic changes of the reduced phase-space density are caused by the following processes (Prigogine & Herman 1971):

- Convection. Pedestrians with a specific velocity flowing out of the considered roadway segment cause changes in the reduced phase-space density.
- Acceleration towards the desired velocity. Pedestrians not walking at their desired velocity will accelerate if possible.
- Deceleration due to interactions between pedestrians. Pedestrians that interact with slower pedestrians will need to slow down or change the angle of movement in order to pass.

More interactions may be defined and also reactions due to conditions on the walkway may be defined, which leads to a probably more accurate, but also more complex model. The gas-kinetic model formulation is the basis for different approaches. Helbing (1992) uses the momentum method to derive macroscopic expressions for the speed, flow, and density, whereas Hoogendoorn (1999) uses a particle discretisation to model individual pedestrians.

According to Kerridge et al. (2001) such models are too limited when trying to simulate the microscopic effect of infrastructural changes resulting from geometric modifications to the pedestrian space, especially when there is conflicted flow.

Continuum macroscopic models Macroscopic traffic flow models assume that the aggregate behaviour of drivers depends on the traffic conditions in the drivers' direct environments (Hoogendoorn 1999). That is, they deal with traffic flow in terms of aggregate variables. Usually, the models are derived from the analogy between vehicular flow and flow of continuous media, yielding flow models with a limited number of equations that are relatively easy to handle. Continuum macroscopic flow model describe the dynamics of macroscopic variables (e.g. density, speed, and flow) using partial differential equations. The independent variables of a continuous macroscopic flow model are location and time instant.

Conclusions

Table 3.7 shows an overview of pedestrian models. In order to model pedestrian behaviour in public transport facilities properly, processes such as walking, route choice, performing activities, and boarding and alighting have to be included in the tool (see chapter 2). Since most of the mentioned models do not include all these processes, the application areas of these models are different. Table 3.7 shows that only the model of Gordge & Veldsman (1998) as well as Pedroute (Maw & Dix 1990) consider these processes. Pedroute seemed the most promising model of these, also due to its commercial availability. Other aspects of pedestrian behaviour, such as distinguishing between frequent users versus occasional users of a facility are not taken into account at all, or only in a few models, such as the role of information provision (Penn 2003).

A more detailed study of Pedroute revealed that it did not support multiple types of rolling stock (characteristics for dutch rail operators) nor a detailed timetable, in which arrival and departures of individual trains could be handled. Also, it did not supply very detailed and flexible output, but pre-defined statistics had to be used. Finally, its route choice algorithm calculated routes for longer periods, which does not meet the requirements of route choice in a transfer station, in which routes may change frequently due to high densities lasting for short periods of time.

The conclusion may therefore be drawn that a dedicated simulation tool for pedestrians in public transport facilities has to be developed.

Table 3.7 shows different types of walking models mentioned in literature, varying from very detailed microscopic models to aggregate macroscopic models. Since many different processes are relevant for pedestrians in transfer stations and thus are included in the simulation tool, the level of detail of these processes needs to be similar. In the previous section, we have chosen to base route choice on shortest routes in a network, indicating an aggregate modelling level. It therefore suffices in the first instance to apply a macroscopic walking model in the simulation tool, whereas a more detailed microscopic model needs to be included in a later stage to derive macroscopic relations for new designed areas.

3.3.4 Modelling results

Henderson (1971) tested his Maxwell-Boltzmann theory on observations on three different locations. Observations on students in walk mode on a footpath in Sydney resulted in $V_x = 1.53$ m/s and $u_{r.m.s.} = 0.20$ m/s. On a zebra crossing also in Sydney, the parameters were $V_x = 1.44$ m/s and $u_{r.m.s.} = 0.23$ m/s. The observed speed is somewhat higher than the generally observed speed (1.34 m/s, see table 3.4), where the standard deviation ($u_{r.m.s.}$) is somewhat lower. Finally, observations have been made on children in walk mode and run mode, which resulted in $u = 0.67$ m/s and $u = 1.91$ m/s respectively. Agreement of the observations with the predictions of Maxwell-Boltzmann theory is generally satisfactory except near the maximum or frequency mode of each distribution. The most natural explanation is that each crowd consists of a mixture of two populations whose distributions are displaced from one another. The two populations are probably males and females.

Tajima & Nagatani (2001) studied crowd flow outside a hall and showed that a dynamical phase transition occurs from congested flow to free flow at a critical time t_c. In the congested flow region is found that the crowd flow rate q scales as $q \propto W^{0.88\pm0.02}$ and the transition time t_c scales as $t_c \propto W^{-1.16\pm0.01}$, where W is the size of the door. Tajima et al. (2001) also studied pedestrian channel flow at a bottleneck by using the lattice-gas model of biased random walkers. It is shown that a dynamical phase transition occurs from free flow to congestion at a critical density p_c with increasing density. The flow rate saturates at higher density than the critical density. In the congested region it is found that the saturated flow rate q_s scales as $q_s \propto d^{0.93\pm0.02}$ and the critical density k_c scales as $k_c \propto (d/W)^{1.16\pm0.02}$, where d is the width of the bottleneck and W is the width of the channel.

For high densities, the interactions between pedestrians are very important. As a consequence, development of pedestrian jams and of separate lanes for different directions of motion occurs. Pedestrian jams can be understood as a deceleration effect due to avoiding manoeuvres, and become worse the greater the velocity variance (Helbing 1992).

The separation into several lanes is caused by asymmetrical probabilities for avoiding a pedestrian to the right or to the left. This asymmetry effect has the advantage of reducing the situations where hindering avoiding behaviour is necessary (Helbing 1992). The formation of lanes is dynamic, indicating that the number of lanes may vary over time. The phenomenon of lane formation also occurs in one directional flows (where it is called layer formation) and in crossing flows (where homogeneous strips are formed) (Blue & Adler 2000), (Hoogendoorn & Bovy 2003).

For pedestrian crowds, the mechanism of approaching equilibrium is essentially given by the tendency to walk with the intended velocity, not by interaction processes. In addition, variations within pedestrian density will show wave-like propagation with a specific velocity which depends on the mean reaction time (Helbing 1992).

3.3.5 Conclusions of the state-of-the-art on walking behaviour

Many observations have been recorded in literature with respect to walking behaviour. In different conditions and in different countries, data has been collected, leading to a range in free walking speeds and densities. Where free walking speeds in Asia are lower than in West European and north American countries, observed densities appear to be higher.

Also the conditions in which observations have taken place varied significantly, that is in transfer stations higher free speeds are observed than in shopping areas. Pedestrian characteristics, composition of the pedestrian flow, and external conditions appeared to have influence on the observations. To which extent and what this implies for the form of the fundamental diagram is not known.

Many (simulation) models have been found in literature describing pedestrian walking behaviour. However, only few of these models are able to model pedestrian behaviour in transfer stations and none of these models are able to microscopically model the interaction of pedestrians with public transport, with different types of rolling stock following a timetable.

The aim of our research is to develop a model with individual pedestrian representation and the possibility of modelling both individual and collective behavioural rules in order to model bottlenecks with individual behavioural rules and to model platforms and other parts of the infrastructure with sufficient space for the pedestrians with collective behavioural rules. Also, the simulation tool needs to anticipate modelling areas with specific spatial lay-outs for which no macroscopic relations are known with individual behavioural rules.

3.4 Interaction with public transport vehicles

Interaction with public transport vehicles deals with processes of boarding, alighting, and transferring. Only a few studies are known with respect to these processes, handling especially empirical data. Theories and models for the interaction of pedestrians with public transport vehicles are therefore identified as blank spots, whereas the following discusses the reported empirical data.

Weidmann (1992*a*) studied *boarding and alighting times* in buses, including occupation of doors. Different types of buses have been distinguished, such as high, average, and low boarding height difference, three and four door cars, and different door locations. The vehicle dwell time starts the moment that the first pedestrian alights and ends at the moment the last passenger boards. Less than 10% of the pedestrians appears to board via the first door (lower capacity), leading to a highly used second door (∼40%), whereas the other doors are used by about the same number of passengers. These data give an indication of the distribution of passengers over the public transport vehicle and thus of the distribution of waiting passengers over the platform, which influences the origin-destination tables and pedestrian flows in the public transport facility.

Table 3.8: Boarding and alighting times for different types of rolling stock

Vehicle	**Average dwell time** (in s/P)	**Door capacity** (in P/ m s)	**Total capacity** (in P/ s)
BVB-4door (Weidmann 1992*a*)	1.36	0.60	2.63
BVB-3door (Weidmann 1992*a*)	1.37	0.57	2.19
MAN-low floor; door 2 (Weidmann 1992*a*)	1.30	0.63	2.23
MAN-low floor; door 3 (Weidmann 1992*a*)	1.43	0.57	
Munchen S-Bahn (Weidmann 1992*b*)	1.18	0.85	30.6
Neoplan bus (Weidmann 1992*a*) (theoretical)		3.2	
NS intercity (ICR/ICM) (Wiggenraad 2001)	1.12	0.99	
NS interregional doubledecker (Wiggenraad 2001)	0.90	0.85	
NS local doubledecker (Wiggenraad 2001)	0.88	0.59	
NS local train (plan T/V 1960) (Wiggenraad 2001)	1.02	0.89	
Trams Genf (Weidmann 1989)	1.5	0.57	
Trams Grenoble (Weidmann 1989)	1.1	0.71	

Wiggenraad (2001) studied *dwell times* of trains at Dutch railway stations. He observed that the lengths of dwell times are determined by the planned dwell times, the numbers of alighting and boarding passengers, train and infrastructural characteristics, and the arrival and departure process of the trains. Measured dwell times, especially those of intercity trains, appear to be longer than scheduled. Dwell times in peak hours and off-peak hours are about the same. Clear concentrations of waiting and boarding passengers occur around platform accesses, but at the arrival of the train the (boarding) passengers distribute more evenly over the platform. A distinction has been made between alighting and boarding in clusters and individual alighting and boarding, where passengers form part of a cluster if the time interval between his predecessor and himself is 3 s at maximum. The mean alighting and boarding time per passenger in clusters are both about 1 s. Trains with wide door passageways show about 10% shorter typical alighting and boarding times and narrower door passageways about 10% longer typical times. The measured dwell times of intercity trains vary from 90 s to more than 120 s. Express trains have dwell times varying from 45 to 120 s and local trains from 45 to 60 s. The total dwell time consists of a number of components: alighting and boarding time (composed of a clustered and an individual part), unused time, and dispatching time. The mean dispatching time and the unused dwell time both are rather constant independent of type of station, type of rolling stock or type of train service. In intercity trains, about four times as many passengers were measured alighting and boarding as in local trains. In peak hours more than twice as many passengers were measured alighting and boarding as in off-peak hours. More train doors were available and indeed used during peak hours. About 25% of the measured passengers were alighting and boarding via the busiest door.

Empirical data on average dwell times and door capacities are shown in table 3.8.

From measurements it appears that times needed for boarding and alighting at a specific door of a public transport vehicle are influenced by (Weidmann 1992*b*):

- Characteristics of the pedestrian: gender, age, height, health, state of mind, personality, baggage.
- External conditions: trip purpose, time of the day, climate, density.
- Characteristics of the entrance: height difference, slope of the steps, surface type, door width.

The specific boarding and alighting times increase with increasing density in the standing room (Weidmann 1992*b*). In the case of a vehicle of the Munchen S-Bahn this may be expressed as follows:

$$T^b = 1.362 - 0.171 \cdot k^{st} + 0.064 \cdot D_{st}^2 \tag{3.15}$$

where T^b indicates the individual boarding time, k^{st} the density in the standing room, and D^{st} the density on a step. At standing densities between 3 P/ m^2 and 4 P/ m^2 the door capacity is higher than at lower densities, due to the denser pedestrian flow. Alighting times are 15 to 22% lower than boarding times, due to the ordered alighting, unawareness of speed reduction while boarding, and slower walking in upwards direction on the steps.

Boarding and alighting times change over time of the day (Weidmann 1992*b*), that is during the morning peak 10% faster than average, in the morning hours 6% slower than average, in the lunch peak 6% faster, in the afternoon 9% slower, and in the evening peak 5% faster than the average times. This is caused by changing physical fitness during the day, different composition of passenger types, and different trip purposes of the passengers.

The occupation of standing pedestrians in the standing room reaches values twice as high as densities in the aisle (Weidmann 1992*b*). Standing rooms are divided into three classes: good accessible (occupation 4 P/ m^2), moderately accessible (2 P/ m^2), and badly accessible (1 P/ m^2) (Weidmann 1989).

3.5 Conclusions

The most important finding of this state-of-the-art is that only a few simulation tools exist able to model pedestrian walking behaviour in public transport facilities. None of these models however models the other aspects of pedestrian behaviour in detail, such as route choice and the interaction with public transport vehicles.

Blank spots found in this state-of-the-art concern empirical data, theories, and models on the following aspects:

- Route choice.
  - Pedestrian route choice in public transport facilities.
- Walking.
  - Knowledge on microscopic pedestrian walking behaviour and transformation of this microscopic behaviour into macroscopic pedestrian flow characteristics.
  - Influence of pedestrian characteristics and composition of pedestrian flows on fundamental diagrams describing pedestrian walking behaviour macroscopically.
  - Walking behaviour in public transport facilities.
- Waiting.
  - Traffic characteristics of waiting, among other things with respect to choice of a waiting location and pedestrian behaviour during waiting (walking around, when to find an alternative, etc.).
- Activities.
  - Activity choice in public transport facilities.
  - Activity area choice in public transport facilities.
  - Activity scheduling in public transport facilities.

The state-of-the-art overview showed generally accepted theories and models with respect to route choice, pedestrian walking behaviour, and interaction with public transport vehicles. Although these theories and models have not been specifically derived for pedestrian flows in public transport facilities, they may be used for a first instance of the simulation tool. When as part of this research more empirical data are available, theories and models may be refined and applied in the simulation tool.

Although extensive data collection is part of the research, not all mentioned blank spots can be covered. After establishing priorities most important aspects appeared to be walking and route choice. Therefore, microscopic pedestrian characteristics as well as the influence of some external conditions on walking behaviour are observed by means of controlled experiments (chapter 4). Pedestrian walking behaviour in public transport facilities (in our case on a train platform) is observed using handheld computers (appendix E), and finally route choice in public transport facilities is observed by 'stalking' (section 4.8). Both waiting and performing activities will be modelled according to queuing theory, while activity choice and activity scheduling are exogenous for the simulation tool.

Results of the data collection and derivation of new theories inspired by these data are described in chapter 4. The development of the simulation tool is described in chapters 5, 6, and 7. Chapter 5 focuses on the functional aspects, chapter 6 on the included models, and chapter 7 on the implementation. The verification and validation of the tool is discussed in chapter 8 and extended in chapter 9 in the form of case studies.

Chapter 4

Laboratory experiments on pedestrian walking behaviour

4.1 Introduction

This chapter describes laboratory experiments performed to study pedestrian walking behaviour. In the previous chapter a number of important blank spots have been identified with regard to the knowledge on e.g. pedestrian walking behaviour in general, pedestrian walking behaviour in transfer stations, and route choice behaviour in transfer stations. The aim of the experiments presented in this chapter concerns pedestrian walking behaviour in general, where microscopic data is collected, which then is generalised to macroscopic pedestrian behaviour characteristics. The emphasis has been put on knowledge indispensable as input for the pedestrian simulation tool, such as fundamental relations between walking speed, flow and density, free speed distributions, speed variances, and capacity estimates of bottlenecks. In this research, also data has been collected with respect to walking behaviour on a platform, which has been used for the validation of the simulation tool (see chapter 8 and appendix E). Data with respect to route choice behaviour has also been collected in two train stations (see subsection 4.8).

In this research, an innovative approach to data collection has been applied, namely the performance of controlled laboratory experiments to develop more detailed insights into pedestrian behaviour. Since walking is a subconscious process being performed automatically, we are convinced that laboratory conditions hardly have any effect on pedestrian behaviour. The conditions of laboratory experiments are fully controlled and all external conditions are known. This is why influences of specific experimental variables may be measured separately and walking behaviour is only influenced by the pedestrians themselves. The experimental variables density, free speed, walking direction, and presence of bottlenecks have been selected as being indicated in literature to be the factors influencing walking behaviour most. The experiments are recorded by video in order to keep all information. All kinds of analyses may thus be performed afterwards, such as converting video data into trajectory information automatically, which is innovative as well.

Finally, new flow capacity estimates show that the relation between the width of a corridor and its capacity is not linear, as is often assumed, but is more like a step-wise function, at least for bottlenecks of moderate width (less than 3 m). It is shown how pedestrians inside bottlenecks form layers or trails, the distance between which is approximately 45 cm. This is less than the effective width of a single pedestrian, which is around 55 cm. The layers are thus overlapping, a phenomenon which is referred to as the 'zipper' effect. For the narrow bottleneck case (1 m wide) two layers are formed; for the wide bottleneck case (width of 2 m), four or five layers are formed, although the lifespan of these layers is rather small.

The first two sections of this chapter (section 4.2 and section 4.2.3) summarise the state-of-the-art in available data collection techniques. Based on this state-of-the-art, the choice has been made to perform laboratory experiments with video recording and to develop dedicated detection and tracking software to transform video images into microscopic data. Section 4.4 describes in short the set up of the experiments, selecting the endogenous and exogenous variables; a more extensive description may be found in Daamen & Hoogendoorn (2003*b*), Hoogendoorn & Daamen (2002) as well as in appendix B. The actual performance of the experiments is presented in section 4.5. The first step in the analysis of the data is to track the pedestrians through space and time. For this purpose dedicated software has been developed, of which the basic principles are shown in section 4.6. Although a number of both microscopic and macroscopic relations and phenomena may be investigated, section 4.7 only describes the analyses relevant for the parameters of the simulation model, consisting of distributions for free speeds and variances of free speed depending on density, fundamental diagrams (relations between speed, density and flow) and capacity estimates in bottlenecks. Section 4.8 describes the data collection for passenger route choice models in train stations, as well as the estimation of such a choice model. The chapter ends with conclusions (section 4.9).

4.2 State-of-the-art on data collection for walking

Based on the long list of blank spots mentioned in section 3.5, data is collected with respect to microscopic walking characteristics (to derive macroscopic flow characteristics), walking behaviour on a platform (including boarding and alighting), and pedestrian route choice in a transfer station. In order to come up with appropriate and well-founded measurement approaches for this data collection, a review of techniques adopted in the past has been carried out.

Subsection 4.2.1 discusses the relevant data types of which the collection was extensively described in literature. Next, various data collection techniques with respect to the different data types are presented in subsection 4.2.2, in order to find the most adequate data collection technique for each data type. Subsection 4.2.3 discusses briefly the advantages and disadvantages of controlled experiments versus observations in practice. Then, an overview of techniques is given for extracting data from video images, in order to decide whether a product is already available or that dedicated software needs to be developed (subsection 4.2.4). Finally, conclusions are drawn in subsection 4.2.5 on which techniques will be applied for the observations in this research.

4.2.1 Types of data

Table 4.1 shows an overview of literature on data collection, indicating data type and the country where the data have been collected. The table consists of three parts, concerning traffic flow characteristics, pedestrian behaviour on a platform which is divided into boarding and alighting, passenger flows, and walking times, and finally pedestrian route choice.

Table 4.1: Data types collected by different authors

Subject	Author(s)	Country
Traffic flow	Armitage et al. (2003)	United Kingdom
	Ladetto et al. (2000)	Switzerland
	Polus et al. (1983)	Israel
	Sarkar & Janardhan (1997)	India
	Virkler & Elayadath (1994)	United States
	Willis et al. (2000)	United Kingdom
Boarding / alighting	Maw & Dix (1990)	United Kingdom
	Weidmann (1989)	Germany, Switzerland
	Wiggenraad (2001)	the Netherlands
Passenger flows	Fadin et al. (1997)	France
	Maw & Dix (1990)	United Kingdom
Walking times	Maw & Dix (1990)	United Kingdom
Route choice	Hill (1982)	United States
	Verlander & Heydecker (1997)	United Kingdom

The following list shows indications of the kind of data for each data type:

- Traffic flow characteristics.
  - Individual pedestrians' trajectories, individual walking speeds, space mean speeds, densities, flows, gender, trip purpose, group size, approximate age, stride frequency, stride length, and adaptation of the gait to the slope.
- Boarding and alighting characteristics.
  - Number of alighting passengers, number of boarding passengers, duration of boarding and alighting, total dwell time, type of station and train service (local, regional, national and international trains), number of sitting passengers, number of standing passengers in a carriage, number of passengers on stairs

of a carriage, number of passengers in remaining areas of a carriage, spatial distributions of passengers on a platform, flows in and out of platform entrances/exits, flows in and out of each car, choice of car by passengers entering the platform, and choice of platform exit by passengers exiting from cars.

- Passenger flows.
  - Counts of passenger traffic in stations in different situations (wide and narrow walkways, one and multi directional flows, sparse and extensive, and regular and intermittent traffic) and turning movements at decision points.
- Walking times.
  - Walking times of passengers (disaggregated on a link by link basis), and walking times and standing times on escalators.
- Route choice.
  - Walked routes and sets of possible routes.

Discussion

Data on passenger flows and origin-destination matrices depend on the situation in which the simulation model will be applied. More general observations may be performed on boarding and alighting characteristics, route choice and traffic flow characteristics.

Weidmann (1989) has already collected data on boarding and alighting characteristics, and Wiggenraad (2001) collected these data recently in the Netherlands. Therefore, the observations in a transfer station will not emphasise on boarding and alighting characteristics.

Several data collection techniques appear to be available to collect the mentioned data collection items (traffic flow characteristics, pedestrian behaviour on a platform, and pedestrian route choice in a transfer station). In the next section, an overview is given of these data collection techniques (among other things mentioned in the literature cited in table 4.1).

4.2.2 Techniques of data collection

Table 4.2 shows an overview of applied data collection techniques and types of data collected. These techniques are described in more detail in the following.

Table 4.2: Data types and applied data collection techniques

	traffic flow chars.	boarding / alighting	passenger flows	walking times	route choice
counting	1	5	9	9	
GPS	2				
infrared	3		3		
questionnaires					7
stalking					8
video	4		6		

Sources: 1. Sarkar & Janardhan (1997); 2. Ladetto et al. (2000); 3. Armitage et al. (2003); 4. McPhail & Wohlstein (1982), Polus et al. (1983), Virkler & Elayadath (1994), Willis et al. (2000); 5. Weidmann (1989), Wiggenraad (2001); 6. Fadin et al. (1997); 7. Verlander & Heydecker (1997); Haas & Morrall (1967), Koushki (1988), Rutherford & Schofer (1976); 8. Hill (1982); 9. Maw & Dix (1990).

Counting Manual counting have been used to collect data on boarding and alighting times (Weidmann 1989), (Wiggenraad 2001) and on pedestrian flow characteristics (Sarkar & Janardhan 1997), (Maw & Dix 1990). Flow was measured by counting the number of persons at a specific cross-section in a certain time interval. The speed was measured by noting down the time taken by randomly selected pedestrians to cross the test stretch length. Speeds of about 25% of the pedestrians crossing the line was measured. Average of these speeds was taken as the speed corresponding to that flow. Maw & Dix (1990) recorded passenger flows throughout a station, including turning movements at decision points, using PSION data loggers. Journey walking times of passengers were observed by both PSION data loggers and the moving observer method, whereby the surveyor had to travel at the speed of the average person.

GPS GPS and so-called ‘accelerators’ are used to measure speed, stride frequency, stride length, and adaptation of the gait to the slope (Ladetto et al. 2000). Raw data have been transformed into information following a physiological approach for an individual stride calibration. The analysed tests of several walking frequencies show differences between the effective and predicted distances of less than 2%.

Infrared Armitage et al. (2003) have used low-cost infrared detectors usually applied to count people moving across a line, but they have read extra data from the detectors in order to extract complete pedestrian trajectories. Preliminary studies show that the detectors are very efficient at gathering large amounts of trajectory data. It is possible to couple multiple detectors to cover larger areas. However, some problems exist with matching pedestrians as they move between the fields of view of adjacent detectors.

Questionnaires Verlander & Heydecker (1997) address route choice for pedestrians using a sample survey of daily walks in an urban area, where the walks undertaken are reconstructed using a geographical information system (ArcInfo) and compared with the shortest available route. The survey data used were derived from diary records of all activities on foot. Questionnaires have been used for a series of origin-destination studies in Riyadh, Saudi Arabia, in which information was obtained on walk trip origin, destination, purpose, and modes of transport before and after the walk, as well as information on the age, gender, education, employment status, and nationality of the individual pedestrian (Koushki 1988). Similar surveys have been applied in Haas & Morrall (1967), Maw & Dix (1990), and Rutherford & Schofer (1976).

Stalking For pedestrian data collection only Hill (1982) used this 'stalking' method. He followed pedestrians from an intersection to their destinations, where he handed them a questionnaire for additional, personal information.

Video A study performed by Willis et al. (2000) examines the relationship between features of walking behaviour and influencing factors of a pedestrian walking towards a pedestrian in the opposite direction on a potential collision course. A combination of observational and interview techniques is used in this data collection. All observational analysis is carried out using custom-recorded video data to collect aggregate measures, such as flow and density. On-street interviews are conducted to collect information not (reliably) obtainable using observational methods alone (such as trip purpose).

Data over a 12 m length of walkway has been collected using an elevated location for video camera placement (Virkler & Elayadath 1994). Space mean speed was estimated from a sample of speeds of four individuals subjectively selected as representative of the time period.

Also, properties and characteristics of pedestrian flow on sidewalks have been analysed (Polus et al. 1983). Data were collected in the central business district of Haifa, Israel, with the aid of a videotape recorder and a digital clock. Pedestrian speed was obtained by recording the times when crossing the boundaries of the marked-off square, and the density was obtained by counting the number of pedestrians within the boundaries of the square at the time the subject pedestrian was approximately in the middle.

The vision group at the University of Leeds has been successful at developing neural network based methods of extracting pedestrian trajectories from long recorded sequences of visible images (Johnson & Hogg 1996). The aim of the developed Integrated Traffic and Pedestrian Vision System is to automatically detect events that may have security or safety implications.

In USA, high-resolution infrared imagers are used to track pedestrians viewed obliquely from an imager installed in a vehicle (Xu & Fujimura 2002). Their goal is to provide information about pedestrian movements relative to the vehicle for safety reasons. The method works in real-time, but relies on the use of relatively expensive thermal imagers to provide high-resolution infrared images.

Visio Pacs (Fadin et al. 1997) is a system counting automatically in real time passenger traffic in stations. The system is said to be more than 97% accurate and has a rapid detection (25 images per second). The trajectory of a person is followed and on passing a central imaginary line, the person is counted in the direction corresponding to his or her trajectory. The system uses a video camera placed above the passageway aimed towards the floor. Detection is ensured by a wired neural network, which memorises floor texture when no one is in the passageway area.

Discussion

The aim of the observations with respect to pedestrian walking behaviour in general is to collect microscopic data and to derive macroscopic flow characteristics. Indicated data collection techniques have been counting, GPS, infrared, and video recordings. In theory it is also possible to derive fundamental relations from cumulative flow curves (counting of pedestrians on cross-sections, including passing moments). However, this data is not sufficient for analyses of microscopic characteristics such as individual free speeds. Theoretically it is possible to know continuously the position, speed, and walking direction of pedestrians using GPS-receivers. However, this has a practical problem, as this equipment is not only costly, but also has to be handed to pedestrians while walking over an indicated area and has to be returned afterwards. This will disturb the process significantly. Infrared detectors are very well capable to count passing pedestrians automatically and even may derive trajectories. However, the range of the recordings is limited to relatively small areas. This leaves data collected by video recordings as the most promising data collection technique. One of the requirements for video data is that the recorder is mounted right above the walking area, which makes it difficult if not impossible to be applied in most transfer stations. Other requirements concern constant light conditions, a fixed location of the camera and continuous supervision on the camera and recorder. After the transformation of the video images into data (discussed in subsection 4.2.4), all kinds of analyses may be performed.

Table 4.2 shows counting as the only technique useful for most processes (boarding and alighting, passenger flows, and walking times) in a transfer stations. Hand-held computers appear to be a very useful tool, especially because their interface might be designed dedicated for each observation.

With respect to data collection for pedestrian route choice in transfer stations, two techniques appeared to be applicable, that is, questionnaires and ‘stalking’. Questionnaires may provide an indication of applicable route choice sets available to the pedestrian, whereas ‘stalking’ will only show realised choices. However, transfer stations are usually not very complex and since most commuters are acquainted with the available routes, the realised route choice will be sufficient for the first observations. ‘Stalking’ is therefore chosen as the method to observe route choice.

4.2.3 Real-world observations versus laboratory experiments

Data from practice may be collected by real-world observations and by laboratory experiments. For observations, the equipment and personnel are moved to the observation location, but the external conditions and the flows cannot be influenced. Despite a thorough preparation, the conditions and the pedestrian flows may be significantly different from the expected situation. Also, influencing factors can not be unambiguously separated, but combinations of these factors are observed.

A laboratory experiment is controlled by the researcher, not only with respect to the conditions (light, weather), but also to the number of pedestrians and direction of flows. In an experiment, one or more experimental variables are deliberately changed in order to observe the effect of the changes on one or more endogenous variables. First, the objectives of an experiment are determined and the process factors for the study are selected for experimentation. Well-chosen experimental designs maximise the amount of 'information' that can be obtained for a given amount of experimental effort. Another advantage of laboratory experiments is the possibility of observing situations which do not or hardly occur in practice, such as very crowded conditions or specific compositions of a pedestrian flow. Also, the influences of obstacles, other pedestrian flows, and the time pressure in which decisions are taken can be observed by instructing pedestrians to behave according to specific conditions.

In order to analyse the influence of different free speeds, walking directions, densities, and obstacles, controlled laboratory experiments have been performed. Also, observation conditions may be influenced by the researchers, leading to higher quality observations. To our knowledge, this is the first time that controlled laboratory experiments of walking have been performed.

One of the disadvantages is the fact that people are not walking in their natural environment, but in an artificial set-up. This may question the generalisations of the data. According to Rasmussen (1986), pedestrians perform activities at three levels of interaction, namely skill-based, rule-based, and knowledge-based. Skill-based behaviour concerns processes being performed automatically with little conscious effort. At the rule-base level the control in a specific task is performed based on 'rules', which are available in a pedestrian's memory. Control at a knowledge-based level is needed when a pedestrian is confronted with a new task, needing a new representation of the task. Walking is a process on the skill-based level, thus being performed subconsciously. The laboratory conditions will therefore have hardly any effect on the observed walking behaviour. Another disadvantage might be the fact that a pedestrian has to repeat his task several times in order to get reliable data. As his incentive is not directly related to a motivation of being in a transfer station, his drive to hurry or stand (very) close to other pedestrians might be lower than in practice. This might lead to pedestrian walking behaviour with lower densities and lower speeds in relation to literature. The degree to which the results are realistic will be indicated by a comparison to literature and eventually in the future to actual speeds and other measurable quantities in reality.

4.2.4 Extracting data from video images

An essential part of using video images is data extraction from (digital) images. This section discusses some of the existing techniques to be used.

One approach is to estimate the number of pedestrians present in a real-life complex scene by processing a sequence of images (Regazzoni & Tesei 1996). A set of parameter values extracted from each acquired image is related to the number of people observed, and the processing steps are based on the difference between the current image and a reference image showing the empty background (Peri et al. 1993). The knowledge describing the correlation between a parameter value and the estimate of the number of people is represented by nonlinear piecewise models. The proposed estimation approach exploits temporal information by means of a distributed Kalman filter network. The current crowding estimate is derived from the application of the static correlation models to the extracted observations (evidence), combined with the prediction obtained from the temporary previous estimate (expectation). Extensive experimental tests carried out in a metro station yielded very promising results in terms of estimation accuracy and real-time response capability.

Attempts to detect overcrowded situations by using neural networks were made for the London underground (Fahlman 1988), and by using regularisation networks (Poggio & Girosi 1990) for the Esprit Project P-5345 Dimus (Ferrettino & Bozzoli 1992).

Furthermore, a method for counting of a passenger stream was presented in Sasama & Ukai (1989) for a railway application, based on hypotheses of human motion. A simple change-detection mechanism has been used to detect the number of changing pixels and to estimate the number of people.

Real-time image-sequence analysis was proposed in Mecocci et al. (1994) as the basis for counting people getting in and out of a bus. Fast and robust algorithms, aimed at detecting motion, estimating its direction, and validating the presence of an actual target, are described; they were tested under critical conditions of vibrations, lighting fluctuations, and environmental variations. An approach to estimating accurately the number of people in conditions of high pedestrian-flow rates or dark shadow was proposed in Zhang & Sexton (1995), being based on the model-based extraction of the pedestrian head feature and is particularly useful for camera top view.

Additional research has been aimed at studying and characterising the behaviour of individuals (Assereto et al. 1994), (Pardas & Salembier 1994), (Tesei et al. 1995), (Yee-Hong & Levine 1992), (Yuhua & Al. 1992).

Yuan (1994) developed mathematical models to process and analyse digitised monochrome and colour images. These models have been integrated to form four algorithms, each dedicated to a specific function: measurement of traffic volume and vehicle speed, detection and count of vehicles intending to turn, classification of vehicles, and measurement of pedestrian flows. The newly developed models and algorithms provide a new method for increasing the capability and reducing the detection error of currently used video traffic detection systems.

4.2.5 Conclusions

From an inventory of available data collection approaches it was decided to perform controlled experiments in order to increase the knowledge on pedestrian traffic flow characteristics in particular on free speed distribution and speed-density relations depending on the composition of the pedestrian flow. These experiments are recorded by a video camera and for the transformation of video images into data, dedicated detection and tracking software are developed. Both the behaviour of the individual pedestrian (microscopic) and the behaviour of pedestrian flows is of interest, for example, the relation between the macroscopic magnitudes density, composition of the flow (with regard to the walking direction of the pedestrians) and mean speed may be investigated as well as the free speed distribution for pedestrians, their headways, etc.

Hand-held computers have been chosen to perform observations on pedestrian behaviour in transfer stations. The interface may be designed dedicated for each set of observations. Another practical aspect is that the Dutch station manager did not give permission to use video cameras, which might have been a promising alternative.

To observe route choice in transfer station, passengers will be 'stalked'. This gives information on the chosen routes (revealed preference research).

4.3 Research questions for the laboratory walking experiments

The main objective of the experiments is to collect microscopic observations of pedestrian walking behaviour in order to derive macroscopic flow characteristics. Microscopic data concern data with respect to the individual pedestrian, such as headways, individual speeds, swerving, and free speed distributions, whereas macroscopic data describes pedestrian flows in terms of speeds, flows (capacity), and densities (including critical and jam density). One of the important outcomes are fundamental diagrams describing the relation between the macroscopic fundamentals speed, flow, and density.

In a transfer station conditions vary significantly over time and over space. Conditions are characterised by the composition of a pedestrian flow, depending on the characteristics of an individual pedestrian, characteristics of the infrastructure, and the external conditions, such as weather. During the experiments, the composition of the pedestrian flow will be changed, whereas the infrastructure remains a level element and the conditions are not varied either.

Characteristics of the pedestrian flow to be changed are, among other things, related to walking direction, speed conditions as they may occur in a transfer station, and the occurrence of bottlenecks in order to study congestion.

Specific research questions that are to be answered are:

- How do pedestrians handle a bottleneck? This question does among other things involve pedestrian behaviour in congestion.
- What is the influence of different walking directions on pedestrian flow behaviour with respect to capacity, relations between speed and density, etc.?
- What is the influence of the interpersonal variance in microscopic free speeds on pedestrian flows? A high variance in free speeds is typical for public transfer facilities.

When the data have a sufficient level of detail, it might be possible to answer more fundamental questions with respect to space occupation and swaying (dynamic space occupation). Walking speeds in relation to space occupation determine traffic flows, indicating that these microscopic characteristics have significant effects on macroscopic flow characteristics.

4.4 Experimental set up

The walking experiments consist of walking tasks to be performed by a large number of subjects. In the walking experiments, experimental and context variables are distinguished, as well as measured characteristics of individual pedestrians and pedestrian flows. Experimental and context variables are exogenous variables, representing the external conditions. Experimental variables are the variables of interest, the impact of which on walking is looked for, controlled during the various experiments. Context variables cannot be influenced and describe external conditions and characteristics of individual pedestrians. The outcome of the laboratory experiments are measured characteristics of the pedestrian flow as well as of individual pedestrians. Examples of these characteristics are speeds, densities, flows, headways, and free speed distributions. An overview of these types of variables is shown in figure 4.1.

The considered experimental variables are free speed, walking direction, bottleneck width, density, size of the observation area, and pedestrian flow composition. These variables are intentionally (systematically) varied in the experiments as follows.

Free speed Free speed is the speed pedestrians like to keep in undisturbed conditions. Since pedestrians can not walk at a predefined (exact) speed, an indication of free walking speeds were assigned during the experiments, ordered in three classes:

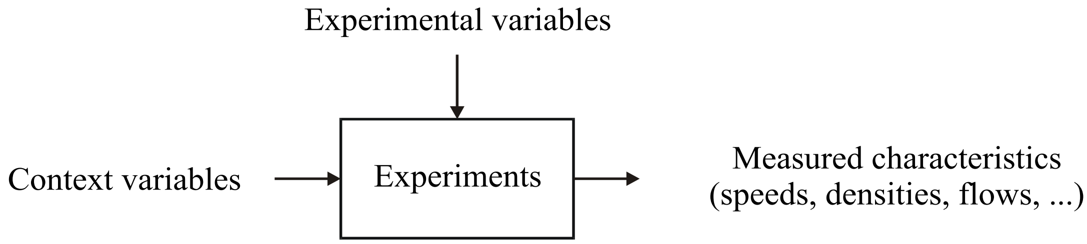


Figure 4.1: Definition of variable types

- Normal speed (N).
- Higher speed, in order to catch a train (H).
- Lower speed, as for window-shopping (L).

Walking direction Basically, a pedestrian can walk in any arbitrary direction in an area. Since this will lead to an infinite number of combinations of directions, the number of walking directions were restricted to four:

- From west to east (→).
- From east to west (←).
- From south to north (↑).
- From north to south (↓).

Bottleneck width To observe the congestion part of the fundamental diagram as well, bottlenecks are considered by placing obstructions in the controlled walking area. These obstructions will narrow the area, leading to congestion upstream of the bottleneck. The width of these bottlenecks may be varied to control the amount of congestion. The following widths are considered:

- Bottleneck with a width of 2 m.
- Bottleneck with a width of 1 m.

Density The density is varied systematically between an almost empty and an almost completely occupied area. During the experiment groups are successively added to the observation area (see appendix B). The density is thus increased in a stepwise manner, until all groups participate.

Size of the floor area The size of the floor area is chosen such that congestion will occur, which also depends on the number of participating subjects. For one- and two-directional experiments the area length equals 10 m and its width 4 m. For the experiments with crossing pedestrian flows, the area is a square of 8 m × 8 m.

Pedestrian flow composition Pedestrian flow composition describes the division of the total pedestrian flow over one of the experimental variables. For example, when in an experiment a two-directional flow is defined, then pedestrian distribution describes the share of each flow with respect to the available number of subjects. Depending on the pedestrian flow composition, the share of each flow may be similar (50%-50%) or not (90%-10%).

Experimental design

Compared to the reference variant (one directional flow with normal free speeds without bottlenecks (experiment 1)) one variable is varied per experiment, resulting in 10 experiments (see table 4.3, figure 4.2, and appendix B for the final choice of these 10 experiments). The choice has been based on a correspondence of the experiments with frequently observed conditions in a public transfer stations in combination with the literature overview on variables highly influencing pedestrian walking behaviour (see also section 3.3). During each of the experiments, the density is increased from zero until all subjects participate and then decreased again.

Table 4.3: Experimental design

	Speed			**Direction**				**Bottleneck**			**Flow**
Experiment	L	N	H	→	←	↑	↓	none	2 m	1 m	**composition**
1		x		x				x			100%
2		x	x	x				x			60%-40%
3	x	x		x				x			40%-60%
4		x		x	x			x			50%-50%
5		x		x	x			x			90%-10%
6		x		x		x		x			50%-50%
7		x		x		x		x			90%-10%
8		x		x	x	x	x	x			25%-25%-25%-25%
9		x		x					x		100%
10		x		x						x	100%

The experiments can further be classified into four categories:

- One-directional traffic
  - Experiment 1: reference variant with normal conditions

  - Experiment 2: station conditions
  - Experiment 3: shopping conditions

- Two-directional traffic
  - Experiment 4: two equal-level opposite flows (walkway)
  - Experiment 5: one small opposite flow (late passengers heading for the already arrived train, while most passengers already alighted)

- Crossing traffic
  - Experiment 6: two equal-level crossing flows
  - Experiment 7: one small crossing flow
  - Experiment 8: four equal-level crossing flows (a station hall)

- Congested conditions
  - Experiment 9: wide bottleneck (walk from a hall into a small walkway)
  - Experiment 10: narrow bottleneck (wide walkway abruptly narrowed)

For details on the measurement set-up see Hoogendoorn & Daamen (2002) and Daamen & Hoogendoorn (2003*b*).

Figure 4.2 provides a graphical overview of the set of experiments, where arrows indicate pedestrian flows.

4.5 Performing the experiments

This section describes the actual carrying out of the experiments. First, the measurement set up is presented. The next subsection goes into detail on aspects concerning subjects (pedestrians) participating in the experiments and finally the course of the experiments is illustrated.

4.5.1 Measurement set up

The walking experiments were conducted in a large hallway. Both rectangular (10 m × 4 m) and square (8 m × 8 m) areas are taped on the floor. Bottlenecks are made of green boards, built up in triangles to increase stability. Traffic lights are used to give signals to pedestrians to enter the area the first time. For more information see Daamen & Hoogendoorn (2003*b*).

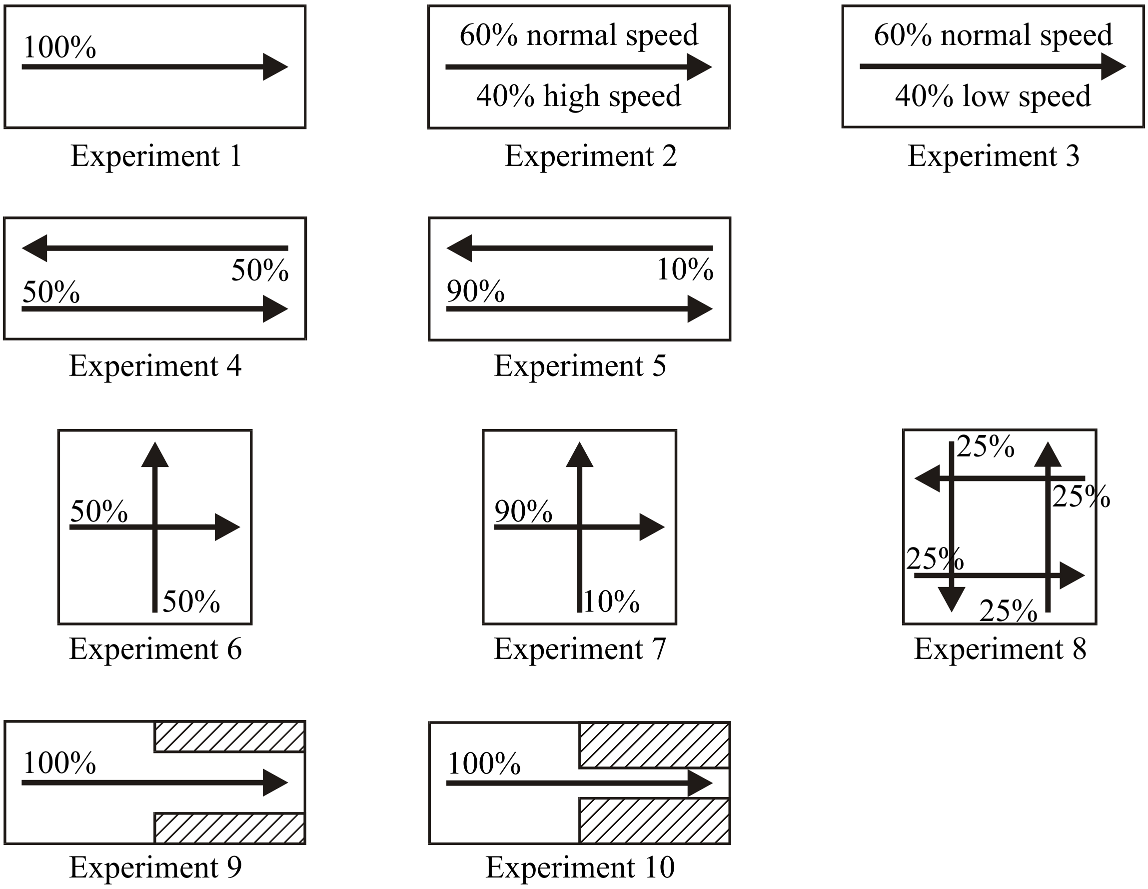


Figure 4.2: Overview of the experimental conditions

Figure 4.3: Example of the narrow bottleneck experiment

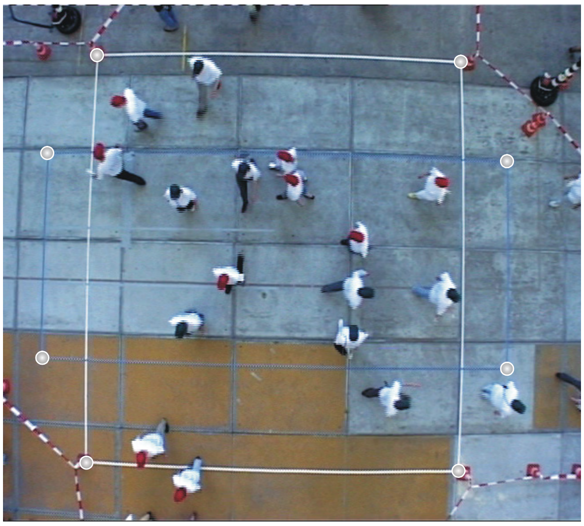


Figure 4.4: Example of the four directional crossing flow experiment

The ambient conditions in the hallway were favourable (reasonably constant light intensity, little shadows, smooth surface), although there was some influence of the sun shining through the windows and the rising temperature in the hallway. The digital video camera was mounted at the ceiling of the hallway, at a height of 10 m, observing an area of approximately 14 m by 12 m. A wide lens has been used enabling the camera to view the entire walking area. The digital camera had a resolution of 720 × 576 pixels, and was attached to a digital video recorder. The quality of the collected video footage was very high.

4.5.2 Experimental subjects

The population consisted of inhabitants of the city of Delft and its near environment and students. In total, 60 subjects participated in the morning experiments and 80 subjects subscribed for the afternoon experiments.

Each subject got a white T-shirt and a red or green cap. Both cap and T-shirt have been used to guarantee a sufficient contrast between the pedestrians and the background.

Due to the impossibility of managing all subjects at the same time, groups have been formed. A group leader has been assigned to each group, informed in advance of the experiments. This group leader was responsible for the subjects in his group and took among other things care of the moment his group had to join the experiment. All members of one group had the same cap colour. In the experiments 2 and 3, the colour of the cap has been used to indicate fast and slow subjects (red = normal speed; green = adapted speed).

Groups consisted of 8-10 subjects. Subjects have randomly been assigned to each group in order to have uniform behaviour for all groups. To achieve this, all subjects have been divided into pedestrian types (child, student, adult, senior, male, and female), equally divided over the groups.

4.5.3 Course of the experiments

During an experiment, groups have been added and removed consecutively. To add the subjects of a group to the experiment traffic lights have been used. After a group joined the experiment, a stable situation was reached and maintained for one minute. This way most observations are obtained from a stable, equilibrium situation. After this time period a next group was added and the process was repeated until all groups (or as many groups as capacity allowed) joined the experiment. This 'capacity' situation was then stabilised for two minutes, after which a group left the experiment. After the removal of a group, the stabilisation period was again one minute, after which the next group could leave the experiment. This continued until all groups left.

The traffic light turned green the moment a single subject could enter the area. After a short time period the traffic light turned red. The length of the area is about 10 m and afterwards, the subject had to return to his starting point. In total he walked about 25 m, which took 16.67 s at a speed of 1.5 m/s. During these 16.67 s 10 persons had to enter the area, leading to one subject per 1.5 s. For the admission of a subject, the traffic light was green for 0.5 s and red for 1.0 s.

The admission of a group of subjects took somewhat less than 20 s. Then, the situation was stabilised. In total this took one minute, so 60 s after the first subject of the preceding group joined the area, the first subject of the next group could be admitted, followed by the rest of the group. Because of the presence of eight groups, it took 480 s until all subjects had joined the experiment. At this moment, the maximum density was reached and the situation has been stabilised for 120 s. As a next step, the density was decreased by removing groups one by one from the area, in the same order as they entered the area. Removing all groups from the area also took 480 s, so the total duration of the experiment is 2 * 480 + 120 = 1080 s = 18 min. In some experiments two groups have been added at the same time. These experiments therefore took less time (4 * 60 + 120 + 4 * 60 = 600 s).

4.6 Video tracking

This section describes in short the algorithm developed to track observed pedestrians in order to create data in a format suited for analysis. This data consists of sequences of locations of each individual pedestrian with the corresponding moment of time. From this data trajectories may be derived, being the basic unit of analysis in traffic flow research. An extensive description of this process is found in Hoogendoorn & Daamen (2002). In broad terms, the different steps of the algorithm are the following:

1. Converting digital video recordings to image sequences followed by a radiometric correction and histogram matches.

2. Identification of candidate pedestrian's positions using fuzzy clustering, with the aim to recognise the pedestrians, and identify the different pedestrian groups, based on special colour patterns to recognize the caps. This pedestrian detection occurs in the so-called detection zone, where lighting conditions are optimal for recognition of the cap colour.

3. Tracking detected pedestrians, i.e. identifying subsequent pedestrian locations in the images. The approach can handle changes in the shape of pedestrians due to both movements of pedestrians (movement of arms, head turning, etc.), as well as the position of the pedestrian on the image. The approach determines the position of the centre of the position of the pedestrian's head, with an accuracy of one pixel.

4. Correction for rotation as well as mapping image co-ordinates to terrestrial co-ordinates. Conversion to real-life coordinates is achieved by linear scaling, using the terrestrial coordinates of a number of reference points (such as the corners of the walking areas).

5. Filtering the pedestrian trajectories. Use of the candidate pedestrian locations identified for the consecutive video images to establish the most likely trajectory, based on Kalman filtering techniques.

6. Visualisation of the results.

Figure 4.5 shows a result of the pedestrian tracking algorithm, depicting pedestrians who have been tracked before (indicated by a dot and a unique id), and the pedestrian that is currently being tracked (indicated by a cross).

Figure 4.5: Example illustration of the pedestrian tracking process

For each tracked pedestrian, the output of the tracking consists of:

- The unique id of the pedestrian.
- The group to which the pedestrian belongs (red caps or green caps).
- The relevant time instants t_i in seconds.
- The location r_i of the pedestrian at instants t_i in screen pixels.
- A reliability measure e_i.

4.7 New behavioural findings from the experiments

Data from these laboratory experiments may be used to describe extensively both microscopic and macroscopic behaviour of pedestrians. However, in the following section only those relations relevant for the simulation model (input parameters) are elaborated (Daamen & Hoogendoorn 2003*b*), (Daamen & Hoogendoorn 2003*a*), (Hoogendoorn & Daamen 2002), (Hoogendoorn & Daamen 2004). First, a distribution for pedestrian free speeds is derived, using the product-limit estimation method. Then, variances of speeds are determined in relation to the density.

One of the most important input parameters in the modelling tool to be proposed is the speed-density relation. Therefore, fundamental diagrams are derived, based on information from cumulative flow curves. This section only describes the speed-density relation of experiment 10 (narrow bottleneck), which is the only experiment where the congestion part of the fundamental diagram may be estimated. Finally, capacities of infrastructure are calculated, depending as well on free speeds and walking direction. To achieve this, the product-limit method has been applied again.

4.7.1 Walking speeds

This section contains an analysis of the distribution of free speeds and the corresponding variances. These speeds and variances are compared for various experiments to indicate the influence of free speed orders (experiments 2 and 3) and walking directions (bi-directional and crossing flows). Free speeds or desired speeds are defined as the speeds pedestrians like to walk with when they are not hindered by other pedestrians. Since pedestrians have different characteristics influencing their choices, free speeds will differ among individuals and may be described as a stochastic variable with a distribution. This distribution plays an important role in many traffic flow models, macroscopic as well as microscopic ones.

In general, only a part of the pedestrians in a traffic flow will be able to walk at their free speed. The observed speeds of pedestrians that walk free are not representative of the free speed distribution of all pedestrians because lower free speeds are over-represented. This is due to the fact that individuals with a higher free flow speed have a higher probability of being hindered by other individuals in the flow. Several methods have been developed to estimate free speed distributions in car traffic (Botma 2001). The product-limit method based on censored observations is used in this section to determine a distribution for pedestrian free speeds. This is the first time to adopt this estimation approach to pedestrian movements.

Observed pedestrians are separated into two categories:

- Pedestrians walking at free speed and
- Pedestrians following other pedestrians, so-called constrained pedestrians.

Several criteria may be used to perform this separation between constrained and non-constrained pedestrians, such as time headway, a combination of time headway and relative speed, and fuzzy interpretation of margin of required and actual distance headway. As pedestrian speed may change rather fast and frequently, criteria based on this speed are not robust enough. Therefore, the criterion of free space ahead is used. Whenever this area in front of the pedestrian does not contain any pedestrians, the pedestrian is considered as 'non-constrained'. Otherwise, the pedestrian is considered 'constrained'. For a description of the applied product-limit method see Botma (2001). Figure 4.6 shows the results of application of the product-limit method for experiment 1, in which the size of the free space criterion was $2.5\,\text{m} \times 0.46\,\text{m}$.

Despite the fact that the densities in experiment 1 were not high, pedestrians did follow others, which influenced their speed. The curve found by the product-limit method indicates, as expected, higher values for the free speed, but due to the absence of congestion, the difference between the two curves is not very large. The mean speed of the non-constrained pedestrians is 1.406 m/ s, whereas the variance is 0.215 m/ s. When also the speeds of the constrained pedestrians are taken into account (product-limit method), the mean speed is estimated at 1.454 m/ s and the variance is 0.226 m/ s.

In order to find the influence of the size of the free space criterion, both its length and its width have been varied, the results of which are shown table 4.4.

Table 4.4 shows that a maximum difference in free speed is found of 10.57%, between the largest and the smallest area. Taking into account the conditions of the experiments, a free area is chosen with a length of 2.5 m and a width of 0.68 m.

It is generally assumed that the free speed is a personal characteristic that is independent of the conditions. To test this hypothesis, the product-limit method is also applied for the free speeds in the other experiments. The method could not be applied for the experiment with the narrow bottleneck, due to an insufficient number of non-constrained observations.

The form of the distribution remains similar, whereas the difference between the non-constrained observations and the estimations from the product-limit method changes. Characteristics of each of the distributions are collected in table 4.5.

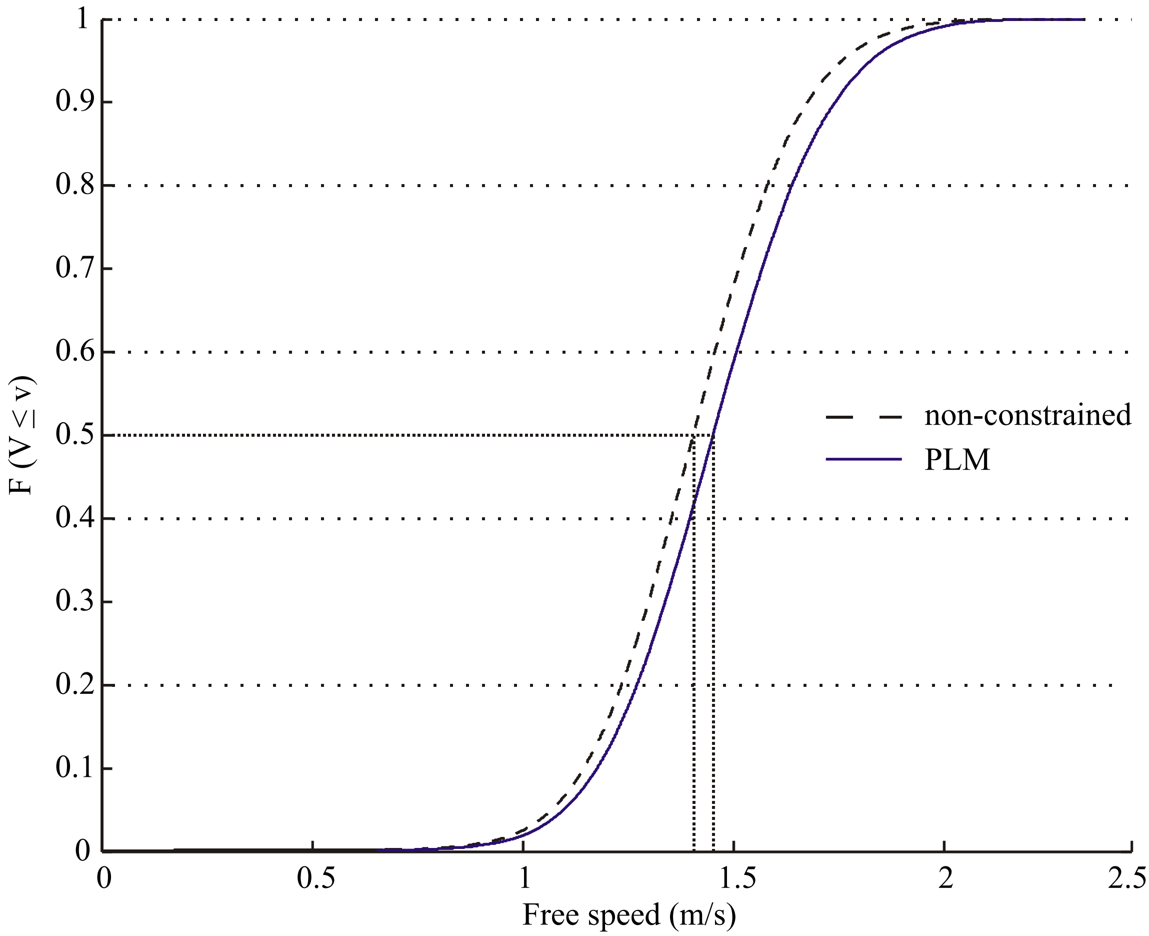


Figure 4.6: Frequency distribution of free speeds (experiment 1) estimated with product-limit method (PLM) compared to the free speed distribution resulting from non-constrained observations

Table 4.4: Mean free speeds (in m/s) calculated with the product-limit method with varying free space size

length \ width	**0.60** m	**0.65** m	**0.70** m	**0.75** m	**max diff**
1.0 m	1.400	1.400	1.402	1.404	0.32%
1.5 m	1.410	1.416	1.421	1.427	1.21%
2.0 m	1.424	1.434	1.445	1.455	2.18%
2.5 m	1.435	1.449	1.463	1.477	2.98%
3.0 m	1.444	1.462	1.480	1.497	3.67%
3.5 m	1.452	1.472	1.493	1.512	4.18%
4.0 m	1.460	1.483	1.506	1.527	4.63%
4.5 m	1.467	1.492	1.516	1.539	4.87%
5.0 m	1.472	1.499	1.524	1.548	5.14%
max diff	5.24%	7.03%	8.74%	10.29%	10.57%

Table 4.5: Mean and variance of free speeds for both unconstrained observations and product-limit method estimations in each of the experiments (in m/s)

Experiments		**# observation**		**Free speeds**		**PLM speeds**		**Diff.**
Nr	Description	All	Unconst.	Mean	Var.	Mean	Var.	
1	Reference	84735	63947	1.406	0.213	1.454	0.226	+3.4%
4	Eq bi-dir.	56050	40391	1.296	0.206	1.349	0.218	+4.0%
9	Wide bottleneck	162428	71281	1.239	0.282	1.387	0.301	+11.9%
10	Narrow bottleneck	178004	61006	0.815	0.405	1.101	0.441	+35.3%

One directional flows may be found in experiments 1, 9, and 10, where in the latter experiment congestion occurs. Due to this congestion, the number of non-constrained observations is reduced (up to 34%). Another effect of congestion (see next section) is hysteresis, where pedestrians appear to have a lower speed after the congestion than on beforehand, indicating that part of the non-constrained observations will be lower, thus reducing the free walking speed calculated by the product limit method. The reference scenario indicates a free speed of 1.45 m/ s, which is significantly higher than the free speed found in literature (1.34 m/ s), whereas the variance is lower than in literature (0.23 m^2/s^2 versus 0.37 m^2/s^2). Both differences may be caused by the composition of the pedestrian flow in the experiments, that is although the distribution of men and women as well as the distribution over age were comparable to the Dutch population composition, only those pedestrians being good walkers might have subscribed.

The experiment with two directional flows indicates a 7% lower free speed than the reference experiment, indicating that opposite flows do cause some hindrance, leading to lower walking speeds. The variance in walking speeds is similar for both experiments. However, taking into account the level of accuracy of other processes modelled in the simulation tool, the indicated difference is negligible. The free speeds are therefore assumed independent of the traffic flow.

4.7.2 Speed variances

This section shows the analysis of the average speeds and the variances in these speeds in relation to the number of pedestrians in the walking area. The hypothesis tested here is that at higher densities the variance in speeds decreases, as pedestrians have less freedom to choose their own speeds. For each time step the number of pedestrians in this area $N(t)$ and their individual speed $v_i(t)$ are determined in order to calculate their average local speed $v(N,t)$:

$$v(N,t) = \frac{\sum_{i}^{N(t)} v_i(t)}{N(t)} \tag{4.1}$$

Only absolute values of the speeds are taken into account, meaning that no distinction has been made in walking direction. The results for experiment 10 (narrow bottleneck) are shown in figure 4.7. Normal distributions have been fitted through the data for each of the density ranges (indicated in the upper right corner of each graph).

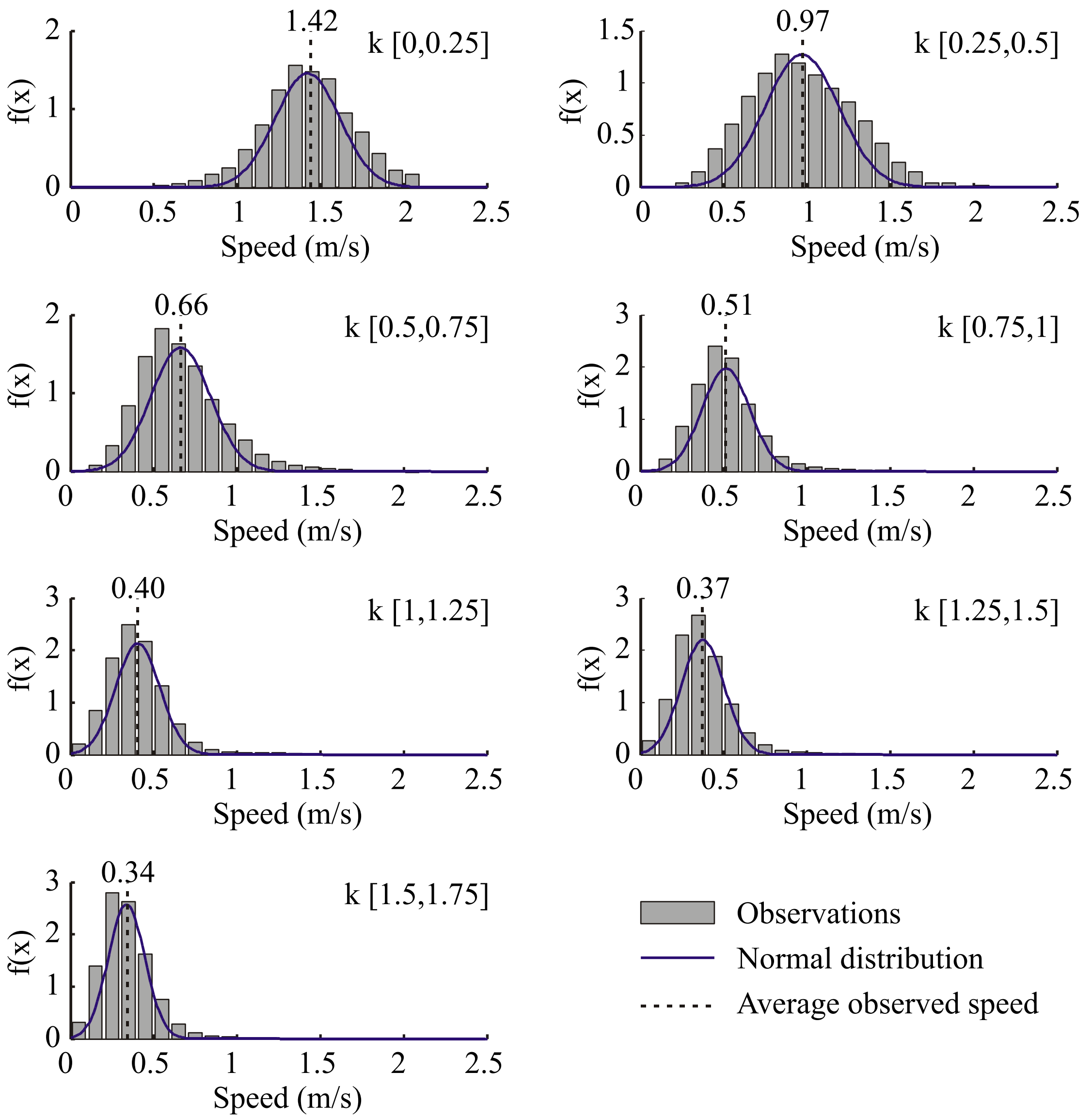


Figure 4.7: Speed distributions and fitted normal distributions for density ranges in experiment 10 (densities k expressed in number of pedestrians per square metre; ranges in upper right corner)

As hypothesised, mean speed decreases when density increases, while the variance does not seem to vary significantly. Similar graphs have been constructed for the other experiments, and all showed this phenomenon. Figure 4.7 also shows that speeds are normally distributed, also in different density conditions.

4.7.3 Fundamental diagrams

In this section, fundamental diagrams are derived from cumulative flow plots (see figure 4.8). A cumulative plot of pedestrians is a function $N(x,t)$ that represents the number of pedestrians that has passed a cross section x from an arbitrary starting moment. The flow q measured at cross section x during a time period from t_1 to t_2 equals:

$$q(x, t_1 \ to \ t_2) = \frac{N(x, t_2) - N(x, t_1)}{t_2 - t_1} \tag{4.2}$$

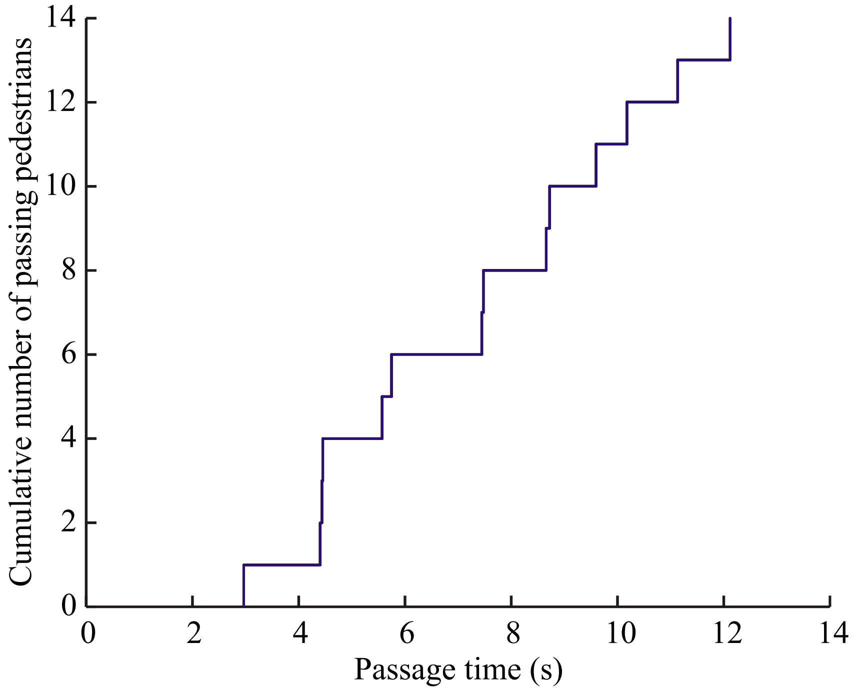


Figure 4.8: Cumulative curve at $x = 7.0$ m in experiment 4

At each time instant t when a pedestrian passes cross section x, the speed of this pedestrian is measured as well. The density at spot x and instant t is then derived from the fundamental relation between speed, flow, and density:

$$k(x, t) = \frac{q(x, t)}{u(x, t)} \tag{4.3}$$

These data have been aggregated for a fixed number of pedestrians (here $N = 30$) passing cross section x. Usually, an aggregation is performed on a fixed period of time, but this may result in a very low number of observations when flows are low. Therefore, an alternative data aggregation method has been applied where fixed sample sizes are considered. From a statistical point of view, this method offers important merits, as is described in Hoogendoorn (1999).

Fundamental diagram for narrow bottleneck experiment

Fundamental diagrams for normal conditions have been constructed from the data of the narrow bottleneck experiment (experiment 10), since this is the only experiment for which the congestion part of the fundamental diagram may be estimated. The cross-sections on which speeds and flows are derived are situated both inside ($x = 4$ m) and upstream ($x = 7$ m) of the bottleneck. Figure 4.9 shows the three fundamental diagrams (speed-density diagram in figure 4.9a; speed-flow diagram in figure 4.9b; flow-density diagram in figure 4.9c).

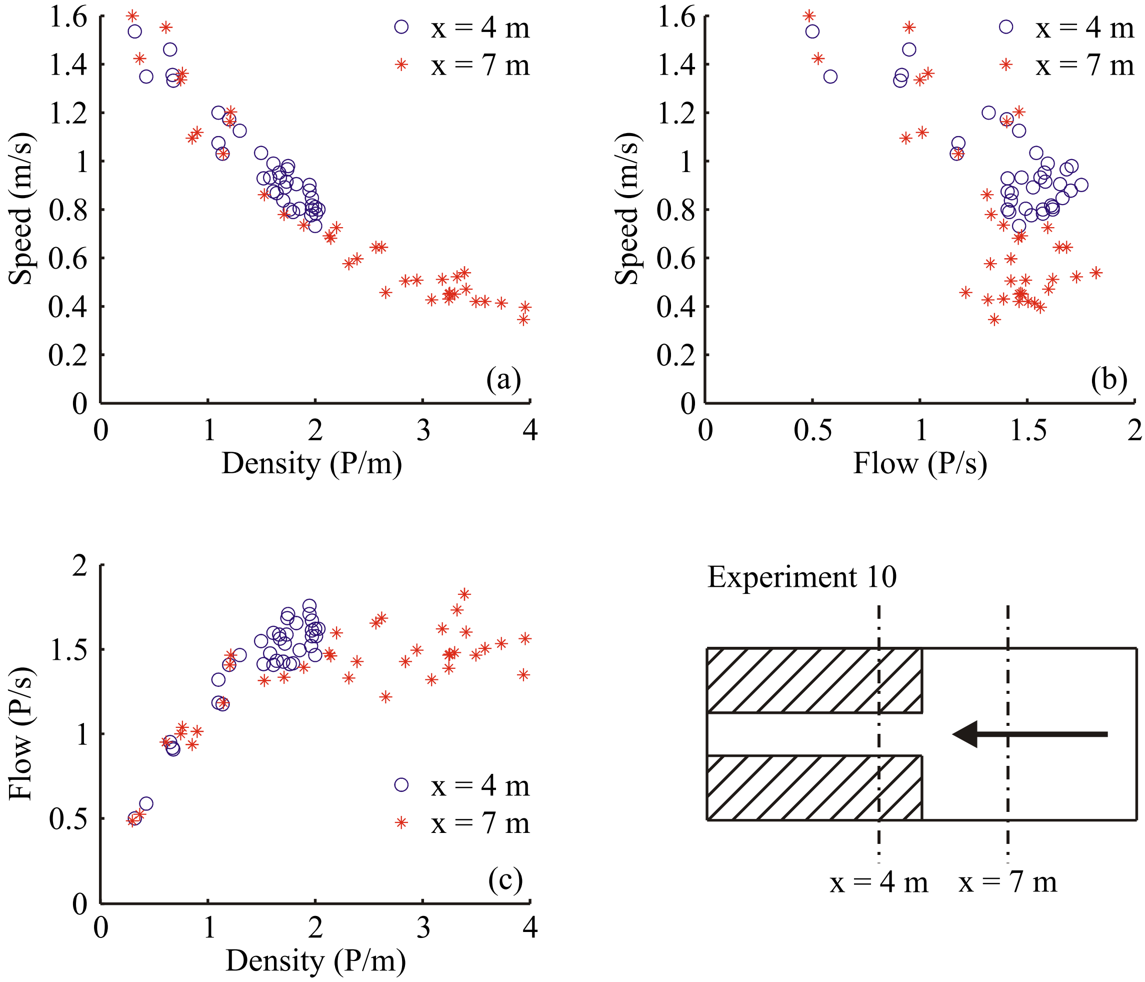


Figure 4.9: Fundamental diagrams of the narrow bottleneck experiment

Although congestion occurs, pedestrians continue walking with speeds higher than 0.4 m/ s. All three diagrams indicate an oversaturated bottleneck, in which variance of the traffic flow variables is noticed. In order to see whether pedestrian behaviour changes over time, figure 4.10 shows speeds, flows, and densities during the narrow bottleneck experiment for both cross sections. First, flows increase, until after some 300 s the bottleneck becomes oversaturated. This capacity situation is maintained during 400 s. After 700 s, free flow conditions are regained, as speeds increase again, while flows decrease. During the capacity situation, both density and speed are slightly decreasing over time, but not sufficiently to conclude that pedestrian behaviour has changed during the experiment.

Let us reconsider figure 4.9, where the large variability of the congested measurements is remarkable, especially in the flow-density diagram. To this end, an analogous situation in

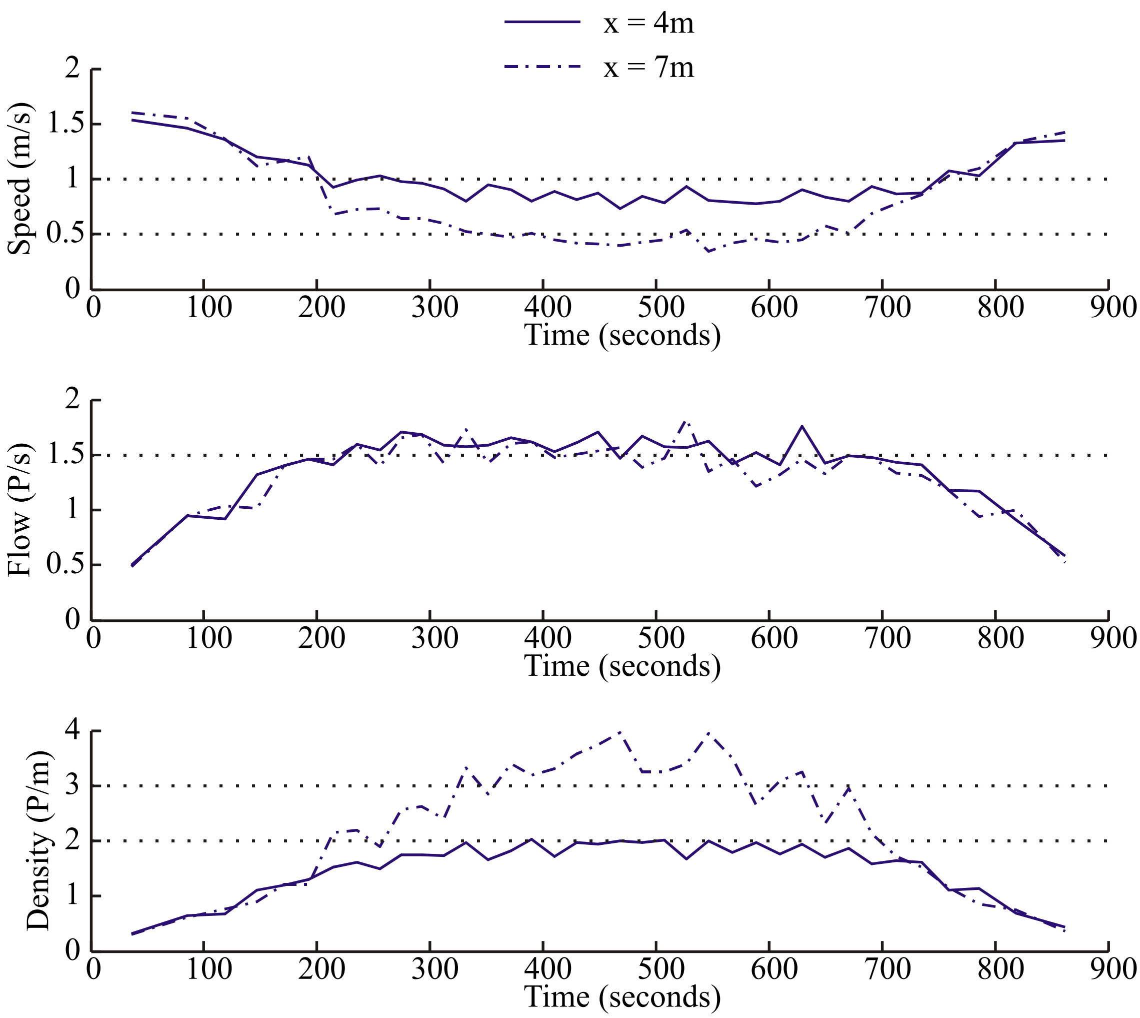


Figure 4.10: Speeds, flows, and densities in the narrow bottleneck experiment

car-traffic is considered, using shockwave theory.

Figure 4.11 shows the flow-density relation for car traffic. The situation is a lane drop of a two lane road, being similar to the narrow bottleneck experiment. Two fundamental diagrams are applied: one fundamental diagram for the two lane part of the road upstream of the bottleneck and another fundamental diagram (dash-dotted line) inside the bottleneck, after the lane drop. During small flows, the free flow part of the fundamental diagram is observed (solid ellipse in figure 4.11). When the flow increases until the bottleneck capacity is reached, congestion occurs upstream of the bottleneck and observations are found on the congestion part of the two-lane fundamental diagram (dotted ellipse in figure 4.11).

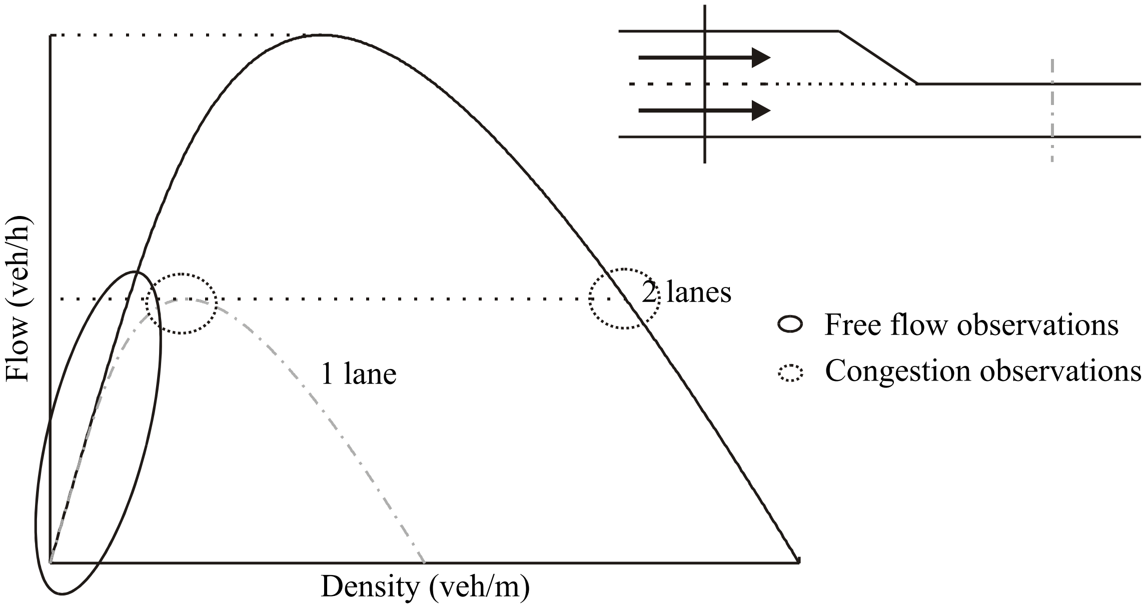


Figure 4.11: Traffic flow theory for car traffic

However, in the flow-density diagram of figure 4.9 the congestion observations in front of the bottleneck do not appear to bo concentrated around a single point in the phase space. Figure 4.12 shows the flow-density diagram for pedestrian traffic in the narrow bottleneck experiment. Again, flows and densities have been determined at two cross-sections. The solid fundamental diagram is valid for the total width upstream of the bottleneck ($w = 4$ m), while the stripe-dotted fundamental diagram applies inside the bottleneck ($w = 1$ m). However, when pedestrians do not occupy the complete width of the area upstream of the bottleneck, another fundamental diagram applies. Therefore, for each width between 1 m (bottleneck width) and 4 m (complete width of the area upstream of the bottleneck) a different fundamental diagram may be applied. Figure 4.12 shows several flow-density relations, all having a similar form, but applicable for different widths.

The flow-density diagram of figure 4.12 is valid for the total width. However, also a fundamental diagram may be derived per metre width. Figure 4.13 shows these two fundamental diagrams and indicates the corresponding locations of different points in the diagrams.

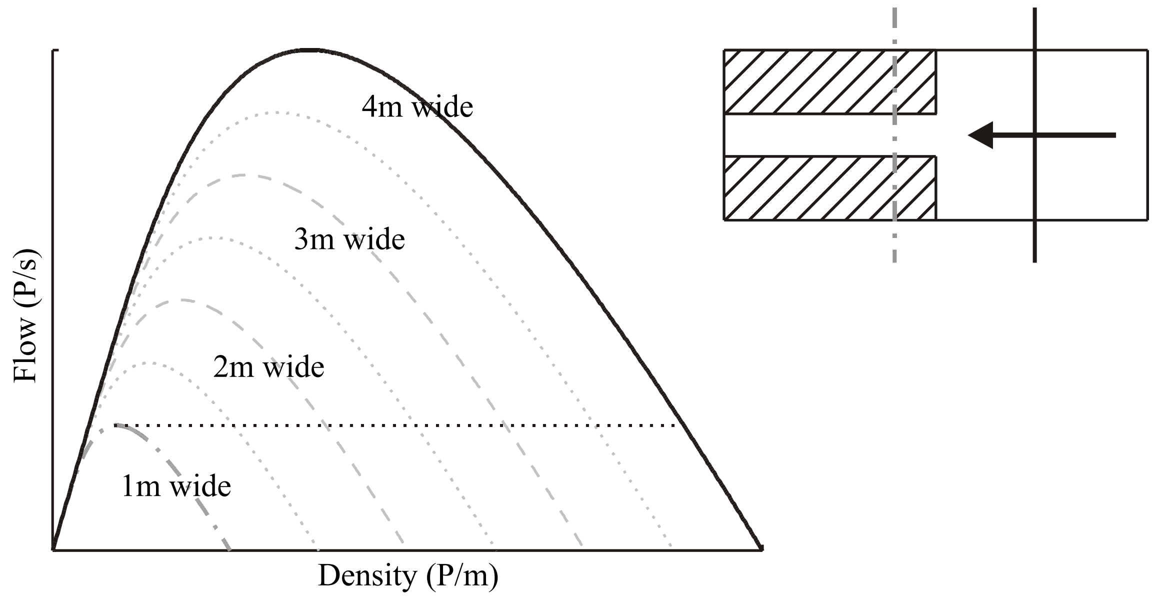


Figure 4.12: Traffic flow theory for pedestrian traffic

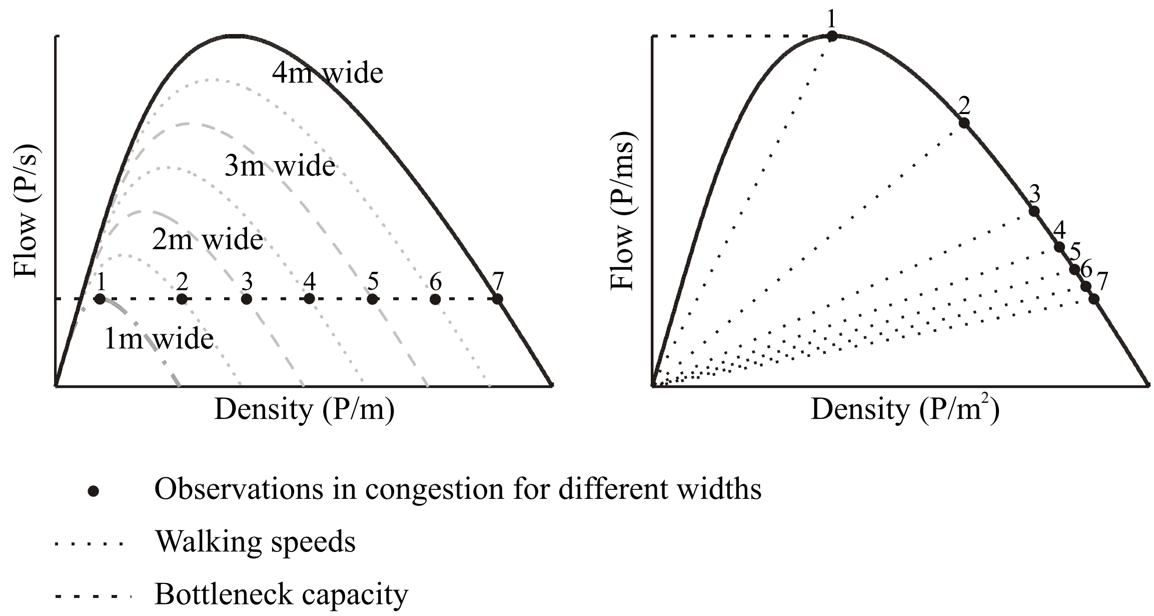


Figure 4.13: Comparison of the flow-density diagram for the total bottleneck width and the flow per metre width

The width used by pedestrians upstream of the bottleneck is thus very important to be able to derive a proper fundamental diagram. Figure 4.14 gives an overview of various pedestrian trajectories during congestion. The pedestrians appear to form a funnel-shaped group while waiting to enter the bottleneck.

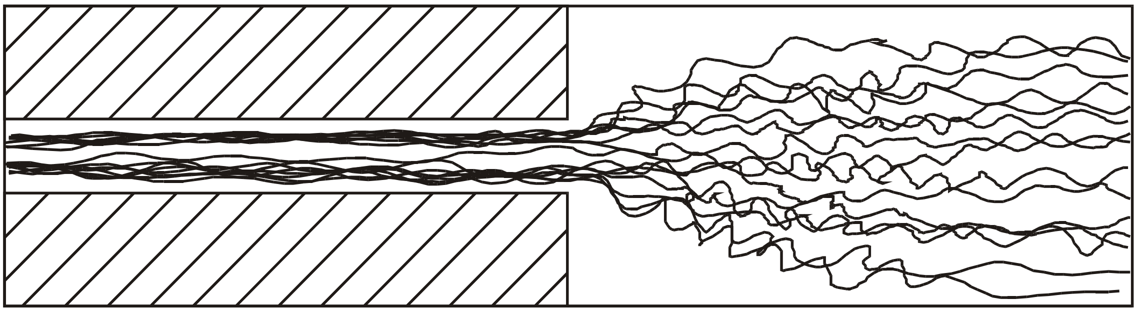


Figure 4.14: Trajectories in space for pedestrians in congestion

However, figure 4.14 only shows trajectories during a very short period of time, whereas figure 4.15 shows the average form that pedestrians adopt during the total congestion period. This figure only shows the area upstream of the bottleneck, which is located on the left side of the figure between the lateral positions $y = 1.5$ m and $y = 2.5$ m. According to the figure, all pedestrians pass the area just upstream of the bottleneck (between $x = 5$ m and $x = 5.5$ m). The further upstream of the bottleneck, the larger width is occupied by pedestrians. However, the outsides of the funnel are only used by about 10% of the pedestrians, whereas most pedestrians use the centre of a cross-section.

Since the density in the flow-density diagram in figure 4.9 is derived from flow and speed (see equation 3.12), figure 4.16 shows the speeds over time in relation to the lateral positions of pedestrians at the cross-section $x = 7$ m, situated upstream of the bottleneck. Each dot in the figure is an observation of a single pedestrian, being categorised in a speed category (see legend of figure 4.16). The horizontal axis shows the time during the experiment. We can see that at low flows ($t < 300$ s and $t > 700$ s) the pedestrian flow is concentrated at the same lateral positions as the bottleneck (lateral position between 1.5 m and 2.5 m). During congestion however, the lateral positions of the pedestrians on the cross section vary significantly. Although figure 4.15 shows a regular distribution of pedestrians over the width, figure 4.16 indicates that this distribution varies significantly over time. Looking at the different speed categories, it is clearly visible that walking speeds are high at low flows, whereas this walking speed decreases in congestion. However, at the outside of the pedestrian flow, pedestrians still encounter free flow conditions (even during congestion) and are thus able to maintain a higher speed.

Figure 4.17 shows the minimum, average, and maximum walking speeds over the lateral position where a pedestrian passes the cross-section at $x = 7$ m. As well as in figure 4.16, it is clear that speeds are higher at the outsides of the flow than in front of the bottleneck. The three lines come together on the right side of the figure, as only during a single time period pedestrians have passed at this position.

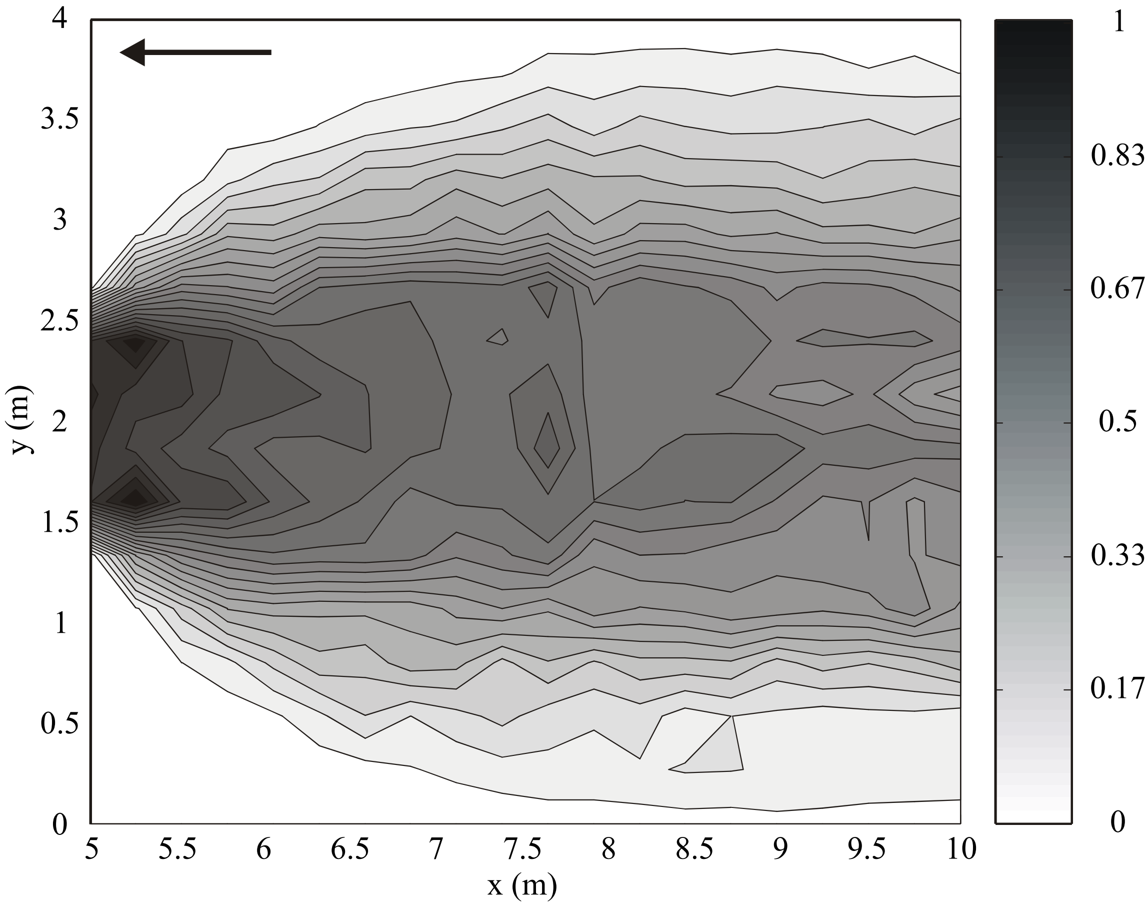


Figure 4.15: Average density of pedestrians in congestion upstream of the bottleneck

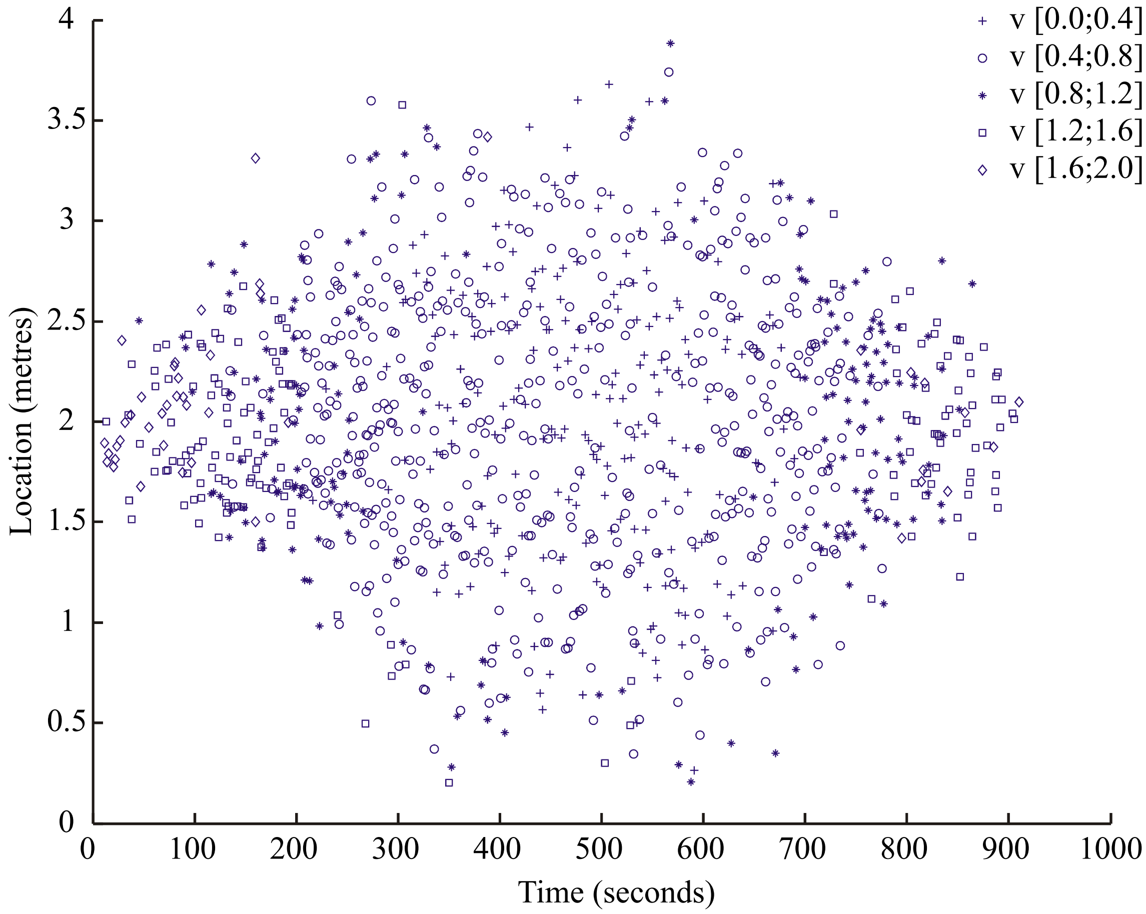


Figure 4.16: Speeds according to the lateral location where pedestrians pass the cross-section at $x = 7$ m for the total simulation period

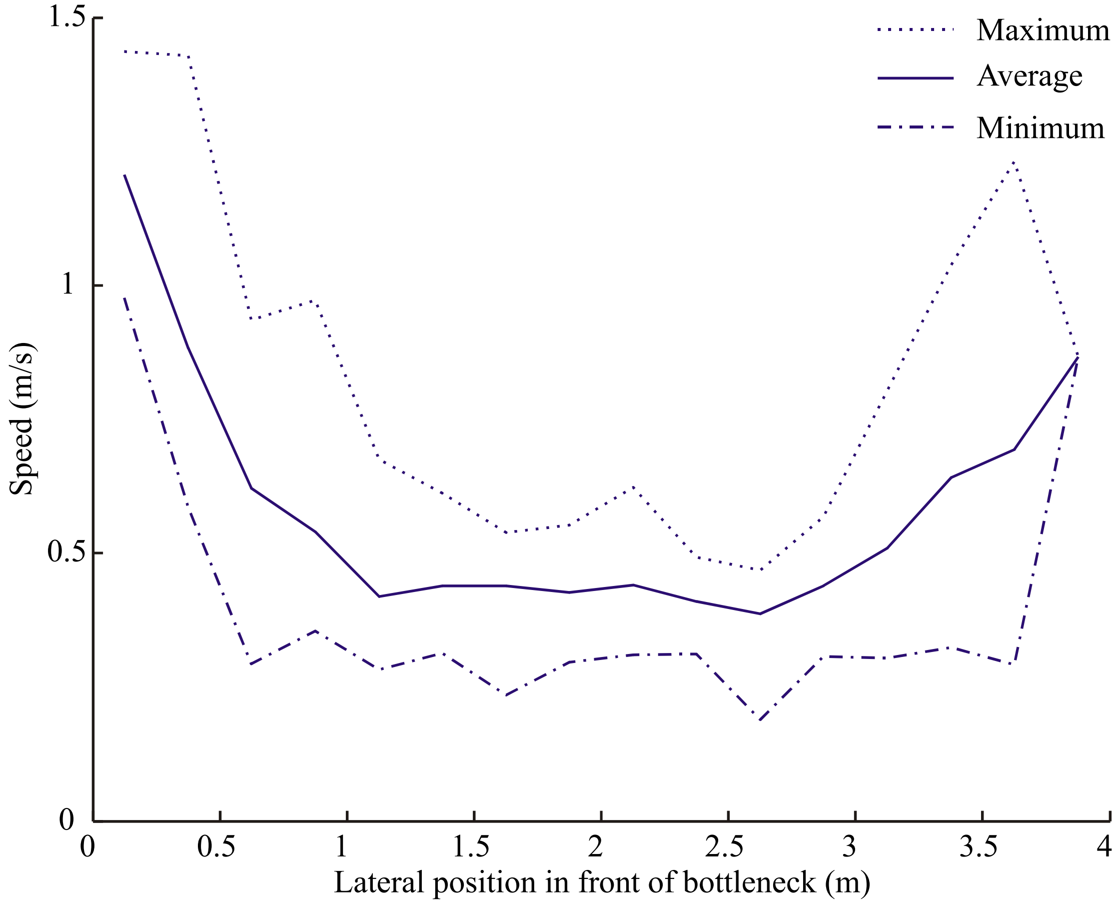


Figure 4.17: Speeds as function of the lateral position in a cross-section for different time periods in congestion

The previous paragraphs have indicated that it is not possible to derive a single flow-density relation for the complete width of an area upstream of the bottleneck. In fact, a number of points may be distinguished, forming together one observation in the flow-density diagram in figure 4.9. This is made clear in figure 4.18. As an example, we have distinguished three equilibrium regions, having similar speed and flow. The two outer regions (with densities k_1 and k_3) are more or less free flow, whereas congestion occurs upstream of the bottleneck (with density k_2). The three observations are indicated in the flow-density diagram by grey dots. However, the observation in the flow-density diagram in figure 4.9 is based on a combination of these three equilibrium points. The result is that the aggregate observation (indicated by the black dot in figure 4.18) may be located anywhere on the horizontal dotted line and does not belong to a specific fundamental diagram. The flow of the aggregate observations only varies slightly, as the flow through the bottleneck will approach bottleneck capacity, which is constant. The congestion part of the fundamental diagram therefore cannot be estimated using aggregate observations for the complete width of a cross-section upstream the bottleneck.

