Research on pedestrian traffic flow in the Netherlands

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Abstract

To assess the design of walking infrastructure such as transfer stations, shopping malls, sport stadiums, etc., as well as to support planning of timetables for public transit, tools to aid the designer are needed. To this end, a microscopic and a macroscopic pedestrian flow model have been developed at Delft University of Technology, the Netherlands. To both calibrate and validate such models, and to gain more insight into the characteristics of pedestrian flows under a variety of circumstances, very detailed pedestrian flow data is required. This is why experimental pedestrian flow research has recently been carried out. Also, observations have been performed on boarding and alighting in Dutch railway stations.

In this paper, an overview is given of the research performed at the Delft University of Technology. Then, several parts of this research are described in more detail. More information is provided on the observations with regard to boarding and alighting, the laboratory walking experiments, the microscopic simulation model NOMAD and the macroscopic simulation model SimPed.

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Researcher

Winnie Daamen got her Masters degree in Civil Engineering on a simulation model for pedestrians in railway station. During her period as a PhD-student this model has been extended and developed further into the simulation model SimPed. After having worked several years as project manager for a railway consultancy, she is now a researcher at Delft University of Technology in order to finish her PhD and to further the scientific knowledge on pedestrian traffic flow and its impact on the design of transport facilities, as well as commercial centers.

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Serge Hoogendoorn is a senior lecturer in the research field of traffic flow theory and modeling in general and in particular with respect to pedestrian flow. He received a personal grant from the Dutch Research Foundation (NWO-MaGW) for the project 'Walking behavior in public areas'. Together with Winnie Daamen, he is involved in experimental research, theory development and modeling of pedestrian flows.

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Introduction

Designers of walking infrastructure such as transfer stations, city center areas and shopping malls need to assess the quality of the plans. Consequently, tools are needed, such as microscopic and macroscopic pedestrian flow models, as developed by the Transportation and Planning Section of the Delft University of Technology. Before the simulation models can be applied in practice, they must be calibrated and validated. In order to do this, as well as to gain more insight into pedestrian behavior under different conditions, very detailed empirical data are required. Also, these data are used to fill existing gaps in knowledge on pedestrian behavior. Delft University of Technology has recently carried out a number of pedestrian flow experiments. Furthermore, observations have been performed of the boarding and alighting process in Dutch railway stations.

Large-scale experimental research on pedestrian flows has not been performed before. Not only pedestrian research in the form of experiments is an important innovation, also the scale of the experiments and the amount of very detailed data on individual pedestrians is unique. Not only the observation technology has unique aspects; also the software specifically developed for automated tracking of pedestrians did not exist. Further innovations in theory are the development of optimal control models and the description of pedestrian behavior in bottlenecks. Finally, two simulation models for pedestrian flows have been developed, to describe individual pedestrian behavior (NOMAD) and to describe pedestrian flows in transfer stations, including the interaction with public transport vehicles (SimPed).

In this paper, first a short overview is given of the research performed at the Delft University of Technology. Then, we focus on several parts of this research. More detailed information is given of observations of boarding and alighting at Dutch railway stations, laboratory walking experiments, the microscopic simulation model NOMAD and the macroscopic simulation model SimPed.

Overview of the research performed at the Delft University of Technology

In general the research lifecycle of physical, psychological, or biological phenomena involves the following stages:

- Empiricism
- Theory
- Models

Empiricism or observations is used to view the actual processes and form a basis for the development of general theories. Models are at their turn based on these theories. Potentially powerful instruments to be used by designers and planners of the walking environment are simulation models, given that these models are adequately calibrated and validated. In the following sections, for each of the topics an overview is given of the research performed by Delft University of Technology, Transportation and Planning Section.

Empiricism

Two empirical studies have been performed in 2000, 2001 and 2002. The first study consisted of large-scale laboratory experiments on walking behavior. Pedestrians, a sample representative for the Dutch population, were invited to participate in these experiments. At May 16, ten experiments were performed in two waves, with about 80 participants per wave. The aim of these experiments was to observe pedestrian walking behavior in standard, station and shopping conditions. Also, pedestrian flows in several directions and in bottlenecks are recorded on video.

The goals of the second empirical project are to quantify boarding and alighting times and to gather basic data for a more accurate planning of the dwell times in public transport and an improved service operation. The project is part of a research program into the quality of train service operation and aiming to develop instruments to improve the operational control. A measurement project was carried out on a number of typical Dutch railway stations. Observed were: type of station, location of the platform accesses, type of train service, type of rolling stock, train door widths, number of boarding and alighting passengers, period of day and duration of the dwell period, split up in alighting, boarding and waiting for departure.

