Estimating the Flow Capacity of Pedestrian Intersections at Railway Stations

A field study at Utrecht Centraal station

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Estimating the Flow Capacity of Pedestrian Intersections at Railway Stations

A field study at Utrecht Centraal station

by

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Preface

This thesis is the final project of my studies. I have enjoyed working on it and I would like to thank everybody that has contributed along the way.

First, I would like to express my gratitude towards my daily supervisors, Dorine Duives, Rik Schakenbos and Jan Anne Annema for their guidance and feedback. I deeply appreciate your enthusiasm and support throughout the project. I would like to thank Serge Hoogendoorn for providing me with many opportunities for my thesis subject and for the valuable feedback during the meetings.

I would like to thank NS, and especially Mike Scheffer and Rik Schakenbos for the opportunity to do my thesis project at NS Stations. Also, I would like to thank my colleagues of team Onderzoek & Portfolio for their warm welcome and their support throughout the project. I enjoyed having lunch together, the teamuitjes and the chats in between work. Furthermore, I would like to thank Jeroen van den Heuvel for the fruitful discussions during the project and for providing insights into my project with his models on local densities. Also, I would like to thank ASE for providing me access to the data.

At last, I would like to thank my dear friends and family for their support and confidence along the way. Special thanks to Stefan and Olli, for your daily love and patience.

Lucia van Schaik,

Delft, December 2019

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1 Introduction

1.1 Problem statement

For the assessment and design of pedestrian transfer areas in stations, Dutch railway operator NS ("Nederlandse Spoorwegen") applies capacity standards for uni- and bidirectional flows. These standards regard the maximum flow capacity and is expressed as pedestrians per meter per minute.

Furthermore, a distinction is made between the capacity that indicates self-reliance ("zelfredzaamheid") and comfort. According to the VRT ("Verbetering Regelgeving Transfer"), a policy document by NS and infrastructure manager ProRail, self-reliance indicates the level of crowdedness in which the safety risks for pedestrians are acceptable (NS & ProRail, 2017a). Comfort indicates the level of crowdedness in which pedestrians can walk undisturbed.

Capacities have been determined for both uni- and bidirectional flows and can be seen in Table 1.1. For bidirectional flows a reduction of 15% of the capacity is applied to the unidirectional flow, which is based on a study by Weidmann (1993).

Table 1.1 Limits for horizontal transfer areas (NS & ProRail, 2017a)

Capacity ↓ / Flow →	Unidirectional	Bidirectional
Self-reliance	66 ped/m/min	56 ped/m/min
Comfort	49 ped/m/min	42 ped/m/min

It has been observed that, at railway stations, also other configurations of flows occur, such as intersecting flows at different angles (e.g. intersections between transfer areas and stairs/escalators or shops). A few studies (Plaue et al., 2011; Wong et al., 2010; Zhang & Seyfried, 2014) have shown that the pedestrian flow characteristics (i.e. the fundamental relation between speed, flow and density) for intersecting flows differ from those of uni- and bidirectional flows.

The current capacity standards at NS, which are based on the fundamental relations for uni- and bidirectional flows, are not applicable to intersecting flows. Hence, using these standards results in unreliable capacity estimations. Without reliable capacity estimations, a certain performance of the transfer area, mostly defined and measured by the level-of-service (LOS), cannot be guaranteed. In response to this problem, NS has expressed the need for capacity estimations of transfer areas at their stations where flows intersect, in order to determine reliable capacity standards.

1.2 Knowledge gap

In contrast to uni- and bidirectional flows, for which many researches have quantitively studied the pedestrian flow characteristics, only little research has been done to intersecting flows (Duives, 2016). Field studies to intersecting flows are limited and, to the knowledge of the author, none of them are conducted at railway stations.

Among the studies that share common aspects with this study, only a few mention methods to estimate capacity. Since there are some significant differences (e.g. the difference between experimental and field studies, between vehicular and pedestrian traffic, among others), none of the capacity estimation methods is directly applicable to this research and therefore needs to be explored. This knowledge gap will be addressed in this research.

1.3 Relevance for practice and science

Understanding pedestrian traffic is essential to estimate the capacity of pedestrian infrastructure and facilities. Among cities, transport facilities (e.g. railway stations and airports) and events (e.g. national festivities, festivals and large-scale gatherings), pedestrian traffic increases and pedestrian congestion is becoming a common phenomenon (Hänseler et al., 2016). Especially at places where large crowds gather and transfer, it is necessary to create safe and reliable infrastructure. There is a growing need to better understand pedestrian traffic in order to design for safe and reliable pedestrian infrastructures, facilities and operations.

In the broader context, this research aims to contribute to the general understanding of pedestrian traffic. In contrast to vehicular traffic, which has been researched extensively over the past 50 years or so, research to pedestrian traffic is relatively new and studies based on field data are limited. Since traffic characteristics and phenomena of vehicles cannot be applied directly to pedestrians, theories and models should be verified with empirical data. Since field studies to intersecting flows are limited, this research aims to add new insights on this topic.