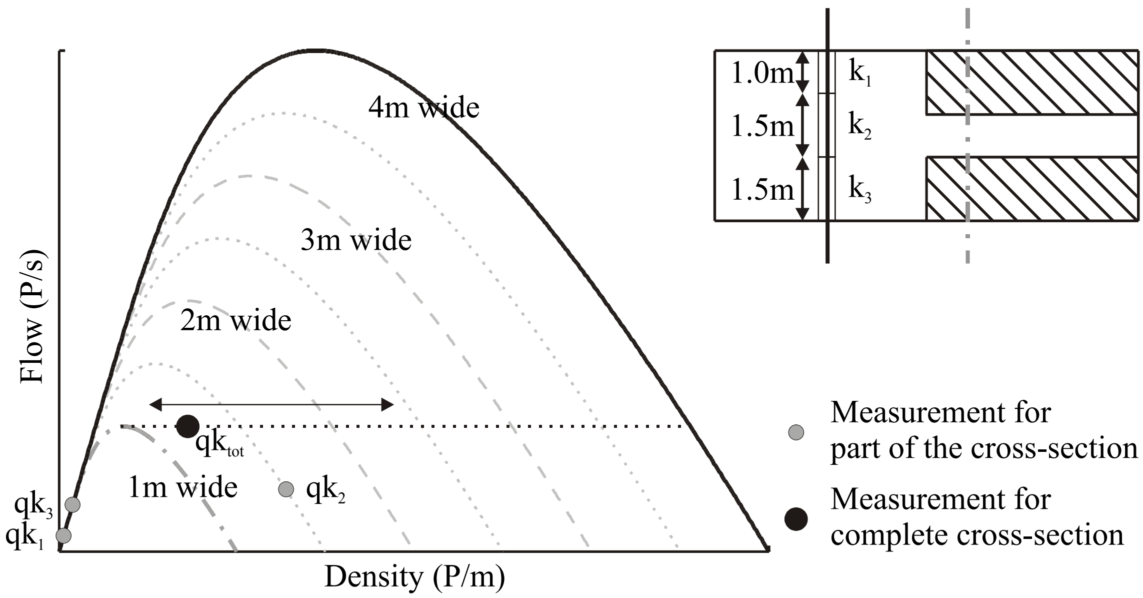


Figure 4.18: Composition of a measurement point in the flow-density diagram for the complete cross-section

4.7.4 Capacity estimates

Congestion occurs when pedestrian traffic demand exceeds available capacity. Capacity is determined by a number of factors, such as width of the bottleneck, wall surface, and interaction behaviour of pedestrians passing the bottleneck. For an elaboration on capacity estimates as described in the sequel, see Hoogendoorn & Daamen (2004).

To assess and improve ways in which walking facilities are used on a macroscopic scale, knowledge is required with regard to the microscopic processes and walking behaviour.

Figure 4.19 shows hypothesised causal relations between microscopic and macroscopic characteristics of pedestrian flows. The figure contains a simplified view to walking behaviour by breaking it up into following, lateral distance keeping, and walking at a certain speed. These microscopic characteristics in turn determine the width of the so-called dynamic layers, and the headways adopted within these layers. From these headways, the dynamic layer saturation flows can be determined. The way in which the layers are used and the width of the bottleneck will determine the capacity of the bottleneck.

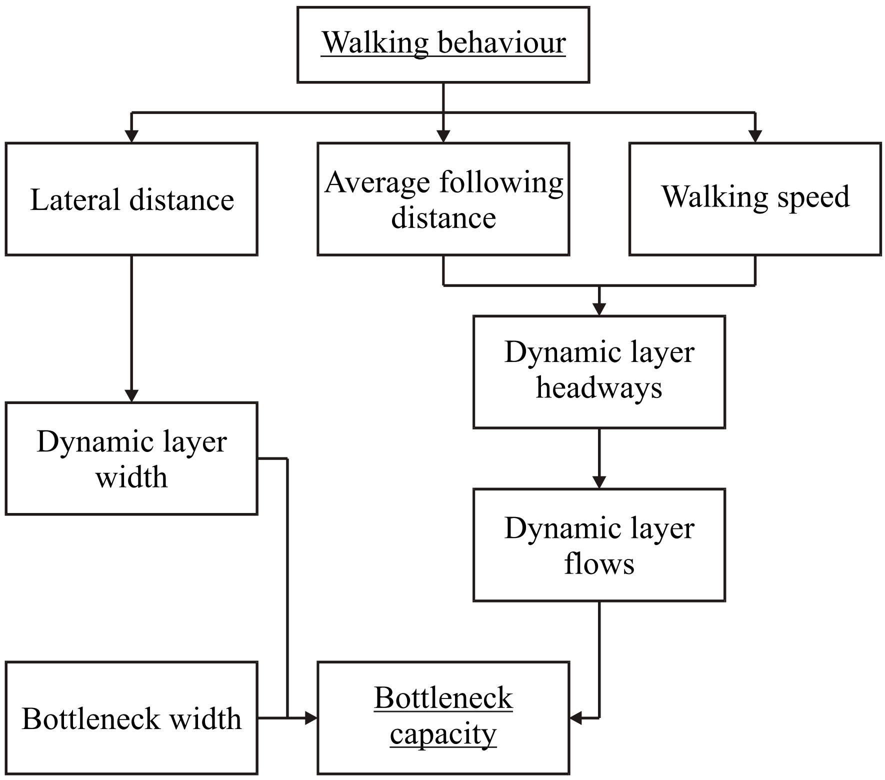


Figure 4.19: Causal diagram of factors affecting pedestrian flow levels and flow distributions (Hoogendoorn & Daamen 2004)

Layer formation

Layers in pedestrian traffic flows may be compared to lanes in vehicles flows. However, pedestrians layers are formed due to self-organisation of the pedestrian flows, whereas lanes are imposed to the vehicular traffic by the infrastructure configuration.

Figure 4.19 also illustrates the assumption of self-organisation of one-directional layers under capacity conditions. The dynamically formed layers are fundamentally different from the lanes formed in two-directional or crossing flows. In fact, the lanes that are formed in a two-directional flow may often consist of one or more layers. The speeds of two adjacent layers are generally equal (approximately 1 m/s), which is caused by the fact that layers are overlapping, that is pedestrians in one layer use up some space in the other layer (with their shoulders) also due to swaying. This overlapping of layers will be referred to as the zipper effect

From the narrow bottleneck experiment it was observed that once congestion occurs, that is when the bottleneck becomes over-saturated, two layers inside the bottleneck were formed. Pedestrian trajectories in the xy-plane clearly show this. Figure 4.20 depicts some of these trajectories collected during different time periods, showing how the spatial behaviour changes when congestion sets in. Upstream of the bottleneck ($x > 5\,\mathrm{m}$), pedestrians will use more of the available space in front of the bottleneck. Some will join the tail of the queue near the middle ($y = 2\,\mathrm{m}$), while others will walk around it. Inside the bottleneck ($x < 5\,\mathrm{m}$), layers are formed as soon as the bottleneck becomes over-saturated. Trajectories of pedestrians in the wide bottleneck experiment also show some layer formation, but traffic demands were not high enough to cause the bottleneck to become over-saturated (Hoogendoorn & Daamen 2004).

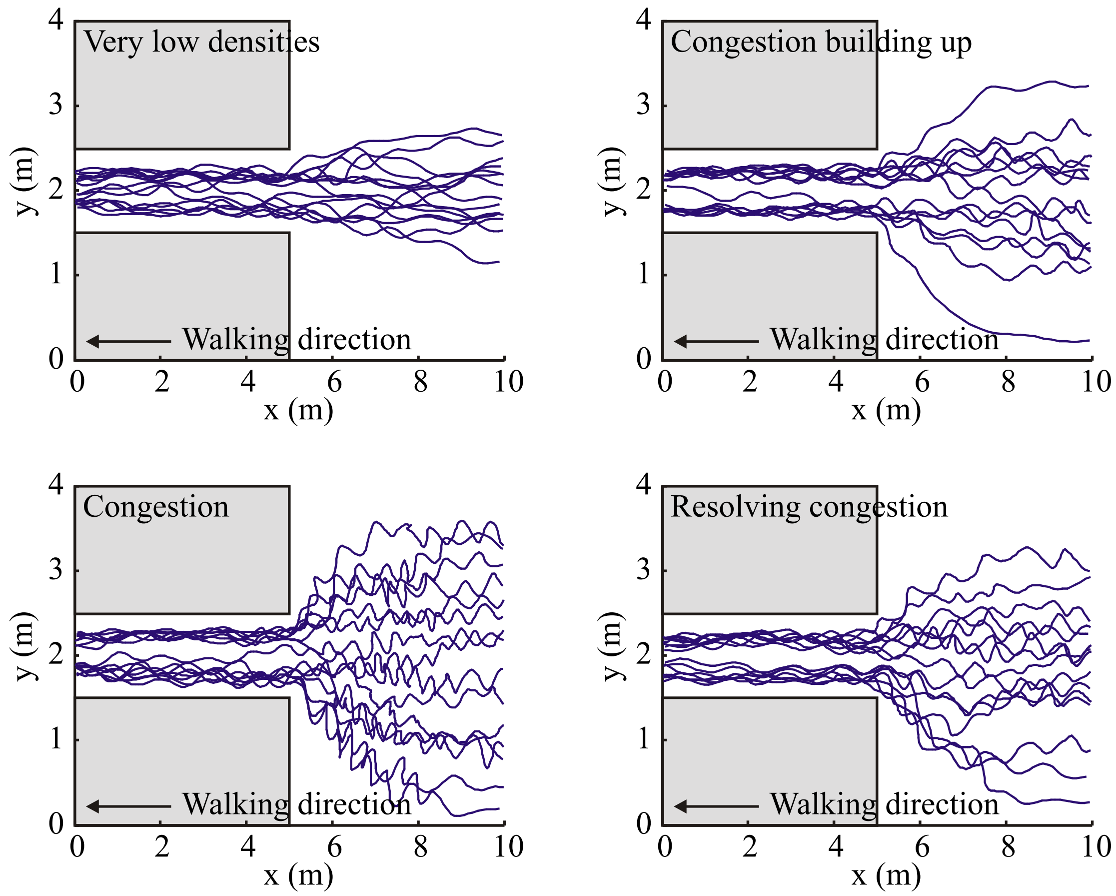


Figure 4.20: Pedestrian trajectories for the narrow bottleneck experiment

From the observations in figure 4.20 it may be concluded that when a bottleneck is operating under capacity conditions, that is when nearly all pedestrians are constrained in their movement and are following their predecessor, dynamic layers are formed. For the narrow bottleneck case, the experimental outcomes suggest that these layers are fixed in terms of their lateral location (located at $y = 2.0 \pm\ 0.22$ m). The lateral centres of the layers have a distance of approximately 0.45 m. Also for the wide bottleneck experiment, the distance between the lateral centres of the layers appears to be about 0.45 m, although the layers last for shorter periods of time.

The lateral distances between the dynamically formed layers also illustrate the 'zipper effect', expressing the fact that the lateral space required by a pedestrian is less than the lateral distances between the layers. The required lateral space is the shoulder width, whereas some additional lateral distance is required due to the swaying motion (see section 3.3). At capacity ($v \approx 1$ m/s), the swaying amplitude is approximately 5 cm, implying that the additional lateral distance equals 10 cm. This implies that the total width taken up by a pedestrian is such that pedestrians inside the narrow bottleneck (in which two layers are formed) cannot pass. A possible explanation of the difference in lateral and longitudinal space needed is that a pedestrian needs sufficient space to take a step, but needs relatively little lateral space to do so. Pedestrians in adjacent layers will hence not interfere, but the pedestrian directly ahead will.

Headway estimation / capacity

To gain more insight into the pedestrian following behaviour, this behaviour is analysed by estimating a composite headway distribution model, distinguishing between constrained (or following) pedestrians and unconstrained (or freely moving) pedestrians. First step is to determine which leader q is actually followed by pedestrian i. Let t_i denote the time pedestrian i passes the cross-section x; let $y_i(t_i)$ denote the lateral position of i at instant t_i. The leader of i is the pedestrian with the largest index $q < i$ for which

$$\left| y_q\left(t_q\right) - y_i\left(t_i\right) \right| \leq 0.5 w_i \tag{4.4}$$

where w_i is the width of a pedestrian. The headway h_i of pedestrian i is then defined by

$$h_i = t_q - t_i \tag{4.5}$$

Figure 4.21 depicts the definition of the time headways. It also shows the headway S_i of i with respect to the first pedestrian q' in the adjacent layer (the so-called lead gap), and the headway G_i of i with respect to the next pedestrian q" in the adjacent layer (the so-called lag gap).

The semi-Poisson model described in (Buckley 1968) is applied to study the following behaviour of pedestrians, distinguishing between constrained headways and free headways. Free headways are headways of pedestrians experiencing no hindrance from pedestrians ahead, thus being able to walk at their free speed. The distribution of the free headway is usually determined by drawing the analogy with a Poisson-point process. Consequently, the free headway is assumed exponentially distributed.

Constrained headways are headways of pedestrians following pedestrians in front that, since no direct overtaking opportunity exists, force constrained walking. The headway

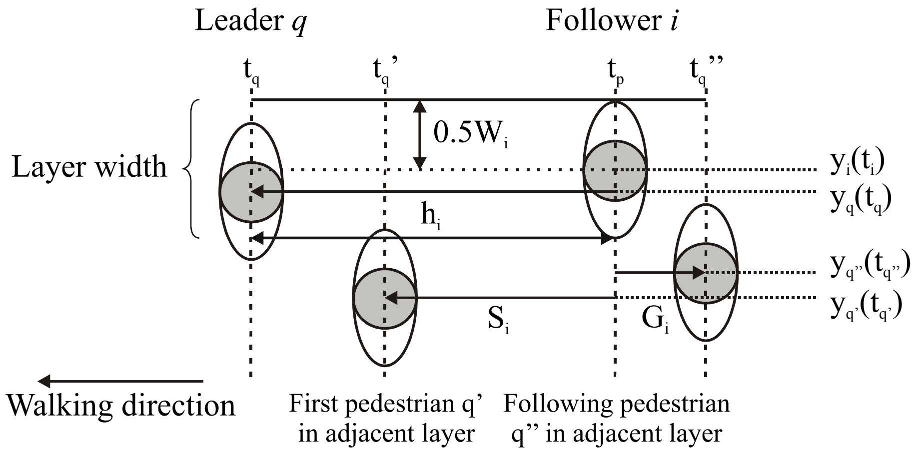


Figure 4.21: Definitions of time headways (Hoogendoorn & Daamen 2004)

will fluctuate around a *desired minimum headway*, the so-called empty zone. It is assumed that different pedestrians will adopt different empty zones. Causes for these inter-personal variations are among other things subjectiveness in what is perceived as comfortable, differences in walking purpose, but also differences in kinematics (such as step size and frequency). Additionally, no pedestrian is able to maintain the same empty zone all the time, and thus the headway of a constrained pedestrian will fluctuate around a desired minimum headway (intra-personal variations). For a detailed description of the application of the composite headway model of Buckley see Hoogendoorn & Daamen (2004).

The estimate for the free arrival rate in case of the narrow bottleneck is not reliable due to the large fraction of constrained pedestrians (only 4% of the pedestrians are walking freely). The capacity estimate determined using the composite headway model is in line with the capacity estimates determined from the bottleneck saturation flows.

The results in table 4.6 indicate that composite headway distribution models can be successfully used for one-directional pedestrian flows, given the headway definition presented in figure 4.21. The concept of the empty zone (constrained headway) makes sense, as does the notion of constrained walking; both can thus be applied to pedestrian flow modelling and analysis.

Table 4.6: Composite headway model estimation results for different experiments

	Narrow bottleneck	**Wide bottleneck**	**No bottleneck**
Free arrival rate (1/ s)	0.356	0.685	0.202
Fraction constr. peds (-)	0.956	0.623	0.276
Mean empty zone (s)	1.282	1.288	1.364
Capacity (P/ m/ $layer$)	0.780	0.776	0.733

Amongst the conclusions that can be drawn from the observations and estimation results is the fact that for one-directional flows, the bottleneck capacity will not be a linear function of the bottleneck width, but will increase in a step-wise manner. This implies that general design guidelines (Weidmann 1993), namely that the capacity of the bottleneck can be determined by its effective width multiplied by the unit width capacity, do not hold.

To determine the capacity of a bottleneck in case of a one-directional flow, first, the effective width of the bottleneck is determined, and subsequently the number of layers that can be accommodated by this effective width. The minimum effective width of a bottleneck must encompass at least one layer, and must hence be larger than the expected maximum shoulder width of a pedestrian (say, 50 cm), assuming that wider pedestrians will take up some of the unused bottleneck width w_{unused}. For example, this means that in case the bottleneck surface is made of concrete ($w_{unused} \approx 25$ cm), the gross width of a bottleneck that can accommodate one layer equals $50\,\text{cm} + 50\,\text{cm} = 100\,\text{cm}$. To be able to serve more than one layer, an additional 40 cm effective bottleneck width is needed for each additional layer.

Following this line of reasoning, a bottleneck with an effective width of 80 cm can accommodate only 1 layer. The capacity of this bottleneck would be 0.78 P/ s (see table 4.6). A bottleneck with an effective width of 90 cm can accommodate two layers, and thus has a double capacity of 1.56 P/ s. In the discussed narrow bottleneck experiment (width of 1 m), two layers are formed. The required effective width is thus $2 \times 25 + 40 = 90\,\text{cm}$. The soft surface of the obstructions making up the bottleneck was such that pedestrians apparently needed only a few centimeters distance between themselves and the obstruction. The headway distribution based estimate of 1.56 P/ s is very near the product limit method estimate of 1.61 P/ s for the capacity of the narrow bottleneck, showing the validity of the proposed approach.

Derived from the above, the following expression can be used to determine the capacity of a (one-directional) bottleneck

$$C = C^y \cdot \left\lfloor \frac{w^e - \left(w_i^{max} - w^y\right)}{w^y} \right\rfloor = C^y \cdot \left\lfloor \frac{w^e}{w^{lane}} - \frac{w^{max}}{w^y} + 1 \right\rfloor \tag{4.6}$$

where $\lfloor x \rfloor$ denotes the smallest integer near x, C_l indicates the capacity of a layer, w_i^{max} denotes the maximum shoulder width of a pedestrian ($\sim$ 50 cm) and w^y denotes the lateral distance between two layers ($\sim$ 45 cm). Relation 4.6 (visualised in figure 4.22) applies to relatively narrow bottlenecks (up to 3 m); for wider bottlenecks, the linear relation between bottleneck width and capacity may be equally appropriate, since the formed layers will be less stable.

4.8 Route choice behaviour in train stations

The aim of the study described in this subsection is to estimate parameters of a utility function describing route choice behaviour as well as to identify the influence of pedestrian and trip characteristics on this route choice behaviour (Van de Reijt 2004). This

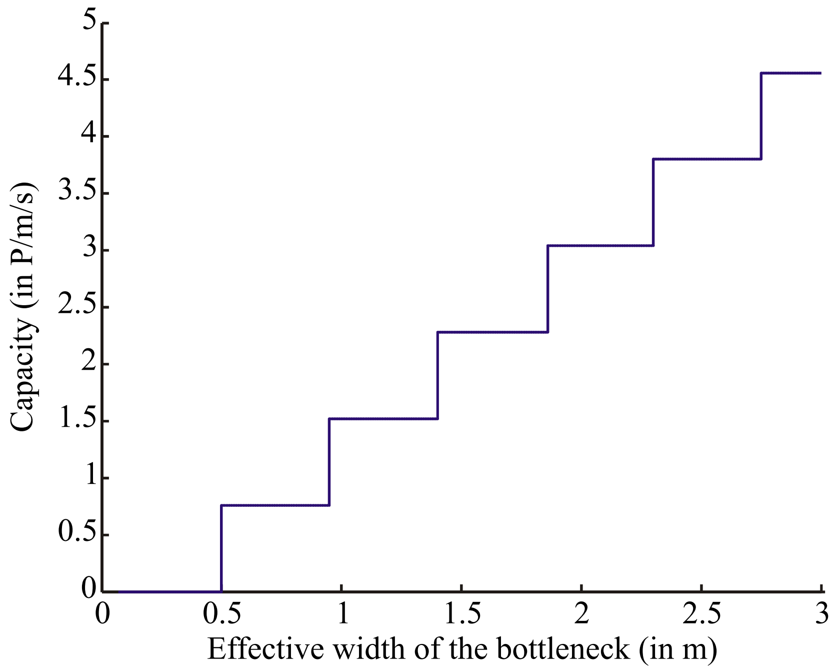


Figure 4.22: Relation between the effective width of the bottleneck and the corresponding capacity

utility function has the following form:

$$U_r = V_r + \varepsilon_r \tag{4.7}$$

where U_r the utility of a route r; V_r is the systematic utility component, while ε_r indicates the error term. The systematic part consists of a number of variables influencing route choice behaviour. After a literature study, the variables which may be included in the utility function concern walking time T_r^{walk}, route length L_r, route overlap PS (path-size), coverage of areas, height difference, and type of infrastructure bridging these heights (stairs, escalator, lift).

To estimate the parameters of this utility function and to determine which factors influence pedestrian route choice behaviour in transfer stations significantly, observations have been collected in the railway stations of Delft and Breda. The method used was 'stalking', that is following pedestrians from their origin to their destination within the station area. For each followed pedestrian several characteristics are registered: origin, destination, followed route, total walking time, gender, age category, amount of luggage, and the type and duration of activities performed during the trip in the station area.

In Delft, 68 choice situations have been distinguished, for which in total 745 observations have been collected, whereas in Breda 180 observations have been collected for 48 choice situations. The height difference in Delft was limited and could only be bridged by slopes and (short) stairs, whereas in Breda pedestrians had to choose between the staircase and the escalator to arrive on the platform. The average size of the choice set was larger in Delft (3-4 route alternatives) than in Breda (2-3 alternatives).

Choice models in the following categories have been estimated:

- Reference models (complete data set with and without overlap factor, Delft, Breda).
- Walking times distinguished for different types of infrastructure (level elements, stairs upwards and downwards, escalator upwards and downwards, and slopes upwards and downwards).
- Person characteristics (men/women, age categories, with/without luggage).
- Observation conditions (weather, day, moment of observation).
- Combined models, combining the four aforementioned categories.

The most important influencing factors appeared to be the walking time (T_a^{walk} on level elements, T_s^{walk} on stairs, T_m^{walk} on escalators, and T_r^{walk} on ramps) and the overlap factor PS, for which the following parameters have been estimated on the complete data set:

$$U_r = 3.10PS - 0.14T_a^{walk} - 0.27T_s^{walk} - 0.19T_m^{walk} - 0.19T_r^{walk} + \varepsilon_r \tag{4.8}$$

The accuracy of this estimated model appeared to be 75.7%, which is relatively high. For more results of this study see (Van de Reijt 2004).

4.9 Conclusions

This chapter described laboratory experiments performed to increase the insights into pedestrian behaviour in general and on pedestrian walking behaviour specifically.

Original in this research is the adopted set up and performance of controlled laboratory experiments to develop more detailed insights into pedestrian behaviour. The conditions of the laboratory experiments are fully controlled among other things by giving specific walking tasks to subjects. Influences of specific experimental variables may thus be measured separately. The experimental variables free speed, walking direction, bottleneck width, density, size of the experimental area and pedestrian distribution over each of the mentioned experimental variables have finally been selected.

New tracking techniques have been developed to establish trajectories automatically.

After establishing pedestrian trajectories, free speeds have been estimated using the product limit method, which was the first time it was applied to the determination of pedestrian walking speeds. The estimated free speed of the reference experiment (see table 4.5) is somewhat higher than in observations described in literature (1.45 m/ s versus 1.34 m/ s), while the variance appeared somewhat smaller (0.23 m^2/s^2 versus 0.37 m^2/s^2). For opposite flows, the mean walking speed was found to be somewhat smaller than for one directional flows. All speeds appear to be normally distributed.

One of the new findings is that traffic flow theory for pedestrian traffic differs slightly from traffic flow theory for cars. Cause for this phenomenon is the fact that pedestrians are not restricted to lanes, but may choose a random route through the infrastructure. During congestion, the width occupied by the pedestrians upstream of the bottleneck varies over time. Over this occupied width, different conditions are encountered by pedestrians: on the outsides free flow conditions occur, while only directly in front of the bottleneck congestion conditions are observed. Observations of speeds and flows upstream of the bottleneck over the total occupied width are thus combination of several observations in different conditions.

Another finding from the experiments is that capacity estimates show that the relation between the width of a corridor and its capacity is not linear, as is often assumed, but looks more like a step-wise capacity function, at least for bottlenecks of moderate width (less than 3 m). It is shown how pedestrians inside bottlenecks effectively form layers or trails, the distance between which is approximately 45 cm. This is less than the effective width of a single pedestrian, which is around 55 cm. The layers are thus overlapping, the 'zipper' effect. The pedestrians within these layers follow each other at 1.3 s, irrespective of the considered experiment. For the narrow bottle-neck case (width of one metre) two layers are formed; for the wide bottleneck case (width of two metres), four or five layers are formed, although the lifespan of these layers is rather small.

In the following chapters, the information presented here will be used for the development of models underlying a simulation tool for pedestrians in transfer stations.

Chapter 5

Identification of processes and elements in a pedestrian flow model

5.1 Introduction

The aim of this research is to develop a tool to aid designers and planners in assessing designs of pedestrian facilities and transfer stations, in particular from the passenger's point of view as well as to support planning of timetables for public transit services. The aim of this chapter is to identify the functional elements and processes influencing pedestrian behaviour in public transport facilities, which therefore will be included in the simulation tool.

Relevant processes to be modelled are identified by applying normative pedestrian behaviour theory, and by referring to literature as well as observing in practice. A combination of these methods has been used in order to have a sufficient overview of all relevant processes. Chapter 3 forms the basic source for the literature review, whereas the observations in a train station described in appendix E contribute to the practical part. Furthermore, general observations have been made by visiting a variety of transfer stations and observing the pedestrian activities there.

Within the simulation tool, different (behavioural) models describe various pedestrian behaviours in public transport facilities. Examples of these models are the route choice model, the pedestrian' movement model and the boarding model, describing the process of pedestrians boarding a public transport vehicle. The combination of all these different models is one of the main contributions in this research.

Classification of the processes has been based on levels of pedestrian behaviour. Three levels have been distinguished, namely the strategic level for long-term decisions, the tactical level for medium term decisions, and the operational level for decisions for the next moment.

Another contribution is that all corresponding types of processes are modelled in a similar way in order to assure comparable levels of detail for all processes. Two main types of processes are distinguished, namely choice behaviour and receiving services. Choice behaviour concerns the decisions of a pedestrian during his stay in the station, e.g. regarding routes and activities to perform. This choice behaviour is modelled using the subjective utility maximisation paradigm. All service facilities of a station are interpreted as service systems with a distribution for service times, a number of service points and consequently waiting times and waiting queues. This applies among other things for (transport vehicle) doors, walkways and service facilities.

Section 5.2 starts with some theoretical background on principles used in the station decomposition. Section 5.3 describes the system decomposition, both from a functional and a spatial point of view. In section 5.4 a station is decomposed into its basic elements, following normative pedestrian behaviour theory. A definition and extensive description of these elements is given in the subsections of section 5.5, including the characteristics of the elements. A further elaboration of the normative behaviour theory indicates relevant processes at each behavioural level (section 5.6), where each subsection is devoted to a specific process. The chapter ends with a summary and conclusions (section 5.7).

5.2 Theoretical background

Pedestrian facilities are buildings, pieces of equipment and infrastructure areas built particularly for pedestrians, in order to facilitate walking and service purposes in general to perform all kinds of activities.

In a transfer station, components of public transport are integrated, such as tracks and platforms, arriving and departing public transport vehicles with different types of rolling stock, manifold passenger flows, and various types of services. One of a station's main functions is serving travellers, for example to board, to alight, to transfer, for ticketing and for information. Passenger stations offer access to public transport services and form even in simple circumstances intermodal junctions between rail and road. Transfer stations become more and more inter- and intramodal nodes to accommodate transfers between car, bus, rail, and air traffic systems, whose convenience, attractiveness and time passing opportunities for passengers form essential factors in their travel choices.

Airports offer access to air services. Nearly always they consist of a public area before check-in, where both travellers and non-airport related pedestrians are allowed (such as 'meeters' and 'greeters') and a private area after check-in and passport control. This area contains shops, catering facilities, and waiting areas. Travellers are in this area while waiting for the departure of their plane. Their walking and shopping behaviour is far less directed and intentional than in transfer nodes. Moreover, while most travellers do not fly on a regular basis, their route choice behaviour deviates from route choice behaviour in transfer nodes in that they mainly rely on information signs and signposts.

It is assumed that pedestrian facilities can be described as a network consisting of nodes and links. In this research, this network is modelled as a queuing network with a limited capacity. Three types of nodes may be distinguished, namely origins and destinations for entering or leaving, activity locations, and nodes connecting different walking links.

Before the decomposition of a facility is considered, underlying behavioural theories and basic aspects of service systems are discussed in short. Subsection 5.2.1 considers normative aspects, section 5.2.2 describes characteristics of service systems, and section 5.2.3 gives details on pedestrian behaviour levels.

5.2.1 Normative behaviour theory

The main behavioural assumption in the normative pedestrian behaviour theory is that all actions of a pedestrian, let it be performing an activity or walking along a certain route, will provide utility (or disutility) to him or her. Pedestrians will predict and optimise the total expected utility, taking into account uncertainty in the expected traffic conditions (similar to microeconomic consumer theory (Frank 2002)). In choosing from available options, a pedestrian tries to realise a maximum net utility, which is the sum of the utilities of performing activities and the disutilities due to the effort of walking towards activity locations. This is called subjective utility maximisation, as each pedestrian has his own subjective view on the situation. Several other decision styles (such as lexicographic ordening (Bovy & Stern 1990)) exist, but this research is confined to the application of subjective utility maximisation. The theory may be described from the point of view of the pedestrian, but also according to the way it is applied in the models. Both descriptions are given below.

Pedestrians have choice sets (see also section 3.2), consisting of alternatives out of which each pedestrian has to make a choice. Alternatives are mutually exclusive ways (possibilities, opportunities). In the choice situation, only feasible alternatives are considered, constituting a feasible choice set. Each alternative is characterised by attributes, which are weighed with a set of parameters, specific for a pedestrian. The pedestrian is assumed to combine the weighted attributes of an alternative to an alternative's utility. This weighted sum expresses the trade-offs a traveller makes between the characteristics of an alternative. The alternative giving the highest utility to this pedestrian is assumed to be chosen. Parameter sets used for each pedestrian will be determined in future observations.

The model identifies the choice situation, of which a feasible choice set is specified, consisting of available feasible alternatives. The model calculates the utility of each alternative, taking into account the parameter set of the considered pedestrian. Based on these utilities, the model calculates the probability of each of the alternatives being chosen. For the choice between the alternatives, different models may be applied, which can be either deterministic or stochastic. A deterministic model gives the alternative with the maximum utility (or minimum disutility). Several probabilistic models exist, such as the logit model (Cramer 1990) and the probit model (Ben-Akiva & Lerman 1985), (Bovy & Stern 1990), (Cascetta 2001). In our developed tool SimPed, in first instance a deterministic method has been implemented, whereas as part of further research other choice models may be applied.

Thus, for each choice process, the following steps are followed:

- Generate a choice set of feasible alternatives.
- Determine attributes of the alternatives, based on prevailing or future traffic conditions.
- Assign weights (parameters) to each attribute.
- Apply the individual utility model.

This chapter only contains qualitative descriptions of the choice processes, while in the next chapter, these choice processes are formalised.

5.2.2 Service systems or queuing theory

All facilities of a station are interpreted as service systems. Characteristics of such a service system are a distribution for service times and a restricted number of servers, leading to waiting times and waiting queues. The capacity is determined by a combination of the number of service points and the service time distribution. The capacity of a facility with 5 service points and a constant service time of 30 s is 600 P/ h.

A single queue may be formed in front of a service facility, independent of the capacity of the facility (indicated as the number of service points in the facility). The pedestrians in this queue are assumed to be served according to the 'first-come-first-served' principle.

A pedestrian arrives at a service facility and joins the queue. When a service point is free, the first pedestrian in the queue is served. The time this takes is indicated by a distribution of service times, which may be specific for each service facility. During this time period the pedestrian keeps the service point occupied. After a pedestrian has finished the activity, the pedestrian continues his route to his (intermediate) destination. If there is no queue when arriving at the facility, the pedestrian is immediately served.

Modelling service systems applies to joints between walkways (such as doors, revolving doors, gates, and turnstiles), service facilities, and walkways (including stairs, escalators, and lifts).

5.2.3 Pedestrian behaviour levels

In normative pedestrian behaviour theory, choices are distinguished at three levels, namely strategic, tactical, and operational. The strategic level includes long-term decisions of the pedestrian, such as choice of activities to be performed and choice of destination. At the tactical level, pedestrians make short-term decisions, based on the prevailing conditions.

The operational level pertains to immediate decisions of the pedestrian concerning his behaviour. Interactions with other pedestrians play an important role at this level.

An overview of the mentioned decision levels, related processes at and interactions between different decision levels are given in figure 5.1. Also, inputs and outputs on each level are indicated in this figure.

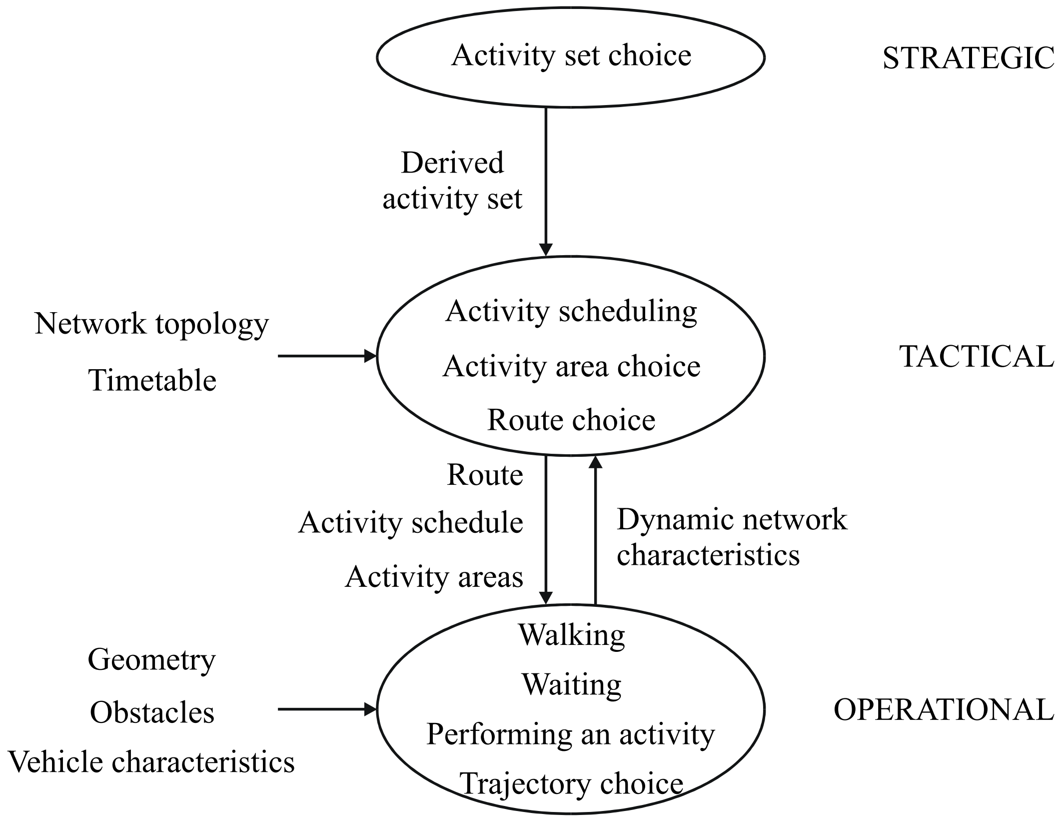


Figure 5.1: Levels in pedestrian behaviour based on Hoogendoorn et al. (2001) and figure 3.1

At the strategic level, travellers decide on the activities to be performed in the station. While some of these activities may be discretionary (e.g. buying a newspaper), others may be mandatory (validating a ticket before accessing a train). The activity choice set may be related to characteristics of the pedestrian as well as of the infrastructure (availability, type and location of shops). At the time of writing, the individual's activity choice set, including the fact whether activities are mandatory or not, is assumed exogenous in SimPed, given in the form of a distribution of various pedestrian types over the activities. The activity choice set contains the maximum number of activities each pedestrian will perform. All other choices at the strategic level, such as mode choice and departure time choice are also exogenous and form input for the simulation tool.

The tactical level pertains to short-term decisions of the pedestrian in the facility, given the choices made at the strategic level. On the strategic level, pedestrians determine a list of activities they want to perform in the transfer node or pedestrian facility. The activities on this list may be performed at different locations. Optimal locations for an individual are chosen on this tactical level. In addition, the route to follow between the pedestrian origin and destination and possible activities (chosen activity areas) is determined at this level.

At the operational level, pedestrians take instantaneous decisions for the immediate next time period, given the choices made at the tactical level. Contrary to Hoogendoorn et al. (2001), walking only includes speed choice, whereas the choice of a pedestrians' walking direction is modelled as a separate processes, namely trajectory choice. Other operational decisions concern waiting and performing an activity (including boarding and alighting in transfer nodes). Pedestrian walking behaviour does not only depend on his personal characteristics, but also on the type of infrastructure he is moving on. Also, obstacles (such as columns and waste-paper baskets) and other hindrances, such as turnstiles and doors influence walking. A pedestrian has various reasons to wait in a station. The most obvious is waiting for the train or another public transport vehicle to arrive, but a pedestrian also has to wait before he is served at a ticket office.

Interactions exist between different processes at each decision level. Figure 5.2 shows an overview of possible interactions between the processes specified in a simulation model for pedestrians in transfer stations. Furthermore, input and output are assigned to individual processes. Processes indicated within the dotted square are endogenous to the model, whereas the input on the left is exogenous.

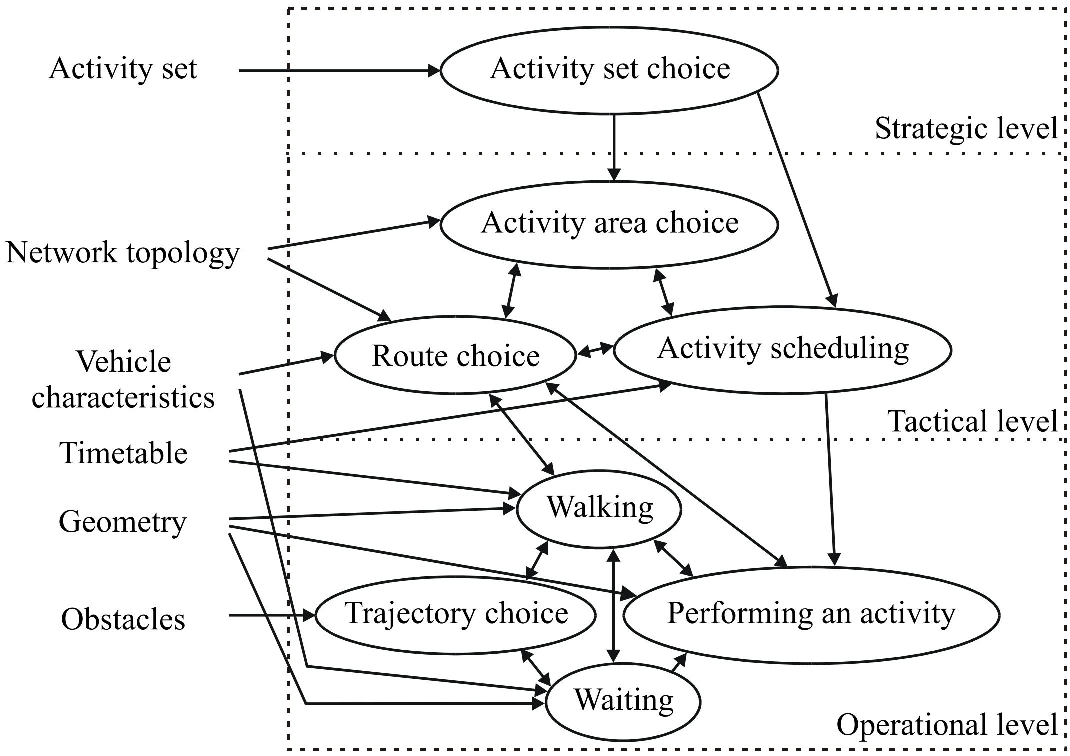


Figure 5.2: Interactions between processes of pedestrians

Focus of the simulation model is in first instance on the processes on the tactical and operational levels. The results of the activity set choice are assumed exogenous and thus are input for the simulation model. Figure 5.2 shows that almost all processes have mutual interactions, indicating that walking influences the performance of an activity, but on its turn, performing an activity influences the walking process. The existence of mutual influences indicates that the modelling of these processes needs to be iterative, which makes the simulation model very complex.

At the moment of writing, only one-directional influences from higher level to lower level processes are modelled in the developed simulation tool, leading to hierarchical decisions shown in figure 5.3. This way, each choice process is assumed independent of other choice processes; only results of earlier choices are taken into account. Also, the adopted process is deterministic, whereas a stochastic choice process would be more realistic. In such a stochastic choice process, the number of alternatives available on lower hierarchical levels leads to a higher probability to choose the corresponding alternative on the higher level. The most realistic process is to perform these choice processes simultaneously, as is indicated in figure 5.2.

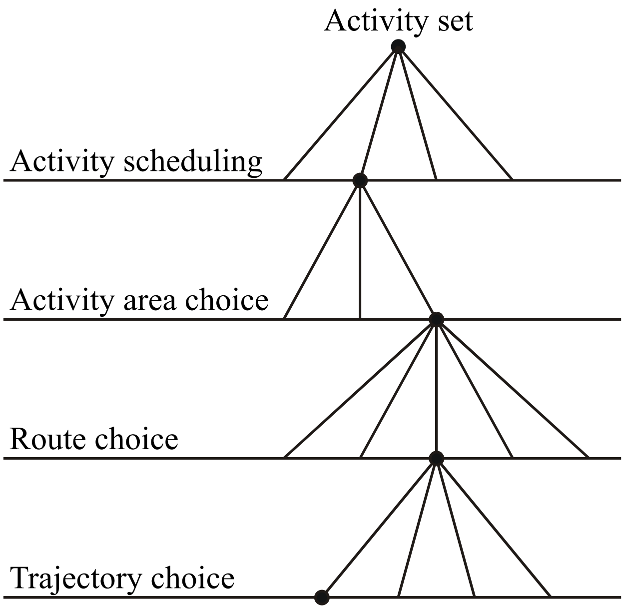


Figure 5.3: Hierarchical representation of decisions of pedestrians

5.3 Decomposition of pedestrian facilities

The decomposition of pedestrian facilities into elements and the relevant processes within these facilities are determined in line with normative pedestrian behaviour theory, pedestrian behaviour levels, and service systems. Both a functional and a spatial decomposition of pedestrian facilities have been performed.

Functional system decomposition

In a public transport facility several functions may be distinguished (Weigelt 1999), namely traffic station (platforms, pedestrian tunnels and overpasses, stairs, waiting rooms, hallways, service points, and (traffic) information points), service and shopping centres (shops, toilettes, stores, hotels, conference centres, sport centres, and health centres) and the forecourt (public transport stops, Kiss & Ride, Park & Ride, taxi-ranks, and facilities for long and short term parking, and rental cars). However, some of these functions overlap, that is services are provided in both the traffic station and the service and shopping centre, while public transport services are available in the traffic station and on the forecourt. Therefore, more specific functions are distinguished in this research:

- Transport facilities for pedestrians (platforms, tunnels, overpasses, stairs, escalators, lifts, hallways).
- Service facilities (service points, waiting rooms, toilettes, (traffic) information points, shops).
- Main transport service (aircraft, train, bus).
- Access / egress services (train, bus, tram, metro, car, bicycle).
- Urban surroundings (sidewalks, traffic signals).

However, not all functions need to be present in a public transport facility (see for example figure 5.5). A schematic overview of the functional decomposition of a pedestrian facility is given in figure 5.4. Arrows indicate possible origins and destinations of travellers using the pedestrian facility. The extent to which the distinguished functions are modelled in a specific study depends on the type of pedestrian facility and the level of interaction between the different functions. For example, in a large train station it may not be necessary to model arrivals and departures of individual buses, but a continuous pedestrian flow to and from the bus platforms may provide a sufficient level of detail; when the bus station is the facility under research, arrivals and departures of buses may be modelled in detail.

The thick lined box in figure 5.4 represents the pedestrian facility, whereas the dotted boxes represent its different functions. The extent to which a function is included in the pedestrian facility model is indicated by the part of its surface within the box. Thus, the model of the pedestrian facility consists among other things of all pedestrian transport facilities and only part of other service facilities.

Pedestrian transport facilities influence pedestrian flows and are thus included in the network description, whereas only those service facilities present in the pedestrian area and influencing pedestrian flows, such as by attracting pedestrians, need to be included in the pedestrian facility model.

In case of a train station, the main transport service is public. Public transport services consist of vehicles, timetables, infrastructure for boarding and alighting of passengers,

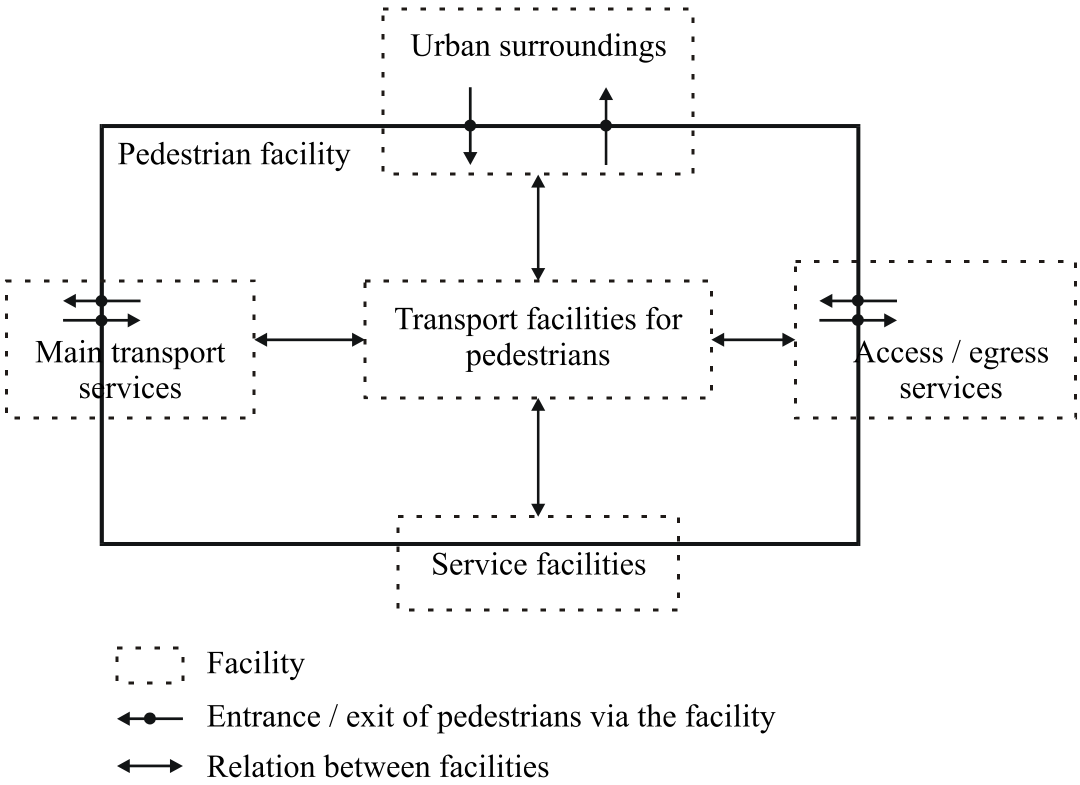


Figure 5.4: Generic functional decomposition of a pedestrian facility

tracks, and other facilities such as communications and power supplies, which all influence pedestrian flows through the station. Vehicle characteristics influence the time it takes for passengers to board and alight, while the timetable determines scheduled arrival and departure times of vehicles, and infrastructure for boarding and alighting indicates locations where pedestrians enter the system, including the exact stopping position of the train.

Station access and egress services can be both private (car, bicycle, or walk) and public (bus, tram, or metro). Public access and egress services have the same characteristics as the main (public) transport service and may be modelled in a similar way without loss of generality. Individual access and egress services do not follow a timetable and often require specific storage locations, such as car parks and bicycle storage locations. The actual storage process is treated as exogenous in SimPed; parking locations are considered to be origins and destinations of pedestrians in the system to be modelled.

Urban surroundings may be important for the pedestrian facility, especially for the size and direction of pedestrian demand indicated in an origin-destination table (which is exogenous to the simulation model). More and more, planners and designers attempt to integrate pedestrian facilities in their urban surroundings. Interactions between pedestrian facilities, especially transfer nodes, and their surroundings increase, so that an overview of the total area (both pedestrian facility and urban surrounding) is relevant. The extent to which the urban surrounding has to be taken into account depends on the individual situation being among other things based on the size of the pedestrian facility, the type of pedestrian facility, the type of surroundings, and the location in the city. In SimPed, it is therefore possible to include some part of the urban surroundings in the network model.

Three ways of entering and exiting the pedestrian facility are included in figure 5.4, that is via the main public transport mode, via access and egress modes or as a pedestrian walking from or into the urban surroundings. The functional decomposition of two specific examples of pedestrian facilities, namely a multimodal transfer node (A) and a shopping centre (B) are shown in figure 5.5.

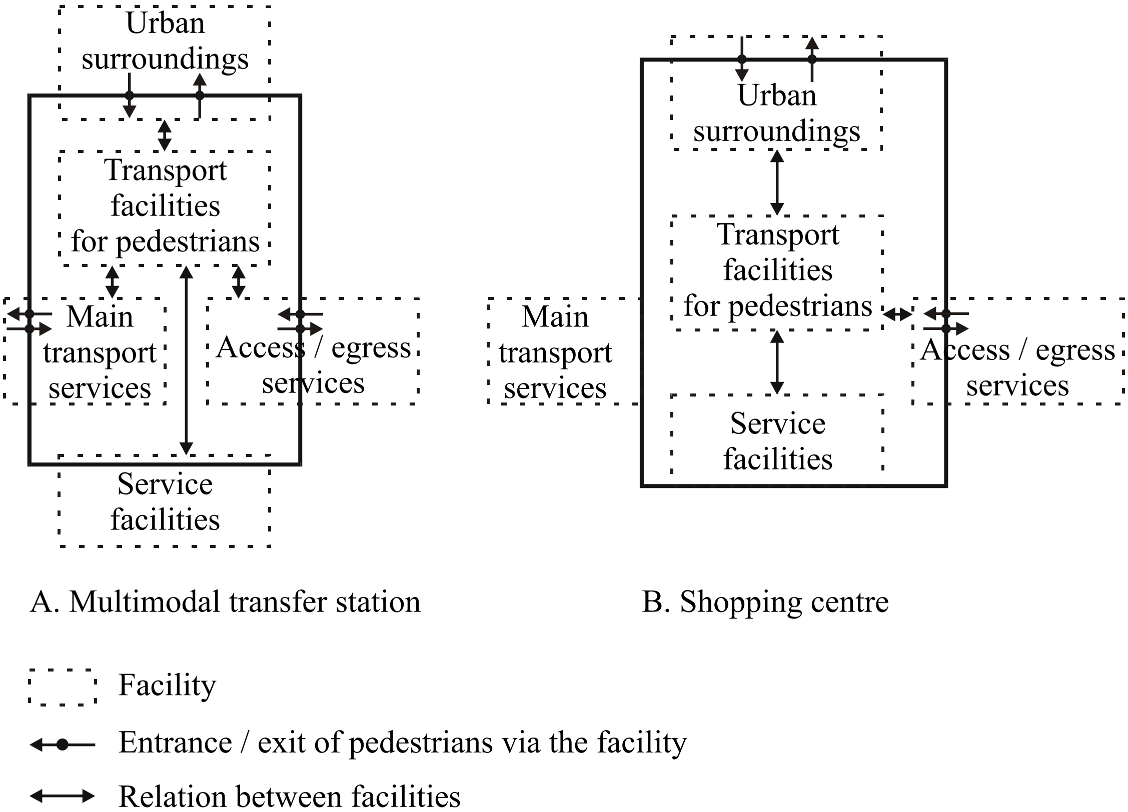


Figure 5.5: Functional decomposition of a multimodal transfer station and a shopping centre

Spatial implications

The functions of a pedestrian facility take place at different locations between which transportation of pedestrians is needed. This subsection deals with the spatial implications of the proposed decomposition.

Essential for the spatial implication are locations of functions in a three dimensional space, physical joints between functions (the infrastructure for the movement of pedestrians), and distances between the functions using the infrastructure. Functions are assigned to areas (an area may contain one or more functions). Each area has a location and dimensions (and the corresponding surface). Two areas are coupled by one or more joints where pedestrians may enter or leave an area. An example of a spatial system view with the functions described in the previous section is shown in figure 5.6. Each function is shown as a elliptical area, whereas transportation facilities for pedestrians are shown as dotted rectangles. Thick lines indicate joints between facilities.

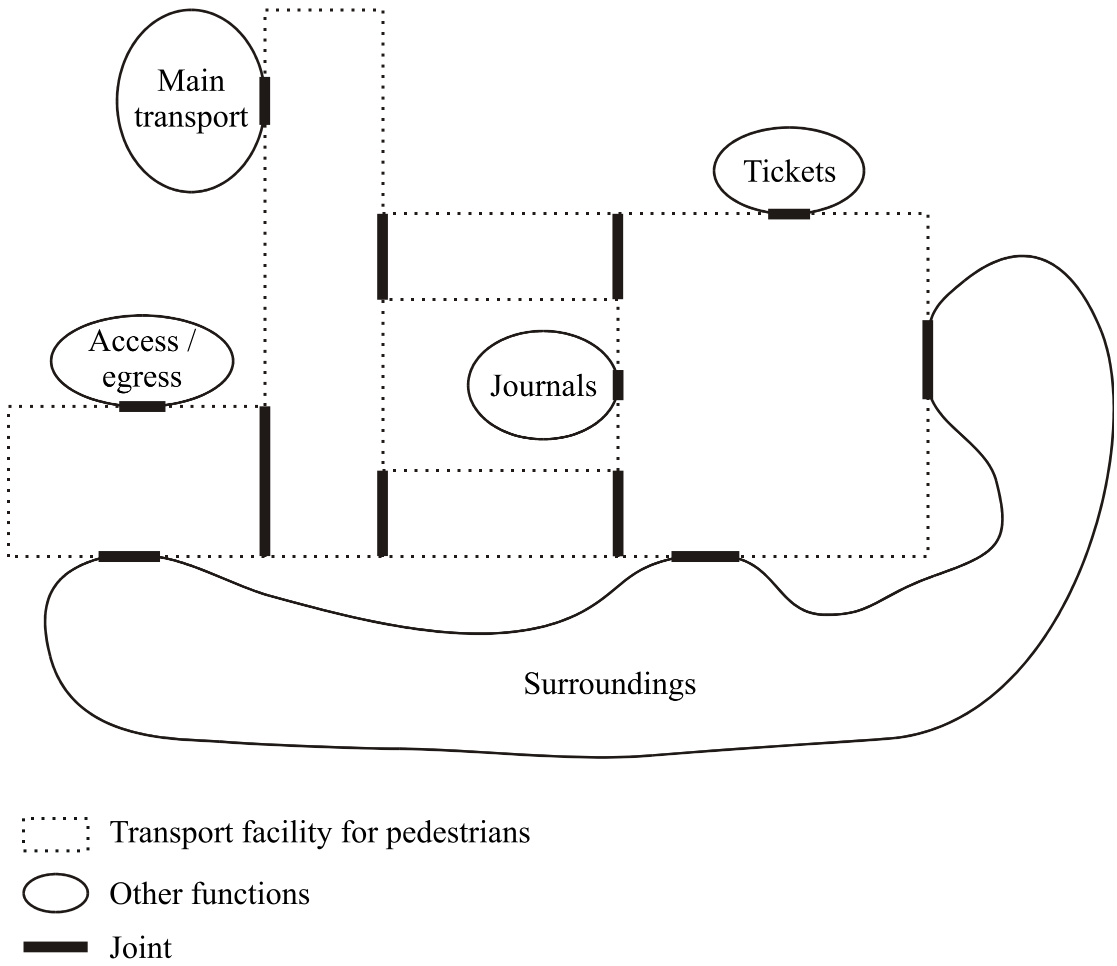


Figure 5.6: Example of a spatial system view of several functions

Levels of detail

In a simulation study different aspects of a design may be assessed. These aspects necessitate different spatial levels of detail in the simulation model. These levels of detail are connected to stages of the design process. In the early planning stage only a little input data is available and the model is used to determine the surface needed for walking (to facilitate pedestrian flows with a sufficient level of service). In later stages of the design, the simulation model is used to produce more detailed information, demanding the infrastructure be modelled on a more detailed spatial level. The same reasoning is valid for different parts of the modelled area. Some parts are modelled in detail, whereas others are only used as an entry and exit for the model. Of course, the modeller has to anticipate the fact that by using a more aggregate level of modelling, potential bottlenecks may be overlooked. A solution may then be to develop a separate model for this part of the infrastructure.

Figure 5.7 shows three levels of detail for spatial modelling of a car-parking and a bicycle storage location as a part of a pedestrian facility.

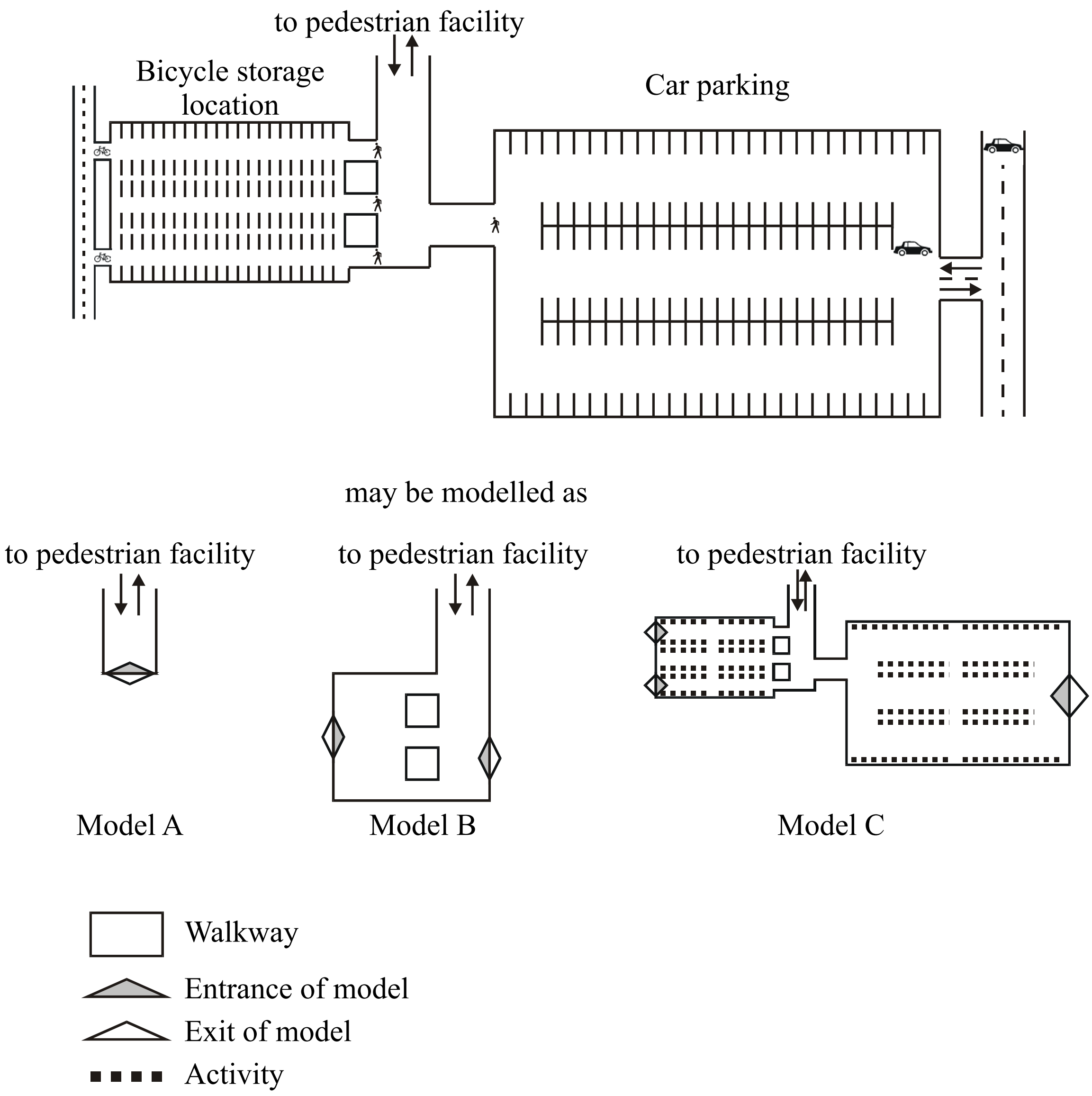


Figure 5.7: Different levels of spatial specification of a bicycle storage location

Model A has a very low level of detail, in which both bicycle storage location and car parking serve as an entrance and exit for the pedestrian facility. In model B, the distribution of the pedestrians over the bicycle storage location and the car parking is taken into account, including the distribution over the three entrances/exits of the bicycle storage. Model C includes the total area, in which parking and retrieving bicycles and cars is included in the simulation model as an activity. Model C may be used to design the walking infrastructure inside the car parking and the bicycle storage location and the distribution of parking bays and bicycle racks over the area.

5.4 Elements in a pedestrian facility

This section presents a functional division of a pedestrian facility based on section 5.3 and serves as a qualitative description of elements as a basis for the detailed object model described in chapter 7. This section identifies relations between the functional elements deduced in the previous section. Characteristics of these elements are described in section 5.5, whereas interactions between these real life objects (also called processes) are described qualitatively in section 5.6.

In section 5.3 five basic types of elements of a pedestrian facility are distinguished. These may be grouped into facilities and public transport services. Facilities consist of all parts of the transport facilities for pedestrians, the service facilities, and the urban surroundings, all being modelled as services. The main transport services and access/egress services together form public transport services. Non-public transport related access/egress services are modelled as part of the surroundings (see also figure 5.7). Public transport services are split up into platform tracks, indicating the stop location of the vehicle for boarding and alighting of passengers, the public transport vehicle, and a timetable describing scheduled arrivals and departures of these vehicles. The most important element in a pedestrian flow simulation model is of course the pedestrian. These three elements and their interrelations are depicted in figure 5.8.

The three element categories are depicted as large dashed rectangles. Elements are subdivided into element classes, indicated by smaller dash-dotted rectangles. Arrows indicate relations between elements and element types of different element categories (e.g. a pedestrian walking over an escalator). Elements of element types within one element class may also have interactions, such as slow pedestrians causing faster pedestrians to either slow down or to start a passing manoeuvre.

5.5 Definition of modelled elements

In this section, the distinguished elements of a pedestrian facility (pedestrians, facilities, and public transport services, see section 5.4) are qualitatively defined and relevant characteristics for the simulation model are described. These characteristics describe an element statically. Dynamic element characteristics, including dynamic processes concerning these elements, are described in section 5.6. These descriptions are not meant to be comprehensive, but rather show which characteristics are to be included in the simulation tool. These characteristics then form a starting point for the models described in chapter 6. Again, only the processes relevant for pedestrian flows are included in the models.

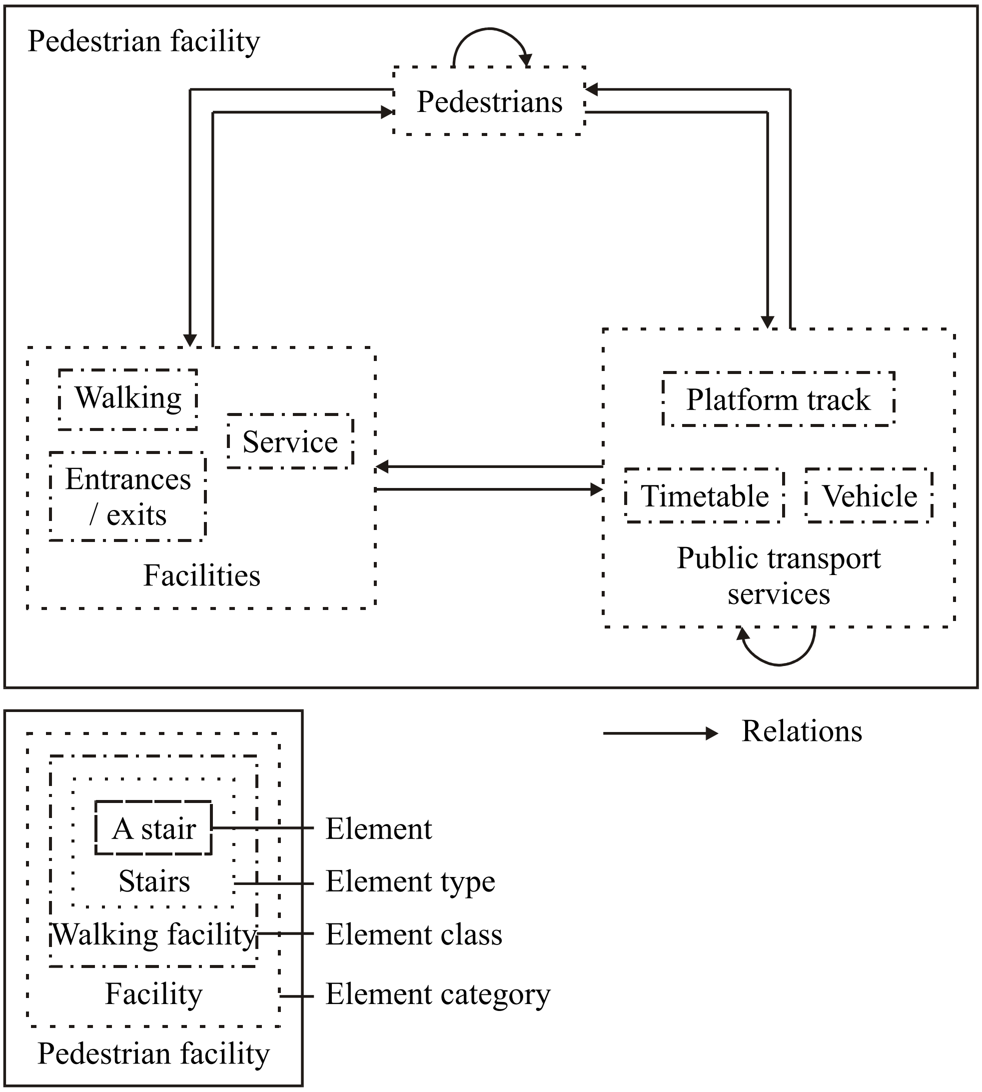


Figure 5.8: Elements and element categories in a pedestrian facility model

5.5.1 Pedestrians

A pedestrian is a traveller, who is walking, waiting, being served or navigating in the pedestrian facility, thereby continuously making choices with respect to activities, activity areas, and routes.

From a walking point of view, each pedestrian has the following behavioural characteristics:

- *Space occupation*. Pedestrian space occupation may be described with different forms, varying between circles, ellipses and rectangles. Most important are size and width of a pedestrian (what width does a pedestrian need to pass a door and how close can pedestrians walk behind each other). These measures also lead to the required area of a pedestrian, which is used to calculate the density on the infrastructure and thus the pedestrian's level of service.

- *Free speed*. Each pedestrian has a specific speed he wants to walk with when no disturbances in his environment occur (low density and common infrastructure). This speed can differ according to the mood of the pedestrian and the external conditions, such as weather or the need to catch a train. Also, free speed is influenced by gender, age, and physiology of a pedestrian. It is assumed that in constant exogenous conditions, this free speed will remain approximately equal.

- *Familiarity* with the environment. The familiarity of a pedestrian with his environment is especially important for his route choice behaviour. Specific influences of this familiarity are described in subsection 5.6.1.

Actions performed by a pedestrian may be described at different levels of detail, for instance a detailed microscopic description, including interactions between individual pedestrians or a macroscopic description of pedestrian flows.

In the walking model proposed later in the thesis (section 6.5), fundamental diagrams are used to model pedestrian movement behaviour macroscopically. In chapter 4, these fundamental diagrams have been derived for a number of specific situations and have been compared with literature. Pedestrian movement behaviour differs according to type of walking infrastructure. Different fundamental diagrams are therefore used for macroscopic modelling.

Other characteristics of pedestrians concern among other things route choice behaviour. Each individual is assumed to have:

- An origin and a destination.

- A desired activity set.

- Restrictions with respect to their walking behaviour. Pedestrians with disabilities are not able to use escalators and stairs, leading to an extra parameter in the route choice process.
- Fixed or flexible arrival time at destination. Pedestrians having to catch a train have to be at the platform some time before the actual departure of this train. They will therefore be limited in the amount of (optional) activities they can perform.
- Familiarity with the environment. This pedestrian characteristic especially influences route choice behaviour. Pedestrians familiar to the environment are able to make a well-founded choice, based on route characteristics, whereas tourists and other unknown pedestrians first look for displays indicating arrival and departure times, platforms of public transport vehicles, area plans and other information signs. Their route choice will be based on provided information and directional information signs.
- Hurry. Pedestrians in a hurry (for example to catch a train) have slightly deviant walking behaviour. They have higher free speeds, pass other pedestrians sooner and closer, avoid less conflicts, walk on escalators and tapis roulants, and will sooner choose to take the stairs instead of the escalator (different route choice behaviour).
- Personal preferences for attributes of alternatives. These preferences are input for all choice models.

As far as possible, values for these characteristics will be based on literature and observations. Otherwise, the model uses default values in a probability distribution.

5.5.2 Public transport services

Public transport services are the main public transport services of the transfer node, but they may also perform for access and egress services. Apart from passengers (see subsection 5.5.1), the distinguished relevant elements of public transport services are vehicles, timetable, and stop facilities. These elements are elaborated in this section.

Vehicles

Public transport vehicles perform services according to a given timetable. In reality however, vehicles do not arrive nor depart exactly at the moments indicated in the timetable. They may arrive early, but often they arrive and depart late. Actual moments of arrival and departure are characterised by delay times distributions. When the scheduled departure time of a vehicle has come, and the boarding and alighting process has not yet finished, the vehicle will wait until this process has finished and will leave afterwards. In the context of the model, trains, metros, trams, buses, and ferries are distinguished as public transport vehicles.

Characteristics of vehicles (also called multiple car units) relevant for the modelling of passenger processes are for instance total vehicle length, and number of cars, and for each car the number of doors and the door characteristics, such as width, times for pedestrians to board and alight, and times needed to open and close doors.

Timetable

A timetable determines planned arrival and departure times of vehicles at stops. It is characterised by type of service (local, regional, or national) and destination station, rolling stock (number and type of multiple car units), planned arrival and departure times per vehicle and the platform (number of the platform and the stopping position of the rolling stock).

Both type of service and destination of a service are important for passengers having missed their service. They have to find the next departing train in the desired direction, stopping at their destination station.

Platform track

Public transport infrastructure consists of basic facilities such as tracks, platforms, communications, power supplies and buildings, which enable public transport services to function properly. In this thesis, only the platform tracks of the public transport infrastructure are important for the interaction between pedestrians and public transport vehicles. With respect to traffic characteristics of vehicles, only the minimum headway is considered to indicate arrival and departure times of passengers in the pedestrian facility. Characteristics of stop facilities in the modelling include location and platform length.

From a passenger's point-of-view using a transport service involves service time and waiting time due to limited capacity of vehicle doors and door characteristics.

5.5.3 Transport facilities for pedestrians

Pedestrian transport facilities are designed to facilitate pedestrians walking from origin to destination possibly using services in between. Transport facilities are divided into categories, based on the walking behaviour of pedestrians. The following types of pedestrian infrastructure are distinguished (CROW 1998):

- Footpaths and split level provisions (footpath, pedestrian foot bridge, deepened pedestrian underpass, semi-deepened pedestrian underpass).
- Ramps and stairs (phased ramp, safety buffers alongside a ramp, guard rail alongside a ramp, stairs, guard rail alongside stairs, overcoming small differences in elevation, overcoming large differences in elevation).

- Obstacles (guidelines, position, shape).

This description takes this classification as a starting point. Most frequently used transport facilities are level walkways. These walkways do not have a height difference and include various elements, such as passages, platforms, tunnels, hallways, arcades and overpasses. Closely related transport facilities are stairs. Pedestrian behaviour on stairs is similar to behaviour on level walkways, but speeds are lower, and differ upwards and downwards. A third category consists of escalators and tapis roulants on which pedestrians are conveyed rather than that they walk themselves. Lifts form a fourth category, with a proper movement cycle and characterised by the fact that pedestrians first have to wait for the lift to appear at the right floor and only then, pedestrians enter and are transported to the desired floor. Finally, joints are distinguished. Joints couple areas and may appear in different appearances, such as empty spaces, turnstiles, and different types of doors. All these types have their typical properties influencing the walking process. For more details on the static characteristics of each of these types of infrastructure see section 7.2.4.

5.5.4 Service facilities

Service facilities are intermediate destinations where pedestrians may perform activities. This can be buying a ticket but also orientation on the route to choose. Two types of facilities are distinguished, namely activity facilities and information signs. This service can be performed by a servant or a machine, or the activity facility offers the possibility of letting the pedestrian serve himself (e.g. information signs).

Activity facilities offer services to pedestrians, such as buying a journal or validating a ticket. Examples of activity infrastructure are ticket machines and kiosks. These facilities are distributed in the building and are considered intermediate destinations.

Activities are characterised by the fact that pedestrians are served, either by a machine or by a person. Furthermore, when the number of service points is not sufficient, it is assumed that pedestrians form queues in front of such facilities, causing hindrance for other, passing, pedestrians.

Each facility is characterised by a service time distribution (time it takes to serve a pedestrian) and a number of service points, determining capacity, waiting times, and queuing characteristics. The waiting time at an activity facility depends on pedestrian demand, capacity, and locations of other available facilities of the same type.

The following characteristics of an activity facility are relevant for modelling:

- Location.
- Number of service points per facility.
- Distribution of service time.

5.6 Definition of modelled processes

In figure 5.2, relevant processes have been distinguished and classified according to the decision levels of the pedestrian (tactical and operational decisions). The decision style assumed in this research is utility maximisation, modelling the ‘pedestrian economicus’ (see section 3.2). In the following subsections, a qualitative description is given of these processes in order to indicate to what extent these processes are modelled in the simulation tool. This section is a qualitative precursor to chapter 6, in which the models included in the simulation tool are described in more detail.

5.6.1 Tactical level

The tactical level pertains to short-term decisions of pedestrians during their stay in the facility. Processes at this level are activity scheduling, activity area choice, and route choice.

Activity scheduling

Starting point for this process is an activity set for the pedestrian, which is input for the simulation model. This list may be ordered (as is assumed in the simulation tool so far) or not. Furthermore, activities on this list can be obligatory or optional to perform. An example of an obligatory activity for a pedestrian willing to use public transport not yet having a valid ticket is buying a (train) ticket. Discretionary activities are characterised by the fact that when a pedestrian is under time pressure (his train is about to leave), he may choose not to perform the activity. Examples of optional activities are buying a journal or a sandwich and walking around in the hallway.

Two types of pedestrians are distinguished to determine the activity schedule, namely those with a fixed (destination) arrival time and those without time constraints. Pedestrians with a fixed arrival time may want to drop optional activities due to a lack of time, whereas ‘flexible’ pedestrians are assumed to perform all activities in their schedule. However, when waiting times become ‘excessive’, pedestrians without constraint may skip this activity. The order in which the activities are performed is determined by a combination of route choice and activity area choice, where the lowest disutility to perform all activities on the list and reaching the destination is the criterion determining the decisions (= subjective utility maximisation). At the moment of writing however, the activity order is exogenous, and thus input for the simulation tool.

An overview of possible results of the activity scheduling process is given in figure 5.9, assuming a fixed order of activities.

When the order of the activity list is not fixed, far more combinations of activities form input for the route choice process and the activity area choice process (examples are O

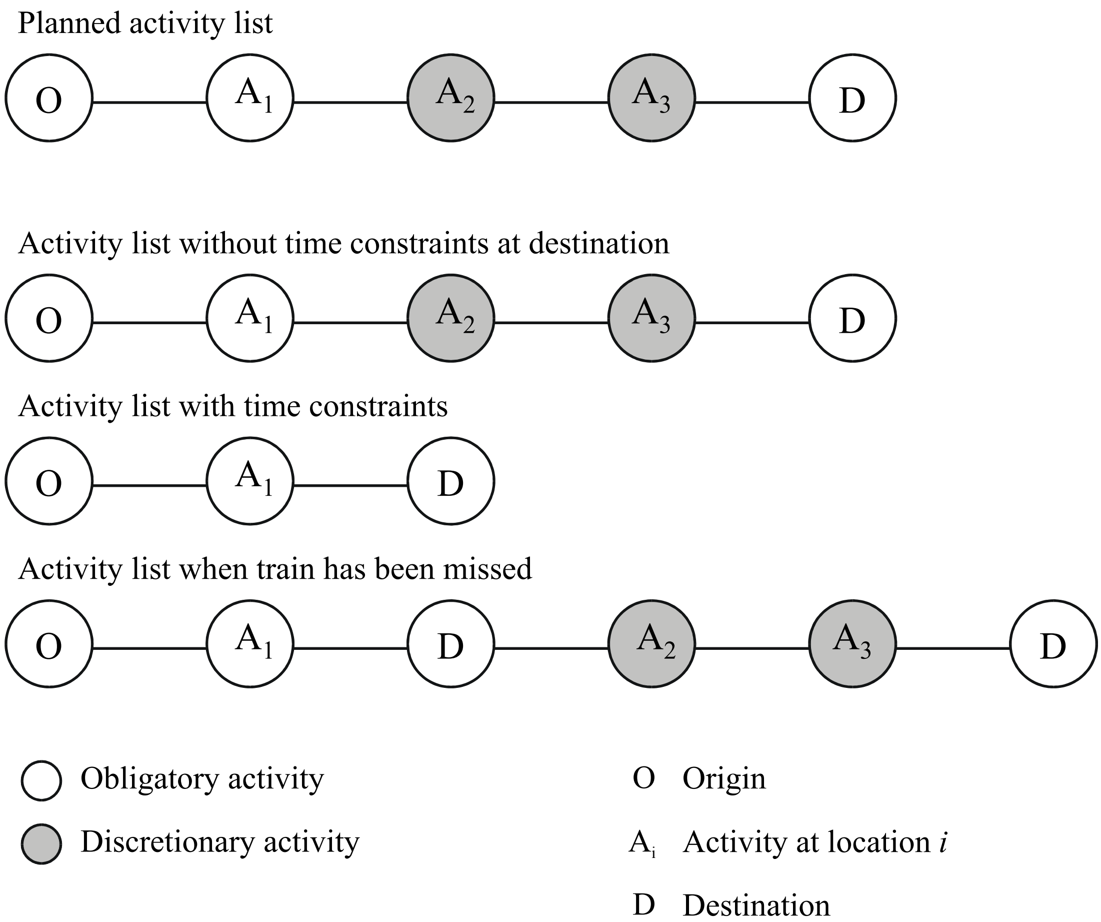


Figure 5.9: Various activity schedules depending on time pressure

– A3 – A1 – D and O – A1 – A3 – A2 – D). The order of the activities may then be determined by the location of the activity areas, their service capacity, waiting times, and the availability of other activities nearby. However, in first instance a fixed activity list order is assumed.

Activity location choice

Each activity in the activity set may be performed at one or more locations. The most important choice criterion (Hoogendoorn & Bovy 2004), (Borgers & Timmermans 1986*a*) is travel time (including walking, waiting, and service times) along the total route passing these activities. However, other parameters do influence choice behaviour, among other things the coherence of activities, the distance between activities (Johnston & Kissling 1971), (Meyer 1977), type and variety of shops (Bennison & Davies 1977), and the pedestrian's awareness of shops (Davies & Bennison 1978). Based on these parameters, a specific choice model may be derived for a general activity location choice model.

In the simulation tool however, *normative* pedestrian theory is used. In this case, pedestrians are assumed to choose those activity locations between which the route has the lowest total disutility. Since the activity schedule is fixed, the utilities of the activities are identical (irrespective of the activity location), assuming similar price and quality of the activity. The utility of performing a particular activity is therefore omitted from the choice modelling. The total disutility is the sum of activity times, which consist of walking time to each activity location (from the pedestrian's origin or the previous activity), waiting times at each activity location, and service times of all activities to be performed. In the simulation tool, the order of the activities is in first instance assumed fixed (see previous section). Also, at one location only one activity can be performed. However, two activity locations can be located very nearby. Whenever activity locations are chosen, they remain fixed for this pedestrian during the rest of his trip. Figure 5.10 shows three possible combinations of activity locations and the order of the activities.

In figure 5.10, three types of activities are distinguished (for example purchasing a ticket, buying a news paper, and visiting a shop). These activities can be performed at different locations, as is indicated in the vertical direction of the figure. At some locations multiple activities may be performed, for example at location 1, the pedestrian can perform activity 1 (purchasing a ticket) and activity 2 (buying a news paper). Depending on the origin and destination of an individual pedestrian, different orders and activity areas are chosen.

Route choice

A route is a chain of nodes, connecting consecutive parts of walking infrastructure (Bovy & Stern 1990), beginning at the origin (or current position) of the pedestrian, passing, if needed, different activity locations and ending at the pedestrian's destination. The specific activity locations are input for the route choice process and are determined in the activity

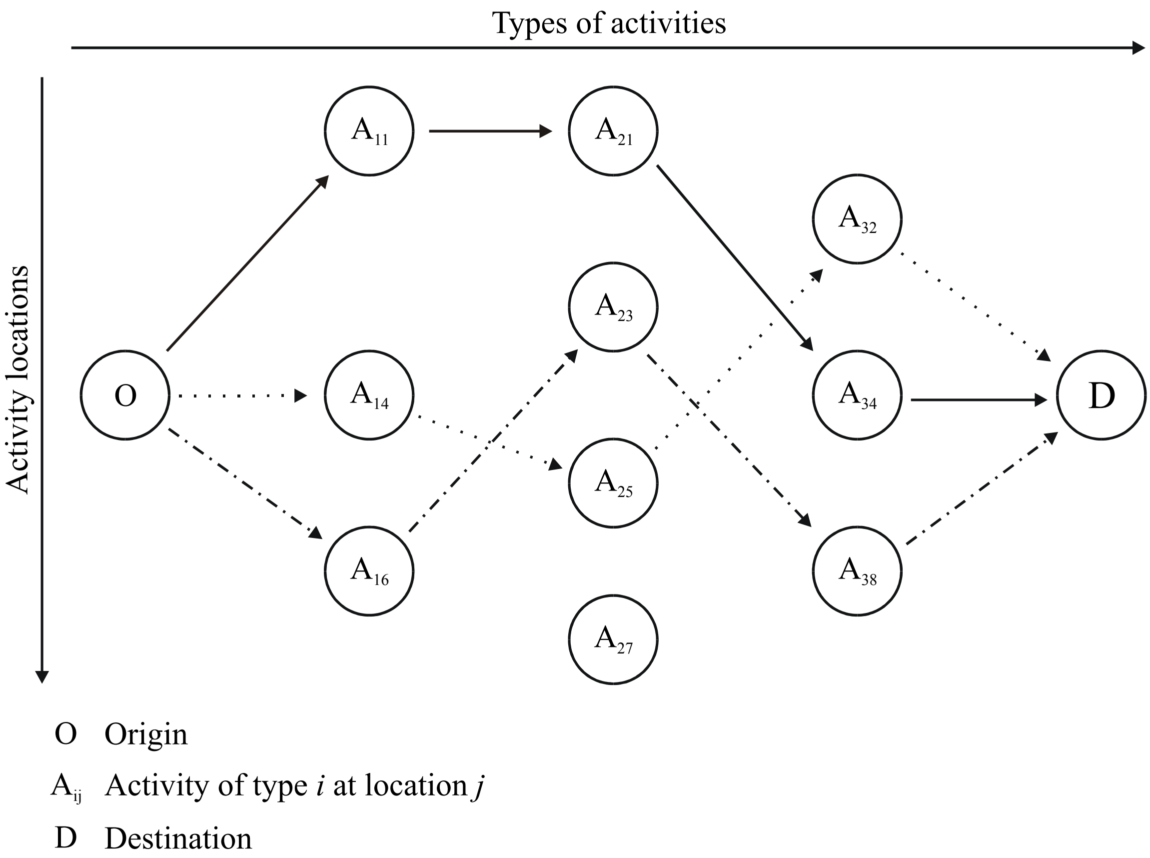


Figure 5.10: Alternatives of combinations of activity locations (fixed order and type of activities)

location choice. The way pedestrians walk through a part of the walking infrastructure is called a trajectory.

Figure 5.11 shows the route of a pedestrian along fixed activity locations using various trajectories.

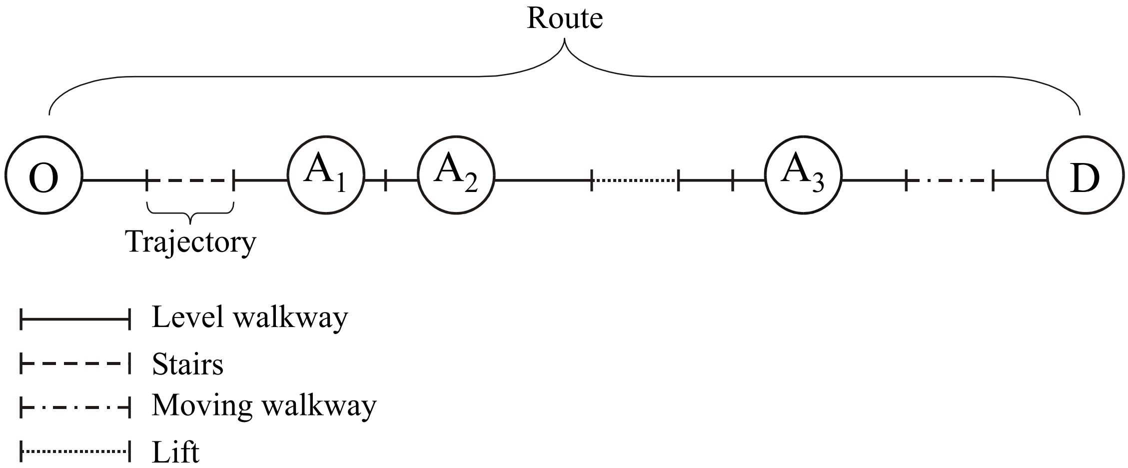


Figure 5.11: A route from origin to destination, consisting of activity locations and trajectories

The aim of route choice modelling is to determine the total route from a pedestrian's current position to his destination, including given activity locations. Route choices depend on dynamically changing conditions in the network. A generic model may be produced for this type of choices, which will be further elaborated in chapter 6.

In the simulation tool, each time a pedestrian completes a link, he arrives at a route decision point where the current optimal route is determined. This estimate may be identical to the route determined at previous decision points. On a link, a pedestrian chooses a specific trajectory, defining this part of the route in both time and space. The specific trajectory is determined during route choice on the operational level (see subsection 5.6.2).

In route choice prediction, experienced and unfamiliar pedestrians are distinguished. Commuters e.g. are representatives of the first type, whereas tourists belong to the second type. Experienced pedestrians are aware of prevailing conditions in the station (occurrence of congestion) and know in advance the fastest route in time to their destination. Unfamiliar pedestrians on the other hand do not know the station infrastructure, so their first activity is to find an information sign to collect information on their destination (at what platform the train will depart, where is a specific exit) and the corresponding route. Both types of pedestrians have pre-determined locations where they re-evaluate and re-optimise their route, so-called route decision points.

In SimPed, currently the route choice criterion is shortest travel time, including waiting and service times at joints and lifts. In transfer nodes, especially during peak hours, most pedestrians are familiar with the station and station conditions. To model route choice for unfamiliar pedestrians, their first intermediate destination is an information sign. Based on this information unfamiliar pedestrians choose their route in a similar way as experienced pedestrians, assuming that the information available is correct.

5.6.2 Operational level

At the operational level, pedestrians take instantaneous decisions for the immediate next time period. Processes distinguished at this level are navigating, walking, waiting, and performing an activity. The process of navigating, or finding a trajectory through an infrastructure element, is called trajectory choice. The process of performing an activity also includes boarding and alighting from public transport vehicles.

Trajectory choice

Route choice on the operational level concerns the choice of a space-time trajectory on a link. The trajectory choice model assumes that the length of a trajectory is such that it can be observed in its entirety, which means that the total trajectory is determined in advance. The trajectory origin is the current position of a pedestrian, whereas the trajectory destination is a route decision point on the route of this pedestrian or his destination. The preferred trajectory of a pedestrian is a straight line. This trajectory is only possible when no obstacles or other hindrances, for example other pedestrians, appear on this desired line. As the model for pedestrian walking behaviour in SimPed is macroscopic, the hindrance of other pedestrians on a trajectory is not taken into account directly, but is included in a lower speed due to the presence of other pedestrians (higher density). If one or more obstacles are located on a straight trajectory, a new trajectory is searched around these obstacles. The length of this new trajectory is again as short as possible, while passing obstacles as close as possible, but ensuring some clearance around the obstacle. Two examples of trajectories are given in figure 5.12. More detailed information on the algorithm used to determine trajectories is given in chapter 6.

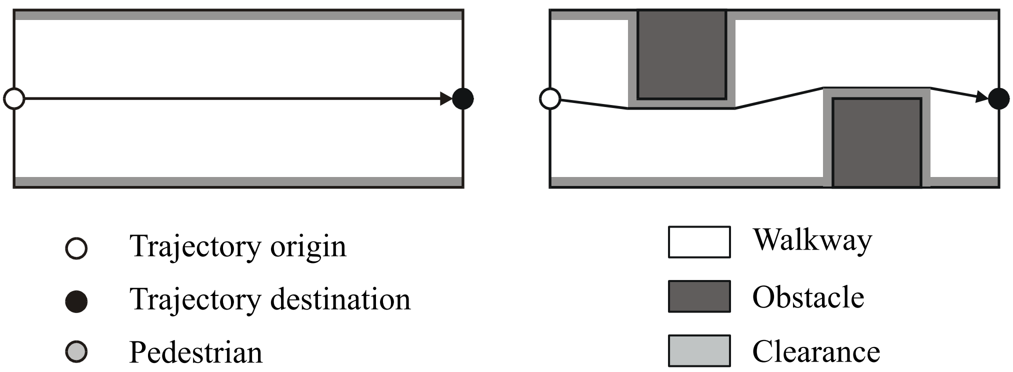


Figure 5.12: Examples of pedestrian trajectories around obstacles

Walking

As stated in subsection 5.5.1, pedestrian walking behaviour is modelled macroscopically in SimPed, using speed-density relations. Individual walking behaviour depends on pedestrian characteristics as well as on infrastructure characteristics. This is why different speed-density relations are used for various types of infrastructure such as level walkways and stairs. For walking behaviour on moving walkways and in lifts, the movement of the infrastructure itself influences pedestrian walking behaviour. These types of infrastructure therefore have a special algorithm for walking. Also passing joints such as doors and turnstiles, and interaction with obstacles are modelled dedicated for these types of infrastructure. For more detailed information and algorithms see chapter 6.

Waiting

A pedestrian may wait for different reasons and thus have various waiting locations. In transfer stations, the main reason for waiting is that the train has not yet arrived and the waiting takes place at the platform. Other reasons to wait are when a pedestrian is in a queue to be served, or when congestion occurs. In all these situations, pedestrians are located as close as possible to the position where they need to be after waiting, see also figure 5.13. Independent of the number of service points of a facility, only a single queue is formed, which is served according to the 'first-come-first-served' principle.

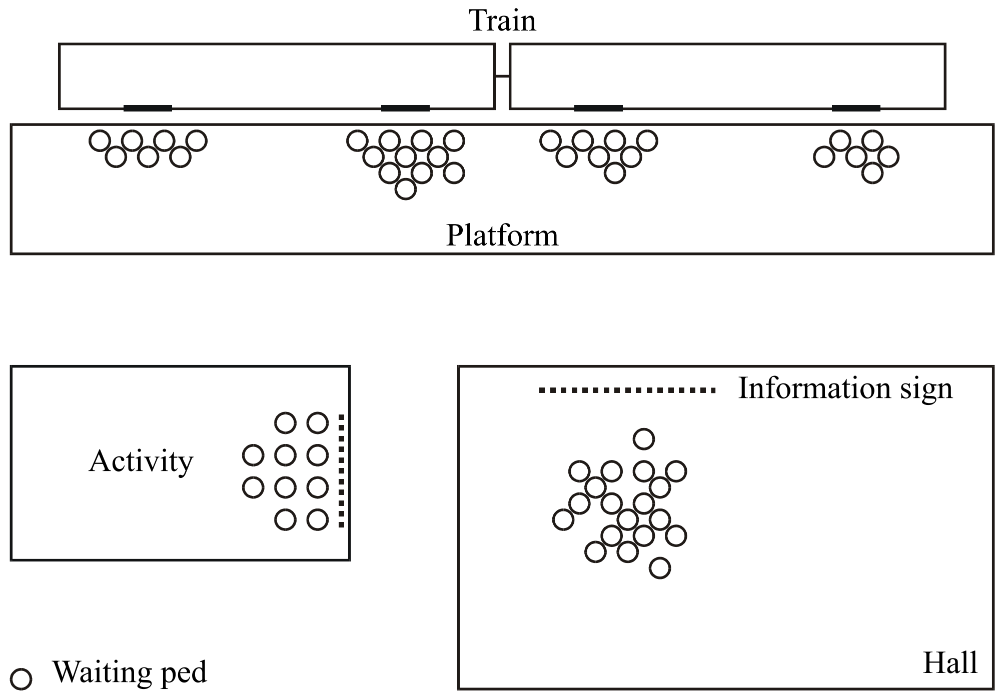


Figure 5.13: Waiting locations and queue order

Performing an activity

When a pedestrian arrives at a service facility and one of the servers of the facility is free, the pedestrian is served during a time period drawn from a given service time distribution, which is specific for each facility. When all servers are occupied, the pedestrian joins the queue and waits until one of the servers is free. A single queue is formed in front of a service facility, independent of the number of servers of the facility. The pedestrians in this queue are served according to the 'first-come-first-served' principle. When all pedestrians previously arrived at the activity are served, this pedestrian is served. During the waiting time as well as during the service time, the pedestrian occupies space in the infrastructure element in which the activity is located.

Interaction with public transport vehicles

Two types of service facilities have been distinguished, namely service facilities where pedestrians perform activities and the facilities for the interaction with public transport vehicles (to model processes of boarding and alighting). The pedestrian behaviour is identical at both facilities and has been described in the previous subsection.

An alighting pedestrian starts his trip through the facility after performing the activity 'alighting', whereas a boarding pedestrian leaves the facility and is removed from the model.

5.7 Summary and conclusions

This chapter offered a functional system decomposition, in which relevant elements and processes in a station are identified. An exhaustive decomposition of a pedestrian facility has been given in which the facility is split up into three basic types of elements, namely pedestrians, public transport services, and facilities. The interactions between elements have been identified, to describe relevant processes. By specifying relations between input and output a good theoretical description of a public transport facility is obtained.