Furthermore, two smaller studies have been performed on observational techniques. The first study concentrated on pedestrian route choice, especially on the choice between stairs and escalators in metro stations. Observations have been made on several locations, resulting in insight into aspects affecting this part of the route choice.
The aim of the second study was to determine distributions for waiting and service times for ticketing. Two ways of obtaining a ticket are available for the passenger: he or she can buy his ticket offices or at ticket machines. Pedestrian aspects involving the choice for either a ticket machine or a ticket office were recorded and distributions were derived to estimate waiting and service times, depending on pedestrian characteristics.

Ongoing research involves pedestrian route choice, especially in transfer stations. The aim of this project is to develop a pedestrian route choice model, predicting routes based on pedestrian and route characteristics. In order to calibrate and validate this model, observations are performed at Dutch railway stations in the months of April and May 2003.

Theory

Based on the observations described in the previous section, existing theories are extended and new theories are developed. Theories on pedestrian traffic flow refer to several fields:

- Walking behavior
    - General applicable under various circumstances
    - Specifically for transfer stations
- Route choice
- Boarding and alighting, or the interaction between public transport vehicles and walking as an access or egress mode
- Activity behavior
    - Decision making (activity choice, location choice)
    - Waiting
    - Being served

Most of the theoretical research is based on observations and function as basis for the development of simulation models. Some of these general innovative approaches are not restricted to pedestrian flows, especially experimental design issues, observation techniques and modeling approaches.

Simulation models

Two simulation models have been developed: NOMAD and SimPed. NOMAD models individual pedestrians. NOMAD consists of two mutually dependent models. The top-level model jointly predicts pedestrian activity scheduling, activity area choice, and route choice in public spaces. A main innovation is that routes may be continuous curves in space and time, rather than an ordered set of links. Moreover, pedestrians can choose between multiple activity areas where to perform their activities. The preferred location will be influenced by the route choice, and vice versa. The down-level model describes the walking behavior. The microscopic model is based on the behavioral assumption that optimal predictive feedback controllers with limited prediction horizon can describe pedestrians adequately.

SimPed is a simulation model for pedestrian flows, developed in co-operation with Holland Railconsult, a Dutch consulting engineering firm for public transport and railway infrastructure. The aim of SimPed is to estimate both mean and variability of walking times incurred by transferring passengers and to visualize walking patterns inside transfer stations and other pedestrian areas. Simulation studies with this tool quantify the effects of station layouts on pedestrians in a transfer station. Moreover, SimPed is used to analyze effects of timetables of the various public transport systems (departure and arrival times, type of rolling stock) on passenger flows in and through the transfer station (congestion, transfer times).

Boarding and alighting in railway stations

The duration of dwell times at stations is determined by the scheduled dwell times, the number of alighting and boarding passengers, train and infrastructural characteristics, and the arrival and departure process of the trains (Wiggenraad (2002)).

Parameters determined are the dwell time and its components (boarding, alighting, waiting, etc.), the distribution of the passengers over the platform, and the influence of type of station, the type of train service, vehicle characteristics (door passageway width) and period of day (peak and off-peak).

In October 2000 and May 2002 measurements were carried out on eleven typical Dutch railway stations, being five local stations and five intercity stations with different locations of the platform accesses. Also, measurements were carried out in a metro station. One observer recorded with a stopwatch the train movements and each of a number of observers was allocated to a platform sector and recorded with a digitiser the number of waiting passengers and the moments of passenger movements (alighting or boarding).