1.4 Research objective and research questions

To address the problem as stated in section 1.1, the research objective is defined:

The objective of this study to gain insight into how the flow capacity of a pedestrian intersection at a railway station is influenced by several factors and to explore methods that can estimate the flow capacity of a pedestrian intersection.

Following the objective, the main research question is as follows:

Which factors theoretically influence the flow capacity of a pedestrian intersection at a railway station, and how can the flow capacity of a pedestrian intersection be estimated?

To structure the preliminary study of this research, the following sub-questions are formulated:

1. What is the current state-of-the-art knowledge with respect to pedestrian flow theory and intersecting flows?
2. Which variables should be included in the theoretical framework and how do they relate?
3. Which cases of intersection flows within our case study are interesting for further analysis?

1.5 Scope and case study

The focus of this research lies at the transfer area of a railway station where pedestrians move horizontally (e.g. a transfer corridor connecting multiple platforms, entrances and possibly shops as well). A field study will be conducted using trajectory data of individual pedestrians.

For our field study we have selected the case Utrecht Centraal station for two reasons. First, the station is an example case for (large) transfer stations, or 'knooppunt' stations, in which they share a similar physical layout. These stations accommodate multiple tracks and platforms, in which the platforms are aligned perpendicular to one or multiple corridors. The corridor is either located below or above the platform and connected by vertical infrastructure such as stairs, escalators and elevators. The main function of the corridor is to enable a flow through the station. Entrances are located often at both sides of the corridor, which enables other traffic to use the corridor as well (e.g. to pass the station). Often, in between the vertical infrastructures, shops (retail, food and beverages) are located. Examples of transfer stations similar to Utrecht Centraal are Leiden Centraal, Rotterdam Centraal and 's Hertogenbosch.

Secondly, in order to perform research to capacity, congested conditions are a necessity. Utrecht Centraal station is known for its high demand to and from the station (on average 194.385 passengers a day in 2018) and a large share of transfer passengers (on average 61.722 passengers a day in 2018). Hence, it is a suitable case for our field study.

1.6 Outline of the thesis

Figure 1.1 presents the research flow diagram of this research, which shows the relation between different chapters. Below, the purpose of each chapter is described.

- **Literature study:** The literature study presents state-of-the-art knowledge regarding pedestrian flow theory and insights from research regarding intersecting flows. With this knowledge, this chapter aims to answer the following research question:

  What is the current state-of-the-art knowledge with respect to pedestrian flow theory and intersecting flows?

- **Theoretical framework:** The theoretical framework is constructed based on insights from literature and practice. The aim of the theoretical framework is to give an overview of the research topic and the related variables. The framework will be used as a tool to scope the research and to verify and identify the strength of the relations. The research question in this chapter is:

  Which variables should be included in the theoretical framework and how do they relate?

- **Static analysis:** As a first step in the field study, a static analysis will be performed using smartcard data. The objective of the static analysis is to identify intersections from the case study for further analysis, by comparing the theoretical capacity of certain cross-sections with its demand. This analysis allows us to answer the following research question:

  Which cases of intersection flows within our case study are interesting for further analysis?

- **Selected intersections:** This chapter presents an elaborate description of the selected intersections for this research. Based on the specifications of the intersections and the flow scenario, several variables from the theoretical framework are selected, which scopes the field study and helps interpret the results from the data analysis.

- **Data collection method:** The data collection method will give insight into the data systems available at NS, their advantages and disadvantages regarding this study and a description of the chosen system.

- **Data processing method:** Since this study deals with large datasets, a preselection of the data is necessary to lower the computational burden. The data processing method presents the steps to select and retrieve the samples from the data.

- **Capacity estimation methods:** Three capacity estimation methods will be presented that are evaluated in this study. The definition of the variables, the selection of a time window and the methods will be discussed.

- **Results:** This chapter presents the results from the data analysis according to the capacity estimation methods as defined earlier.

- **Conclusions, discussion and recommendations:** Based on the insights obtained in the previous chapters, now conclusions can be drawn, and an answer can be given to the main research question:

  Which factors theoretically influence the flow capacity of a pedestrian intersection at a railway station, and how can the flow capacity of a pedestrian intersection be estimated?

  In the discussion, the results and limitations of this research will be discussed. The topics for discussion include a reflection on the theoretical framework, the chosen capacity estimation methods, decisions regarding data processing and limitations of computational power. In the final section, several recommendations for both research and practice will be formulated.