New in this chapter is the categorisation of the processes according to levels of pedestrian behaviour. This theory distinguishes three levels of pedestrian decision-making, that is strategic, tactical, and operational. These levels indicate the term for which pedestrians make their decisions. On the strategic level, long-term decisions are taken, whereas on the operational level decisions are taken for the immediate next instant.

In this chapter, a few general principles have been specified governing the modelling of the described processes. Firstly, various instances of individual choices have been identified. In principle, these are all modelled similarly by means of the subjective utility maximisation principle. Secondly, all facilities may be interpreted as service systems with a distribution for service times, a restricted capacity, and consequently waiting times and queuing. This applies among other things to (transport vehicle) doors, walkways, and service facilities.

In the next chapter, two types of models are elaborated, namely individual choice models and facility service models. Also, most of the process descriptions given in this chapter are further elaborated in the next chapter in the form of models and algorithms. These models are combined yielding the overall simulation tool. Also, the given partition of the pedestrian facility into basic types of elements is the basis for the object model in chapter 7.

Chapter 6

Models for pedestrian behaviour in public transport facilities

6.1 Introduction

This chapter describes the models developed for the quantitative analysis of pedestrian facilities constituting the SimPed simulation tool, of which the current version still exhibits some simplifications, mostly because of lack of sufficient empirical data about pedestrian behaviour. The starting point for these models are the elements and processes identified in chapter 5. In the present chapter, only those models important in SimPed or new for traffic engineering practice are elaborated upon.

Most of the existing pedestrian flow models only consider pedestrian movement behaviour as such (AlGadhi et al. 2001), (Blue & Adler 2000), (Burstedde, Klauck, Schadschneider & Zittartz 2001), (Helbing & Molnar 1995), (Jiang 1999), (Kukla et al. 2001), (Løvas 1994), (Muramatsu & Nagatani 2000). Some more extensive models also include the performance of activities by pedestrians (Dijkstra et al. 2001), (Hoogendoorn & Bovy 2004), (Schelhorn et al. 1999), (Still 2000), while only very few models include the interaction with public transport vehicles (Pedroute (Maw & Dix 1990), (Turner et al. 1991)). For a more detailed overview of existing models, see section 3.3.3 and table 3.7. A major innovation in our approach is that our simulation model not only includes walking behaviour and route choice, but it also describes the performance of activities, including activity area choice. In addition, it includes pedestrian interaction with public transport vehicles, where public transport vehicles arrive and depart based on a given timetable. Also, transferring travellers are modelled, including those needing to find a new connection, having missed their transfer.

We developed a novel hierarchical route choice model assuming that pedestrian route choice takes place at two levels. The tactical level route choice model determines the total route from the pedestrian's origin (or his current position), via intermediate destinations, such as activity areas, to his destination. A route consists of a series of subsequent trajectories, each of which indicates the exact spatial path pedestrians follow within a specific area. It is not always possible to walk in a straight line from the entrance of an area to the exit (locations indicated in the route choice model) due to the presence of obstacles such as waste-baskets, columns, kiosks and waiting areas with seats. Therefore, a second model is applied, the so-called trajectory generation model, defining the shortest trajectories through a part of the infrastructure (in two dimensions).

Normative pedestrian behaviour theory has been applied (see chapter 5) in all described choice processes. For each of these processes, a similar structure holds, that is constraints are defined in order to exclude non-relevant choice options for the individual, and a choice set of feasible alternatives is specified. Attributes of these alternatives are determined, to which weights are assigned. An individual utility choice model is applied to find individual choice probabilities for the identified alternatives.

Finally, interpersonal differences between pedestrians have been modelled in terms of walking behaviour. For example variability occurs in walking times, due to different individual free speeds, even when the traffic conditions on the network are similar.

The interrelationships among the models described in this chapter (see figure 5.2) are indicated in figure 6.1. In the figure, behaviour models, network models, and exogenous data are distinguished. The arrows in the figure indicate data flows between the elements, whereas next to these arrows the content of the data flows is indicated. The variables i, t and ΔT indicate the aggregation level (i stands for an individual pedestrian) and time scale of the involved elements respectively.

The figure indicates a feedback process. The traffic state at moment t is determined in the operational network. Based on this, travel characteristics are derived for the tactical level which determine activity and route choice decisions. These, on their part, determine the evolution of the traffic state in the operational network in the next time slice.

This chapter has been divided into four parts, describing the modelling of respectively the network (section 6.2), the processes on the tactical level (activity location choice in section 6.3 and route choice in section 6.4), and the processes on the operational level (walking in section 6.5, performing activities in section 6.6, and the interaction of pedestrians with public transport services in section 6.7).

The chapter concludes with a summary and an overview of the most important and innovative aspects of the presented approach (section 6.8).

6.2 Modelling walking infrastructure

Designers and planners of public transport infrastructure use (computer) drawings to illustrate their designs. For their understanding it is useful to represent the infrastructure network in a similar way as these drawings, not only for the input modelling, but also as graphical background for the output registration. A three-dimensional building is split

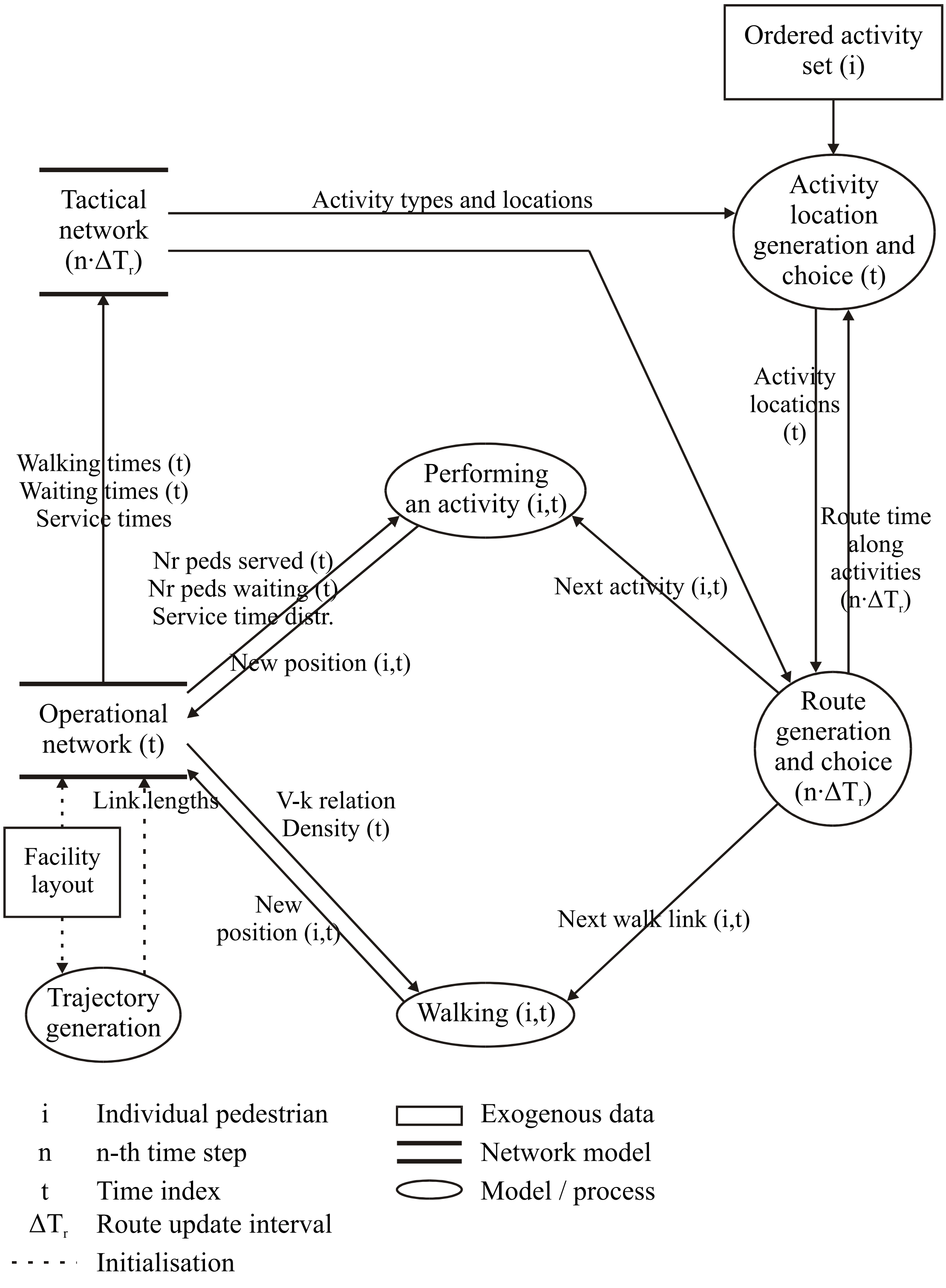


Figure 6.1: Overview of models and their interrelationships constituting the pedestrian flow simulation tool

into floors while a plan is drawn for each of the floors. Also, various types of walking infrastructure, such as stairs, escalators, and platforms are modelled because of different pedestrian behaviour on each of these types of infrastructure.

Subsection 6.2.2 describes the two-dimensional representation of the infrastructure needed for the trajectory generation model, while subsection 6.2.3 explains how the trajectory generation model calculates trajectory lengths in the operational network model to be used in the tactical network model. The translation into a tactical network with one-dimensional links is illustrated in subsection 6.2.4. This tactical network is input for behaviour models such as the route choice model. Subsection 6.2.4 also presents in detail the performance indicators regarding pedestrian behaviour describing expected walking times, waiting times, and service times. As these performance indicators are variables of the tactical network model on which among other things route choice is based, these indicators are described in this section instead of in the sections describing the behavioural processes.

6.2.1 Distinction of two network models

Processes modelled in a pedestrian simulation tool may be split into two groups. One group needs as an input a detailed spatial description of the infrastructure in two dimensions, whereas coarse information regarding the geometry of the infrastructure suffices for the remainder of the processes. Therefore, two network models have been developed, which are mutually dependent, as they describe the same infrastructure.

In figure 5.2, the input for each of the relevant processes in the simulation tool has been identified. The input concerning the infrastructure consists of three parts, namely network topology, geometry of the infrastructure, and obstacles. The network topology serves as an input for the activity area choice and the route choice process. It consists of route choice points and links between them. Most route choice models use links, of which the resistance (cost) mainly is expressed in terms of time. One of the differences between a car network and a pedestrian network however is that a pedestrian moves through a two-dimensional area, thus having more degrees of freedom in choosing his walking direction than a car. Related to this is the fact that a pedestrian can alter or divert from his route at nearly all locations, leading to continuous route choice behaviour in two dimensions (Hoogendoorn & Bovy 2004), (Hughes 2000). The SimPed tool, however, uses an abstraction of the (two-dimensional) infrastructure, where the network model consists of links and nodes. The length of each link is expressed in time, whereas a node only indicates a choice point (route diverting points).

The walking time on a link depends on the length and type of the walking path and on the traffic density, taking into account congestion. The length of this path is calculated in the trajectory generation model, which needs as an input the geometry of the infrastructure and a description of the obstacles (location and form). As the distance traversed on a link depends on the movement of a pedestrian in both the longitudinal and lateral direction, these links need to be described in at least two dimensions. Some infrastructure elements in addition bridge a height difference and thus have a third, vertical dimension. This third dimension may be continuous in a general model, but it makes the model more complex and detailed, while it does not highly influence the results, due to the fact that the number of height bridging elements in transfer stations is limited. The approximation made in the simulation tool is similar to what designers do in their drawings. A facility is split into levels, where each level part of the infrastructure is assigned to one level, while height bridging elements are assigned to two or more levels. The height difference of an element is then expressed in the pedestrian behaviour of this element and may be taken into account as type of infrastructure in the route choice process. This connectivity data is included in the coarse network model, which leaves a second network to be built with more detailed spatial information and therefore consisting of two-dimensional links (with a description in longitudinal and lateral direction) to indicate the exact walking path of a pedestrian.

An overview of the input regarding the infrastructure, the split up into two network models, and the corresponding pedestrian processes is shown in figure 6.2.

Thus, the simulation tool adopts two network representations, namely a network model with two-dimensional links to indicate exact positions of infrastructure (length, width) and to describe the performance of activities and waiting areas, and a network model with one-dimensional links (with costs expressed in travel times, consisting of times for walking, waiting and service). The former one is used for the operational level of pedestrian behaviour and is called *operational network model*, whereas the latter one is used for the tactical level and is called *tactical network model*.

In this section, first the operational network model is described, on the basis of which the time-varying traffic states are determined. Next, the trajectory generation model is elaborated which determines optimal walking trajectories in each infrastructure element given its geometry and obstacles present. Finally, the tactical network model is presented, to be derived from the operational network model.

6.2.2 Operational network model

Function of an operational network model

The function of an operational network model is to provide a detailed spatial description of the infrastructure in two dimensions. The free form (defined by the locations of vertices) is indicated, as well as locations and forms of obstacles and other parts of the infrastructure inaccessible for walking purposes. Locations of possible origins and (intermediate) destinations are indicated as well.

The operational network model is input for the processes of walking, waiting, trajectory choice, and activity performance. These processes take place at a specific location (waiting, performing activities) or in between two locations (navigating, walking). Not only

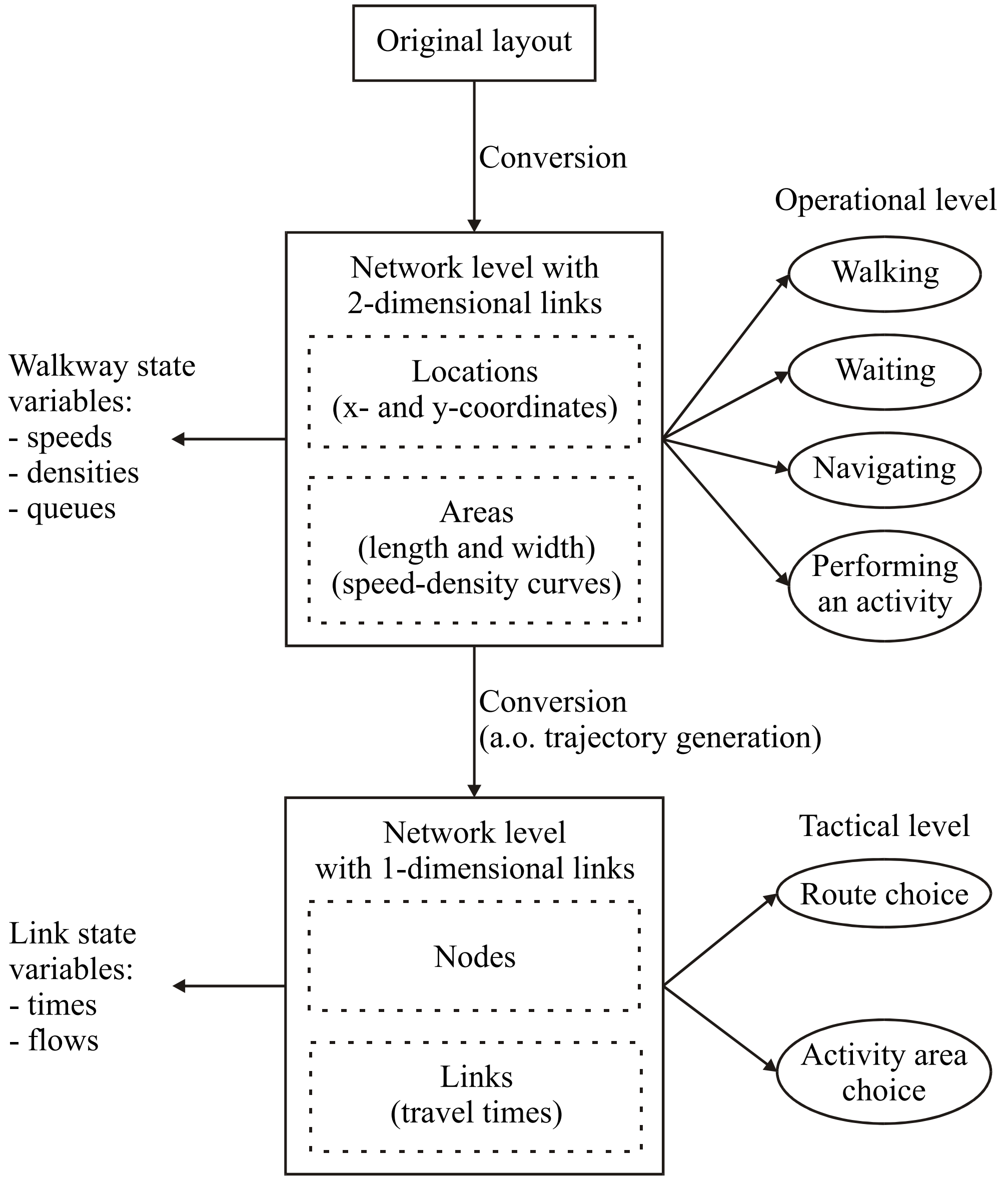


Figure 6.2: Two network model levels adopted in SimPed, and their use in pedestrian processes

the location is important, also the type of infrastructure and the type of activity needs to be included in the network model. In the functional system specifications (section 5.5), the different types of transport and service facilities have already been indicated.

Example of an operational network model

An example of the two-dimensional representation of the infrastructure in a transfer station facility is shown in figure 6.3. To distinguish between the different types of infrastructure, each of the elements is filled with its specific hatch.

The model shows a part of a train station. At the upper part of the figure, a train is dwelling alongside of the platform. From the platform, two risers (a stairs on the left-hand side and a lift on the right-hand side of the traverse) lead to the traverse, passing over the train and leading to the district at the other side of the track. A stairs and an escalator connect the traverse with the entrance hall. In this hall, several ticket machines are located on the left-hand side, whereas the ticket offices are situated in a separate area, connected by a door to the hall. The hall and the stairs and escalator are connected by means of gates, which also conduct ticket control.

Types of infrastructure

Two types of infrastructure are distinguished (see also section 5.4): *transport facilities* for pedestrians (for walking) and *service facilities*. Both types are presented below.

Transport facilities for pedestrians The transport facilities that are distinguished are (see also section 5.5.3) level walkways (platforms, hallways, and passages), stairs, moving walkways (escalators and tapis roulants) and lifts. Transport facilities are described in two dimensions. Each part of the infrastructure can have its own free form, which is described by an ordered set of vertices, enclosing the modelled area. The net surface of this area is used when determining the level-of-service of pedestrians (a measure of comfort indicating the number of pedestrians per unit area, see appendix A) and to model walking using a speed-density relation (see section 6.5). Characteristics of transport facilities are thus their spatial form, grade, number of steps (for stairs), speeds (for escalators and lifts), and capacity (for lifts and joints).

Service facilities Service facilities (see also section 5.5.4) are modelled by a line, indicating the locations where pedestrians stand while being served. The surrounding area is used for waiting, where passing pedestrians may be hindered by waiting pedestrians. Characteristics of service facilities are the number of servers and a distribution for the service time. The combination of these characteristics determine the capacity of a service facility and, related with the demand, the formation of queues (see section 6.6). The impact of the use of activities on their capacity are not taken into account.

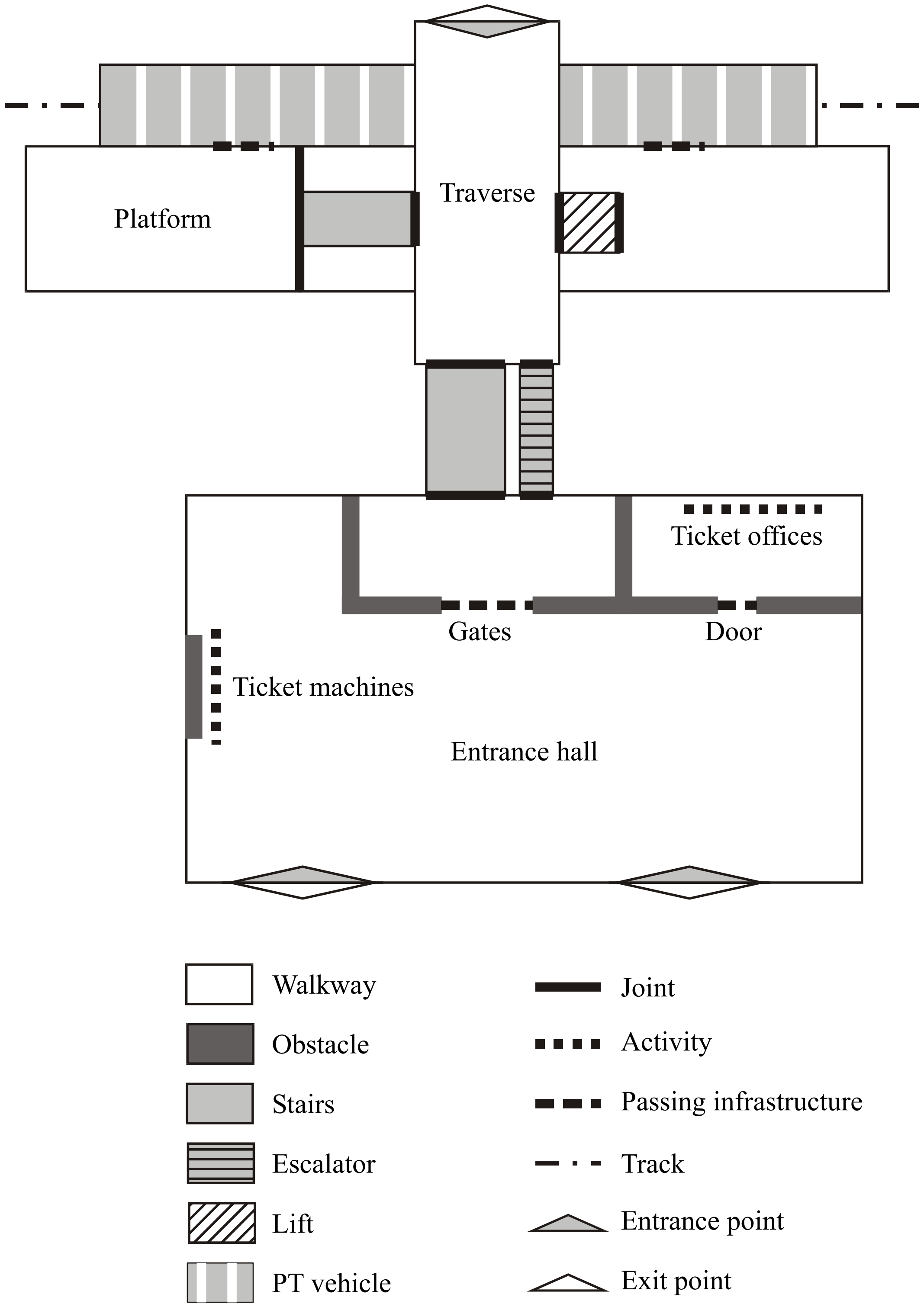


Figure 6.3: Example of an operational network model in SimPed

Adjacent walkways are always connected by a joint. Various types of joints with different capacities exist in order to model doors, turnstiles, gates and other types of connecting facilities. As for service facilities, joints have a capacity and a distribution for the service time, indicating the hindrance pedestrians experience.

Service facilities for boarding and alighting are not part of the infrastructure, but belong to the vehicles dwelling alongside the platform. In railway systems, many different types of rolling stock are available. For each type, locations of doors and specific door characteristics (such as boarding and alighting time headway distributions) are therefore required as input. For each public transport vehicle described in the timetable by a scheduled arrival and departure time, the platform and the stop location is needed (see section 6.7).

In general, the infrastructure for service facilities consists of static infrastructure remaining the same during the total duration of the simulation, and dynamic infrastructure especially used to model the boarding and alighting processes.

Walkway state variables

Walkway state variables are time-varying attributes of pedestrian flows in a walkway. They indicate among other things density, occupation and the average speed on walkways in the operational network model. Walkway state variables describe the conditions pedestrians experience in walkways.

Walkway state variables generally depend on the physical and functional characteristics of the facility or service involved and are related to the number of pedestrians using the walkway. Link state variables are often based on walkway state variables, for example the individual walking time of a pedestrian in a walkway depends on the prevailing density.

Homogeneity of the infrastructure

The spatial scale of transport facilities for pedestrians may be very different. For instance, a platform can have a length of 300 m, whereas an escalator usually has a length of about 20 m. When pedestrian behaviour is modelled microscopically, this scale difference is not influencing pedestrian behaviour, since a pedestrian continuously takes care of his direct environment and other pedestrians. Macroscopic models often assume homogeneous conditions in an area, and thus the spatial scale may have a significant effect

If at just one side of a long infrastructure element congestion occurs, pedestrians are assumed to be homogeneously distributed over the element, leading to a nearly free flow situation on the total link (see figure 6.4). It is thus necessary to split this infrastructure element into smaller areas, satisfying the assumption of homogeneous conditions. This may be done dynamically depending on the actual situation during the simulation run or it may be required as input. One of the requirements of the simulation tool is that it supports infrastructure with free forms such that the user is not restricted in its drawing possibilities. This may lead to complex forms, which are not straightforward to be split up automatically by the tool. Therefore, in the simulation tool, the user has the responsibility for splitting up large elements at those locations where congestion is likely to occur. In a later stage of the research, a more general infrastructure model which is able to do the split up endogenously may be developed.

For more information on the walking model see section 6.5 and appendix D.

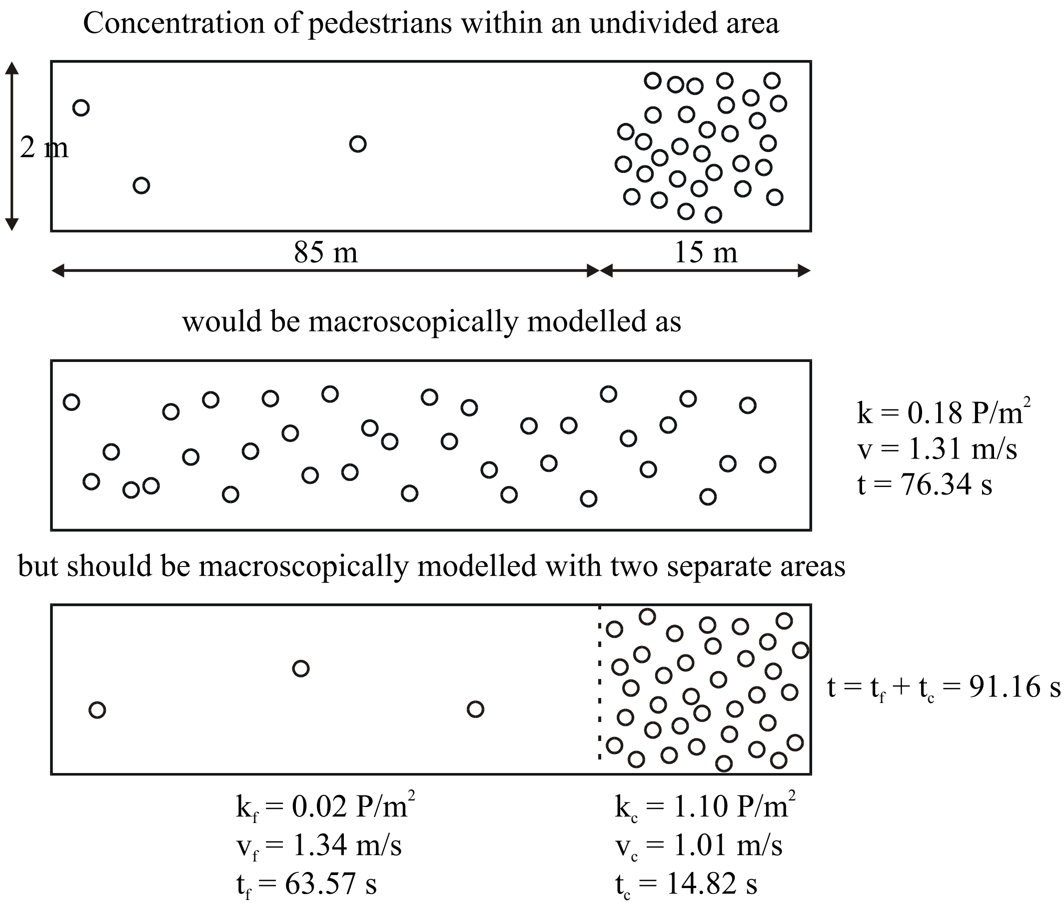


Figure 6.4: Assumption of homogeneous conditions on an undivided walkway

6.2.3 Trajectory generation model

A trajectory represents the exact path of a pedestrian through a part of the walking infrastructure. The trajectory generation model generates trajectories between two joints (including gates, entrances, exits and public transport vehicle doors) and determines the shortest trajectory (in length). The trajectory length is input for the tactical network model, where it is used in the calculation of the walking time between two nodes in the tactical network model (joints in the operational network model).

Trajectory algorithm

The infrastructure element is defined as a free form and described as an ordered list of coordinates. To give the user of the simulation tool the possibilities to model according to his own insights, the only requirement of the form is that it is convex. A possible algorithm to find the shortest trajectory through such a free form is a backtracking algorithm, finding all existing trajectories between two given joints, associated with the same part of the infrastructure.

The trajectory generation algorithm consists of three parts: 1) the choice set enumeration using a backtracking algorithm, 2) the utility calculation to find the length of each trajectory, and 3) the choice function indicating the shortest trajectory. The input of the algorithm is the list of vertices describing the form of the infrastructure element and the start and end nodes, to be connected by the trajectory. The result of the trajectory generation algorithm is the length of the shortest trajectory between the start and end nodes. The exact path of the trajectory is not relevant, since in the model the pedestrian does not physically follow this path, but remains at no further specified location in the walkway during his walking time.

Trajectory generation example

The remainder of this subsection contains two examples of the trajectory generation model. The first example (see left part of figure 6.5) is a direct connection between the start node X and the end node Y of the trajectory. The length of the shortest trajectory is then the distance between the two nodes X and Y.

The second example is shown in figure 6.5 on the right, in which the trajectory is to be found from start node X to end node Y. A straight trajectory is not possible, as this line crosses the lines CD and DE.

All trajectories starting at node X via intermediate nodes to end node Y are constructed by following the surroundings of the area and looking for direct connections of each vertex with end node Y. An overview of these trajectories and the corresponding distances is given in table 6.1 showing that the shortest trajectory is XDY with length 15.4 m (as may also be seen in figure 6.5).

6.2.4 Tactical network model

The network model needed as an input for the route choice and activity models consists of nodes and links. Nodes are joints between links and serve as route decision points. Dedicated links are used to model walking, the performance of activities (serving), and waiting. The nodes represent both static and dynamic infrastructure (varying over time). This dynamic infrastructure consists of doors of public transport vehicles, where travellers

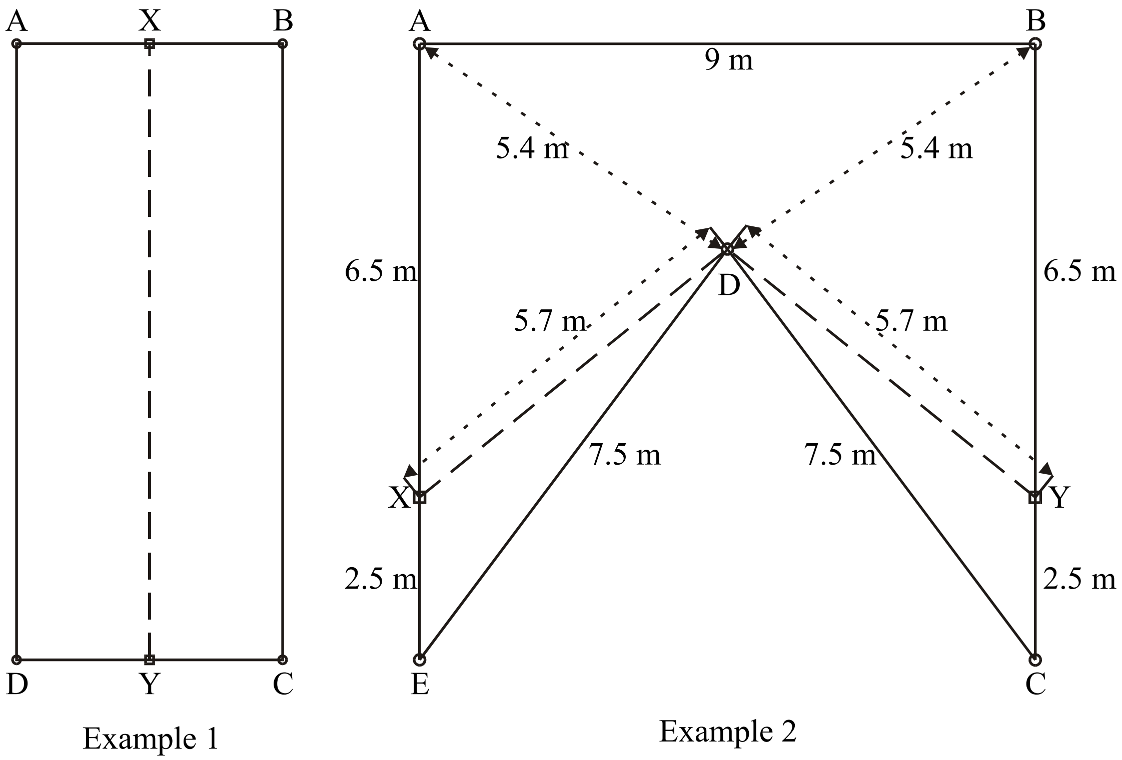


Figure 6.5: Two examples of the trajectory generation model

Table 6.1: Results of the trajectory generation model for the walkway in example 2

Step	Trajectory					Length (in m)	Shortest
1	X	A	B	Y		6.5+9+6.5=22	22
2			D	Y		6.5+5.4+5.7=17.6	17.6
3			E	A		-	17.6
4				D	Y	6.5+9+7.5+5.7=28.7	17.6
5		D	Y			5.7+5.7=15.4	15.4
6		E	A	B	Y	2.5+9+9+6.5=27	15.4
7				D	Y	2.5+9+5.4+5.7=22.6	15.4
8				E		-	15.4
9			D	Y		2.5+7.5+5.7=15.7	15.4

enter and leave the model, while boarding and alighting. The following subsections describe these nodes and the links for the example shown in the preceding subsection. The final subsection contains a description of link performance variables, used to give each link a cost (in time).

Nodes

The essential function of a node is to *connect two or more links*. However, a node may have additional functions, such as indicating the location of an activity or a passing hindrance between two links, such as a door or (a set of) gates. The following types of nodes are distinguished:

- Connection node.
- Origin or entrance node.
- Destination or exit node.
- Activity node.
- Passing infrastructure node.

The function 'connection' is valid for all nodes, indicating the location where two or more links are connected. An origin is a node where pedestrians enter the system, while a destination indicates the location for leaving. An activity node indicates the location where an activity may be performed. The activity itself is modelled as a queuing process (see also chapter 5 and section 6.6). Nodes with the function of passing infrastructure indicate locations where pedestrians move from one link to the next link, but are hindered by a specific type of infrastructure, such as different types of doors (revolving doors, swing doors), gates or turnstiles, where also ticket control may take place. These nodes are also modelled as a queuing system.

This node coding technique leads to a high number of nodes, but is necessary for a correct modelling of pedestrian behaviour.

Links

All nodes in an infrastructure element (walkway) are connected by links. The detailed walking path over a link is calculated in the trajectory generation model (discussed in subsection 6.2.3). The lengths of the links in this tactical network model are expressed as walking time T_a^{walk}, waiting time T_a^{wait}, and service times $T_a^{service}$. The processes (walking, waiting, and serving) are expressed in time and location, as is shown in figure 6.6.

Thus, the following three types of links are distinguished:

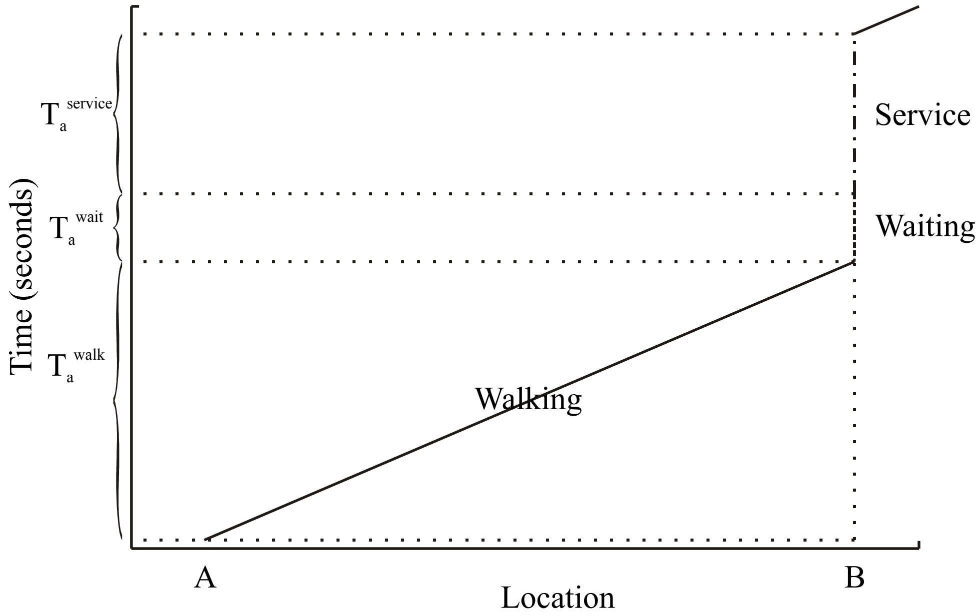


Figure 6.6: Walk link, wait link, and service link over time between locations A and B

- Walk link.
- Wait link.
- Service link.

The types of links between two consecutive nodes depend on the type of to-nodes as shown in table 6.2.

Table 6.2: Type of links depending on the type of to-node

Type of to-node	Types of links
Joint	walk
Joint (lift)	walk and wait
Destination	walk
Destination (vehicle door)	walk, wait, and service
Activity	walk, wait, and service
Passing infrastructure	walk, wait, and service

The time length of each link varies with the conditions on the network (density and demand for activities and passing infrastructure).

Example of a tactical network model

The example of a tactical network model is based on the same infrastructure as for the operational network model given in figure 6.3. Figure 6.7 shows the links with the nodes on the correct geographical locations. In figure 6.8, these links are split into separate consecutive walk, wait and service links.

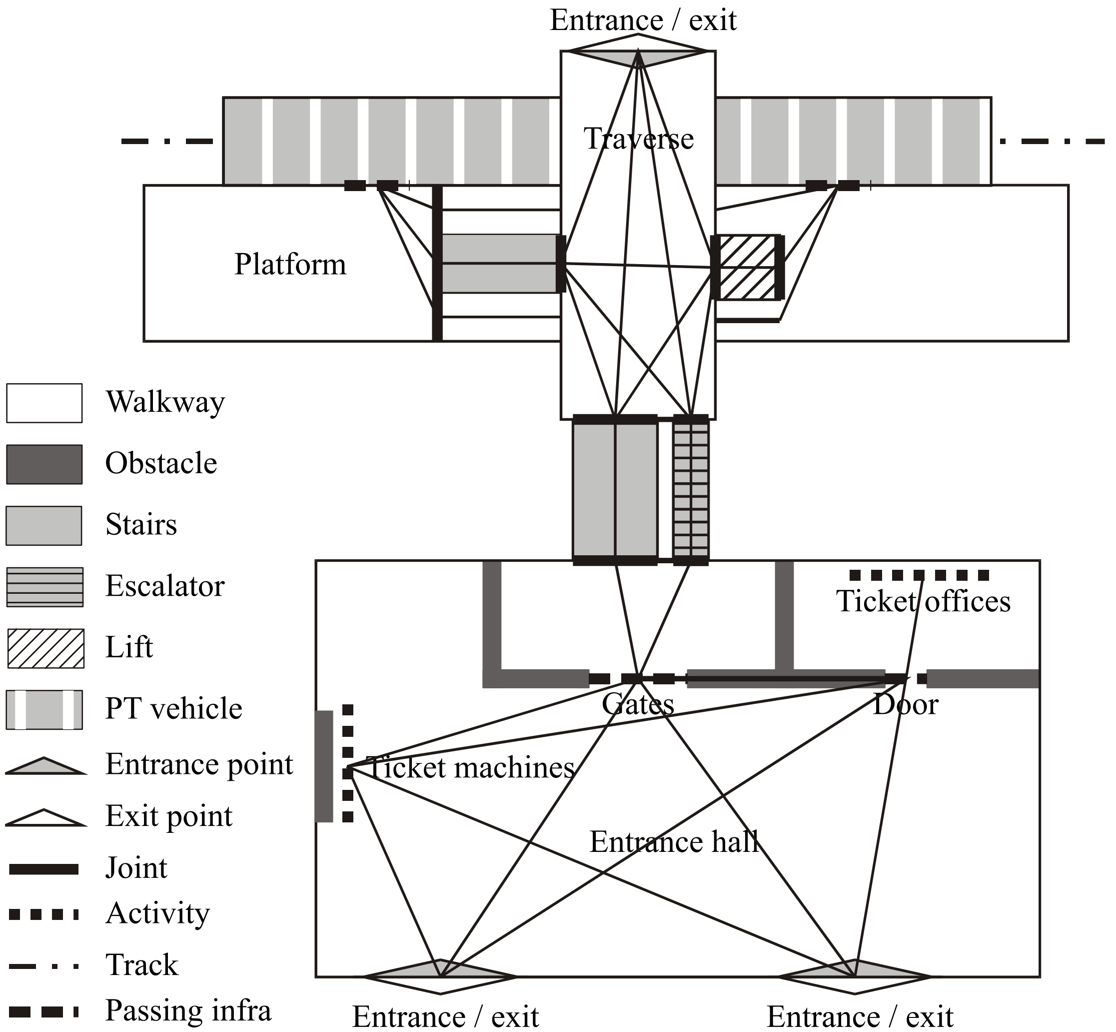


Figure 6.7: Overview of links and nodes as a basis for the tactical network model

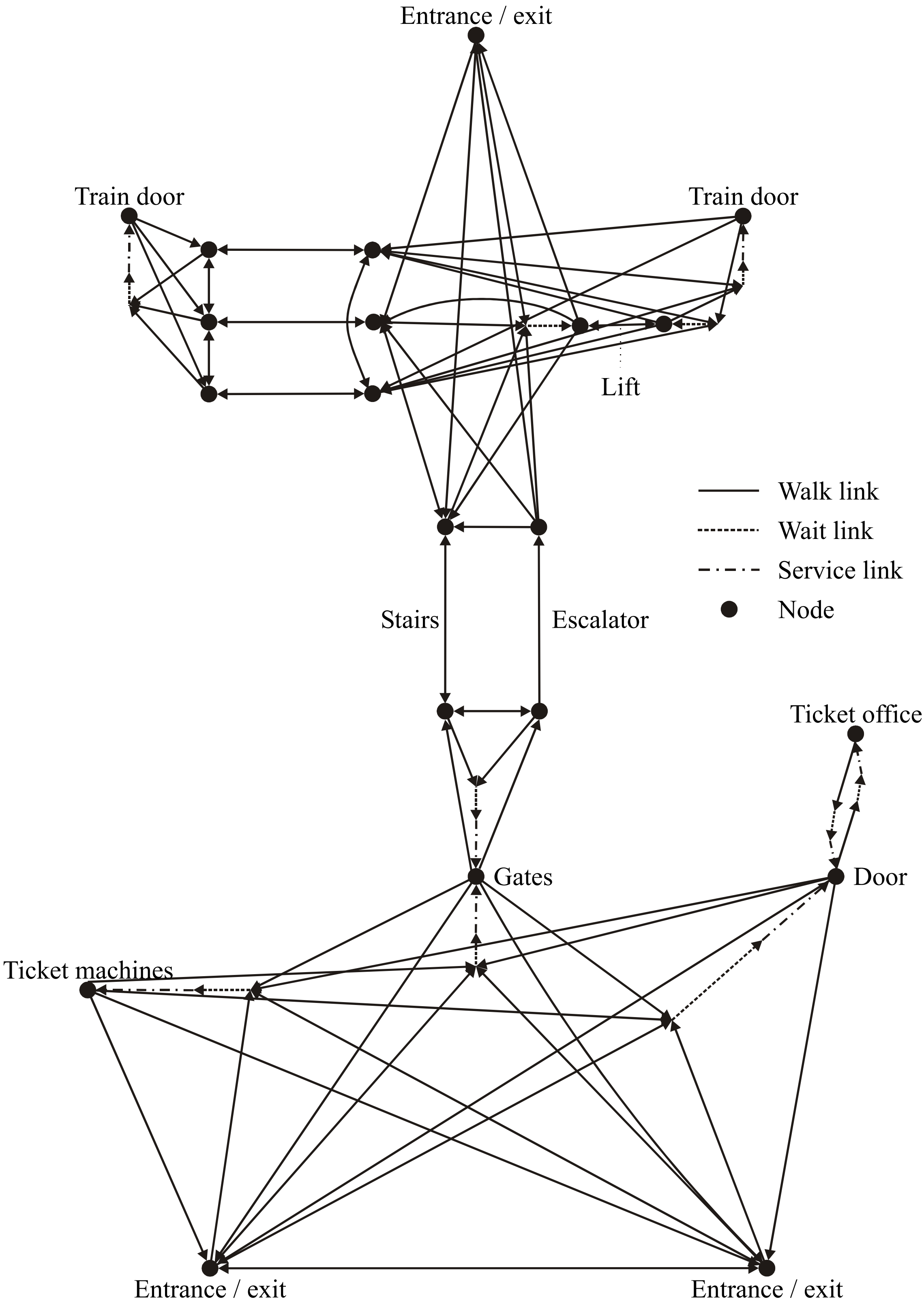


Figure 6.8: Graph representation of the tactical network model from the example infrastructure in figure 6.7, including link type distinction

Link state variables

Link state variables are *time-varying* attributes of pedestrian flows on a link. They indicate the time length of links in the tactical network model, corresponding to subjective disutilities for the user. The average transportation link disutility is a variable comprising different state variables perceived by users in travel related choices. State variables are assumed link-wise additive, which means that their route value can be obtained as the sum of link values for all links making up the route.

Link state variables generally depend on the physical and functional characteristics of the facility or service involved and the prevailing conditions (such as flows and densities) on these facilities. Typical examples are travel time on a section, dependent of its length, and density, and waiting time for a service facility, dependent of the number of service points, service time, and demand (Cascetta 2001).

Link state variables are average values for the total population of pedestrians, where each link has its own state value varying over time. In determining this state value, the characteristics of a default pedestrian (such as free walking speed) and average characteristics of facilities (such as average service time) are taken into account. An overview of the iterative interactions between tactical and operational processes is shown in figure 6.9, including as well the application of individual and average performance indicators.

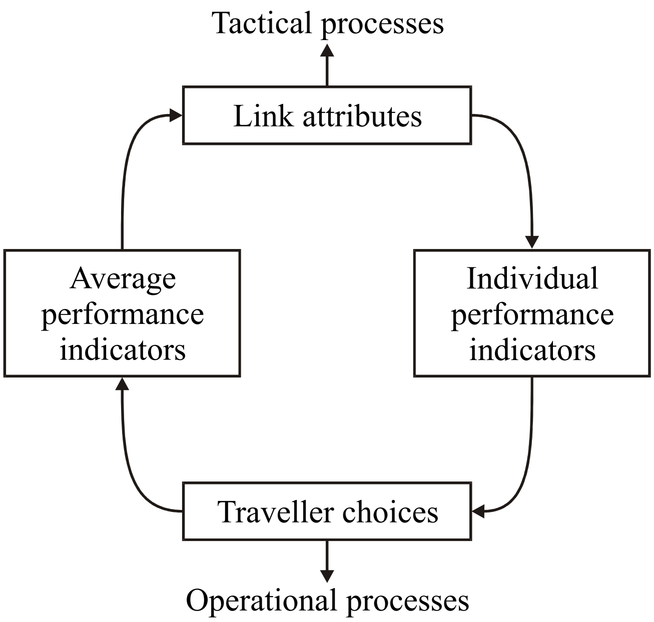


Figure 6.9: Relations between individual and average performance indicators

In chapter 5, several types of infrastructure (such as level walkways, lifts, and activities) have been distinguished. In the following, the mathematical expressions for walking times, waiting times, and service times are given for each of these types of infrastructure. Table 6.3 shows which aspects of each type of infrastructure are described. The total time spent at a part of the infrastructure is the sum of the times in each row. Thus, the time of a pedestrian using a lift consists of waiting time for the lift to arrive and moving time to the requested floor ($T_a = T_a^{walk} + T_a^{wait}; a \in \mathcal{L}$).

Table 6.3: Types of delays corresponding to each type of infrastructure

	Set	**Walk**	**Wait**	**Service**
Level walkway	$a \in \mathcal{A}$	T_a^{walk}		
Moving walkway	$a \in \mathcal{M}$	T_a^{walk}		
Lift	$a \in \mathcal{L}$	T_a^{walk}	T_a^{wait}	
Activity	$a \in \mathcal{C}$		T_a^{wait}	$T_a^{service}$
Passing infrastructure	$a \in \mathcal{P}$		T_a^{wait}	$T_a^{service}$
Boarding / alighting	$a \in \mathcal{B}$		T_a^{wait}	$T_a^{service}$

In the remainder, the link state variables for each of the three aspects (walking, waiting, and service) are specified.

Walking Walking or moving is relevant for three types of elements (see table 6.3), namely level walkways, moving walkways, and lifts. For each a specific method is adopted to calculate pedestrian walking time.

Level walkway A pedestrian follows a specific trajectory in a level walkway (for the construction of this trajectory see section 6.2.3). Based on the current density in this walkway and prevailing speed-density relation describing pedestrian walking characteristics in this walkway an average walking speed is derived (see also section 6.5). With this speed and the known trajectory length, the walking time T_a^{walk} in walkway a when starting at moment t is approximated by the following value:

$$T_a^{walk}(t) = \frac{L_a}{u(k_a(t))}, \; a \in \mathcal{A} \cup \mathcal{M} \cup \mathcal{L} \tag{6.1}$$

where L_a is the trajectory length and $u(k_a(t))$ is the walking speed of a pedestrian on this link starting at time t, depending on the dynamic, instantaneous density on this link $k_a(t)$.

Moving walkway For the average time on a moving walkway, it is assumed that pedestrians do not walk on this moving walkway. The average walking time is then determined by the length of the moving walkway L_a and its turning speed u_a:

$$T_a^{walk}(t) = \frac{L_a}{u_a}, \; a \in \mathcal{M} \tag{6.2}$$

The speed of pedestrians on a moving walkway thus does not depend on the density, which makes its walking speed independent of time t.

Lift The movement time in a lift depends on the height difference H between the origin and the destination floor, the speed of the lift u_a and its acceleration a_a and deceleration $-a_a$. The assumption is made that this acceleration and deceleration are constant over time. Another assumption concerns the number of intermediate stops. At the moment of calculation, this number is unknown, hard to predict and therefore left out in SimPed. First, algorithms are derived for the case that the height difference is so large that the lift reaches its maximum speed, while in the second case the lift does not reach this maximum speed.

In the first case, the time of the lift movement consists of three parts, namely the time for the lift to accelerate to its maximum speed (first term in equation 6.3), the time to move with constant speed (second term in equation 6.3) and the time to decelerate to standstill (third term in equation 6.3). Applying fundamental kinematics, the expression for the total movement time of the lift becomes:

$$T_a^{walk}(t) = \frac{1}{2}\frac{u_a}{a_a} + \frac{H}{u_a} - \frac{3}{2}\frac{u_a}{-a_a},\ a \in \mathcal{L} \tag{6.3}$$

In the second case, the lift does not reach its maximum speed, but accelerates and decelerates once more. Again based on fundamental kinematics, first the maximum speed u_a reached by the lift is calculated:

$$u_a = \sqrt{\frac{2H \cdot a_a \cdot -a_a}{-a_a - a_a}},\ a \in \mathcal{L} \tag{6.4}$$

and the movement time for the lift becomes

$$T_a^{walk}(t) = \frac{u_a}{a_a} - \frac{u_a}{-a_a},\ a \in \mathcal{L} \tag{6.5}$$

Waiting Waiting is (sometimes) necessary at lifts, and at services such as performing activities, passing infrastructure, and boarding public transport vehicles.

Waiting for a lift As a lift is modelled as a separate process (which is not explained further in this thesis), the waiting time for the lift to arrive at the requested floor is specified in detail. This waiting time depends on the current floor of the lift and the current floor of the pedestrian. It is assumed that the probability of a lift being at a specific floor is equal for all floors. The expected waiting time then equals the average time it takes for the lift to move to the demanded floor, which is:

$$E\left(\underline{T_a^{wait}(t)}\right) = \sum_{f \in \mathcal{F}} E\left(\underline{T_a^{walk}(t)} \mid f\right) \cdot P\left(\underline{F} = f\right) = \sum_{f \in \mathcal{F}} (\underline{T_a^{walk}(t)} \mid f) \cdot P(f),\ a \in \mathcal{L} \tag{6.6}$$

where $\mathcal{F}$ is the set of floors served by this lift and $T_a^{walk}(t)$ indicates the time for the lift to move from floor $\underline{F}$ to the requested floor, assuming that the lift has no intermediate stops. Also, instead of using the movement time from equation 6.3 an approximation is used of the time it takes the lift to move between two adjacent floors (ΔT_a^{walk}). When the probability of the lift being at a specific floor is assumed equal for all floors ($P(f) = \frac{1}{N^f}$ for all $f \in \mathcal{F}$), where N^f is the number of floors, the expression for the waiting time for the lift becomes:

$$T_a^{wait}(t) = \frac{1}{N^f} \sum_{f \in \mathcal{F}} \left| f^i - f \right| \cdot \Delta T_a^{walk} = \frac{\Delta T_a^{walk}}{N^f} \sum_{f \in \mathcal{F}} \left| f^i - f \right|, \; a \in \mathcal{L} \tag{6.7}$$

where f_i is the current floor of the pedestrian and ΔT_a^{walk} is the time it takes the lift to move between two adjacent floors.

Waiting at an activity location The waiting time of a pedestrian at an *activity location* depends on the demand for and the capacity of the service. As link state variables are only specified at a specific moment, only the number of pedestrians waiting at the moment of calculation are included. Each service has a distribution for the service time and the number of servers. To calculate the expected waiting time of a default pedestrian at an activity, the average service time is used. The expected waiting time for a pedestrian arriving at random at an activity location at instant t may then be expressed as:

$$E\left(\underline{T_a^{wait}}(t)\right) = \frac{N^w(t) + \frac{1}{2}N^S(t)}{N^{sp}} \cdot \overline{T_a^{service}}, \; a \in \mathcal{C} \tag{6.8}$$

where $N^w(t)$ is the number of waiting pedestrians for the service, $N^S(t)$ is the number of pedestrians being served at the moment of arrival, N^{sp} is the capacity of the service (corresponding to the number of servers) while $\overline{T_a^{service}}$ is the average service time at this activity location.

Waiting to pass infrastructure The procedure for calculating the waiting time for *passing infrastructure nodes* corresponds to the procedure for the waiting time at an activity:

$$E\left(\underline{T_a^{wait}}(t)\right) = \frac{N^w(t) + \frac{1}{2}N^p(t)}{N^{sp}} \cdot \overline{T_a^{service}}, \; a \in \mathcal{P} \tag{6.9}$$

where $N^w(t)$ is the number of waiting pedestrians for the passing infrastructure node, N^p is the number of pedestrians passing the infrastructure at the moment of arrival, N^{sp} is the capacity of the passing infrastructure while $\overline{T_a^{service}}$ is the average time it takes a default pedestrian to pass this part of the infrastructure (door, turnstile, etc.).

Waiting for a public transport vehicle Finally, the waiting time for *boarding a public transport vehicle* depends on the actual arrival time of the vehicle, the number of pedestrians alighting, and the number of pedestrians boarding before the default pedestrian (equal to the number of pedestrians already waiting on the platform). The actual arrival time of the vehicle is determined by the planned arrival time T_a and its delay T_d, which can be either positive or negative, indicating that the vehicle arrives earlier than its scheduled arrival time. The waiting time for a traveller arriving at instant t on the platform before boarding a public transport vehicle is then described by:

$$E\left(\underline{T_a^{wait}(t)}\right) = (T_a + T_d - t) + T^o + N^a \overline{T^{a,avg}} + N^w(t)\overline{T^{b,avg}}, \; a \in \mathcal{B} \tag{6.10}$$

where T^o is the time it takes to open doors and to make the vehicle ready for boarding and alighting, N^a is the number of alighting pedestrians from the door the pedestrian is waiting to enter, $\overline{T^{a,avg}}$ is the average time for a default pedestrian to alight at this door, N^w is the number of boarding pedestrians that were already waiting at the platform at instant t and $\overline{T^{b,avg}}$ is the average boarding time for a default pedestrian at this door.

Service Service links are used to model activities, passing infrastructure, and boarding a vehicle. The service times for these links are similar as a distribution describes the service times at a specific service location. Thus, each pedestrian has an individual service time, which can not be predicted in advance as it is drawn on the operational level when the pedestrian arrives at the service facility. To calculate service times the expectation of this distribution is used (by definition equal to the average value of the distribution describing these service times):

$$E\left(\underline{T_a^{service}}\right) = \overline{T_a^{service}}, \; a \in \mathcal{C} \cup \mathcal{P} \cup \mathcal{B} \tag{6.11}$$

The state indicators for all links have now been defined which completes the description of the tactical network model, to be used for the route choice model and activity location choice modelling.

6.3 Activity location choice model

The aim of the activity location choice model is to determine the locations where the pedestrian is going to perform his planned activities depending on the prevailing conditions in the network. These locations are determined at the moment the pedestrian enters the facility and are assumed to remain fixed from then on (pre-route activity location choice in the simulation tool). The activity location choice model uses the tactical network model as an input.

6.3.1 Assumptions

The order of the pedestrian activities is assumed fixed in the current version of the model, implying that this activity order does not depend on current or later conditions in the network.

Given a lack of data concerning the individual preferences, a second assumption is that all pedestrians have the same preference for an activity location.

The third assumption deals with the updates of the predicted activity locations. Following Cascetta (2001), we distinguish pre-trip choice and en-route choice. At a pre-trip choice, the choice is made the moment the pedestrian enters the system. Independent of the changes in conditions on the network, the pedestrian visits those activity locations initially chosen. In en-route choice, these locations may be changed during the trip, while the order and type of activities remain the same. It is assumed that the conditions at the activities do not differ significantly over time, as they are not directly station-related and time spent at activities are reckoned with in advance. Therefore, a pre-trip choice is assumed for the activity locations to visit.

In the calculation of the waiting and service times of a service facility, the variances in the arrival patterns, in the service times, and in the number of servers are not taken into account. This may have consequences for the reliability of the calculated waiting and service times.

The walking times on which the activity location choice model will be based, are instantaneous walking times (where future dynamic conditions on the network are not taken into account). This way of choosing activity locations may cause a deviation between the actual walking times and the predicted walking times, used as an input for the model.

The adopted choice modelling implies a simultaneous choice of activity locations, as combinations of activity locations are compared instead of first determining the closest activity location for the first activity and subsequently resolving the optimal location for the second location, and so forth.

6.3.2 Modelling approach

The starting point of the activity location choice model is an exogenous list of scheduled activities to be performed by a pedestrian, given a description of the infrastructure with activity locations, indicating the type of activity as well, and their static activity characteristics (such as average service time and the number of service points). The activity location choice depends on the actual conditions in the network and at the activity locations (such as the number of waiting pedestrians and the number of pedestrians currently being served). As for route choice, the criterion of activity location choice is overall weighted travel time (consisting of walking, waiting, and service time, see also chapter 3 for a theoretical and empirical foundation of this choice type).

If all relevant attributes were link-additive, it is possible to formulate the activity location choice problem as a shortest path problem through a network, described by nodes (activities) and links (routes between two activities, expressed as travel times). Instead, SimPed constructs a spanning tree of alternatives, in order to be prepared to include non-link-additive values. As the number of alternatives remains low, this approach does not affect the efficiency of calculation. A substitute method may be found to avoid combinations of activity locations that are poor alternatives (including large detours, containing loops).

Figure 6.10 shows a flow diagram of the activity location choice model.

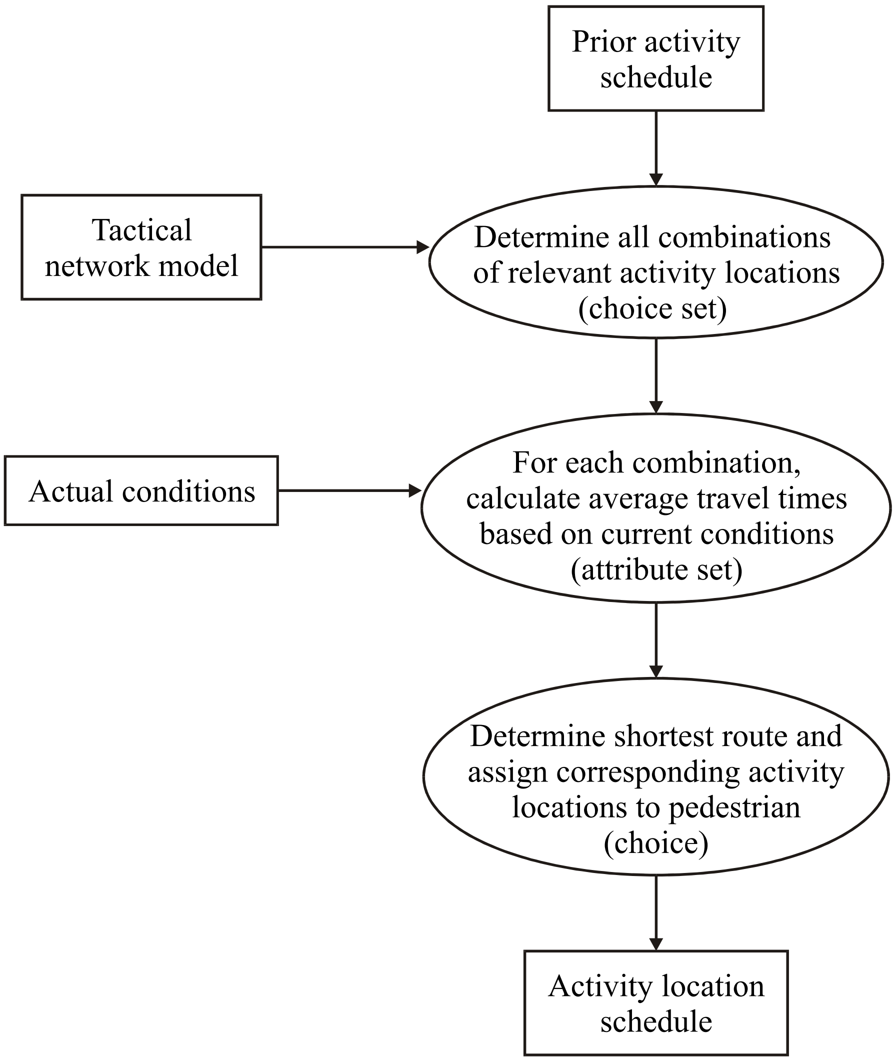


Figure 6.10: Flow diagram of the activity location choice model in SimPed

First, all combinations of the locations of the given personal activity list are determined. Following the scheduled activity order, for each type of activity all locations where this activity can be performed are listed and combined. To do this, a standard spanning tree algorithm is used (Evans & Minieka 1992). The complete tree thus consists of all possible combinations of activity locations for this pedestrian (see also figure 5.10).

The second step is to determine the total time it takes for a pedestrian in the current conditions to walk along these activity locations, wait for the different activities (taking into account the number of pedestrians currently waiting), and perform these. For each entry in the tree (each combination of activity locations), the corresponding travel time is calculated.

Finally, the minimum cost alternative is assumed to be chosen by the pedestrian. Those activity locations leading to this shortest travel time for the pedestrian (in the current conditions) are assigned to the pedestrian, who starts walking towards the first activity location.

6.3.3 Mathematical formulation of an activity location choice model

For each choice model described in this chapter, a formulation is given, consisting of the choice situation, the constraints to the choice set, the choice set itself, the choice factors (or elements of the utility function), and finally the utility function. Most important elements of the utility functions are times, such as walking times, waiting times and service times, which may be found in both the utility function of the activity location choice model and the utility function of the route choice model.

The *choice situation* consists of the origin and destination of the pedestrian, a list of activity types the pedestrian is going to perform, and the alternative locations of each of these activities.

Currently, in SimPed, the order of the activities is assumed fixed and given in the activity schedule. In a general model, this constraint does not need to be the case.

The *choice set* consists of all combinations of activity locations R where the required activities may be performed.

The *choice factors* in a general model are walking time between the activities, waiting time, service time, total walking distance, and attractiveness and familiarity of the activity. The utility derived from performing the activity is assumed equal for all choice alternatives. Currently in SimPed, only the most important disutility factors are taken into account, which are walking time, waiting time and service time.

The general *utility function* $U_R(t)$ describing the utility of activity location schedule R when arriving at instant t, for this choice process is assumed as:

$$\begin{aligned} U_R(t) &= \alpha \sum_{\substack{a \in \mathcal{A} \cup \mathcal{M} \cup \mathcal{L} \\ a \in \mathcal{R}}} T_a^{walk}(t) + \beta \sum_{a \in (\mathcal{C}^i \cup \mathcal{P} \cup \mathcal{B})} T_a^{wait}(t) + \gamma \sum_{\substack{a \in \mathcal{C}^i \cup \mathcal{P} \cup \mathcal{B} \\ a \in \mathcal{R}}} T_a^{service}(t) \\ &\quad + \delta \sum_{j \in \mathcal{R}} L_j + \zeta \sum_{c \in \mathcal{C}^i} A_c + \varepsilon \end{aligned} \tag{6.12}$$

in which a indicates a link on route R, T_a^{walk} is the expected walking time of a default pedestrian on link a, T_a^{wait} is the expected waiting time and $T_a^{service}$ is the expected service time. $\mathcal{C}^i$ indicates an activity in the activity set $\mathcal{C}$ of pedestrian i. L_j indicates the walking distance along trajectory j and A indicates the attractiveness of an activity. α, β, γ, δ, and ζ indicate the weights given to each of the corresponding attributes. ε indicates a random term, indicating subjective choices of individual pedestrians, including all unknown aspects of the activity location choice.

Currently in SimPed, this utility function simplifies to:

$$U_A(t) = \alpha \sum_{\substack{a\in\mathcal{A}\cup\mathcal{M}\cup\mathcal{L} \\ a\in\mathcal{R}}} T_a^{walk}(t) + \beta \sum_{a\in\mathcal{C}^i\cup\mathcal{P}\cup\mathcal{B}} T_a^{wait}(t) + \gamma \sum_{\substack{a\in\mathcal{C}^i\cup\mathcal{P}\cup\mathcal{B} \\ a\in\mathcal{R}}} T_a^{service}(t) \quad (6.13)$$

where α, β, and γ are assumed equal for all pedestrians, lacking accurate data.

A deterministic minimum disutility choice model has been implemented as *choice function* so far, which however can easily be extended to a probabilistic choice model, such as for example multinomial logit or more advanced model forms (Cascetta 2001). Also, the choice of the order of the activities may be included in such a model.

6.3.4 Activity location choice example

The process of activity location choice is explained with an example, see figure 6.11 for the operational network model, including waiting pedestrians and pedestrians being served (current conditions) and figure 6.12 for the tactical network model.

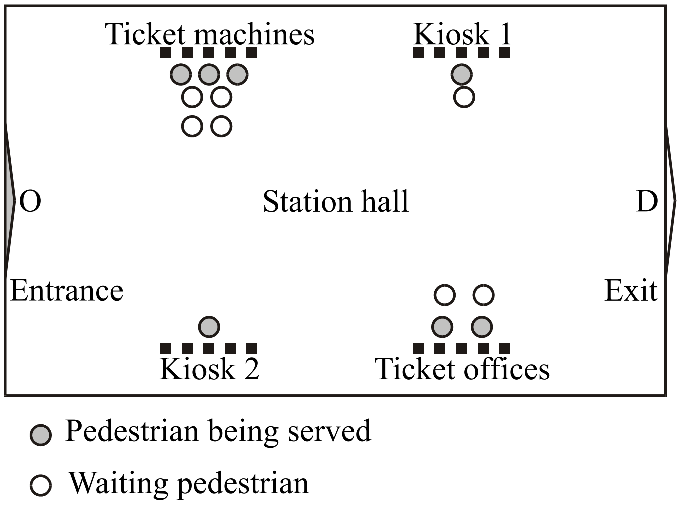


Figure 6.11: Operational network model to illustrate the activity location choice model, showing current conditions

A pedestrian enters the area on the left side (at location O, labelled 'Entrance') and has a destination on the right side (at location D, labelled 'Exit'). He has to perform two activities; first, he has to buy a ticket after which he wants to buy a cup of coffee at the kiosk. The activity 'buying a ticket' may be performed at the ticket machines, as well as at the ticket offices, whereas two kiosks to buy a cup of coffee are situated in the modelled area (again two alternative locations (kiosk 1 and kiosk 2) for the activity 'buying a cup of coffee'). The static average characteristics of these activity locations are shown in table 6.4.

In the current situation (instant t), pedestrians may already being served or waiting to be served. These dynamic data are shown in table 6.5 (and are drawn in the overview in figure 6.11).

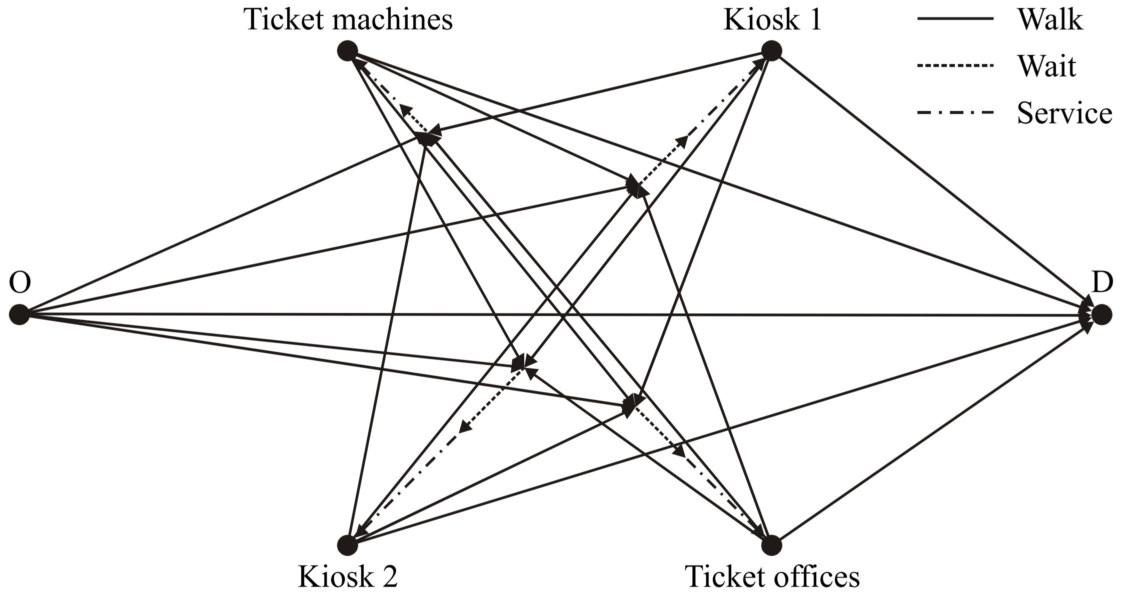


Figure 6.12: Tactical network model corresponding to the operational network model in figure 6.11

Table 6.4: Static average characteristics of the activity locations

Activity	Nr of servers	Service time	Avg. service time
Ticket machines	3	Exponential (30)	30 s
Ticket offices	2	Exponential (45)	45 s
Kiosk 1	1	Exponential (35)	35 s
Kiosk 2	1	Exponential (55)	55 s

Table 6.5: Dynamic characteristics of the activity locations at entering

Activity	Nr waiting	Nr served	Waiting time
Ticket machines	4	3	45 s
Ticket offices	2	2	67.5 s
Kiosk 1	1	1	52.5 s
Kiosk 2	0	1	27.5 s

The aim of the activity location choice model is to choose the activity locations such that the total instantaneous travel time (including walking, waiting, and service times) from the pedestrian origin via the activities to his destination is minimal. In comparing the alternatives, also the walking times between the locations and the origin and destination are needed (see table 6.6).

Table 6.6: Walking times in seconds between the activities and the pedestrian's origin and destination valid at time t

From / to	Dest.	Kiosk 1	Kiosk 2	Ticket mach.	Ticket off.
Origin	*	21	11	11	21
Kiosk 1	11	*	14	10	10
Kiosk 2	21	14	*	10	10
Ticket mach.	21	10	10	*	14
Ticket off.	11	10	10	14	*

The first step (see figure 6.10) is to determine the spanning tree of the activity locations. The pedestrian starts at his origin O at instant t. Then, he walks to his first activity, being buying a ticket, which can be performed at either the ticket machines or the ticket offices (two alternative locations between which needs to be chosen). Then, the pedestrian wants to buy a cup of coffee at either kiosk 1 or kiosk 2 (again two alternative locations). After these activities, the pedestrian walks to its destination D. The order of the activities, and thus the order of the nodes to visit, is indicated in the activity schedule, which is input for this model. The resulting spanning tree contains four alternatives shown in figure 6.13.

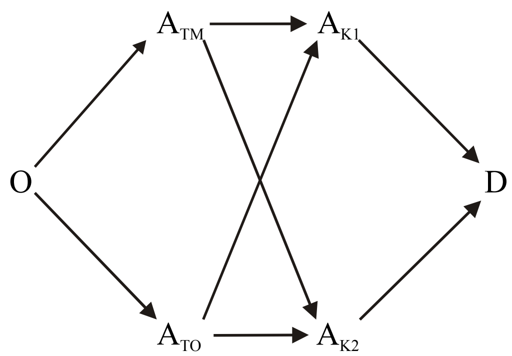


Figure 6.13: Spanning tree of combinations of activity locations in example

In the second step, the total (weighted) instantaneous travel times for these alternatives are calculated. Therefore, walking, waiting and service times of the different activity locations in an alternative are summed. The result of this step is shown in table 6.7.

In the third step, the minimal instantaneous route time is determined. In this example, alternative 1 has the shortest route time. The pedestrian will thus buy his ticket at the ticket machines and his cup of coffee at kiosk 1.

Table 6.7: Route times for each alternative (in seconds)

Alternative	Walking	Waiting	Service	Total
$O - A_{TM} - A_{k1} - D$	11+10+11	45+52.5	30+35	194.5
$O - A_{TM} - A_{k2} - D$	11+10+21	45+27.5	30+55	199.5
$O - A_{TO} - A_{k1} - D$	21+10+11	67.5+52.5	45+35	242
$O - A_{TO} - A_{k2} - D$	21+10+21	67.5+27.5	45+55	247

6.3.5 Future improvements of activity location choice modelling

A number of model improvements are envisaged for the future.

One of the planned improvements of the model is to take into account the changing conditions on the network in the immediate future (en-route activity location choice). A pedestrian needs time to walk to its first activity location and due to the changing conditions on the network, the optimal location for the second activity may have changed (see figure 6.14, where after performance of activity 1, the best location to perform activity 2 is at location 2, due to the presence and thus hindrance of other pedestrians on the route to location 1). However, these future conditions are extremely hard to predict, thus an approximation is to fix the location of the first activity and, after having performed this activity, again run the activity location choice model to determine the optimal location for the next activity, taking into account the updated conditions on the network (and other activities that may be performed subsequently).

This leads to the adapted flow diagram for pedestrians performing activities, shown in the right part of figure 6.15, in which the moment of the activity location choice is stressed. A shift thus is proposed from a simultaneous choice based on instantaneous conditions to a sequential choice based on dynamic conditions.

A second improvement concerns the weight values for the different types of times (for walking, waiting, and service). These time weights are assumed equal, although literature (Guo & Wilson 2004) indicates that especially waiting time is perceived more negatively by customers. An improvement thus is to include distinct weight values in the calculation of the overall travel times. Also, these weights may vary according to pedestrian' taste variations in order to model individual choice behaviour.

A third potential improvement concerns the service time. In the disutility calculation, the average service time is used, without taking into account its variance. This variance might be taken into account by using e.g. the 80% value of the service time distribution instead of the average service time.

The fourth improvement consists of including the scheduling of the activities in this activity location choice model and transform the existing choice model in a simultaneous activity location and scheduling model. This new model may be based upon the same algorithms as the current model, but the improvements mentioned earlier this section may also be taken into account on behalf of the combined choice model.

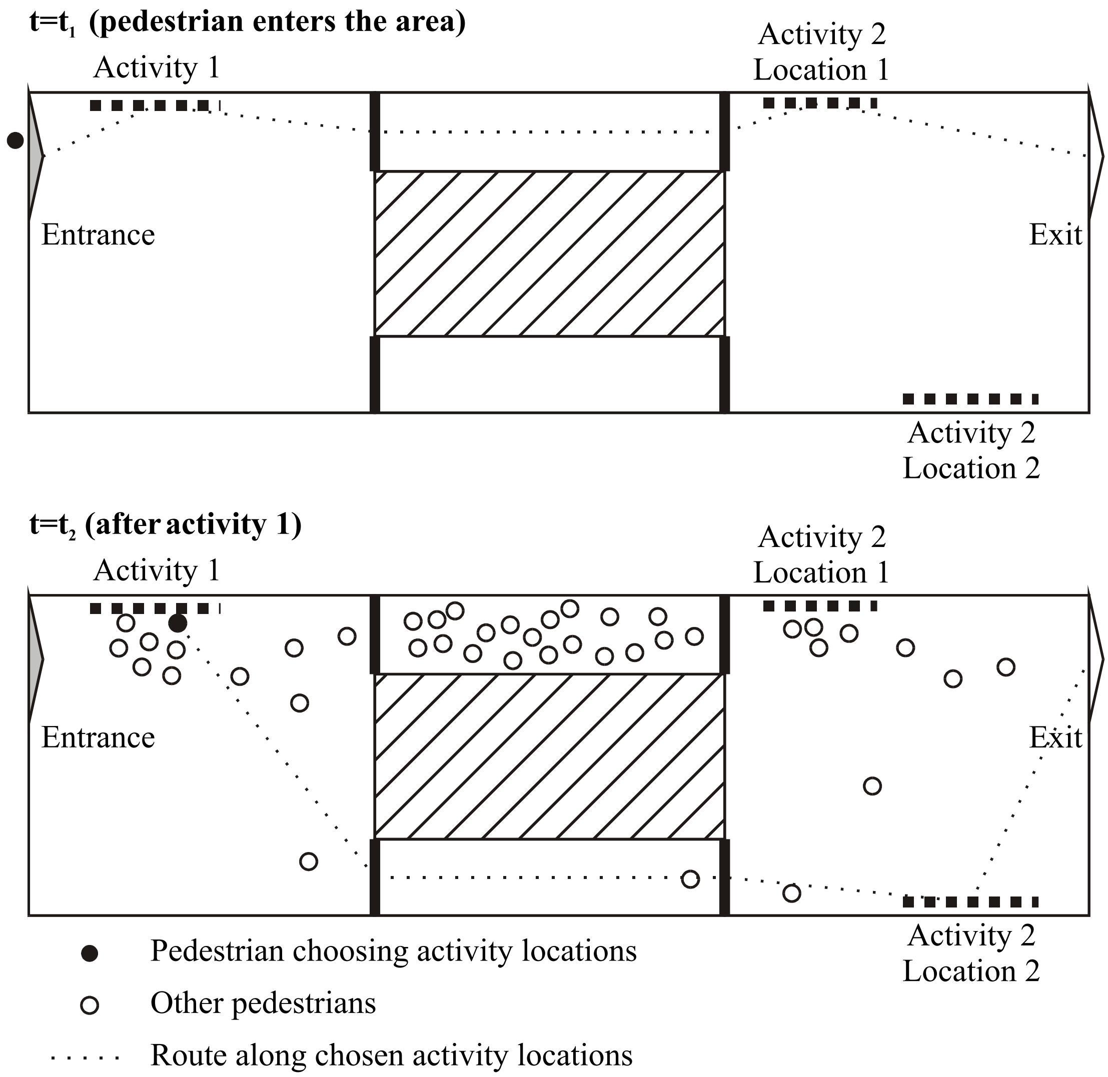


Figure 6.14: Influence of the evaluation moment of the outcome of the activity location choice model on the choice for the location of the second activity

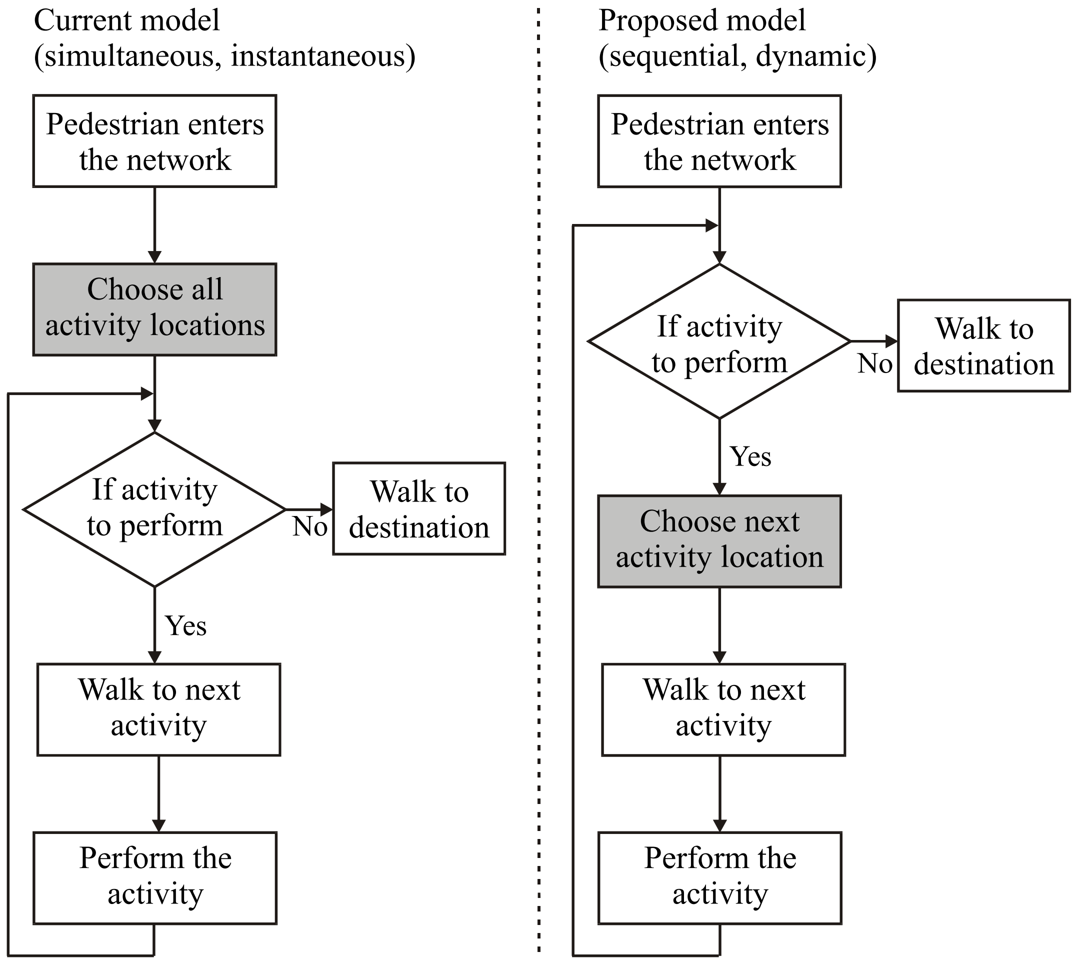


Figure 6.15: Flow diagram of both current and proposed model for activity location choice

6.4 Route choice model

In this section, the route choice model of pedestrians in public transport nodes is elaborated. The aim of this model is to find for each pedestrian its optimal route through the network, from the pedestrian's origin to his (intermediate) destination, depending on the instantaneous conditions in this network. Input for the route choice model is the tactical network model, describing the network topology and the interfaces between the various parts of the infrastructure.

First, the assumptions of this model are given. Then, the general principles of the route choice model are presented, followed by the formulation as a choice model. Finally, the split up of the route choice model into three separate models is discussed, after which the shortest path module is described in more detail.

6.4.1 Assumptions

As is indicated in the literature (see chapter 3), route choice of travellers is based on a variety of factors. The simulation model described in this thesis has especially been developed to model walking through transfer stations in order to predict densities and pedestrian comfort in capacity situations. We argue that commuters and peak conditions are most important when assessing a design, since capacities are generally reached during peak hours. Commuters often make similar trips, developing thereby experience of transfer stations. They become not only familiar with the static situation, such as the station layout and the shortest routes in distance to their destination, but are also acquainted with the dynamic situation, such as the location of possible congestion in the station (including evaluations of corresponding delay times) and the shortest routes in time. The model therefore assumes all pedestrians to have complete information on both static and dynamic conditions in the station (no uncertainties). This is in turn affected by considering the prevailing instantaneous conditions in the route choice model at each decision point.

The second assumption is based also on the fact that mainly commuters use the transfer station during peak hours. The main aim of commuters in a station is to walk as efficiently as possible and to reach their destination as fast as possible. They arrive at the station only a short time before their train will leave and, when they will perform activities, they will do that very efficiently. Alighting passengers will walk straight to connecting services or to their destination. Due to their focus on travel time, it is assumed that their route choice behaviour mainly depends on shortest walking times. Shortest walking times (including necessary waiting and service times at activity sites) are thus the only criteria on which the route choice modelling is based.

A third assumption concerns the similarity in route choice behaviour of individual pedestrians. According to the theory, each individual makes his own assumptions and evaluations on which his choices are based. In the same conditions, each individual has its own view on this situation and makes a subjective choice. However, due to the greater experience of commuters, it is assumed that their assumptions are similar and their decisions, especially concerning route choice, will not vary significantly. All decisions are assumed to be objective and, based on the same objective information (such as route travel times and densities on the network), all decisions are similar. Due to changing conditions on the network and different combinations of origins and destinations, different routes will be chosen anyway.

The fourth and final assumption deals with updates of the predicted route. Following Cascetta (2001) we distinguish pre-trip choice and en-route choice. At a pre-trip choice, the total route is determined the moment the pedestrian enters the system. Independent of the changes in conditions on the network, the pedestrian keeps following the same route, which may lead to suboptimal routes. In en-route choice, the optimal route may change during the walking trip. Transfer stations are characterised by strongly fluctuating conditions due to the frequent arrival and departure of highly occupied public transport vehicles. Therefore, the route choice model is based on en-route choice behaviour accounting for dynamically changing conditions.

6.4.2 Route choice principles

The basis of pedestrian route choice behaviour is that pedestrians chose individually optimal routes. Which route a pedestrian perceives as optimal, depends on his personal taste as well as on the conditions in the network. In addition, walking times on links are flow dependent, taking into account congestion and thus change over time in relation to the demand. These two principles lead to a distribution of demand over alternative routes and in the end tend to an equilibrium state.

Input for the *route choice model* is the tactical network model, in which performance indicators are used to describe the state (expressed in travel times depending on densities on the walkways) on the network. These indicators are updated regularly in order to represent the current, instantaneous situation. In such a situation, shortest routes are found from all nodes in the network to all other nodes in the network to enable en-route route choice. The shortest routes are regularly updated as well. The resulting route choice model appears to be a quasi-dynamic deterministic equilibrium approximation, see appendix C.

The route choice model outcomes do not influence pedestrian behaviour with regard to the travel time following from the route choice. This means that demands are assumed inelastic, indicating that neither arrival nor departure times are changed. Also, free walking speeds are independent of route choice and current conditions on the network and will thus not anticipate to longer travel times.

6.4.3 Mathematical formulation of the route choice model

The *choice situation* consists of the actual position of a pedestrian at a node, the destination of the pedestrian and all locations of intermediate destinations, such as activities, at a given moment.

The *choice set* will only contain feasible routes. There are no *constraints* on the size of the choice set. The choice set consists of all feasible routes from the actual node to the destination.

The most common *choice variable* in the route choice process is time-dependent travel time, consisting of walking time, waiting time and service time (see also the formulation of the activity location choice model, section 6.3.3). Other potential variables are distance (L_r), pleasantness (p), habit (h), number of crossings with other modalities such as cars (N_r^{cross}), pollution and noise levels (L_r^{noise}), safety (F), shelter from poor weather conditions (W_r) and trip motive (M_i^{trip}) of pedestrian i.

If the choice between the use of stairs and escalators is taken into account separately, the variables for this choice are delay on the walkway leading to the escalator and stairs, delay on the escalator and stairs section and the length of the escalator and stairs (see (Cheung & Lam 1998)). This more detailed choice situation is currently under development (Van de Reijt 2004), and will be included in SimPed.

The general *utility function* $U_R(t)$ for this route choice process then is assumed as:

$$\begin{aligned} U_R(t) &= \alpha \sum_{\substack{a \in \mathcal{A} \cup \mathcal{M} \cup \mathcal{L} \\ a \in \mathcal{R}}} T_a^{walk}(t) + \beta \sum_{a \in \mathcal{C}^i \cup \mathcal{P} \cup \mathcal{B}} T_a^{wait}(t) \\ &\quad + \gamma \sum_{\substack{a \in \mathcal{C}^i \cup \mathcal{P} \cup \mathcal{B} \\ a \in \mathcal{R}}} T_a^{service}(t) + \delta \sum_{a \in \mathcal{R}} L_a + \zeta p_r(t) + \eta h_r \\ &\quad + \theta N_r^{cross} + \iota L_r^{noise}(t) + \kappa F_r(t) + \lambda W_r + \mu M_i^{trip} + \varepsilon \end{aligned} \tag{6.14}$$

in which a indicates a link on route R, T_a^{walk} is the walking time, T_a^{wait} is the waiting time, and $T_a^{service}$ is the service time at activity a in the activity set $\mathcal{C}$ of pedestrian i. α, β, γ, δ, ζ, η, θ, ι, κ, λ, and μ indicate the weights given to each of the attributes by the pedestrian. ε indicates a random term, indicating subjective choices.

Currently, in SimPed, the route choice is only based on travel time:

$$U_R(t) = \alpha \sum_{\substack{a \in \mathcal{A} \cup \mathcal{M} \cup \mathcal{L} \\ a \in \mathcal{R}}} \xi T_a^{walk}(t) + \beta \sum_{a \in \mathcal{C}^i \cup \mathcal{P} \cup \mathcal{B}} T_a^{wait}(t) + \gamma \sum_{\substack{a \in \mathcal{C}^i \cup \mathcal{P} \cup \mathcal{B} \\ a \in \mathcal{R}}} T_a^{service}(t) \tag{6.15}$$

However, when pedestrians choose between an escalator and a stairs, the comfort effect of the escalator has to be taken into account. Therefore, a comfort parameter ξ is introduced. This comfort parameter will decrease the generalised walking time on the escalator (until it is smaller than the walking time on a stairs of similar length in free flow conditions), but in crowded conditions, this parameter is increased, as the number of pedestrians choosing the stairs increases. The parameter ξ is formulated as:

$$\xi = \frac{1}{\xi_0 + (1-\xi_0)\left(1-\frac{N_l}{N^{max}}\right)}, l \in \mathcal{M} \quad (6.16)$$

$$\xi = 1,\ a \in \mathcal{A} \quad (6.17)$$

where ξ_0 is an initial value for the comfort parameter, N_l is the number of pedestrians present on link $a \in \mathcal{R}$, and N^{max} is the maximum number of pedestrians present when the escalator is used at capacity. In chapter 8, a comparison is made between this route choice model with the discussed comfort parameter and literature.

The *route choice function* is a deterministic minimum (weighted) time choice, repeated at successive instants t.

6.4.4 Calculation of route choices

The developed route choice model for SimPed consists of three separate modules:

- Shortest path module. This module calculates at a given instant t all shortest paths in time through the network, based on the current link travel times, so-called instantaneous shortest path.
- Individual route module. This module determines the next walkway to be followed by a pedestrian arriving at a route decision point (a node in the network). This walkway is part of the route calculated in the shortest path module.
- Walking module. This module calculates individual travel times for pedestrians on the next walkway, depending on the current conditions in this link. The walking model is described in more detail in section 6.5.

As is motivated in chapters 2 and 7, the pedestrian simulation tool SimPed uses an event-based approach. In this simulation tool, three parallel time lines are used, that is one time line for the route choice model and two time lines for the events of a pedestrian (arriving at the next walking link and arriving at a service location). The events on all three time lines are grouped in an event list, containing all events during the simulation. The three time lines and the event list are indicated in figure 6.16.

The first time line concerns the shortest route update, consisting of a repeated shortest path search at consecutive fixed instants. As may be seen in the figure, the update period ΔT is constant during the simulation, independent of the conditions on the network. This

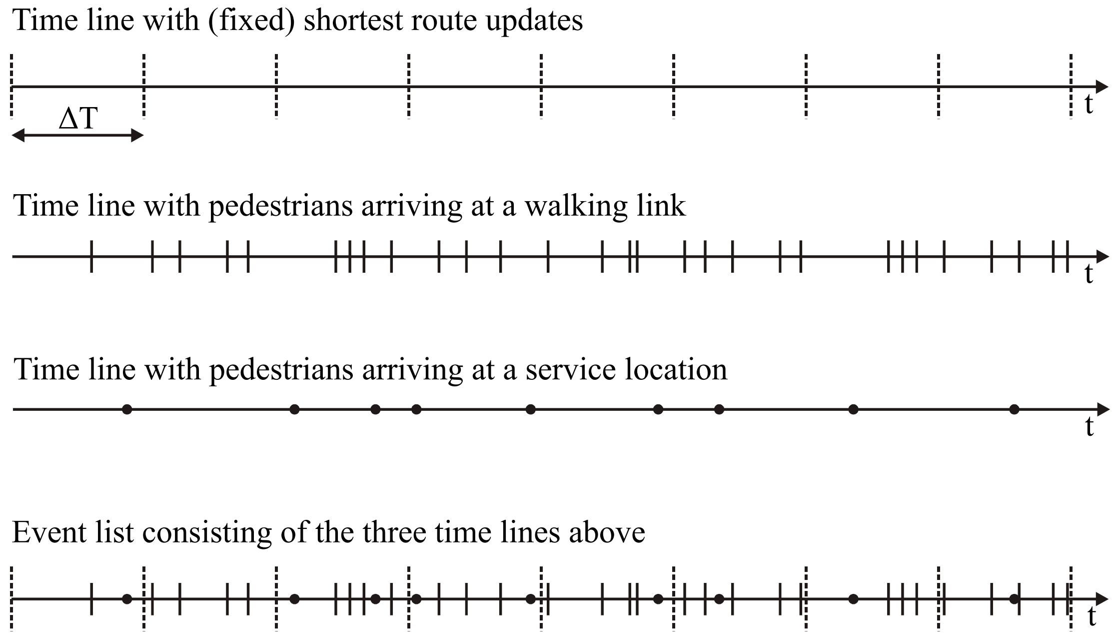


Figure 6.16: Three parallel time lines used in SimPed, integrated in an event list

update interval is one of the input parameters of the model, depending on the application area and the type of simulation study. The second time line handles the arrival of individual pedestrians at the next walking link, whereas the third time line indicates the arrival moment of pedestrians at a service location. The time period between arrival moments of pedestrians (second and third time line) is generally smaller than the route update interval and depends on the pedestrian demand. The bottom line shows the event list used during the simulation. This event list is a combination of all earlier mentioned time lines, being updated continuously during the simulation (adding and removing events).

The route choice model therefore consists of two time cycles, namely one time cycle concerning the route updates, whereas the second time cycle involves arrival moments of pedestrians at specific parts of the infrastructure determining the link travel times in the next link of the route.

The data flow diagram of the route choice model, in which the interaction of these modules is indicated, is shown in figure 6.17.

Pedestrians are generated (according to the OD-matrices) and are assigned to the next link of their route (individual route module). For these pedestrians, the individual walking time along this link is calculated, based on the current density (walking model see section 6.5). Pedestrians continue walking, arriving at the next node and determining their next link, until the update period has expired. At that moment, the shortest paths are recalculated and the process re-iterates, until no more pedestrians have to be processed and the simulation has ended.

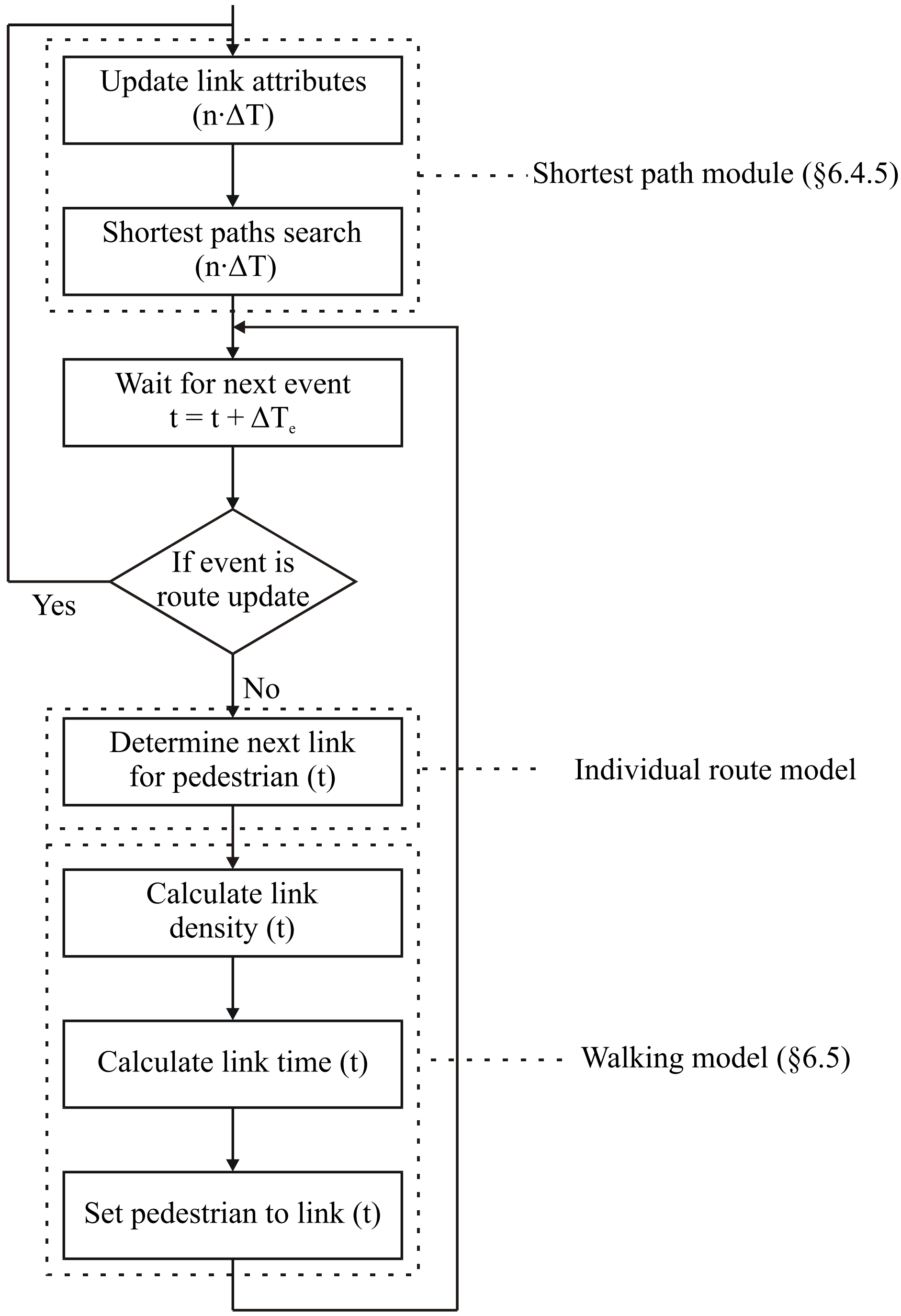


Figure 6.17: Flow diagram of the route choice model

6.4.5 Shortest path module

In order to enable en-route route choice, the pedestrian route may be updated during a trip. This means that not only routes are needed from origin to destination, but also routes from an arbitrary node on this route towards a (intermediate) destination. The shortest route algorithm thus needs to find a shortest path between every pair of vertices in the graph.