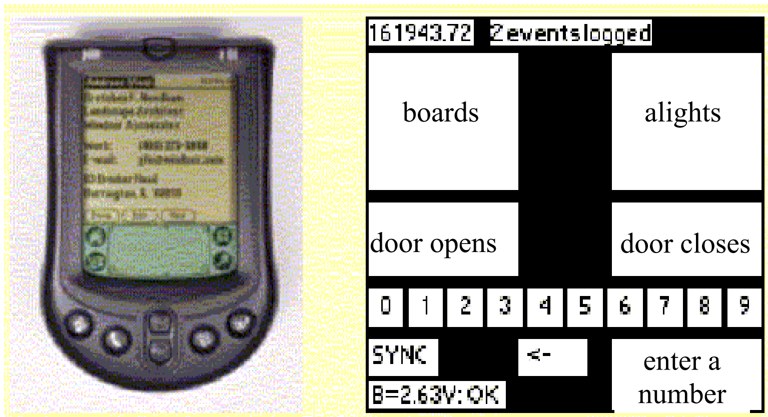

Figure 1. Digitiser used for observations in Dutch railway stations

The measured dwell times, especially for intercity trains, in general exceeded the scheduled ones. In the timetable local trains are scheduled to dwell 60 seconds. In practice the dwell time varies from 90 to 120 seconds. On the average, trains arrive generally late at stations (intercity trains about 210 seconds). Added with the dwell times longer than scheduled, trains depart with even longer delays (intercity trains about 280 seconds).

Dwell times in peak and off-peak hours are about equal. In peak hours the length of alighting and boarding time in clusters is longer due to the larger numbers of passengers, but this is compensated by the shorter remaining alighting and boarding time of individual passengers. The percentage of the wasted time and the dispatching time in general is constant, up to 20%.

There are clear concentrations of waiting and boarding passengers around platform accesses. Stairs at the end of the platform lead to higher concentrations than locations in the middle or on one third and two thirds of the platform.

The mean alighting and boarding time per passenger in clusters is about 1 second. A clear difference exists in time length between types of rolling stock, i.e. dependent on the width of the passageway. Wide door double-decker trains have 10% shorter time values and intercity rolling stock with narrow door width results in about 10% longer time values than this average. Surprisingly, there is no difference found in alighting and boarding times per passenger in clusters between peak and off-peak hours.

Laboratory experiments

Delft University of Technology has recently collected data by carrying out experimental pedestrian flow research.

Experimental set up

In the walking experiments, two types of variables have been distinguished: 'experimental variables' and 'context variables'. Experimental variables are influenced during the various experiments, while context variables are specific for each pedestrian. The following experimental variables are considered:

- Free speed
- Walking direction
- Density
- Bottlenecks

These variables are varied in the experiments as follows:

Free speed

A. Normal (100% of the pedestrians maintains its own free speed)
B. Station conditions (60% normal speed, 40% higher speed)
C. Shopping conditions (60% normal speed, 40% lower speed)

Walking direction

The various directions are abbreviated: we = from west to east, ew = from east to west, ns = from north to south and sn = from south to north.

A. One direction (100% we)
B. Equal flows in two directions (50% we, 50% ew)
C. One small opposite flow (90% we, 10% ew)
D. Two equal crossing flows (50% we, 50% sn)
E. One small crossing flow (90% we, 10% sn)
F. Four equal crossing flows (25% we, 25% ew, 25% ns, 25% sn)

Bottlenecks

A. No bottlenecks
B. Bottleneck with a width of 2 meters
C. Bottleneck with a width of 1 meter

Density

The density varies between an almost empty and an almost completely occupied area. During the experiment extra groups are admitted to the observation area. The density is thus increased in a stepwise manner, until all groups participate. The size of the area is chosen such that congestion is possible.

Compared to the reference variant (one directional flow with normal free speeds without bottlenecks (experiment 1) one variable is varied per experiment. This leads to 10 experiments (see Figure 2):

Table 1. Overview of the ten experiments

	Free speed			Walking direction						Bottlenecks		
	A	B	C	A	B	C	D	E	F	A	B	C
1 (ref)	x			x						x		
2		x		x						x		
3			x	x						x		
4	x				x					x		
5	x					x				x		
6	x						x			x		
7	x							x		x		
8	x								x	x		
9	x			x							x	
10	x			x								x