The shortest path module calculates all shortest paths through the network from all nodes to all nodes, given the instantaneous conditions on the network. The route choice model updates the shortest paths after a fixed (independent of the conditions on the network) period of time, the so-called update interval ΔT. The shortest paths may differ between two consecutive time instants, due to changes in density on the links, leading to changing travel times on these links, and thus to changing link state variables.

To solve this shortest path problem, several algorithms are known (Evans & Minieka 1992), all leading to the same result with similar efficiency. From these methods, the Dantzig algorithm has been chosen, among other things due to the straightforward manner of implementation (Dantzig 1967), (Evans & Minieka 1992), (Steenbrink 1974). This algorithm keeps track of the length of the shortest route between two nodes, but also of the route itself, which is important to determine the next link on the route of a pedestrian (in the individual route model).

The result of this shortest path module is a matrix with the lengths of all shortest routes between all nodes in the network and a description of these routes, consisting of the consecutive nodes of a route. This matrix is the basis of all routes during this period of time in the simulation.

6.5 Walking model

In the previous sections on choices at the tactical level, average link travel times have been used. The walking model, however, yields actual individual walking times, given individual pedestrian characteristics and current conditions on the network. In the proposed model interactions between individuals are not modelled explicitly, but on an aggregate level by means of speed-density relations. The speed-density relations used in SimPed have been derived from experiments, described in chapter 4.

6.5.1 Individual walking times on a walkway

When arriving on a walkway, the pedestrian's walking time on this walkway is calculated. This depends on the traffic conditions ahead as well as on the individual pedestrian's characteristics. This walking time is the time a pedestrian needs to pass the walkway and to arrive at the next joint. During this period of time, the pedestrian remains in the walkway, occupying some part of its surface, and contributing to its density.

The individual walking time follows from the length L_a of the trajectory over walkway a and the speed of the individual pedestrian v_i (depending on the density k on walkway a) at entering instant t:

$$T_i^{walk}(t) = \frac{L_j}{v_i(k_a(t))} \tag{6.18}$$

where $T_i^{walk}(t)$ is the walking time for individual pedestrian i entering walkway a at time t. This individual speed also depends on the free speed of the individual pedestrian. Not every pedestrian chooses the same walking speed, even in free flow conditions, as may be seen in the results of the laboratory experiments (figure 4.6). The difference in free speeds, resulting in different speeds in similar conditions is shown in figure 6.18.

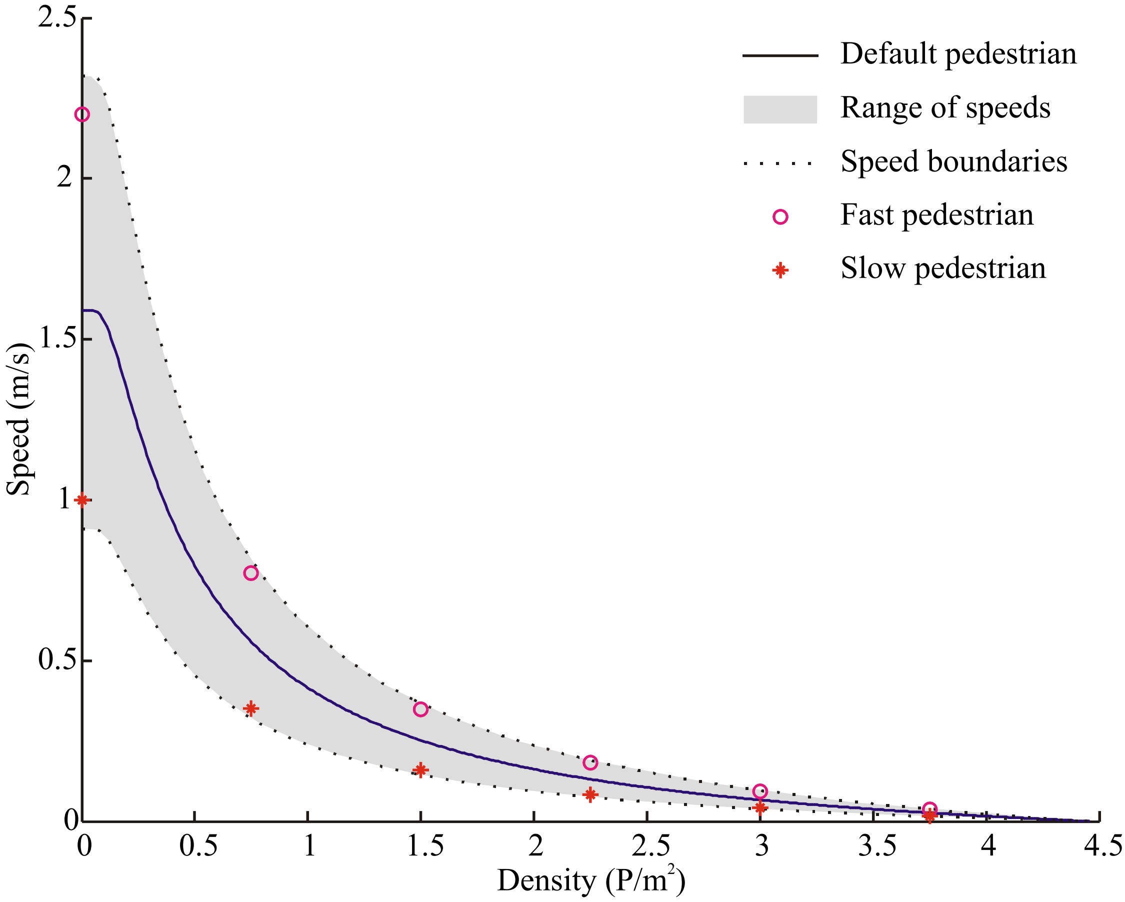


Figure 6.18: Determination of the individual speed in several conditions

The individual speeds v_i in a walkway are derived from the corresponding default speed-density relation by multiplying the average speed v_i at a given density k by the quotient of the known individual free speed of a pedestrian v_i^0 and the free speed of a default pedestrian $v^{0,avg}$:

$$v_i\left(k(t)\right) = \frac{v_i^0}{v^{0,avg}} \cdot v\left(k_a(t)\right) \tag{6.19}$$

where v_i^0 is drawn from the free speed distributions derived from the experiments.

By changing the distribution of the free speeds over the pedestrian population different walking characteristics may be modelled (in station conditions more pedestrians have a significantly higher free speed in order to catch their train, whereas in shopping areas this free speed is lower to support window-shopping).

The current density is calculated as follows:

$$k_a\left(t\right) = \frac{\sum\limits_{N(t)} A_i}{A^{avg} \cdot A_a^{net}} = \frac{N(t) \cdot \overline{A}}{A^{avg} \cdot A_a^{net}} \tag{6.20}$$

where $k_a(t)$ is the current density on walkway a, A_a^{net} is the net surface of the walkway (the area available for walking, thus without obstacles and other hindrances), and $N(t)$ is the current number of pedestrians on the walkway. The density is expressed in the current number of average pedestrian surfaces per square metre. As each pedestrian has an individual occupied area A_i (indicating the area occupied his luggage), a pedestrian equivalent is used, which is the number of average pedestrian areas A^{avg} corresponding to the area of this individual pedestrian. Both A_i and A^{avg} are input parameters of the model.

6.5.2 Pedestrian order

The order in which pedestrians enter the walkway does not necessarily correspond to the order in which they leave the walkway. In other words, the model does not satisfy the so-called FIFO principle. This is, among other things, caused by different free speeds of pedestrians (a pedestrian arriving later may have a higher free speed and thus pass an earlier arrived pedestrian; both pedestrians having the same origins and destinations in the walkway). It also might be the consequence of changing densities. The last pedestrian of a group encounters a low speed due to higher densities. A later arriving pedestrian will encounter a lower density (the first pedestrians of the group have already left the area) and thus will have a higher speed (even when all free speeds are similar). Depending on the form of the fundamental diagram, the later arriving pedestrian might pass the preceding pedestrian (see figure 6.19).

The left part of figure 6.19 indicates pedestrian trajectories in a walkway, while the right part indicates the flow-density diagram, in which the slopes of the trajectories have been indicated. The solid trajectories indicate that pedestrian order is not according to FIFO, whereas the dashed trajectory (based on the dashed fundamental diagram) indicates a FIFO order in this situation. The pedestrian order at the exit of a walkway therefore also depends on the form of the fundamental diagram in the considered walkway (assuming similar pedestrian free speeds).

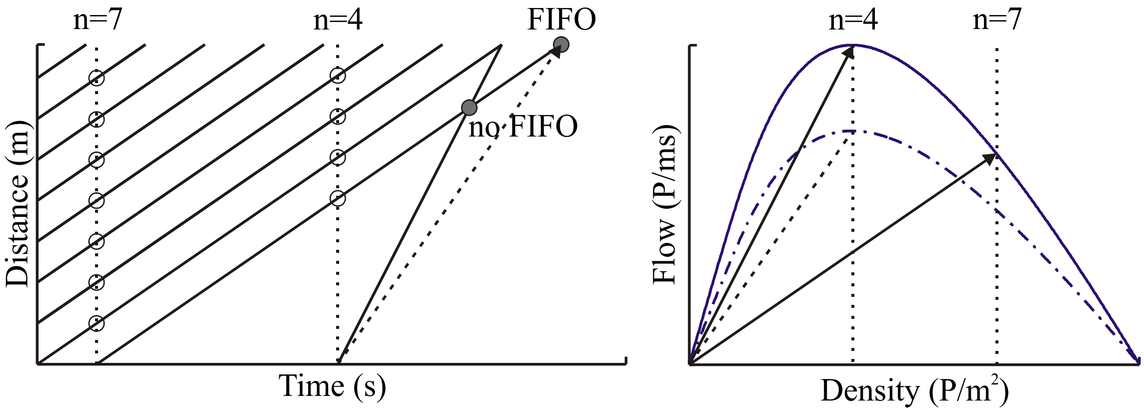


Figure 6.19: Pedestrian order in a walkway

6.5.3 Waiting time in front of joints with restricted capacity

Joints may have a restricted capacity, for example when representing turnstiles or doors. The capacity of a joint has been modelled by a service for the pedestrian in the joint. Thus, when the joint capacity equals 0.8 P/ s, each pedestrian will incur a waiting time of $\frac{1}{C} = 1.25$ s, independent of the pedestrian demand. The number of pedestrians being at the same time in a joint is restricted to 1 in this case, but both parameters may be changed by the user.

When pedestrian demand is higher than capacity, a vertical waiting queue is formed in the walkway upstream of the joint with reduced capacity. This vertical queue implies that pedestrians walk through the total walkway until they arrive at the joint. There, they incur a waiting time, but during this waiting time they remain in the walkway thus increasing density for pedestrians entering the walkway.

Figure 6.20 shows trajectories for pedestrians passing a joint with restricted capacity. The upper part of the figure shows the conditions in free flow, while the lower part indicates congested flow. The figure on the right indicates more clearly the trajectories in the vertical queue.

6.5.4 Passing joints

A joint is characterised by the number of pedestrians that can be present at the same time as well as a delay distribution, indicating the time pedestrians need to pass this joint. Figure 6.21 shows several examples of pedestrians passing joints in different conditions (varying capacity and delays, one and two directional flows).

Joints with restricted capacity may cause so-called deadlock problems in multi directional flows (see figure 6.22). In the simulation model this has been solved by ensuring that an area cannot be completely filled with pedestrians walking in the same direction or more precisely, to the same joint. Each area should have at least one pedestrian (or area for one

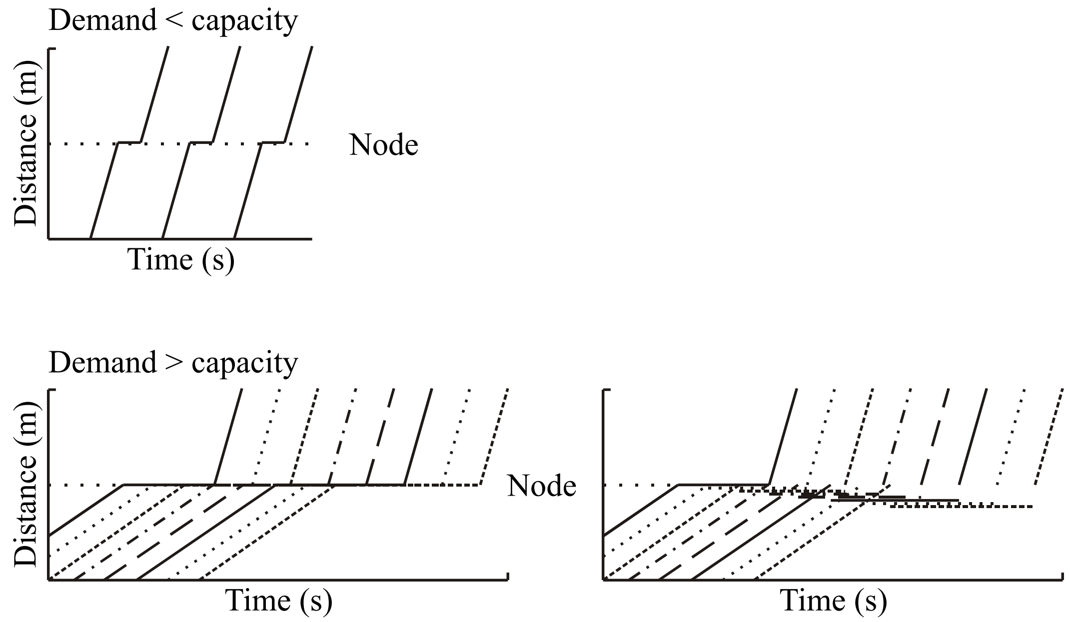


Figure 6.20: Pedestrians passing a joint with restricted capacity

pedestrian) walking to each joint connected to this area. This explains the open area in the left walkway of the model solution, which can not be taken by a black pedestrian, but may be filled by a grey pedestrian, walking in opposite direction.

Figure 6.23 shows pedestrians passing joints with limited capacity in congested conditions. Both joints may handle only one pedestrian in each direction at the same time, whereas the right joint causes pedestrians to stay during period T_d. Pedestrian demand from left to right is larger than the capacity of the right joint, thus congestion is building up in the area upstream (left) of the bottleneck. The opposite (grey) flow is relatively small. Despite the high flow from the left, both joints are capable of handling a grey pedestrian the moment he arrives at the joint. Since the middle walkway is completely filled with pedestrians, congestion is building up in the left walkway as well. Traffic in each part of the infrastructure (modelled by a separate walkway) depends therefore on the traffic situation in other (downstream) areas.

6.5.5 Multi directional flows

As previous examples showed, flows in each walkway may be one directional or multi directional. Pedestrian walking behaviour might be influenced by different walking directions (as indicated in literature). Also the experiments described in chapter 4 show a slightly lower free speed in the two directional experiment compared to the reference situation. Taking into account the accuracy of the other processes modelled (especially route choice), only one speed-density relation is used for each walkway. When further experiments show a significantly different walking behaviour, several speed-density relations might be provided for each walkway, each modelling different conditions $u = u\left(k_d\right)$

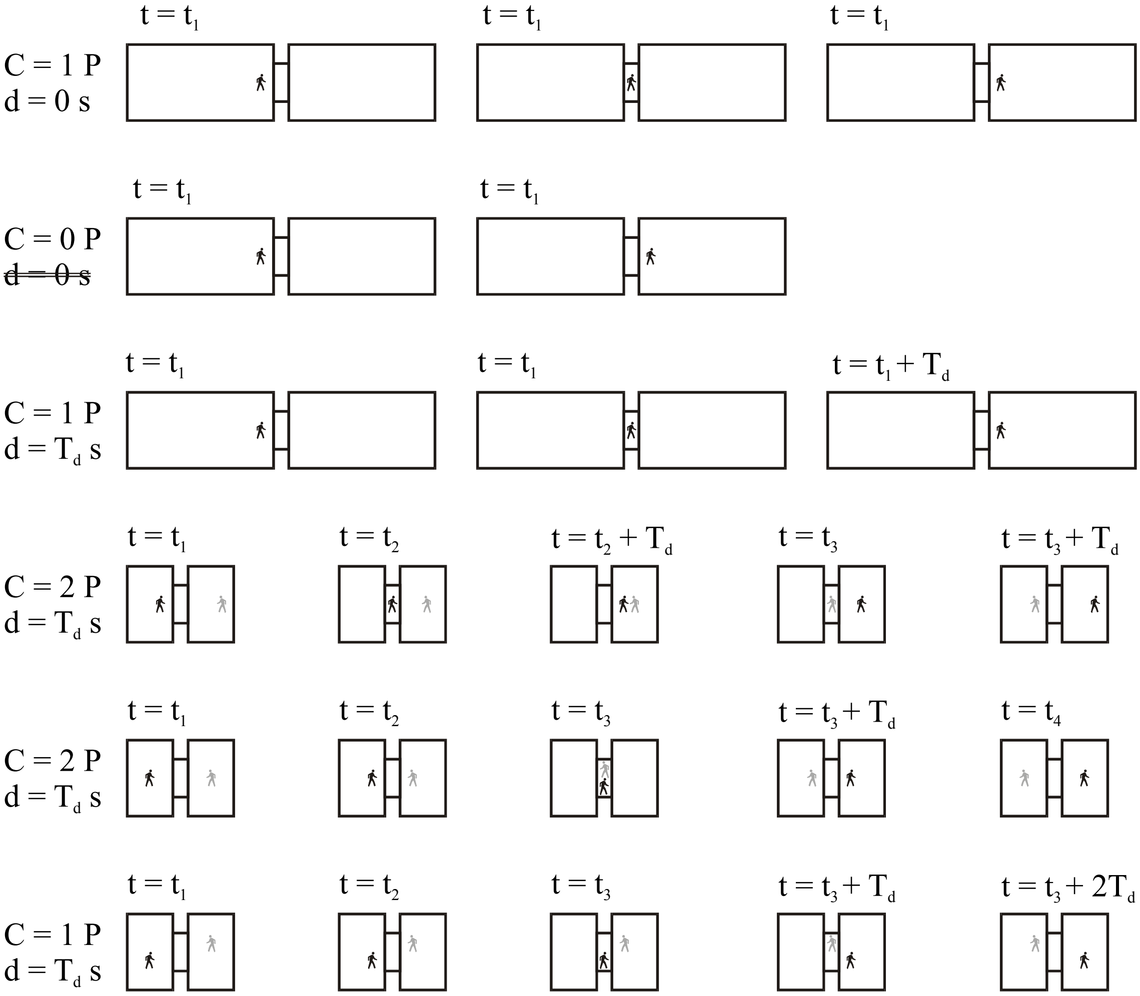


Figure 6.21: Pedestrians passing joints

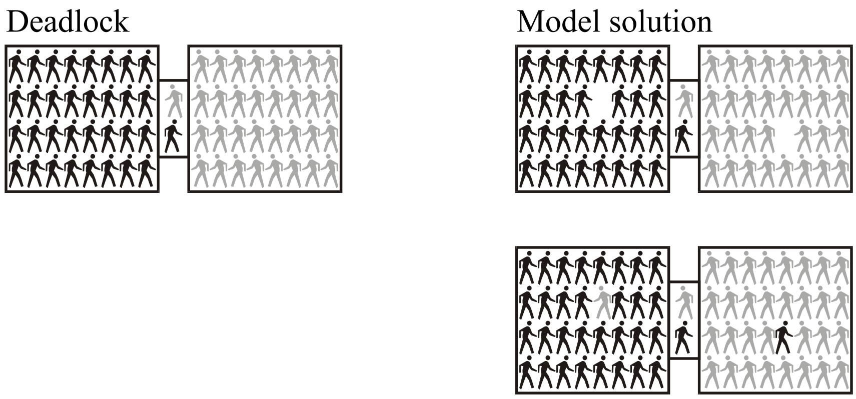


Figure 6.22: Model solution to prevent deadlocks

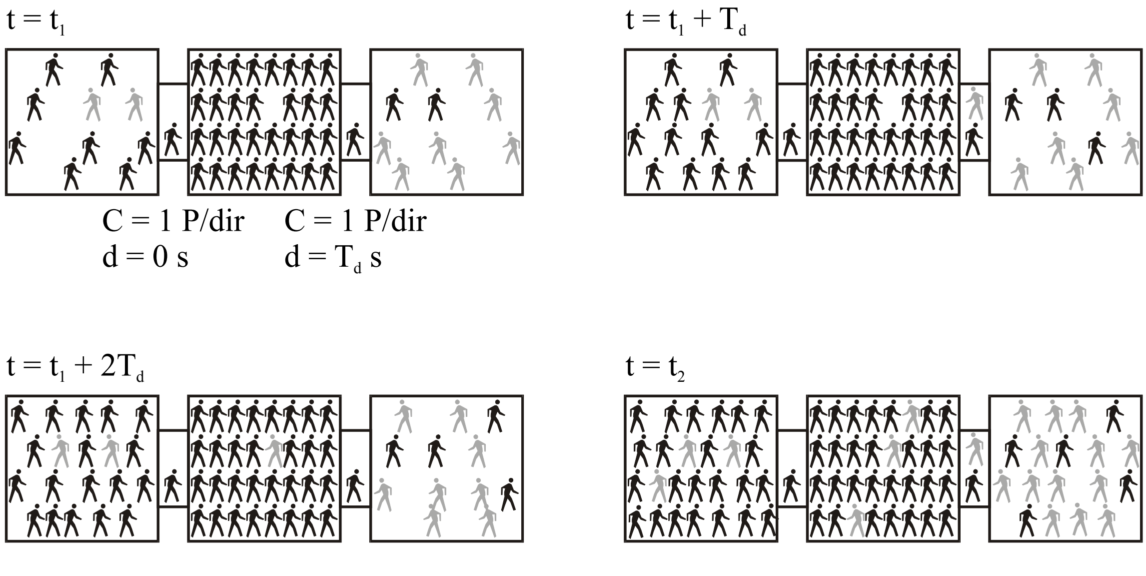


Figure 6.23: Pedestrians passing limited capacity joints in congestion

in which k_d indicates the density in each walking direction d. For a comparison of this simulation approach with shockwave theory see appendix D.

6.6 Model for performing activities

Classical queuing theory concerns customers served at a service facility. This corresponds to pedestrians performing an activity at an activity location, pedestrians passing infrastructure joints such as gates and doors, and travellers boarding and alighting. The facility requires a certain time to serve each customer and is capable of serving only a limited number of customers at the same time. If customers arrive faster than the facility can serve them, a queue builds up and customers have to wait. This queue may disturb other processes such as walking.

The process of pedestrians performing an activity consists of three basic components (Gipps 1986), which need to be described in sufficient detail:

- Arrival pattern. This includes the distribution of arrivals over time. In the simulation model described here, this arrival pattern is implicitly determined by the allocation of activities to pedestrians, while the pedestrians are present in the model during a specific period of time and choose the optimal location to perform the activity.
- Service mechanism. The service mechanism describes when the service is available, how many resources are available (thus how many customers can be served at the same time) and the time the service takes. This service time is described by a statistical distribution, from which individual service times are drawn during the simulation.

- Queue discipline. Queue discipline concerns the way in which the next customer or set of customers is selected to be served. This customer is chosen from the waiting customers, based on a specific criterion. The simplest queue-discipline, first-come-first-served, consists of serving customers in order of arrival.

In the remainder of this section, these three components are described in more detail

Arrival pattern The headway distribution at an activity location, describing the arrival process at an activity location, depends on the headway distribution (arrival of individual pedestrians in the simulation) in the system and of the consecutive choices made by each individual. There is therefore no need to specify these arrival processes at an activity location, because they are completely determined by the event driven simulation process. Since an analytical treatment of the arrival process is untractable, the event simulation approach has been chosen to model these processes.

Whether the pedestrians are spread more evenly over time when they arrive at a facility or whether they arrive more clustered, depends on the situation (infrastructure, but also arrival and departure of public transport vehicles and existence of other pedestrian flows). The higher the variance in the arrival pattern of the pedestrians at a facility, the higher the average waiting time (Hillier & Lieberman 1995).

Service mechanism As described in section 6.2, an activity location is indicated as a line, describing a zone. This activity zone is located in (and thus connected to) a walking area. The pedestrians being served and those waiting to be served occupy space in this walking area. This way, pedestrians being served and waiting pedestrians hinder passing pedestrians. Due to the fact that pedestrian behaviour is modelled macroscopically, the exact physical location of the waiting pedestrians and the form of the queues are taken into account implicitly by increasing the density of the area with waiting passengers.

Queue discipline Three types of queue disciplines are distinguished (see also (Gipps 1986)):

- Service points with queuing. Waiting customers form one or more (depending on the number of service points) queues and are served in order of arrival. Examples are ticket offices, and ticket and soft drink machines.

- Service zones with competition. Waiting customers form a group around the service zones and are served based on their proximity to the service points. An example of such a service point is a (crowded) counter, where the server can not keep control of the order of arrival of the customers.

- Service zones with random service. Waiting customers gather together around a counter and the order of service is independent of the order of arrival. An example is baggage collection at an airport.

The main application area of the simulation model being a transfer station, most activities are service points with queuing. This type of system is implemented in SimPed, whereas other types of queue disciplines may be added for specific applications, such as modelling baggage collection to assess an airport terminal. We discuss this type of queue discipline in the next subsection.

Service points with queuing in pedestrian flow simulation model

The most analytically tractable queuing situation is one in which both the inter-arrival times and the service times are exponentially distributed (Hillier & Lieberman 1995). In SimPed, service times may be exponentially distributed, whereas the arrivals depend on other conditions and activities in the network. Due to the random character of these processes, the inter-arrival times at a service facility may be assumed to be exponentially distributed. For more information on queuing systems we refer to Hillier & Lieberman (1995).

Two types of queuing disciplines have been indicated, namely a single queue for all customers and a queue for each specific server, see figure 6.24.

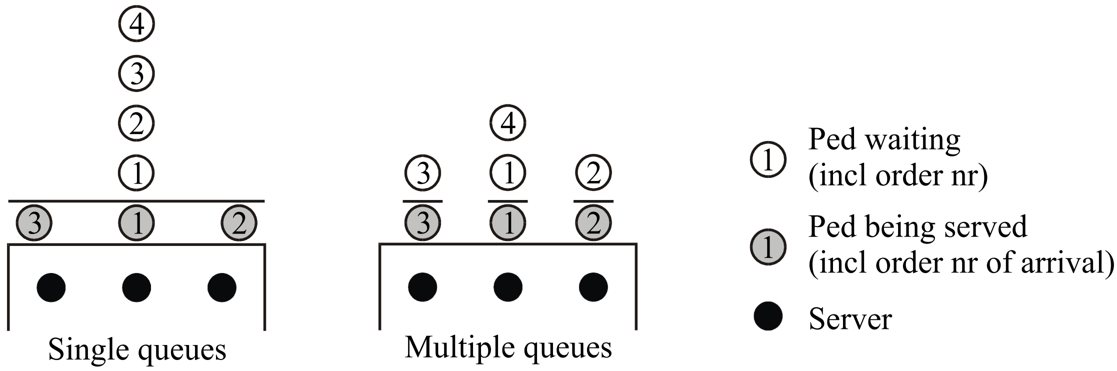


Figure 6.24: Two types of queue formation

The waiting times in each of the queue disciplines are somewhat different. A single queue system minimises the waiting time for each individual and optimises the efficient use of the servers. The variance in walking times is higher in a multiple queue system, due to the possibility of choosing the wrong queue. This on its turn may lead to an inefficient use of servers, increasing the average service time. Also, the hindrance may differ as can be seen in figure 6.24, where the single queue causes more hindrance for pedestrians walking from left to right than multiple (shorter) queues. Due to the macroscopic modelling of pedestrian walking behaviour, this hindrance is ignored, and only taken into account indirectly by increasing densities. Compared to this aggregate level of modelling the single queue system is sufficiently adequate with respect to average waiting times. SimPed therefore models all queuing situations as single queues with multiple servers in which customers are served in order of arrival (FIFO). Since only individual pedestrians are modelled, and no groups of pedestrians, each pedestrian is served by one server. Several pedestrians may be served simultaneously when a sufficient number of servers is available.

Now that the modelling principles for the arrival process and the queuing have been defined, a short overview is given of the actual activity performance. The pedestrian arrives at the activity. When one of the servers is available, the pedestrian is served, otherwise he joins the queue. The service time is drawn from the given service time distribution, which is specific for each of the activity locations. During this service time, the pedestrian occupies space in the walkway in which the activity is located. After this time period, the pedestrian continues his trip and walks to his next (intermediate) destination. In the queue, a pedestrian waits until all previously arrived pedestrians have been served. Then, this pedestrian is served by the first available server.

6.7 Interactions of pedestrians with the public transport system

This section describes the interactions of pedestrians with the public transport system. The actual interaction occurs between pedestrians and public transport vehicles. The behaviour of these vehicles and the actual arrival and departure times in particular are derived from a timetable. For the public transport related pedestrians, a separate origin-destination table is used in SimPed attached to the timetable, due to the specific relations of pedestrian origins and destinations with the different public transport services, even specified per public transport vehicle. For more information on the static characteristics of public transport vehicles, the timetable, and the public transport related origin-destination table, we refer to chapters 5 and 7.

In practice, the boarding and alighting processes take place more or less simultaneously, or these processes may be gradually integrated. In SimPed it is assumed that the two processes take place consecutively, which has only consequences for the individual waiting, boarding, and alighting times, but does not affect the total process time. If in some situation this assumption is not met, the individual boarding and alighting times may be increased to model this mutual hindrance of boarding and alighting pedestrians.

This section starts with a description of the public transport vehicles and the timetable. Characteristics of both vehicles and timetable influence the processes of boarding and alighting, described in the remainder of this section.

6.7.1 Public transport vehicle and timetable

The timetable contains parameters for the arrival and departure times of public transport vehicles and the boarding and alighting process. A simple flow diagram of public transport vehicle processes is given in figure 6.25.

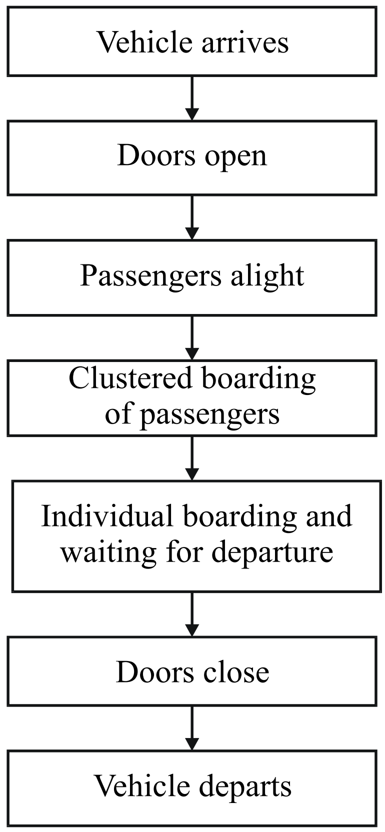


Figure 6.25: Flow diagram for a public transport vehicle process simulation

The actual arrival moment of a public transport vehicle is determined by its scheduled arrival time and the distribution for early or late arrival. At the arrival moment, the vehicle is halted next to the platform and vehicle doors are opened. Each door has its individual opening time, but in most situations all doors are opened simultaneously.

Attached to the timetable is the number of boarding and alighting passengers and the geographical distribution of these passengers over the public transport vehicle. Boarding passengers are already in the system and have been assigned to a specific door of the vehicle. Alighting passengers are entering the system. The timetable distributes alighting passengers over the different doors, following the given exogenous distribution. Boarding and alighting processes are treated separately for each door.

When all passengers assigned to a door have alighted, waiting passengers may board (clustered boarding process), which process is presented in subsection 6.7.3.

After the waiting passengers have boarded, the vehicle starts waiting for its scheduled departure moment. If the vehicle arrives late and the scheduled departure moment has already passed, the vehicle waits until all boarding has taken place (all passengers waiting on the platform have boarded), closes the doors, and departs. Otherwise, the vehicle waits for its scheduled departure time. During this time period individual passengers may still board (individual boarding process). At the scheduled departure moment, the vehicle closes the doors, and departs.

6.7.2 Alighting

The alighting process is modelled separately for each door as a queuing process. The arrival pattern of this process is very simple. At the beginning of the alighting, the queue consists of all alighting passengers at the door. When this queue is empty, the process has finished.

Individual alighting times are derived from a door-type specific distribution, which is one of the parameters describing the rolling stock. Boarding and alighting times measured in Dutch railway stations for different types of rolling stock (Wiggenraad 2001) are used as default input in SimPed.

Depending on the door width, one or more passengers may alight simultaneously. Since the number of servers (being the number of simultaneously alighting pedestrians) can only be an integer, the capacity is not modelled by extending the number of servers, but by reducing individual service time (two pedestrians being simultaneously served during 1 s takes just as long as two pedestrians being served consecutively during 0.5 s).

$$T_i^{service} = T_i^{service} \cdot \frac{w_i}{w^{avg}} \tag{6.21}$$

where w_i is the width of an individual pedestrian, w^{avg} is the width of a default pedestrian and $T_i^{service}$ is the individual service time (which may be drawn from a distribution). This approach only gives a negligible deviation from the real arrival times of pedestrians in the system.

6.7.3 Boarding

The boarding process is modelled for each door separately, due to the possibly non-uniform distribution of pedestrians over the public transport vehicle and the different door characteristics, such as width.

Each boarding pedestrian has a randomly determined specific vehicle door as his destination. He arrives at the platform and is waiting near the location where the vehicle door is going to arrive. The pedestrian remains waiting at this location until all passengers have alighted from this door. Then, the boarding process starts, that is, waiting passengers board in the same order as they arrived at this location (FIFO). This has not been observed, but it is a simplification of the modelling process. The boarding process is, as well as the alighting process, a queuing system, where only one pedestrian boards at the same time, with similar consequences for service time distribution and individual waiting times when more than one pedestrian can board at the same time.

6.8 Summary

This chapter provided assumptions of the models and some relevant algorithms implemented in a simulation tool for the analysis of pedestrian facilities (and SimPed in particular). The models are based on the elements and processes described in chapter 5. Only those models which are deemed important and contain new aspects in relation to traffic engineering have been included extensively in this chapter.

6.8.1 Assumptions

The simulation tool described is especially developed for application in the design process of transfer stations, which means that it has to simulate all types of situations and time periods, including peak hours. During peak hours, mainly commuters travel by public transport. Commuters are assumed to make similar trips everyday, developing this way experience on both static and dynamic conditions in the station. Furthermore, commuters want to travel from their origin to their destination as fast as possible. This has consequences for both route and trajectory choice, which are based on travel time and distance respectively. In the formulated route choice model therefore all commuters have complete information and there are no uncertainties concerning this information.

Pedestrians are considered to be rational and, combined with complete information on the network, it is assumed that, in equal conditions, pedestrians make similar choices. Due to changing conditions on the network, pedestrians do choose other routes. The allocation of pedestrians to routes will be validated in chapter 8.

As conditions may change very fast in transfer stations due to the arrival of highly occupied trains, pedestrians do not necessarily adhere to the route they chose when they entered the station, but change these routes while walking (so-called *en-route route choice*). In the modelling however, due to performance reasons, routes are not updated continuously in space and time, but after a specific time period. This time period, which is an input parameter for the simulation is fixed, and does not depend on the actual conditions in the network.

In the calculation of waiting and service times of a service facility, being input for the route choice process, variances in arrival patterns, in service times, and in number of servers are not taken into account. This may have consequences for the accuracy of the calculated waiting and service times. In the waiting and service times which are an output of the tool, this variance is taken into account.

Walking times, waiting times, and service times on which the activity location choice model and the route choice model are based, are instantaneous times (where future dynamic conditions on the network are not taken into account). This may cause a deviation between the actual walking times and the predicted walking times, used as input for both choice models.

6.8.2 Modelling approaches

This chapter described how the infrastructure is translated into two network levels. Also, this chapter showed the fundamental processes, that is activity location choice, route choice, walking, performing an activity, and the interactions of pedestrians with the public transport system. In principle, all choice models follow the utility maximisation principle of discrete choices.

The network model of the infrastructure consists of an *operational network model* describing infrastructure elements in two dimensions (with a length and a width) and a *tactical network model*, built of links and nodes. The operational network is used to determine exact lengths of paths of the pedestrian over the infrastructure (trajectory generation model). The walking times along these paths are input for the tactical network model, used in the activity location choice model and the route choice model. Three different types of links are specified, namely for walking, for waiting, and for service, on which the average travel time per pedestrian is specified.

The activity location choice model determines at which locations pedestrians perform their activities. Combining all possible locations and adding the corresponding walking times, waiting times, and service times for each of these activity location combinations, the activity locations with the shortest overall route cost are assigned to the pedestrian.

The route choice model determines the route of a pedestrian through the infrastructure. The utility function in this model is weighted travel time, consisting of walking time, waiting time, and service time. After an update of all link performance attributes representing the current conditions in the network, the shortest paths from all nodes to all nodes in this network are calculated. Each pedestrian uses the shortest path corresponding to his current position and destination.

The individual walking model determines the actual walking times for each individual pedestrian under prevailing conditions. This walking time depends on the link characteristics, described by a speed-density relation defining the walking behaviour on this link, the actual density, and the individual free speed of the pedestrian.

In principle, all processes are modelled as service systems. Performing an activity is modelled by classical queuing theory. Parameters describe when the service is available, the number of servers, and the service time (following a statistical distribution). While waiting, only a single queue is assumed from which the pedestrians are served according to the first-come-first-served principle (FIFO).

6.8.3 Contributions of the work

Most of the existing pedestrian flow models only consider pedestrian movement behaviour. Some more extensive models also include the performance of activities by pedestrians, while other models include the interaction with public transport vehicles. An innovation of this work has been integrate all relevant models in describing pedestrians in transfer stations consistently (including walking behaviour, route choice, performance of activities, and interaction with public transport vehicles). The simulation tool has been designed as a mixture of microscopically and macroscopically modelled processes. A macroscopic model is used to model pedestrian flows, where pedestrian walking behaviour has been modelled using a speed-density relation. All other processes are microscopically modelled, such as route choice, activity location choice, and performance of activities.

Two basic principles in modelling have consequently been applied, in order to maintain similar levels of accuracy for all implemented processes:

- Choice modelling is based on normative pedestrian behaviour theory (see also chapter 5) assuming that pedestrians are subjective utility maximisers in choosing from a limited set of discrete travel options.
- Modelling of activities is based on general queuing systems.

Another innovation is the development of a hierarchical route choice model, in which the choice behaviour is split into choice behaviour on the tactical level and on the operational level. On the operational level, the trajectory generation model calculates the shortest trajectories between a start and an end joint through a part of the walking infrastructure, taking into account the two dimensional description of this infrastructure. On the tactical level, the shortest route is chosen in the tactical network, where the lengths of the links depend on the trajectory lengths and the conditions on the network, indicating walking times and waiting times on the different links. The link performance indicators of the tactical network model are frequently updated in order to have dynamic route choice.

A final contribution concerns the modelling of interpersonal differences between pedestrians in terms of walking behaviour. Assuming different individual free speeds, variability occurs in walking times, even when the conditions on the network are similar.

6.8.4 Future research

Thorough research should be performed to indicate which assumptions imply severe shortcomings and may lead to unacceptable simulation results. It is an aim for further research to make the simulation model more widely applicable and thus to refine the different processes. One of the first models that should be elaborated is the route choice model, in which more criteria should be introduced than only time. Also, it may be necessary to adapt the type of route choice model and introduce stochastic elements in it (Van de Reijt 2004).

The behavioural models described in this chapter form the basis for implementation of SimPed. The most important and new aspects of their implementation are described in the next chapter, such as the object model and a software architecture, containing different modules designed for different aspects of a simulation system (such as input, simulation, animation, and analysis) and a specific system to control the communication between all these modules. Verification and validation of the route choice model and the traffic flow characteristics on a platform are discussed in chapter 8.

Chapter 7

Implementation of a pedestrian flow simulation model

7.1 Introduction

This chapter describes the implementation of the pedestrian simulation tool SimPed. This implementation has been based on the functional system specifications in chapter 5 and the models and algorithms described in chapter 6. The remaining models have been elaborated in the design documentation of SimPed (Daamen 2002*c*), (Daamen 2002*d*).

The overview of the implementation is restricted to the developed object model and the software architecture. From a literature review it appears that both object models for transfer stations and software architectures developed for such type of simulation tools are hardly described in literature. The literature found has been taken as a starting point for the development of a dedicated object model and a dedicated software architecture for SimPed.

The development of a dedicated object model for SimPed is one of the innovative aspects of our work. Our object model is designed to cover three kinds of information, as well as the dynamic relations between the different objects. First, our object model does not only describe static pedestrian infrastructure, but also infrastructure needed for stops of public transport vehicles. Second, characteristics of pedestrians and public transport vehicles are included in the object model, both static ones (such as length or size, origin, and destination) and dynamic ones (such as current location, arrival time, and departure time). Finally, origin-destination information is stored, again in static and dynamic situations.

A second innovative element of our work is the developed software architecture. The aim of this architecture was to be as generic as possible, in order to support multi-process simulations (coupling of several simulation tools as well as running one simulation model on several processors to reduce simulation time), flexibility (modular set up), and maintainability. An overview of the interactions of the different modules of the simulation tools with each other and / or the user served as the basis of the software architecture.

Section 7.2 describes the object model developed for SimPed, while section 7.3 shows the dedicated software architecture. Both sections are divided into subsections, describing respectively related literature, the SimPed object model / software architecture, and an overview of the fundamental objects and modules in SimPed.

7.2 Object model

The simulation model for pedestrians in public transport facilities has been developed as an object-oriented application. One of the important characteristics of object oriented modelling is its ability to describe the real world in a simple way and, based on this description, model this real world in the same simple and straightforward way. Objects have become standard elements in simulation thanks to their flexibility and the ability to design a dedicated object model. Also, maintainability and extendability are supported by object oriented analysis and design, since new objects may be added without changes in existing objects and structure. The requirement of maintainability is met by re-using and replacing (parts of) objects and the possibility to work with several programmers on the same code, where parts of the programming code may be updated.

The first part of this section describes the main aspects of an object model and gives an overview of object models concerning the transport system from the literature. After discussing these object models from literature, the developed new object model for SimPed is shown and some of the objects are elaborated in more detail.

7.2.1 Introduction to object model notions

An object in the real world can be any person or thing that you interact with in any way (Rumbaugh et al. 1991). Not all objects are equally important, thus a process of focussing has to be started on those features that are essential for the task at hand, in this case the behaviour of pedestrians in transfer stations, and ignoring those that are not. All different objects and types of objects that are significant to the research aim are included in the object model.

Data objects are representations of real world objects. An object is therefore formally defined as an abstraction of some thing in the real world, that carries both the data describing the real-world object and the operations (program code) that have the only allowable access to that data (Jacobson et al. 1999).

Each object contains data values (about itself), called attributes. The state of an object is defined by the set of values currently held by its attributes. The domain of an attribute is the set of all permissible values for an attribute, in the way they can occur in the real world. Objects also exhibit behaviour in the real world, which means that objects do something. This behaviour is captured by so-called methods, which are procedures or

Class:
Pedestrian

Attributes:
v : current speed
x_0 : start location
t_0 : start time

Methods:
GetCurrentLocation(t)

Elaboration of the method:

```
Pedestrian::GetCurrentLocation (t)
Begin
   Return x0 + v · (t - t0)
End
```

Figure 7.1: Overview of an (example) object Pedestrian with its attributes and a method

functions that belong to an object. An example of such an object is given in figure 7.1, using the Visual C++ specification language.

A *class* is a group of objects with similar properties (attributes), common behaviour (operations), common associations to other objects, and common semantics (meaning) (Rumbaugh et al. 1991). Classes are used in such a way that the internal structure of the system will closely match the structure of the real world. An overview of all relevant classes and the relations between them is usually given in an object model.

A *subclass* is a class made up of selected instances from another class, referred to as the parent class or superclass. A subclass instance inherits both the attributes and the behaviours of the superclass. Inheritance applies when a subclass instance, in addition to the attributes and behaviour it has by virtue of belonging to the subclass, also has all the attributes and behaviour that instances of the superclass have. Another key property of the object-oriented paradigm is polymorphism, indicating that subclasses behave differently than superclasses and may ‘override’ superclass behaviour.

An *association* is a relationship expressing the interactions between instances of two classes, represented by the verb that describes what they do to each other, and/or by the nouns for the roles that each class plays in the life of the other. In an object model, these associations are represented by a connection between the classes.

7.2.2 Object models from literature

Only a few examples of dedicated object models were found suitable for the modelling of public transport nodes. This section describes these object models, which are then critically evaluated.

Van der Spek (2003) divides the transfer station into building blocks in order to develop a tool which improves the possibility to select the best design of a transfer station in a sample of possibilities by calculating the average connection distance per transfer weighted by the number of transfers in that relation. He distinguishes four elements which together form an object model:

- Components. Components are the main elements of the node. Component markers represent locations of different modalities, travel facilities, or additional functions in a transfer station. Two types of components are distinguished, namely platform types and space types containing travel facilities or additional functions or areas where modalities are spread equally.
- Gates. Gate markers represent horizontal and vertical access points. Horizontal access points are access locations to spaces or constraint narrowings in routes. Vertical access points are risers like stairs, escalators, and lifts.
- Lines. Lines represent links between elements, access points, or constraint points. Each line has a specific length and represents the distance between two points.
- Routes. A route from one modality to another is organised by the shortest combination of links or the average of all logical routes.

These elements describe the static infrastructure of a transfer station, whereas in case of a simulation tool it is necessary to describe also dynamic aspects. One of the missing elements of this split up is the pedestrian and also public transport vehicles play an important role in the arrival and departure of pedestrians. This indicates a second lack of information for the purposes of the simulation tool, which is a description of an origin-destination table for pedestrians (number of pedestrians including origins and destinations over time).

Nielsen et al. (2001) developed the Transportation Object Platform (TOP), which is a data storage and management platform, developed to ease the maintenance and use of transportation related data such as network data, infrastructure data (for both individual and multi-modal traffic), and planning data (such as timetables and routes). TOP is an open and extendable object model created as an extension to the ArcGIS Geodatabase, which is a combination of object oriented GIS and relational databases. Storing the Geodatabase in a relational database enables relations between objects to be navigable (visible) in e.g. ArcMap. The authors have sought to create a data model for transportation data focussing mainly on inheritance, relations, and connectivity rules, in order to make and keep the data consistent.

The purpose of the TOP object model is twofold. First, a complete transportation system has to be described in detail, and second, the classes in the object model should contain embedded functionality that assists the user while working with the data. Here, especially the first purpose is considered, which means that the model should be able to handle the infrastructure (such as road, rail, air, bicycle, and pedestrian networks), scheduled transportation running on top of the infrastructure networks including complete timetable data, the possibilities of changing between scheduled modes of transportation at the terminals and between stops of scheduled transportation networks, and demand and supply data describing origins and destinations of persons that are being transported. The overall structure of Nielsen's conceptual object model is shown in figure 7.2.

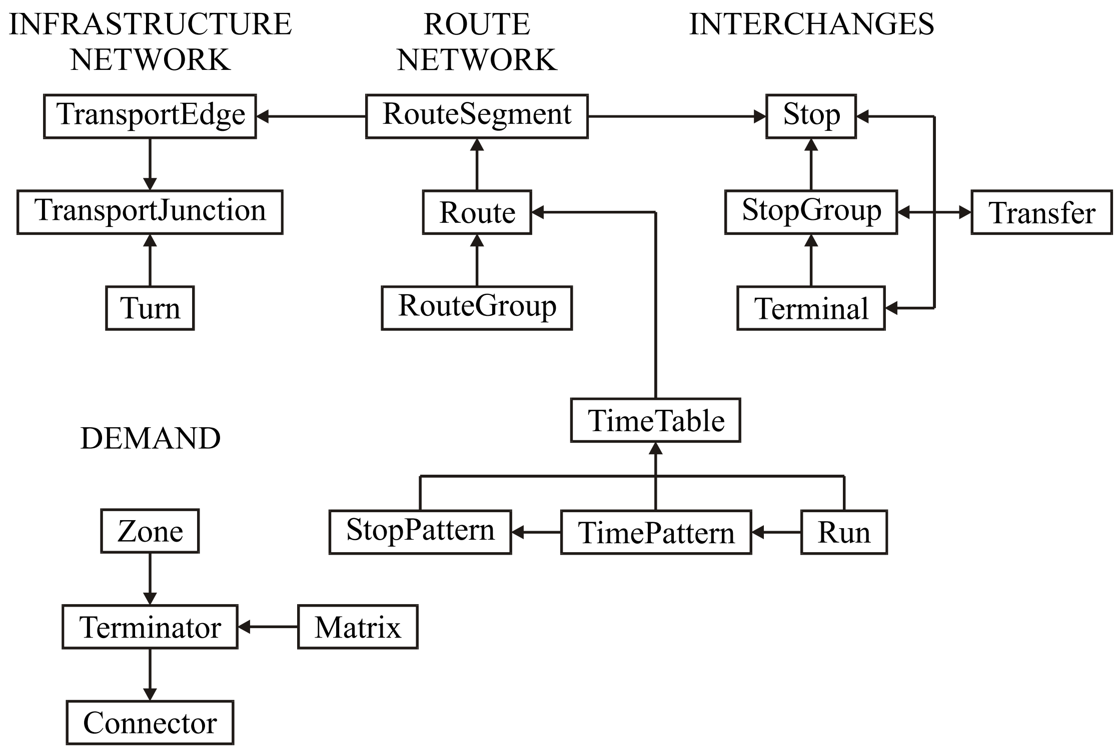


Figure 7.2: Object model for Transportation Object Platform (Nielsen et al. 2001)

The basic layer of data describes the Infrastructure Network, for instance road, rail, air, and water. The second layer, the Route Network, describes the scheduled transportation on the physical networks.

Stops represent nodes in the scheduled transportation network, where it is possible to change routes and transportation mode. *Stops* are defined in relation to edges in the infrastructure network. The possibility of moving from one *Stop* to another is described by connecting two *Stops* with a *ChangeEdge*. *Stops* can be organised in *Stop-Groups*, and these can be organised in *Terminals*.

The connection between the two layers of network data is created by using an element called *RouteSegment*. A *RouteSegment* defines a connection between two *Stops*, using a series of *TransportEdges* (or rather, a series of parts of *TransportEdges*). A *Route* can then be defined as a sequence of *RouteSegments*. Apart from being general and flexible, this approach also offers an additional advantage. The number of *RouteSegments* is kept to a minimum, by ensuring that they are unique, and re-used in all *Routes*, using the same path to connect two *Stops*.

Routes can be grouped in *RouteGroups*, in order to reflect the fact that a certain bus-route might follow different paths through the road-network throughout the day. A *Route* can have from one to many *Timetables* associated with it, reflecting the fact that travel times might vary during the day, even when using the same path (for instance road speeds might be lower during rush-hour).

Timetable data are described by elements corresponding to the sequence of *RouteSegments* describing a *Route*. The *StopPattern/TimePattern*-data describe the time used to travel from *Stop* to *Stop* along the *Route* and the possibilities of embarking/disembarking at each *Stop*. The *Run* element combines with the *StopPattern/TimePattern* data to describe a specific *Run* of the *Route*. Basically *Run* is a starting time, which, when combined with the *StopPattern/TimePattern* data, accurately describes when the bus will arrive and depart from the *Stops* in the *Route*. In this way, redundancy is reduced when describing timetables.

Finally some elements are used to describe the demand for transportation and the connections to the underlying area (e.g. a *Traffic Analysis Zone*).

One of the disadvantages of the object model by Nielsen et al. (2001) is the assumption that it is based on GIS-data. GIS-data is not widely available or used by architects, due to the fact that the level of detail needed for the design of a transfer station is much higher than provided in a GIS-database. Also, the object model by Nielsen et al. (2001) covers a much larger scope than is intended for the simulation tool described here, where only arrivals and departures of public transport vehicles are taken into account at the considered station and not subsequent stations on one line. A subset of the principles adopted by Nielsen et al. (2001) is however used as a starting point for the object model of SimPed, including the principle of data storage in a relational database to guarantee consistent relations between objects. As well as in the structure of Van der Spek (2003), detailed aspects concerning pedestrians are not included in this object model. This is another reason why the description of the infrastructure network is not detailed enough for the purposes described in chapter 2.

The last object model discussed here has been developed by Bockstael-Blok (2001), see figure 7.3. The objective of her research was to develop a design approach to improve interorganisational multimodal passenger transport systems from a chain perspective. The metamodel used is an adapted version of an object-oriented metamodel described in Babeliowski (1997).

The basic concepts in the model are the object classes *Process*, *Resource*, *Item*, and *Actor*. The object Item represents the things that are transformed, for example transported goods. The object type *Resource* represents the resources used by a *Process*. Capacity is a typical attribute for a *Resource*. A *Process* transforms *Items* and uses *Resources*. A *Process* can

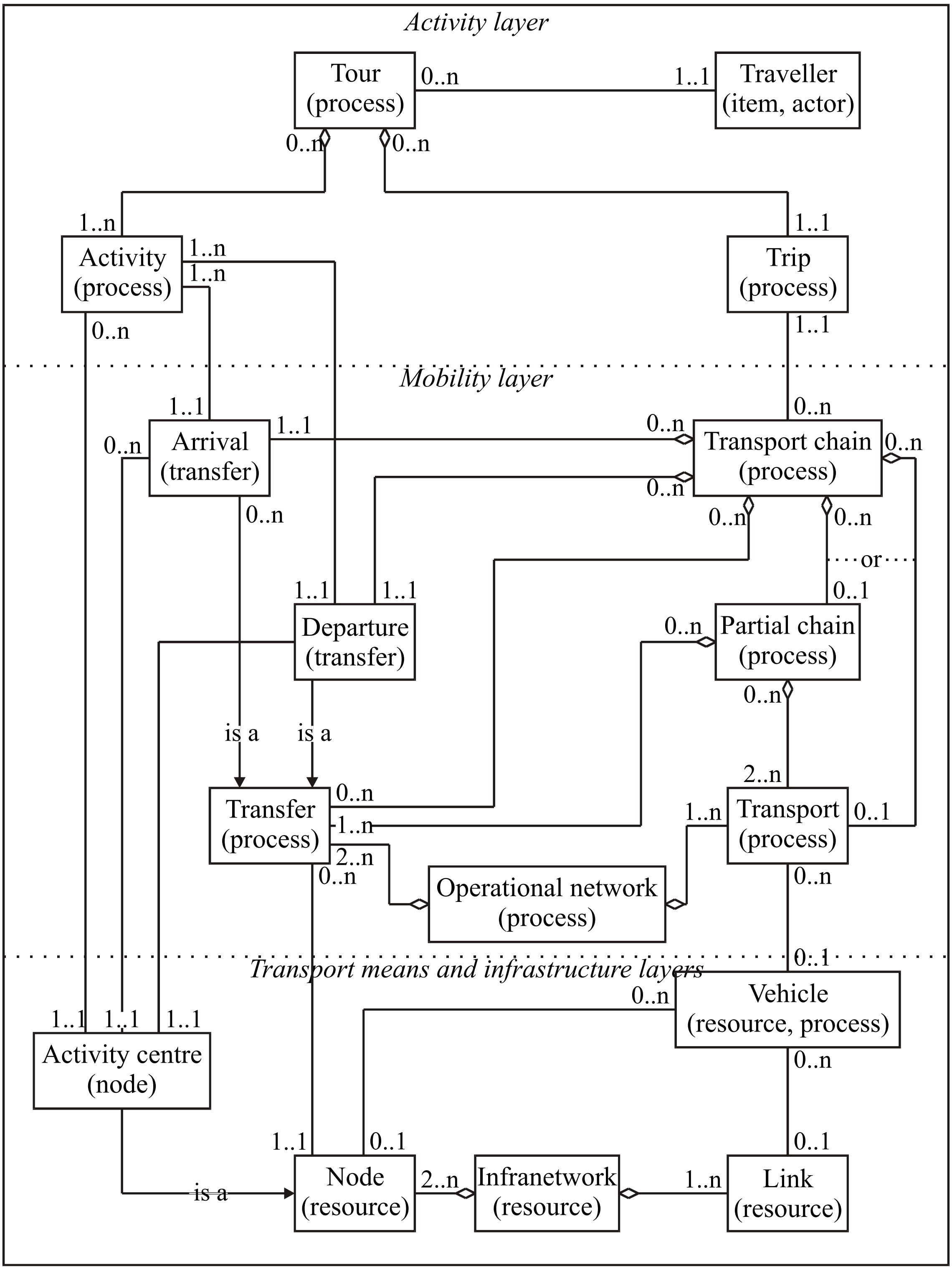


Figure 7.3: Object model for chain modelling (Bockstael-Blok 2001)

be compound, i.e. containing one or more subprocesses. The choice of whether a *Process* is modelled as a compound *Process* or not is a modelling choice and determines the level of detail of the model. A *Process*, a *Resource*, or an *Item* can be associated with one or more *Actors*, such as transport operators, transport information service providers, legal owners, a travel group, or an employer.

The transport system has been split into three layers, namely activity layer, mobility layer, and transport means and infrastructure layer, which can be found in the object model. These layers are comparable with the split up made in this research regarding strategic, tactical, and operational level. The activity layer describes the type of transport-generating activities, the type of travellers, and the type of tours that are considered. The mobility layer describes a transport system in such a way that the model produces system performance indicators from a chain perspective, i.e. on the level of links in a chain and for a chain as a whole. The transport means and infrastructure layer highlights resources in the *Process*, *Item*, *Resource*, and *Actor* framework.

The structure of chain modelling concepts supports making a static conceptual and empirical description of multimodal transport systems.

The object model designed by Bockstael-Blok (2001) has been aimed at the description of pedestrian behaviour at a higher (strategic) level, whereas the aim of our simulation tool is to model pedestrian behaviour at tactical and operational level. This leads to the introduction of dynamic elements (not included in the object model of Bockstael-Blok) and the introduction of the object *Pedestrian*, which is the most important object in our object model described in the following section.

7.2.3 SimPed object model

In the previous section, three object models from literature have been presented. Van der Spek (2003) used building blocks to split up the station into components, which do not have the same characteristics as objects, but form a good starting point for a dedicated object model. However, dynamic aspects are missing as well as one essential object, namely the *Pedestrian*.

Nielsen et al. (2001) developed an object model for a total transportation system, the set up of which is very general, but is based on GIS-data. GIS-data are not widely used by architects and designers, because the required level of detail of station design is too high to use GIS-data effectively. Many advantages of the general concept of Nielsen et al. (2001) are not applicable, although a subset of the elements, especially those elements concerning rail traffic and the split up of the infrastructure may be used. Also, the principle to store an object model in a relational database to guarantee consistent relations between objects is included in the SimPed object model.

The third model, developed by Bockstael-Blok (2001), has been especially designed to model trip chains, in which traveller decision behaviour in an earlier stage (whether or not to make the trip) is taken into account. This model is more suited for the strategic and tactical level of pedestrian or passenger modelling, whereas the purpose of the simulation model described here is to model tactical and operational pedestrian behaviour. The model therefore lacks opportunities to describe the dynamic part, which is essential for a simulation system.

As none of these models as a whole was suited to be applied in the envisaged simulation model and since one of the advantages of an object-oriented model is its flexibility, a dedicated object model has been designed.

Several aspects have been taken as starting points for the development of a dedicated object model for SimPed. First, dynamic aspects are essential in a simulation, indicating that both pedestrians and public transport vehicles are indicated as objects. Furthermore, the pedestrian infrastructure needs to be described, where both the spatial layout and the pedestrian behaviour on these elements are distinguished. The spatial layout again depends on the required level of detail of modelling pedestrian behaviour. A third aspect to handle are (static) origin-destination tables, describing locations of origins and destination and the distribution of pedestrians over these in time. Dynamic aspects concern activities of pedestrians, of which walking is the most important, but also performing activities needs to be taken into account. Walking is an interaction between infrastructure and pedestrians, where characteristics of both infrastructure and pedestrians influence the final results. As the interaction with public transport vehicles is explicitly taken into account, detailed information on these vehicles and boarding and alighting characteristics are required as well.

To come to this object model, all steps of UML (Unified Modelling Language) have been applied (Warmer & Kleppe 1999). However, as they are not relevant in this thesis, only the resulting (somewhat simplified) object model is presented in figure 7.4. For more information see Daamen (2002*c*) and Daamen (2002*d*).

Most relations between the class *Model* and other classes have been left out of the figure to ensure its readability. *Model* namely performs the administration of all objects in the simulation and thus contains lists of all objects in the simulation model.

7.2.4 Elaborations on the distinguished object classes

This section describes in more detail some of the object classes (indicated below in italics) of the developed object model.

SimPed is the main object in the simulation, checking whether the input is consistent and, when this is the case, reading the input model from the database, starting the initialisation of all objects in the simulation, and finally starting the simulation itself. *SimPed* takes care of the communication between objects in the simulation model and other applications in the architecture (see section 7.3). The initialisation of the model consists of reading information from a database and creating the corresponding objects. The simulation itself

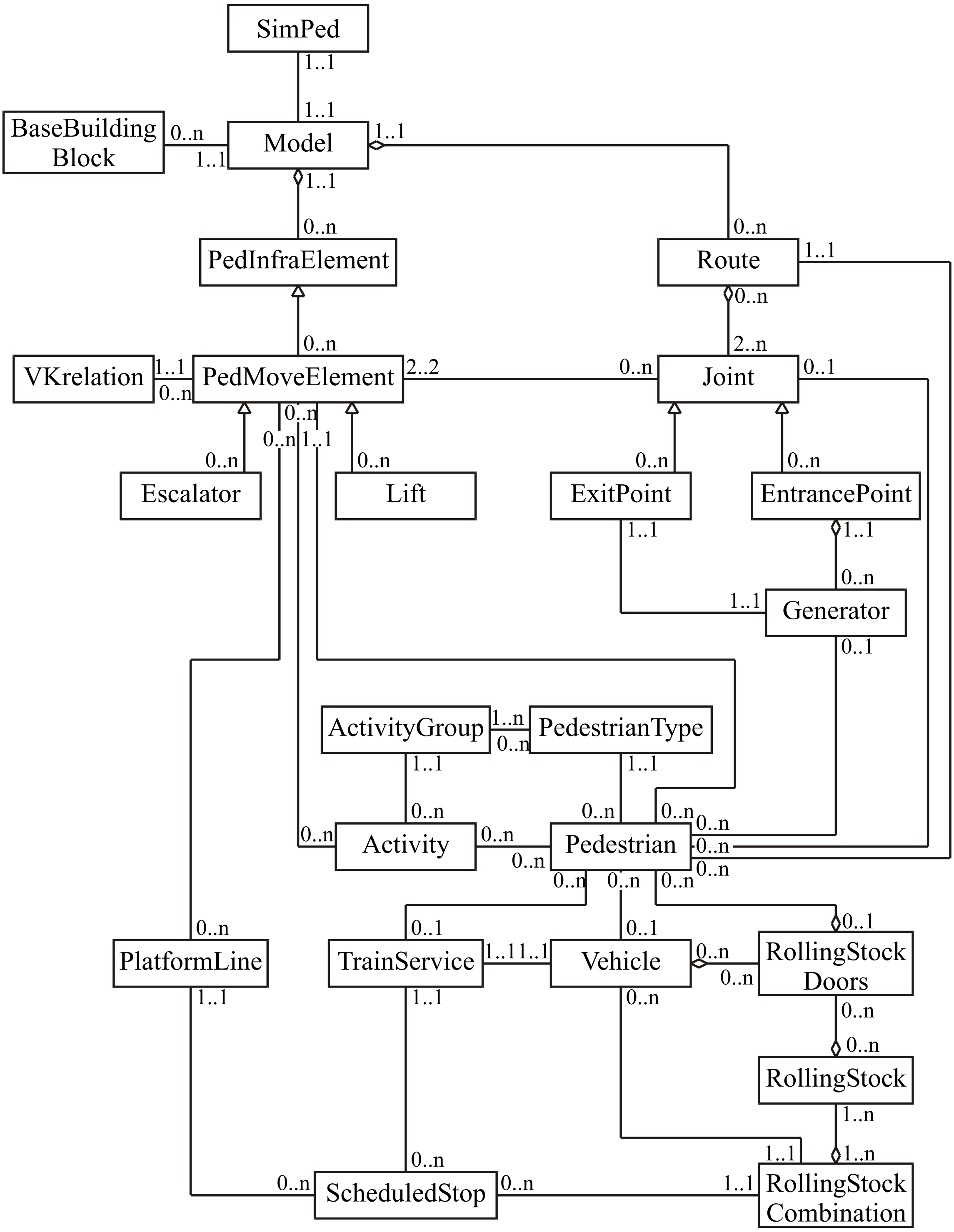


Figure 7.4: Outline of the object model of SimPed

consists of the generation of pedestrians and vehicles and their movement through the infrastructure.

The main purpose of *Model* is to co-ordinate the administration of objects by maintaining lists of objects and disposing them (including all their references) when they become obsolete. Also, *Model* creates the tactical and operational network model, updates link variables, and calculates shortest paths through the infrastructure network.

A *PedInfraElement* is a part of the infrastructure for pedestrians. *PedInfraElements* may be used to walk on or to be transported with (*Escalators* and *Lifts*), to serve (*Activities*), or to represent those parts of the infrastructure inaccessible for *Pedestrians* (such as columns and walls). The main characteristics of a *PedInfraElement* are a list of vertices, indicating the spatial form of this element. Information concerning length, width, and surface of a *PedInfraElement* may be derived from this information.

PedMoveElements are those parts of the infrastructure that *Pedestrians* can use to walk on or to be transported with. The spatial form is inherited from *PedInfraElement*. Two specific types of infrastructure are derived from *PedMoveElement*, namely *Escalator* and *Lift*. Both *Escalator* and *Lift* have an active role in transporting *Pedestrians*. When *Pedestrians* enter these elements, they may stand still and yet arrive at the end of the *Escalator* or at the requested floor in a *Lift*. *Pedestrian* walking behaviour in *PedMoveElements* is described by a *VkRelation*, representing the relation between average speed and density. This relation may be identical for all *PedMoveElements*, but can also be dedicated for each part of the infrastructure. *Pedestrians* may enter and leave *PedMoveElements* via *Joints*. To indicate *Pedestrian* comfort, the level-of-service of a *PedMoveElement* is recorded, calculated by the quotient of number of *Pedestrians* present and the net surface.

Joints link two *PedMoveElements*, where their capacity is determined by the number of *Pedestrians* who may use the *Joint* at the same time and the time it takes each *Pedestrian* to pass the *Joint*. This time period may either be zero (when the *Joint* only represents empty space), but also several seconds, when a *Joint* represents a gate with ticket control. Specific types of *Joints* are those passages forming the boundary of the modelled infrastructure. Specific classes have been realised to model these boundaries, inheriting from *Joint*. *EntrancePoints* model locations where *Pedestrians* enter the model, while they leave the model at *ExitPoints*.

An origin-destination table contains the numbers of *Pedestrians* going from an origin to a destination during a given time period, where both origin and destination are locations in the transportation network. A *Generator* models one origin-destination relation from this table. In addition to the *EntrancePoint* (origin) and *ExitPoint* (destination) of the *Pedestrians*, characteristics of a *Generator* are number of *Pedestrians* to be generated, start and end point of the generation period, and distribution of the generation of *Pedestrians* during this time period (uniform with similar headways, but also peaks may be modelled using a normal or exponential distribution or defining a dedicated distribution by means of a histogram). *Pedestrians* generated by *Generators* are not related to public transport services; they neither board nor alight.

In our object model, a distinction has been made between function (*ActivityGroup*) and location (*Activity*) of an activity. The function of the activity (*ActivityGroup*) may be performed at several locations (*Activity*) between which the *Pedestrian* has to make a choice. Characteristics of an *Activity* are the number of service points and a distribution to indicate individual service time. The combination of these characteristics determines the *Activity* capacity (see also chapters 5 and 6) and together with pedestrian demand, the formation of queues.

The key object in the simulation is the *Pedestrian*. The *Pedestrian* is related to a *PedestrianType*, indicating different types of *Pedestrians* (such as commuters, tourists, and children) with similar characteristics, while describing not only their walking characteristics (such as free speed) but also the type of activities (*ActivityGroups*) they perform during their stay in the simulation model. Each *Pedestrian* is part of exactly one *PedestrianType*. A *Pedestrian* is either generated by a *Generator* (having an *EntrancePoint* as origin and an *ExitPoint* as destination) or by a *RollingStockDoor* (indicating that the *Pedestrian* is an alighting, a boarding, or a transferring passenger). After entering the model and determining the *Activity* locations he wants to visit, a *Pedestrian* starts walking along the shortest *Route* in time over the infrastructure network, performs *Activities*, when ordered and arrives at his destination. When this destination is a *RollingStockDoor*, the *Pedestrian* waits until the *Vehicle* arrives, and the boarding and alighting process starts.

A public transport *Vehicle* is characterised by its *RollingStockCombination* and the *TrainService* it executes. The *RollingStockCombination* describes the length of a *Vehicle*, the number of *Doors* and their positions, whereas the *TrainService* indicates the driving direction of the *Vehicle* and thus which *Pedestrians* may board (similar final direction as the public transport *Vehicle*). The *TrainService* also gives the delay distribution, because the delay is often caused by the infrastructure and by the interaction with other conflicting services, and possesses similar characteristics for individual *Vehicles* of a similar *TrainService*. A *RollingStockCombination* consists of one or more elements of *RollingStock*, which is characterised by the *RollingStock* length, capacity, indicated as a number of *Pedestrians* and the orientation of the *RollingStock*, due to the possibly non-symmetrical location of the *Doors*. The *RollingStock* contains one or more *RollingStockDoors*, which model the interaction with a *Pedestrian*. For each *RollingStockDoor* the position measured from the head of the *RollingStock* is indicated as well as the width. Moreover, distributions are identified for the time to open and close *RollingStockDoors* and distributions for boarding and alighting times of individual *Pedestrians*.

Passenger origin and destination are time dependent and directly related to public transport *Vehicles* with their planned arrival and departure times. An origin or destination is therefore a specific public transport *Vehicle*, or specifically a *Door* of this public transport *Vehicle* (the distribution of the *Pedestrians* over the *Doors* depends on characteristics of both *RollingStock* and station infrastructure (location of the *Lifts*, *Escalators*, *Exit* and *EntrancePoints* in particular)).

In the SimPed approach it is chosen to describe all public transport related data in an origin - destination matrix being a characteristic of *ScheduledStops*, which are defined in a timetable. Each public transport *Vehicle* contains information on the number of boarding passengers with distribution over the origins, their distribution over the *Vehicle*, and (boarding) *PedestrianTypes*, the number of alighting passengers with a distribution over the destinations (which may also be another train service in case of transferring passengers), their distribution over the *Vehicle*, and (alighting) *PedestrianTypes*.

7.3 Software architecture

7.3.1 Introduction into notions concerning software architecture

The aim of the simulation model is to distinguish individual pedestrians, with their own attributes, autonomous behaviour, and decision making. This demands a lot of processor time of an ordinary office PC. Thus, the total simulation model is split up in parallel or distributed processes. Distributed programming is the spreading of a computational task across several programs, processes, or processors (Brown 1994). Benefits of distributed programming are tool building, concurrency, parallelism, and resource sharing. Parallelism is a way to view a computer program as a set of parallel processes, which, because of their mutual independence, can be executed simultaneously (Raynal 1988).

Competition and co-operation among processes gives rise to specific problems whose solution requires mechanisms for synchronisation and communication respectively. Time-aspects of communication make it even more complicated. That is, during the execution of the simulation the order of events in the simulation has to be maintained, in order for the model to represent the real-world situation (a pedestrian first opens a door and then passes it, instead of the other way round). Synchronisation among processes is especially important in the interaction with the user. If the user clicks the 'Pause'-button in the animation, the simulation must temporarily stop and should continue as soon as the user clicks the 'Start'-button again.

The processing architecture defines the framework in which applications are designed and implemented. The programs that compose an application generally perform three core functions:

- Presentation services: interface between the program and the external environment.
- Processing/algorithmic services: execution of the logic of the application.
- Data manipulation services: addition, modification, retrieval, and deletion of records in the data store.

Several parallel architectures are available, of which 'client/server' and 'publish/subscribe' are best known principles. In a client-server model, two processes are involved, one on the client machine and one on the server machine (Tanenbaum 2003). Communication takes the form of the client process sending a message over the network to the server process. The client process then waits for a reply message. When the server process gets the request, it performs the requested work or looks up the requested data and sends back a reply. The communication is always initiated from the client, whereas the server is passive in communication.

Publish/subscribe (Boar 1993) is a communication pattern in which the information flow is directed by the interest of receivers rather than by explicit addresses determined by senders. Applications known in the network as publishers generate messages and send them through the network. All applications interested in messages from this publisher (so-called subscribers) receive these messages; other applications let these messages pass unopened.

From the functional description of all modules in SimPed (see subsection 7.3.2), the publish/subscribe architecture appeared most appropriate because of:

- Obvious publisher of data (simulation kernel).
- Obvious subscribers of data (animation, archive).
- Relief of the simulation kernel by differentiating graphics handling (animation and input) and data storage (results).
- Some applications do not have a user interface (archive, simulation kernel).

Local and wide area networking are used to tie the geographically dispersed publishers and subscribers together. A software layer called bonding software is resident on all computers connected to the network and handles the message routing between applications (Tanenbaum 2003).

The bonding software places a layer of software above the peer-to-peer protocol (directly from one application to another) that vastly simplifies the application programming and hides the underlying protocol from both clients and servers (see figure 7.5). The application accesses the bonding software through an application program interface (API) (Boar 1993).

A network architecture defines protocols and layers used within that architecture (Dewire 1993), (Tanenbaum 2003). Basically, a protocol is an agreement between communicating parties on how communication is to proceed (Tanenbaum 2003), consisting of a set of rules governing the format and meaning of messages that are exchanged between the applications. Several standard network architectures exist, such as Open Systems Interconnection (OSI) and Systems Network Architecture (SNA). Figure 7.6 shows the seven layers of the OSI-model, which is the standard model for communication and therefore adopted in SimPed.

In reality, no data are directly transferred from layer n on one machine to layer n on another machine. Instead, each layer passes data and control information to the layer

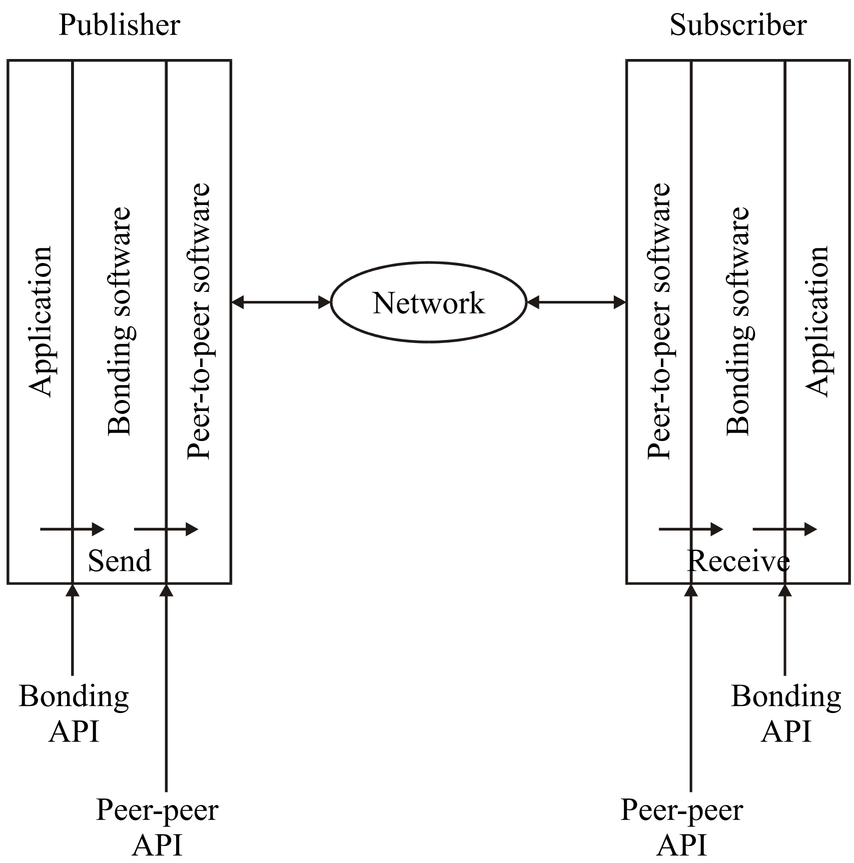


Figure 7.5: Overview of the communication between distributed applications (Boar 1993)

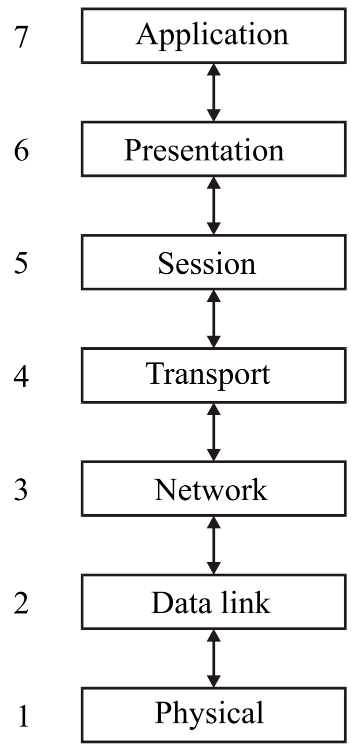


Figure 7.6: Standard layers of the OSI-model for network architecture (Tanenbaum 2003), adopted in SimPed

immediately below, until the lowest layer is reached. This physical layer is concerned with transmitting raw data over a communication channel to another computer. The main task of the data link layer is to transform a raw transmission facility into a line that appears free of undetected transmission errors to the network layer. The network layer controls the operation of the subnet (how messages are routed from origin to destination). The basic function of the transport layer is to accept data from above, split it up into smaller units if needed, pass these to the network layer, and ensure that the pieces all arrive correctly at the other end. The session layer allows users on different machines to establish sessions between them, offering various services including dialog control (keeping track of whose turn it is to transmit), token management (preventing two parties from attempting the same critical operation at the same time), and synchronisation.

Several models have been developed to cover the lowest layers. The best known models are Remote Procedure Calls (RPC, covering the four lowest OSI layers) and Transmission Control Protocol (TCP/IP, covering the three lowest OSI layers). The two models do not have significant differences in functionality or efficiency. The choice for SimPed has therefore been based on a very practical criterion, that is knowledge of (and experience with) the protocols, which led to the choice for TCP/IP.

7.3.2 SimPed software architecture

Since little literature on existing software architectures concerning simulation tools for pedestrians or traffic in general has been found (Andersson 1997), (Casper et al. 2000), (Liu & Qin 1997), (Sydelko et al. 1999), (Sydelko et al. 2001), (Zaidi et al. 1998), a dedicated software architecture has been developed, which may also be used for other simulation tools.

As a basis for the software architecture the (functional) interactions between the simulation tool and the user need to be described. An overview of these interactions is given in figure 7.7.

As indicated in chapter 6, the simulation tool needs three types of data, namely information on the infrastructure for both pedestrians and public transport vehicles, characteristics of pedestrians and public transport vehicles, and origin-destination data for pedestrians and public transport vehicles, including time aspects of each trip (such as arrival and departure time of a train). These data are provided in the form of plans, timetables and origin-destination tables, where the user determines the scope of the simulation model and thus the relevant information to be included. To transform these data into databases and object descriptions handled by the simulation tool, editing processes take place, initiated and performed by the user. Before a simulation is started, characteristics of the simulation run are provided by the user, such as number of replications, length of a replication, and whether the simulation is animated or not. The next step is to start the simulation, tracking generated pedestrians and vehicles while walking, performing activities, etc. To validate and calibrate the process, pedestrians and vehicles are animated and for a final analysis, the results need to be stored. The user is involved in the animation and the analysis of the results, by creating graphs and tables summarising the data.

From the interactions between the user and the simulation tool, the following modules of the simulation tool are derived:

- Input module (SimInput).
- Control module for the execution of the simulation (SimControl).
- Simulation kernel (SimPed).
- Data storage module (SimArchive).
- Visualisation modules (SimAnimation, SimReplay, and Virtual Reality).
- Analysis modules (SimAnalysis and SORViewer).
- Communication and synchronisation module (SimDistribution).

A software architecture has been designed to combine these different modules into a single simulation tool. Figure 7.8 shows an overview of the software architecture designed for SimPed.

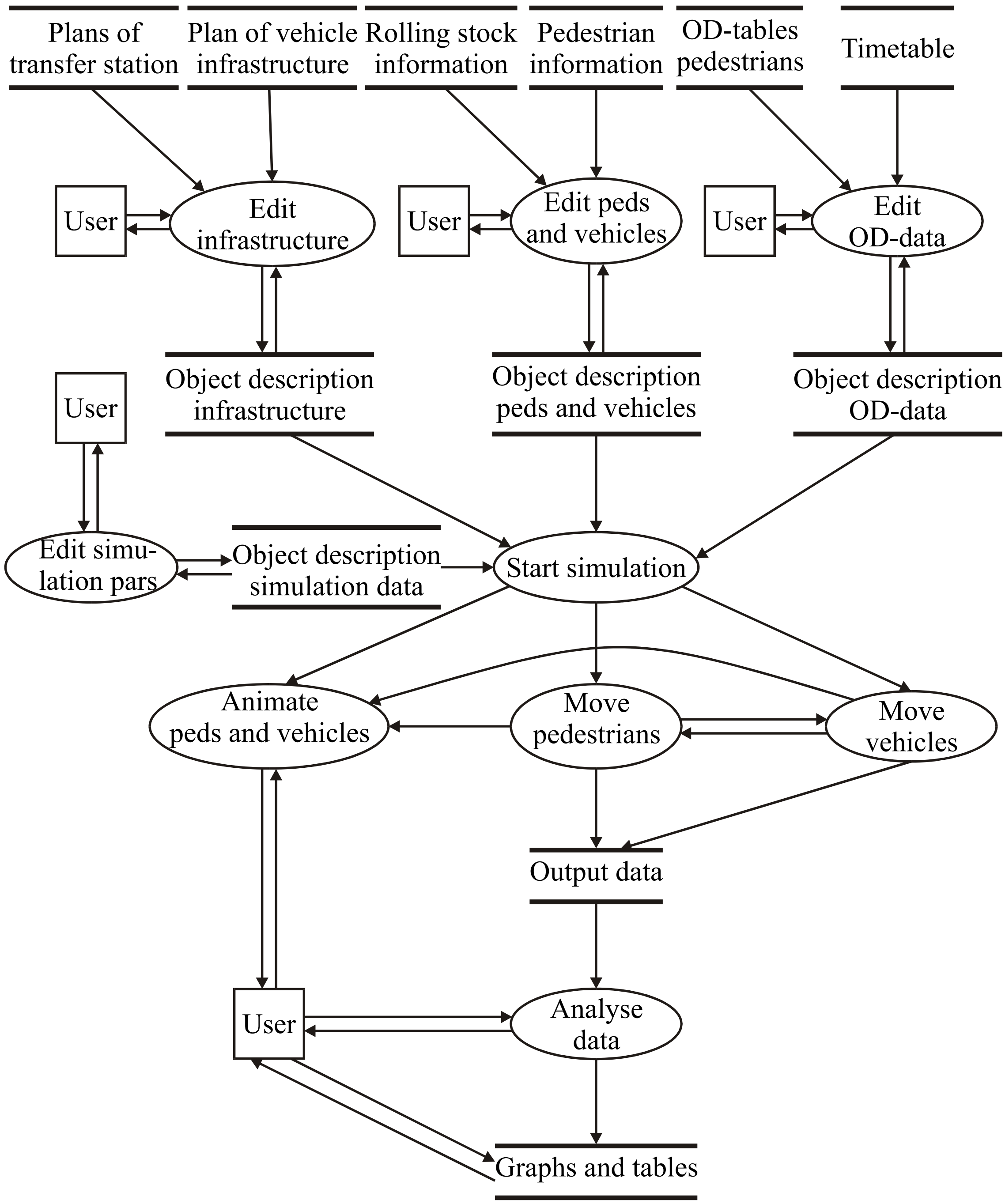


Figure 7.7: Interactions between the simulation tool SimPed and the user

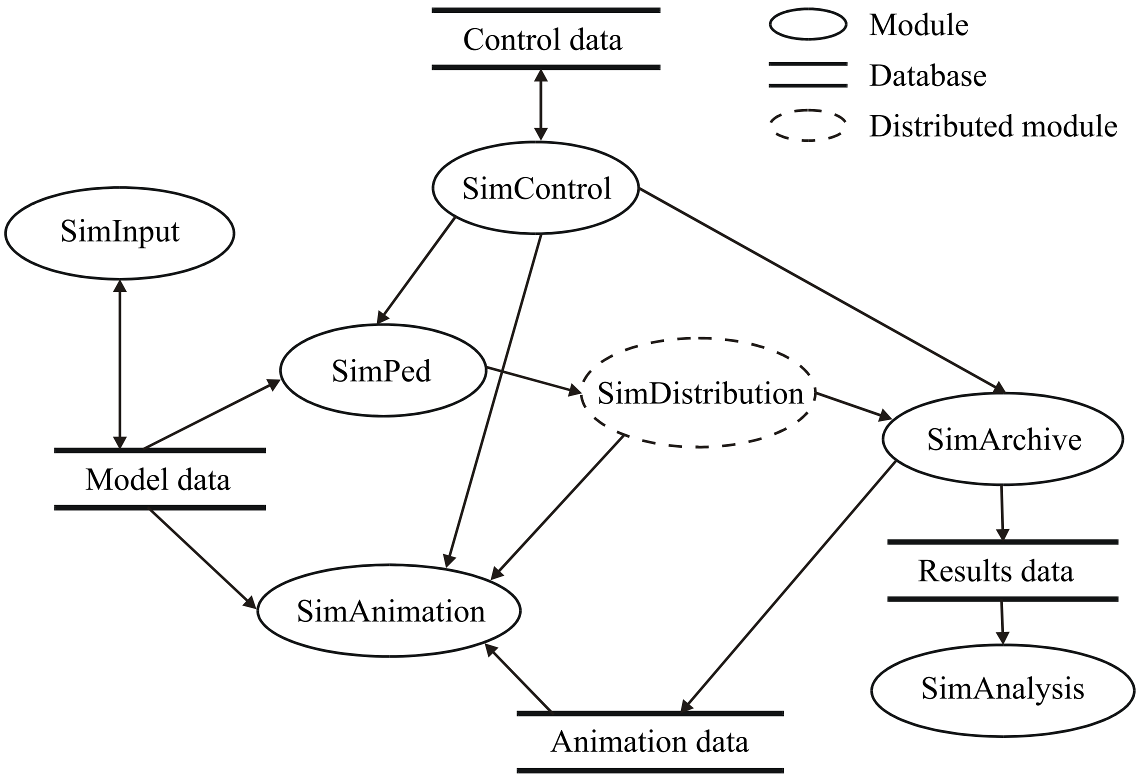


Figure 7.8: Software architecture developed to integrate the simulation tool

The simulation process is divided into three phases:

- Initialising: input of all data.
- Simulating: execution of the actual simulation.
- Analysing: analysis of the results.

Initialising In this phase, the input model is drawn in SimInput. This application converts graphical data into a database Model Data, that is used by other applications. These data consist of characteristics of infrastructure (such as length, width, and spatial form), characteristics of pedestrian types (such as free speed and familiarity with the environment), characteristics of public transport vehicles (such as length, number, and width of doors), and origins and destinations of both pedestrians and public transport vehicles in pedestrian generators and timetables.

Then, information on the simulation run to be executed is entered in SimControl. These data are also saved in a database (Control Data) and consist of among other things the input models to be simulated, the applications with which the simulation is executed, and the length and number of simulation runs.

Simulating A simulation is started in SimControl. Then, SimPed is initialised and a 'ready-to-go' message is sent back to SimControl, starting SimAnimation (if required) and SimArchive. Both applications initialise and return a 'ready-to-go' message. SimControl gives a 'Start' signal to SimPed, to start generating pedestrians. Produced data are sent by SimPed through an application for distribution of messages called SimDistribution to SimAnimation and SimArchive. SimAnimation visualises its messages, so the user can view the processes and the progress of the simulation. SimArchive registers the data in the messages into two databases. The first one (Results data) contains all results and is used for the analysis of this simulation run. The second file (Animation data) contains stream data, necessary for a replay of the animation (by SimReplay, being integrated in SimAnimation). This replay is some kind of film, which after the simulation has been executed, allows the user to look at some parts of it. Also, these films may be used for presentations.

Analysing Before the actual analysis of simulation results takes place, the input to the simulation tool needs to be checked. Two ways may be used for validation, that is, first an animation of the processes may be used to see whether pedestrian flows have correct origins and destinations and consist of the proper number of pedestrians. Also, it may be checked whether congestion occurs at the expected and predicted locations. A more detailed analysis may be done (without stochasticity in the model to make results more predictable) by generating some statistics. SimAnalysis is the module designed to perform statistical analyses and to create tables and graphs containing relevant and summarising information, based on raw simulation data. SORViewer generates spatial analyses, such as distribution of pedestrians over the infrastructure and routes used by pedestrians with the same origin and destination. These analyses are shown using the station plan as a background (see figure 9.11).

7.3.3 Functional description of some modules in the architecture

This section describes functionalities of the most important modules identified in the preceding section. Where this is of additional value, also screen shots of the output of each module are shown.

SimInput

SimInput is the tool to edit infrastructure and origin-destination tables for both public transport vehicles and pedestrians. This tool is based on a graphical library and behaves like a CAD drawing tool. Facilities are provided for the input of all data on pedestrians, timetable, and infrastructure as described in chapters 5 and 6 and section 7.2.3. An example of the specification of the infrastructure in SimInput is given in figure 6.3. A graphical overview of the timetable is shown in figure 7.9.

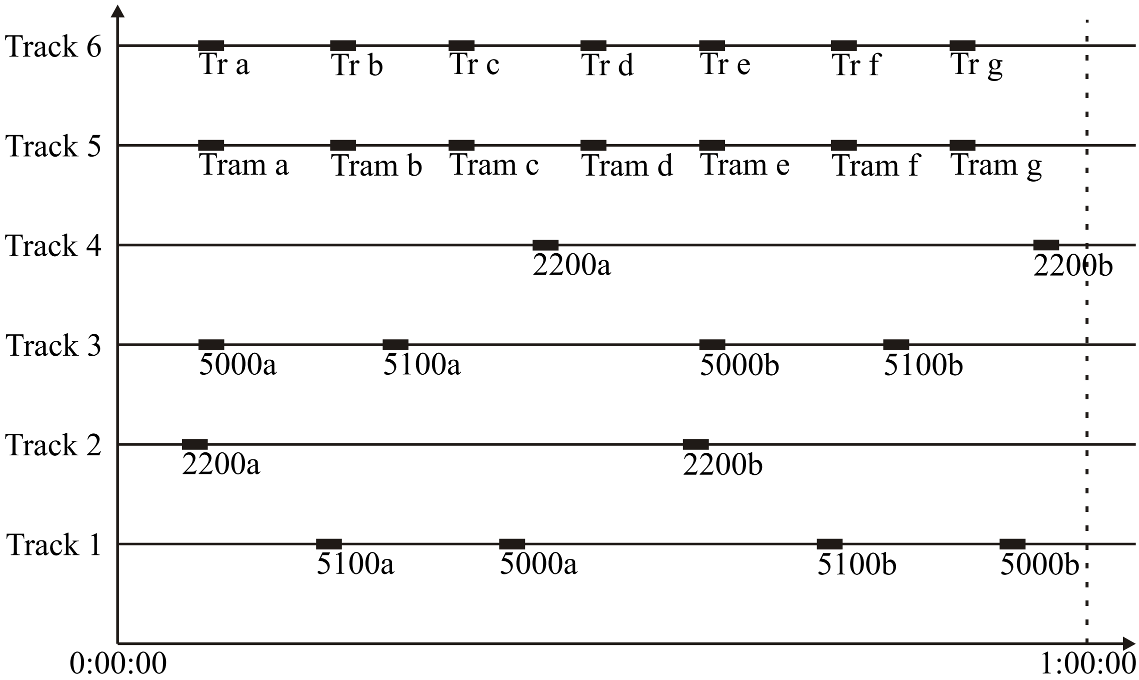


Figure 7.9: Example of timetable input in SimInput

Dwell locations of the public transport vehicles (indicated in this figure by numbered tracks) are set along the vertical axis, whereas the time is set along the horizontal axis. Each thick line in the timetable indicates a train or other public transport vehicle, identified by the number of the train series (e.g. '5000') and the number of the train in this series (e.g. 'a'). The thick line starts at the moment a vehicle has been scheduled to arrive along the platform and is ready to open its doors and ends at the scheduled departure time of the vehicle. For each public transport vehicle the rolling stock may be determined. Especially in the Netherlands many different types of rolling stock are used, all having doors of different widths at different locations. The rolling stock characteristics concern length of the vehicle, number of cars, number and location of doors, and characteristics of each door such as door width and height above the platform. For each public transport vehicle numbers of boarding passengers and their origins and numbers of alighting passengers and their destinations are specified. A destination may also be another public transport vehicle, thus creating transferring passengers.

SimControl

The control of the simulation is done by SimControl. Its interface, shown in figure 7.10, consists of several tab pages.

In SimControl, the user defines configurations to be simulated. Each configuration consists of a model, a parameter set, and a set of executables.

The model is the model drawn in SimInput, determining origins and destinations of pedestrians and the infrastructure network pedestrians walk through. On the page under the tab

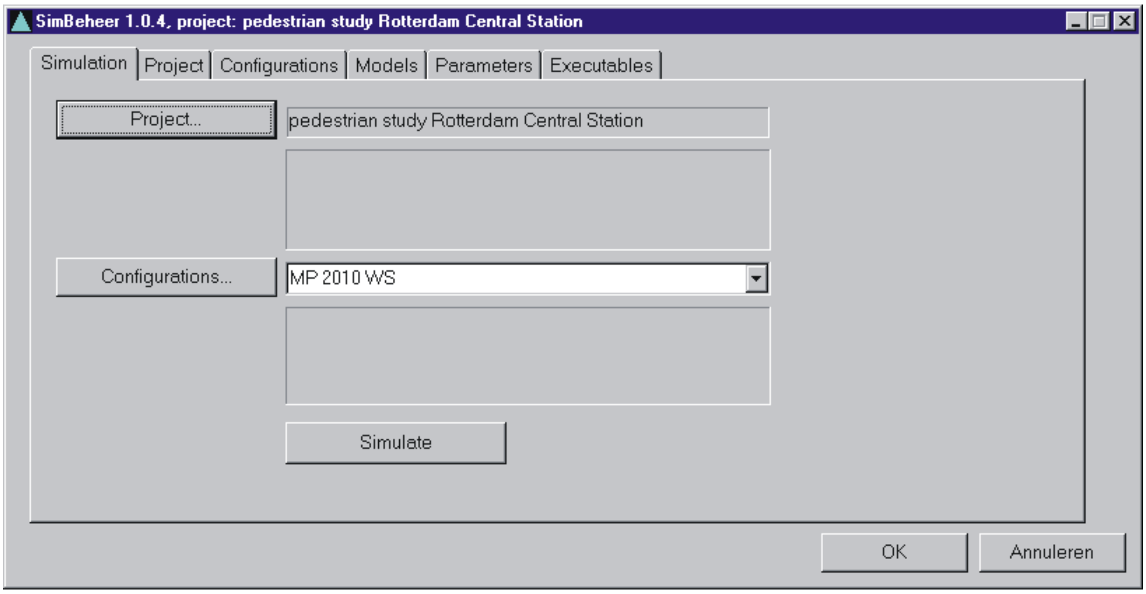


Figure 7.10: Interface of SimControl for execution of the simulation

'Models' the path to this file is set.

The parameter set (tab 'Parameters') consists of parameters concerning the simulation itself (the number of replications to get statistically confident results), the animation (to directly start animating, speed of the animation), and the archive (when a logging file has to be made to replay the animation after the simulation has ended, the start time and stop time of these loggings have to be specified).