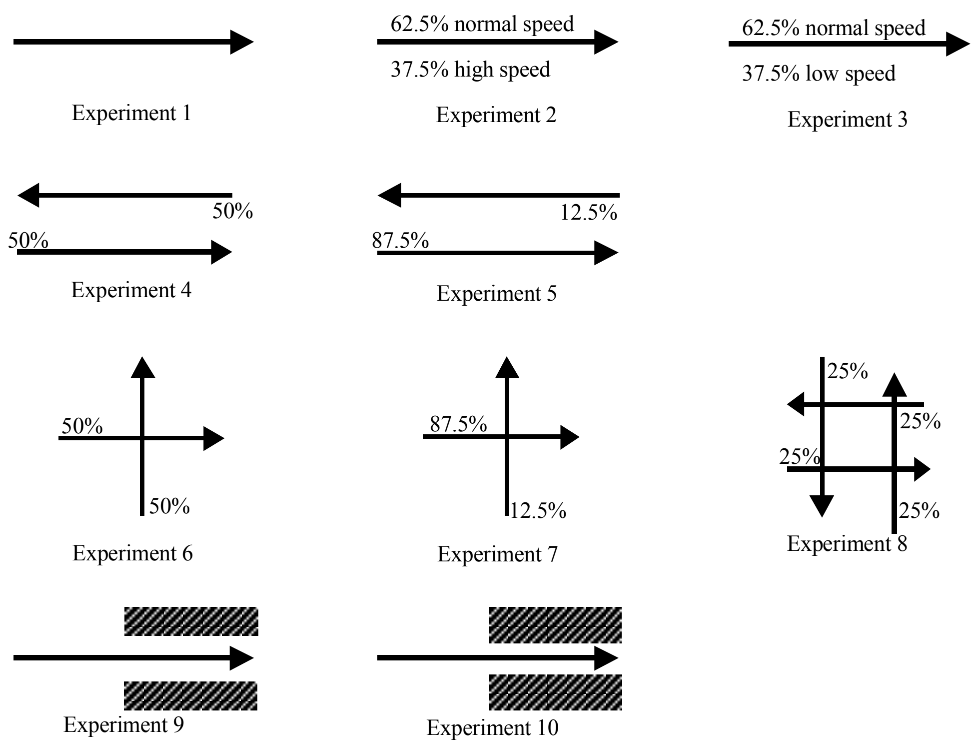

Figure 2. Overview of the ten experiments

The experiments can further be classified in four categories:

- One directional traffic
  - Experiment 1: reference conditions
  - Experiment 2: station conditions
  - Experiment 3: shopping conditions
- Two-directional traffic
  - Experiment 4: two equal opposite flows (walkway)
  - Experiment 5: one small opposite flow (late passengers heading for the already arrived train, while most passengers already got out)
- Crossing traffic
  - Experiment 6: two equal crossing flows
  - Experiment 7: one small crossing flow
  - Experiment 8: four equal crossing flows (a station hall)
- Bottlenecks
  - Experiment 9: wide bottleneck (walk from a hall into a small walkway)
  - Experiment 10: small bottleneck (wide walkway suddenly narrowed)

Carrying out the experiments

Measurement set up

Two observation areas are used. For the one and two-directional experiments and the experiments with a bottleneck a rectangular area is taken of 10 meters long and 4 meters wide. For the crossing flow experiments a square observation area is used with a side of 8 meters. The images in Figure 3 give an impression of the experiments.

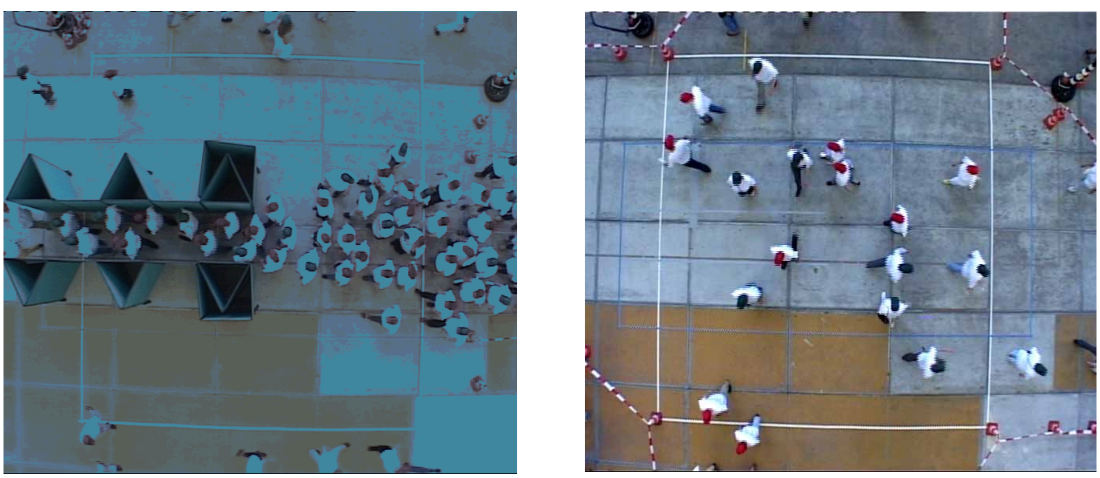

Figure 3. Impression of the experiments

The experiments have taken place in a large hallway in the Civil Engineering building of Delft University of Technology, and have been measured using a digital video camera, fixed at the ceiling at a height of 10 meters (for details see Daamen and Hoogendoorn (2003) and Hoogendoorn and Daamen (2003)).

Experimental subjects

Participants were recruited by advertising in local newspapers, the university newspaper and newsletters. Also an Internet site has been developed. This resulted in 140 registrations; the sample appeared representative for actual practice.

Realization

Each participant wore a white t-shirt and a cap (red or green) to facilitate automatic processing of the video images. The participants have been divided into groups, which received a specific walking order in each experiment. The color of the caps made the groups distinguishable.

A traffic light indicated when a pedestrian could enter the area in order to divide the pedestrians equally over the area and to prevent that already in the beginning of the experiment clusters are formed. The pedestrians walked then in the indicated direction over the area, while behaving as normal as possible. After leaving the area the pedestrians walked around the area back to the starting point. The process was then stabilized during a minute, after which the next group was admitted to the observation area. This continued until all groups participated in the experiment, after which a longer stabilization period was applied. Then, the groups left the area one by one.

Microscopic simulation model NOMAD

NOMAD (Hoogendoorn (2003)) distinguishes different levels of pedestrian behavior:

- Activity area and route choice level (tactical level)
- Walking behavior (operational level)

NOMAD is *activity based*, implying that the actions of the pedestrians are largely determined by the different activities pedestrians have planned to perform while being in the walking facility. Given an activity pattern (ordered set of activities; e.g. buying a train ticket and subsequently getting to the train platform), and given the (multiple) areas where these activities can be performed (ticket counters, train platforms), NOMAD determines the most likely areas where activities are performed, and the most likely routes between them. NOMAD allows for completely free route choice: pedestrians do not walk along linear, predetermined paths; rather, the routes are continuous paths in the continuous space.

Furthermore, the route choice and the activity area choice depends on the prevailing traffic conditions, meaning that when routes become congested, pedestrian avoid these routes provided that there are good route alternative available. Finally, it is possible to define preferred walking areas (e.g. next to shopping windows, well-illuminated areas, etc.), as well as to include specific kinds of walking infrastructure, such as escalators, and stairs. While walking, pedestrians aim to adhere to the shortest route. However, due to encounters with other pedestrians, they will generally not be able to do so. This holds equally for the interaction with obstacles and walls. If a pedestrian drifts away from the shortest route, the shortest route *from that point onwards* is used.

The modeling of the *operational walking task* (e.g. acceleration and interaction processes) is based on known empirical facts and theory on pedestrian behavior. The calibration of the model parameters is done using a microscopic approach, where model results have been compared to observed microscopic pedestrian behavior (trajectories determined from video). The user of the model is free to change the model parameters to best suit the pedestrian behavior for the situation at hand. For instance, the effect of age, trip purpose, and gender of the walking speeds can be described. NOMAD automatically computes the effect of these factors on the pedestrian walking speeds, based on results of empirical studies, such as reported by Weidmann (1993).

Model structure

Figure 4 depicts an overview of the NOMAD model, its inputs and outputs. The figure indicates that the user of the model must provide the topology of the network (walls, obstacles, stairs, escalators, activity areas, etc.), the traffic demand patterns for each activity schedule, the parameters describing the walking behavior for each of the pedestrian types that are considered (e.g. men, women, commuters, etc.), and finally the composition of the pedestrian flow with respect to the pedestrian types. The latter describes the composition of the flow at the different origins in the model. Finally, the user can define incident conditions, for instance to simulate the effect of an evacuation.