Finally, in the set of executables the user indicates the version of SimPed to simulate with, whether an animation is shown, what executable is used to store the data, and the location of the results database.

When the configuration is completed, the user selects one or more configurations to be executed, where each configuration stands for one simulation. It is possible to execute several configurations in succession. Finally, the user presses the 'Simulate'-button (see figure 7.10) and, one after another, all selected configurations (and corresponding simulation runs) are executed.

SimAnimation

Both a 'technical' animation and a 'three dimensional' animation have been developed. The technical animation shows levels-of-service for pedestrians over time in the total infrastructure. This kind of animation is especially suited for specialists in the field of pedestrian traffic. A three dimensional or Virtual Reality animation has been developed to improve the communication between designers and all people involved in the design process, such as managers and contractors, but also inhabitants.

Technical animation SimAnimation is to a large extent based on the same sources as SimInput. It shares code for reading the input model from the database and for showing graphical elements of the model. A communication part has been added to receive messages from SimPed and to transform these messages into information accessible for the user. It is thus possible to see on-line animation, but the opportunity is also available to store the animation data and watch the animation afterwards (off-line replay functionality).

The animation was especially developed to visualise levels-of-service (as defined in Fruin (1971*b*)) on infrastructure elements. For each element, a dialog may be opened, to show characteristics of this element (such as number of pedestrians present, level of service, length, width and name) and to show a diagram with the number of pedestrians present over time. Different levels-of-service and diagrams of four stairs indicating the number of pedestrians over time in a specific part of the infrastructure are shown in figure 7.11.

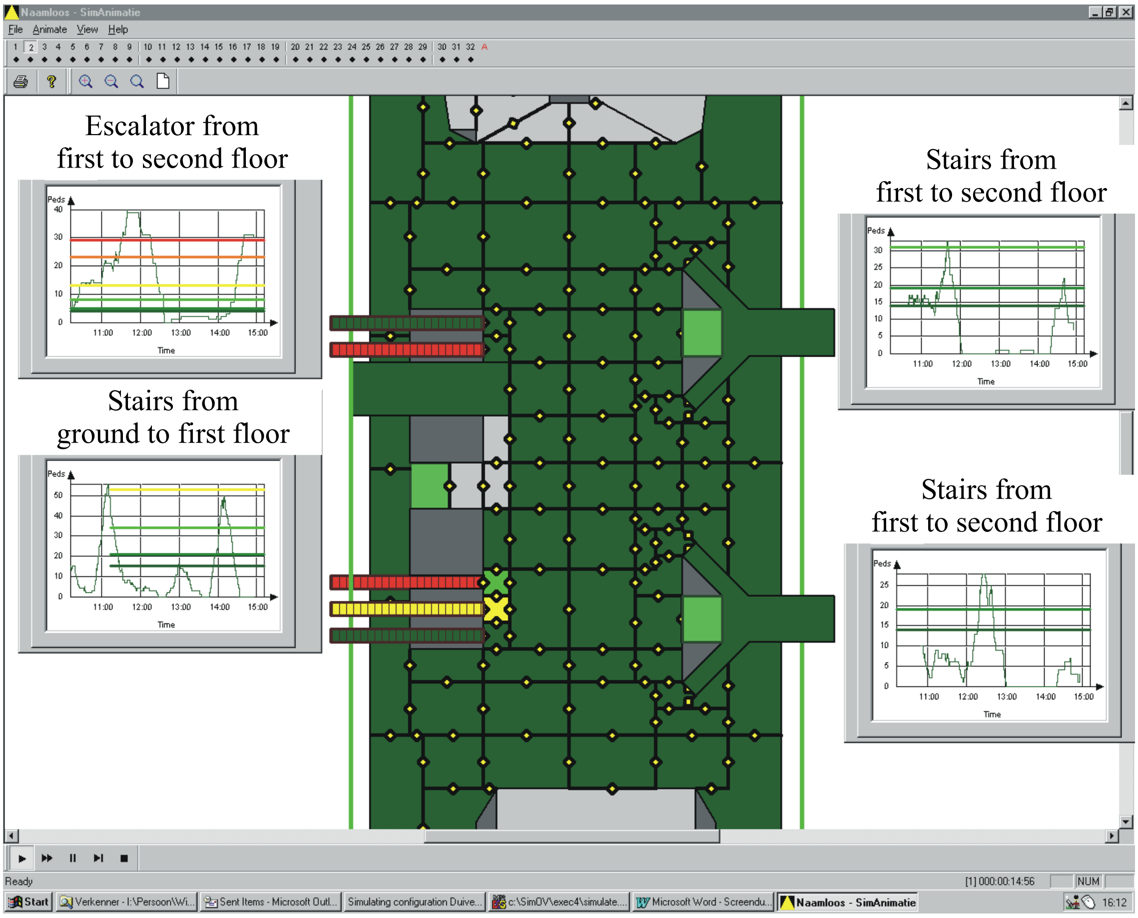


Figure 7.11: Overview of the technical animation, produced by SimAnimation

Three-dimensional animation This three-dimensional animation is a separate part of the simulation tool, developed by Holland Railconsult. It is a Virtual Reality environment and uses the results database. First, the infrastructure is read from the database and the model is drawn. Then, positions of both pedestrians and public transport vehicles are read from the database. At the given moments pedestrians are shown in the walkways and public transport vehicles arrive and depart from the platforms.

Figure 7.12: Three dimensional animation of Houten Station

This three dimensional animation provides a realistic view on the crowds within the station. Figure 7.12 shows a three dimensional animation of Houten Station in the Netherlands, when two trains have arrived at the same time and the platform is occupied with boarding and alighting pedestrians. The heads of the pedestrians have the same colour as the level-of-service they experience.

SimArchive

SimArchive stores simulation data in a Microsoft (MS) Access database. As a start, SimArchive makes a copy of the model database (input) and adds the output tables. This way, input data and results are in one database, so the relation between input and results is persistent and consistent.

SimArchive receives messages sent by SimPed. It looks for the right information in these messages, transforms this information into a recordset, and adds this recordset to the corresponding table. When the simulation has ended, the resulting database is copied to the location specified by the user and SimArchive is closed. SimArchive does not have a user-interface. It only opens a message window to show how far the simulation has advanced in simulation time.

SimAnalysis

The data produced by the simulation kernel are analysed by means of the application SimAnalysis. This application consists of forms in MS Access, where several analyses in the form of tables and graphs are prepared. For example, mean walking times for specific origin-destination relations and routes of pedestrians may be generated automatically. Also, SimAnalysis automatically produces diagrams and other overviews in Excel.

Thanks to the openness of the data structure, all kinds of diagrams and graphs can be produced, suited for the actual simulation, which may be easily added to meet the desires of the user.

SORViewer

The SORViewer generates spatial analyses, shown on a background of (a part of) the station plan. This way, the spatial distribution of passengers over the station, the location of congestion, and the routes of individual pedestrians through the station are visualised.

As in SimAnalysis, several statistics have been prepared, but additional statistics may be created by the user. In the results database, a query needs to be made, and in SORViewer, this query may be selected and the results are shown in the graphical background. An example created with the SORViewer may be found in figure 9.11.

Background applications

When the user starts simulating a configuration, communication between the different applications commences. Each application (archive, kernel, animation) can run on a separate (network) computer. To copy all executables to the right computer and to start these executables from a remote computer, the service SimStart has been designed.

Communication is directed by the service SimDistribution, among other things with respect to synchronise applications and to send results. SimDistribution holds a list of participating executables in the network, which executables are publishers, which are subscribers, and what are their addresses. SimDistribution checks whether applications are still able to receive and send messages, and if not, the user is informed and the simulation may be interrupted. Also, SimDistribution synchronises the starting process and stops applications (by means of sending 'Stop'-messages) when the user indicates this in SimControl or when the simulation has ended.

In case of irregularities (computers going down, failures in the software) these must be made known to the user, even in the case that the connection has been lost. To collect these messages, a named service SimLog has been designed, which is able to send these messages to SimControl which at its turn shows the messages to the user.

7.4 Conclusions

This chapter has described the developed object model and the software architecture established for SimPed. In the literature, only a few dedicated object models were found.

Unfortunately, these object models describe the transportation system on a more functional and global level and do not take into account interactions with pedestrians. Due to this lack of existing object models and given the fact that object models are relatively simple to create, a dedicated object model has been designed for SimPed.

The innovative aspects concerning the object model in SimPed may be found in the three types of information stored in the object model and the dynamic aspects with regard to pedestrians. The information concerns a static description of the infrastructure, characteristics of pedestrians and public transport vehicles, and origin-destination data over time with regard to both pedestrians and public transport vehicles. The dynamic aspects concern all information to be stored during a simulation run regarding activities of the pedestrian (walking, waiting, performing an activity, route choice), and status overviews of the infrastructure (such as a list with pedestrians present and levels-of-service) and the pedestrian (such as actual location, chosen route, and delay).

This object model is the basis of the developed simulation tool, consisting of several modules. The most important modules are SimInput, SimPed (simulation kernel), SimAnimation, SimArchive, and SimAnalysis. Also, some background modules had to be designed to coordinate the communication between the modules and to synchronise all modules in time. This software architecture is also dedicated for SimPed. Innovative aspects of the designed software architecture are its general applicability (also useful for other simulation models), its modularity (to include various behaviour models), and its support of parallel processing in order to increase simulation speed.

With the information provided in this chapter, the functional system specifications in chapter 5 and the models and algorithms from chapter 6, a complete description of the simulation tool SimPed has been given. In the following chapter, the verification and validation of the SimPed tool are described.

Chapter 8

Verification and validation of SimPed

8.1 Introduction

The development cycle of a simulation tool (see figure 8.1) consists of four subjects, namely *empirical and experimental data* (either observations or experiments, see chapter 4), behavioural *theory* (chapters 3 and 4), *mathematical models* (chapters 5 and 6), and the final *simulation tool* (chapter 7).

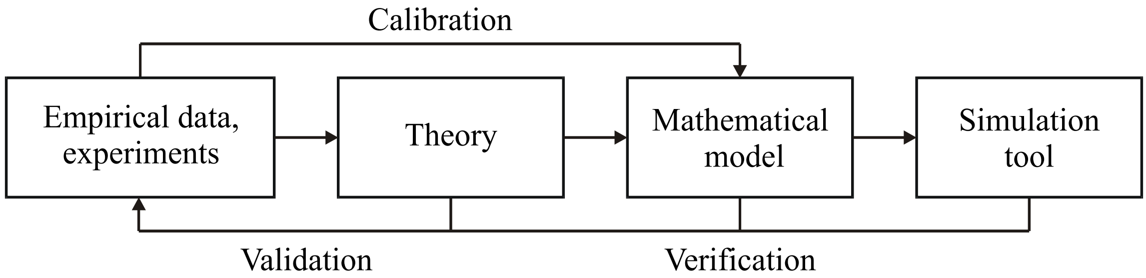


Figure 8.1: Development cycle of a simulation tool

This chapter presents briefly the issues of model *verification* and *validation* of this simulation tool. In the verification it is tested if the simulation results are as expected (have the models been correctly implemented), whereas in the validation the simulation results are compared to observations in reality. Calibration has already been discussed in chapters 3, 4 and 6, where, based on literature as well as observations some parameters (such as the speed-density relation) of the simulation tool have been determined.

Our verification consists of comparing the simulation results to theoretical results. Table 8.1 in section 8.2 shows that the largest difference between the theoretical results and the simulation results is 1.6%, indicating that the simulation tool passed this verification test. The other tests are combined in a special report (Daamen 2000) and are not further elaborated in this chapter. It appears that all tests lead to satisfactory results.

The validation of the simulation tool has been split up into two parts. The first part concerns the validation of the route choice model based on expert opinions and a comparison with observations described in Cheung & Lam (1998). The second part compares simulation results on the aspect of traffic flow characteristics. For validation of these characteristics, simulation results have been compared to observations of Delft Station, the Netherlands. This comparison has been performed based on two macroscopic traffic flow characteristics, namely walking speeds and densities. The route choice model appears to be satisfactory in the way that the expected routes are in fact used. However, further research is needed to find out whether the exact distribution of pedestrians over each route is realistic. The validation of the traffic flow fundamentals appeared to be satisfactory. Some of the differences, such as the significantly smaller speeds on the first part of the platform, have to be studied further to see whether this is an occasional occurrence or whether it is structural. On the whole, both the verification and the validation of the simulation tool have been satisfactory.

Importantly, the case studies reported in chapter 9 also contributed to the verification and validation of the developed tool.

This chapter contains two main sections, that is, section 8.2 describes the verification of the simulation tool, while section 8.3 describes the validation. This chapter ends with conclusions (section 8.4).

8.2 Verification

Verification is referred to as a check whether no mistakes have been made in the implemented algorithms (Kleijnen 1992) in order to find whether both tool and underlying algorithms work as intended.

To perform the verification of SimPed, a dedicated verification plan has been written (Daamen 2000). This plan consists of a series of tests meant to check the functionality of the application with the specifications and to see whether the results are in line with opinions of 'experts' in the field. In principle, all algorithms implemented in SimPed should be tested. However, it is impossible to test them all separately (also due to the high number of algorithms). Therefore, some tests have been put together to test a group of algorithms.

The description of a test contains both the input and the expected output. When the simulation results conform to the expected output, the simulation tool is considered to be verified in this respect. The aspects on which the tests are not passed have been registered and the simulation tool has been improved. This section only describes an example of one of the verification tests in order to show how the verification has been performed. Most of the test describe very simple situations for which analytical results are easy to derive. More complex situations are dealt with in the validation and the case studies. For further information on the verification we refer to the mentioned documentation (Daamen 2000).

The complete set of tests has been divided into several categories:

- Pedestrian traffic characteristics (walking in a network).
  - Level elements.
  - Special types of infrastructure, such as escalators and lifts.
- Interaction with public transport vehicles (boarding, alighting, and transferring).
- Performance of an activity.
- Route choice.
- Activity scheduling.

Only the verification of the first test in the first subcategory of the first category is presented here.

Verification of pedestrian traffic characteristics with level elements

This test concerns pedestrian walking characteristics and checks the simulation results of a simple infrastructure configuration with one directional pedestrian traffic. First, the required input is described and then an overview is given of the comparison between the simulation results and the expected results, manually calculated according to the pedestrian flow theory.

Verification scenario

The *infrastructure configuration* consists of corridor divided into three walkways connected by joints. The walkway in the middle is half the length of the outer walkways. The walkways are situated next to each other, with an entrance point on the left-hand side and an exit point on the right-hand side. An overview of this configuration is shown in figure 8.2. Both the *walkway* on the left and on the right have a length of 536 m and a width of 5 m. The walkway in the middle has a length of 268 m and a width of 5 m. All these elements are level. A default speed-density relation is used for the description of pedestrian walking behaviour.

The *joints* connect the walkways over their total width and thus have a length of 5 metres. The entrance and exit only have a width of 3 metres, but this length does not affect the traffic flow characteristics at low densities.

The origin of the pedestrian flow of this *generator* is the entrance, whereas its destination is the exit. The generator starts generating pedestrians at the beginning of the simulation and generates pedestrians during ten hours. During this period, 1000 pedestrians are generated, which is a relatively small pedestrian flow, thus this simulation will not show any congestion. The pedestrians are generated uniformly distributed over time. All pedestrians have similar (default) characteristics, such as a free walking speed of 1.34 m/s.

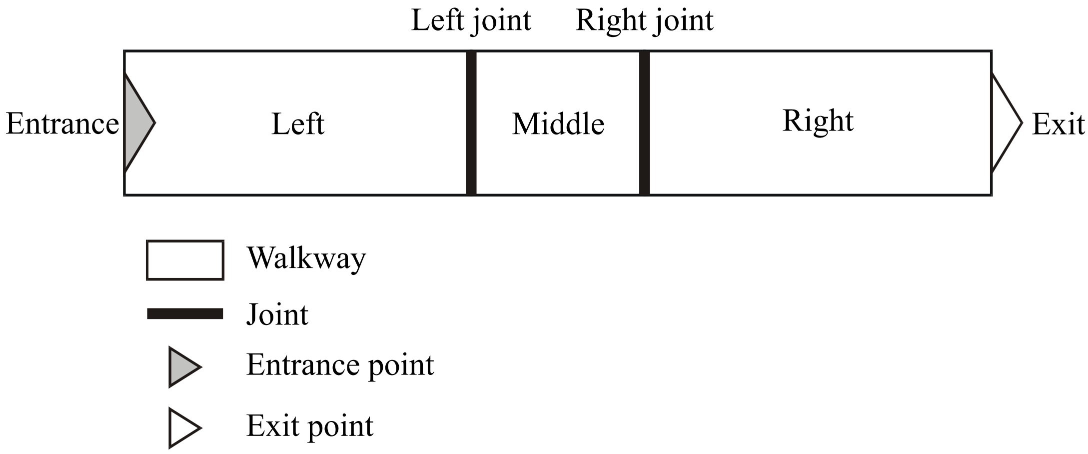


Figure 8.2: Infrastructure configuration for the first verification test

Output of the simulation tool

An overview of the output of the simulation is given in table 8.1, as well as the expected values and the difference between the expected and the measured output.

Table 8.1: Expected and realised output of the first verification test

Parameter	Expected	Simulation	Diff.
Nr of pedestrians generated	1000	1000	0%
Avg follow time of pedestrians	36 s	35.87 s	0.36%
Route of the pedestrians	entrance - left - left joint - middle - right joint - right - exit	entrance - left - left joint - middle - right joint - right - exit	0%
Avg total walking time	1000 s	994.56 s	0.54%
Avg time in Entrance	0 s	0 s	0%
Avg walking time in Left	400 s	400.21 s	0.05%
Avg time in left joint	0 s	0 s	0%
Avg walking time in Middle	200 s	200.11 s	0.06%
Avg time in right joint	0 s	0 s	0%
Avg walking time in Right	400 s	394.23 s	1.44%
Avg time in Exit	0 s	0 s	0%
Avg nr of peds in Left	11.1 pedestrians	11.08 pedestrians	0.18%
Avg nr of peds in Middle	5.56 pedestrians	5.56 pedestrians	0%
Avg nr of peds in Right	11.1 pedestrians	10.92 pedestrians	1.62%

The maximum difference between the manually calculated output and the realised output is 1.62%. Identity between the expected output and the realised output is not possible, due to the stochastic aspects of the simulation tool. This stochasticity is as far as possible reduced, but for example the inter arrival times of pedestrians at the entrance are always derived from a distribution. Therefore, the model has passed the first verification test.

Remaining aspects of this test are delay times in the joining elements (for example to simulate passing a turnstile), slower walking pedestrians, faster walking pedestrians, increasing pedestrian flows, adapting the configuration to cause congestion, a normal distribution for the arrival of pedestrians during the simulation period to model pedestrian peak flows and changes in the start and end moment of the generation of pedestrians, which should not have any effect on the results. For a detailed overview of these aspects and the remaining tests the reader is referred to Daamen (2000).

Conclusions

This subsection described the first test of the verification plan. Table 8.1 shows both the manually calculated and the realised simulation results and the difference between the results. It appears that the largest difference is 1.6%, which is due to some random aspects of the simulation tool which can not be made deterministic. The results of the remaining parts of the verification were as positive as the results of this very simple first test, thus the simulation tool is found to be verified.

8.3 Validation

Validation is described as a check whether the model gives a sufficiently accurate representation of reality (Kleijnen 1992). During the validation of a simulation tool or a similar application, predictions from the simulation model are compared with observations from reality (see figure 8.3), or, if that is not possible a less desirable form, such as 'expert opinion' may be applied.

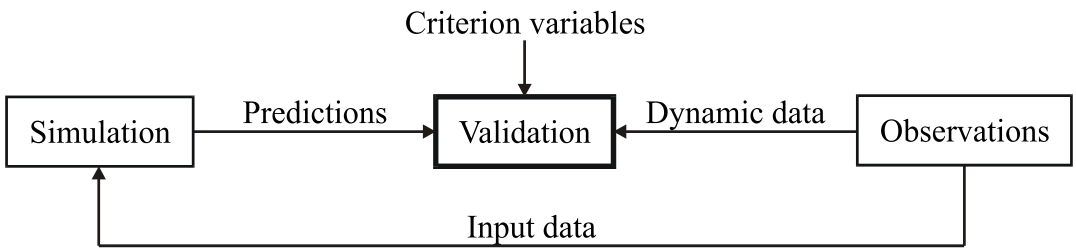


Figure 8.3: Overview of the elements of the validation process

The comparison of simulation results with observations is restricted to several relevant aspects, so-called *criterion variables*. In order to make practice and simulation model correspond, the input data for the simulation tool has to be observed as well (the arrow '*Input data* (static)' in figure 8.3). Examples of this input are the configuration of the infrastructure and the dynamic origin-destination matrix.

Validation of the tool may handle each process (submodel) separately, or the tool as a whole. Zhang & Owen (2004) describe a systematic validation approach of a microscopic traffic simulation program. This procedure includes animation comparison and quantitative/statistical analysis at both macroscopic and microscopic levels. For validation at the macroscopic level, the averages and other statistics of traffic variables are compared, and fundamental relationships of traffic flow parameters are studied. For validation at the microscopic level, the speed change pattern, vehicle trajectory plots, and headway distribution from simulations are compared with those of the real-world system. The validation of SimPed, as described in this thesis, validates the most important processes, namely the route choice model and the pedestrian traffic flow operations. All other processes (such as the performance of an activity and activity location choice) will be validated in the near future.

In order to validate the route choice model within SimPed a large amount of observations are needed. As a first step, the validation of the route choice model is based on a graphical comparison (*animated Turing test*) between model and reality. Additional research is to be performed for a comparison of simulation results and observations on how pedestrians are assigned to the different routes. At the time of writing, observations on pedestrian route choice have been performed in two Dutch train stations.

Validation of the pedestrian traffic flow operations is based on a comparison of simulation results with observations on platform 2 of Delft Station, the Netherlands. This platform has only one staircase, functioning as an exit / entrance to the platform and is visited by a sufficient number of passengers to cause congestion. Decision variables of the validation are walking speeds, both on the platform and on the stairs, and density both as a function of time and space, on the stairs and on the platform.

Subsection 8.3.1 describes the validation of the route choice model, whereas subsection 8.3.2 goes into detail into the validation of the pedestrian traffic flow operations.

8.3.1 Route choice model

For the validation of the route choice model a situation is taken, in which pedestrians (both in upwards and in downwards direction) have to choose between a stairs and an escalator to bridge the height difference between a concourse and the platform. Two escalators are present, the top one turning in upwards direction and the bottom one turning in downwards direction (see figure 8.4).

This subsection describes the predictions of the route choice model in both upwards and downwards direction. First, the input parameters of the simulation model are described, and then the results of the route choice are shown and compared to results for a similar situation from the literature.

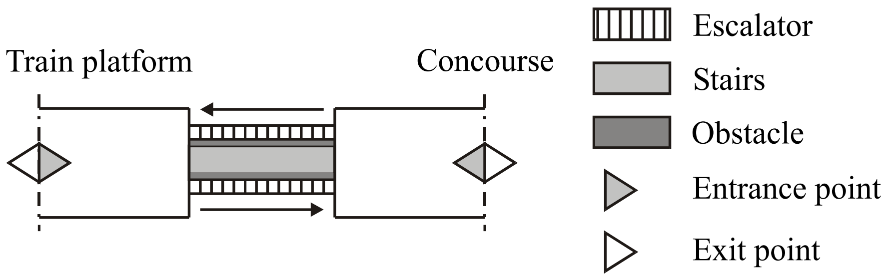


Figure 8.4: Infrastructure configuration for the validation of the route choice model

Description of the simulation input

The configuration of the infrastructure of the simulation model is similar to the configuration drawn in figure 8.4. The staircase leading to the platform has a width of 2 metres, whereas the escalators have a standard width of somewhat less than a metre and have a speed of 0.65 m/ s.

During the simulation, pedestrians in upwards direction (to the train platform) are generated uniformly distributed over time, whereas the pedestrians in downwards direction are simulated according to a timetable. The numbers of pedestrians are similar to the number of passengers predicted for Rotterdam Central Station in the year 2020 (VHP & Holland Railconsult 1999) in which a similar situation occurs (see sections 9.3 and 9.4). 2122 passengers will walk from the concourse to the platform and 2923 passengers arrive on the platform by train and walk to the concourse.

Route choice sets

The aim of the route choice model is to find for each pedestrian the shortest route through the network, from the pedestrian's origin to his (intermediate) destination, depending on the instantaneous conditions in this network (see section 6.4). First, the route choice set is generated and then, a choice is made between the alternatives in the choice set. Figure 8.5 gives a graphical overview of the route choice set in the given configuration.

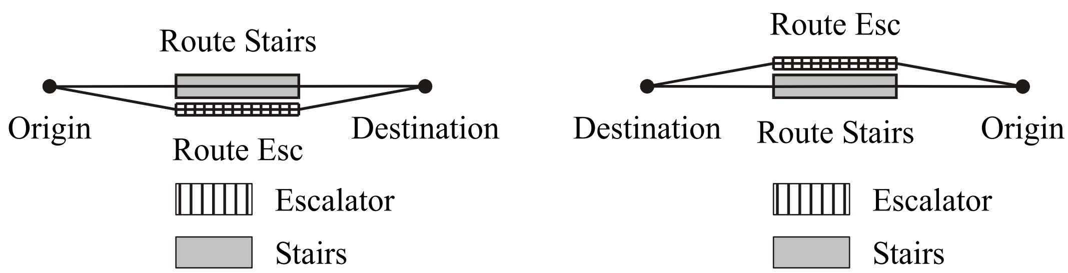


Figure 8.5: Route choice set between the platform and the concourse (left) and vice versa (right)

Table 8.2 shows walking distances for each of the identified routes, as well as the generalised times in an empty infrastructure.

Table 8.2: Distances and generalised walking times for routes for both OD-pairs

	Distance (m)		**Generalised Time** (s)	
	R Esc	R Stairs	R Esc	R Stairs
Cc-Platform	53.99	52.94	49.00	56.54
Platform - Cc	50.91	52.48	46.70	56.20

Although the walking distance along the escalator is larger, the generalised walking time is smaller thus more pedestrians are expected to choose the escalator. During the simulation, the generalised walking time on the escalator increases, due to additional discomfort of the crowd on the escalator. The actual walking time on the escalator does not change (equals the speed of the escalator times the height distance bridged), but the discomfort increases and relatively more passengers will choose the stairs.

Results of the route choice process

Table 8.3 shows the volumes per hour on each of the routes as well as the corresponding mean walking time.

Table 8.3: Load and realised average walking times for routes of both OD-pairs

	Load (P/ h)		**Mean walking time** (s)	
	R Esc	R Stairs	R Esc	R Stairs
Cc-Platform	2050	72	51.66	50.37
Platform - Cc	1949	974	69.06	71.37

From table 8.3 it can be seen that the distribution of pedestrians over the two routes between the concourse and the platform differs significantly due to walking direction on the stairs. In downward direction, 33.3% of the pedestrians use the stairs, whereas only 3.4% of the pedestrians use the stairs in upward direction. The actual travel times on both routes are similar.

A comparison with the research of Cheung and Lam with respect to the choice between escalators and stairs (Cheung & Lam 1998) shows that in the ascending direction it was found that 96.6% of the passengers used the escalators, whereas Cheung and Lam predict 99.6%. In descending direction, the difference is much larger, that is 66.7% versus 94.9% predicted by Cheung and Lam. This difference may be explained by the densities of the pedestrian flows, which is not explicitly taken into account in the relation defined by Cheung and Lam. In the descending direction, the difference is much larger, probably due to the fact that passengers arrive in peaks. When passengers arrive in peaks (after the arrival of a train), more passengers will choose the stairs, especially in the descending direction. Further research is therefore recommended to derive the influence of peak flows on the choice between escalator and stairs, as well as to take into account probable cultural difference, as Cheung and Lam performed their research in Hong Kong and the developed simulation tool is to be used in west European public transport facilities.

The validation of the route choice model with dedicated observations, described in section 4.8, is separately reported in Van de Reijt (2004). The dedicated estimated model indicated that walking time is the most important factor in route choice, corresponding to the shortest path approach in SimPed. Although the dedicated model predicted the observed route choice better, the SimPed results did not deviate significantly. The current route choice approach performs sufficiently well to be applied in the applications so far.

8.3.2 Pedestrian traffic flow operations

As has been indicated in the introduction, the criterion variables to validate pedestrian traffic flow operations are:

- Walking speeds.
  - On the stairs, upwards and downwards.
  - On the platform, of boarding and alighting passengers.
- Density over time and space.
  - Density over time on the stairs and on a specific part of the platform.
  - Density over space and over time.

The validation is performed by comparing observations with simulation results. A description of the set up of the observations and the derivation of some of the input parameters in SimPed is given in appendix E. In the following, first a description is given of the input for the simulation tool, partly derived from the observations in Delft Station. Then, the actual comparison between the observations and the simulation results is illustrated with respect to walking speeds and density.

Description of SimPed input

This section contains the relevant input for the simulation tool, partly as a result of configuration measurements and partly derived from the observations (see appendix E). An overview of the input model of the simulation tool is shown in figure 8.6. The input consists of timetable data and a platform configuration, including the definition of the rolling stock.

Since the types of rolling stock and their corresponding lengths had inadvertently not been observed, a typical train has been constructed, consisting of ten carriages, with one door situated in the middle of each carriage. The number of boarding and alighting pedestrians have been distributed over the different carriages according to the observations (figure 8.7).

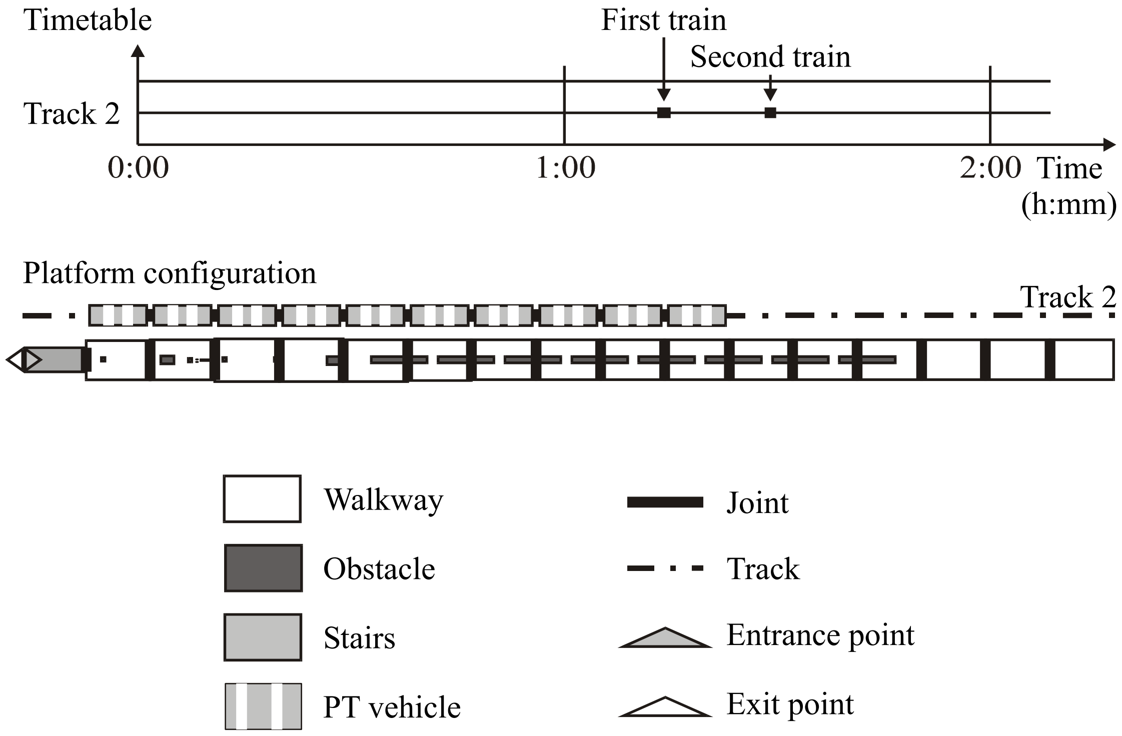


Figure 8.6: Overview of the configuration of Delft Station as input for the simulation tool

The y-axes of the figures indicate the percentage of the total number of boarding and alighting passengers. This total number of passengers for each train is a separate input and is shown in table 8.4.

Table 8.4: Number of boarding and alighting passengers per train

	Train 1	Train 2	Total
Alighting	78	25	103
Boarding	98	50	148
			251

Boarding and alighting pedestrians have different origins and destinations and slightly different walking characteristics. It is assumed in the model that alighting passengers walk purposefully and efficiently and therefore, this type of pedestrians has an average free speed of 1.34 m/s, whereas boarding passengers will stroll around, resulting in a lower average free speed of 1.27 m/s (= 95% of the default free speed). The free speeds of both pedestrian types follow a normal distribution with a standard deviation of 0.25 m/s.

The following subsections show a comparison between observations and simulation results on the aspects of walking speed and density.

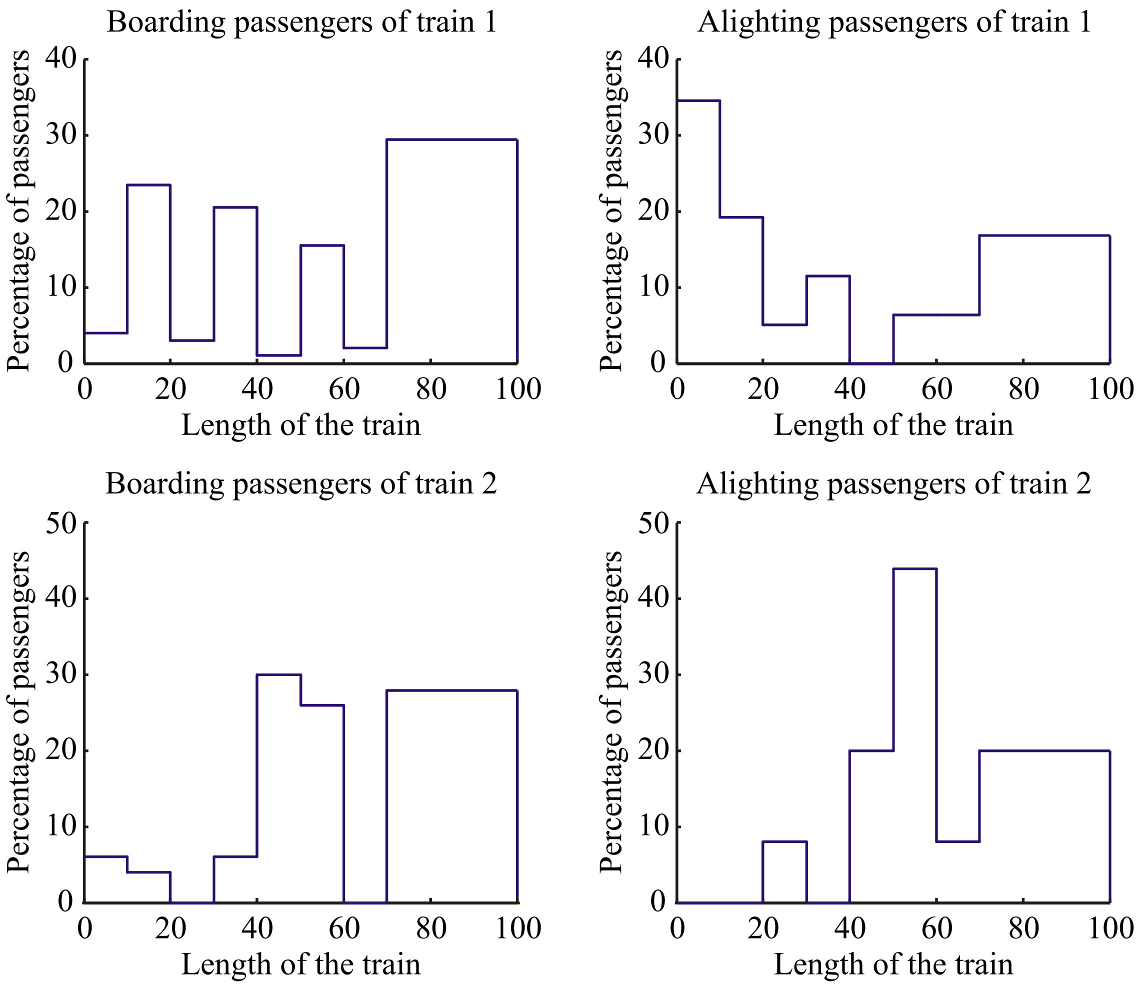


Figure 8.7: Input distribution of boarding and alighting passengers over the two trains in the simulation, derived from the observations

Comparison of walking speeds

The comparison of walking speeds has been split into a comparison of walking speeds on the stairs and on the platform respectively. The reason for this is to distinguish different types of infrastructure (stairs and level platform). Also, a distinction has been made for walking speeds of boarding and alighting passengers.

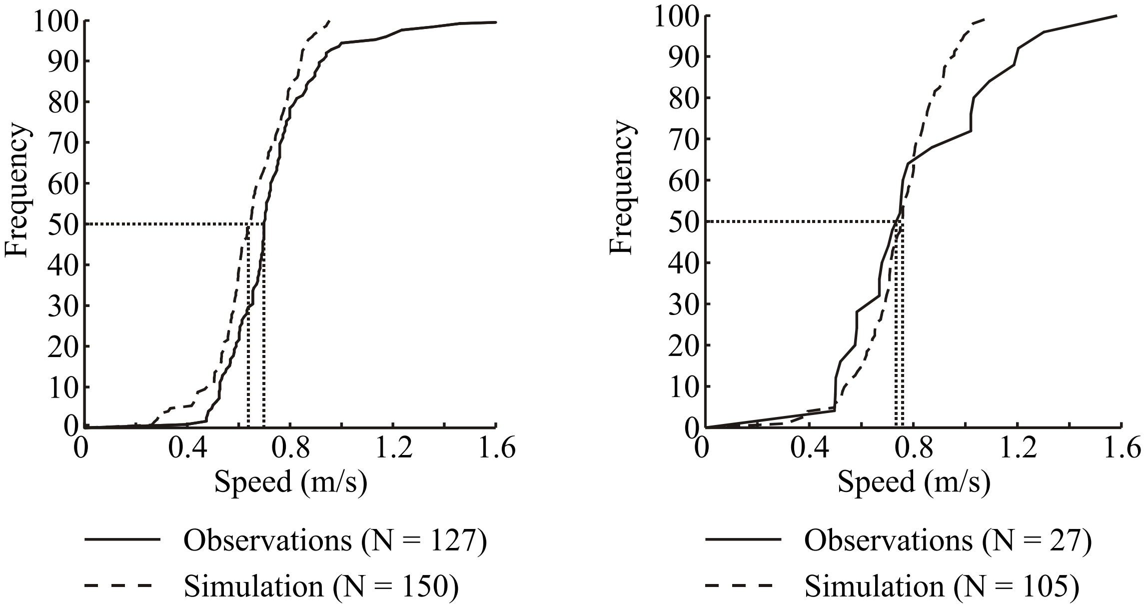
Table 8.5: Comparison of observed and predicted median walking speeds (in m/s) and variances (in m/s)

		Observations		Simulation results	
		Median	**Variance**	**Median**	**Variance**
Stairs	**Upwards**	0.70	0.06	0.64	0.04
	Downwards	0.75	0.16	0.76	0.04
Platform	**Alighting**	1.35	0.11	1.34	0.07
	Boarding	0.99	0.11	1.21	0.14

The following contains figures of these comparisons. Table 8.5 summarises the results and indicates variances in walking speeds as well. From table 8.5 it may be concluded that the median speed of pedestrians walking on the stairs in downwards direction and walking speeds of alighting passengers on the platform are similar in the observations and the simulation results. The observed median speed on the stairs in upwards direction is remarkably high, as other studies in literature indicate lower speeds as well (see chapter 3). Reasons for the phenomenon might be that the passengers on the stairs cannot see the train arriving (and thus hurry too much), that the length of the stairs (and the height to be bridged) is rather small and that the passenger flow consists mainly of students and commuters, although a detailed flow composition had not been observed. In spite of this quite high observed speed, the difference in median speed on the stairs in upwards direction is relatively small. As this is one of the input parameters of the model, further research is needed to see whether this is a common observation in railway stations and when this is the case, the input parameters need to be adapted. The difference of the median speed of boarding passengers can be explained by the behaviour of boarding pedestrians in choosing their waiting location on the platform. It appears that a correlation may be found between the walking speed and the destination of the passenger on the platform (see also figure 8.9), which is different from the assumptions. This is subject for future research as well.

On the stairs Figure 8.8 shows cumulative frequency distributions of walking speeds on the stairs in upwards respectively downwards direction.

Figure 8.8A shows that both distributions have a similar form, and similar variances. The predicted speeds are smaller than the observed speeds. To get a better match, the free speed in the simulation might be increased, in order to shift the total frequency distribution to the right.



A. Stairs, upwards direction

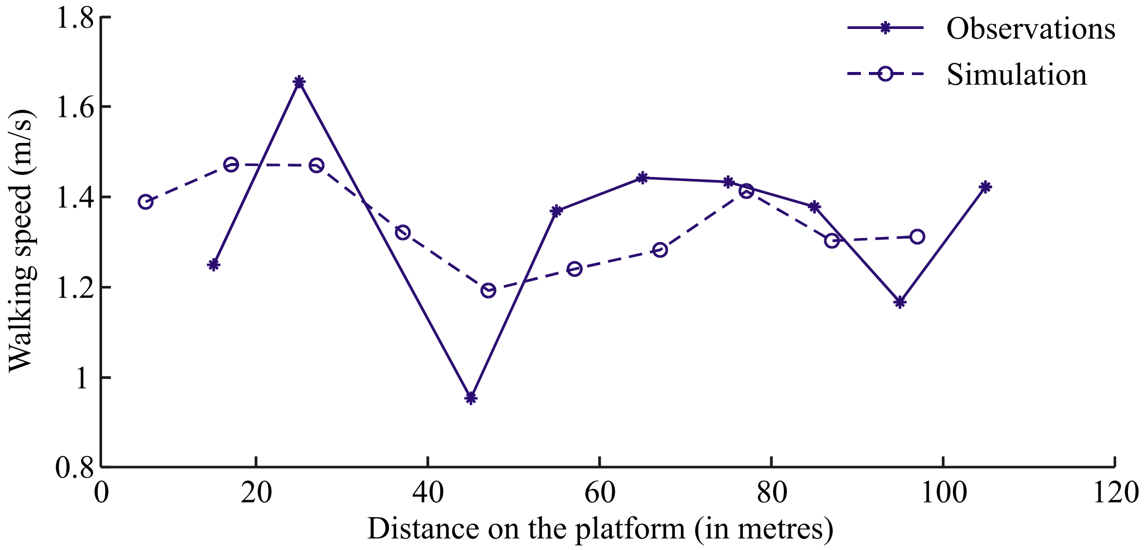
B. Stairs, downwards direction

Figure 8.8: Observed and predicted frequency distributions of walking speeds on the stairs in upwards and downwards direction

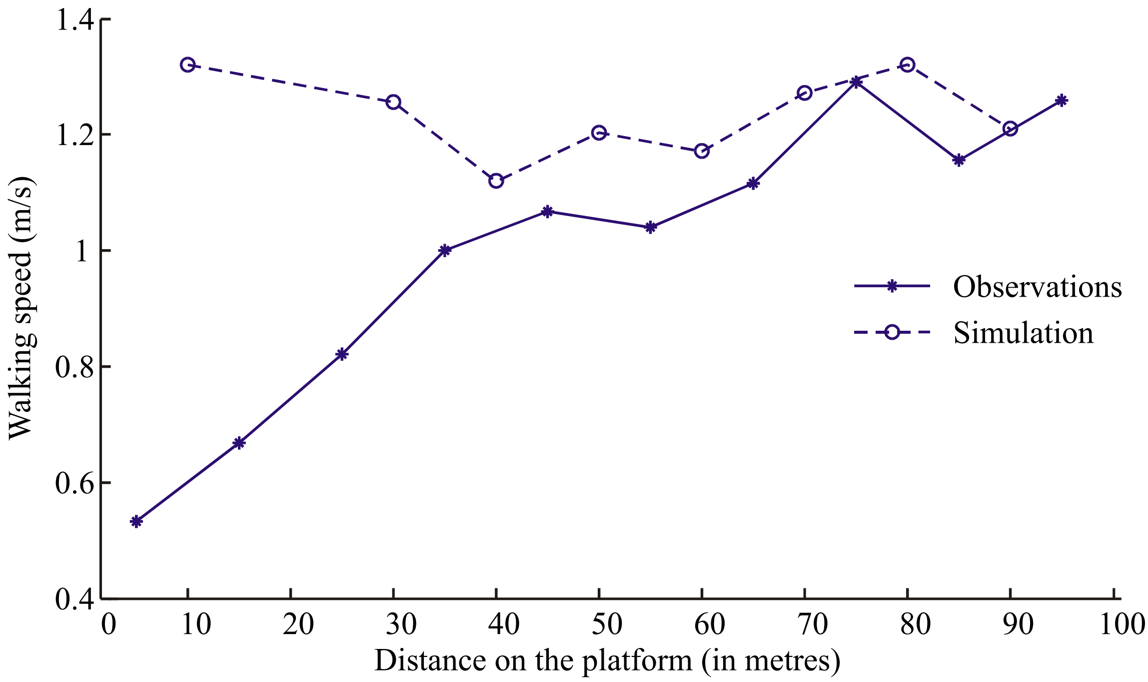
The distribution for the observed walking speeds on the stairs in downwards direction (see figure 8.8B) does not have a smooth form due to the fact that the number of observations is relatively small. Figure 8.8B also shows that the median speeds of both observations and predictions are similar. However, the observed maximum speeds are much higher than the maximum speeds in the simulation. The variance of the observed speeds is even four times as high as the variance in the predictions. When the variance remains high when more observations have been performed, the distribution of walking speeds in the model might be adapted.

On the platform Figure 8.9 shows the median speed of alighting respectively boarding passengers, depending on the location of their origin respectively destination on the platform. In this figure, both mean and variance of the simulated results and the observations are tested, also in relation to the location on the platform.

Figure 8.9A shows that the median speeds of both the observations and the predictions do not differ significantly along the walking distance on the platform. Figure 8.9B indicates that the observed walking speeds vary with the destination of the passenger on the platform. The walking speeds of passengers walking 50 metres or more on the platform do not vary significantly, whereas the walking speeds of passengers having their destination in the first 50 metres on the platform increase from 0.55 m/ s to 1.2 m/ s. The median speeds of passengers walking more than 50 metres on the platform are similar in the observations and predictions. However, for smaller walking distances, the walking speeds in the simulation remain on the same level (about 1.2 m/ s), whereas the observed walking



A. Speeds of alighting passengers on the platform



B. Speeds of boarding passengers on the platform

Figure 8.9: Median speeds of alighting and boarding passengers, depending on their origin respectively destination on the platform

speeds increase significantly. It appears that passengers choose their walking speeds in a different way than is assumed in the simulation tool, and probably incorporate some hidden waiting time which could not be observed. However, before this process is modified in the simulation tool, more observations need to be collected in order to compose a general valid theory and mathematical model on the passenger choice process of both walking speed and waiting location on the platform.

Comparison of densities over time and space

The final aspect on which the observations and the simulation results are compared is density. Figures 8.10 and 8.11 show the distribution of density over space and time for respectively observations and predictions. The arrival and departure moments of the trains are clearly visible as darker peaks, whereas the densities between these peaks are low. Roughly speaking, the density plots look alike.

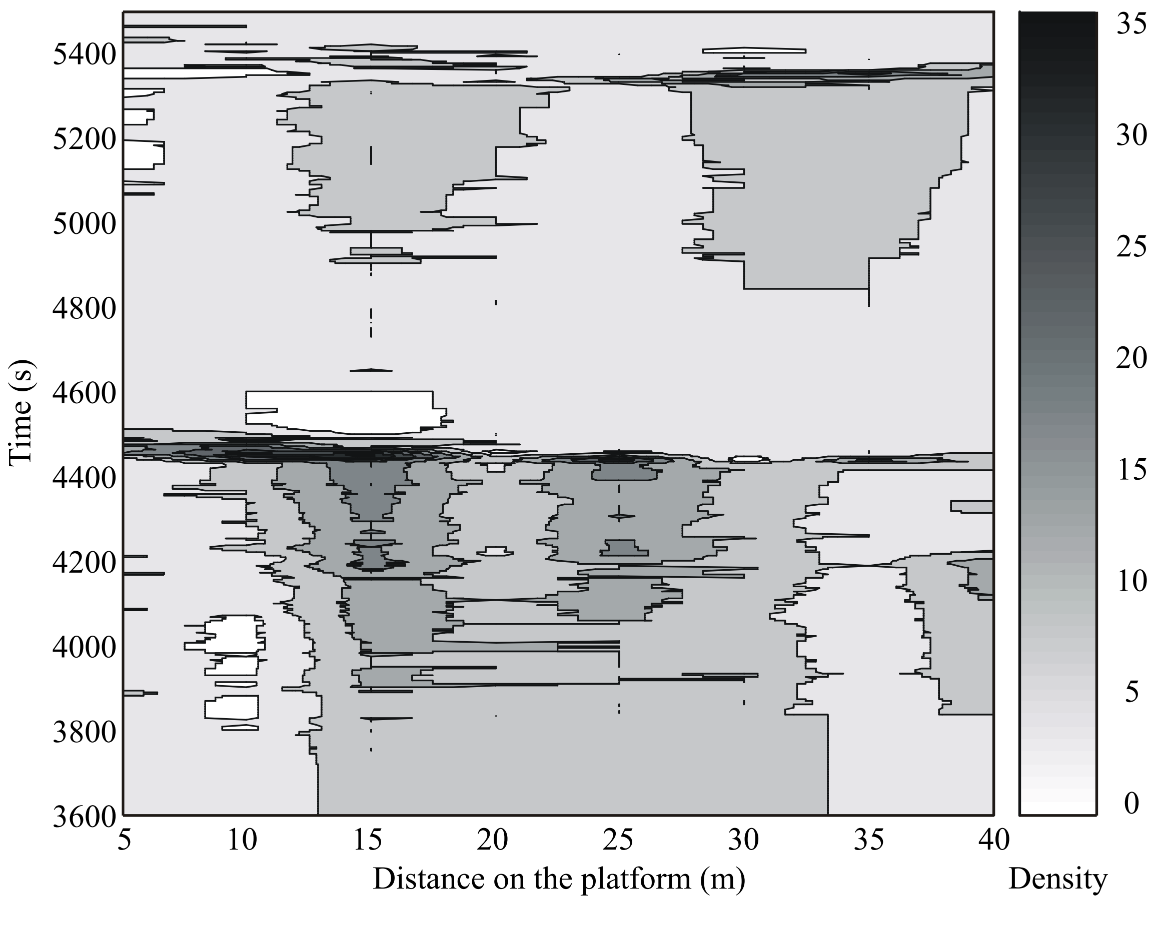


Figure 8.10: Observed densities on the platform in time and space

The process in the simulation is clearly more smooth than the process in the observations, which is a very common observation. At the beginning of the observations, already some passengers are present on the platform, while the simulation starts empty. In general, the number of passengers on the platform is higher in the observations than in the simulation,

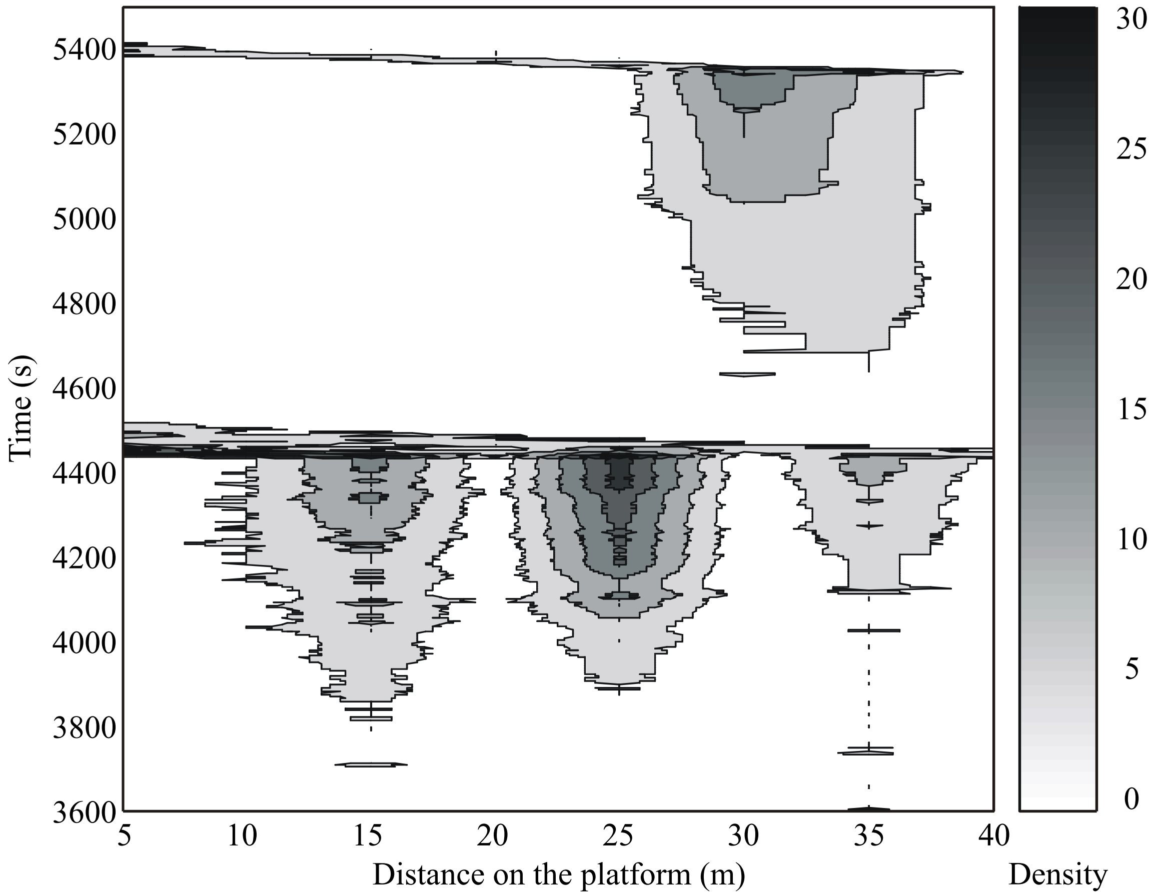


Figure 8.11: Simulated densities on the platform in time and space

partly due to the initial state of the platform. However, the height of the peaks is similar as well as the clustering over the platform at the arrival moment of the train. The moment of clustering differs: in the simulation passengers walk straight to the expected location of the door, whereas in the observations passengers only start to cluster at the arrival moment of the train due to the walking of passengers in the driving direction of the train the moment it enters the station. The duration of the peak of alighting passengers from the first train is similar for both observations and simulation results (about 100 seconds on the stairs). The process of ‘walking with the train’ is clearly visible for the second train, where the observations show two peaks before the train arrival reducing to one cluster when the boarding process starts. This is due to the fact that this train did not stop nearby the stairs, but its rear carriage passed the first cluster of passengers and stopped at the second cluster.

Summarising it can be stated that although the density over time and space is not completely similar, the main characteristics of the process (peaks at the arrival moment of the train, clustering on the platform) are modelled satisfactorily.

Comparison of densities over time In this subsection densities of different parts of the platform are compared over time, which is a detail of a vertical cross-section of figures 8.10 and 8.11 at two specific locations, namely the stairs and the first part of the platform ($0-10\,\mathrm{m}$). Figures 8.12 and 8.13 indicate these densities (expressed as the number of pedestrians present) over time.

The arrival moments of the two trains are clearly visible in figure 8.12 (after 4420 s respectively 5300 s) in both the observations and the simulation results. From the first train many more passengers alight than from the second train, indicated by two peaks with different heights. The duration of the passenger peak of the first train is about the same for the observations and the simulation data, but the simulation data indicate a higher peak (maximum of 34 passengers present on the stairs), whereas no more than 17 passengers have been observed. However, the duration of this maximum is very short and after the peak, the simulated density is similar to the observed density. For the second train, the simulated density peak occurs about 20 s earlier than the observed peak, but its height, duration, and form are similar. Between the peaks, passengers arrive randomly and the number of passengers present remains constant, with an occasional small peak. Due to the randomness in this arrival pattern (both in reality and in the simulation) these occasional peaks do not occur at exactly the same moments, but the number and the form of the density peaks are alike. As the number of boarding passengers of the first train is higher than that of the second train, the average number of passengers present is higher as well, which is valid for both the observations and the simulation results as is seen in the figure.

In figure 8.13, the density peak for the first train is also much higher than the peak for the second train, in both the observations and the simulation results. Along this part of the platform, a train door may occur, thus some passengers decide to wait on this part of the platform for the arrival moment of the train. Therefore, the number of passengers

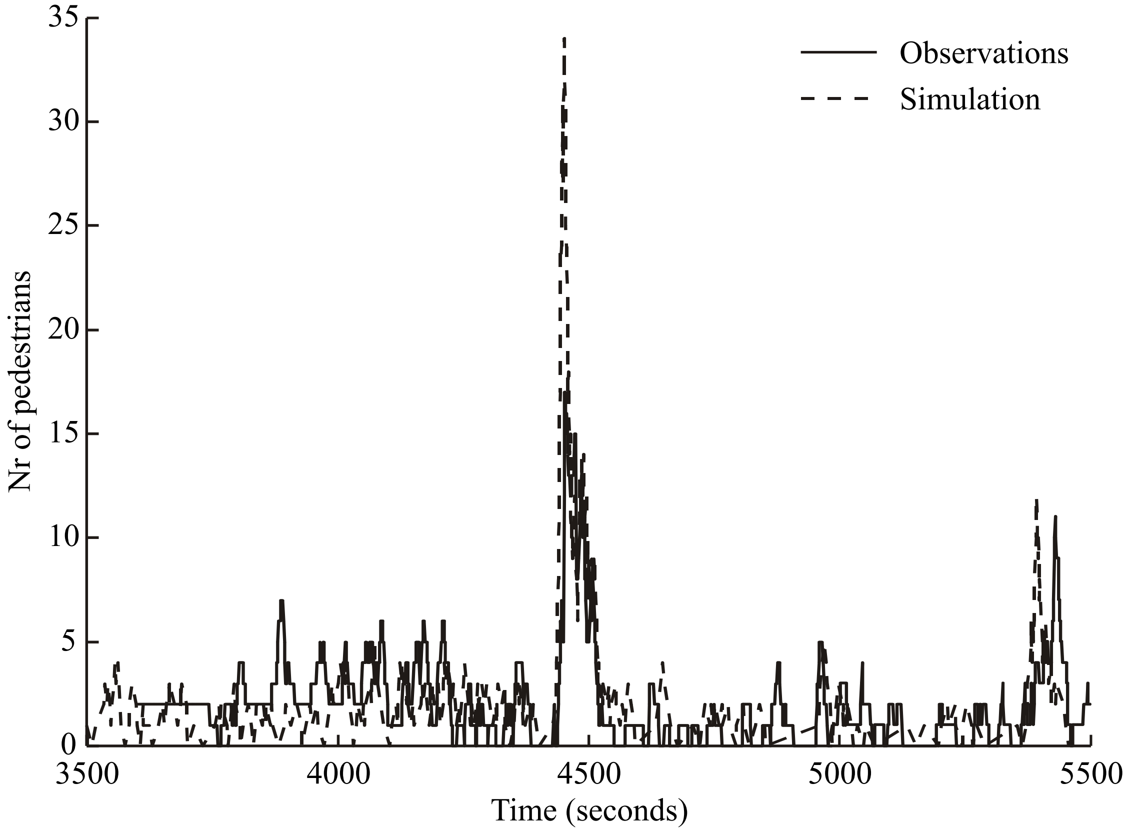


Figure 8.12: Number of pedestrians over time on the stairs

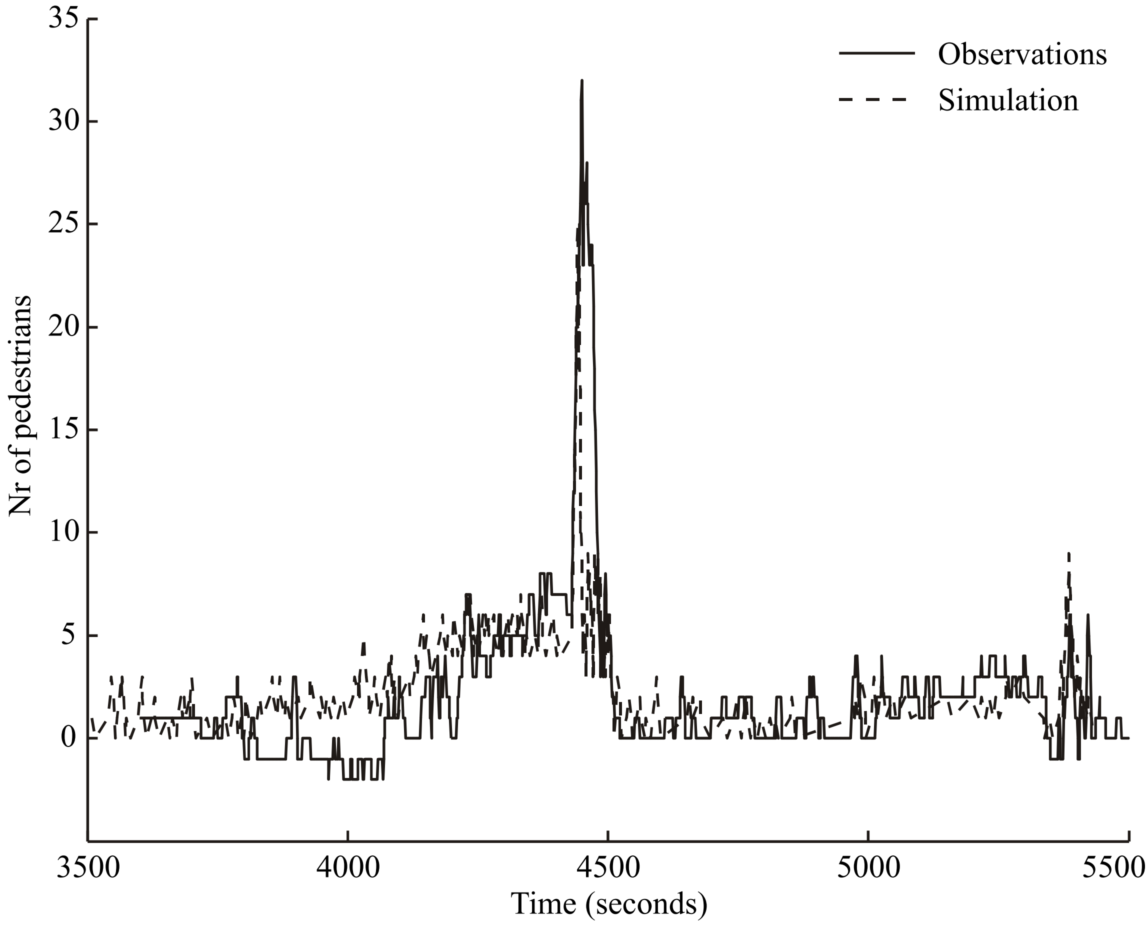


Figure 8.13: Number of pedestrians over time on the first ten metres of the platform

present on this part of the platform slowly increases over time, which is the case for both the observations and the simulation results. The density peaks occur at similar moments (contrary to the peaks on the stairs) and the height of these peaks are alike as well. Only the duration of the first peak is somewhat shorter in the simulation results than in the observations. Around t = 4000 s a slight deviation occurs between the observations and the simulation data due to an irregularity in the observational data (negative numbers of passengers are impossible, indicating that an observation error has taken place).

8.4 Summary and conclusions

This chapter has discussed part of the verification and validation of SimPed. For verification, a dedicated verification plan has been followed in which tests are described including the manually calculated results. The difference between the expected results and the predicted results for the first test in the verification plan was on all aspects lower than 1.6%. The difference is due to some random aspects of the simulation tool. The results of the remaining parts of the verification were as positive as the results of this very simple first test.

The validation of the simulation tool has taken place with respect to two aspects, namely *route choice* and predicted *traffic flow characteristics*. The route choice model has been validated by means of ‘expert opinions’, where it was checked whether the predicted routes are in line with the expectations of experts, which appeared to be the case. A satisfying comparison has also been made with a similar situation reported in literature. A comparison of the route choice model with observations appeared to be sufficient for the applications mentioned in chapters 1 and 2.

The part of the validation concerning the traffic flow characteristics, is performed by comparing simulation results with real-life observations collected in Delft Station, the Netherlands. These observations concerned boarding and alighting, walking times on the platform and on the stairs and finally data to construct cumulative curves. The performance indicators of the validation are walking speeds (on the stairs and on the platform, for both boarding and alighting passengers) and density over time and over space. The median speed of pedestrians walking on the stairs in downwards direction and walking speeds of alighting passengers on the platform are similar for the observations and the simulation results. The observed walking speed on the stairs in upwards direction is about 10% higher than predicted. This is remarkable, as studies in literature indicate lower speeds as well (see chapter 3). Also, a difference is found in the median speed of boarding passengers on the platform. The observations show that a correlation may be found between walking speed and the destination of the passenger on the platform, which is at the time of writing not included in the simulation tool. Both the walking speed in upwards direction on stairs in transfer station and a possible correlation between the walking speed and the destination location on the platform are subject for future research.

The second criterion variable of the validation is density. The graphs of density over time and space are roughly similar. Peaks due to the arrival of a train are clearly visible in both observations and simulation results. Between arriving trains, the passenger arrival process is random in both observations and predictions, which leads to small peaks with a similar pattern and height. At the moment of the arrival of a train, all boarding passengers are present on the platform and the distribution is similar for observations and simulation results. Twenty seconds after the arrival of a train the passenger flow in the simulation is somewhat faster than in the observations, but both indicate high densities on the platform near the stairs. Thus, the simulation results are very useful to give an aggregate analysis of the pedestrian flows on the platform, but detailed phenomena need further research.

These findings indicate that while some subjects are left for future research, simulation results appeared similar to expected results, expert opinions, and observations. We therefore argue that the simulation model may be applied. The following chapter describes some case studies of the application of the simulation tool in different application areas and conditions, which are also used as an extension of the verification and validation handled in this chapter.

Chapter 9

Case studies with SimPed

9.1 Introduction

This chapter will consider several case studies, the results of which are not only used to assess the design of a public transport facility, but also to show the applicability of the simulation tool for several types of facilities in different stages of the design process, to extend the validation given in chapter 8, and finally to gain insight into the processes modelled.

In each case study, several questions are answered. The assessment of the design of a facility is shown, consisting of a definition of the purpose of the facility and a specific formulation of the questions to be answered. The applicability of the simulation tool is expressed by an overview of information needed and the way this information is transformed into input data of the tool. Several types of graphs as results of analyses of output data are shown, on the basis of which conclusions are drawn on the assessment of the facility design. On top of this assessment, the simulation tool itself is assessed.

In order to extend the validation of chapter 8, simulation results are compared with expert opinions to gain insight into the correspondence of simulation results with reality. As the case studies discussed in this chapter are the first extensive simulation studies with the tool, recommendations are given for the handling of the tool, not only with respect to the various interfaces and the intuitive handling of the input application, but also for the way to handle the simulation tool, that is how to compose an input model with a sufficient level of detail to answer questions while at the same time reducing calculation times.

Section 9.2 discusses the selection of case studies described in this chapter and the set up of each of the case studies. Then, each of the case studies is reviewed (sections 9.3 to 9.6). The chapter ends with conclusions, not only on the assessments of the case studies, but also on the assessment of the simulation tool itself (section 9.7).

9.2 Selection and set up of case studies

The aim of the case studies included in this chapter is to show the applicability of the simulation tool, to check whether the tool works properly (part of the verification), to extend the validation by checking whether the simulation results are in line with expectations, and to learn more about the processes at hand. The simulation tool has been designed to provide support during the different stages of the design process. One of the case studies will therefore assess a design in the early planning stage, while another case study concerns the detailed design of a similar facility to compare the approaches used in both case studies. Another requirement concerning the application areas of the tool is the applicability for public transport facilities other than train stations. The third case study will therefore cover the design of the ferry terminals Vlissingen and Breskens. Finally, the tool may be applied for a theme investigation instead of a dedicated design for a specific location. In a theme investigation, the design is not the key element of a study but a process, for example the boarding and alighting process. The results of such a case study may be used to compose a design guideline concerning the considered process. We chose the theme 'investigation of the headway of trains on the open track in relation to the number of available dwelling tracks in the station' as a case study.

These considerations result in the following four case studies described below:

1. Rotterdam Central Station in the early planning stage.

2. Assessment of a detailed design of Rotterdam Central Station.

3. Ferry terminals Vlissingen and Breskens.

4. Theme investigation on the headway of trains on the open track in relation to the number of available dwelling tracks in the station.

Each case study has a similar set-up. First, the purpose of the transfer facility and the facility itself is described. Then, the relevant processes are described only roughly when a number of standard processes is modelled, but in more detail when the simulation handles new processes. Often, different scenarios are analysed, in which among other things origin-destination matrices and infrastructure configuration may differ. A single characteristic scenario is elaborated on and a description of the network model is provided, followed by the assessment criteria. Characteristic simulation results are given for one of the scenarios to assess the design. Finally, conclusions are drawn and an assessment is made for the case study itself, consisting of suggestions for improvements of the tool contents, the tool handling and opportunities for analysis.

9.3 Case study 1: Rotterdam Central Station in the early planning stage

9.3.1 Facility purpose

Rotterdam Central Station is the main public transport terminal in the southern part of the urban agglomeration of Western Holland. Its current condition is not flourishing, that is the pedestrian underpass under the train platforms is too narrow, the platforms themselves are draughty, the underground station is tight, the trams on the forecourt are poorly organised and the transfer is correspondingly inadequate (VHP & Holland Railconsult 1998). This leads to an insufficient level of passenger comfort and on a longer term to a stagnation in public transport use (VHP & Holland Railconsult 1998). For years, plans for improvement exist on aspects (such as underground, train and urban environment), but a comprehensive plan is lacking, based on which sound investments may take place.

Recently, the American bureau of architects Alsop & Störmer developed a master plan, in which the entire station area is involved as well as a part of the urban environment (Alsop 2000). This plan consists of a large underground concourse, continued from the underpass beneath the train tracks, in the direction of the inner city of Rotterdam. All pedestrians, including transferring passengers to the underground, the tram, both regional and local bus and pedestrians heading for the inner city use this concourse. Plans for an extended station have been integrated, as well as new locations for bus and tram stops and bicycle storage. A schematic overview of the infrastructure in the plan is shown in figure 9.1.

In this plan, the tram is located at the same level (-1) as the underground concourse, which is a very expensive element in the design. Therefore, a combination of public transport operators (consisting of the tram operator RET, the train operator NS Reizigers and the bus operator ConneXXion), which also have been involved in the planning process of the Masterplan Rotterdam Central, suggested four scenarios with alternative locations of bus and tram stops.

A separate study has been performed to evaluate the expected comfort of pedestrians in this concourse for the original design (reference) and these four scenarios. In this study, the scenarios are evaluated on three aspects, namely size and pattern of pedestrian flows between public transport modes and the inner city, walking distances, and pedestrian levels-of-service. This section only describes a few relevant aspects with respect to the assessment of these scenarios; for more details see Daamen (2001).

9.3.2 Overview of pedestrian flows

As a start, an overview is made of the expected pedestrian flows in the terminal, based on origin-destination estimates of passengers within the terminal for the year 2010, as

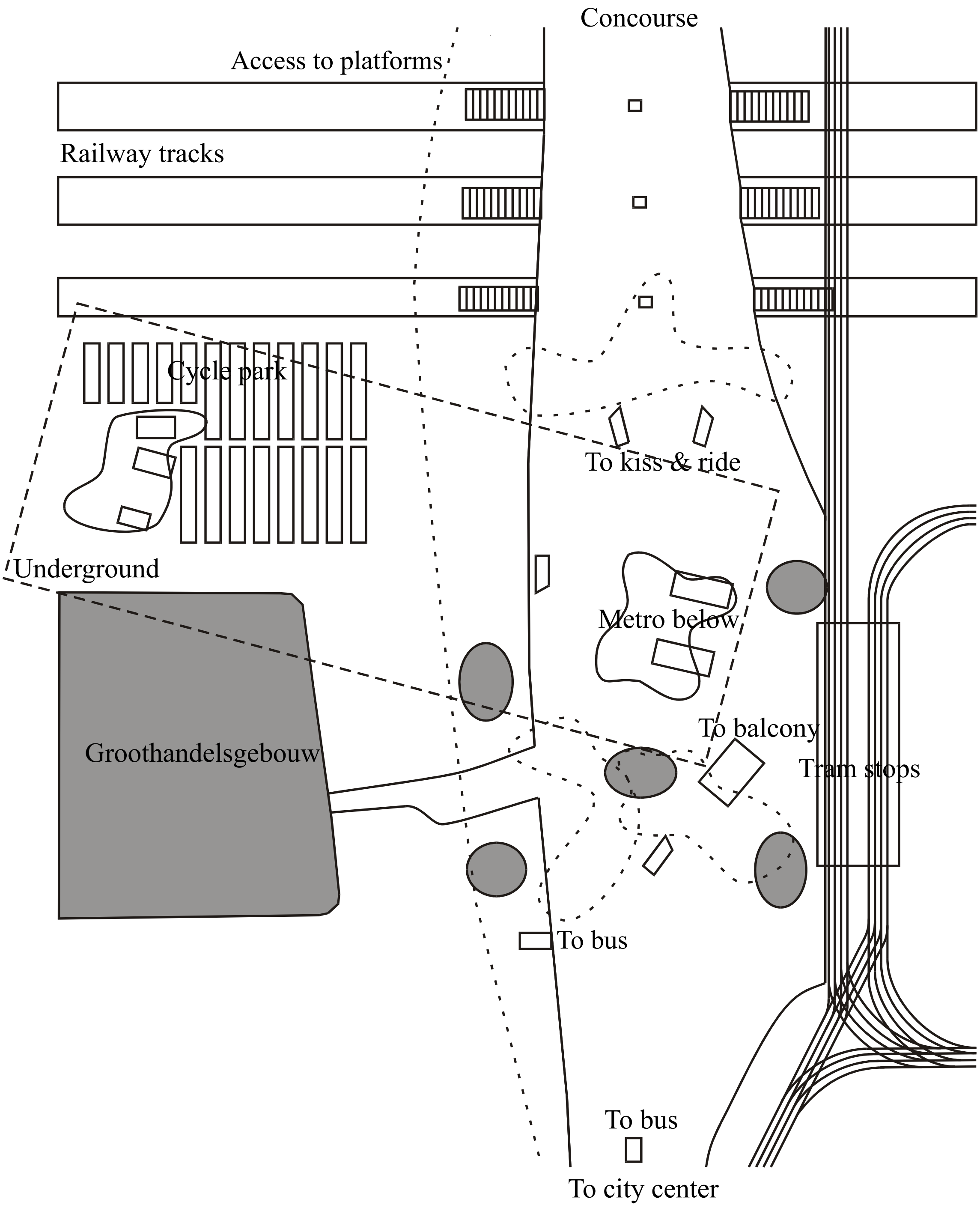


Figure 9.1: Overview of the new plan for Rotterdam Central Station

Table 9.1: Estimated numbers of passengers in the transfer node Rotterdam Central Station during afternoon peak hour in the year 2010

	City	Local bus	Regional bus	Tram	Underground	Train
Train	3675	100	100	2000	2025	1950
Underground	2550	525	200	3950	0	
Tram	2900	400	275	2275		
Regional bus	0	25	100			
Local bus	275	25				
City	0					

given in table 9.1 (VHP & Holland Railconsult 1998). This will give an indication of the bottlenecks to be expected.

Figure 9.2 depicts an overview of pedestrian flows for the reference scenario, in which arrows are drawn, where the width of the arrow indicates the relative size of the pedestrian flow. Origins and destinations are the centre points of each of the (public) transport modes and the inner city. The locations where broad arrows cross denote possible bottlenecks. The number of cross locations of the arrows, the number of passengers involved and the number of height differences are considered to give a first estimation of pedestrian comfort in each of the scenarios. For more details see Daamen (2001).

9.3.3 Walking distances

Another important criterion for pedestrian comfort is walking distance. Before the detailed design had been worked out, a plan with requirements had been formulated by the involved parties (VHP & Holland Railconsult 1999). One of these requirements concerned walking distance and described standards like ‘at least 50% of the passengers have a walking distance of less than 100 m‘. Table 9.2 shows this standard in detail.

Table 9.2: Adopted standards for walking distances in Rotterdam Central Station

Percentage passengers	Max. walking distance
$\geqq$ 50%	$\leqq$ 100 m
$\geqq$ 60%	$\leqq$ 150 m
$\geqq$ 70%	$\leqq$ 200 m
$\geqq$ 80%	$\leqq$ 250 m
100%	$\leqq$ 300 m

For all public transport modes, platforms are provided with specific lengths, depending on the vehicle lengths. Pedestrians will choose their waiting location freely, which has a direct relation with their walking time. For each origin-destination relation a minimum, an average, and a maximum walking distance are therefore specified.

In order to compare scenarios based on the standards of table 9.2, the number of pedestrians on a specific origin-destination relation having a specific walking distance is de-

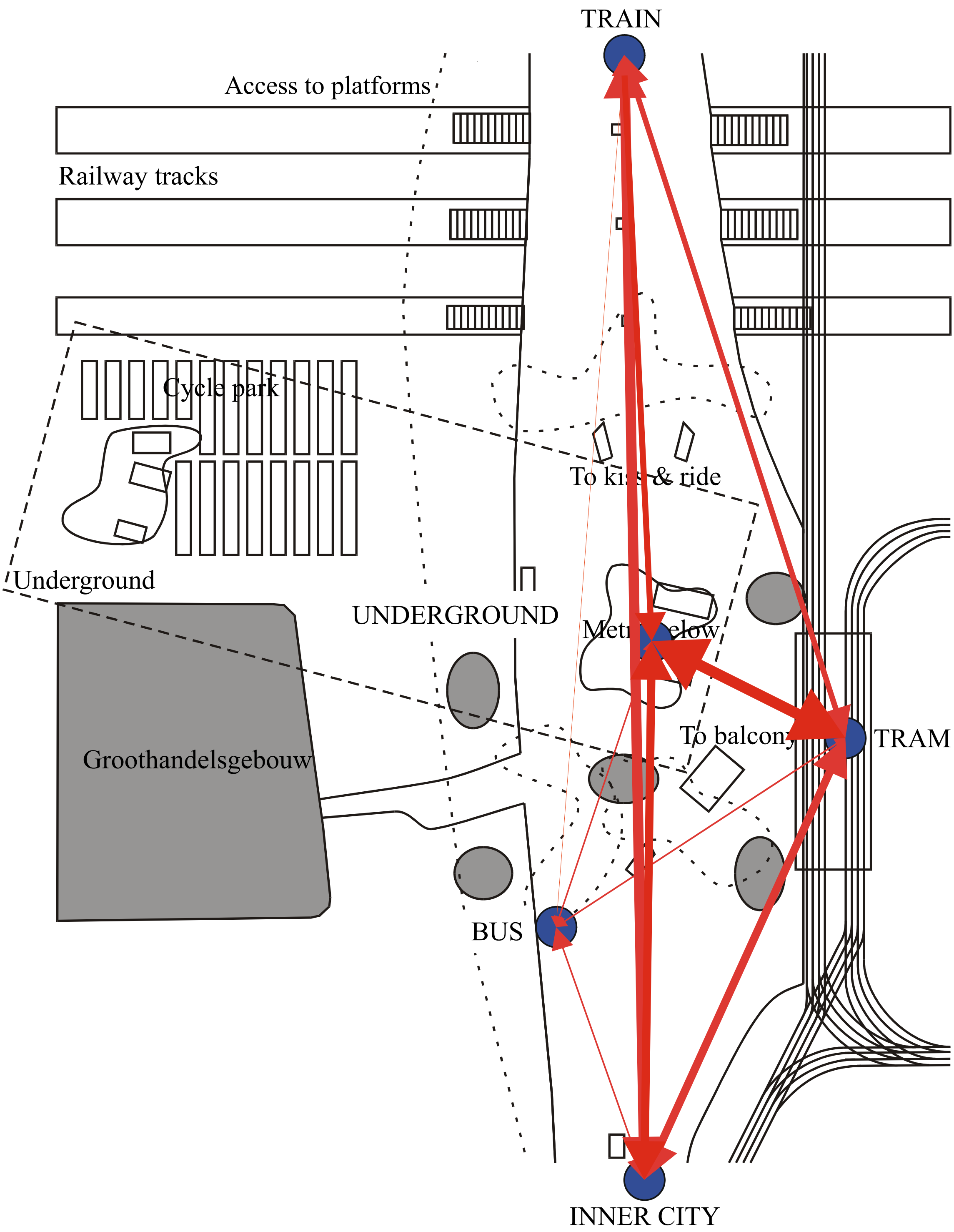


Figure 9.2: Pedestrian flows between different modes of transport estimated for the reference scenario (2010)

termined. A histogram is composed in which the percentages of pedestrians having a walking distance smaller than the indicated standard value is shown. For all scenarios compared to the standard see figure 9.3 .

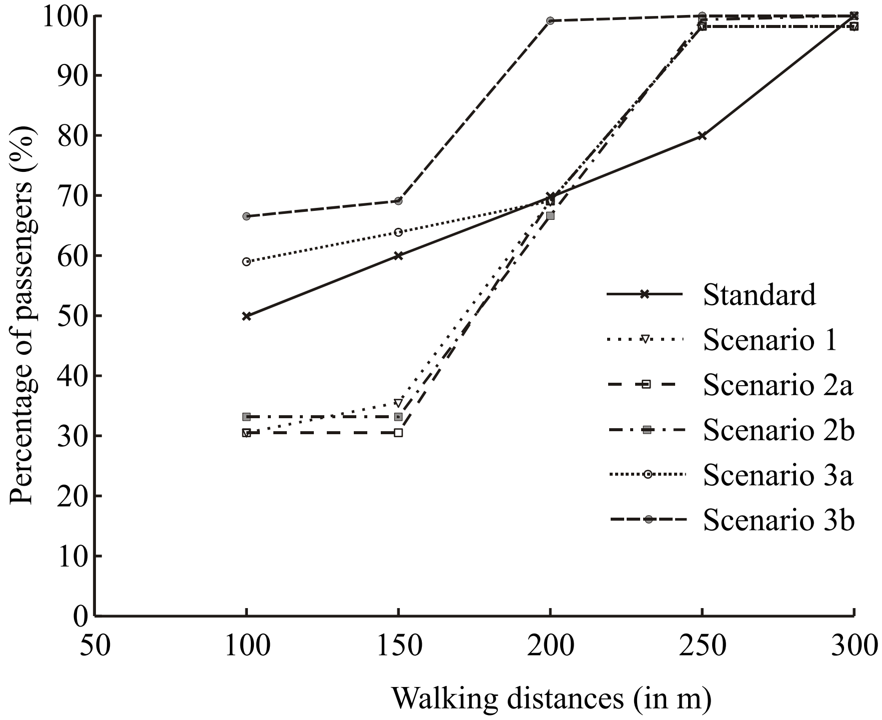


Figure 9.3: Walking distances of each scenario, compared to the standard

Figure 9.3 shows that scenario 3B is the only scenario meeting the standard for all distance classes and therefore scores even better than the original plan, scenario 1. When the passengers transferring within a public transport node are not taken into account, none of the scenarios meets the standards, but except for the lowest distance class, scenario 3B remains the best (Daamen 2001).

9.3.4 Pedestrian levels-of-service

Another aspect concerns pedestrian levels-of-service, which is a measure of pedestrian (walking) comfort in relation to the available free space (expressed in number of pedestrians per square metre). Fruin (1971*a*) discusses six levels-of-service, which are adopted in our study.

To determine the level-of-service, different transport modes have been 'represented' as entrance and exit points (sources and sinks). As the public transport vehicles arrive and depart with a high frequency, the influences of a timetable are neglected and pedestrians are generated uniformly over time. The concourse is a large pedestrian area, where the entrances to company buildings form major obstacles (non-walking areas). The stairs and escalators are included in the simulation model, but the model does not take the boarding and alighting process into account. This means that pedestrians reach their destination as soon as they arrive on the platform. The pedestrian flows are described by the origin-destination matrix in table 9.1.

For all parts of the infrastructure the percentage of time that this part of the infrastructure has a specific level-of-service is calculated. Figure 9.4 shows the levels-of-service for the disturbed parts of the infrastructure in the reference scenario. Level-of-service A indicates a low density and correspondingly a high level of comfort, whereas level F is the worst comfort level in which heavy congestion occurs. Depending on the purpose of the facility and the requirements of the facility manager a certain minimum level-of-service is required. Often, level C is taken as this minimum implying that all parts of the infrastructure having a worse level-of-service, especially when this lasts during a longer period of time, need to be redesigned.

As could be expected, figure 9.4 shows that low levels-of-service occur at parts of the infrastructure bridging heights, such as stairs and escalators. Especially the escalators to and from the underground platforms are overloaded more than half the time, due to the fact that the largest pedestrian flows are expected to and from the underground platforms. As the level and the location of the underground station is fixed, the only solution to solve these bottlenecks is to add stairs and escalators. The location and the number of required risers is not part of this research, but optimisations in a design may always be evaluated by using the simulation tool.

9.3.5 Conclusions

The performed study gives answers to the question of the involved public transport operators whether the design satisfies comfort needs of passengers.

Three aspects of pedestrian comfort have been considered, namely the spatial distribution of pedestrians over the facility and the corresponding sizes of these pedestrian flows, pedestrian walking distances relative to predefined standards, and finally an overview of levels-of-service, generated by the simulation tool.

The study has also been used to increase insight into the relation between pedestrian level-of-service and the desire to minimise walking distance. A generally applicable dilemma in optimising pedestrian comfort appears to be that when pedestrian flows are separated to a large extent, the number of crossing flows decreases (leading to a higher level-of-service), but consequently public transport modes are more dispersed over the area, leading to increased walking distances. In the assessment of a design these two aspects (level-of-service and walking distance) need to be weighed and priorities or minimum standards need to be met. Output of the simulation tool may help in the assessment and evaluation process, but does not produce the ‘best’ design.

As this was one of the first complete studies in which SimPed was used, a number of recommendations resulted with respect to the contents of the tool, the knowledge of modelled processes, and the tool handling, which could already be handled during the study.

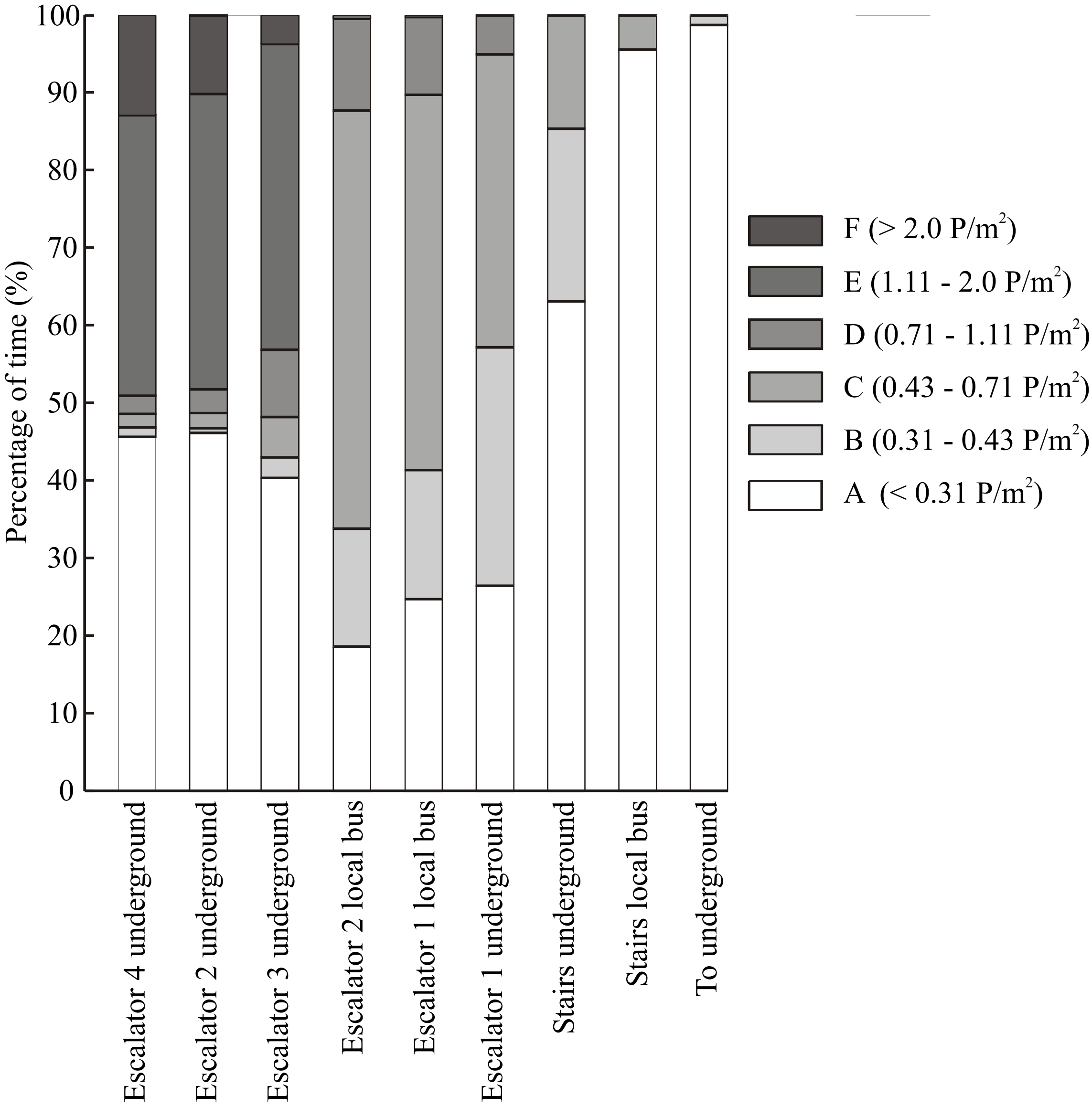


Figure 9.4: Percentage of time that a specific part of the infrastructure has a specific level-of-service for the pedestrians (reference scenario)

The results of the simulation part of the study added value to the analytical results and did not lead to discussions on the validity of the results.

9.4 Case study 2: Assessment of the detailed design of Rotterdam Central Station

9.4.1 Facility purpose and scenarios analysed

The facility under consideration is again Rotterdam Central Station and its surrounding area. The original design has already been discussed in the previous section (see figure 9.1). Since the Masterplan for Rotterdam Central Station appeared to be too expensive, a so-called *Optimised Masterplan* was designed. Again, a simulation study has been performed to evaluate pedestrian flows in different design scenarios. However, the level of detail in this study is much higher. The scenarios considered are:

- Masterplan 2010 with activities. Activities are performed by passengers in order to create passengers strolling around and conflicting passenger flows as they behave in reality. An origin-destination matrix predicts expected passenger flows in the year 2010.
- Optimised Masterplan 2010 with activities. The configuration of the infrastructure is based on a more compact (less expensive) adaptation of the original Masterplan design.
- Optimised Masterplan 2010 without activities. This model shows the functioning of the transfer station without disturbing commercial activities, where passengers walk directly from their origin towards their destination. The influence of commercial facilities on pedestrian comfort is made visible.
- Optimised Masterplan 2010 with activities and an extra series of stairs. As the first results showed problems with the number of stairs and escalators between the train platforms and the concourse, this scenario includes extra stairs to each of the train platforms located in the middle of the concourse.
- Optimised Masterplan 2025 with activities. Based on the mentioned configuration of the Optimised Masterplan, the origin-destination matrix for the year 2025 has been applied. This way, the robustness of the design and its future perspective is assessed.

Although the study contained results of all scenarios (Daamen 2002*a*), this section is restricted to the Optimised Masterplan with activities and time horizon 2010. The infrastructure configuration consists of five levels, namely underground level, concourse level, ground level, train platform level and balcony. The concourse level is the essential part of the design on which most pedestrian flows will occur.

9.4.2 Facility description

Modelling assumptions

Since the concourse is the essential part of the design, it is modelled in detail, whereas the remaining infrastructure is modelled on a more aggregate level in terms of spatial division of the infrastructure elements.

In order to judge pedestrian comfort, the levels-of-service as defined by Fruin (1971*b*) have been adapted. An extra level-of-service A1 has been introduced to find the areas where no or hardly any passengers appear. At these locations personal security might become an issue and as the area is not used for walking, the efficiency of the design might be increased by changing the function of this area, for example into commercial facilities. Also, level-of-service C has been split into two, as one of the requirements (brought up by the station manager) was a limit of acceptable pedestrian comfort of at least $1.9\,\mathrm{m}^2/\mathrm{P}$. In the simulation, the shown density is not averaged over a specific time period, but represents the density at each moment during the simulation. The requirement implied that a density higher than $1.9\,\mathrm{m}^2/\mathrm{P}$ does not occur at any moment of the simulation. However, this appeared to be a very strict requirement, which was not met by any of the scenarios.

Parameters

This section describes input parameters of the model with respect to passenger types and activities. The following types of pedestrians are distinguished:

- Normal pedestrians, which are pedestrians not having a specific origin or destination.
- Train passengers, having a platform as destination. Some of these passengers will need to acquire a ticket to travel by train.
- High speed line passengers. High speed line passengers travel by low frequency high speed transport vehicles. Some of them use the high speed line waiting accommodation.
- Concourse pedestrians using the concourse below the train platforms not having the train platforms as destination. These passengers pass commercial facilities and may perform an impulsive purchase.

Table 9.3 shows the probability that a specific type of passenger will perform a given type of activity.

Table 9.4 shows for each activity the parameters describing the normal distribution for the service times as well as the number of servers; a combination of these parameters defines the capacity of a service.

Table 9.3: Overview of activity types performed by pedestrians

Service type	Normal	Train pass	HSL pass	Concourse
Commerce (planned)	15%	15%	-	15%
Commerce (impulsive)	-	10%	-	10%
Ticket acquisition	-	10%	-	-
HSL-accommodation	-	-	30%	-
Toilets and lockers	1%	1%	1%	1%
Information signs	-	30%	30%	-

Table 9.4: Characteristics of service types

Service type	Service time (in s)		Nr of servers
	μ	σ	
Commerce (planned)	150	60	60
Commerce (impulsive)	10	15	4
Ticket sale	20	10	4
HSL-accommodation	420	60	200
Toilets and lockers	150	60	8
Information signs	150	60	40

For the sake of accuracy, shortest routes have been determined each 30 seconds. However, the Optimised Masterplan 2010 also has been simulated with only a single shortest route calculation for the whole simulation. Pedestrians with similar origin-destination pairs will in this latter case choose similar paths during the total simulation, independent of the occurring densities. This way, those parts of the infrastructure most favourable for pedestrians are determined and extra attention may be paid during the design to optimise the width and walking conditions of this infrastructure.

9.4.3 Simulation results

Although simulation results have been produced for each of the scenarios, this section only includes the results of the Optimised Masterplan, where for each relevant aspect only a single graph is shown. For more information see Daamen (2002*a*). Figure 9.5 shows a screen shot from the animation of the concourse level in the Optimised Masterplan. This animation is used for verification of the infrastructure input model and modelled pedestrian flows through the facility. Also, it gives a first impression of the bottlenecks with respect to the total infrastructure configuration and it may be used as a starting point for discussions between designers and assessors. Screen shots of this animation form a background on which discussions with designers and decision makers may be entered among other things on the processes taking place. A more detailed overview of levels-of-service per part of the infrastructure is shown in figure 9.7. Again, these levels-of-service occur instantaneously and have not been aggregated over a time interval.

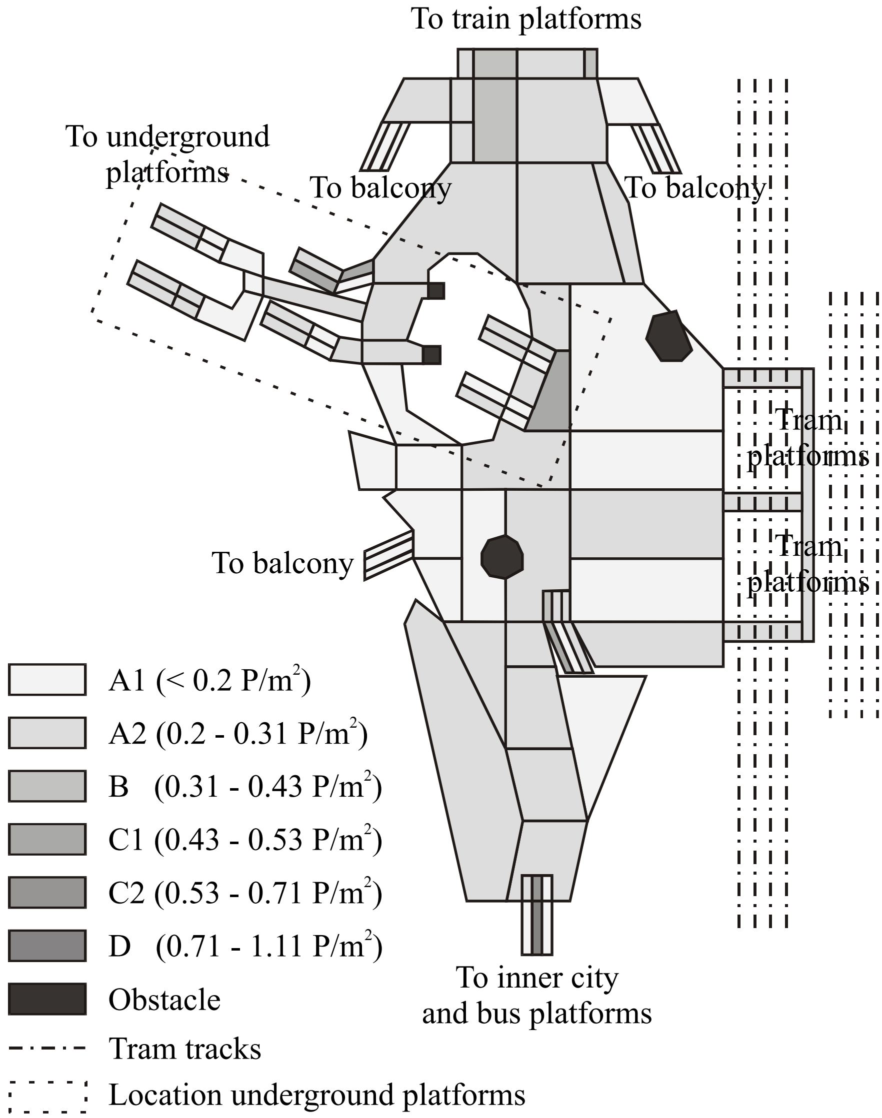


Figure 9.5: Overview of animation indicating the spatial distribution of pedestrian levels-of-service on the concourse level after a quarter of a peak hour

Figure 9.6 shows the results of a shortest path assignment. All pedestrians walking between the same origin and destination are assigned the same, shortest, route in time, with route times calculated in free flow conditions. No updates take place during this simulation run, thus the routes are only calculated at the beginning of the simulation. In each distinguished part of the infrastructure the number of passing pedestrians is counted. Figure 9.6 is used to determine the infrastructure parts with a high congestion probability (the more passing pedestrians and the smaller the area the higher the congestion probability). This infrastructure is crucial in the network function of pedestrian infrastructure and therefore has to remain free for walking purposes and need some overcapacity to accommodate pedestrian flows during emergencies. The figure also shows the parts of the infrastructure that may be used as alternative routes, but will be avoided in normal, quiet conditions (for example the stairs and escalators to the balcony at the top-right side of the concourse and the bottom entrance to the tram platforms).