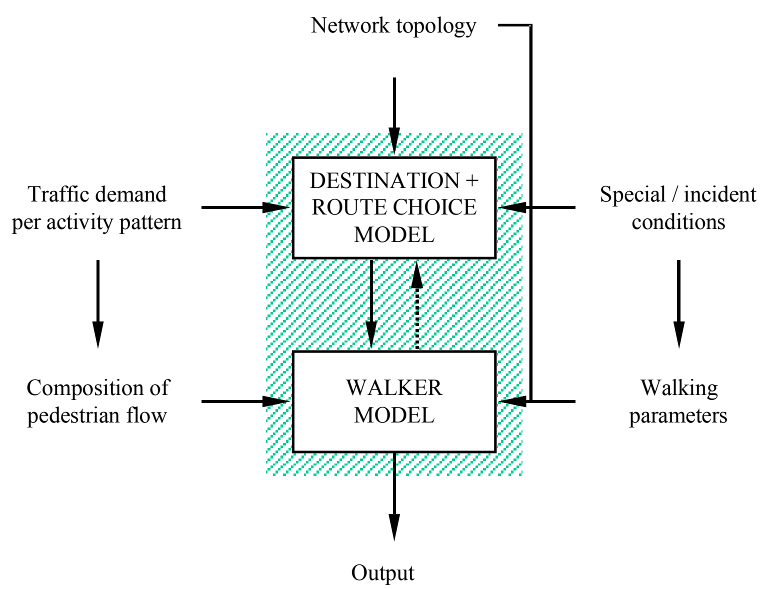

Figure 4. Components of the NOMAD model

After the input data being established, NOMAD first determines the destination and route choice. This is achieved by computing the *minimal route cost function*, from which the optimal walking directions are easily determined. In turn, the walker model determines the preferred walking direction and speed using the minimal route cost.

The prevailing traffic conditions predicted by the walker model may cause delays to occur, for instance upstream of narrow bottlenecks. In turn, deterioration of traffic conditions may cause pedestrians to choose a different route. NOMAD inhibits a feedback mechanism that predicts the effect of worsening conditions on flow behavior. Note that also a dynamic assignment model version has been developed in which it is assumed that pedestrians in choosing their routes have perfect information on current and future travel conditions (i.e. considering actual walking times).

Walker modeling

In NOMAD, pedestrians are described in terms of a closed feedback control system. Their model, which is similar to other models that have been proposed to describe the execution of human control tasks, naturally leads to an optimal control formulation, where pedestrians are assumed to minimize the predicted costs of walking. These costs are determined by among other things the extent to which pedestrians can walk at their desired velocity, the proximity of other pedestrians, walking near to obstacles, and the need to accelerate or decelerate.

Furthermore, it is hypothesized that the costs are discounted over time, implying that events in the near future are deemed more important than events that are expected to happen much later. Besides a control model, predicting the optimal walking behavior of a pedestrian, a *physical model* describes the effects of physical contact between pedestrians and obstacles. NOMAD predicts the effects of special infrastructure on the walking speeds of pedestrians.

In case of stairs or grades, the desired speed of the pedestrians is reduced in accordance with the grade of the walking surface or the stairs. The behavior on an escalator is described in a simplified manner by assuming that the pedestrian moves at the same speed as the escalator.

Mathematical description of route choice

NOMAD models the *destination area and route choice* by assuming that pedestrians jointly optimize the subjective utility of these choices, where utility depends on the utility of performing an activity at a certain activity area, and the access route costs. In turn, these costs depend on the preferences and the physical capabilities of the pedestrians. The route costs are among other things determined by the walking time, walking at uncomfortable speeds, attractiveness of the walking environment, and the proximity of obstacles (walls, etc.). As mentioned earlier, routes are continuous functionals in the walking space. In the NOMAD model, routes are not considered explicitly; rather, the velocities that constitute the optimal route (or rather, the optimal trajectory) are determined.

The NOMAD model is activity based. Activities can often be performed at multiple destination (or activity) areas D_j. For instance, a ticket can be bought at multiple ticket counters. The preferred destination area depend will depend on the current location of the pedestrian, and thus of the cost of getting to the respective destination areas. Furthermore, destination-area specific costs can be defined that describe the preference of performing an activity at one destination area over another.

The NOMAD model allows for the definition of activity sequences: pedestrians might first buy a train ticket, subsequently buy a newspaper, and finally catch a train. To correctly describe the path choice and destination area choice in case of activity sequences, the terminal costs are modified accordingly.

Macroscopic simulation model

SimPed (Daamen (2002)) is a modeling tool to analyze the impacts of station design and station layout, timetable design and platform allocation as part of the timetable and design and layout of large pedestrian areas on pedestrian traffic flow, to assess the performance of the transfer station in terms of bottleneck capacity, experienced level of service, and to determine the feasibility of the timetable. To this end, the behavior of pedestrians in unusual or seldom occurring layouts of rooms or larger walking areas needs to be described as well.