Figure 9.7 gives an overview of the levels-of-service on the worst functioning parts of the infrastructure. Each bar indicates the percentage of time that a specific part of the infrastructure exhibits a specific level-of-service. The worst functioning elements appear to be part of the platform leading to tracks three and four as well as the stairs and escalators leading to this platform (see figure 9.8 in which the element numbers are indicated as a legend). Platform 3 and 4 are the platforms where the international high speed trains dwell, having a high number of boarding and alighting passengers. High frequent fast national trains to Amsterdam, using the same tracks as the high speed trains, will also dwell alongside these platforms. In principle, all elements incurring level-of-service C2 or worse do not meet requirements concerning pedestrian comfort. The infrastructure configuration or processes influencing the origin-destination matrix therefore need to be revised.

While figure 9.7 shows the time duration each level-of-service occurs on a part of the infrastructure, figure 9.9 shows the percentage of pedestrians experiencing the distinct levels-of-service on each distinct part of the infrastructure. This figure results in a far worse and sometimes even unacceptable level of comfort than when related to the time. The reason for this is that at low levels-of-service, densities are high, indicating that many pedestrians are present. All these pedestrians experience this low level-of-service, whereas high levels-of-service are only experienced by few pedestrians. However, it is a better indication of pedestrian comfort, as these are the levels-of-service pedestrians really experience.

Figure 9.10 shows the distribution of walking times for seven origin-destination relations. Representative relations have been chosen between different modes of transport. For the train, the relations have been selected with platform 11/12, along which high speed trains and long distance shuttles stop. This platform is one of the two most heavily used train platforms of Rotterdam Central Station. The smallest walking times are related to pedestrians walking directly from their origin to their destination. These direct walking times have only a small variance (except for the relation train-bus). The reason for this is that bottlenecks have to be passed by all pedestrians, incurring similar delays, whereas at

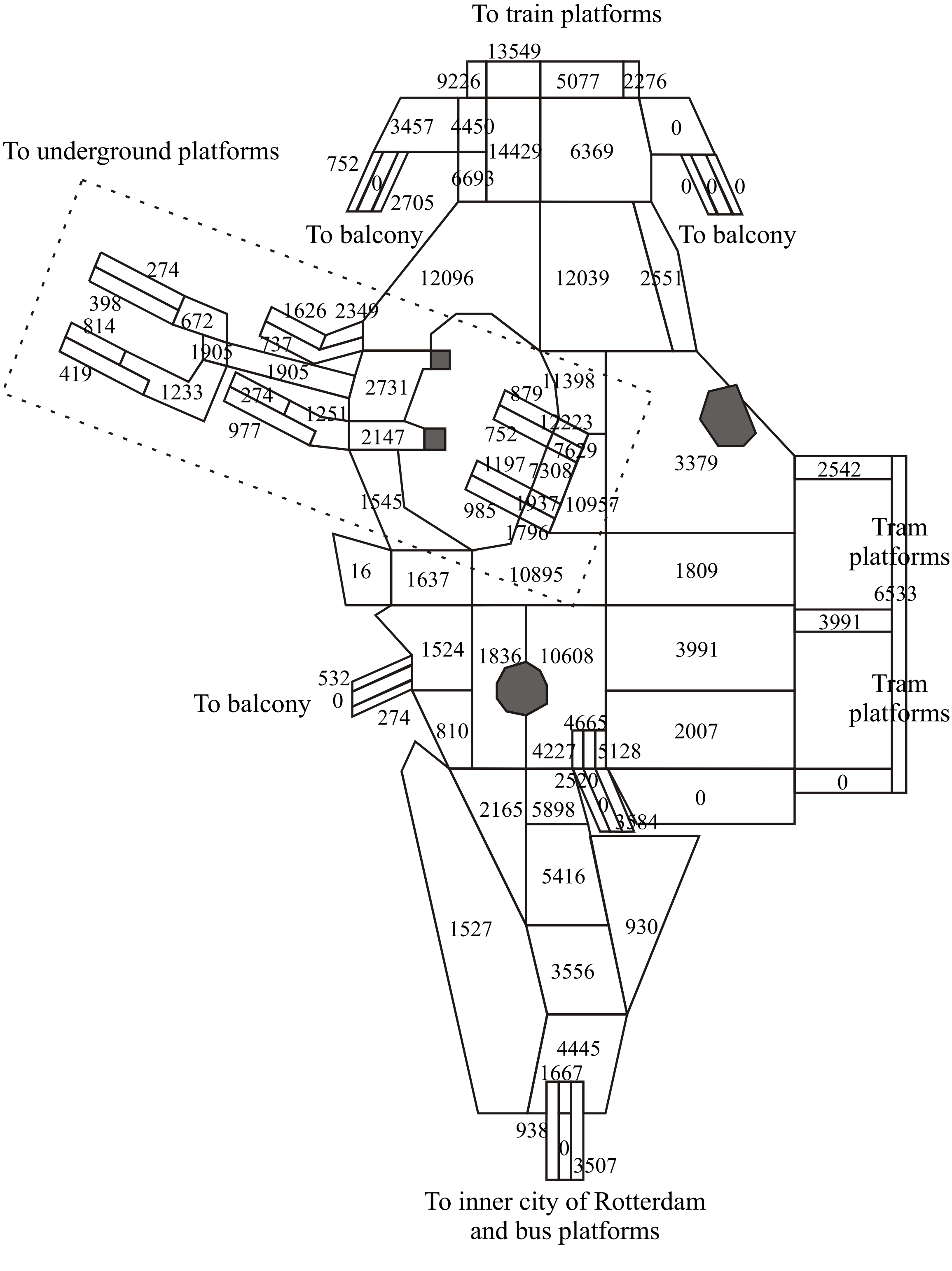


Figure 9.6: Summed space occupation (numbers of pedestrians passing a walkway) of flows in a shortest path assignment without route updates

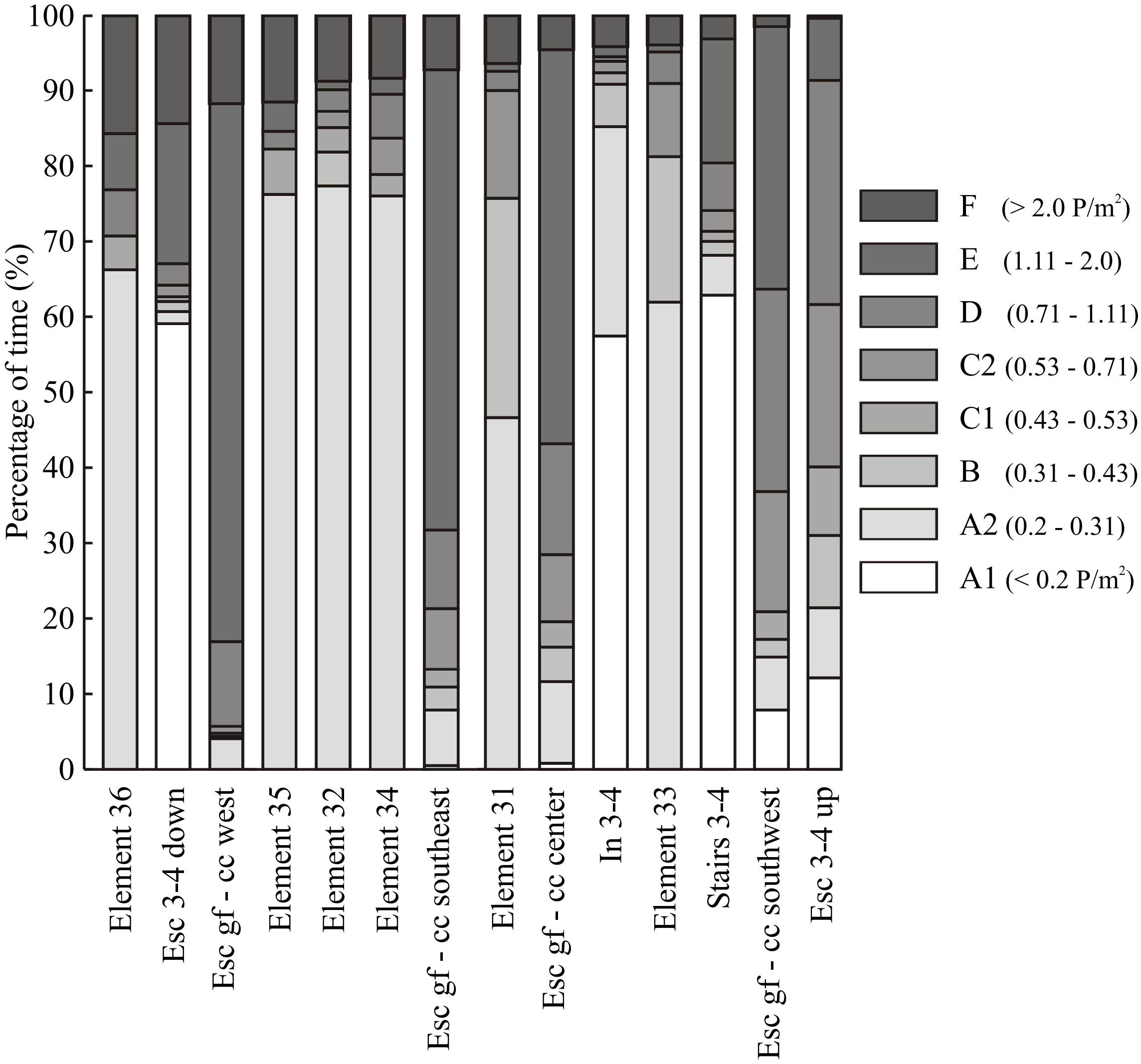


Figure 9.7: Levels-of-service summed over time for the worst functioning parts of the infrastructure of the Optimised Masterplan 2010 (locations of infrastructure shown in figure 9.8)

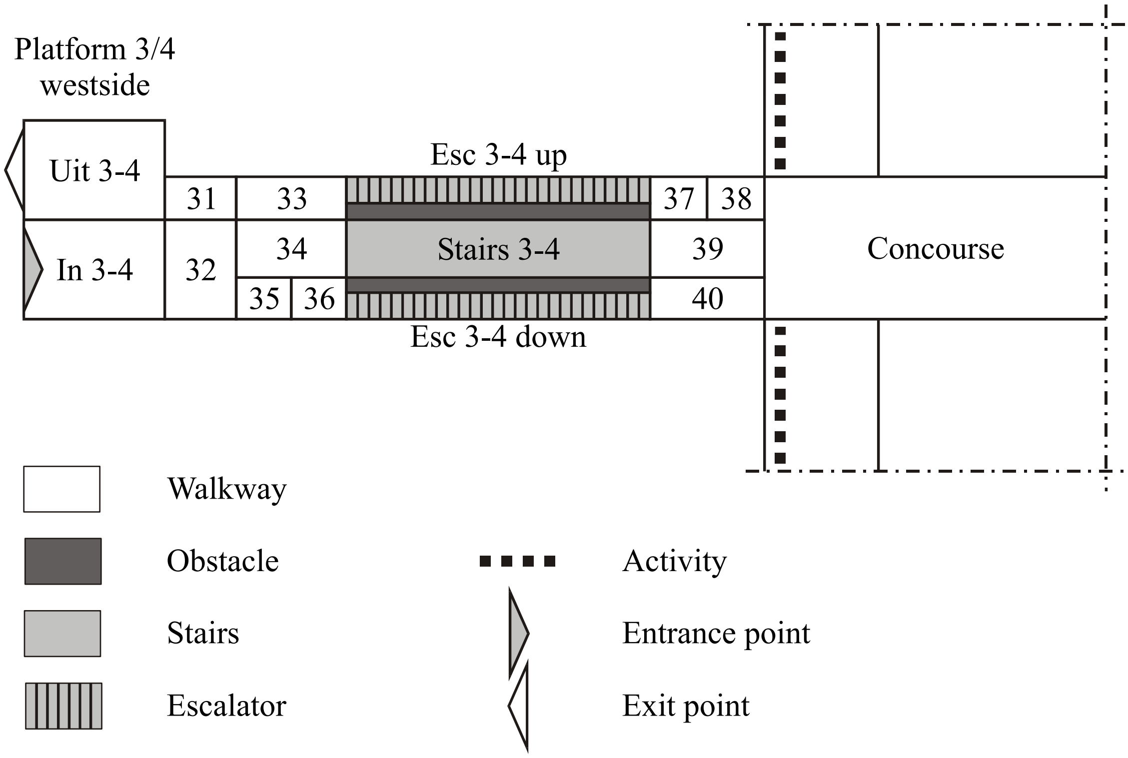


Figure 9.8: Legend of the infrastructure mentioned in figure 9.7

higher densities in the concourse a number of alternative routes are available, not being significantly different in distance and other characteristics. The remaining variances are due to the performance of one or more activities during a trip.

Figure 9.11 shows the predicted routes for pedestrians with the left part of platform 11/12 as origin and the tram platforms as destination. The most frequently used route is indicated by a continuous line, whereas the dotted lines indicate alternative routes and routes used by pedestrians performing an activity (such as going to the shop in the upper part of the infrastructure model). As expected, the most frequently used route is similar to the shortest route in distance.

9.4.4 Assessment of the case study

A simulation study has been performed to assess new designs of Rotterdam Central Station, the so-called Masterplan as well as an Optimised Masterplan, in which the infrastructure has been reduced to decrease the costs. Seven scenarios have been investigated (with different time horizons and with and without performance of commercial activities). These designs have been assessed on the aspects pedestrian level-of-service, walking time, and use of routes.

This Rotterdam Central Station study has been the first study where the considered study area is large. It showed the necessity of tuning the infrastructure model to the information

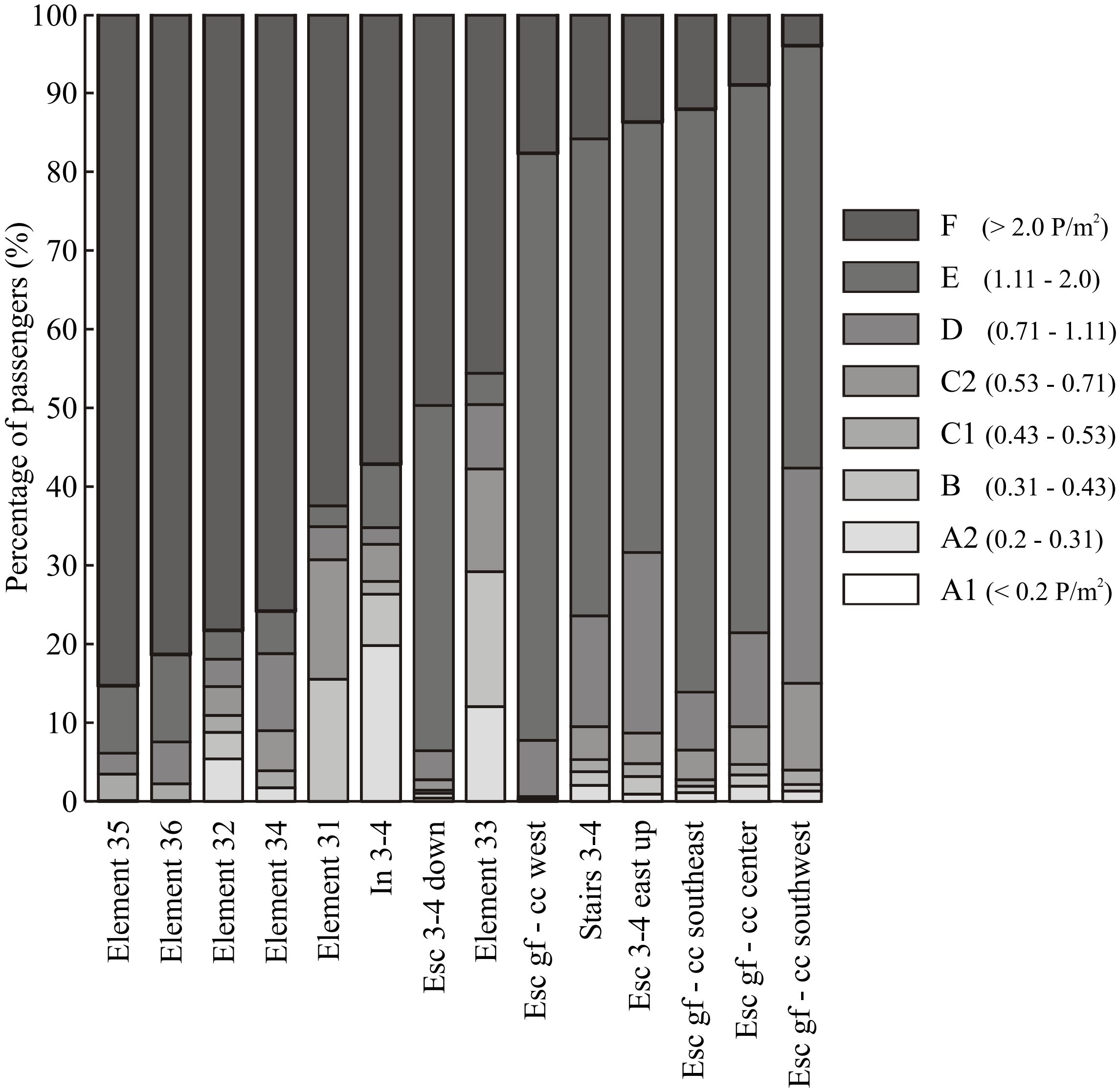


Figure 9.9: Levels-of-service experienced by passengers on the least comfortable parts of the infrastructure in the Optimised Masterplan 2010

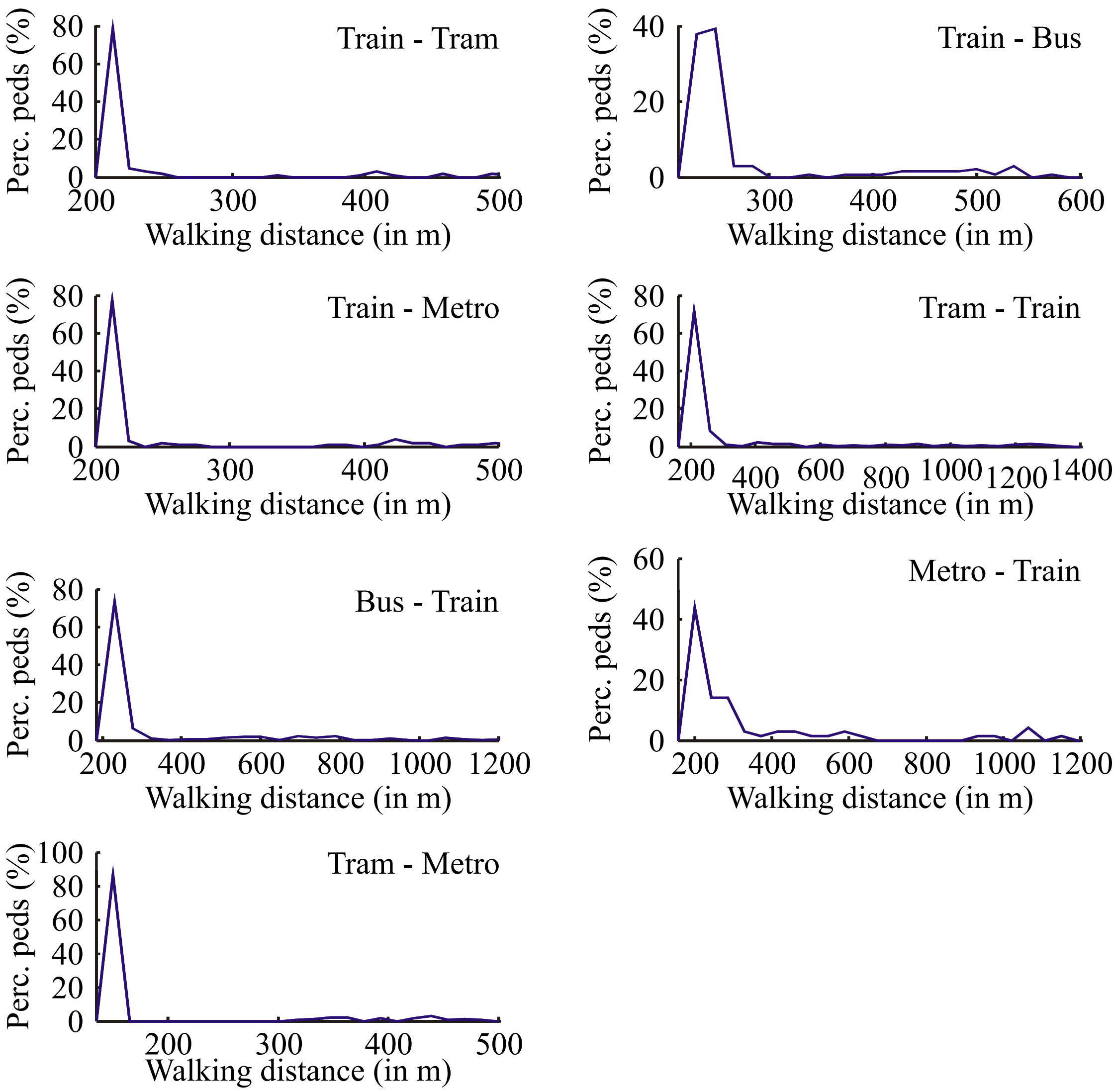


Figure 9.10: Walking distance distributions for seven origin-destination relations

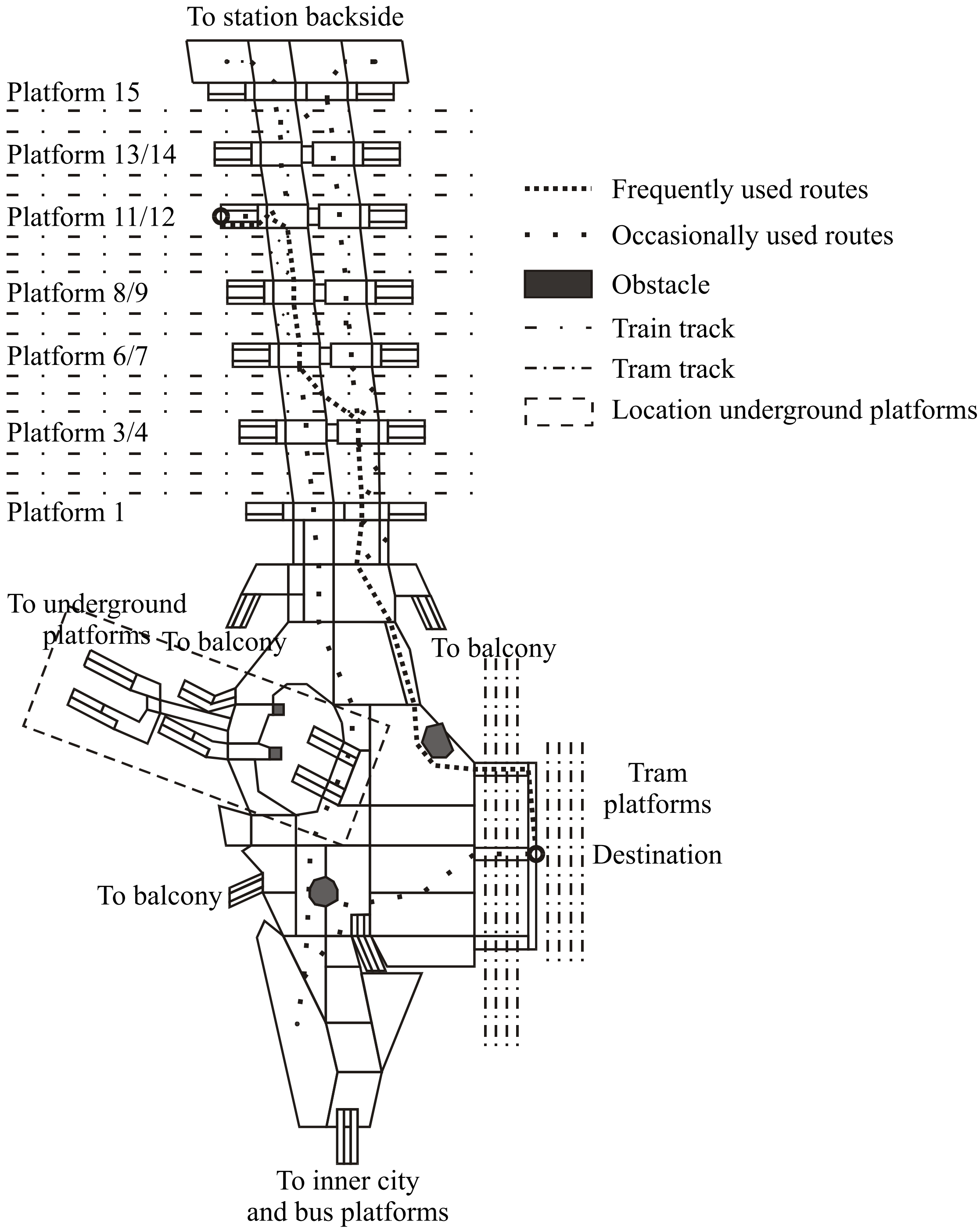


Figure 9.11: Alternative routes predicted for passengers between the train platform 11/12 and the tram stop

needed and the congestion probability. Regions for which detailed information is needed or having a high congestion probability are modelled with many spatial details. The remaining parts have less spatial detail, since this would only increase calculation time.

A second lesson of this study is that exogenous input information needs to be thoroughly checked in order to prevent unjustly attributing mistakes to the functioning of the simulation tool instead of the use of incorrect input data. In this study heavy congestion and thus unacceptably long waiting times were due to an excessive number of pedestrians doing some impulsive shopping.

In most studies, the level-of-service of the infrastructure is used to indicate pedestrian comfort. However, in congestion (low levels-of-service) many pedestrians are involved, indicating that a higher percentage of pedestrians experience a lower level-of-service. When the level-of-service of a part of the infrastructure over time seems to be appropriate, the levels-of-service incurred by pedestrians may become unacceptable (compare figures 9.7 and 9.9).

A shortest path assignment of pedestrians to the infrastructure network appears very well suited to detect crowded areas. Infrastructure parts used by many pedestrians are potential bottlenecks in the network, which have to be kept unrestricted to fulfil the pedestrian's desire of short routes in distance.

9.5 Case study 3: Design of the ferry-terminals in Vlissingen and Breskens

9.5.1 Purpose of the ferry terminal

Vlissingen and Breskens are two cities in the province of Zeeland in the southwest of the Netherlands, which were until 2003 connected through a ferry link, transporting cars, bicycles and pedestrians. On 14 March 2003, the new Westerscheldetunnel has been opened for car traffic between Zuid-Beveland and Zeeuws-Vlaanderen, offering a new, fixed connection (see figure 9.12).

Due to this new tunnel, the existing ferry service will be restricted to bicycles and pedestrians only. The current ferry boats are therefore replaced by new ones, which are faster and only suited for bicycles and pedestrians. The new ferry boats will also moor on another place of the quay, requiring new terminals at both ends with a new type of mooring facility with a pontoon. Figure 9.13 shows the current terminal in Breskens.

To determine whether the design of both the terminal infrastructure and the ferry timetable do not cause any problems, a pedestrian flow study has been performed. Two infrastructure models have been set up, for Vlissingen terminal and a model for Breskens terminal respectively, given the different terminal layouts in both situations.

The question to be answered is whether the total process of embarking and disembarking can take place within ten minutes after the arrival of the ferry.

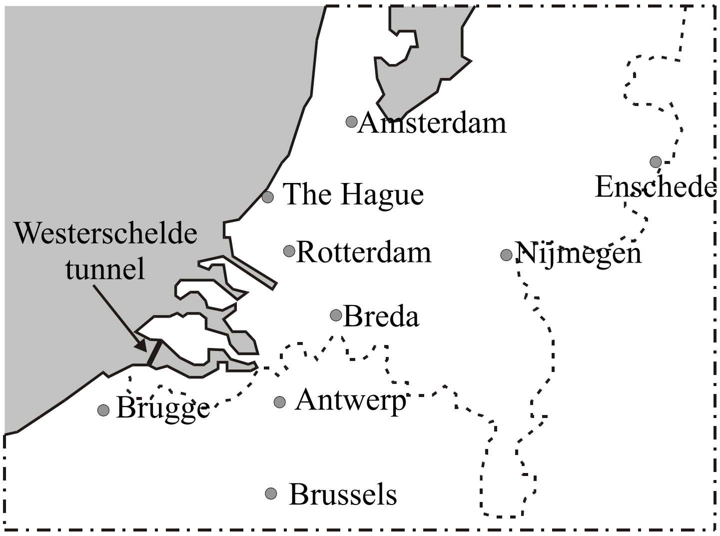


Figure 9.12: Location of the Westerscheldetunnel in the Netherlands

Figure 9.13: Current terminal building of Breskens

9.5.2 Description of the ferry terminals

The new ferry service will sail each half hour with two vessels, one in each direction. Because of a crossing time of twenty minutes, the embarking and disembarking has to take place within ten minutes. Taking into account difficult sailing conditions causing a longer crossing time and thus a shorter period for embarking and disembarking, the terminal design contains space for bi-directional (pedestrian) traffic in the terminal.

The terminal consists of a terminal building used for ticket sale and waiting, the walking infrastructure towards the bridge, connecting the shore with the pontoon where the ferry boat moors. An overview of this infrastructure is given in figure 9.14.

The ferry is also accessible for bicycles, mopeds and scooters. It is prohibited to use these vehicles on the walking infrastructure on shore. Pedestrians and passengers with vehicles are strictly separated on the ferry, but the walking infrastructure is used by both groups. The capacity of the ferry boat is 75 bicycle places and 100 pedestrians.

9.5.3 Process description

All processes between the moored ferry boat and the terminal building are modelled. In the terminal building, tickets for the ferry service are sold and a waiting area is available. Passengers are not allowed to leave the transfer building in the direction of the ferry boat until a signal is given. When the ferry boat arrives and has moored, the passengers disembark and walk towards the exit of the terminal. When all passengers have left the ferry terrain, the boarding passengers are allowed to leave the waiting area, walk to the ferry and board. The time for the total process of embarking and disembarking (with a maximum of ten minutes) is measured from the moment the ferry boat is mooring until the moment the last passenger embarks the ferry.

The pontoon floats and the height difference between the ferry boat and the pontoon is constant in order to facilitate boarding and alighting. The Westerschelde is open water so that the mooring process is significantly influenced by the tides. The walking infrastructure on shore is fixed, thus the bridge is needed to cover the height difference between the shore and the pontoon.

The area between the turnstiles and the ferry is only accessible for ferry passengers in order to control the process.

9.5.4 Scenarios analysed

Pedestrians experience the least hindrance when embarking and disembarking pedestrians are strictly separated between the terminal and the ferry. This leads to one-directional flows, in which the embarking and disembarking processes do not interfere. This is a worst case scenario with maximum comfort for the pedestrians.

Also for the number of embarking and disembarking pedestrians a worst case scenario is taken (100 pedestrians, 70 pedestrians with bicycles and 5 pedestrians with scooters) both for embarking and disembarking. Since the total process of embarking and disembarking in this worst case scenario appears to last less than the required 10 minutes, no further scenarios have been analysed.

9.5.5 Model description

Adopted model

As can be deduced from the process description, the entire infrastructure between the ferry boat and the terminal building needs to be modelled. This includes a part of the ferry, the pontoon, the bridge and the infrastructure on shore as far as the waiting area in the transfer building. The waiting area is separated from the walking infrastructure by four turnstiles. These turnstiles are also used to count the number of pedestrians and vehicles to assure that the capacity of the ferry is not exceeded.

An overview of the modelled infrastructure in Breskens in shown in figure 9.14.

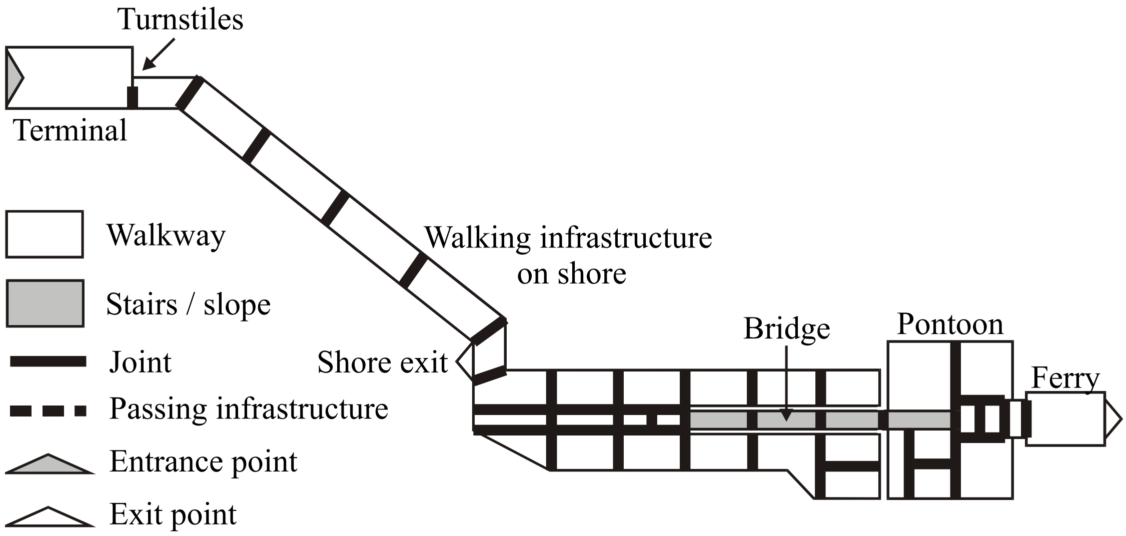


Figure 9.14: Infrastructure of Breskens: the terminal, the infrastructure on shore, the bridge, the pontoon, and the ferry

80% of the embarking pedestrians is assumed already present in the waiting area when the embarking process starts, while 20% arrives during the boarding process. No more pedestrians are allowed to embark later than one minute before departure of the ferry.

Modelling assumptions

The maximum slope of the bridge is 1:11, which usually occurs about four times a year during spring tide (which is not necessarily during service time) and is thus the most critical situation.

Parameters

Pedestrians with bicycles occupy a larger surface (1.0 m^2 instead of the default 0.4 m^2) and have a lower free speed (0.94 m/ s instead of 1.34 m/ s). These parameters are derived from video images from the ferry boats in Amsterdam, where also mixed traffic occurs (pedestrians with and without bicycles).

Each of the turnstiles in the terminal building leading towards the walking infrastructure has a delay of 0.7 s, where no distinction has been made between turnstiles only for pedestrians and turnstiles for passengers with bicycles.

9.5.6 Model results

First, an overview is made of the number of pedestrians in the terminal over time based on the simulation results (see figure 9.15). In this figure, the processes taking place are indicated, such as disembarking, leaving the terminal, and embarking.

This overview has been used to verify the input of the simulation model, for it indicates the modelled processes. The characteristic times derived from figure 9.15 and the simulation results are shown in table 9.5.

Table 9.5: Overview of process times for Vlissingen and Breskens (in min:sec)

Moment of	Phase figure 9.15	Vlissingen	Breskens
Last disembarker out of ferry boat	B	0:54	0:55
First disembarker out of terminal	C	1:10	1:20
First embarker leaving waiting area	D	2:40	2:55
All disembarkers out of terminal	E	3:25	3:40
First embarker in ferry boat	F	4:00	4:48
Last embarker in ferry boat	G	4:42	5:31
First cyclist embarks ferry boat	G	4:51	5:48
Last cyclist embarks ferry boat	H	5:40	7:20

After the embarkation of the last cyclist, latecomers still arrive at the terminal building and embark later, until 3.5 minutes before the scheduled departure moment of the ferry boat, which is similar to the average walking time between the terminal building and the ferry boat. Thus, even in a worst case situation the required boarding and alighting time is met.

The next step was to look into more detail to the walking characteristics of different types of pedestrians (embarkation and disembarkation, with and without bicycles) and check whether the given characteristics can be found in the results (part of the validation of the

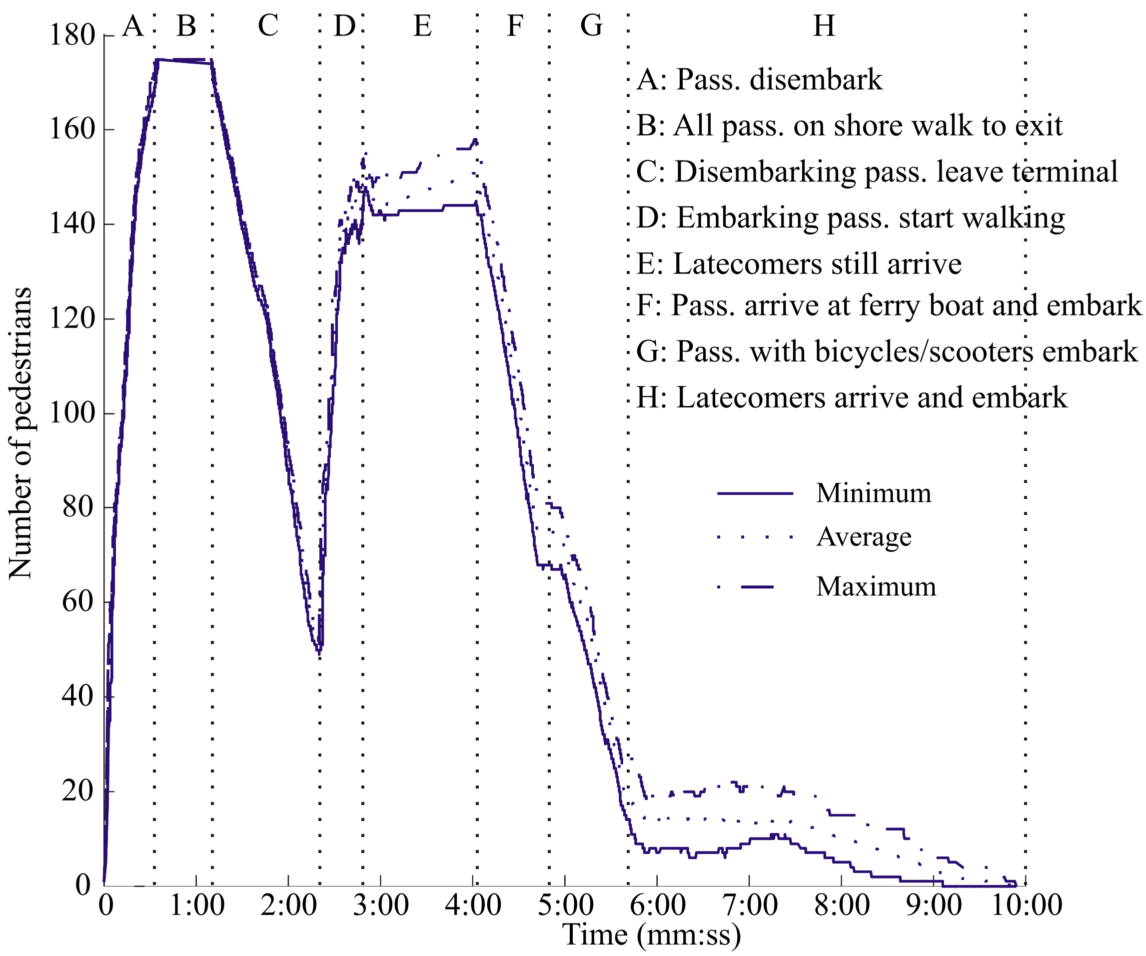


Figure 9.15: Number of pedestrians in the Vlissingen terminal per replication

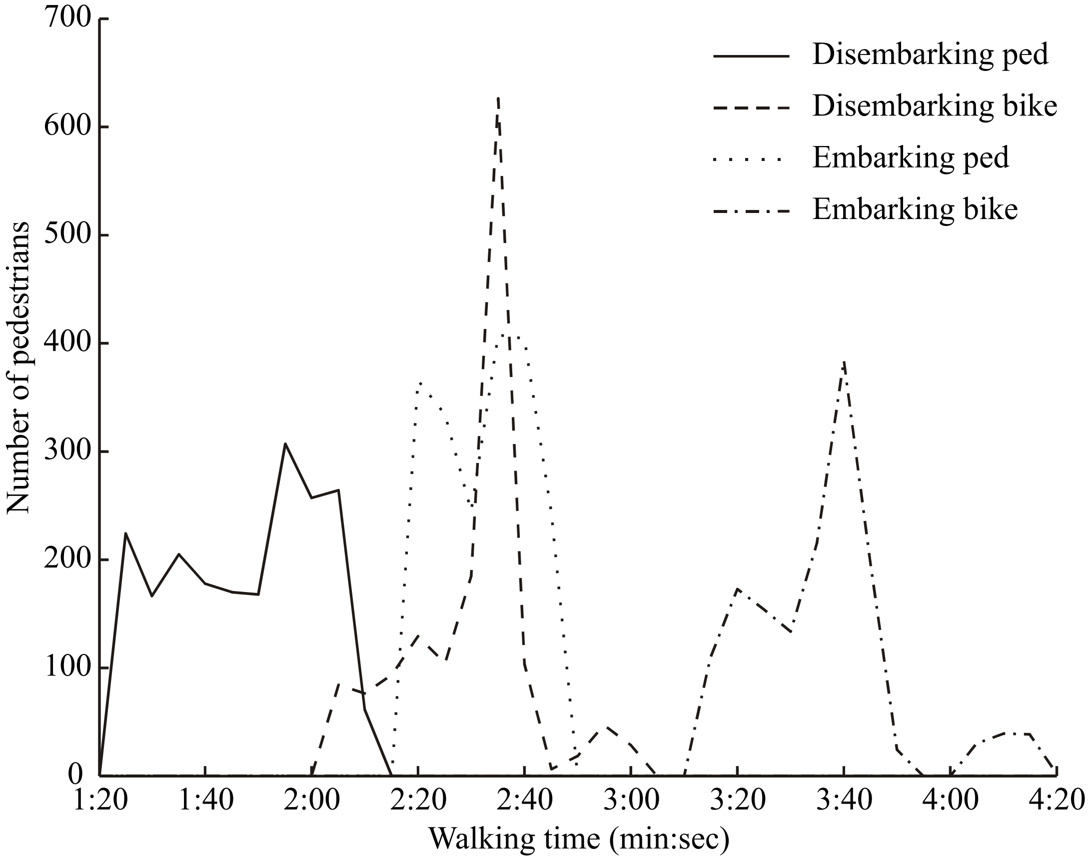


Figure 9.16: Walking time distributions of different types of pedestrians in Breskens

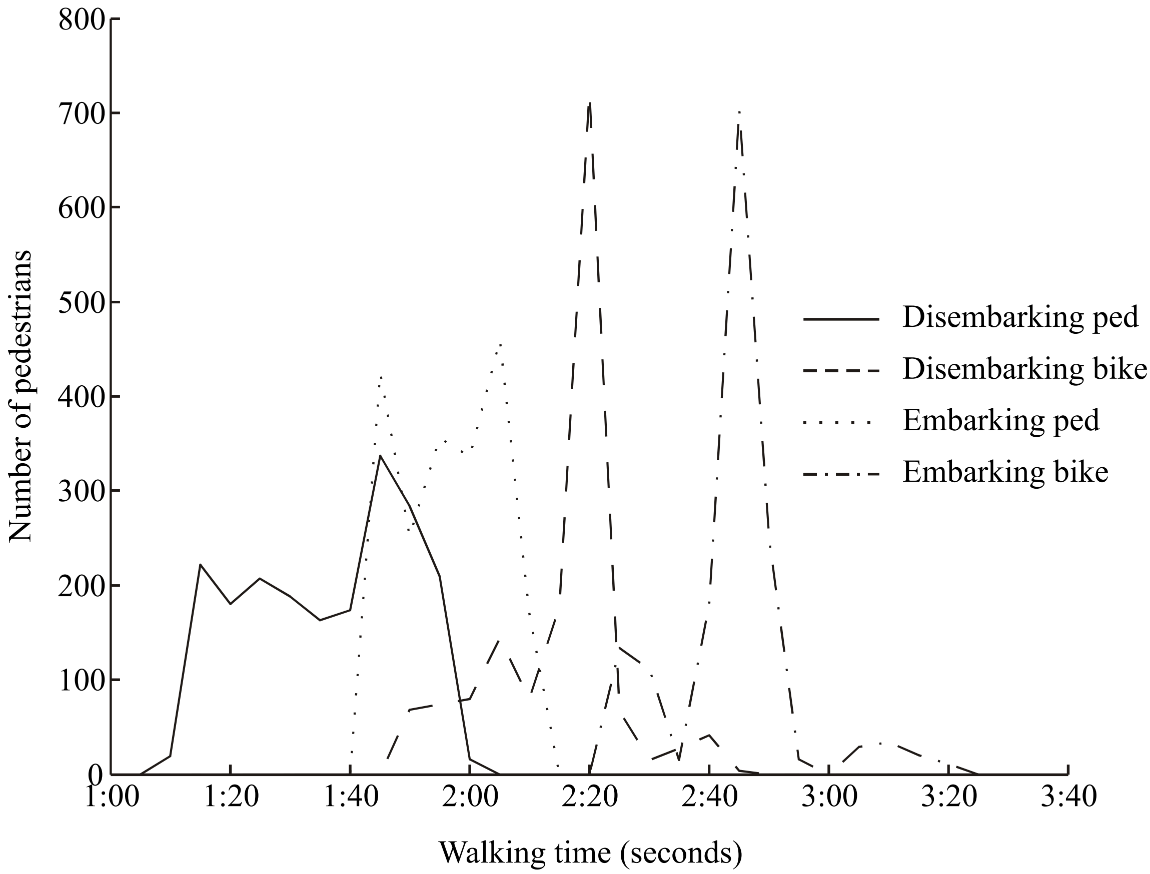


Figure 9.17: Walking time distributions of different types of pedestrians in Vlissingen

model). Overviews of these walking times are given in figure 9.16 for Breskens and in figure 9.17 for Vlissingen.

Since the walking speed of pedestrians is higher than that of pedestrians with bicycle or scooter, pedestrians have to lower their walking speed. Further, the trip length for embarking passengers is longer than for disembarking passengers, leading to longer walking times. Two categories have been distinguished (pedestrians and pedestrians with bicycles), whereas also pedestrians with scooters are modelled. These pedestrians are included in the pedestrians with bicycles, which is seen in the figures in a small amount of larger walking times (the second peak on the right). In table 9.6 free flow walking times are calculated in Breskens and Vlissingen for both pedestrians and pedestrians with bicycles. These free flow walking times are lower than the times measured in the simulation, which is due to the platooning effect and the hindrance of other pedestrians.

Table 9.6: Calculated free flow walking times

	Breskens		**Vlissingen**	
	distance (m)	**walking** time (min sec)	**distance** (m)	**walking** time (min sec)
disembarking ped	100	1:14.6	84	1:02.7
disembarking bike	100	1:46.4	84	1:29.4
embarking ped	172	2:08.4	127	1:34.78
embarking bike	172	3:03.0	127	2:15.1

9.5.7 Assessment of the case study

This pedestrian flow study shows that the total amount of time needed for all passengers to embark and disembark is, even in a worst-case scenario, beneath the required time of ten minutes, in order to guarantee a half hour ferry service.

It also shows that the pedestrian model can also be applied in other terminals than railway stations. Moreover, the study shows the ability to answer questions concerning capacity of walking infrastructure in an early planning stage or at least before the actual situation exists in a short period of time (several weeks).

9.6 Case study 4: Theme investigation on dwell times in relation to platform configuration

9.6.1 Purpose of the theme investigation

As part of a better exploitation of the Dutch railway network, new safety systems are designed to decrease time headways between trains on the open track and thus to increase the capacity of the rail network. In order to reduce the number of platform tracks as much as possible and to maintain a short time headway, the process of boarding and alighting as well as pedestrian flow handling on a platform need to be optimised.

The design question to be answered in this study is: how long does it take to empty the platform, given the type of rolling stock, the number of boarding and alighting passengers, and the platform configuration. Based on this dwell time, the headway on the open track, and the time table, the number of necessary platform tracks may be determined. It is also possible to calculate the capacity of the open track, given the number of platform tracks, the time table, and the platform configuration.

The result of this study is a relation between the time to empty a platform and the number of exit points per 100 *m* platform length, given the number of boarding and alighting passengers.

9.6.2 Process description of boarding and alighting

The process studies in this investigation concerns boarding and alighting. This section therefore elaborates on the boarding and alighting process, which consists of four stages, see also figure 9.18:

1. Boarding passengers arrive and wait on the platform for the train to arrive.
   - Arrival of the train.
2. Passengers alight, while boarding passengers queue in front of the doors.
3. Passengers board and leave the platform as well when boarding.
   - Departure of the train.
4. Alighted passengers walk to the platform exit.

To have a stable system, the number of waiting passengers on the platform needs to be stable at the moment a train arrives. That is, all alighting passengers must have left the platform when the next train arrives. This study indicates a minimum headway of trains on the open track, in order to maintain the stable system.

9.6.3 Scenarios analysed

Three scenarios have been simulated. In the first scenario, 1000 pedestrians alight from the train; the second scenario handles 500 alighting and 500 boarding pedestrians, while the third and final scenario concerns 1000 alighting and 1000 boarding passengers.

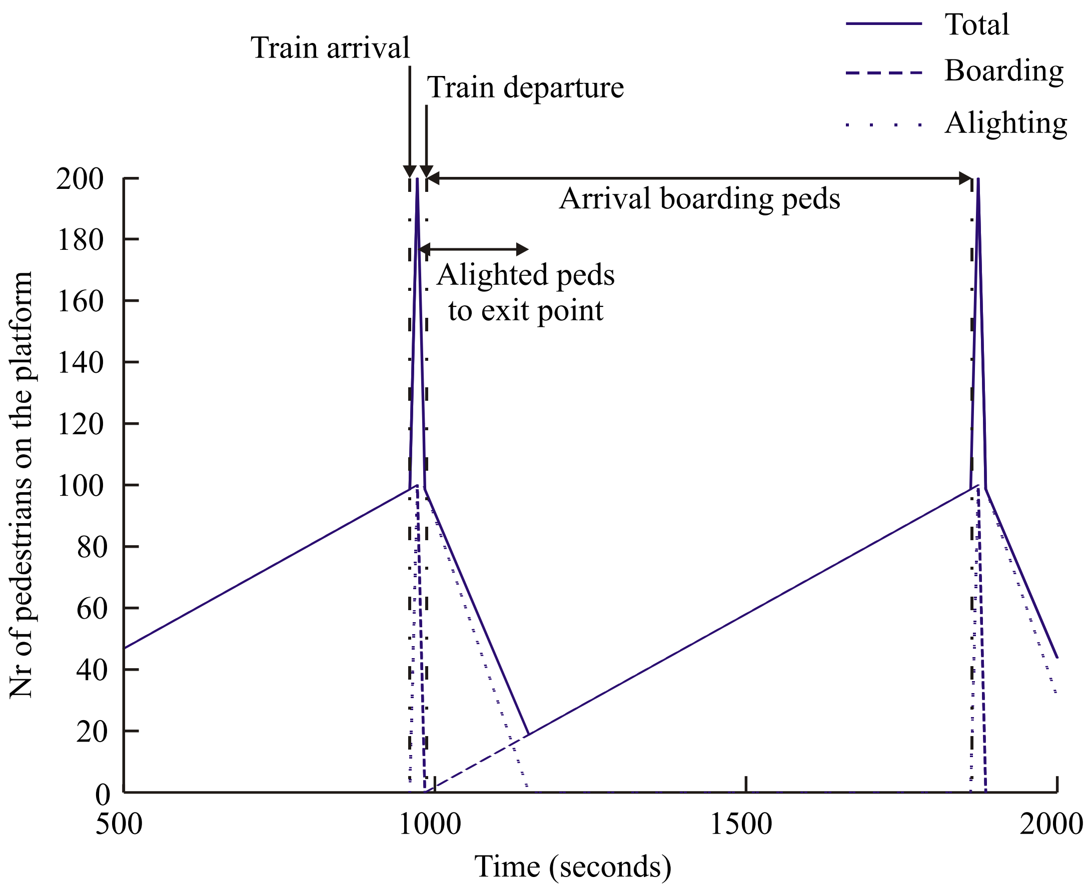


Figure 9.18: Overview of the process of boarding and alighting, including the arrival and departure of passengers from the platform

9.6.4 Model description

The following assumptions have been made:

- The arrival pattern of boarding pedestrians are assumed uniformly distributed over time.
- The numbers of boarding and alighting pedestrians is assumed equal for each train.
- Both boarding and alighting pedestrians are distributed uniformly over time. Thus, even when only one entrance is available, the number of passengers boarding at each door is similar.
- An optimal distribution of the exit points over the platform justifies the assumption that each exit is used by a similar number of pedestrians.
- Exit points do not cause any capacity restriction on the pedestrian flows.
- Each exit on the platform leads to the same hallway in order to prevent pedestrians to choosing the exit point favourable for their final destination. Passengers that do not walk to the nearest exit cause extra pedestrian traffic along the platform and increase the dwell time.
- Pedestrians wait on the platform, as no additional waiting facilities (for example in the hallway) are assumed available.
- Variances in train headways and numbers of boarding and alighting passengers are not taken into account.

The simulated platform has a length of 300 m. Alongside this platform a train with a length of 300 m stops, consisting of twelve passenger coaches with two doors for each coach. The width of a door is 1.42 m, while the individual boarding and alighting time equals one second and two passengers may board or alight at the same time. Exit points form the limits of the model. In the study, the number of exit points is varied between 1 and 12 exit points. Figure 9.19 shows the different infrastructure configurations.

Alighting passengers are hindered by boarding passengers when they are walking on the platform. For the actual boarding and alighting process the alighting times have not been adapted.

9.6.5 Model results

Figure 9.20 shows the average time needed to empty the platform, consisting of alighting, boarding and the time needed for alighting passengers to walk to their destination in relation to the number of exit points on the platform. Each line in the figure shows a scenario and the indicated points are simulated configurations.

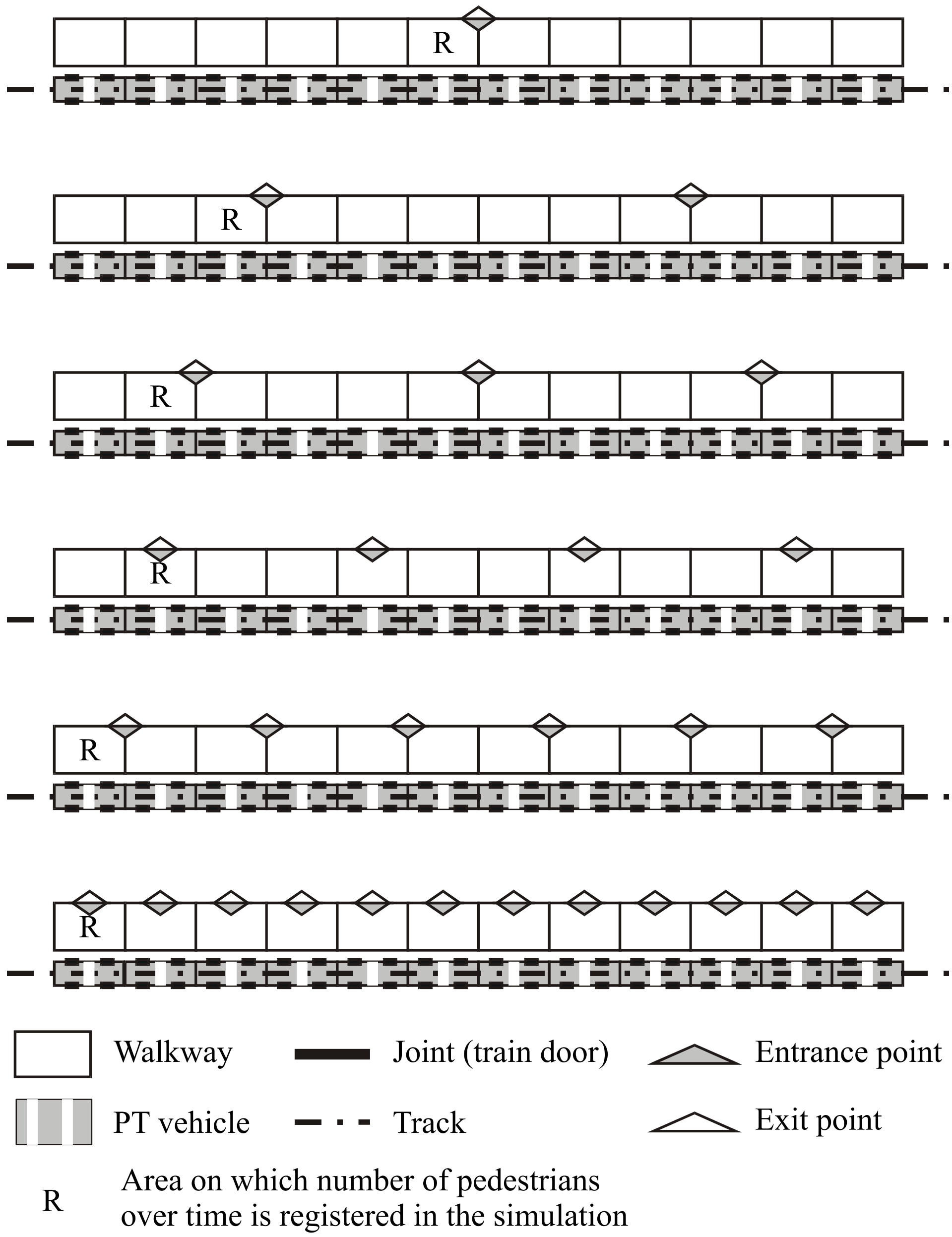


Figure 9.19: Tested configurations of the infrastructure

As expected, the simulated relation is continuously decreasing, but the relative benefit of adding an exit point decreases when the number of available exit points increases. The duration to empty the platform is highest for the scenario with the most boarding and alighting passengers (as expected). However, the difference with the scenario with only alighting passengers is very small, indicating that the hindrance of boarding passengers is limited. This hindrance might become more apparent when the width of the platform is reduced. The difference between the scenario with 500 boarding and alighting passengers and the scenario with 1000 boarding and alighting passengers is found to be between 12% and 34%. Thus, although the number of boarding and alighting passengers has doubled, the time to empty the platform has only decreased by at maximum one third. The time to empty a platform appears to be more sensitive for the number of exit points on the platform than for the number of boarding and alighting passengers.

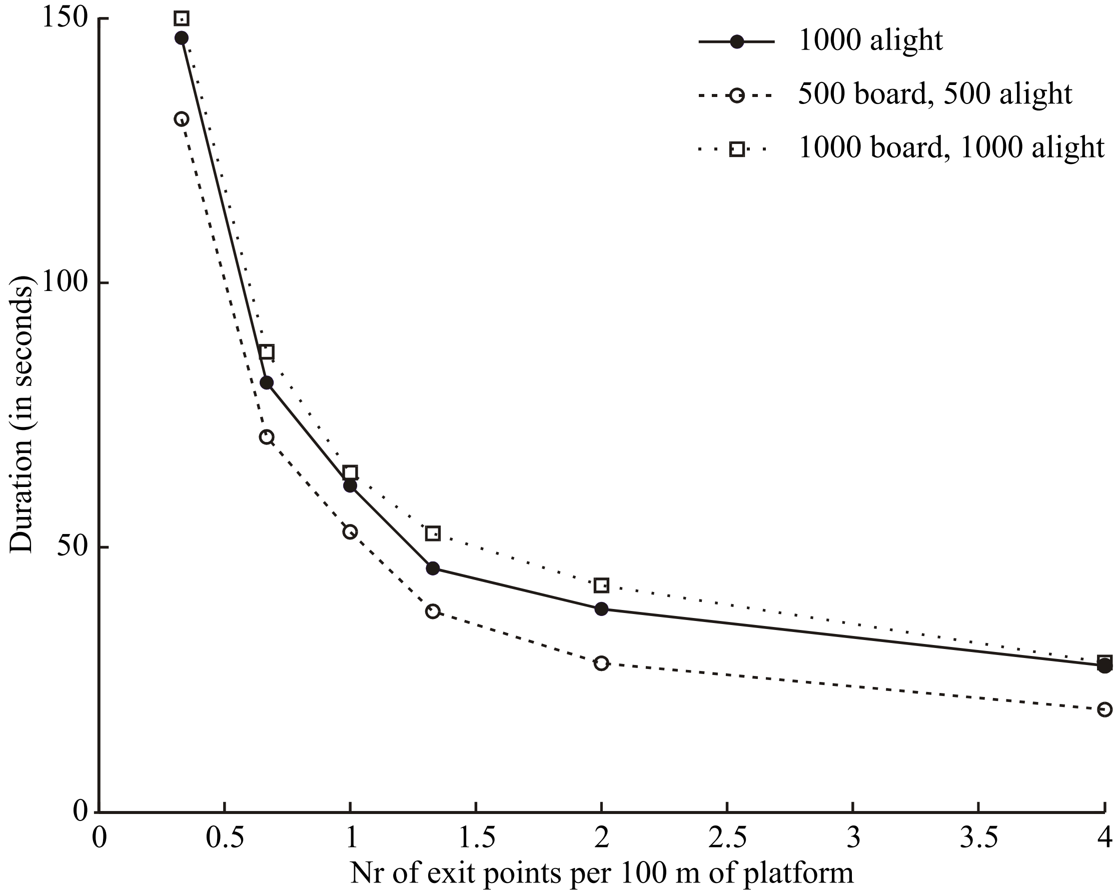


Figure 9.20: Duration of platform occupation in relation to the number of exit points on the platform and the number of boarding and alighting passengers

Figure 9.21 presents an overview of the densities just in front of an exit point over time. As is indicated in the assumptions, even with one entrance point, passengers will board at the doors at either end of the train. These passengers have to walk from this entrance alongside the platform (up to 150 m). The simulation tool generates boarding pedestrians at such moments they can all board. Thus the smaller the number of available entrances, the longer are the walking times, and the earlier these passengers will be generated.

The fewer exit points available, the longer it takes until the platform is empty again and the lower the pedestrian comfort. The small decrease of passengers in the configuration with only one exit point is due to the distribution of passengers over the platform, where the number of passengers is only recorded on the area of the platform in front of this single exit point. Only when more than six exit points are available, the level-of-service will not be worse than D, which is one of the comfort requirements of station managers.

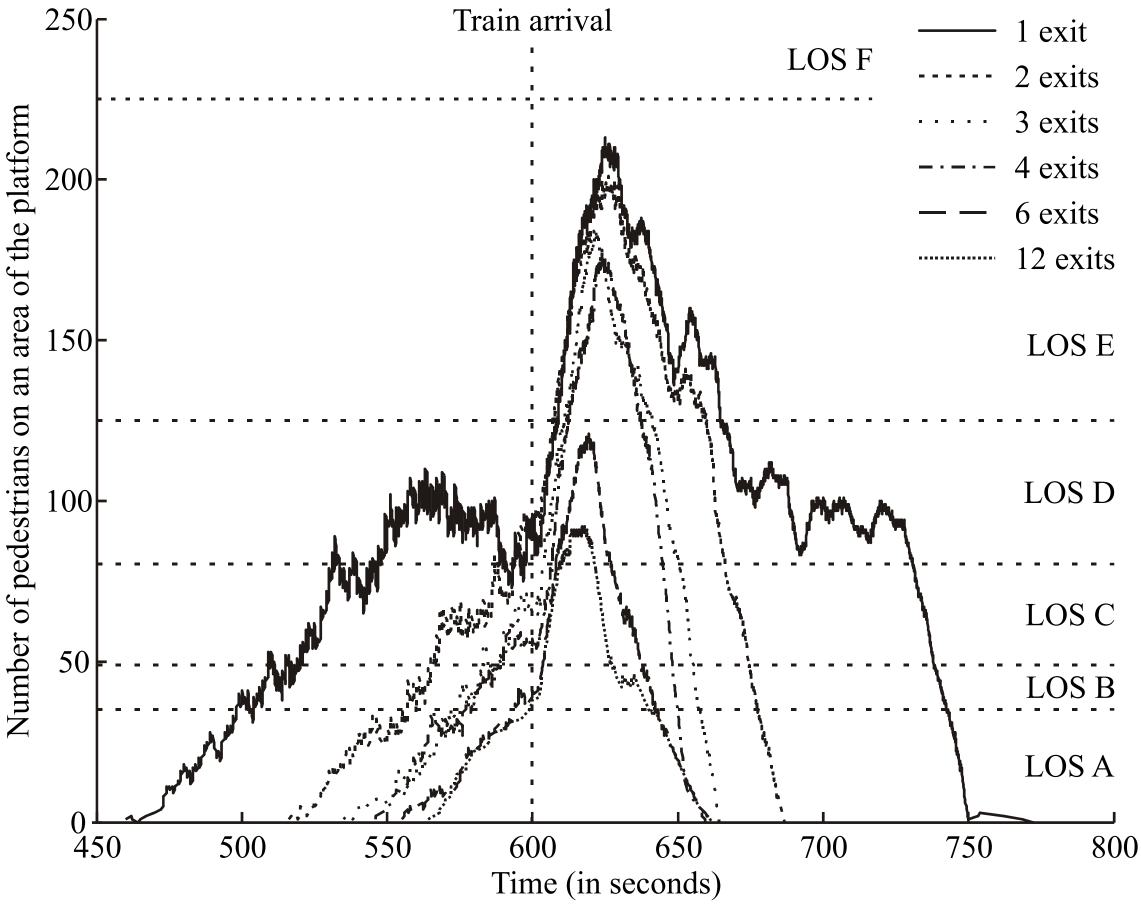


Figure 9.21: Density on the platform over time for each of the infrastructure configurations (locations in figure 9.19)

9.6.6 Assessment of the case study

This study clearly shows the applicability of the tool for so-called theme-investigations, where a specific design is not assessed, but a methodology or set of guidelines is to be defined, applicable for all sorts of transfer facility configurations.

9.7 Summary and conclusions

In this chapter, four case studies have been presented illustrating the use of the developed simulation tool. Each of the studies concerned a different design stage, that is a public transport station in the early planning stage, detailed designs of a public transport station, a ferry terminal, and finally a theme investigation on the influence of the boarding and alighting process on train dwell times. The applicability of the simulation tool to assess designs of several types of public transport facilities is shown. Also, the validation given in chapter 8 has been extended by Turing tests and 'expert opinions' in the sense that the simulation results did not deviate from what the experts expect in reality.

In the first case study, three aspects of pedestrian comfort have been considered, namely a spatial overview including size of pedestrian flows, pedestrian walking distances including a comparison with predefined standards, and finally levels-of-service. One of the more generic conclusions of the first case study is a fundamental dilemma in optimising pedestrian comfort, that is when pedestrian flows are to a large extent separated, the number of crossing flows decreases (corresponding to a higher level-of-service), but consequently public transport modes are more dispersed over the area, leading to increased walking distances.

In the second case study, seven scenarios for the Rotterdam Central Station have been investigated (with different time horizons and with and without performance of commercial activities), which have been assessed on the aspects pedestrian level-of-service, walking time, and use of routes. With respect to the assessment of the simulation tool, the need has been identified to tune the infrastructure model to the information needed, that is very detailed modelling of congested infrastructure and infrastructure with a high probability of congestion and less details for the remaining parts in order to reduce calculation time. A second lesson of this study is that exogenous input information needs to be thoroughly checked in order to prevent falsely attributing mistakes to the functioning of the simulation tool instead of the use of incorrect input data. With respect to the analysis of the results, a new method of using level-of-service has been applied. Instead of showing the level-of-service on the infrastructure, the percentage of pedestrians is indicated experiencing a specific level-of-service. This measure gives less favourable performance estimates (in congestion many pedestrians are involved), but is a better indication of pedestrian level-of-service.

An assessment of two ferry terminals has been made as third case study showing that the pedestrian model may be applied to terminals other than railway stations. Moreover, the study shows the ability to answer questions concerning service timetables in relation to capacity of walking infrastructure in an early planning stage.

The final case study is an example of a theme investigation, in which not the design of a specific facility has been assessed, but a design guideline has been constructed based on the assessment of a process.

This chapter showed the applicability of the simulation tool for the assessment of designs of various types of public transport facilities in different stages of the design process. Some of the case studies showed a need for additional processes to be included in the simulation tool, such as the modelling of pedestrians arriving in peaks. Performing these case studies also resulted in recommendations with respect to the tool handling, especially regarding the input application. In spite of this, all case studies have resulted in valuable recommendations and clear understandings in the functioning of a design with respect to passenger flows for both designers and decision makers.

Chapter 10

Conclusions

The main research theme in this thesis is pedestrian behaviour in transfer facilities (stations, airports, passenger terminals) and the translation of this behaviour into an operational simulation tool. This final chapter summarises the main results of the thesis. First, a short summary is given of the problem studied in this thesis and the approach used to develop such a simulation tool, including some case studies performed with this tool. This is followed by a discussion of the findings of this research and the conclusions on modelling pedestrians in transfer stations. Next, implications of the research for both science and practice are presented, and finally recommendations for future research are given.

10.1 Short summary

This thesis presents the developed simulation tool SimPed concerning pedestrian behaviour in transfer facilities. In presenting this tool, a specification is given, split up into the requirements of the simulation tool (chapters 1 and 2) and the identification of relevant elements and processes (chapter 5). Both the requirements and the identification have been elaborated using a dedicated theoretical framework based on three levels distinguished in pedestrian decision making. Each of these levels (strategic, tactical, and operational) indicates the term on which pedestrians make their decisions. On the strategic level, long-term decisions are taken, whereas on the operational level decisions are taken for the immediate next instant. The tactical level covers the decisions in the intermediate term.

The theoretical framework of the simulation tool has been based on a broad literature survey (chapter 3) and new empirical findings (chapter 4). General aspects of route choice and pedestrian walking behaviour have been extensively discussed in literature. However, only little knowledge is available on pedestrian behaviour in public transport facilities. Therefore, as part of this research, new empirical data have been collected to analyse the influences of pedestrian characteristics and flow composition on pedestrian walking behaviour, pedestrian behaviour on a platform of a train station, and route choice behaviour in train stations. Blank spots were identified with regard to the traffic characteristics of waiting pedestrians and of pedestrians performing activities (such as activity choice behaviour, determining the order in which activities are performed, and deciding on the location where activities are performed) which are subjects for future research. Activity choice and activity scheduling provisionally are exogenous to the simulation tool, whereas for waiting processes general queuing theory has been applied.

For the first time, *controlled walking experiments* have been performed to extend current knowledge on pedestrian walking behaviour in a variety of conditions. New methods have been successfully developed to observe individual walkers and to establish their trajectories from video images. Various methods known from car traffic have been applied for the first time to pedestrian traffic such as the use of cumulative flow curves and the product-limit method to derive cumulative distribution functions of pedestrian free speed and of capacity.

The experiments produced new findings with respect to free speed distributions, speed variances, fundamental diagrams (including influences of opposite and crossing flows), capacity of bottlenecks, self-organisation. These findings constitute important improvements relative to existing knowledge. The resulting empirical data have not only been used to generate input data for the simulation model (speed-density relations), but also to extend and verify existing theories and models on pedestrian walking behaviour and to calibrate and validate the developed simulation tool.

As a precursor to the operationalisation of the simulation tool, a system delineation and decomposition of transfer nodes have been established specifying in detail constituting elements and processes relevant for modelling. Such a transfer node is seen as a network of interlinked service systems. Characteristic of this decomposition is the distinction of three levels of decision making of pedestrians into strategic, tactical, and operational decisions. All decisions of travellers are assumed to follow the subjective utility maximisation principle whereas all activities performed in the transfer facility are considered to be service queuing systems.

A detailed account is given of the specific models developed to describe in sufficient detail the various travel and activity choices of the pedestrians as well as to describe the various processes going on in a transfer facility. Discrete choice utility maximising models are derived and specified for all relevant activity choices (activity scheduling, activity performance locations) and travel choices (routes, trajectories). In addition, procedures have been developed to derive individual walking speeds and aggregate densities in all types of walking infrastructures.

The operational simulation model was described by means of overviews of the dedicated object model and the dedicated software architecture, in which the different applications are coupled. Roughly speaking, the simulation tool consists of a simulation kernel, an animation (both two and three dimensional), an archive, and an analysis application. The performed verification and validation of the operational simulation tool was discussed as well. The validation was confined to modelling pedestrian traffic flows, based on application of the tool in a part of an existing railway station (Delft, the Netherlands), where the model predictions were compared to actual observations. Validation of route choice modelling has been based on plausibility of predicted routes. Recently, this validation has been extended with a comparison of model predictions with observations. In order to demonstrate the applicability of the tool, several practical studies were performed with different application areas, such as existing transfer stations, transfer station design in an early planning stage, preliminary transfer station designs, and the operational effects of another operator of a ferry terminal on pedestrian flows.

10.2 Achievements on modelling pedestrians in transfer stations

The main result of this research is a validated operational simulation tool for pedestrian traffic, which does not only model pedestrian walking behaviour, but also includes route choice, performance of activities, and the interaction of pedestrians with public transport vehicles. This tool is developed to model pedestrian behaviour in passenger transfer facilities, but may also be applied in other pedestrian areas, such as inner cities, shopping malls, and stadiums, after choosing the proper parameter values.

One of the innovative characteristics of the simulation tool is a (flexible) combination of microscopic and macroscopic models. The simulation tool consists of several models, including a route choice model, activity area choice model, walking model, trajectory generation model, activity performance model and a model describing the interactions between pedestrians and public transport vehicles (processes of boarding and alighting). This results in a simulation tool modelling pedestrian behaviour at both the tactical level and the operational level. The combination of modelling all these processes (including the detailed modelling of the interaction with public transport vehicles) makes the simulation tool innovative relative to currently available pedestrian traffic simulation tools.

Models with respect to choice behaviour are all microscopic, that is pedestrians make individual choices, depending on current (traffic) conditions in the network. Also, performance of activities (including queue formation and servicing) is modelled microscopically as is the interaction with public transport vehicles (boarding and alighting). Pedestrian walking behaviour on the other hand is modelled quasi-macroscopically, by applying relationships between speed and density for various types of infrastructure.

A state-of-the-art overview has been made of walking characteristics in various conditions (stations and shopping areas, but also pedestrian behaviour on stairs and escalators) and for different pedestrian categories (tourists, commuters). The literature study resulted in the identification of blank spots regarding influences of bottlenecks, of walking direction, and of desired walking speed on pedestrian walking behaviour and on fundamental traffic relations for pedestrians in particular (relation between speed, flow, and density). Also, measurements on walking specific for the Dutch situation appeared to be lacking.

To fill the most important knowledge gaps, dedicated controlled laboratory experiments were performed. Apart from substantive outcomes, in setting up these experiments important new experimental tools have been developed such as dedicated detection and tracking software to automatically transform video-images into trajectory data describing location and speed of each pedestrian for each tenth of a second. Amongst the new findings of these experiments were speed-density relations, parameters of pedestrian following behaviour, and capacities of bottlenecks.

In two of the experiments, pedestrian behaviour in and in front of bottlenecks was studied. Analysis of video images showed that, contrary to existing capacity rules, capacity does not linearly increase with the width of the bottleneck, but rather step-wise. This finding requires reconsideration of capacity formulae and design guidelines for narrow walkways. A new theory was developed about walking in narrow walkways to explain observations on layer formation and zipping.

A large set of route choice observations (over 1000 trips) were performed in two Dutch railway stations from which the impact of specific factors such as availability of escalators, stairs, and ramps were estimated for various passenger categories. From these observations, route choice models for railway stations were established with high predictive performance.

Existing object models and software architectures did not satisfy our requirements. Therefore, a dedicated object model as well as a dedicated software architecture were developed. The set up of the simulation environment has been generic in order to be able to facilitate using different modules to add or overrule current pedestrian modelling. This generic approach makes it possible to implement microscopic pedestrian walking behaviour in the near future or more elaborate activity and route choice models. The level of modelling (microscopic or macroscopic) may then be indicated by the user for each part of the infrastructure.

The simulation tool was successfully applied in several studies in different fields of application, such as the design of the Rotterdam railway station (the Netherlands) with simulation models of both early planning stage and preliminary design, and the consequences of new operational schemes for ferry boats between Vlissingen and Breskens (province of Zeeland, the Netherlands). The outcomes of these applications corroborate the usefulness of the tool.

10.3 Conclusions

The main conclusion of this thesis is that modelling pedestrian behaviour for public transport passenger facilities turns out to be feasible and offers a valuable contribution to the work of designers of pedestrian facilities in general and, using the described simulation tool SimPed, of designers of transfer stations particularly. The extra complication for designers of transfer stations lies in the clustered arrivals and departures of pedestrians, due to the arrival and departures of trains and other public transport vehicles. Vehicles arriving or departing with a (small) delay have a significant effect on both the size of pedestrian flows and their direction. Especially in complex stations (complicated layout of the infrastructure and many transferring passengers), these flows can not be predicted using analytical models. The use of a simulation tool taking into account all pedestrian behaviour, not only walking, but also route choice, activity performance and boarding and alighting, is therefore indispensable for designers of transfer stations.

However, pedestrian behaviour is not yet fully covered in existing theories and models. A literature research revealed many basic interpretations of pedestrian walking behaviour and route choice behaviour. However, many blank spots were found as well, concerning among other things bottleneck capacities and influences of multi directional flows on fundamental relations between speed, flow, and density (such as walking direction and variety of free speeds). Performing experiments in order to increase this knowledge on pedestrian behaviour in different situations is very useful, thanks to the possibility to identify the effect of changing single variables on pedestrian behaviour. Both the setup of the laboratory experiments and the processing of the video images are original in this research.

Taking the three pedestrian behaviour levels (strategic, tactical and operational) and using two types of models (queuing models and choice models) results in a unambiguous, coherent description of pedestrian behaviour, at least to the extent to which this is needed for the simulation tool.

A number of case studies have shown the validity and the applicability of the developed simulation tool in different conditions and various application areas.

10.4 Implications for science and practice

From a scientific point of view, the performance of experiments is most relevant. Especially the bottleneck experiments give a new look at pedestrian behaviour concerning layer formation and the 'zipping' effect, as well as self-organisation in two directional and crossing flows. Another implication is the free speed distribution of pedestrians, indicating a range of design speeds. Also, the locations of waiting pedestrians upstream of a bottleneck are different, compared to outcomes of most simulation models. Findings reported by other researchers, such as lane formation and self-organisation of pedestrian flows, also emerge from the experiments.

Implications for practice concern both designers and the design itself. For the designer, the developed tool may serve as an aid during the design process and as support to evaluate improvements in current situations. The simulation tool may be used from the start of the design process (indicating the amount of infrastructure needed and locations of modalities in a multimodal transfer station) to the final design (indicating bottlenecks, not frequently used areas indicating problems for personal security, and shortcomings during evacuation). Also, the robustness of the design in case of a growing number of travellers may be identified, both for future situations and unusual events. The design itself will become more efficient and safer, in case of emergencies. Theories and models resulting from the experiments also have effects on design guidelines, the most important of which is the step-wise relation between capacity and bottleneck width.

10.5 Recommendations for future research

Although this research has given many new insights into pedestrian behaviour and also yielded a simulation tool in which different aspects of pedestrian behaviour are covered, particularly with respect to behaviour in transfer stations, further research in a number of directions is needed. This future research may address a number of topics, such as theory building, performing experiments and other observations, improvements in models, and recommendations for design guidelines.

10.5.1 Empirical research

Experiments described in this thesis only concerned pedestrian walking behaviour on level indoor infrastructure. Moreover, only a few variables influencing this walking behaviour could be explored. Additional experiments are necessary on different compositions of the flow (aspects are among other things gender, age and amount of luggage), various bottleneck widths, group formation, various types of underground, and emerging behaviour. Also, different types of infrastructure such as stairs, escalators, and people movers are supposed to influence pedestrian walking behaviour and might be included in an (indoor) experiment. Therefore, real-world observations are essential, not only to observe pedestrian behaviour on various types of infrastructure, but also to exclude the artificial behaviour of pedestrians due to laboratory conditions (repeating aspects and negotiating with the same pedestrians throughout the experiments, weather, temperature, trip motive, grouping behaviour, time pressure).

Another subject to be studied is the different time components of pedestrian behaviour in a transfer station and the weighting of these components, that is as a pedestrian has only a limited amount of time until the departure time of his train, he has to decide which activities he will perform, taking into account not only the location of these activities, but also the probability of missing his train when an activity lasts longer than expected and may not be interrupted. These time weightings may be found by a combination of video observations and questionnaires, in which passengers indicate alternatives for activities (location, type and duration of an activity).

10.5.2 Theory building

Good theories concerning walking behaviour and route choice behaviour are essential in developing a powerful (simulation) model. Especially on walking behaviour, many theories have been developed in the past, but blank spots still remain concerning precise descriptions of microscopic pedestrian behaviour (in passing pedestrians and other obstacles and head-on encounters). Most of the developed theories remain concepts, not applicable to practice. Also, with respect to macroscopic flow characteristics, such as speed-density relationships, much needs to be done. Current knowledge is hardly consistent, due to the fact that relationships have been drawn up for different conditions, which could not be influenced by the researcher, and the use of different definitions of macroscopic variables (instantaneous, local, space-time, etc.). It would be valuable to derive macroscopic speed-density relations from microscopic speed distributions valid for different conditions on the same types of infrastructure and in similar conditions on different types of infrastructure.

Another aspect of pedestrian behaviour showing demand for research is choice behaviour. Specific aspects of route choice behaviour in transfer stations such as have not yet been studied at all. Also, differences in decisions of similar pedestrians in different conditions (transfer stations, shopping areas) are an essential part in increasing knowledge (theories and models) on pedestrian route choice behaviour and activity choice behaviour.

10.5.3 The simulation tool

As described in chapter 6, the simulation tool consists of various models. Each of these models may be improved, as has been indicated in for example section 6.3 concerning the activity location choice model. The route choice model may be improved by including individual parameter sets in the various choice functions, aspects of unfamiliarity with the environment on route choice, and other choice mechanisms. Other aspects for consideration are dynamic conditions in the network (instead of using instant travel times) and continuous time updates for the calculation of link performance variables (instead of the current discrete updates). A final advance concerns the inclusion into the walking model of microscopic walking behaviour.

In recent years, safety and security are more and more emphasised. The design therefore has to meet specific requirements concerning safety in order to handle evacuations. Unfortunately, little knowledge exists on pedestrian behaviour during evacuations, but this knowledge may be included in the simulation tool to see the consequences of a major accident or act of terror.

10.5.4 Design guidelines and decision support

The simulation tool may be used to develop design guidelines concerning transfer stations, but also for pedestrian facilities in general. These guidelines enable designers to create plans that can efficiently handle pedestrian flows, thus preventing bottlenecks and social insecure and unsafe situations. Guidelines prevent the application of costly simulation studies in non-complicated situations, with small pedestrian flows, or few conflicting flows and/or standard shaped areas.

In more complicated situations, design guidelines may not be sufficient. Designers of such facilities may need a (simplified) design support tool, on which successive design decisions and design choices are based. An extensive design support tool will cope with the total design process for all different kinds of facilities with varying complexity and will cover the total range of design support from guidelines to the application of a simulation tool such as SimPed. The aim of a simplified design support tool is to facilitate the design process, to help the designer with his design decisions and choices, and to hand the designer guidelines valid for his specific design.

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Appendix A

SimPed input and output

This appendix gives detailed information on the input and output values of SimPed, part of which has been derived from literature. Sections A.1 (literature) and A.2 (SimPed) discuss the input, while sections A.3 (literature) and A.4 (SimPed) describe the output in detail.

A.1 Input values from literature

A.1.1 Dimensions

A pedestrian needs space in the lateral direction, due to the fact that pedestrians can not walk along a straight line, but are swerving (Knoflacher 1987), (Predtetschenski & Milinski 1971), (Weidmann 1993). These swerving movements also cause hands and baggage to move, resulting in a dynamic distribution of the pedestrian width, and thus of occupied pedestrian surface. Dynamic pedestrian widths (Weidmann 1993) vary between 60 cm (Predtetschenski & Milinski 1971) and 78.5 cm (Knoflacher 1987). Specific values are given for pedestrians in groups (68 cm (Knoflacher 1987)), on stairs (60 cm (Weidmann 1993)) and pedestrians with luggage (82 cm (Weidmann 1993)). The surface of a pedestrian is 0.4 m^2 (CROW 1998), (Weidmann 1993). SimPed also has the possibility of modelling persons in wheelchairs and with prams, see for measures (CROW 1998).

Distances within throughpasses may be neglected when they are less than 0.70 m, which corresponds to the length of one step (Predtetschenski & Milinski 1978), indicating that such small areas may be omitted from the infrastructure configuration. Between opposite flows an extra width of 0.6 m is required, whereas the minimum net width of connecting walkways in a transfer stations is 2.4 m (NS Reizigers 1999). A minimum net width of 2.4 m is also needed for stairs, while the minimum width of a fixed or mechanical inclination is 1.10 m. Maximum width of stairs appears to be 4.0 m (Knoflacher 1995). The height difference bridged by stairs should be less than $4.0 - 5.5$ m. For larger height differences, a level surface should be placed about halfway with a length of $1.5 - 2.0$ m.

Lifts should have a width of at least 1.4 m and a depth of at least 1.6 m. Platform widths should be larger than 2 m.

At the track side of the platform, a safety zone is needed of 1.5 m width; when trains pass with a maximum speed of 16.7 m/ s, this safety zone is reduced to 0.75 cm. SimPed considers these areas as shy away zones, which are excluded from the net area of a platform part.

Pedestrian comfort decreases rapidly from a density of 1.0 P/ m^2. In normal conditions a density of only 0.2 P/ m^2, a speed of 1.34 m/ s and a pedestrian flow of 0.27 P/ m s are normative for the design. For stairs, these values are (upwards / downwards) 0.4 P/ m^2, 0.61/0.69 m/ s and 0.24/0.28 P/ m s. In extreme conditions on level infrastructure, a density of 1.5 P/ m^2 is allowed, leading to decreased speeds of 0.81 m/ s and a pedestrian flow of 0.73 P/ m s. For stairs, the maximum density is 1.5 P/ m^2 as well, leading to speeds of 0.51/0.58 m/ s and a pedestrian flow of 0.76/0.87 P/ m s. At these maximum values, the situation is still stable. The capacity of an escalator with a speed of 0.45 m/ s is 1.58 P/ s; with a speed of 0.6 m/ s its capacity is 1.97 P/ s and with a speed of 0.75 m/ s, capacity is 2.1 P/ s. Which quality level is chosen for specific designs of infrastructure depends on the frequency of maximum flows. Therefore, the levels of service should be related to the duration of the load on the infrastructure (Weidmann 1993).

A.1.2 Design speeds

CROW (1998) distinguishes three pedestrian types (fast, average, and slow) and three age classes (children, adults, and elderly). These different types might be modelled in SimPed. The default pedestrian has the characteristics of an average adult with a free speed of 1.34 m/ s. For design speeds of elderly pedestrians see TRB (2000), Coffin & Morrall (1992).

A.2 SimPed input

This section starts with an overview of the input needed for a simulation. Not all input has to be defined by the user since some objects are given default values. An overview of these default values is given in the second part of this section. Table A.1 shows an overview of the required input of a SimPed simulation model.

All graphic elements have default line colours, line styles, and colours, as well as a label indicating the name of each element. Default input with respect to pedestrian infrastructure and origin-destination tables is described in table A.2, while default input values with respect to public transport services is shown in table A.3.

Table A.1: Input for the SimPed simulation tool

Element	**Attributes**
Activity	Name, descr, height level, spatial descr, nr of servers, service time distr, activity group, PedMoveElement for waiting queue
Activity group	Name, descr
EntrancePoint	Name, descr, height level, spatial descr, generators, delay distr, capacity in, capacity out
Escalator	Name, descr, height level, spatial descr, levels-of-service, vk-relation, surface angle, turning direction, speed, step length
ExitPoint	Name, descr, height level, spatial descr, delay distr, capacity in, capacity out
Generator	Name, descr, entrance point, exit point, ped type, nr of peds to generate, start and end moments generation
Joint	Name, descr, height level, spatial descr, element 1, element 2, delay distr, one- or two-directional
Lift	Name, descr, height level, spatial descr, levels-of-service, speed, acceleration, time to open doors, time to close doors, capacity, start floor, end floor
Model	Name, descr, infinite, epsilon, early arrival margin for pass on platform, route update interval, reduced walking speed on escalators, criterion for public transport vehicle departure
PedestrianType	Name, descr, speed, surface, width, activities to perform
PedInfraElement	Name, descr, height level, spatial descr
PedMoveElement	Name, descr, height level, spatial descr, level-of-service, vk-relation, surface angle
PlatformLine	Name, descr, height level, spatial descr, heading
RollingStock	Name, descr, length, capacity
RollingStockComb	Name, rolling stock, order, heading of rolling stock
RollingStockDoors	Name, descr, rolling stock, width, position from head rolling stock, alighting time per ped, boarding time per ped, time to open, time to close
ScheduledStop	Name, descr, scheduled arrival time, scheduled departure time, platform track, type of rolling stock, dwell location vehicle head, nr of boarding pass, origins of boarding pass, boarding pass types, distr of boarding pass over vehicle, nr of alighting pass, destinations of alighting pass, alighting pass types, distr of alighting pass over vehicle
TrainService	Name, descr, heading, distr of arrival delay
Vehicle	Name, descr, rolling stock combination, train service
descr : description; distr : distribution; pass : passengers; ped : pedestrian	

Table A.2: Default input values in SimPed with respect to pedestrian infrastructure and origin-destination tables

Element	Attribute	Value
Activity	Number of servers Service time	1 0 s
EntrancePoint	Delay Capacity in Capacity out	0 s 1 P/ s 0 P/ s
Escalator	Surface angle Step length Speed	inclined 0.4 m 0.5 m/ s
ExitPoint	Delay Capacity in Capacity out	0 s 0 P/ s 1 P/ s
Generator	Start of generation End of generation Nr of pedestrians to generate Pedestrian type	0 00 00 1 00 00 2400 Default
Joint	Delay Capacity 1 → 2 Capacity 2 → 1	0 s 1 P/ s 1 P/ s
Lift	Time to open doors Time to close doors Capacity Speed Acceleration	2 s 2 s 8 persons 0.5 m/ s 0.33 m/ s^2
Model	Infinite Epsilon Update interval routes Max distance train-platform Train departure criterion Reduced walking speed on escalator Margin early arrival pass on platform	10000 0.01 600 s 3 m no boarding during 10 s 75% 60 s
PedestrianType	Pedestrian width Pedestrian area Walking speed Activities to perform	0.6 m 0.4 m^2 100% none
PedMoveElement	Level-of-service Surface angle Vk-relation	see figure A.1 level see figure A.1

Table A.3: Default input values in SimPed with respect to public transport services

Element	Attribute	Value
RollingStock	Length	25 m
	Capacity	80 P
RollingStockDoors	Width	2 m
	Distance from head vehicle unit	5 m
	Time to open door	2 s
	Time to close door	2 s
	Alighting time	1 s/P
	Boarding time	1 s/P
ScheduledStop	Number of boarding passengers	100
	Distr. of boarding pass over train	uniform
	Type of boarding passengers	default
	Number of alighting passengers	100
	Distr. of alighting pass over train	uniform
	Type of alighting passengers	default
TrainService	Distr of arrival delay	0 s

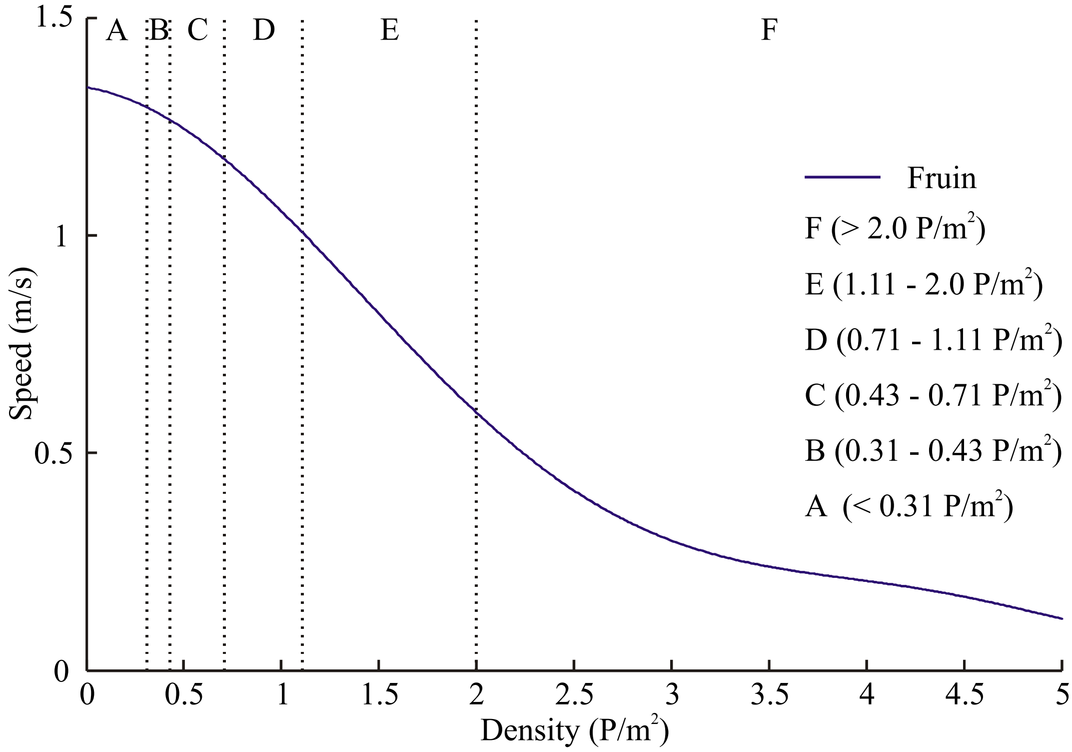


Figure A.1: Speed-density relation and levels-of-service as defined by Fruin (1971*b*)

A.3 Performance measures found in literature

A part of the infrastructure may become a bottleneck due to (NS Reizigers 1999):

- Size of the area (too small areas lead to high densities, too long areas lead to long travel times, and too large areas may indicate a lack of personal security).
- Layout of the area (length/width, obstacles).
- Structure of the network (may lead to longer walking times, inefficient use of some parts of the network).

A.3.1 Levels-of-service

While designing the infrastructure for pedestrians, pedestrian comfort must be taken into account, depending on the frequency of occurring densities. This comfort is described by the so called ‘level-of-service concept’. Criteria for judgement are freedom of speed choice, frequency of a forced change in speed, constraint to take care of other pedestrians, frequency of forced changes of direction, hindrance of crossing a pedestrian flow (in two directional flows and crossing flows), hindrance of passing pedestrians, and frequency of physical contacts.

Research on this level-of-service concept has been extensive (BGC 1998), (Copley & Maher 1973), (Fruin 1971*b*), (Knoflacher 1995), (Milazzo et al. 1999), (Oeding 1963), (Polus et al. 1983), (Pushkarev & Zupan 1975*b*), (Soligo et al. 1998), in which all kinds of factors have been indicated influencing pedestrian level-of-service. However, default values in SimPed follow the quite simple and straightforward concept described in Fruin (1971*b*).

Levels-of-service depend on densities k in an area, calculated by:

$$k = \frac{N^{walk}}{A_a^{net}} \tag{A.1}$$

where N^{walk} is the number of pedestrians in the considered area and A_a^{net} is the effective surface of area a, being the part of a walkway that can be used effectively by pedestrians. Several types of walkway obstructions tend to make pedestrians shy away. The effective walkway width w^e is computed by:

$$w^e = w_a^{walk} - w_o \tag{A.2}$$

where w_a^{walk} is the total width of walkway a, and w_o is the sum of widths and shy away distances of obstructions on the walkway, where all widths are measured in metres (TRB 2000), (Fruin 1971*b*).