Station design and layout assessment

The simulation model can be applied to quantify the level of service of pedestrians while they are moving through the station and while they are waiting at the platform or in the hall. These situations can be simulated for existing stations, extensions of existing stations, stations under development and stations under design. The emphasis is at the spatial shapes (layout) of the station and the amount of space available for the passengers to move. Also, a passenger can perform activities at a transfer station, which are or are not related to transferring. Examples of these activities are buying a ticket, waiting for the train and shopping. The influences of these activities on the level of comfort of the transferring passengers are also taken into account, when they hinder other pedestrians while waiting for their turn.

Timetable design and platform allocation

Timetables or train frequencies have a substantial influence upon the level of service of transferring passengers and especially upon their waiting times within the station. High frequent trains in a regular pattern imply a low waiting time and less stress for the passengers to catch their train. Whenever the amount of passengers can not be coped with, not even with this high frequency, the level of service will lower quickly, which can lead to dangerous situations. When the supply of passengers does not justify high train frequencies, train services need to be tuned in order to create optimal transfers. These transfers need to be maintained in case of delay or other disturbances, which demands an intelligent train management system and possible non-optimal station platform occupations.

Dynamics of pedestrian flows

As mentioned before, the layout of a station building influences the behavior of passenger flows. SimPed uses macroscopic relations between density in the walking areas and pedestrian speeds to model pedestrian walking behavior. Route choice and the performance of activities is based on individual pedestrians. Oversaturated bottlenecks in, for instance, before an escalator or near an entrance or exit can already be found in the design phase and thus saving a lot of expenses.

In short, SimPed is used to evaluate:

- The layout of (parts of) existing transfer stations,
- Effects of extensions and/or adaptations of existing transfer stations,
- Layout alternatives for newly developed stations,
- Alternatives of and changes in different platform allocations,
- Alternatives of and changes in different timetables and
- Layout alternatives for large pedestrian areas without connections to public transport.

Modeling pedestrian flow operations

The model will be used to quantify the effects of station layouts on pedestrians in a transfer station. Visualizing these effects helps to identify and to understand the causes for the presence of bottlenecks, long walking distances and large transfer times. The visualization is achieved in two ways: *technical* (indicating the level of service of a walkway) and *three-dimensional* (three-dimensional view with individual pedestrians). Furthermore, the model makes it possible to determine the effect of disruptions during operation of the timetable (delays and early arrivals of trains) on transfer times of passengers.

In evaluating the resulting pedestrian flows, the model is considered as a black box, containing an assignment model, which assigns pedestrians to the network (see Figure 5). Inputs for the assignment model are the network topology with different links and a matrix of pedestrian origins and destinations. The assignment model assigns pedestrians to routes, which are optimal for the pedestrian (shortest in time). The route choice is based on the current conditions on the network. The behavior of the different types of pedestrians (tourists, workers, etc) is taken into account in a separate behavior model.

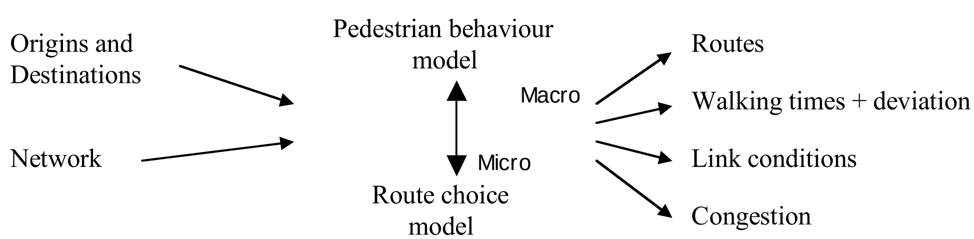

Figure 5. The pedestrian movement model including inputs and outputs

During the simulation, the model performs the following activities repetitively:

- Determining origins and destinations of the pedestrians present,
- Assigning routes through the station network,
- Calculating walking times based on the behavior models and
- Executing situation updates and dynamic evaluations.