Table A.4: Average flow level-of-service criteria for walkways and sidewalks

LOS	Space (P/ m^2)	Flow rate (P/ m s)	Speed (m/ s)
A	≤ 0.18	≤ 0.27	> 1.30
B	$0.18 - 0.27$	$0.27 - 0.38$	$1.27 - 1.30$
C	$0.27 - 0.45$	$0.38 - 0.55$	$1.22 - 1.27$
D	$0.45 - 0.71$	$0.55 - 0.82$	$1.14 - 1.22$
E	$0.71 - 1.33$	$0.82 - 1.25$	$0.75 - 1.14$
F	≥ 1.33	variable	≤ 0.75

Table A.5: Level-of-service criteria for stairs

LOS	Space (P/ m^2)	Flow rate (P/ m s)	Speed (m/ s)
A	≤ 0.53	≤ 0.27	> 0.53
B	$0.53 - 0.63$	$0.27 - 0.33$	> 0.53
C	$0.63 - 0.91$	$0.33 - 43$	$0.48 - 0.53$
D	$0.91 - 1.43$	$0.43 - 0.6$	$0.42 - 0.48$
E	$1.43 - 2.0$	$0.6 - 0.82$	$0.40 - 0.42$
F	≥ 1.33	variable	≤ 0.40

Table A.6: Level-of-service criteria for pedestrian queuing areas

LOS	Space (P/ m^2)
A	≤ 0.83
B	$0.83 - 1.11$
C	$1.11 - 1.67$
D	$1.67 - 3.33$
E	$3.33 - 5.0$
F	≥ 5.0

Values of levels-of-service are depicted in table A.4 for walkways and sidewalks, table A.5 for stairs, and table A.6 for queuing areas (TRB 2000), (Milazzo et al. 1999).

An impression of the densities corresponding to the levels-of-service and a description of each level-of-service is shown in figure A.2.

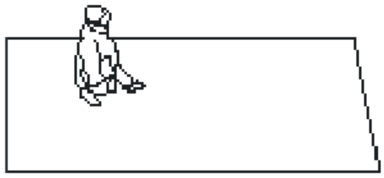
Extra levels-of-service might be introduced in SimPed, for example level-of-service A1 might be used to find the areas where no or hardly any passengers appear (very low densities). At these locations, personal security might become an issue. Since the area is not used for walking, the efficiency of the design might be increased by changing the function of this area, for example into commercial facilities. When a station manager has set limits to occurring densities, for example a density higher than 1.9 P/m^2 may not occur in the station, a level-of-service (LOS C in this case) might be split into two, where all higher levels-of-service are 'good' and all lower levels-of-service are 'not allowed'.

A.3.2 Qualitative levels-of-service

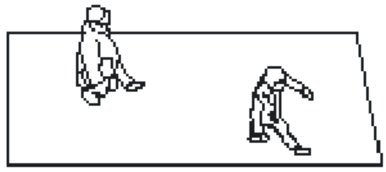
Although quantitative measures of flow, density, and speed affect convenience factors, additional environmental factors should be taken into account. These factors contribute to the walking experience and ultimately to the perceived level-of-service. The combined effects of quantitative and qualitative performance measures contribute to the level-of-service of a particular facility. The following qualitative performance measures have been distinguished (Benepe 1965), (Dixon 1996), (Khisty 1994), (Miller et al. 2000), (Mori & Tsukaguchi 1987), (Morrall 1985), (Rogers 1965), (Sarkar 1995), (Sarkar 1993), (Seneviratne & Morrall 1985*b*):

- Attractiveness, considering latent functions such as pleasure, delight, interest, and exploration.
- Comfort, containing factors such as weather protection, climate control, properly designed shelters, condition of walking surface, cleanliness of terminals, and provision of adequate seating arrangements.
- Convenience with respect to pathway directness, grades, sidewalk ramp locations, directional signing, activity maps and directories, convenient connections between frequently used locations, and other features making walking easy and uncomplicated.
- Safety. In transfer stations and in other vehicle-free areas such as malls, stairs, elevators, and escalators, ease of movement in walking is also considered part of safety.
- Security. The ability to design pedestrian facilities that provide clear observation by the public and the police through unobstructed lines of sight, good lighting, absence of concealed areas, and camera surveillance is considered a measure of good performance.

LOS A
Pedestrian density < 0.18 P/m^2; flow ≤ 0.27 P/ms
At a walkway LOS A, pedestrians move in desired paths without altering their movements in response to other pedestrians. Walking speeds are freely selected, and conflicts between pedestrians are unlikely.

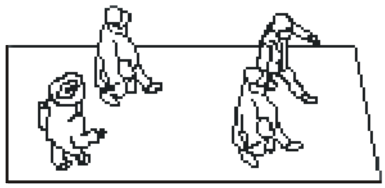


LOS B
Pedestrian density 0.18-0.27 P/m^2; flow 0.27-0.38 P/ms
At LOS B, there is sufficient area for pedestrians to select walking speeds freely, to bypass other pedestrians, and to avoid crossing conflicts. At this level, pedestrians begin to be aware of other pedestrians, and to respond to their presence when selecting a walking path.



LOS C
Pedestrian density 0.27-0.45 P/m^2; flow 0.38-0.55 P/ms
At LOS C, space is sufficient for normal walking speeds, and for bypassing other pedestrians in primarily unidirectional streams. Reverse-direction or crossing movements can cause minor conflicts and speeds and flow rate are somewhat lower.

LOS D
Pedestrian density 0.45-0.71 P/m^2; flow 0.55-0.82 P/ms
At LOS D, freedom to select individual walking speed and to bypass other pedestrians is restricted. Crossing or reverse-flow movements face a high probability of conflict, requiring frequent changes in speed and position. The LOS provides reasonably fluid flow, but friction and interaction between pedestrians is likely.



LOS E
Pedestrian density 0.71-1.33 P/m^2; flow 0.82-1.25 P/ms
At LOS E, virtually all peds restrict normal walking speed, frequently adjusting gait or shuffling. Space is not sufficient for passing slower peds. Cross or reverse flow movements are possible only with extreme difficulties. Design volumes approach limit of walkway capacity, with stoppages and interruptions to flow.

LOS F
Pedestrian density ≥ 1.33 P/m^2; flow varies
At LOS F, all walking speeds are severely restricted; forward progress is made only by shuffling. There is frequent, unavoidable contact with other peds. Cross- and reverse-flow movements are virtually impossible. Flow is sporadic and unstable. Space is more characteristic of queued peds than of moving ped flows.

Figure A.2: Impression and description of levels-of-service on a level walkway (TRB 2000)

- System coherence. Mental imagery and selectivity play a major role in perceiving and understanding the world of time and space. A strong correlation exists between activity systems and the cognitive images people have of the physical environment. Even perception of the distance of facilities is affected by such things as the geometry of paths.

- System continuity. Continuity is particularly important for multimodal facilities connected to pedestrian paths that unify the system efficiently.

Although these qualitative factors are very important, only a few of them are included in the simulation tool, such as safety, system coherence, and system continuity.

A.3.3 Analytical analyses

Van der Spek (2003) developed the (static) connector value, in which the performance of the composition of a transfer station is measured with respect to average transfer distance. Also, the number of transfers is taken into account. However, it is erroneous to focus on averages or static measures: it is the local extremes that will limit the performance of a facility during a critical period. Therefore, SimPed follows the method described in De Neufville & Grillot (1982) to give a complete and detailed analysis of pedestrian flows at specific areas:

- Determine loads on the area, taken over the identified critical time appropriate to that particular area.

- Calculation of the area width needed for the pedestrian flow, based on the level-of-service expected of that facility.

- Calculation of the range of queue length and areas at service facilities, associated with the various service rates that are provided.

- Integration of the previous steps into a complete, detailed analysis of the interaction of flows and queues at the potential trouble spot. This includes taking care of obstacles occupying area not available to pedestrians.

Economic analyses have not been included in the simulation tool, see for this e.g. Seneviratne & Wirasinghe (1989).

A.3.4 Formulation of criteria

The Dutch railway company uses the levels-of-service shown in table A.7 for different parts of the infrastructure and different types of pedestrian flows (Van Soeren 1996).

Table A.7: Minimum levels-of-service for different types of infrastructure

Infrastructure	Pedestrian flow	Level-of-service
Platform	Walking	D
	Waiting	C
	Boarding passengers	E
Stairs		E
Tunnel / passage	Walking	D
Hall	Walking	C
	Waiting	C

The Dutch Railway Company NS Reizigers (1999) aims to facilitate railway stations for large pedestrian flows, while also CROW (1998) indicates design criteria for bus stations concerning pedestrians. Translated to the design of the transfer, they aim at minimisation of travel times and improvement of subjective or perceived travel time.

Other methods and criteria for the dimension of pedestrian facilities have been developed for:

- Walkways, crossings, and urban areas (Brilon 1993), (Kirsch 1964), (Oeding 1963), (Schubert 1990), (TRB 2000).
- Places of residence (Müller 1971).
- Airports (Davis & Braaksma 1988), (De Neufville & Grillot 1982).
- Buildings (Pauls 1984), (Predtetschenski & Milinski 1971).

The most important and quantitative requirements selected from the mentioned sources are listed beneath:

- Connection function.
  - Maximum density allowed is 0.56 P/ m^2 with a corresponding walking speed of 1.2 m/ s and a capacity of 0.68 P/ m s.
- Hall function.
  - Circulation area is 40% of the net surface, needed for the performance of the processes being part of the hall function. This area is divided over walking and waiting passengers, depending on the corresponding numbers of travellers.
  - The waiting area has a minimum of 4 seats with 1.5 m^2 gross per seat and for each standing place 1 m^2. The capacity of the standing waiting area is 1% of the total number of boarding and alighting passengers per day.

- Platform function.
  - When the walking time between the hall and the platform is more than 3 minutes, the platform needs a separate waiting facility.
  - Just as for the hall, the circulation area on a platform is 40% of the net surface.
  - The platform has a seat capacity of 0.2% of the number of boarding and alighting passengers at the platform with a minimum of 4 seats.

A.4 SimPed standard output

SimAnalysis is a dedicated application to automatically generate standard output. As indicated in chapter 7, the application is implemented in Microsoft Access, in which format the simulation results are stored. The user-interface is shown in figure A.3 and consists of a number of buttons. After a click on the button, the user has to supply input parameters and after starting the analysis a dialog is presented with the required output.

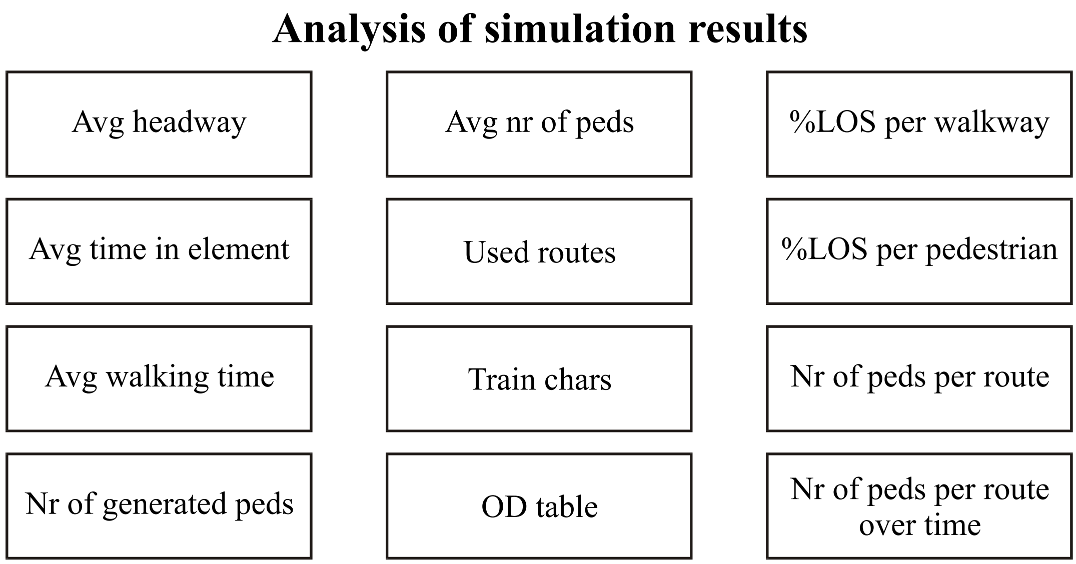


Figure A.3: Interface of analysis application

Two types of output are distinguished. The first part of this section describes analytical output, while the second part includes graphical output.

A.4.1 Analytical results

The following analytical results are automatically calculated by the analysis module of SimPed:

- Average headway at a specific entrance in the model. Input for the calculation is the name of this entrance, which either may be an entrance point or a public transport vehicle door.

- Average time that a pedestrian is present in an infrastructure element. Input may either be an element type (such as stairs, escalators, and gates) or a specific element in which case the name of this element is to be identified.

- Average, minimum, and maximum walking time from a specific origin to a specific destination. Input for this calculation are origin and destination of the considered relation. An origin may be an entrance point, a joint, or a public transport vehicle door, while the destination may be an exit point, or also a joint, or a public transport vehicle door. This way, walking times on complete routes as well as on subroutes are available.

- Average number of pedestrians present in a part of the facility during a specific time period. The specified input consists of the name of the infrastructure element and the begin and end moment of the time period over which the average is taken.

- Numbers of pedestrians per origin-destination relation. Input for this overview is the name of an origin (an entrance point, a joint, or a public transport vehicle door) and the name of a destination (an exit point, a joint, or a public transport vehicle door). Since also a joint may be indicated as an origin or destination, also the number of pedestrians on a partial route may be identified, used by pedestrians with different origins and destinations.

- Overview of all routes used during the simulation, independent of their origin and destination.

- Overview of public transport characteristics. Characteristics may be identified for all public transport vehicles, for all vehicles of a specific public transport service, or only for a specific vehicle.

A.4.2 Figures

The analysis module of SimPed also produces the following figures automatically:

- Numbers of pedestrians in a specific part of the infrastructure over time in relation to the levels-of-service (see figure A.4).

- Spatial overview of routes used by pedestrians from a specific origin to a specific destination (see figure A.5).

- Walking times over time (see figure A.6).

- Numbers of passengers on a specific route over time (see figure A.7).

- Percentage of time that a part of the infrastructure has a specific level-of-service (see figure A.8).
- Percentage of passengers experiencing a specific level-of-service on a specific part of the infrastructure. The resulting figure is similar to figure A.8.

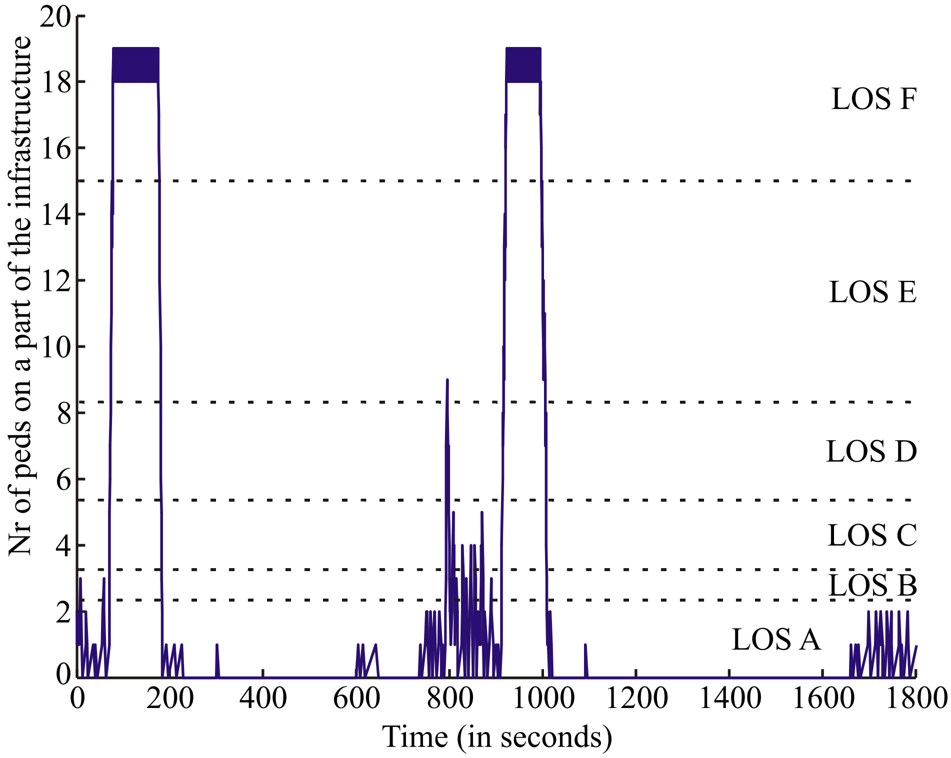


Figure A.4: Density on a part of the infrastructure over time

A.4.3 Animation

Apart from analyses on simulation results and on-line animation, it is also possible to make a file that enables a replay of the animation. This animation may be two or three dimensional, as indicated in chapter 7. Figure A.9 shows a two dimensional animation, in which each part of the infrastructure is coloured according to occurring levels-of-service.

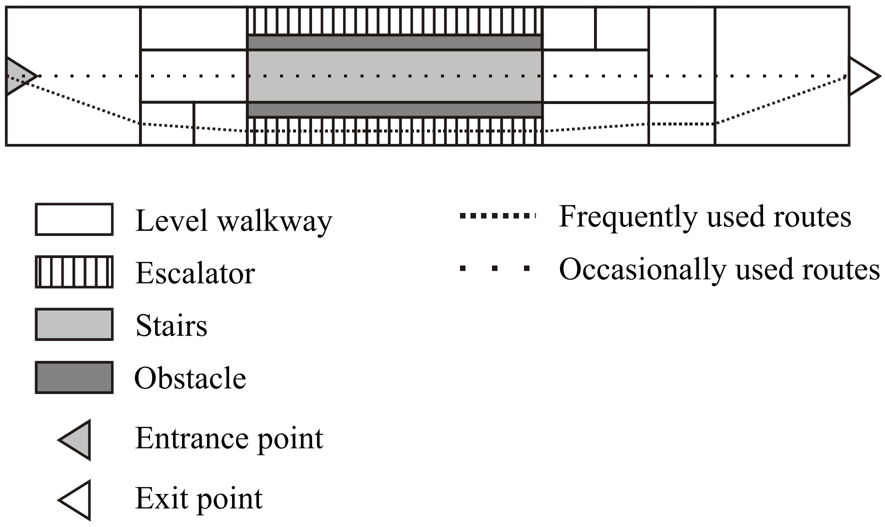


Figure A.5: Alternative routes predicted for passengers between an origin and a destination

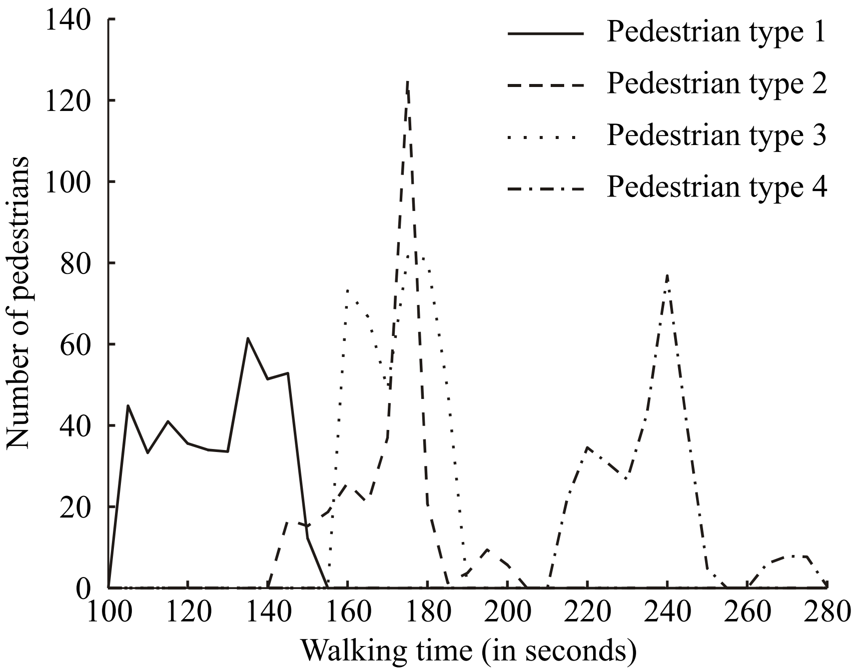


Figure A.6: Walking times distributions of different pedestrian types

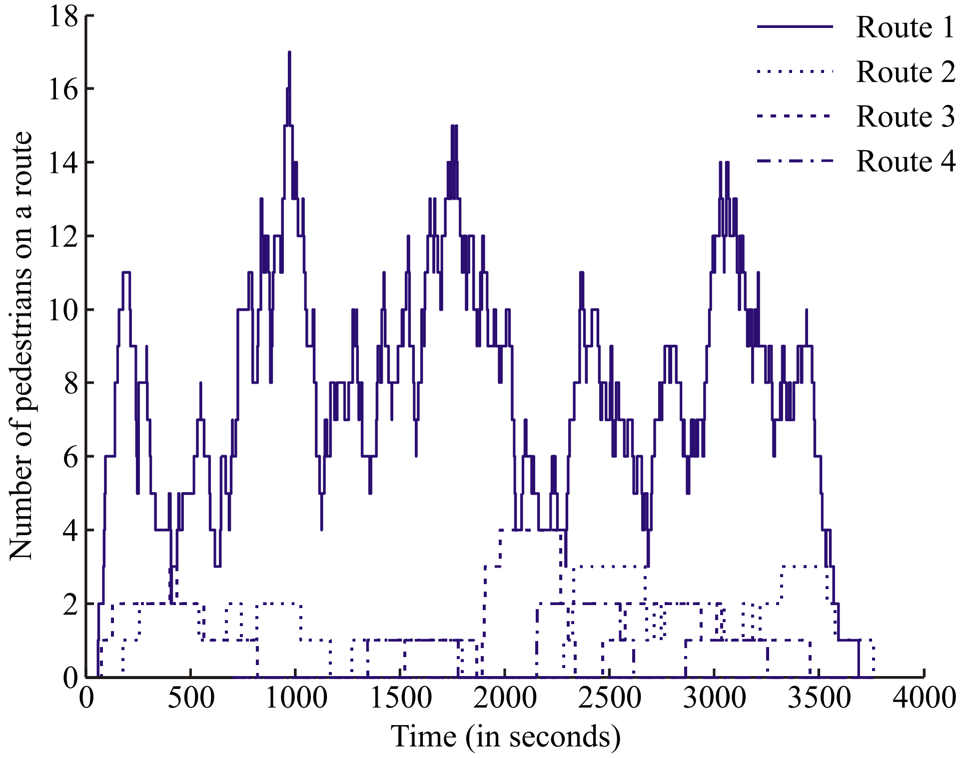


Figure A.7: Distribution of pedestrians on a route over time

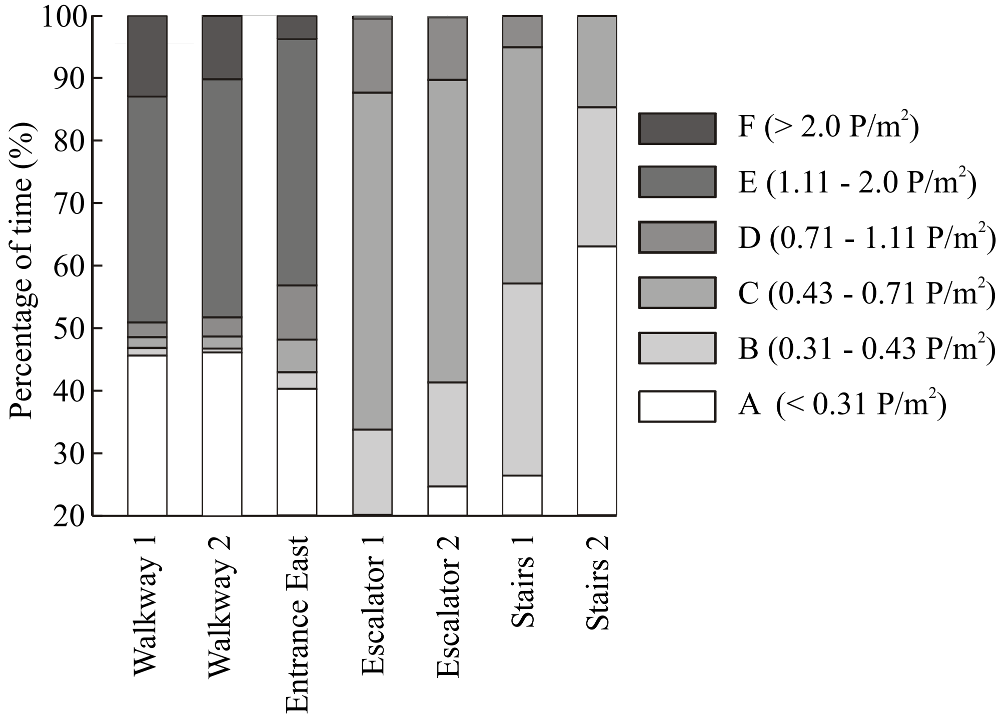


Figure A.8: Levels-of-service summed over time on specific parts of the infrastructure

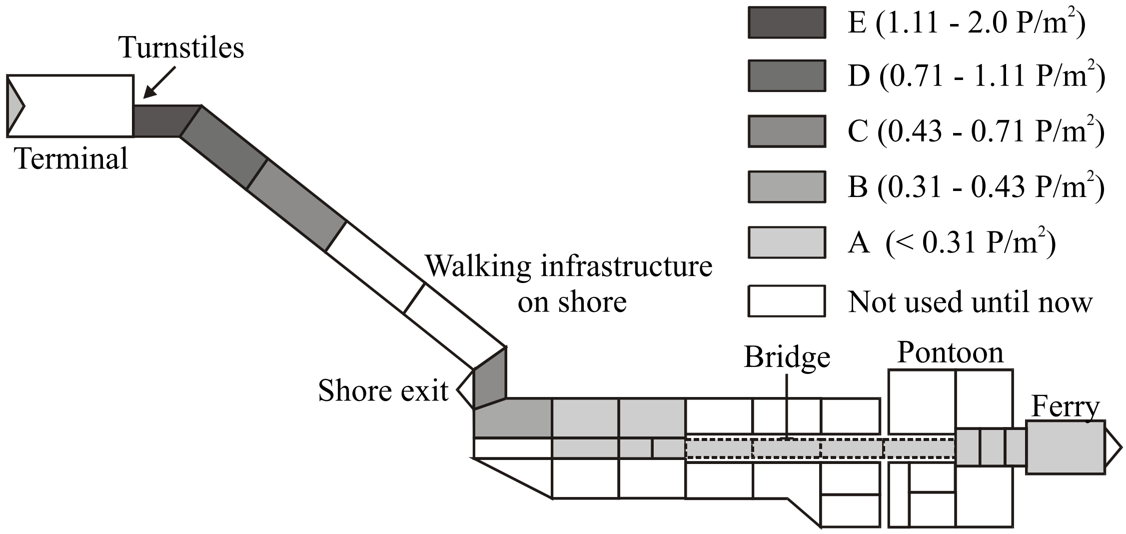


Figure A.9: Example of animation indicating the spatial distribution of pedestrians in the facility at a specific moment in time

Appendix B

Set up and test of the laboratory experiments

This appendix describes the set up of the laboratory experiments (what factors and what responses have been selected and how were the enormous number of potential experiments reduced to the ten performed experiments), what experimental aspects have been tested, which test experiments have been performed, and finally the conclusions of these test experiments are mentioned.

Essential in these experiments is that individual subjects had to perform particular walking tasks.

B.1 Experimental set up

Process variables include both inputs and outputs. Inputs are exogenous variables varied during the experiments and context variables remaining constant during the experiments. Outputs are endogenous variables. Some variables, for example walking speed, may be both endogenous and exogenous, that is pedestrians choose their own speed depending on the walking conditions (endogenous), but they can be assigned to change their free speed in order to catch a train (exogenous variable). The selection of these variables has taken place in a brainstorm process, in which the most relevant and influencing factors and responses have been identified (see subsection B.1.1). The variables not included in chapter 4 are discussed in detail. Depending on the expected influence on the walking process, the most promising variables have been selected, including their ranges (see subsection B.1.2). The final experiments have been chosen as combinations of the ranges of these variables.

B.1.1 Brainstorm experimental and context variables

To determine the (relevant) exogenous variables a long list of tentative variables has been set up:

- Free or desired speed.
- Walking direction.
- Formation of groups.
- Extent in which the free speed is maintained (indicator of aggressiveness).
- Density.
- Bottlenecks.
- Presence of obstacles.
- Size of the floor area.
- Pedestrian flow composition.

The variables free speed, walking direction, density, bottlenecks, floor area size, and pedestrian flow composition have already been discussed in chapter 4. The remaining variables are elaborated on in this section.

Group formation Especially during shopping groups are formed, that is, two or more pedestrians try to stay together in a pedestrian flow. In this experiment three types of groups may be distinguished, namely individuals, pairs, and large groups, where the number of 'members' depends on the number of pedestrians on the area during an experiment.

Extent in which free speed is maintained (indicator of aggressiveness) At higher densities it becomes more difficult to keep a free speed higher than the speed of most pedestrians. Depending on external conditions (for example for someone trying to catch a train) the mental pressure to maintain this relatively high free speed will rise, thus this person will take much trouble to find a path, by overtaking others and changing walking direction for short periods of time in order to maintain his desired speed. Ultimately, he will nudge or even push away pedestrians walking in his way. In this experiment two classes are distinguished, namely pedestrians easily adapting their free speeds and pedestrians maintaining their free speeds as long as possible.

Presence of obstacles Obstacles hinder pedestrians, making them change direction and speed, thus creating unpredictable situations with more pedestrian interactions. The following characteristics of obstacles are important:

- Size (length, width, and surface of the ground area).
- Shape (in both horizontal and vertical direction).
- Sight (material, cleanliness).
- Number of obstacles.
- Location (inside or outside the flow).

Types of obstacles can hardly be changed during an experiment. Only number, size, and location of obstacles may be changed.

B.1.2 Choice of exogenous variables

Over all, nine exogenous variables have been distinguished. When these variables are combined in all possible ways, tens of thousands of experiments would result. This is impossible to handle, so the number of exogenous variables is reduced, the variable ranges are restricted, and the number of combinations of variables is decreased. Furthermore, a smart selection of variable values makes it possible to derive many relations from a reduced number of experiments.

The aspect ‘formation of groups’ is left out of the experiment. Especially during morning peak hours, most public transport passengers travel alone and do not have any attraction towards other passengers. Then, the variable regarding the adaptability of the free speed is combined with free speed. It is assumed that pedestrians with a (significantly) higher free speed are in a hurry and therefore they are more willing to maintain this free speed. Slowly walking pedestrians feel no pressure and will therefore sooner adapt their speed. The remaining exogenous variables are:

- Free speed.
- Direction.
- Bottleneck width.
- Density.
- Size of the floor area.
- Pedestrian flow composition.

Also, ranges of values of exogenous variables have been restricted, which are shown in table B.1 (see also section 4.4).

Table B.1: Value ranges of process variables of the experiments

Speed	Direction	Bottleneck	Density	Floor area	Flow comp.
normal	west-east	none	0.25%	10×4 m	100%-0%
high	east-west	2 m wide	0.50%	8×8 m	50%-50%
low	south-north	1 m wide	0.75%		10%-90%
	north-south				

B.1.3 Determining the final experiments

An important aid for the final determination of the experiments is the 'analysis matrix'. This matrix describes experiments in a structured way. The columns of the matrix contain different exogenous variables, whereas the rows describe different experiments. Each cell contains the value of a variable. Combining these variables leads to different experiments, which are then given a priority value.

Variables playing a part in the determination of the experiments are free speed, direction, density, bottlenecks, area size, and pedestrian distribution. During an experiment the density is varied by adding and removing groups of pedestrians, while the remaining variables are constant. Looking only at the fixed variables, 432 ($= 3 \cdot 6 \cdot 3 \cdot 2 \cdot 4$) experiments are distinguished. This number is reduced further by excluding 'impossible' or inconvenient combinations of variables (for example having bottlenecks in multi directional pedestrian flows). Even after removing these 'conflicting' experiments, 144 experiments are left. Therefore, additional priorities have been set:

- Different free speeds of pedestrians are only relevant in one directional flows without bottlenecks. In this reference variant the influences of these free speeds are determined and can later be added in the rest of the experiments.

- The first variant (all pedestrians keep normal free speed, one directional flow, and no bottlenecks) will be the 'reference' variant. To compare the influence of the exogenous variables, only one of these variables will deviate from the values in the reference variant.

- Size of the pedestrian area depends on the walking directions. Crossing flows require a square (8 m × 8 m), while a rectangular area (10 m × 4 m) is more convenient for one directional and opposite flows.

Application of these additional priorities leads to ten experiments (see table 4.3). Figure B.1 provides a graphical overview of the experiments, where arrows indicate the pedestrian flows. The areas valid for each experiment are indicated by the thick lines in figure B.1.

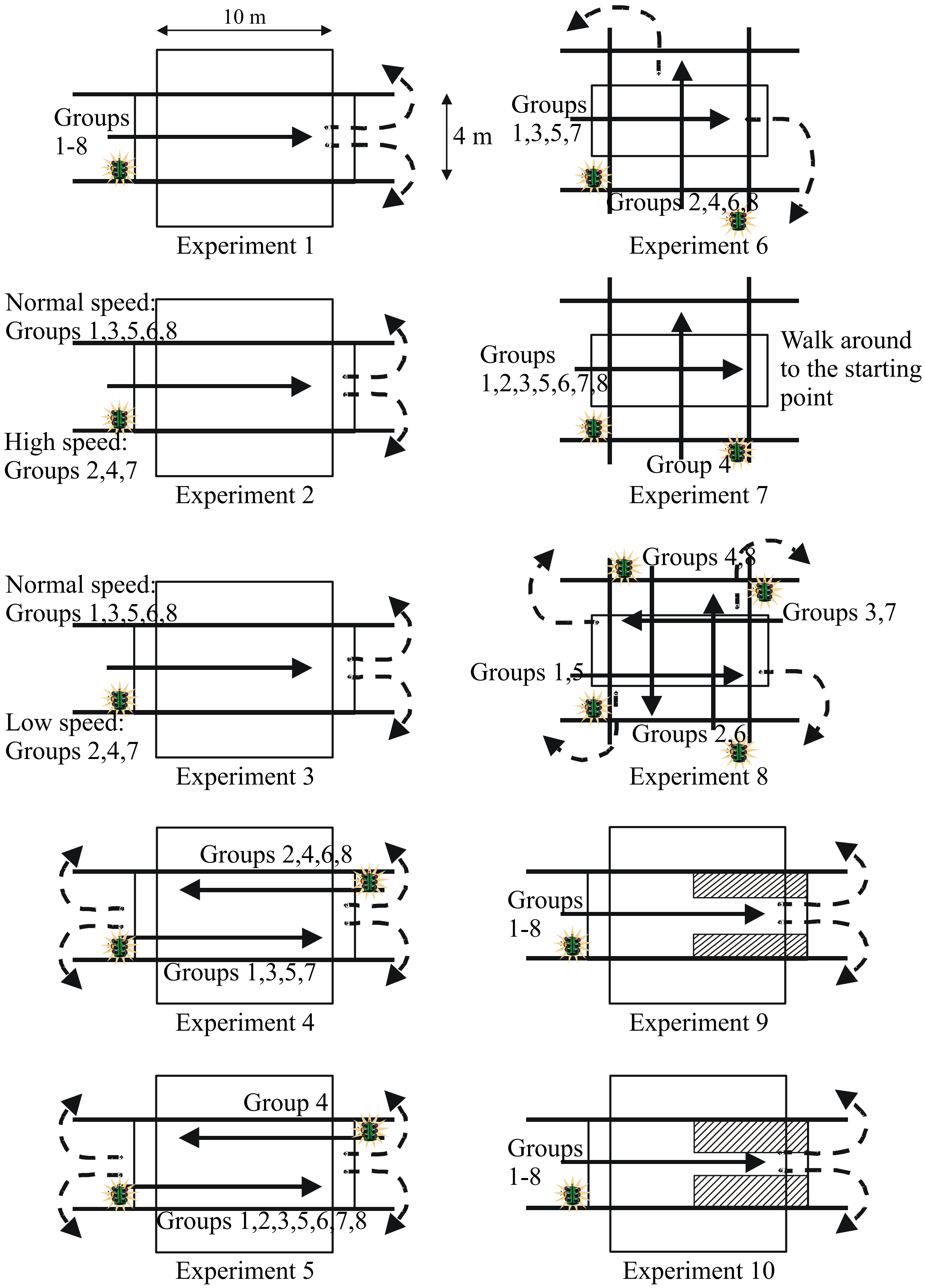


Figure B.1: Overview of the ten experiments, including walking back

B.2 Test experiments

Test experiments have been performed to study aspects of observation more closely as well as to see whether the experiments can be carried out the proposed way. The aspects are both in the technical area and in the organisational area:

- Technical aspects.
  - Position of the camera.
  - Contrast between different pedestrians and the background.
  - Visibility of the area marking.
- Organisational aspects.
  - Working with group leaders.
  - Functioning of the instructions.
  - Working with a clock to measure headway times.
  - Working with traffic lights.

Before the test experiments

- Markation of the observed areas with lines on the floor and pylons. The lines for the limitation of the walking area are marked with tape (easily removable and leaving the underground intact). In order to carry out the experiment with two observed areas, both areas are put up in advance. The areas have, like in the final experiment, a length of 10 m and a width of 4 m. To prevent returning pedestrians to accidentally enter the observed area pylons are placed around the area.
- Preparation of obstacles. The obstacles used in the test experiments are panels of wicker-work with a width of 1 m. For the final experiments green boards are used, which can be coupled in triangles or squares, thus creating any bottleneck form.
- Detection of pedestrians. To detect and distinguish different pedestrians, caps or building helmets (easy to attach numbers on) may be used. However, not everybody likes to wear this kind of head-gears. Therefore, also vests are tested with some kind of barcode on both shoulders. To distinguish caps, combinations of cap colours (preferably primary colours red, yellow, and blue), attached numbers or forms and their colours are tried. During the test experiments different pedestrians are equipped with different kind of identification to get an image of the distinction measure.
- Testing the quality of the video footage.

After the test experiments

- Assimilation of the results of the evaluation of the test experiments.
- Evaluation of the technique (usefulness/clearness of images, especially for the observation of microscopic pedestrian behaviour).
- Evaluation of the organisation.
- Evaluation of the plan of the seven experiments.
- Checking the appropriateness of the images for automatic data assimilation.

B.2.1 Principles to test

Seven experiments have been constructed to test several principles of the walking experiments, such as walking back of pedestrians towards the starting point during the experiment, observation of dense crowds with video cameras, two directional flows, and pedestrian reaction to a bottleneck. Figure B.2 gives a graphical overview of the test experiments, while in the sequel each test experiment is discussed in more detail.

Test experiments 1-3: Walking around

In the experiments, participants are divided into groups. The first group starts the experiment. If all pedestrians start to enter the area at the same time, the density over space and over time is not uniform. Therefore, pedestrians start with a headway (calculated in advance) which will separate them. Starting moments for each pedestrian to enter the area are managed by the group leader.

The experiment starts by ordering the participants in a queue in front of the area. The group leader has an overview of the starting moments of all pedestrians. The moment the first pedestrian enters the area, the clock starts. The group leader gives a signal to the next participant to enter the area by turning a traffic light to green (and back to red afterwards). This continues until all group members have entered the area, including the group leader.

Pedestrians walk with their desired speed over the area, follow the most suited path, and react to other pedestrians in a usual way (overtaking, side-stepping). The moment a pedestrian reaches the end of the area, he looks at the clock and calculates the moment he has to re-enter the area on the other side, at the starting point. After leaving the area, the pedestrian walks back towards his starting point, avoiding the surveyed area marked with cones. Back at the starting point, the pedestrian waits until the moment has come he can re-enter the area and the process repeats from the beginning.

To maintain headways in the first test experiment, a fixed time period of 20 s to walk back to the starting point has been provided. Each pedestrian has to take care of his own

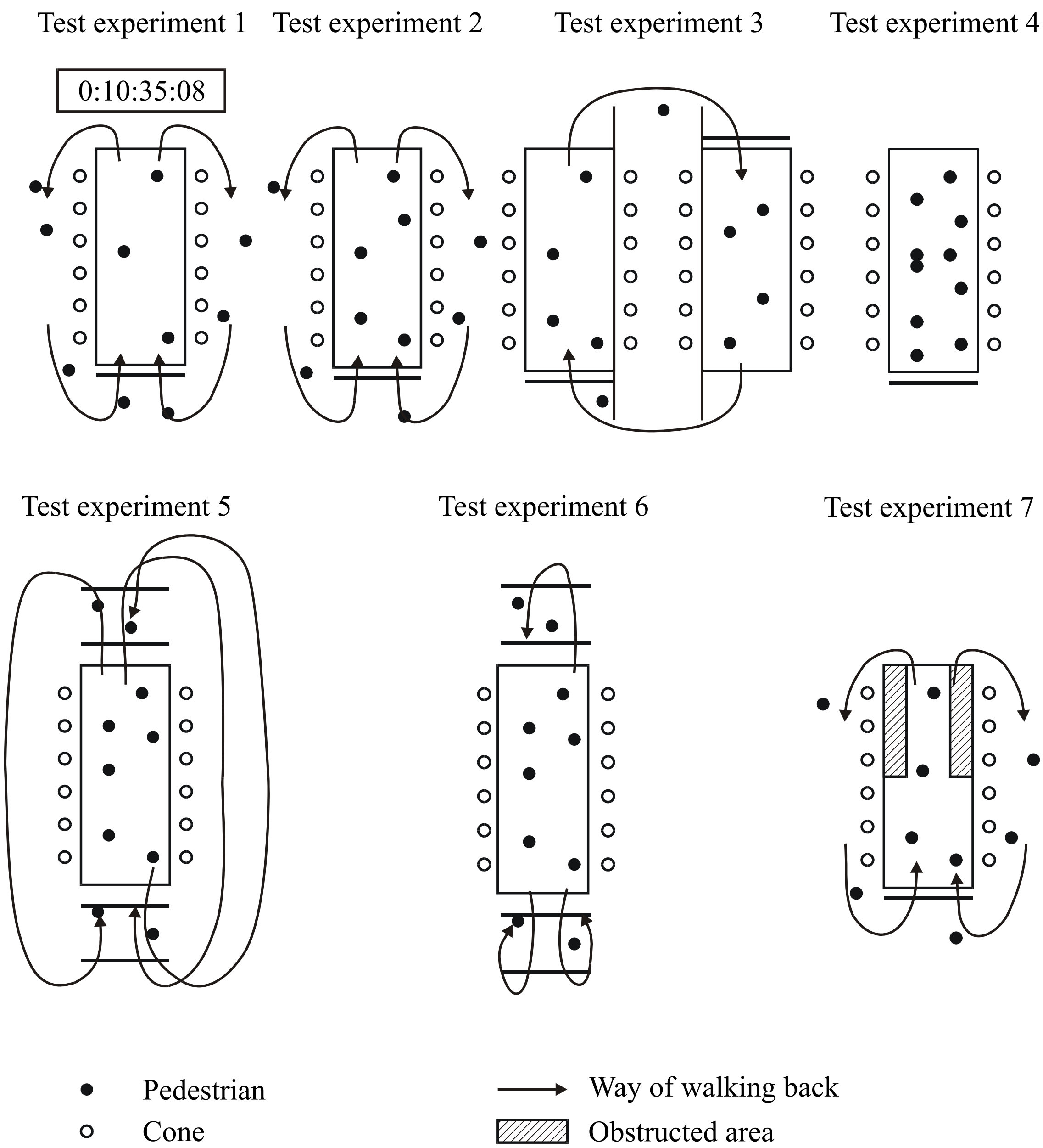


Figure B.2: Overview of the performed test experiments 'walking back time' and re-enter the area at the right moment. This way, the outgoing flow is similar to the incoming flow 20 s later. One of the disadvantages is that pedestrians cannot maintain their desired speed while walking back. The flow, however, will remain equal. In practice, this principle appeared too complex. The clock was not good visible from all positions, but pedestrians forgot to look at it when they left the area. Also, it was hard to add up 20 s and at the same time concentrating on walking. This resulted in complex, confusing situations which did not lead to the intended goal of uniform flows and densities over time and space.

Another way of leading pedestrians to the area is to leave them free in walking back to the starting point, being tested in the second test experiment. All other behaviour in the test was similar to the first test experiment. This resulted in a continuous flow and was easy to interpret by the participants.

Until now, only one area has been observed, while pedestrians had to walk back towards their starting point for a new observation. It would be more efficient when also the walking back movement could be observed. Therefore, a second area was marked next to the first one and tested in the third test experiment.

Again, the experiment started by ordering the participants in a queue in front of the area on the left. Pedestrian walking behaviour is again similar to normal conditions. After leaving the area, pedestrians walk to the next area and enter it. On the area pedestrians behave ordinary until the end of this area is reached. The first area can then be re-entered and the process continues.

Unfortunately, pedestrians diverted at the end of the area already in the direction of the second area, even though the lines at the sides of the areas were prolonged and cones were set, which the pedestrians had to walk around. This influenced the observed walking patterns and especially space use significantly.

Observing

Crowding is created to test whether the equipment is well adjusted for automated assimilation of data by the developed software, even in unfavourable conditions with many pedestrians on a very small area. The assignment is therefore to move through the area arbitrarily. To enlarge chaos and hindrance, four groups are formed. Pedestrians are given a specific assignment, such as speedy walking (in order to catch a train), normal walking, slow walking (during shopping or window hopping), and looking for conflicts.

Special experiments

Until now, only one directional flows have been tested, but the final experiments include multi directional flows. Test experiments 5 and 6 are used to see which method of walking back to the starting point is most effective in the case of two directional flows. In experiment 5 both pedestrian flows walk back towards their starting point, while in experiment

6 pedestrians walk to a line behind the area, turn around, and walk back over the area. Walking back after the line (experiment 6) again created chaotic situations, so the method of experiment 5 is applied.

The final test experiment concerned pedestrian behaviour in a bottleneck (test experiment 7). The total speed-density diagram needs to be observed and thus a bottleneck is created. The final appearance of the bottlenecks is not decided on yet, but for the test experiments light screens have been used. During the test experiment the reaction of pedestrians on the bottleneck has been observed. It was seen that pedestrians do not have the intention to push the screens aside and no panic has occurred either.

B.2.2 Conclusions

From the completed test experiments a number of conclusions have been drawn. These are ordered with respect to organisational aspects, technical features, experiments, pedestrians, and interpretation of the results.

Organisational aspects

1. While explaining experiments, demonstrate the walking patterns. This may be done by the group leaders, who are informed in advance.

2. Watch the duration of the experiments; an experiment must not take too long, for people get annoyed and their walking behaviour is influenced by their mindset. After the test experiments, which took about an hour, all participants were quite tired. Therefore, breaks between experiments need to be provided and chairs need to be available, as well as drinks and some small snacks.

3. Use a microphone while speaking to the audience. Otherwise, it is hard to be heard in a large hall.

4. Use a projector and slides to explain the experiments, possibly even in a dynamic way with dots moving over the screen, representing pedestrians.

5. During the explanation, the choice of words needs to be consistent. Also, the area and the sheets used for explanation need to be similar.

6. Managing 20 persons participating in the test experiments was already a challenge. Management in the final experiments need to be prepared and thought over carefully (good preparation, good appointments and allocation of tasks, detailed planning).

7. Make sure that pedestrians form clear queues before the area, so everybody knows whose turn it is to enter the area.

8. The use of caps in different colours implies that participants must not wear clothes in these colours (to be announced in the invitation). This is needed for an automated interpretation of the data (a person with a red sweater and a red cap becomes one blurred spot, the next moment falling apart again in different persons, thus introducing complete chaos).

Technical aspects

1. It is only possible to view one area of 10 m × 4 m with this combination of video camera and lens.
2. To improve image quality, it is better to use a digital camera. With improved images, automated processing of the data is possible.

Experiments

1. Make sure participants walk straight over the area by extending the sidelines significantly.
2. Use one observation area. Surveying two areas at the same time encourages walking in circles. In the lower field, the upper part is used, while in the upper field the lower part is used.
3. Do not restrict walking back. Walking back to the starting point in a fixed time period is too complex for the participants. Uncoordinated walking back does not have significant influence on the behaviour at the beginning of the area. The second test experiment worked out fine. Also, the intensities did not fluctuate as expected, but remained regular.
4. Use a traffic light controlled by a staff member to impose initial headways. The headway at the beginning of the experiment (which was calculated in advance) is hard to follow.
5. Assign each pedestrian one walking direction. The experiment with a two directional flows is less chaotic when participants walk back towards their starting point instead of moving in both directions over the area (turning back when they arrive on the other side).

Pedestrians

Experiments appear to be quite intense (tiring). It would be preferable to have people participating the experiments only half a day. This will also prevent bias of lower walking speeds due to tired pedestrians.

Interpretation of the results

1. Red caps may be used to follow different pedestrians in order to observe their trajectories. Especially the lid of the cap is significant.
2. Numbers or figures on the cap to identify individuals are not visible on the video data.

Appendix C

Dynamic quality of the route choice model

C.1 Introduction

As indicated in section 6.4, the current route choice model approximates actual dynamic route choice by recalculating shortest routes through a network after short periods of time. This update interval is an input parameter and depends on the required level of detail of the simulation results. When this time interval is very short (in the order of 1 s), the results of the route choice model will approximate a dynamic deterministic user optimal equilibrium flow pattern. This is demonstrated in this appendix, taking into account the influences of route length, demand distribution over time, and update intervals.

Each scenario (defined by combinations of the variables mentioned above) is evaluated on the distribution of the flow over the alternative routes, fluctuations in this distribution over time, and walking times on the alternative routes. The overall result is to see whether the equilibrium principle is met.

C.2 Analysis set-up

Variables to be varied are route length, demand distribution, and update interval, each of which are discussed in more detail below.

In order to consider the distribution over routes with different lengths, a situation is modelled with two routes. Route 1 is the shortest walkway with a length of 142.8 m, whereas route 2 has a length of 154.9 m (see figure C.1). Both walkways are 2 m wide.

Two distributions describing the demand of pedestrians over time are applied. A 'uniform' demand indicates a continuous flow of pedestrians, uniformly distributed over time. A 'normal' demand is a demand with a normal distribution with a mean of 50% of the

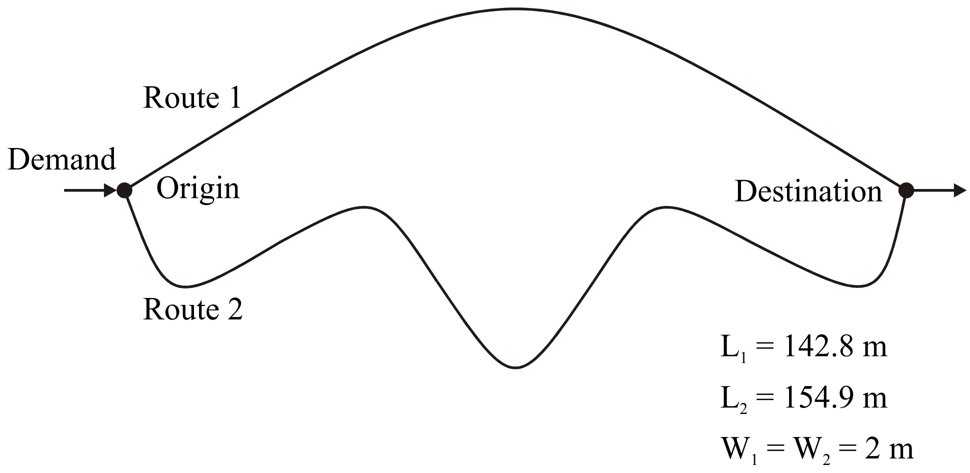


Figure C.1: Lengths and width of the compared routes

total simulation period of one hour (= 30 min) and a standard deviation of 12.5% (= 7.5 min). These two distributions are shown in figure C.2. The total number of pedestrians generated in each simulation is 6000 per hour.

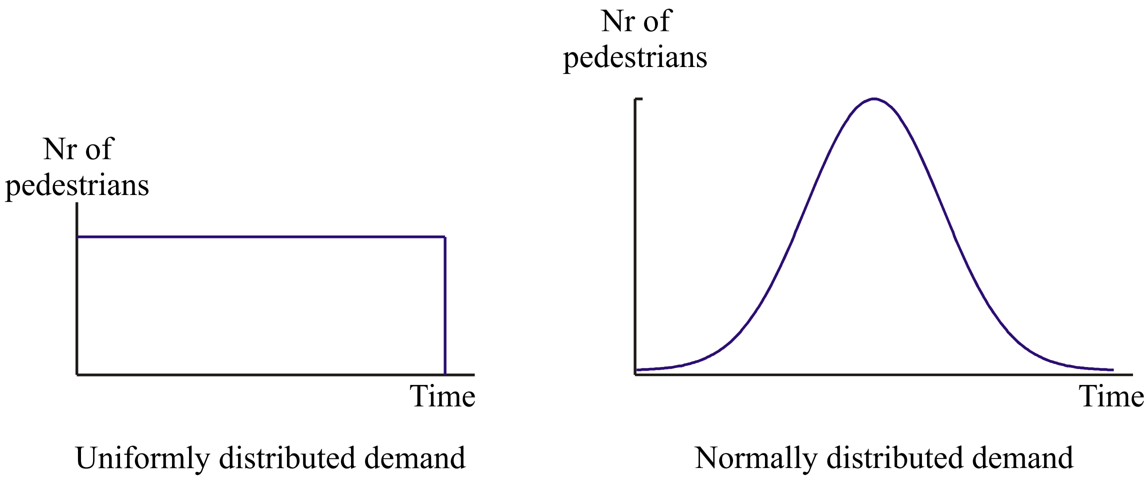


Figure C.2: Distributions describing pedestrian demand over time

The update interval is varied between *one second* to approximate continuous choice conditions and *one minute* (discrete route choice in time, where the results of route updates become clearly visible).

Table C.1 shows an overview of the scenarios, with a reference to the section in which the results of each scenario are presented.

Different assignment approaches are compared by looking at resulting pedestrian densities and walking times (both means and fluctuations around the means over time).

Table C.1: Aspects with respect to route choice

	Equal routes		**Different routes**	
Demand	Continuous (1 s)	Discrete (1 min)	Continuous (1 s)	Discrete (1 min)
Uniform	C.4.1	C.4.1	C.4.3	C.4.3
Normal	C.4.2	C.4.2	C.4.4	C.4.4

C.3 Findings

Table C.2 shows the mean and variance in densities of each of the two routes for all scenarios, whereas table C.3 shows the mean and variance in walking times on each of the two routes for all scenarios. A graphical summary of all these numbers is depicted in figure C.3. In the following, graphs are shown for each route of the distribution of density and walking times during the simulation periods for each of the eight scenarios.

Table C.2: Mean and variance of resulting densities in each of the route choice scenarios (in P/mš)

	Equal routes		**Different routes**	
Demand	Continuous (1 s)	Discrete (1 min)	Continuous (1 s)	Discrete (1 min)
Uniform	$\mu_1 = 0.30$ $\sigma_1 = 0.002$ $\mu_2 = 0.30$ $\sigma_2 = 0.002$	$\mu_1 = 0.28$ $\sigma_1 = 0.012$ $\mu_2 = 0.32$ $\sigma_2 = 0.013$	$\mu_1 = 0.52$ $\sigma_1 = 0.004$ $\mu_2 = 0.12$ $\sigma_2 = 0.001$	$\mu_1 = 0.44$ $\sigma_1 = 0.020$ $\mu_2 = 0.17$ $\sigma_2 = 0.010$
Normal	$\mu_1 = 0.90$ $\sigma_1 = 0.180$ $\mu_2 = 0.90$ $\sigma_2 = 0.179$	$\mu_1 = 0.92$ $\sigma_1 = 0.300$ $\mu_2 = 0.97$ $\sigma_2 = 0.258$	$\mu_1 = 0.94$ $\sigma_1 = 0.184$ $\mu_2 = 0.95$ $\sigma_2 = 0.129$	$\mu_1 = 1.03$ $\sigma_1 = 0.274$ $\mu_2 = 1.03$ $\sigma_2 = 0.234$

As could be expected, update periods of one second give a more stable distribution of pedestrians (small density variances) over the two routes than route updates each minute. Also, the walking time along each route is more stable for continuous updates than in the discrete case. In the scenarios with long update intervals a flip-flop effect is seen, resulting from the all-or-nothing assignments during each interval.

The normally distributed demand is clearly visible in the amount of pedestrians using each route, with a peak after 30 min. The mean walking times differ in the scenarios with such a demand and different routes, due to the fact that at small demands, pedestrians choose for the shortest route and only when the demand exceeds the demand in which the walking times on both routes are similar, pedestrians choose for the longer route. Since the walking times are averaged over pedestrians (and not over simulation time), these smaller walking times at the beginning and the end of the simulation have a significant influence on the mean walking time.

Table C.3: Mean and variance of resulting walking times in each of the route choice scenarios (in seconds)

	Equal routes		**Different routes**	
Demand	Continuous (1 s)	Discrete (1 min)	Continuous (1 s)	Discrete (1 min)
Uniform	$\mu_1 = 104.91$ $\sigma_1 = 0.660$ $\mu_2 = 104.97$ $\sigma_2 = 0.675$	$\mu_1 = 104.76$ $\sigma_1 = 4.066$ $\mu_2 = 105.38$ $\sigma_2 = 5.941$	$\mu_1 = 109.68$ $\sigma_1 = 1.905$ $\mu_2 = 110.69$ $\sigma_2 = 0.257$	$\mu_1 = 108.12$ $\sigma_1 = 12.869$ $\mu_2 = 111.40$ $\sigma_2 = 2.118$
Normal	$\mu_1 = 128.52$ $\sigma_1 = 352.516$ $\mu_2 = 128.47$ $\sigma_2 = 350.107$	$\mu_1 = 134.93$ $\sigma_1 = 1363.360$ $\mu_2 = 135.73$ $\sigma_2 = 889.646$	$\mu_1 = 130.89$ $\sigma_1 = 425.127$ $\mu_2 = 139.88$ $\sigma_2 = 305.771$	$\mu_1 = 139.86$ $\sigma_1 = 1009.104$ $\mu_2 = 148.72$ $\sigma_2 = 786.926$

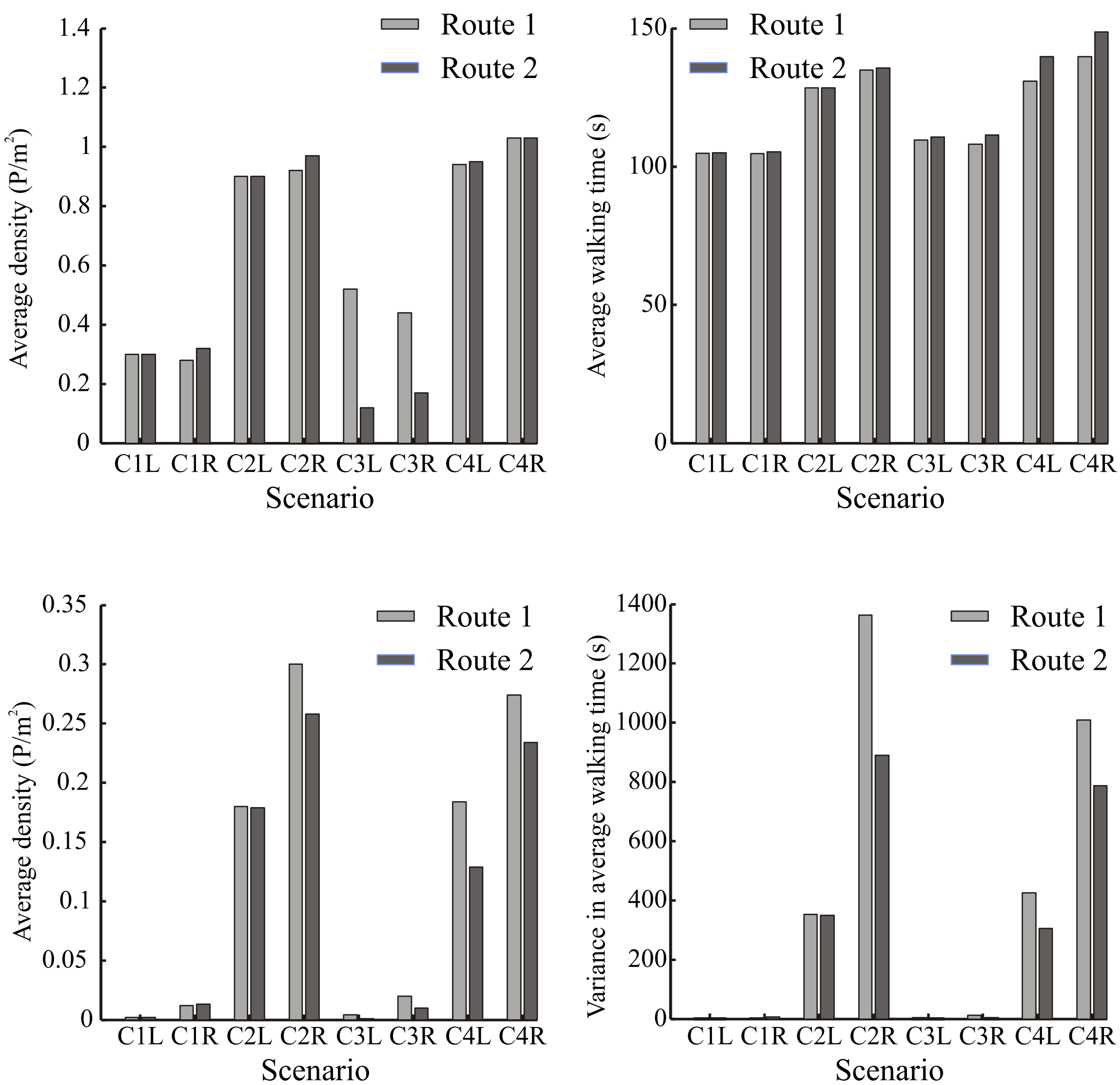


Figure C.3: Results of the different scenarios for the comparison of route choice

Routes with different lengths attract different numbers of pedestrians. In the continuous case (with a uniform distributed demand) 80% of the pedestrians choose the shortest route, whereas 20% chooses the longest route; travel time on both routes then equals about 110 s. These large differences are due to the form of the speed-density relation. In our case, speed decreases only slightly when density increases. Density therefore has to increase significantly before it affects walking behaviour. When routes are updated each minute, a much larger spread over the routes is found, in which the longest route is regularly not used at all.

C.4 Conclusion

The conclusion may be drawn that, when the update interval is chosen sufficiently small, the current route choice model in SimPed approximates a dynamic deterministic user-optimal equilibrium flow pattern sufficiently well.

C.4.1 Equal routes, uniformly distributed demand

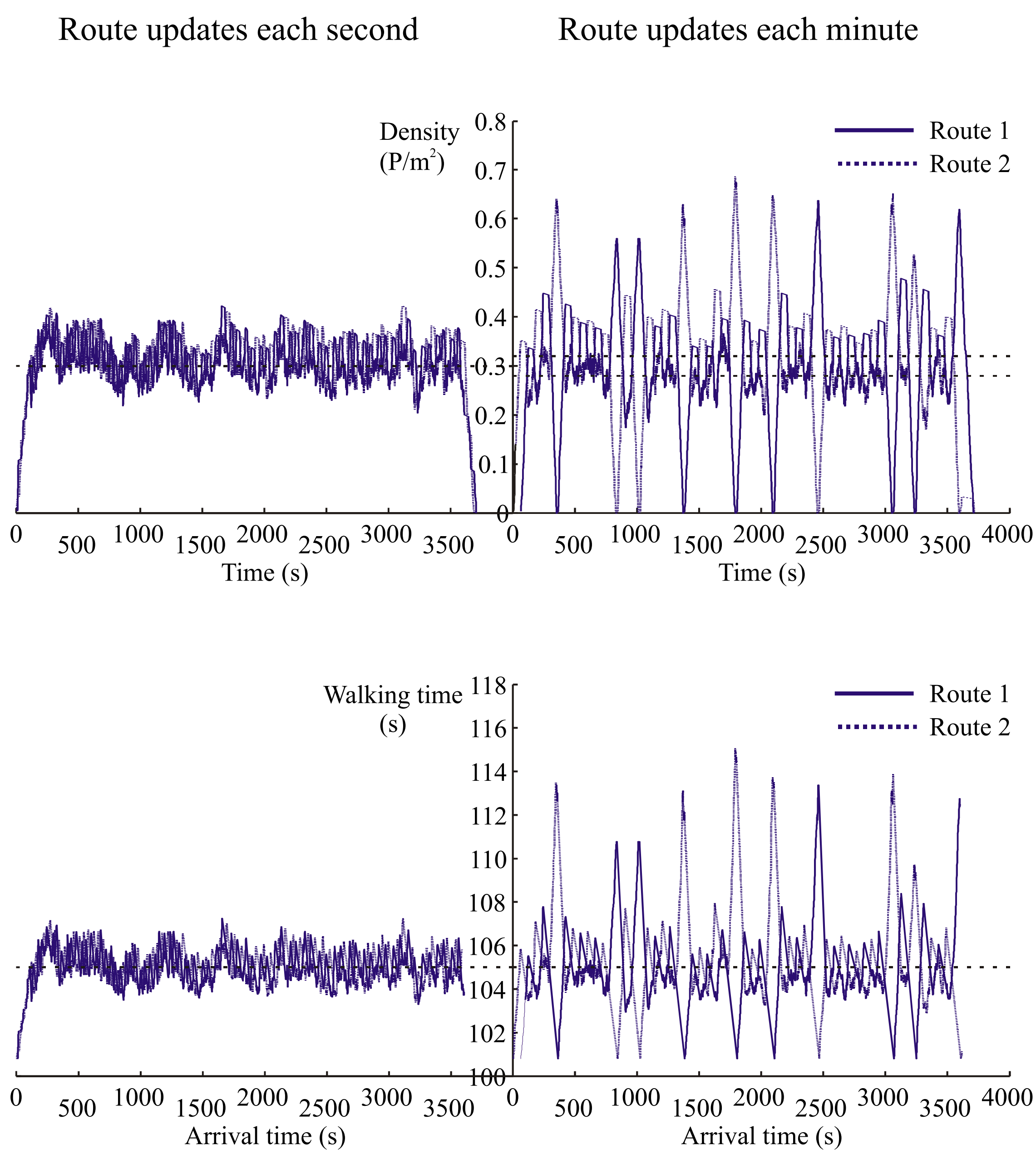


Figure C.4: Density and walking time related to simulation time for equal routes and a normally distributed demand

C.4.2 Equal routes, normally distributed demand

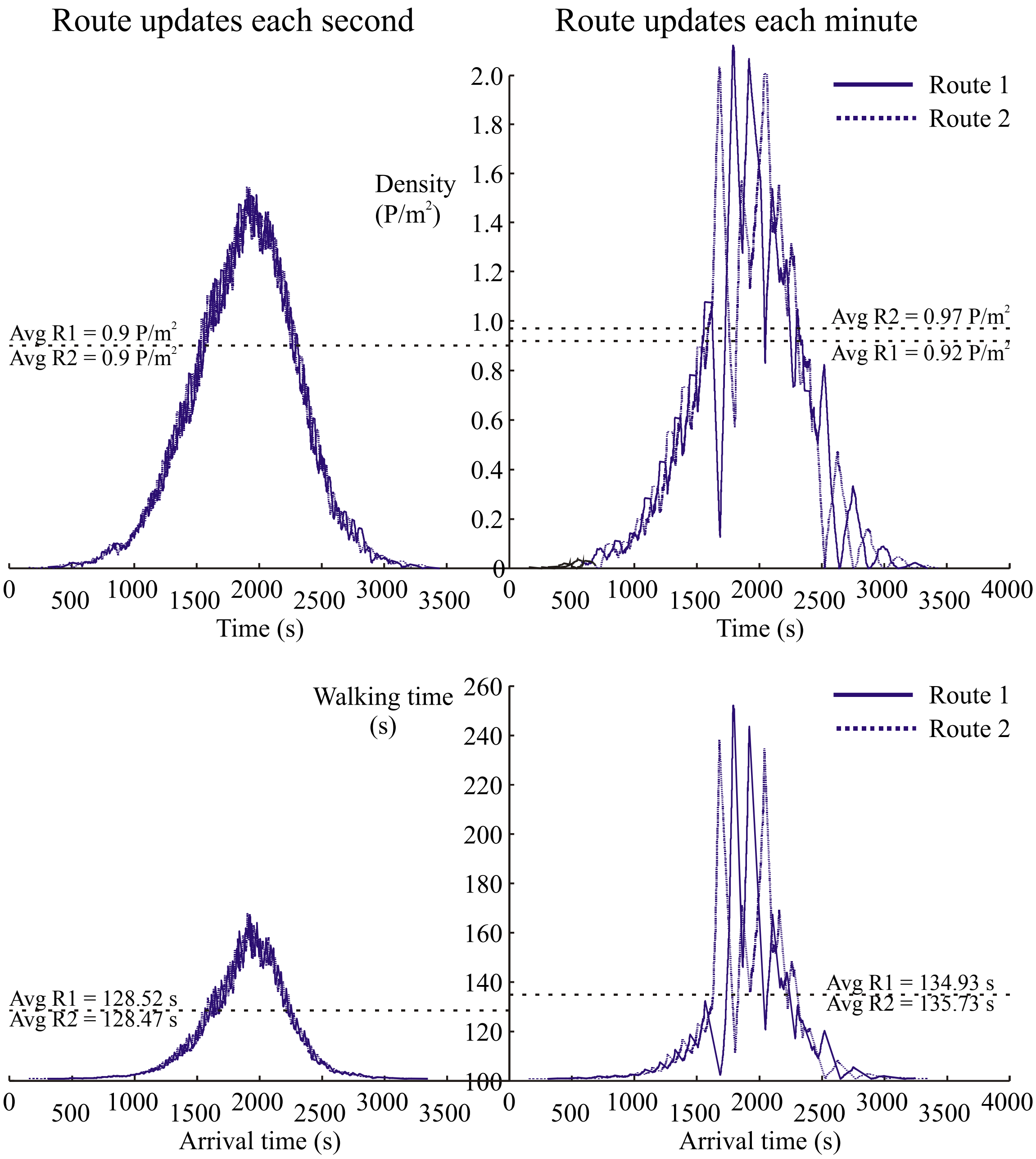


Figure C.5: Density and walking time related to simulation time for equal routes and a normally distributed demand

C.4.3 Different routes, uniformly distributed demand

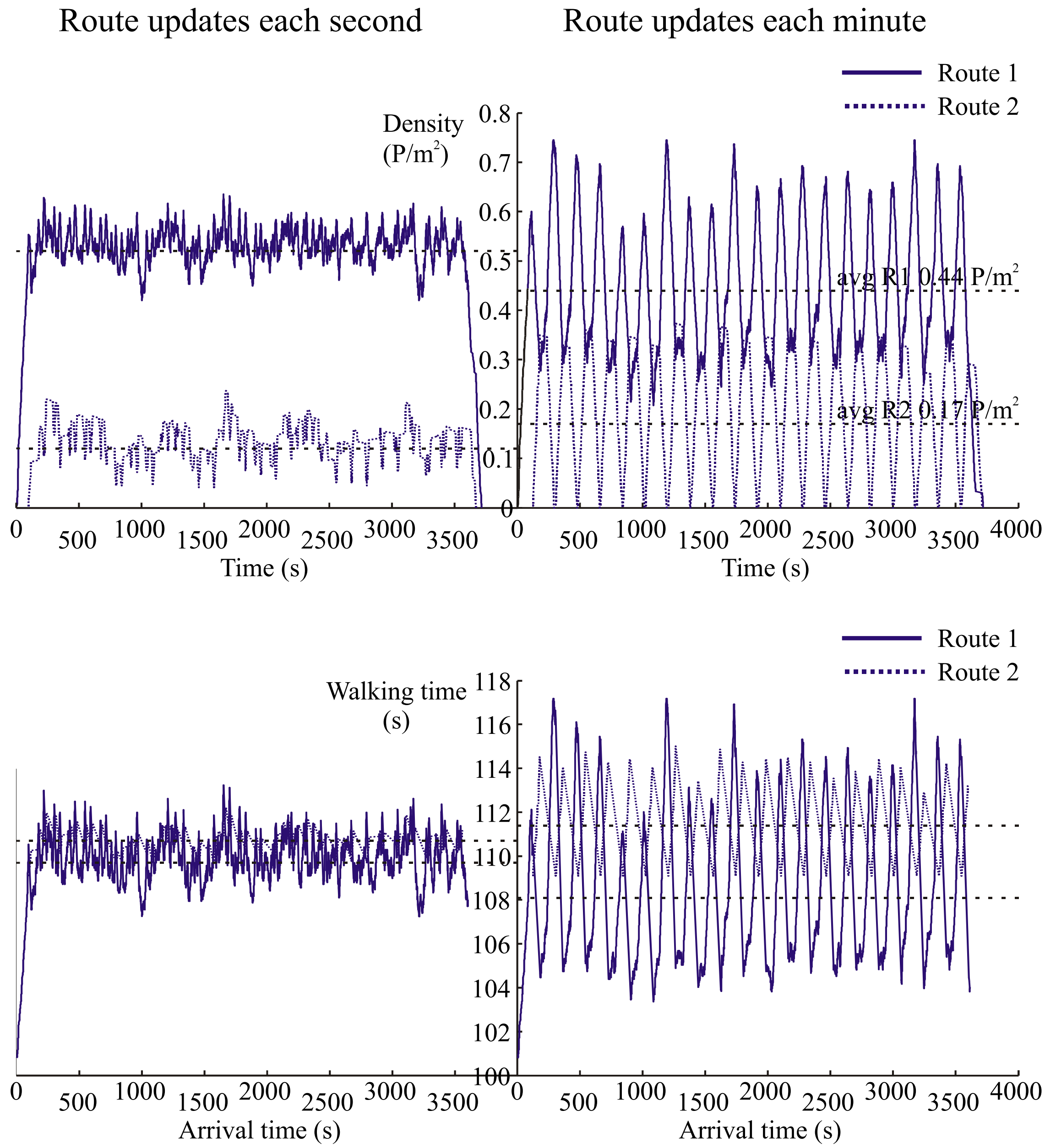


Figure C.6: Density and walking time related to simulation time for different routes and a uniformly distributed demand

C.4.4 Different routes, normally distributed demand

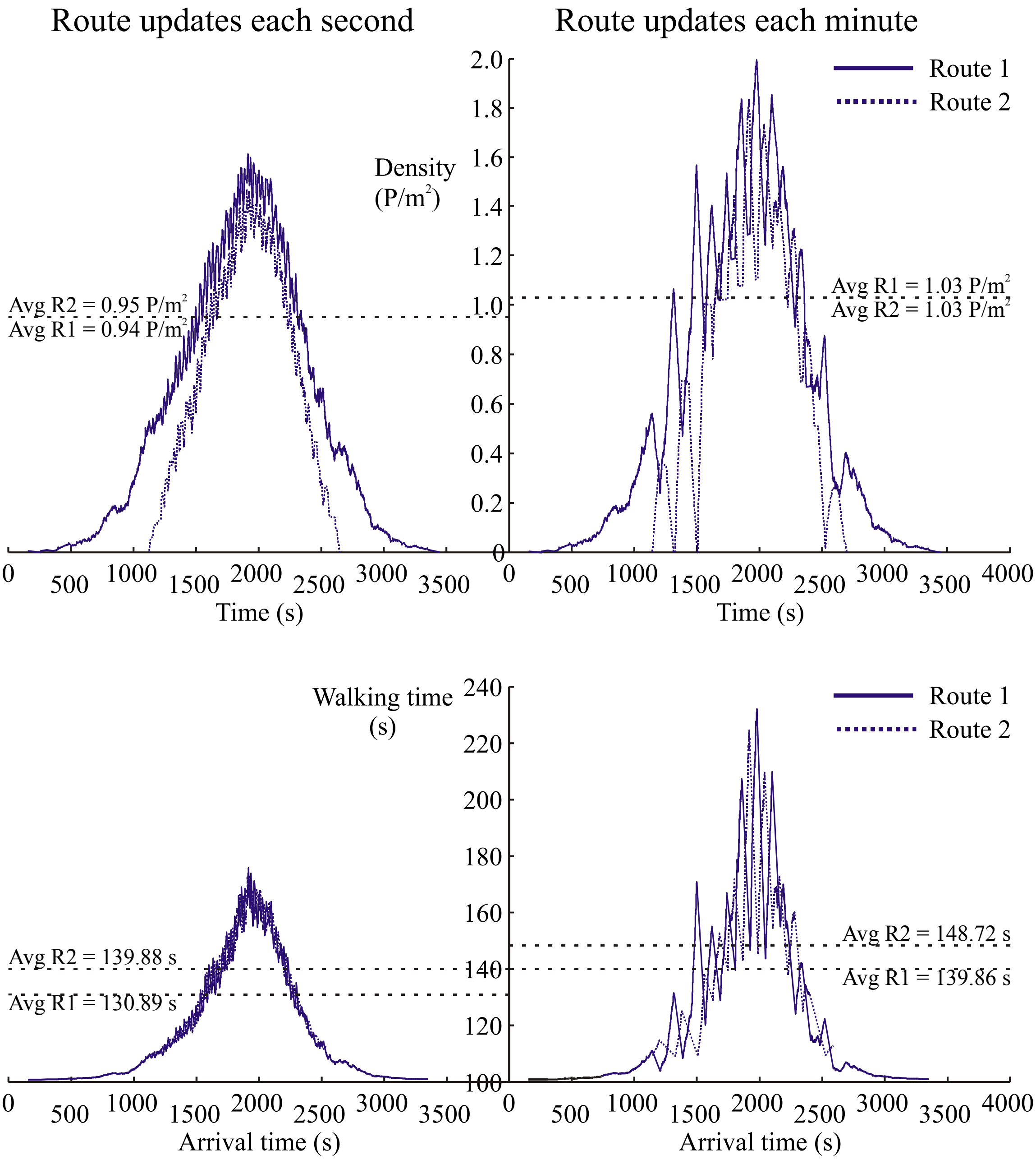


Figure C.7: Density and walking time related to simulation time for different routes and a normally distributed demand

Appendix D

Comparison of SimPed walking model with traffic flow theory and shockwave theory

The aim of this appendix is to compare pedestrian behaviour modelled by SimPed with fundamental traffic flow theory and shockwave theory in order to investigate differences in predicted traffic flow operations and to perform a validation of the walking model.

A comparison has been made for the following scenarios:

- Stationary free flow (section D.1).
- Stationary congestion (section D.2).
- Build up, stationary, and resolving congestion (D.3).

Each of the following sections describes a scenario. The first part of each section contains the simulation results predicted by SimPed, while the second part contains a theoretical calculation using traffic flow theory and shockwave theory. The final part of each section contains a comparison between the two calculations.

D.1 Stationary free flow

In this section, differences in travel times are calculated for stationary free flow conditions for several scenarios, where each scenario has a different intensity. The infrastructure consists of a corridor of 1 m wide and a length of 100 m (see figure D.1).

Twelve scenarios have been compared where pedestrian demand q_a is varied between 0.1 P/ m s (scenario 1) and 1.2 P/ m s (scenario 12).

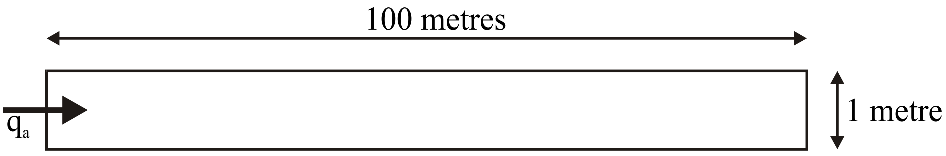


Figure D.1: Infrastructure for scenarios with stationary free flow conditions

D.1.1 SimPed

Travel times have been calculated according to the SimPed walking model (see section 6.5). SimPed needs some start-up time to reach an equilibrium as the first pedestrians entering the area always encounter an empty area. This start-up time depends on the demand, that is, the higher the demand, the longer the start-up time. In the comparison, walking times in the equilibrium situation have been compared.

D.1.2 Traffic flow theory

For each of these demands, the travel time according to fundamental traffic flow theory is calculated, depending on pedestrian walking speed v and the length L of walkway a. The pedestrian walking speed depends on its turn on the given input flow q_a, leading to the following expression:

$$T_a^{walk} = \frac{L_a}{v(q_a)} \tag{D.1}$$

The used speed - flow relation comes from Fruin (1971*a*).

Traffic flow theory only considers stationary situations, in which the time-component is not included. Therefore, all time-indices have been left out of the formula.

D.1.3 Comparison

Table D.1 shows travel times predicted according to fundamental traffic flow theory, SimPed travel times during the equilibrium situation, and absolute and relative differences between these times.

In case of a shorter walkway (10 m instead of 100 m), the relative differences between theoretical walking times and SimPed walking times are larger (maximum difference of 16.7% versus 2.4% in the worst case scenario with a demand of 1.2 P/ s).

D.2 Stationary congestion

The second scenario is concerned with stationary congestion. The infrastructure in this scenario consists of a similar walkway as in the previous scenario (length 100 m, width

Table D.1: Comparison between theoretical travel times and SimPed travel times in stationary free flow conditions

Demand (P/ s)	**Shockwave theory** (s)	**SimPed** (s)	**Abs. diff.** (s)	**Rel. diff.** (%)
0.1	74.6	74.6	0.0	0.0
0.2	74.6	74.6	0.0	0.0
0.3	74.6	74.6	0.0	0.0
0.4	74.8	74.8	0.0	0.0
0.5	75.3	75.2	0.1	0.1
0.6	76.3	76.2	0.1	0.2
0.7	77.9	77.8	0.1	0.2
0.8	80.5	80.4	0.1	0.2
0.9	84.3	83.9	0.4	0.4
1.0	89.8	89.5	0.3	0.4
1.1	98.9	97.9	1.0	1.0
1.2	119.4	116.5	2.9	2.4

1 m), but the end of the walkway is formed by a revolving door with a capacity of 0.67 P/ s (see figure D.2).

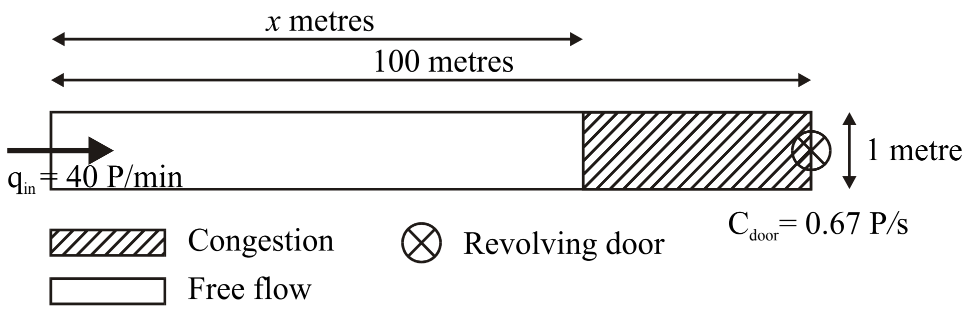


Figure D.2: Infrastructure for stationary congestion case

In figure D.2, congestion has built up (indicated by the shaded rectangle on the right side of the walkway), due to earlier demands higher than the capacity of the revolving door. In this scenario, the demand is equal to the capacity of the revolving door, causing stationary congestion. The time pedestrians pass in the revolving door is not taken into account (the end of the walkway is thus the entrance of the revolving door, where the distance between this entrance and the entrance of the walkway is 100 m). The length of the congestion is varied, creating several scenarios, between 0 m (all walkway is free flow) and 100 m (all walkway is congested).

D.2.1 SimPed

In SimPed, the capacity at the door is modelled as a passing delay T_a^{pass} for each pedestrian, which is calculated as follows:

$$T_a^{pass} = \frac{1}{C_{door}} = \frac{1}{0.67} = 1.5\,\mathrm{s} \tag{D.2}$$

The total travel time on a walkway then consists of the walking time on the walkway (see again section 6.5) and this passing time:

$$T_a = T_a^{walk} + T_a^{pass} \tag{D.3}$$

D.2.2 Traffic flow theory

In traffic flow theory, two regimes are distinguished, that is the free flow regime and the congestion regime. The total walking time is then the sum of the free flow walking time $T_a^{walk,ff}$ and the walking time in congestion $T_a^{walk,c}$:

$$T_a^{walk} = T_a^{walk,ff} + T_a^{walk,c} = \frac{L^{ff}}{v^{ff}(q_a)} + \frac{L^c}{v^c(q_a)} \tag{D.4}$$

D.2.3 Comparison

The resulting travel times are depicted in figure D.3. In this figure, four lines are shown, namely the total theoretical travel time, the SimPed travel times, the walking time in congestion (traffic flow theory), and the walking time in free flow (traffic flow theory).

The percentual difference between traffic flow theory walking times and SimPed travel times may be derived from this figure. This difference amounts to about 1.2% on average, which is acceptable. Similar results follow from a study with shorter walkways.

D.3 Formation of congestion, stationary congestion, and dissipation of congestion

The third and final scenario concerns successively formation of congestion, stationary congestion, and dissipation of congestion, due to varying pedestrian demands. The infrastructure is a corridor with a length of 10 m and a width of 1 m. The end of this corridor is, as in scenario 2, formed by a revolving door with a capacity of 0.67 P/ s. After this door, another corridor starts, also 1 m wide, but having a length of 5 m.

In this scenario, pedestrian demand varies over time. In the first period, the demand is so low that free flow conditions occur. Then, congestion is caused by creating a demand

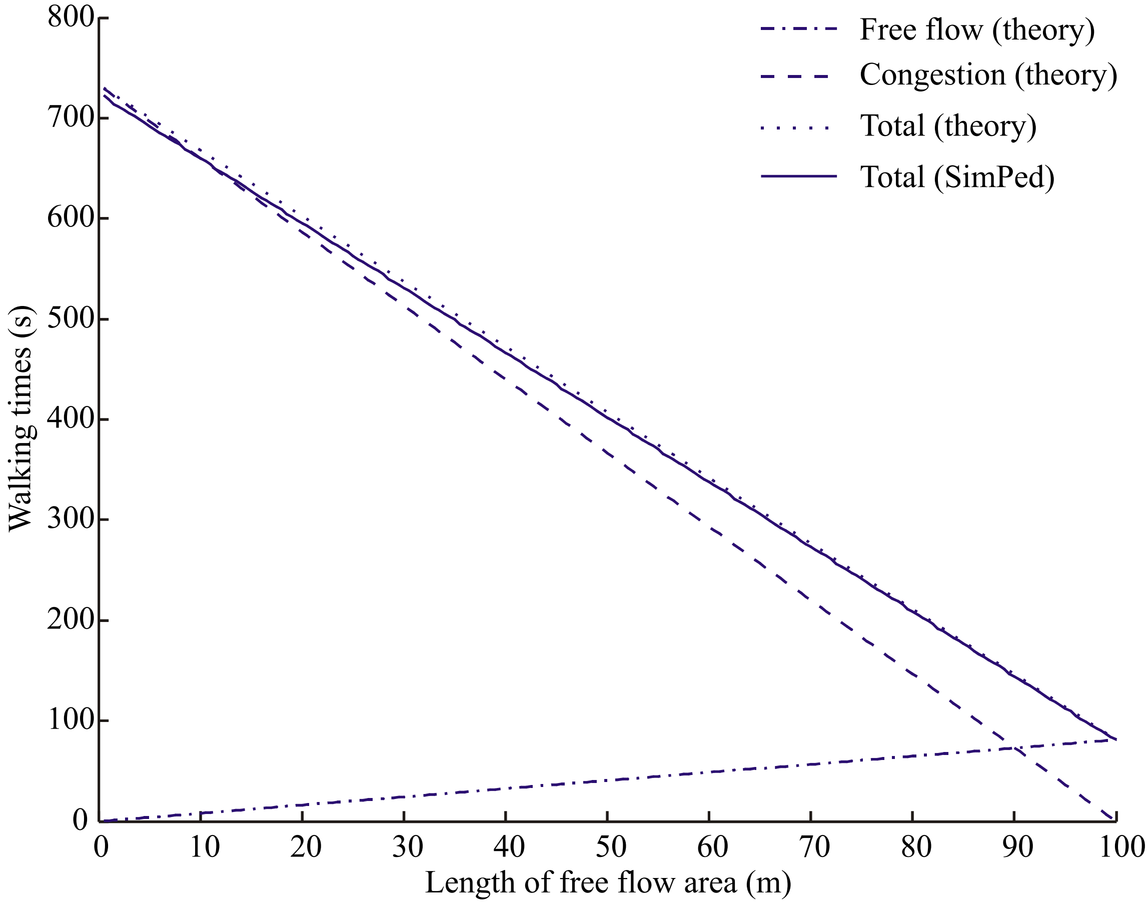


Figure D.3: Difference in theoretical and SimPed travel times in stationary congestion

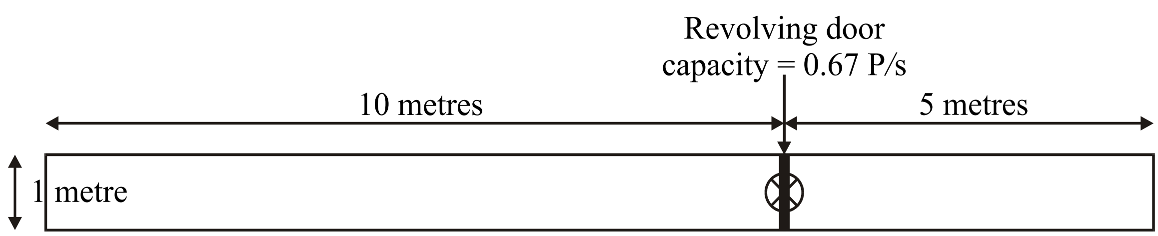


Figure D.4: Infrastructure for scenario 3: forming, stationary, and dissipating congestion larger than the capacity of the door. In order to have stationary congestion, the demand is decreased until it is equal to the door capacity (0.67 P/ s). Finally, the congestion is dissipated and free flow conditions return, due to a lower demand. The following list contains an overview of these demands, while figure D.5 indicates the time periods corresponding to each demand.

1. Demand < door capacity (free flow conditions, $q = 0.4$ P/ m s)
2. Demand > door capacity (congestion is building up, $q = 1.0$ P/ m s)
3. Demand = door capacity (congestion remains constant, $q = 0.67$ P/ m s)
4. Demand < door capacity (congestion is removed, $q = 0.4$ P/ m s)

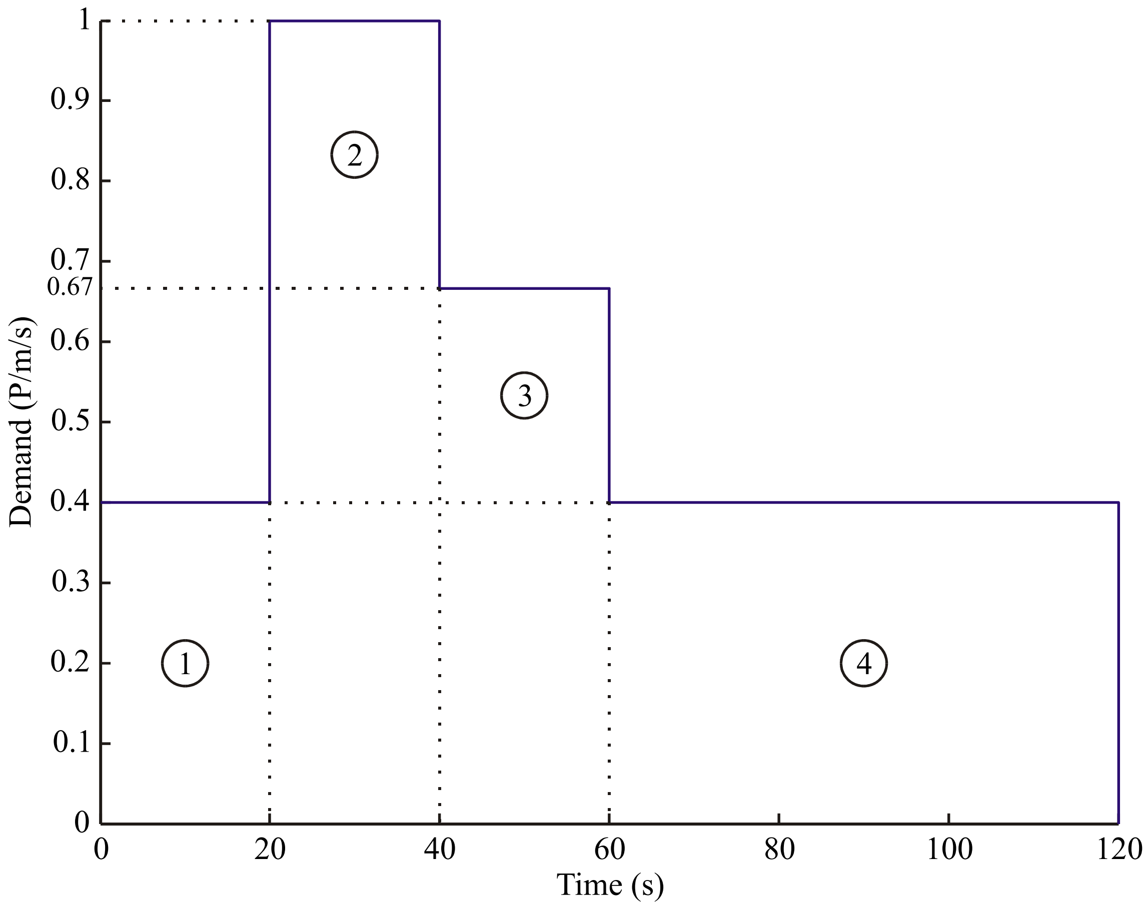


Figure D.5: Traffic demand pattern over time in scenario 3

D.3.1 SimPed

Trajectories are used to visualise the walking process in the different walkways. First, the way in which the trajectories of the pedestrians in SimPed have been drawn is described.

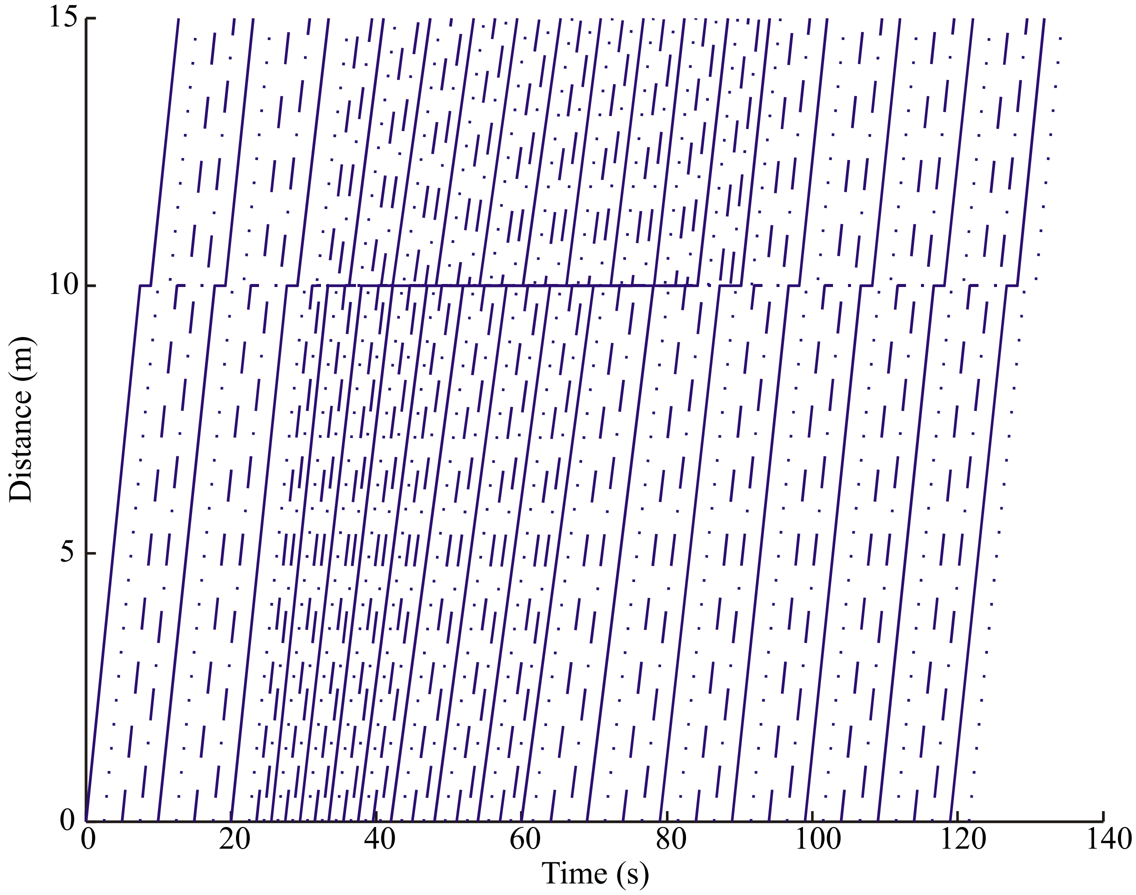


Figure D.6: Trajectories resulting from SimPed

A pedestrian starts walking towards the door. This 10 m is traversed with a speed depending on the density existing at the moment of arrival in the first walkway. In order to give a part of the infrastructure (in this case the revolving door) a capacity, each pedestrian experiences a delay. This delay is similar to the headway, corresponding to the given capacity at this location. After this delay, the pedestrian walks through the second walkway. When a pedestrian arrives at the door, while another pedestrian is still being processed, this new pedestrian has to wait for his turn. Waiting pedestrians are modelled as a vertical queue in the trajectory diagram, but do occupy space in the area upstream and thus cause hindrance for later arriving pedestrians (waiting pedestrians are included in the density of the total area). When there is space for the first waiting pedestrian to enter the door, this pedestrian also ‘frees’ his area in the walkway upstream of the door (decreases the density). For a description of these models see section 6.5. Figure D.6 shows the resulting pedestrian trajectories.

The travel time of a pedestrian is thus comprised of four elements, namely walking time upstream of the door, (probable) waiting time in front of the door, delay time in the door, and walking time downstream of the door. Each of these elements of the SimPed travel time are depicted in figure D.7.

D.3.2 Traffic flow theory and shockwave theory

First, theoretical travel times are calculated by applying fundamental traffic flow theory and shockwave theory. Flow-density diagrams for both the walkway and the revolving door are derived from the Fruin (1971*b*) data and are shown in figure D.8.

These flow-density diagrams indicate different stages in the pedestrian traffic. Also, the shockwave speeds are indicated in both the flow-density relations and the trajectory diagram (figure D.9).

D.3.3 Comparison

From the trajectories according to shockwave theory drawn in figure D.9 total travel times may be derived. These travel times are compared to the total travel times calculated by SimPed, as is shown in figure D.10. Also, the relative differences between the travel times are calculated and shown in figure D.11.

The maximum difference is 16% and concerns the last few pedestrians in free flow. Travel times calculated by SimPed are higher than theoretical travel times; only when the queue is dissipated, SimPed travel times are less than 3% lower than theoretical travel times. This comparison indicates that the SimPed travel times only differ significantly in some specific situation for just a few pedestrians. It is therefore concluded that the adopted approach is valid for the application areas mentioned for the simulation tool.

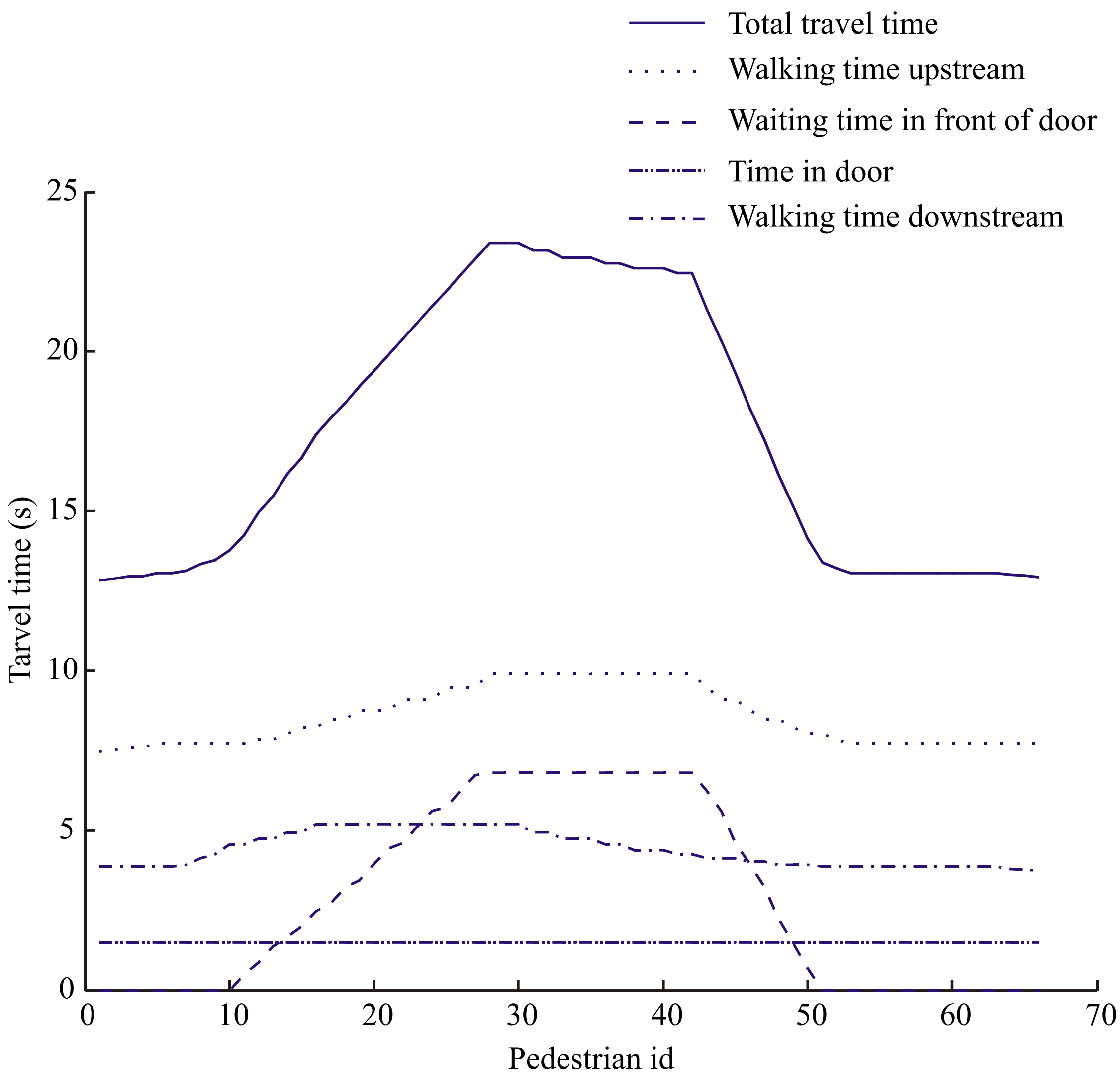


Figure D.7: Elements of the SimPed travel times

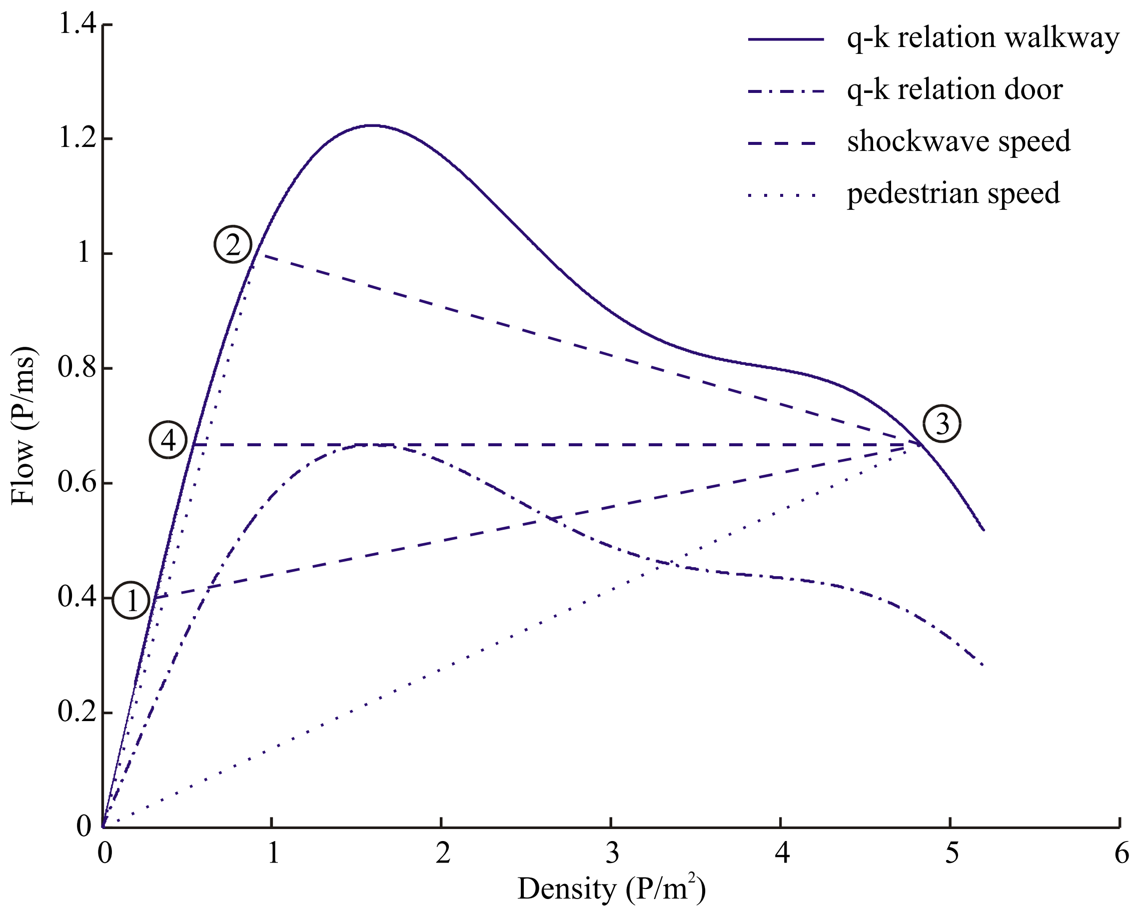


Figure D.8: Flow-density relations of Fruin (1971*b*) for the walkway and the revolving door

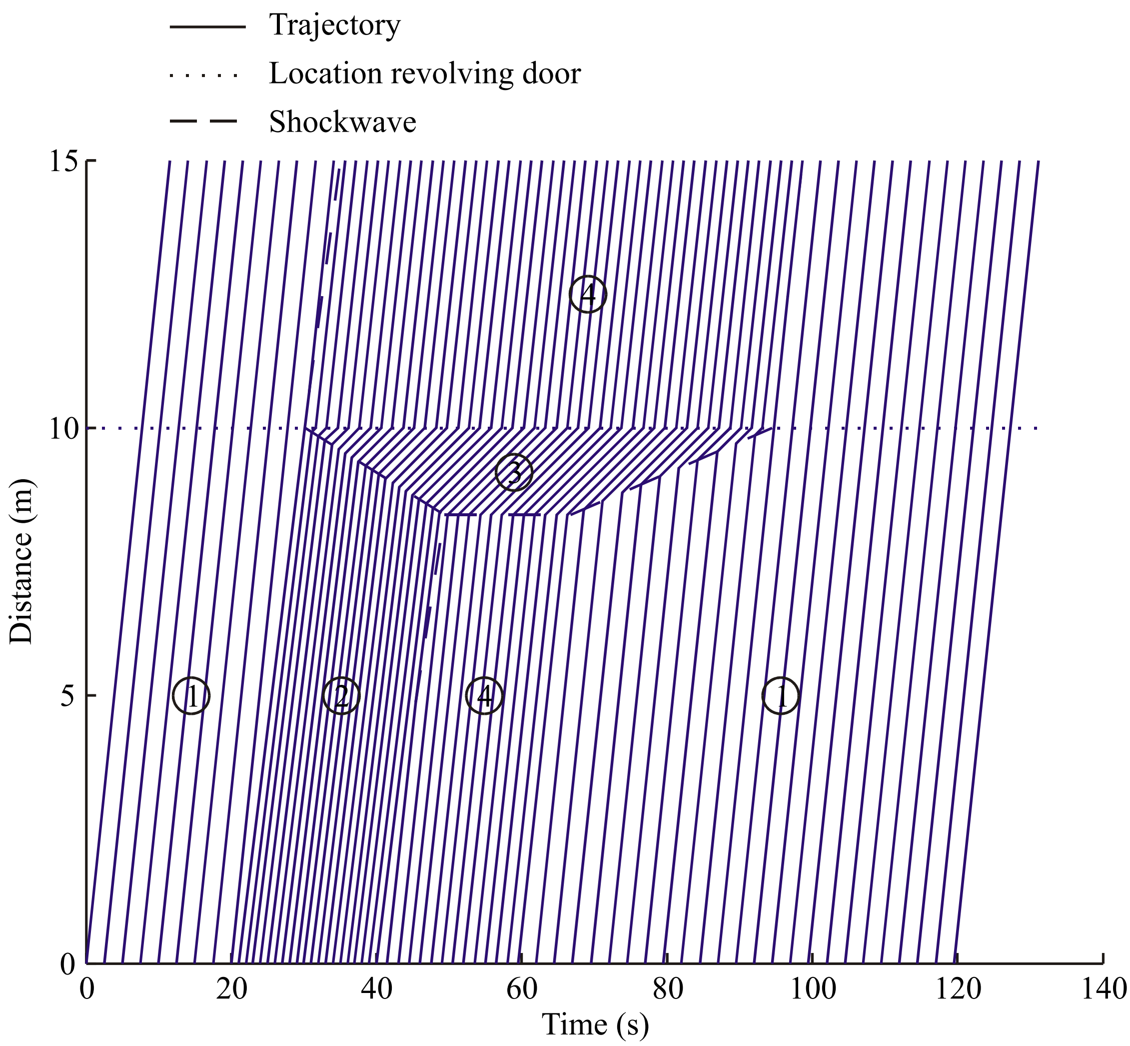


Figure D.9: Trajectories according to shockwave theory

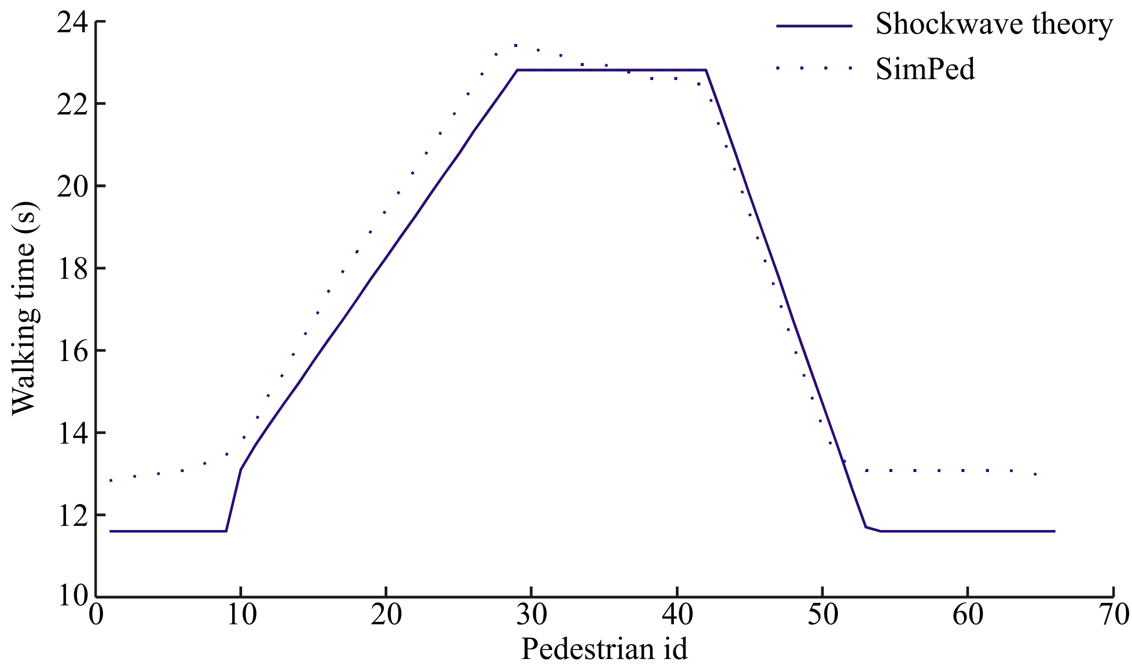


Figure D.10: Comparison of the theoretical travel times and those computed by SimPed in scenario 3

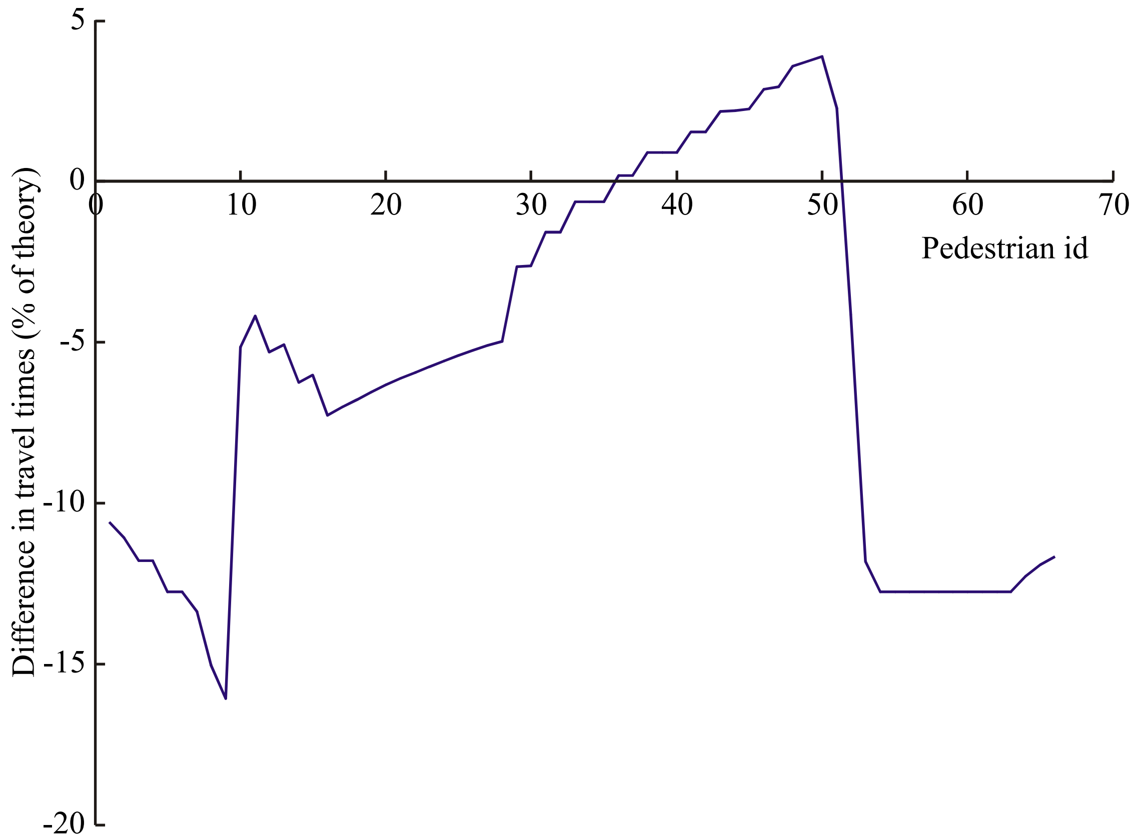


Figure D.11: Percentual difference in travel times between theory and SimPed

Appendix E

Data collection for validation of SimPed

This appendix describes the data collection for validation of the traffic flow characteristics in the simulation tool SimPed. The validation purpose and the chosen criteria are discussed in section 8.3.

This appendix starts with a description of Delft Station, where the observations have been performed (section E.1). The second part of this appendix (section E.2) describes the set up of the required observations, while the third part (section E.3) discusses the derivation of the input data for the simulation tool as well as a translation of the observations into data directly comparable to simulation results.

E.1 Situation at Delft Station

Delft is situated in the western part of the Netherlands with 100.000 inhabitants. Delft has two train stations, namely one in the southern part of the city (Delft South, about 1500 passengers per day), while the central station is situated near the inner city (more than 20.000 passengers per day). One of the three Dutch universities of technology has been settled in Delft, so many students and employees use public transport to travel to and from the university.

Position in the national rail network

Delft Station is situated alongside the main rail connection between The Hague and Rotterdam (see figure E.1). Delft Station has the function of regional train station, indicating that both local and regional trains stop in Delft Station.

The rail connection between The Hague and Rotterdam has two tracks on the main part of the traject. A passing track is located in Delft Station in the direction to Rotterdam, which may also serve as dwell track. However, in the regular timetable no stops have been scheduled on this track. Also, a fourth track is present, without a connection to a platform.

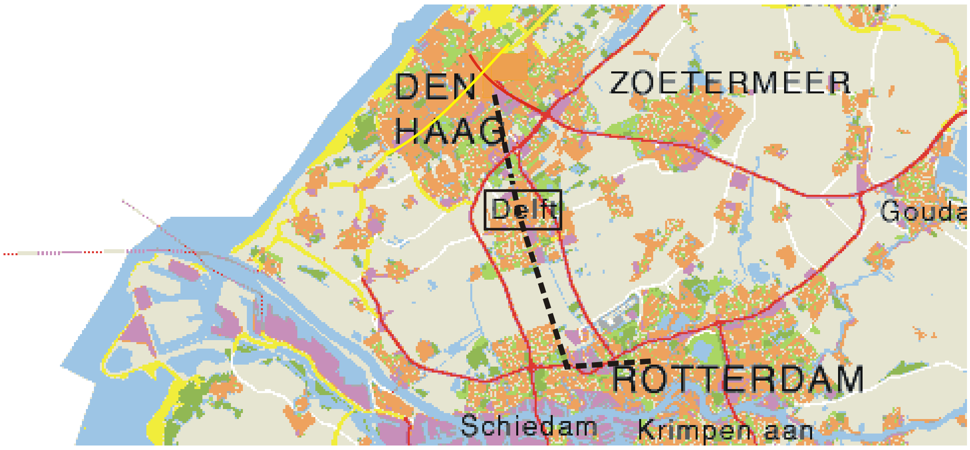


Figure E.1: Location of Station Delft alongside the main rail connection between The Hague and Rotterdam

Plan of Delft Station

Figure E.2 shows an overview of the rail infrastructure, as well as the platforms, the remaining pedestrian infrastructure, and the buildings in the nearby surroundings.

The observations are performed at platform 2 (between tracks 2 and 3), as there is no route choice on this platform. The only entrance and exit to this platform is the staircase on the right-hand side, thus only pedestrian traffic flow characteristics are observed. Figure E.3 shows platform 2 in detail, (note: the platform has been mirrored with regard to figure E.2, thus the staircase is on the left-hand side and platform 2 is on the top of the drawing).

On the platform, several obstacles are located, such as ticketing machines, benches and dustbins. These obstacles are already indicated in figure E.3, but are shown in detail in figure E.4.

Timetable

The timetable has an hourly pattern during the observation period between 14:00 h and 17:00 h. The scheduled departure times of trains in the direction of Rotterdam are shown in table E.1.

Table E.1: Timetable with trains to Rotterdam

Departure (min)	Train service	Rolling stock
06	Regional train	Doubledecker
14	Local train	Doubledecker
36	Regional train	Doubledecker
44	Local train	Doubledecker
56	Local train	Single deck train

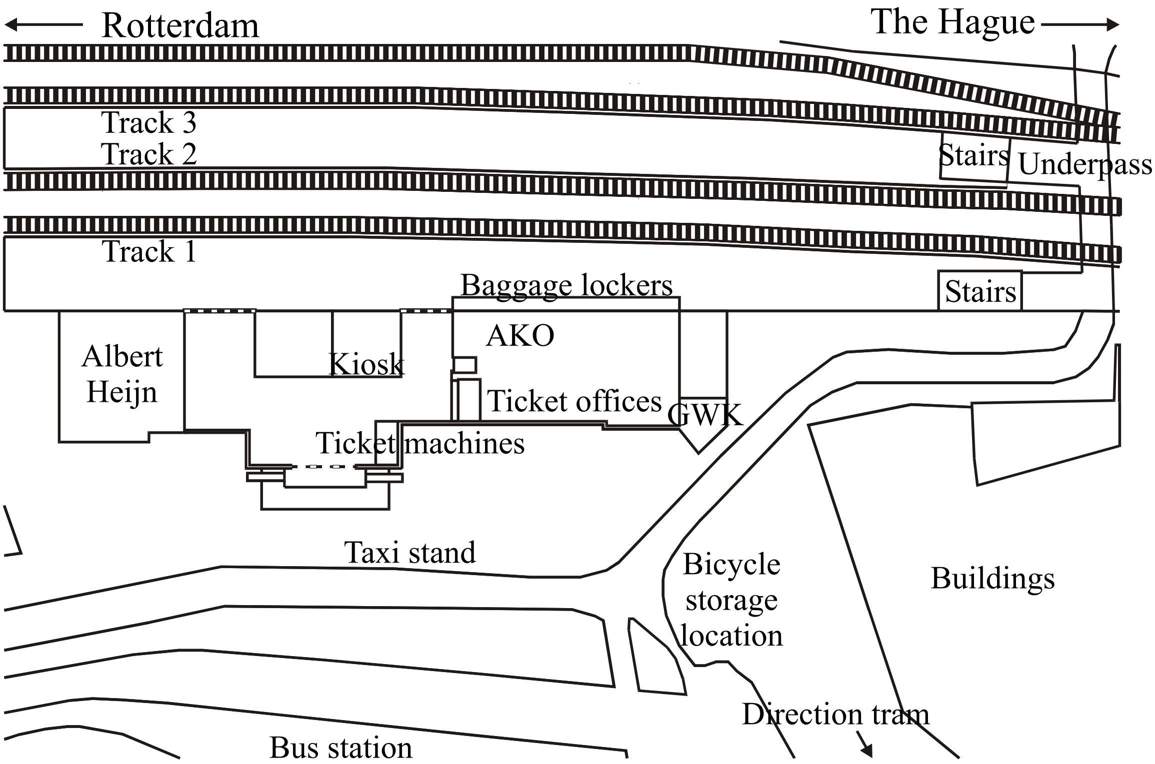


Figure E.2: Rail and pedestrian infrastructure at Delft Station

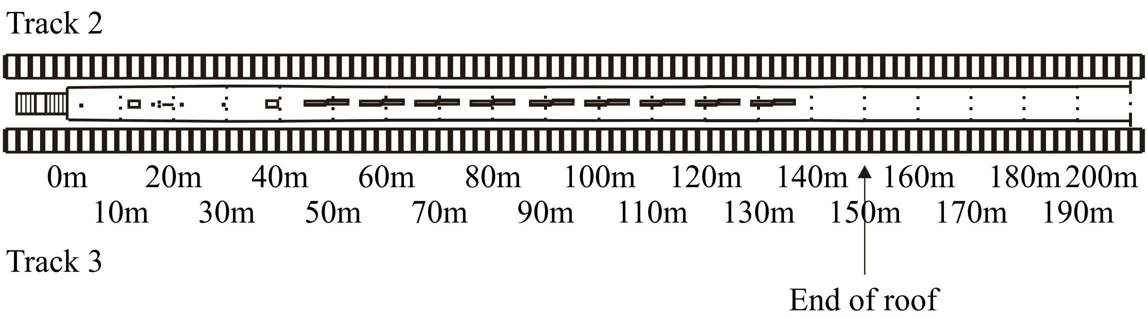


Figure E.3: Platform 2 of Delft Station

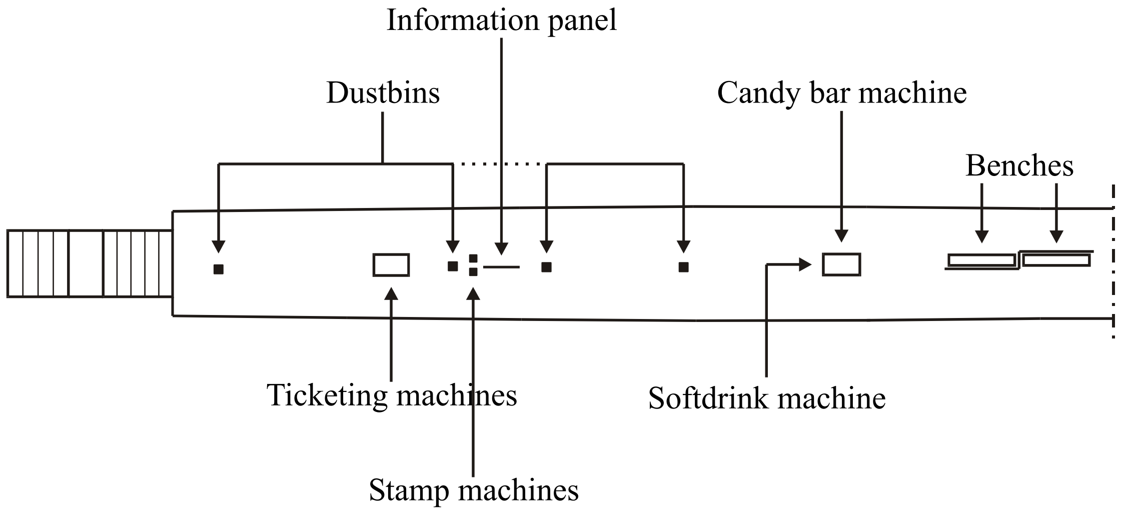


Figure E.4: Obstacles on platform 2 in Delft Station

E.2 Observations in Delft Station

This section first gives an overview of the type of observations needed to perform the validation of the simulation tool (section E.2.1). Then, the choice for Delft Station to perform the observations is described, followed by an overview of the situation in Delft Station (sections E.2.2). Section E.2.3 goes into detail into the specific conditions to be measured as well as the detailed time schedule of the observations.

E.2.1 Type of observations

As has been indicated in section 8.3.2, the criterion variables corresponding to pedestrian traffic flow operations are:

- Walking speeds.
  - On the staircase, both upwards and downwards.
  - On the platform, for both alighting and boarding passengers.
- Density over time and space.

To be able to compare SimPed simulation results with the observed situation, the SimPed input needs to be observed as well. Therefore, more information is needed to draw the network model and to complete the origin-destination table as input for the tool. This information concerns:

- Walking distances.

  - Length and width of (parts of) the platform.
  - Length and width of staircase.
  - Shape and location of benches and columns.
  - Shape and location of ticket machines, candy bar machines, and softdrink machines.

- Origin-destination table.
  - Number of boarding passengers per door.
  - Number of alighting passengers per door.
  - Number of passengers performing an activity.

- Timetable.
  - Planned arrival and departure times.
  - Realised arrival and departure times.
  - Composition of the rolling stock.
  - Number of doors.
  - Location and width of the doors.

The observations are both static (constant over time) and dynamic. The following subsections indicate for both types of data which observations are needed.

Static data

The static data concern mainly observations with respect to walking distances. Therefore, an accurate layout of the station is mapped. The detailed data to be collected have already been indicated in the previous section. To measure these distances and locations, a measure wheel is used.

Other static data involve rolling stock, with respect to the location and width of doors for each type of rolling stock. These data may be found in documentation of the Dutch railway company and in Peters & Koene (1995) and Van Gestel et al. (1997).

Dynamic data

Observations of the dynamic situation are split up into three parts:

- Boarding and alighting.
  - Realised arrival and departure times of the trains.

- Total number of boarding passengers per train.
- Total number of alighting passengers per train.
- Distribution of boarding times per door per type of rolling stock.
- Distribution of alighting times per door per type of rolling stock.
- Distribution of boarding passengers over the train.
- Distribution of alighting passengers over the train.

- Walking times.
  - Origin (staircase or part of the platform).
  - Destination (staircase or part of the platform).
  - Walking time on the platform.
  - Walking time on the staircase.
  - Waiting and service times for activities.

- Density.
  - Number of pedestrians per time period on a part of the platform.
  - Number of pedestrians per time period on the staircase.

E.2.2 Measurement location

We have chosen to perform the measurements at Delft Station on platform 2. This platform satisfies the following requirements:

- The platform has only one entrance / exit. This way, only the traffic flow characteristics are measured and influences of route choice are omitted.
- In order to measure one directional flows without large influences of boarding and alighting passengers, the measurements are performed on a platform with an entrance / exit at one of the ends of the platform.
- The trains stopping at the platform will not have different destinations, so all waiting passengers will board the first arriving train.
- The number of passengers needs to be sufficient, in order to observe higher densities. However, this number must not be extremely large as the flows become unmeasurable or may only be measured with a high probability of errors.

The final consideration has a very practical nature, that is, Delft is a location nearby the working location, thus the travelling time to and from the location is very short, the conditions on the station are known due to regular visits, and, when some problems come up with the data, this familiarity and understanding of the processing leads most probably to faster solutions. Also, the situation on platform 2 is very surveyable, which simplifies the observations.

E.2.3 Observations in Delft Station

Traffic flow characteristics of pedestrians are validated based on observations in Delft Station. Observations will be performed on a Monday evening between 14:00 h and 17:00 h. The number of boarding and alighting passengers is reasonable during this period of time, that is, enough passengers are present to cause some congestion, while the number of passengers is sufficiently reduced to get accurate (manual) observations.

Three processes are observed (boarding and alighting, walking times and density on the platform), which are elaborated in the following subsections. The final subsection shows the interface of the palmtop the observations are performed with.

Boarding and alighting

For the boarding and alighting process, observations concern the number of boarding and alighting passengers per door, per train, and the individual boarding and alighting times. The distribution of both boarding and alighting passengers over the train may be derived from these data.

In an ideal situation, individual boarding and alighting times are recorded. However, sometimes this is not possible (too many boarding and alighting passengers per door causing situations difficult to survey), and then the total time for boarding and the total time for alighting are recorded, as well as the total number of boarding and alighting passengers. Recording the correct number of passengers has a preference on recording the corresponding boarding and alighting times. Figure E.5 shows the events to be recorded during the boarding and alighting process in ideal conditions.

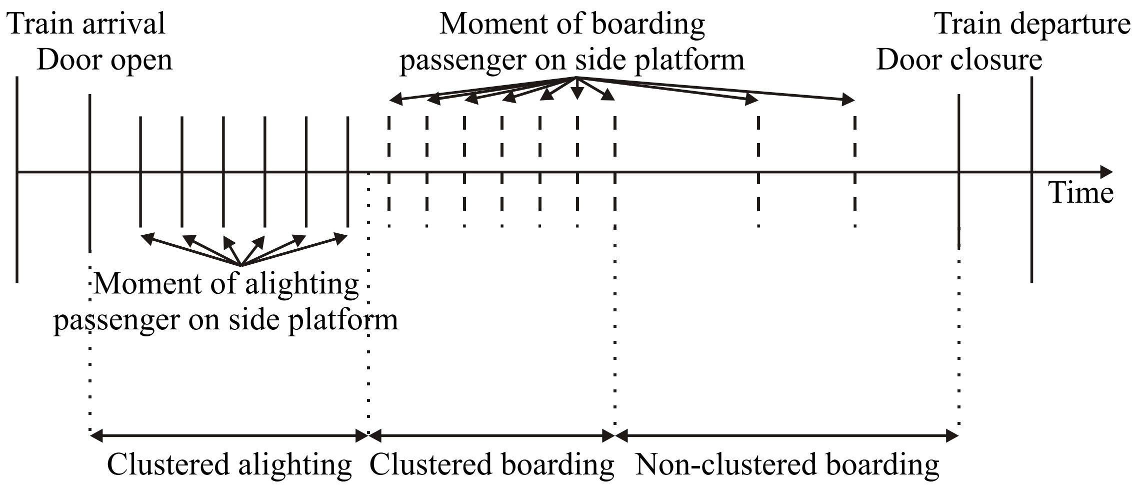


Figure E.5: Events recorded in the boarding and alighting process in ideal conditions

For each door of the train, a single observer registers the moments of the events and the number of boarding and alighting passengers. It is assumed that the number of passengers decreases when the distance between the door and the staircase increases. In case of a long train, with more doors than observers, the doors at the rear of the train are measured and doors of the first part of the train (further away from the staircase) are not measured, see also figure E.6.

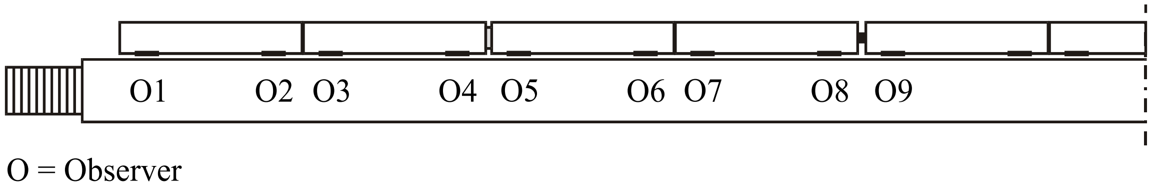


Figure E.6: Locations of observers with regard to train door locations and train length

Walking times

The aim of this part of the observations is to record individual walking times. Since the number of observers is limited (in this case there were nine observers), the walking times are not registered at the same time as the boarding and alighting process. To measure walking times, both boarding and alighting passengers are followed. The moment that a passenger is at his origin and the moment that he is at his destination are registered, as well as the moment of passing the top of the staircase in order to distinguish between walking times on the staircase and walking times on the platform. Also, the start and duration of activities, such as buying a ticket or looking at the information panel, are measured.

The origin of a boarding passenger is the staircase, which is also the destination of an alighting passenger. To determine the destination of a boarding passenger and the origin of an alighting passenger, the platform is divided into areas with a length of 10 m. Each area is assigned a number (written with crayon on the side of the platform), indicating the origin or destination.

In ideal conditions, for each origin-destination relation a similar number of observations should be collected. However, it is impossible to keep track of this during the observations as the destination of a boarding pedestrian can not be predicted. The destination of alighting pedestrians is clear (the number of transfers on platform 2 is nearly zero), but they arrive in clusters when the train arrives and it will therefore be impossible for an observer to follow more than one alighting passenger per train.

Density over time and space

To observe the density on a part of the platform, the average number of passengers being present during a specific period of time needs to be measured. This may be done by counting the number of pedestrians at a specific moment, but especially when a train has arrived, the number of pedestrians changes too quickly to observe. Therefore, this number will be determined afterwards, using cumulative curves (see also subsection 4.7.3). For the construction of a cumulative curve, the moment a pedestrian passes a cross-section of the platform is logged, as well as his walking direction. The difference along the y-axis between two cumulative curves indicates the number of pedestrians present on the area between the two cross-sections at a specific moment of time. Again, the parts of the platform nearest to the staircase are observed (see figure E.7).

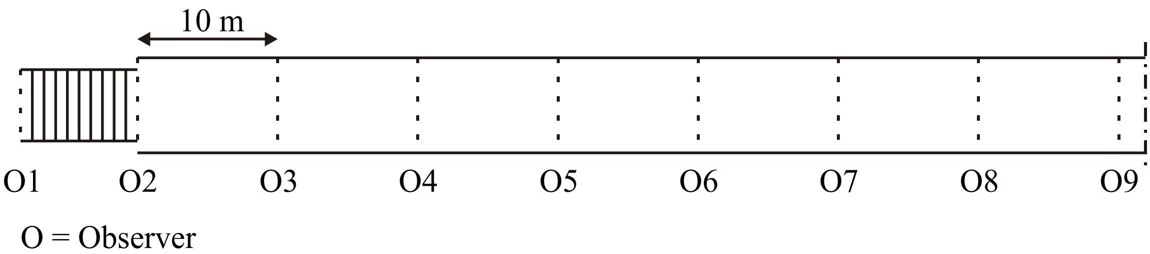


Figure E.7: Locations of observers measuring passing times of pedestrians on a cross-section

Performing the observations

The observations are performed using a digitiser or so-called palmtop. A palmtop is a handheld computer with a touch screen which records the moments that the screen is touched and the corresponding code to identify the type of event logged. The layout of the screen is free and is designed dedicated for these observations. The resulting interface is shown in figure E.8.

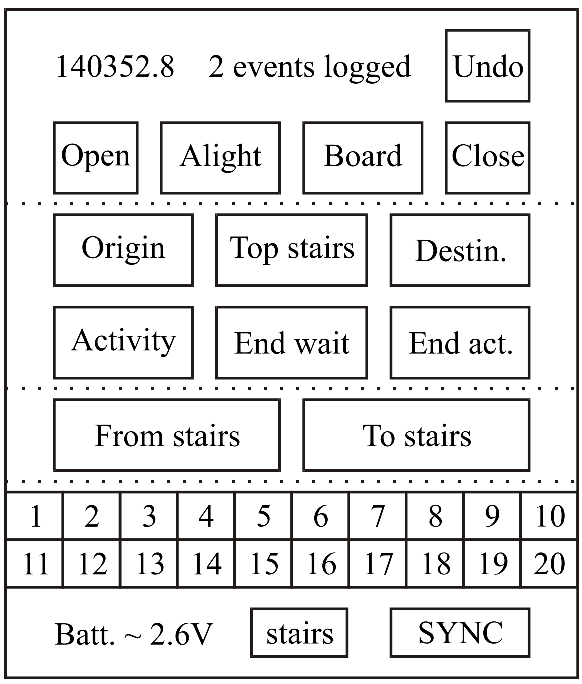


Figure E.8: Interface of the palmtop used for the observations

The interface of the palmtop has been divided into four parts, that is, the upper part is used for the boarding and alighting process; the second part is to measure walking times; the third part measures cumulative curves, and the bottom part is multi-functional. It is used to indicate origins and destinations of pedestrians and to indicate number of boarding and alighting passengers and size of groups passing cross-sections.

The total observation period between 14:00 h and 17:00 h is split into half hour periods, as all trains have a frequency of 2 or 4 trains per hour. During this half hour, at least one train of each train series will stop. Changing the observation activity will be done each half and full hour, which is between two train arrivals. The alighting process of the previous train has already ended, while the boarding process of the next train and the arrivals of most of the boarding passengers still have to take place. The time schedule of the observations is shown in table E.2.

Table E.2: Time schedule of the observations

Time period	Activity
14:00-14:30	Boarding and alighting
14:30-15:00	Walking times
15:00-15:30	Densities
15:30-16:00	Walking times
16:00-16:30	Boarding and alighting
16:30-17:00	Densities

E.3 Derivation of input data for the simulation model

This section describes the input data needed for the simulation model. All conditions not related to traffic flow characteristics of pedestrians have to be similar between the observations and the simulation tool to prevent that other characteristics or conditions influence the validation process.

The static configuration of the platform has already been described in figure E.4 and contains relevant lengths and widths in order to determine walking distances.

As all different processes have been observed consecutively, not all information is available during one specific half hour, for example when walking times are measured, the total number of boarding and alighting passengers is unknown, whereas when boarding and alighting times are measured, densities on the platform are unknown. However, from the observed cumulative curves the number of boarding and alighting passengers may be derived (see figure E.12). The individual boarding and alighting times and individual walking times are less situation dependent. These times are thus compared with the observed times in another time period.

In the following subsections, the precise arrival and departure times of trains are determined as well as the number of boarding and alighting passengers, but first, the synchronisation of the data is discussed.

E.3.1 Synchronisation of the palmtops

Each palmtop has its own clock, which all have been synchronised before the observations started. Unfortunately, the clocks are not very accurate and to be able to synchronise the observation data afterwards, each hour a synchronisation button has been hit. Comparing the recorded times with the actual time indicates the deviation in each of the data sets. Figure E.9 shows the deviations from the synchronisation moments for each observer.

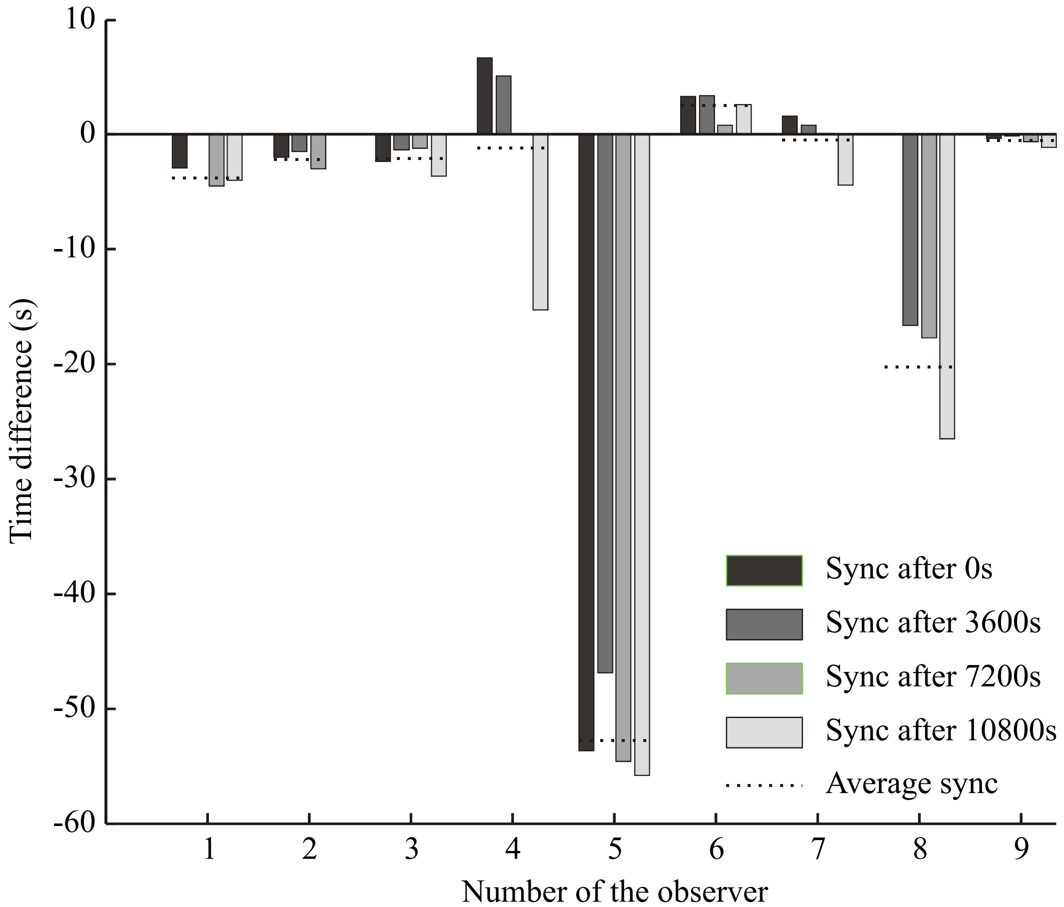


Figure E.9: Deviation of the synchronisation moments for each observer

For each observer, the average deviation has been calculated (the dotted lines in figure E.9) and all recorded moments have been shifted by this offset.

E.3.2 Arrival and departure times of trains

Unfortunately, the precise arrival and departure times of trains have not been observed during the observations of the density and therefore need to be derived from the available data. One of the characteristics of the train arrival is that passengers alight, causing a large flow in the direction of the staircase. At all other moments of the observation, this flow will be negligible, only consisting of an incidental passenger strolling around on the platform instead of standing still while waiting. To determine the precise arrival times of the trains, the number of loggings of passengers walking in the direction of the staircase is shown in figure E.10 (first train) and figure E.11 (second train), for each observer.

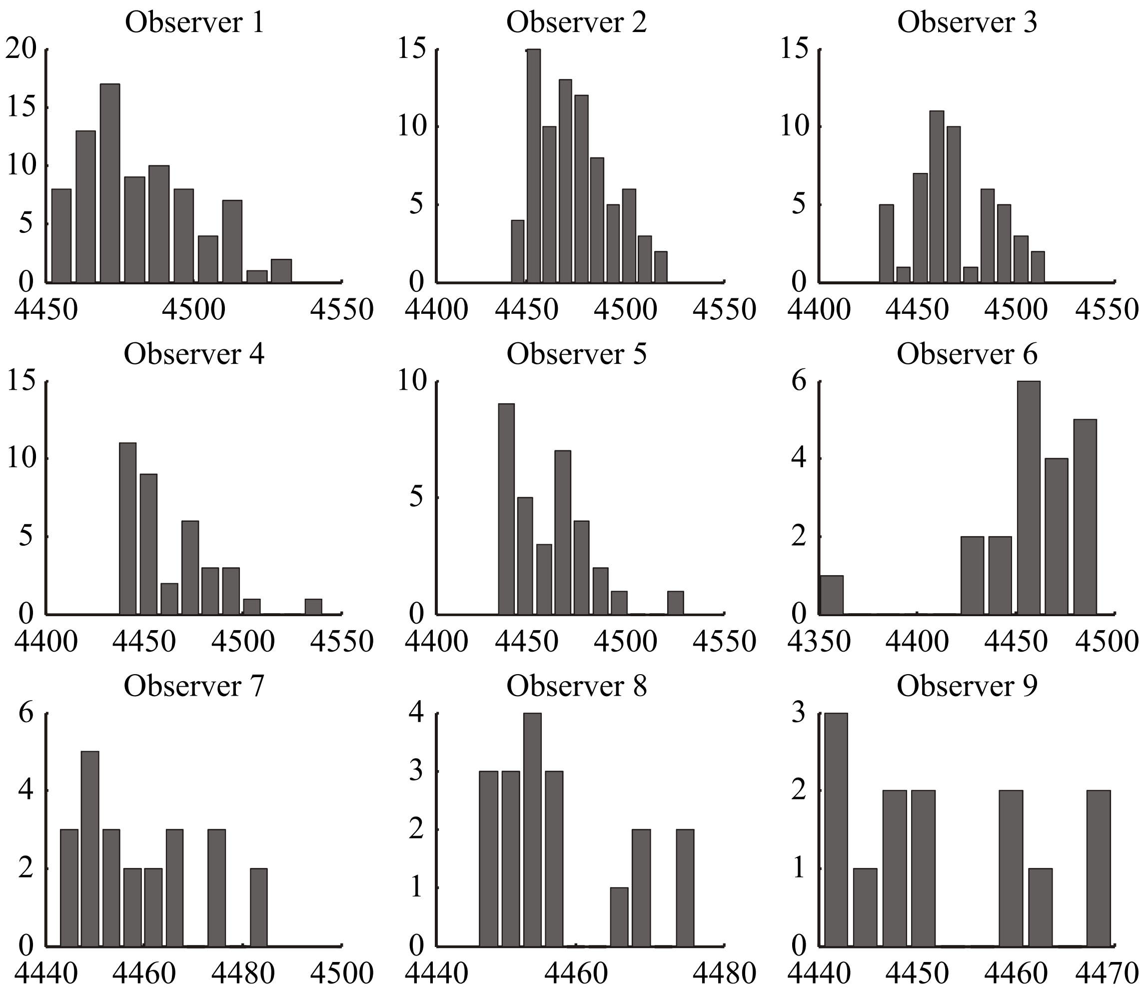


Figure E.10: Histogram of passengers walking to the stairs per observer for train 1

As can be seen in figure E.10, most observers start logging around $t = 4440$ s. Observer 2 (at the top of the staircase) starts logging pedestrians in the direction of the staircase at $t = 4440$ s. This means that before this moment, the train has arrived and has opened its doors. Observer 3 is the earliest observer, logging from $t = 4430$ s on. Therefore, the first train is assumed to arrive at $t = 4430$ s.

For the second train (see figure E.11), the loggings do not have a clear starting point. Observers 1 and 2 start logging around $t = 5370$ s, whereas observers 3 and 4 start logging somewhat earlier. As the total number of loggings is 25 for all these observers, no pedestrians have alighted at the first or the second part of the platform. As observer 5 only measures 23 pedestrians, the first part of the platform where passengers have alighted is part 3 (between observer 4 and 5). Observers 4 to 9 measure the first alighting passengers, so their starting times are indicative for the arrival moment of train 2. Observer 9 indicates that at $t = 5340$ s, the first alighting passengers have passed his line, thus the arrival time

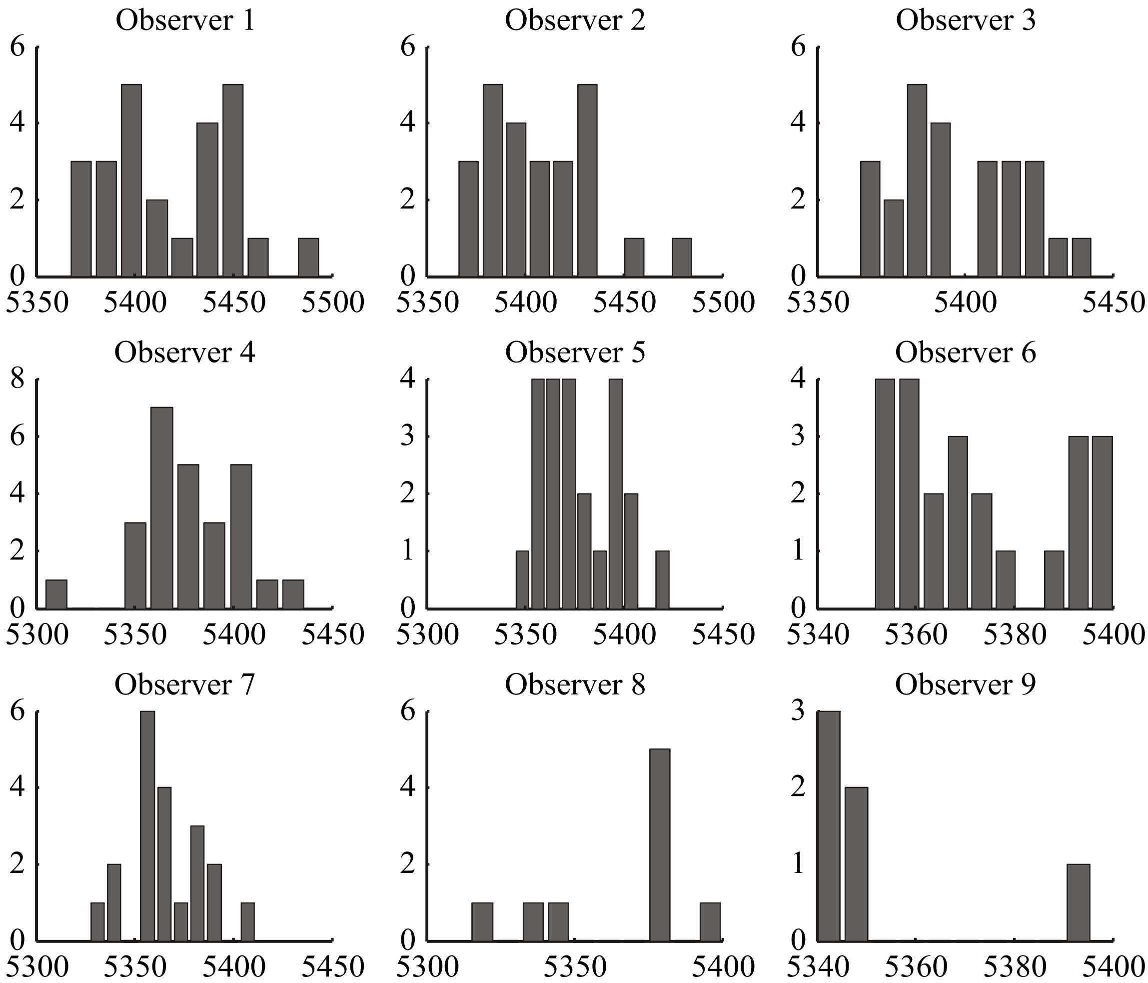


Figure E.11: Histogram of passengers walking to the stairs per observer for train 2 of the second train is assumed at $t = 5340$ s.

E.3.3 Number of boarding and alighting passengers

The number of boarding and alighting passengers is derived from cumulative curves. A cumulative plot of pedestrians is a function $N(x,t)$ that represents the number of pedestrians that has passed a cross section x from an arbitrary starting moment (see also subsection 4.7.3). The flow measured at a cross section x during a time period from t_1 to t_2 equals:

$$q(x, t_1 \; to \; t_2) = \frac{N(x,t_2) - N(x,t_1)}{t_2 - t_1} \tag{E.1}$$

Now, consider two cumulative plots at positions x_1 and x_2 respectively, where $A(t) = N(x_1,t)$ is the arrival curve denoting the cumulative person count at the entry of the pedestrian way (location x_1) while $D(t) = N(x_2,t)$ is the departure curve denoting the cumulative person count at the exit (location x_2) of the pedestrian way (see figure E.12). The time t at which an individual i passes the cross section can be obtained by finding the time t where a horizontal line across the ordinate i meets the crest of a step. Let $N^{-1}(x,N)$ denote the function that returns t for a given N. If pedestrians pass the area in a First-In-First-Out (FIFO) order, then these N-th observations correspond to the same individual, and hence the trip time $T_N^{walk}(t)$ of the N-th pedestrian through the section $x1, x2$ equals:

$$T_N^{walk}(t) = A(N) - D(N) \tag{E.2}$$

When the assumption of FIFO is not met, $T_N^{walk}(t)$ does not indicate individual trip times, but average trip times.

At time instant t, the average density is:

$$k(x_1 \; to \; x_2, t) = \frac{N(x_1,t) - N(x_2,t)}{x_2 - x_1} \tag{E.3}$$

Each observer observes one cross section, situated at the bottom and the top of the staircase and each 10 m on the platform (see figures E.7 and E.14). Two cumulative curves are constructed for each cross section, namely one for passengers walking from the staircase (figure E.13) and one for passengers walking to the staircase (figure E.15).

Before starting the observations, the number of pedestrians present in each area between two observers has been counted (see figure E.14).

Usually, cumulative curves start in an empty infrastructure, but with these observations, this is not the case. Therefore, the cumulative curves of pedestrians walking from the

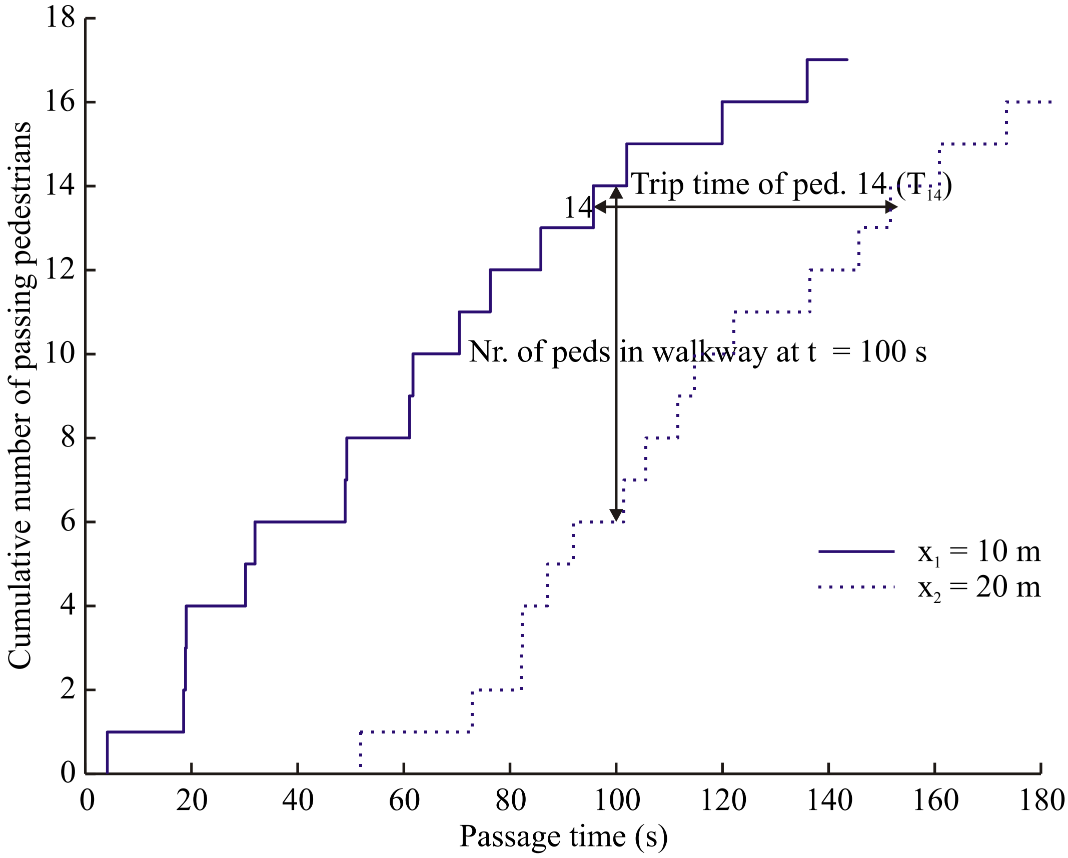


Figure E.12: Cumulative curves at $x = 10.0$ m and $x = 20.0$ m respectively

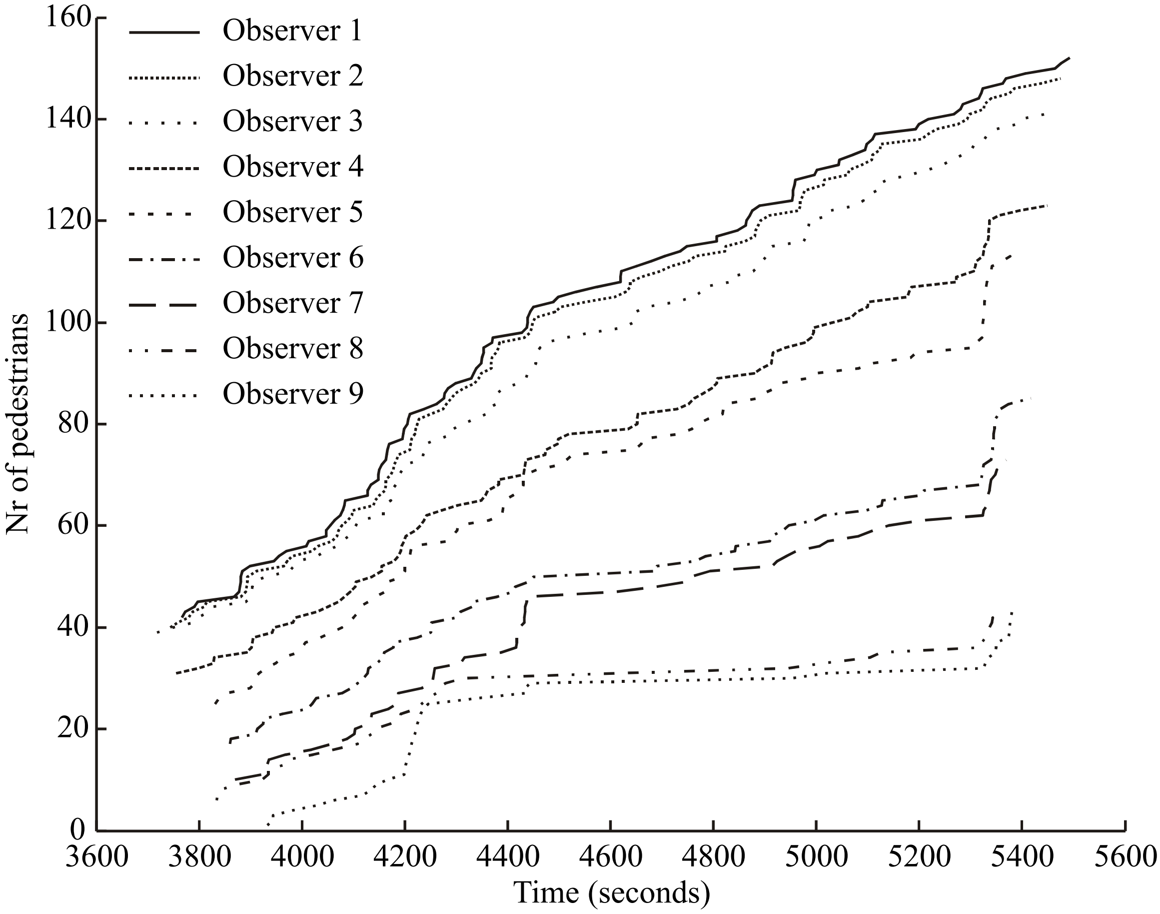


Figure E.13: Cumulative curves of pedestrians walking away from the stairs

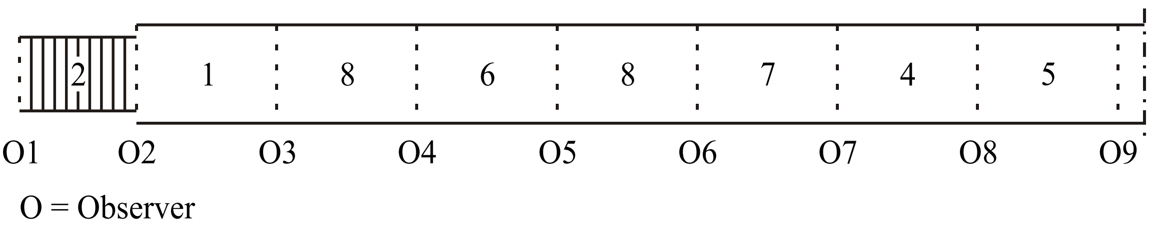


Figure E.14: Number of pedestrians present on each part of the platform when the observations started staircase start with the pedestrians already present on the platform, assuming they are all boarding passengers and have already passed the observers between the bottom of the staircase and the left cross section of the area they are located. As the number of pedestrians on the right of observer 9 is unknown, cumulative curve 9 starts at 0. Five pedestrians have already passed observer 8 before the observations started (now being present in the area between observer 8 and observer 9) thus cumulative curve 8 starts at 5 pedestrians counted. This procedure is applied for each observer, ending with cumulative curve 1 starting at 41 ($= 2 + 1 + 8 + 6 + 8 + 7 + 4 + 5$) pedestrians counted.

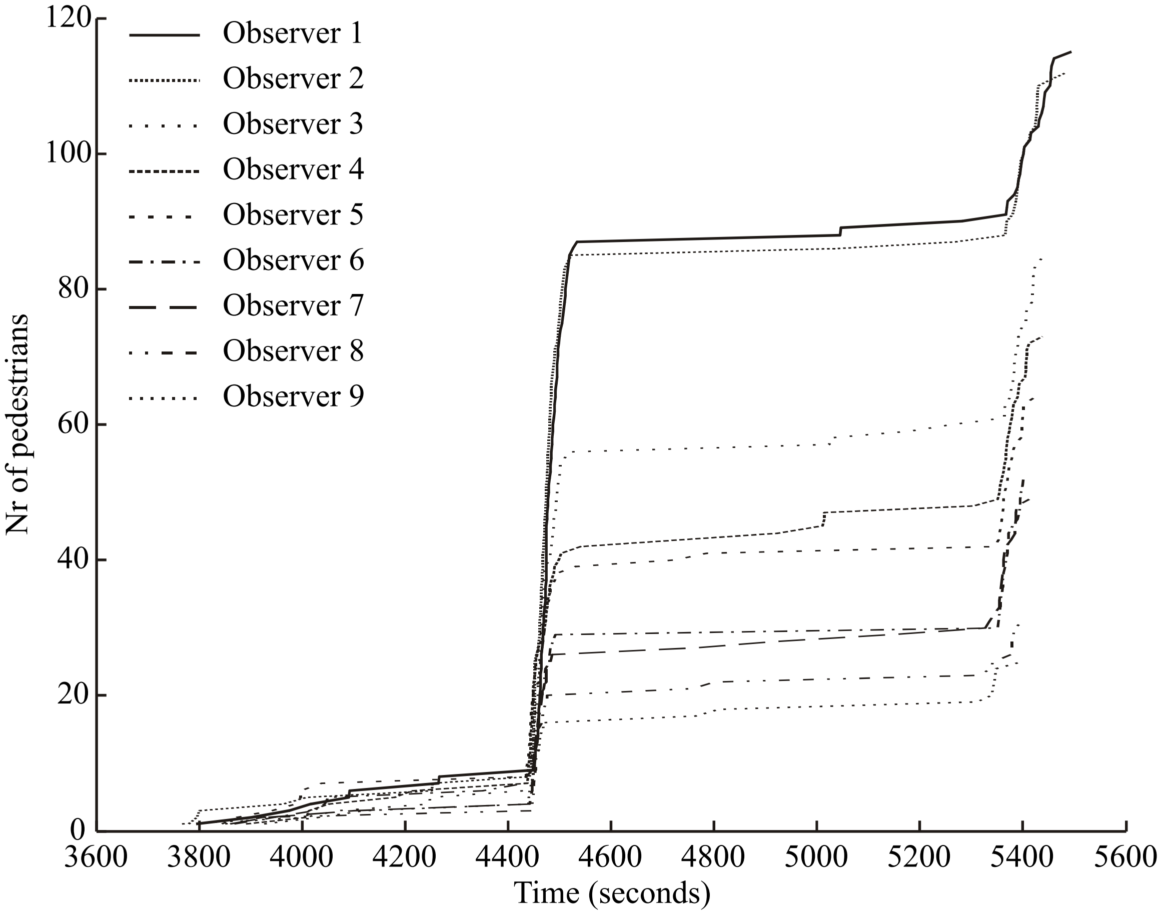


Figure E.15: Cumulative curves of pedestrians walking to the stairs

As indicated before, pedestrians walking to the staircase are mostly alighting passengers. It is therefore assumed that at the beginning of the observations no pedestrians are present on the platform walking in the direction of the staircase, thus all cumulative curves start at 0 pedestrians counted.

The vertical difference between two cumulative curves indicates the number of pedestrians being present in a part of the platform, whereas the horizontal difference indicates the average walking time in these conditions. Unfortunately, this is not the case for these observations, as is shown in figure E.16, indicating all flows on a part of the platform.

The orientation of the figure is similar to previous figures, which means that the track is

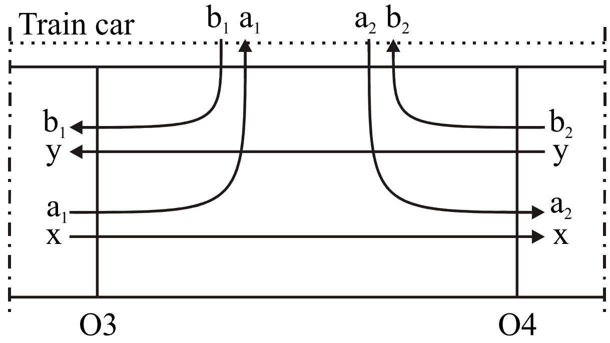


Figure E.16: Pedestrian flows on a part of the platform

situated at the top of the figure (the dotted line indicates a train carriage), whereas on both sides of the area two observers (number 3 and 4) are situated, measuring moments that pedestrians pass a cross section. The observers only indicate the walking direction and not whether these passengers boarded in the adjacent area. Known are thus $b_1 + y$, $a_1 + x$, $b_2 + y$, and $a_2 + x$. Separate flows and individual parameters are not available.

It is thus necessary to do some assumptions. As the staircase is the only way to enter or leave the platform, nearly all alighting passengers will head in that direction. This leads to the assumption the a_2 is non-existent. The same reasoning accounts for b_2, that is, before the alighting process has started, some pedestrians will walk in the direction of the staircase to find a good location to board. However, when the first pedestrians have alighted, the platform becomes crowded and boarding passengers will not change their waiting location easily, thus b_2 also is assumed zero. The difference in the number of pedestrians measured by both observers is therefore the number of passengers boarding and alighting at the intermediate part of the platform. Figure E.17 shows an overview of the total number of observed pedestrians passing each observer. The difference between these measurements indicate the number of alighting passengers (figure E.18). The number of boarding passengers (figure E.19) is derived in a similar way.

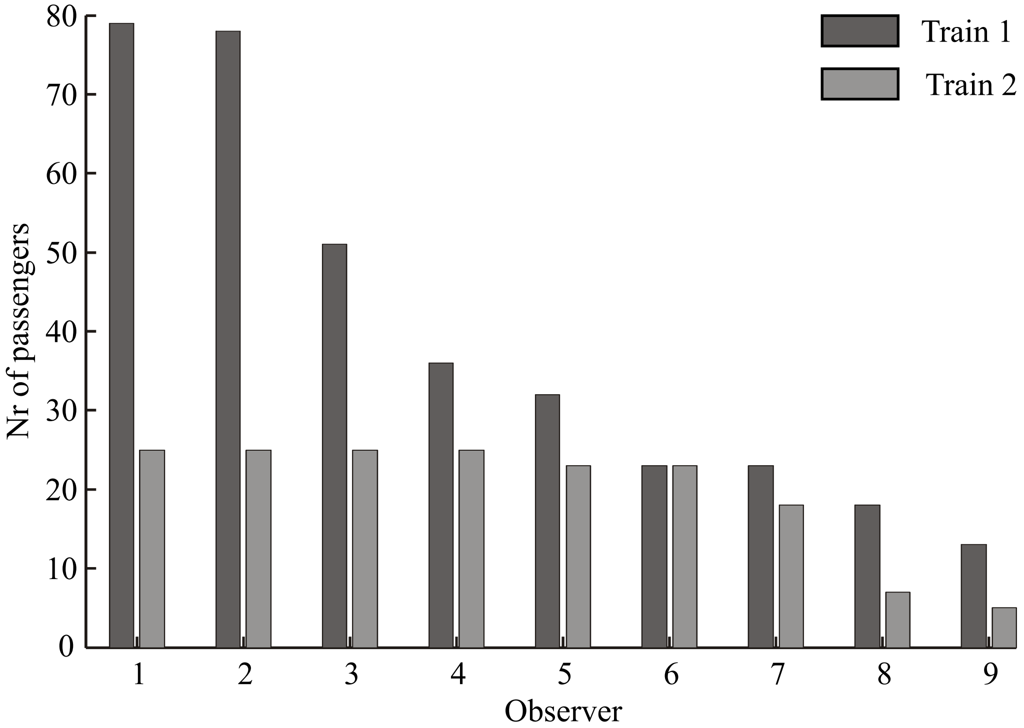


Figure E.17: Number of alighting passengers passing each observer

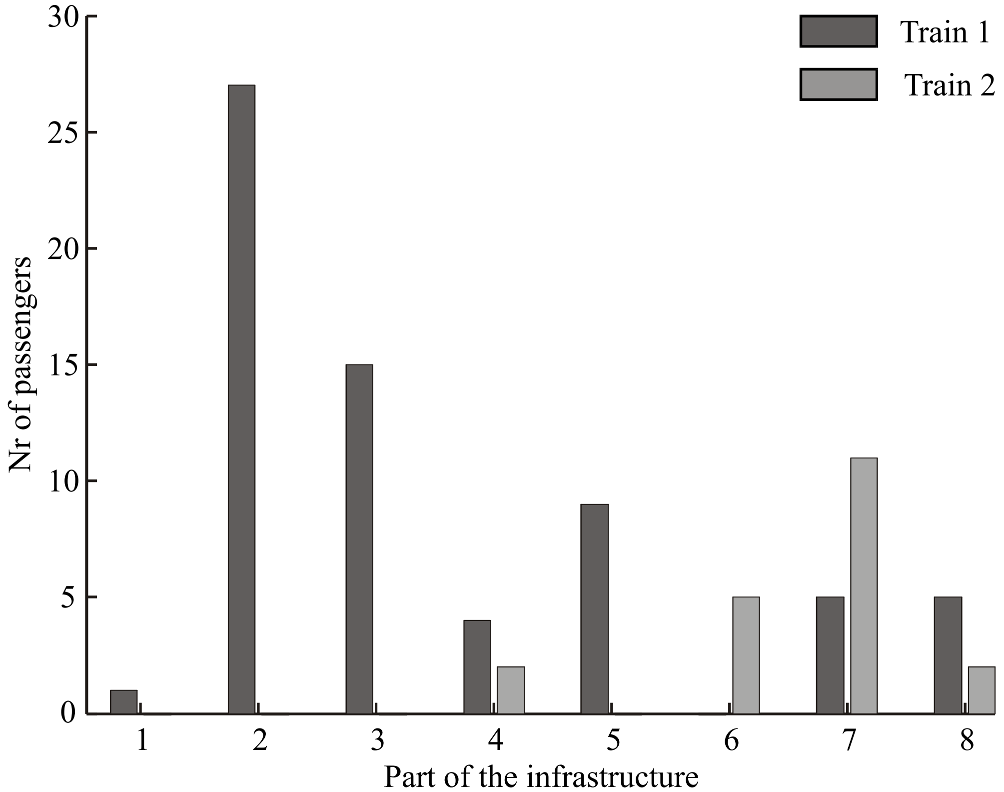


Figure E.18: Number of alighting passengers per part of the infrastructure

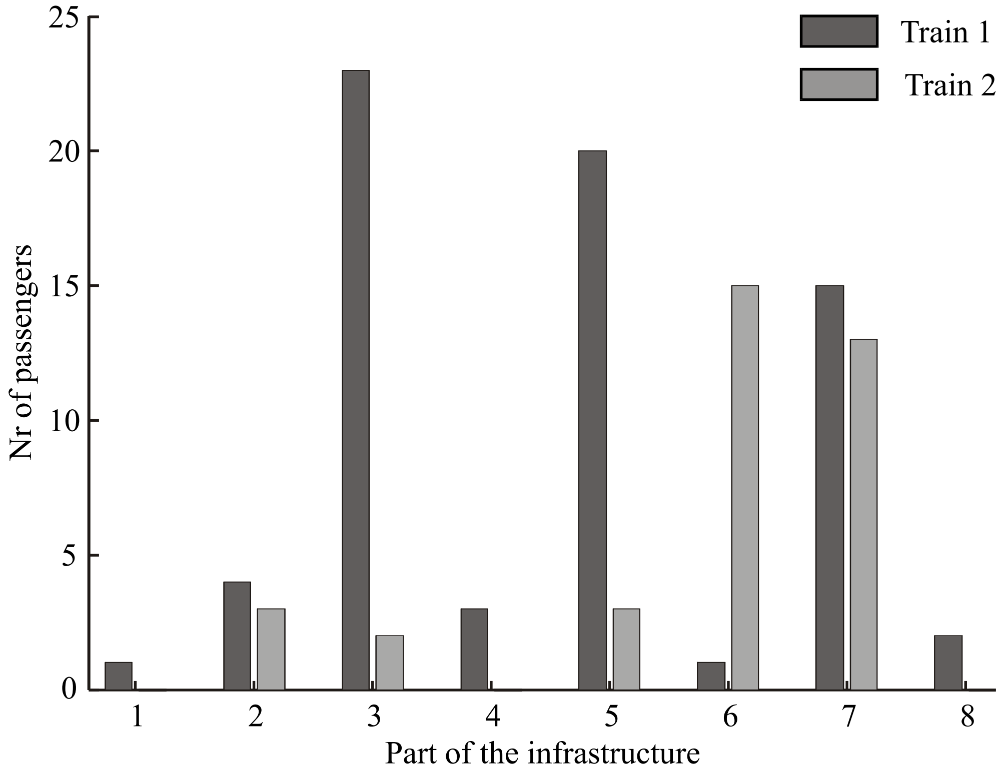


Figure E.19: Number of boarding passengers passing each observer

Summary

The aim of the research described in this thesis is to develop a *validated operational simulation tool* supporting design assessments of public transport facilities (stations, airports, passenger terminals) and public spaces with intensive pedestrian flows. Since increasingly the available area for these public facilities is reduced, the efficiency and accuracy of their designs is becoming more important. The developed simulation tool is meant as an aid in the planning and design process, supplying quantitative information by predicting the quality of pedestrian (traffic) flow. This information might be used to compare multiple designs, but also to optimise a specific design.

In order to cover all passenger processes in public transport facilities adequately, the resulting simulation tool does not only include walking per se, but also covers multiple other aspects of pedestrian behaviour, such as route choice, performing activities, and boarding and alighting from public transport vehicles. The work presented in this thesis therefore has a fairly broad scope: it contains a comprehensive overview of the state-of-the-art on pedestrian route choice and pedestrian walking behaviour, as well as data collection and analysis on both microscopic and macroscopic pedestrian behaviour, models dealing with multiple aspects of pedestrian behaviour, verification and validation of the simulation tool, and model applications. In this summary, the main achievements and conclusions of this thesis are presented.

An extensive *state-of-the-art overview* is provided on pedestrian route choice and walking behaviour in public transport facilities. One of the conclusions is that only little knowledge is available on pedestrian behaviour in this specific application area, while more literature has been found on general aspects of pedestrian route choice and walking behaviour. Blank spots found in this state-of-the-art concern empirical data, theories, and models on route choice, walking, waiting, and activities especially in relation to public transport facilities. With respect to walking, specific knowledge is missing about microscopic pedestrian walking behaviour and the transformation of this microscopic behaviour into macroscopic pedestrian flow characteristics, and about the influence of pedestrian characteristics and composition of pedestrian flows on fundamental diagrams. Also, traffic characteristics of waiting, among other things with respect to choice of a waiting location and pedestrian behaviour during waiting (walking around, when to find an alternative, etc.) are found absent in literature as well. Finally, activities of pedestrians in such accommodations form a blank spot, especially regarding the choice which activities are performed in public transport facilities, at which locations, and finally how these activities

are scheduled.

In order to fill the gaps identified in the state-of-the-art overview a variety of *empirical data* has been collected with respect to microscopic walking behaviour, pedestrian traffic characteristics on railway platforms, and pedestrian route choice in train stations. Controlled experiments have been applied for the first time in pedestrian flow research. These experiments have been used to observe pedestrian walking behaviour in different conditions. Experiments have been performed for station and shopping conditions, one, two and four directional traffic flows, and with narrow bottlenecks. Pedestrian trajectories have been automatically estimated by dedicated detection and tracking software. The experiments produced achievements with respect to free speed distributions, speed variances, fundamental diagrams, self-organisation (layer formation and zipping effect), and capacity of bottlenecks both for one directional and multi directional flows. For example, the estimated free speeds appear somewhat higher than in observations described in literature ($1.45\,\mathrm{m/s}$ versus $1.34\,\mathrm{m/s}$), while the variance appeared much smaller ($0.23\,\mathrm{m}^2/\mathrm{s}^2$ versus $0.37\,\mathrm{m}^2/\mathrm{s}^2$). With respect to the fundamental diagram, we found a slight difference from car traffic flow theory. During congestion, also free flow conditions occur at the outsides of the funnel-shaped congestion upstream of the bottleneck. An observation of the flow over the total width is thus a combination of several observations in different conditions. Capacity estimates show that the relation between the width of a corridor and its capacity is not linear, as is mostly assumed, but looks more like a step-wise capacity function, at least for bottlenecks of moderate width (less than 3 m). It is shown how pedestrians inside bottlenecks effectively form layers or trails. These layers are overlapping, a phenomenon which is referred to as the ‘zipper’ effect.

Observations of pedestrians on a railway platform have been used for the validation of the simulation tool with respect to pedestrian traffic flow characteristics on platforms. These observations have been obtained with handheld computers, recording boarding and alighting times, walking times on the platform, and densities on different parts of the platform over time. Finally, data have been collected on route choice in two Dutch train stations by following passengers discretely, so-called ‘stalking’. These data have been used to estimate discrete route choice models to identify the impact of factors such as walking times, infrastructure type, and shelter on passenger route choice.

A system demarcation and decomposition of public transport facilities have been established specifying elements and processes relevant for modelling. A characteristic of this decomposition is the distinction of three levels of pedestrian decision-making. The strategic level concerns long-term decisions, the tactical level concerns medium term decisions such as route choice, while the operational level concerns decisions for the immediate next instant. *Discrete choice utility maximising models* are derived and specified for all relevant choices with respect to activity scheduling, activity area locations, routes, and walking trajectories. Most of the remaining processes (performing activities, boarding, and alighting) are modelled as *service queuing models*. In addition, procedures have been developed to derive individual walking speeds and aggregate densities in all types of walking infrastructures.

The simulation tool includes the processes of activity location choice, route choice, walking, waiting, performing an activity, and the interactions of pedestrians with the public transport services. The infrastructure that is input of the simulation tool is translated into two different network models. The *operational network model* describes infrastructure elements in two dimensions (with a length and a width), while the *tactical network model* is built of links and nodes. The operational network is used to determine exact lengths of paths of pedestrians over the infrastructure (trajectory generation model). The walking times along these paths are input for the tactical network model, used in the activity location choice model and the route choice model. Three different types of links are specified in the tactical network model, namely for walking, for waiting, and for service, on which the average travel time per pedestrian is specified.

Existing object models and software architectures for modelling public transport transfer facilities did not satisfy our requirements. Therefore, a *dedicated object model* as well as a *dedicated software architecture* have been developed. The object model is designed to handle both static and dynamic information concerning infrastructure, pedestrians, and public transport vehicles. The simulation tool consists of different coupled modules, such as a simulation kernel, an input module, animation modules (both two and three dimensional), an archiving module, and an analysis application supplying automatically generated statistics and graphs based on simulation results. Characteristics of this software architecture are its general applicability (also useful for other simulation models), its modularity (to include various behaviour models), and its support of parallel processing in order to increase simulation speed.

The *verification* and *validation* of the simulation tool have been based on observations, experiments, and on plausibility of simulation results. For verification, a dedicated verification plan has been followed including comparisons of simulation results with predictions from traffic flow theory. The difference between expected and predicted results was for all tests lower than 3%. This is due to some stochastic aspects of the simulation tool, which cannot be excluded. Validation of route choice modelling has been based on plausibility of predicted routes and a comparison with literature as well as on observations in practice. All comparisons appeared satisfactory for the indicated application areas. A comprehensive validation on traffic flow characteristics has been performed by comparing model predictions with observations on a Dutch railway platform. The performance indicators of the validation are walking speeds (on the stairs and on the platform, for both boarding and alighting passengers) and density over time and over space. Most indicators were found similar, whereas satisfying explanations could be found for the revealed dissimilarities.

In order to demonstrate the applicability of the tool, several *case studies* have been performed with different application areas, such as existing transfer stations, preliminary transfer station designs, and operational effects of new schedules for a ferry terminal on pedestrian flows. The findings from these case studies support the main conclusion of this thesis that modelling pedestrian behaviour in different types of public transport facilities turns out to be very useful offering a valuable contribution and support to the work of designers of pedestrian facilities in general and, using the described simulation tool SimPed, of designers of public transport facilities in particular.

On top of these practical benefits achieved, a number of contributions to traffic flow theory have been realised, such as on the shape of fundamental diagrams for pedestrian traffic in congested conditions, the layering and zipping phenomena of dense one directional and multi directional pedestrian flows, and derived from the latter, a new, namely stepwise look at capacity of pedestrian flows in narrow walkways. These theoretical contributions only were possible thanks to a number of methodological innovations for pedestrian measurements, the most essential of which is the automatic identification of individual space-time trajectories from high-position video images.

Samenvatting

Het doel van het onderzoek dat in dit proefschrift is beschreven, bestaat uit het ontwikkelen van een *gevalideerd operationeel simulatiemiddel* dat als ondersteuning kan dienen bij het beoordelen van ontwerpen voor openbaar vervoervoorzieningen (stations, luchthavens, passagiersterminals) en openbare ruimtes met grote voetgangersstromen. Aangezien de beschikbare ruimte voor de inpassing van deze openbare voorzieningen steeds meer wordt beperkt, wordt de efficiëntie, de nauwkeurigheid en de betrouwbaarheid van de ontwerpen steeds belangrijker. Het ontwikkelde simulatiemiddel is bedoeld als hulpmiddel in het plannings- en ontwerpproces. Het verstrekt kwantitatieve informatie op basis van voorspellingen van de kwaliteit voor voetgangersstromen. Deze informatie kan worden gebruikt bij het vergelijken van verschillende ontwerpen, maar eveneens voor het optimaliseren van een bepaald ontwerp.

Om de invloed van alle processen in een overstapstation op voetgangersgedrag in voldoende mate mee te nemen, omvat het ontwikkelde simulatiemiddel niet alleen het loopproces, maar ook vele andere aspecten van voetgangersgedrag, zoals het routekeuzegedrag, het uitvoeren van activiteiten (aanschaffen en valideren van een vervoerbewijs, het verkrijgen van een krant, etc.) en het instappen in en uitstappen uit openbaar vervoervoertuigen. Het werk, dat gepresenteerd is in dit proefschrift, heeft een brede scope:

1. Het bevat bijdragen aan een uitgebreid overzicht van de state-of-the-art op het gebied van routekeuze van voetgangers en hun loopgedrag.
2. Er worden data verzameld and geanalyseerd van zowel het microscopische als het macroscopische voetgangersgedrag.
3. Er zijn modellen ontwikkeld met betrekking tot meerdere aspecten van het voetgangersgedrag.
4. De ontwikkelde modellen zijn geïmplementeerd in het simulatiemiddel SimPed.
5. Er is een verificatie en validatie uitgevoerd van het simulatiemiddel.
6. Het model is toegepast in verschillende praktijksituaties.

In deze samenvatting worden de belangrijkste bijdragen en conclusies van het proefschrift gepresenteerd.

Een uitgebreid *literatuuroverzicht* is samengesteld, dat betrekking heeft op voetgangersgedrag in openbaar vervoervoorzieningen. Eén van de conclusies hieruit is dat er slechts weinig kennis beschikbaar is over voetgangersgedrag in dit specifieke toepassingsgebied, terwijl meer literatuur is gevonden met betrekking tot algemene aspecten van routekeuze van voetgangers en loopgedrag. Witte vlekken die gevonden zijn in deze state-of-the-art hebben betrekking op het gebrek aan empirische data, theorieën en modellen voor route keuze, lopen, wachten en activiteiten in relatie tot openbaar vervoervoorzieningen. Voor wat betreft lopen mist specifieke kennis over microscopisch loopgedrag en de afleiding van macroscopische stroomkarakteristieken uit dit microscopische gedrag. Ook de invloed van kenmerken van voetgangers en de samenstelling van voetgangersstromen op het fundamenteel diagram is onbekend. Bovendien is geen literatuur gevonden over de verkeerskundige kenmerken van wachtgedrag, onder andere met betrekking tot de keuze van een locatie voor het wachten en het voetgangersgedrag tijdens het wachten, zoals ronddrentelen op een perron. Tenslotte vormen activiteiten van voetgangers in deze verblijfsgebieden een witte vlek, vooral met betrekking tot de keuze welke activiteiten voetgangers uitvoeren in openbaar vervoervoorzieningen, op welke locaties en tenslotte in welke volgorde deze activiteiten worden gepland.

Om de lacunes die zijn geïdentificeerd in het literatuuroverzicht te vullen is een verscheidenheid aan *empirische data* verzameld, die betrekking heeft op microscopisch loopgedrag, verkeerskarakteristieken van voetgangers op treinperrons en routekeuze van voetgangers in een treinstation. Voor de eerste keer zijn gecontroleerde experimenten toegepast in een onderzoek naar voetgangersstromen. Deze experimenten zijn gebruikt om loopgedrag te observeren in smalle gangen. De uitgevoerde experimenten hadden betrekking op stations- en winkelgebieden, eenrichtingsstromen, twee- en vierrichtingsstromen en tenslotte op versmalling in de infrastructuur. Trajectoriën van voetgangers zijn automatisch geschat met behulp van een specifiek ontwikkeld detectie en tracking softwareprogramma. De experimenten hebben resultaten opgeleverd, die betrekking hebben op verdelingen van vrije snelheden van voetgangers, varianties in snelheden, fundamenteel diagrammen, hysterese, zelf-organisatie (strookvorming en het rits-effect) en de capaciteit van bottlenecks. Hierbij zijn zowel eenrichtings- als meerrichtingsstromen bekeken.

Op basis van de data verzameld met deze experimenten is een veelvoud aan fenomenen onderzocht. Hieruit bleek dat de geschatte vrije snelheden iets hoger liggen dan in waarnemingen beschreven in de literatuur ($1.45\,\mathrm{m/s}$ versus $1.34\,\mathrm{m/s}$), terwijl de variantie veel kleiner bleek te zijn ($0.23\,\mathrm{m^2/s^2}$ versus $0.37\,\mathrm{m^2/s^2}$). Verder is een kleine afwijking gevonden ten opzichte van het fundamenteel diagram, dat gebruikt wordt in de verkeersstroomtheorie voor autoverkeer. Tijdens congestie treedt in voetgangersstromen namelijk ook vrije doorstroming op aan de buitenkanten van de trechtervormige congestie stroomopwaarts van de bottleneck. Waarnemingen van de intensiteit over de totale breedte van deze congestie is dus een combinatie van verschillende waarnemingen in verschillende toestanden. Ook laten schattingen van de capaciteit van een bottleneck zien dat de relatie tussen de breedte van een bottleneck en de bijbehorende capaciteit niet lineair is, zoals veelvuldig wordt aangenomen, maar meer een getrapte vorm heeft. Dit geldt met name voor bottlenecks met een beperkte breedte (minder dan 3 m). Tenslotte is aangetoond dat voetgangers in de bottleneck zeer effectief omgaan met de ruimte door het vormen van stroken, vergelijkbaar met strookvorming in het autoverkeer. Deze stroken overlappen, waardoor het zogenaamde rits-effect ontstaat.

Waarnemingen van voetgangers op een treinperron zijn gebruikt voor de validatie van het simulatiemiddel met betrekking tot de verkeerskundige kenmerken van voetgangersstromen op perrons. Deze waarnemingen zijn verzameld met behulp van zakcomputers, waarmee gegevens over in- en uitstaptijden, looptijden op het perron en dichtheden op verschillende delen van het perron in de tijd zijn vastgelegd. Tenslotte zijn waarnemingen gedaan met betrekking tot de routekeuze in twee Nederlandse treinstations door het discreet volgen van voetgangers. Deze waarnemingen zijn gebruikt voor het schatten van discrete routekeuzemodellen om de invloed van factoren als looptijd, type infrastructuur en overkappingen op het routekeuzegedrag van passagiers te bepalen.

Afbakening en decompositie van openbaar vervoervoorzieningen zijn gerealiseerd door het specificeren van elementen en processen, die relevant zijn voor het modelleren. Eén van de karakteristieken van deze decompositie is het onderscheid in drie niveaus in de besluitvorming van voetgangers. Het strategische niveau betreft lange termijn beslissingen, het tactisch niveau beinvloedt beslissingen op middellange termijn, terwijl het operationeel niveau betrekking heeft op de beslissingen in de eerstkomende periode. *Discrete nutsmaximalisatie keuzemodellen* zijn afgeleid en gespecificeerd voor alle relevante keuzes ten aanzien van programmering van activiteiten, locaties om activiteiten uit te voeren, routes en voetgangerstrajectoriën. Het merendeel van de overige processen (het uitvoeren van activiteiten, in- en uitstappen) wordt gemodelleerd met behulp van *service wachtrij-modellen*. Bovendien zijn procedures ontwikkeld om individuele loopsnelheden en geaggregeerde dichtheden af te leiden voor allerlei soorten loopinfrastructuur.

Het simulatiemiddel omvat de volgende processen: keuze van de locatie om activiteiten uit te voeren, route keuze, lopen, wachten, het uitvoeren van een activiteit en de interacties van voetgangers met openbaar vervoer diensten. De infrastructuur, die invloed is op het simulatiemiddel wordt vertaald in twee verschillende netwerk modellen. Het operationele netwerk model beschrijft de infrastructuur in twee dimensies (met een lengte en een breedte), terwijl het tactische netwerkmodel opgebouwd is uit links en knopen. Het operationele netwerk model wordt gebruikt voor het bepalen van de exacte lengtes van trajecten afgelegd door de voetgangers over de infrastructuur (trajectorie generatie model). De looptijden over deze paden zijn vervolgens invoer voor het tactische netwerk model, dat op zijn beurt weer invoer is voor het activiteit locatie keuze model en het route keuze model. In het tactische netwerk model zijn drie verschillende soorten links gespecificeerd, namelijk voor lopen, voor wachten en voor het uitvoeren van een activiteit. Voor elk van deze links wordt een gemiddelde reistijd voor de voetganger gespecificeerd.

Bestaande objectmodellen en software architecturen voor het modelleren van openbaar vervoer overstapvoorzieningen voldeden niet aan de eisen. Derhalve is zowel een *specifiek objectmodel* als een *specifieke software architectuur* ontwikkeld. Het objectmodel is ontworpen om statische alsmede dynamische informatie over de infrastructuur, voetgangers en openbaar vervoer voertuigen vast te leggen. Het simulatiemiddel is opgebouwd uit verschillende modules, zoals een simulatie kernel, animatie modules (zowel twee- als drie-dimensionaal), een module voor de archivering en een analysemodule, die voorziet in automatisch gegenereerde statistieken en grafieken gebaseerd op simulatieresultaten. Kenmerken van deze software architectuur zijn de algemene toepasbaarheid (ook geschikt voor andere simulatiemodellen), de modulariteit en de mogelijkheid om verschillende gedragsmodellen te specificeren. Bovendien ondersteunt de software architectuur 'parallel processing' om de rekensnelheid van de simulatie te verhogen.

De *verificatie* en *validatie* van het simulatiemiddel zijn gebaseerd op waarnemingen, loop-experimenten en op de plausibiliteit van de simulatieresultaten. Voor de verificatie is een specifiek verificatieplan opgesteld en gevolgd waarbij simulatie resultaten zijn vergeleken met voorspellingen uit de verkeersstroomtheorie. Het verschil tussen de verwachte en de voorspelde resultaten was voor alle testen lager dan 3%. Dat de verschillen niet nog kleiner zijn wordt veroorzaakt door de stochasticiteit in het simulatiemiddel. Validatie van het routekeuzemodel is gebaseerd op de plausibiliteit van de voorspelde routes, een vergelijking met de literatuur, en bovendien met waarnemingen uit de praktijk. Alle vergelijkingen bleken toereikend voor de gestelde toepassingsgebieden van het simulatiemodel. Een uitgebreide validatie van de verkeersstroomkarakteristieken van de voetgangers is uitgevoerd door het vergelijken van de modelvoorspellingen met de waarnemingen op een Nederlands treinperron. Hierbij zijn indicatoren gebruikt over loopsnelheden op de trap en op het perron voor zowel in- als uitstappende reizigers en dichtheden over tijd en ruimte. De meeste indicatoren bleken overeen te komen, terwijl bevredigende verklaringen konden worden gevonden voor de verschillen.

Om de toepasbaarheid van het simulatiemiddel aan te tonen zijn verschillende *casestudies* uitgevoerd met verschillende toepassingsgebieden, zoals bestaande overstapstations, voorlopige ontwerpen van overstapstations en de operationele effecten van nieuwe dienstregelingen voor veerboten op voetgangersstromen. De bevindingen van deze casestudies ondersteunen de belangrijkste conclusie van dit proefschrift, namelijk dat het modelleren van voetgangersgedrag in verschillende soorten openbaar vervoervoorzieningen mogelijk blijkt en dat het gebruik van SimPed het werk van ontwerpers van voetgangersvoorzieningen in het algemeen en ontwerpers van openbaar vervoervoorzieningen in het bijzonder ondersteunt.

Daar komt nog bij dat naast de bereikte praktische resultaten ook een aantal bijdragen aan de verkeersstroomtheorie zijn gerealiseerd, bijvoorbeeld met betrekking tot de vorm van fundamenteel diagrammen, de fenomenen van strookvorming en ritsen van dichte een- en meerrichtings voetgangersstromen. Van het laatste fenomeen is bovendien een nieuwe, stapsgewijze relatie afgeleid tussen de breedte en de capaciteit van voetgangersstromen in smalle doorgangen. Deze theoretische bijdragen waren alleen mogelijk dankzij een aantal methodologische innovaties op het gebied van waarnemingen van voetgangers, waarvan de meest essentiële is: het automatisch identificeren van individuele trajectoriën in ruimte en tijd op basis van videobeelden gemaakt van grote hoogte.

About the author

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Winnie Daamen was born in 1975 in Leidschendam, the Netherlands. In 1993, she started her study in Civil Engineering at the Delft University of Technology. During the last year of this study, she spent six months in the Ecole Nationale des Ponts et Chaussées in Paris. After returning in Delft, she started her practical work at Holland Railconsult. Her masters thesis concerned the development of a simulation tool for pedestrians in transfer stations.

In 1998 she joined Holland Railconsult as a (junior) consultant. Here and at the Transport & Planning section of the Delft University of Technology she conducted her Ph.D. research on modelling pedestrian behaviour in public transport facilities. At Holland Railconsult, she was also involved in applications of a microscopic simulation model on railway traffic. Together with Serge Hoogendoorn, she set up extended laboratory experiments with respect to pedestrian walking behaviour, in which almost 100 volunteers participated and many media were present.

In January 2003 Winnie joined the Transport & Planning department of the Faculty of Civil Engineering and Geosciences of the Delft University of Technology in order to finish her PhD research. During this research she has presented various papers in the Netherlands and at international conferences, and published articles in national and international journals. At the moment she is working as a researcher in the Transport & Planning department, still in the area of pedestrian behaviour.

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