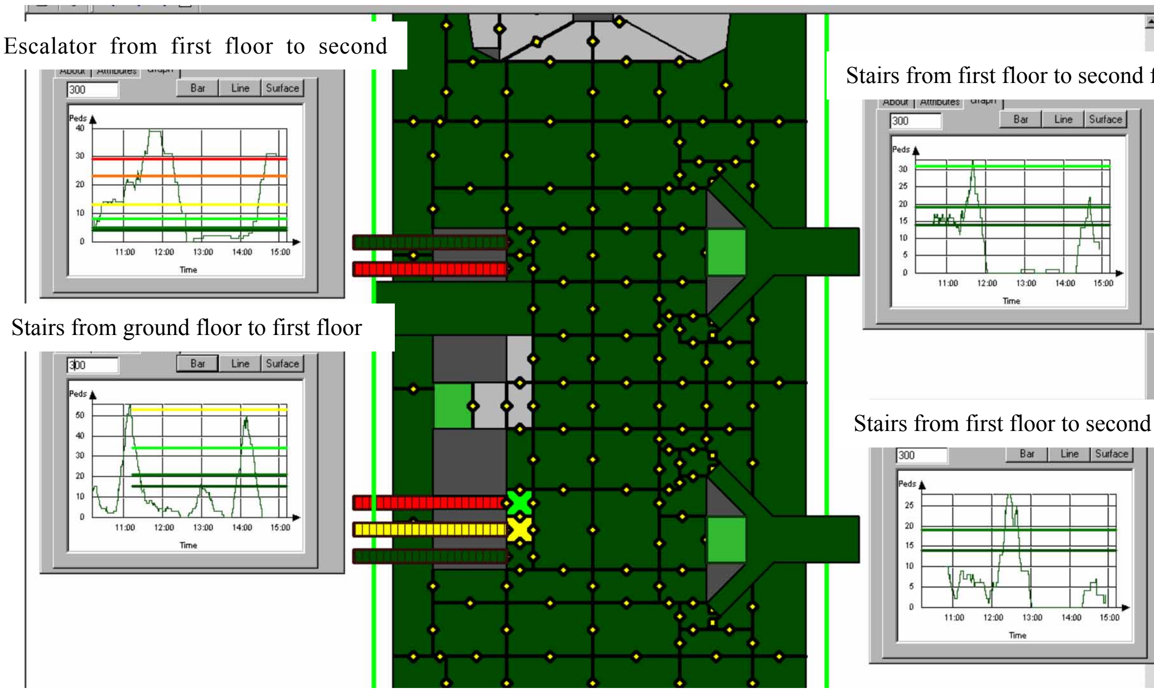

Figure 6. Animation of SimPed

The model produces different walking routes used by pedestrians, depending on the current conditions of the network. The stochastic route choice model may cause the situation that two pedestrians, having the same origin and destination choose different routes. Also, the model calculates walking times (means and standard deviations). From the number of pedestrians on a link, the mean available space for each pedestrian can be derived which, in turn, is an indication for the performance on the link. This quantity is expressed in a level of service. Low levels of service indicate congestion in the network.

Table 2. Characteristics of levels of service on walkways (Fruin (1971))

Level of service	Color	Density (m^2 / ped)	Intensity (ped/m/min)	Speed (m/s)
A	Dark green	> 3.2	< 23	1.30
B	Light green	2.3 – 3.2	23 – 33	1.25
C	Bright green	1.4 – 2.3	33 – 49	1.15
D	Yellow	0.9 – 1.4	49 – 66	1.00
E	Orange	0.5 – 0.9	66 – 82	0.70
F	Red	< 0.5	> 82	

Modeling and visualizing the dynamic behavior of pedestrians, especially at railway stations is relatively new. At transfer stations, people behave differently compared to normal circumstances (eg. they may be in a hurry to catch their train or they are milling about because they have missed it). Moreover, walking conditions in stations differ substantially from those outside (higher densities of people, wider range of walking purposes and speeds). As a consequent, specific behavior of passengers in transfer stations needs to be studied.

Conclusions and recommendations

This paper describes innovative research of the Transport and Planning Section of the Delft University of Technology. Two large empirical studies have been performed during the last years. The first study consisted of large-scale laboratory experiments on walking behavior. The second study concerned measurements on the boarding and alighting process on a number of typical Dutch railway stations. Furthermore, two smaller studies have been performed on pedestrian route choice and a last study had the aim of determining distributions for waiting and service times for ticketing, both at ticket offices and at ticket machines. Two simulation models have been developed: NOMAD and SimPed. NOMAD is a microscopic simulation model, whereas SimPed is a macroscopic simulation model for pedestrians in transfer stations

Despite the fact that this research contains major improvements in existing theories and models on pedestrian behavior and an extension of the amount of available data on pedestrians, still gaps in knowledge on pedestrians and their behavior exist. Consequently, further research is needed in all research stages: more observations, further extensions of existing theories and development of new theories and a refinement of existing (simulation) models.

Acknowledgments

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