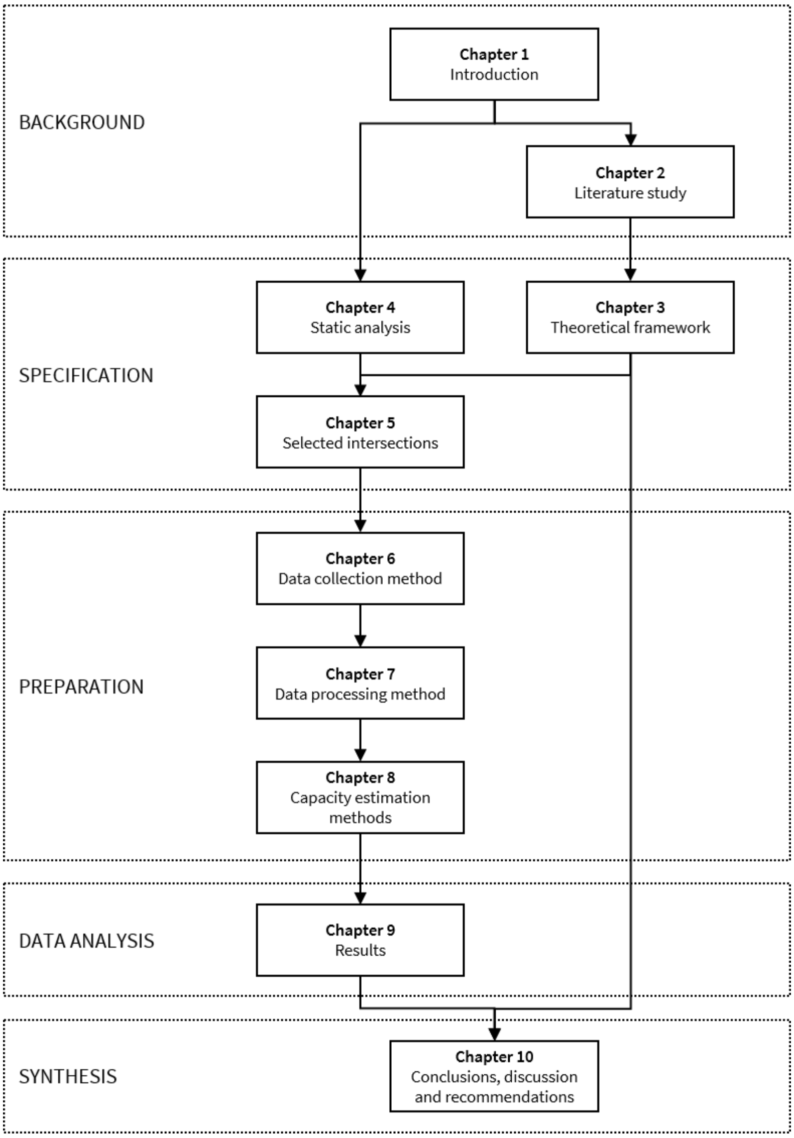


Figure 1.1 Research flow diagram

2 Literature study

This literature study presents state-of-the-art knowledge regarding pedestrian flow theory and insights from research regarding intersecting flows. With this knowledge, this chapter aims to answer the following research question:

What is the current state-of-the-art knowledge with respect to pedestrian flow theory and intersecting flows?

Section 2.1 describes how pedestrian dynamics is often quantified, by both macroscopic and microscopic flow variables. In section 2.2, several factors will be discussed that influence pedestrian dynamics. In section 2.3 the level of service concept is explained. Section 2.4 describes several phenomena in pedestrian dynamics. Section 2.5 presents several movement base cases, which is followed by section 2.6 which elaborates on previous studies regarding intersecting flows. At last, section 2.7 will present an overview of several capacity estimation methods found in literature.

2.1 Pedestrian traffic flow variables

Pedestrian dynamics can be quantified on an individual level by microscopic variables, and on an aggregate level by macroscopic variables. In summary, the most important microscopic variables are the position of a pedestrian $\vec{x}_i$, the velocity of a pedestrian $\vec{v}_i$ and the time-headways between two pedestrians $h_{i,j}$. The most important macroscopic variables are the density k, the flow q and the speed u. We will discuss these variables, among others, and their relations in more detail in the following subsections.

Microscopic variables

Microscopic variables describe the dynamics of an individual pedestrian i at a certain time instant t. We will discuss both the basic variables that regard a single pedestrian i, as well as variables that consider the interaction with other pedestrians j. Since pedestrian traffic takes place in a 2-dimensional plane, a vector notation will be used for most variables.

The most detailed level of description of an individual pedestrian is the trajectory (Hoogendoorn, 2019a). The trajectory describes the position $\vec{x}_i(t)$ as (x, y) coordinates of pedestrian i over a certain time period Δt. Figure 2.1 illustrates the trajectory of several pedestrians in a crossing flow experiment performed in 2002 (Hoogendoorn, 2019b).

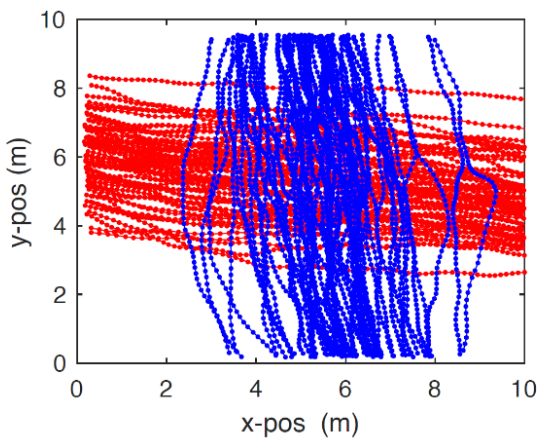


Figure 2.1 Trajectories crossing flows (Hoogendoorn, 2019b)

From this trajectory, several other microscopic variables can be derived, among which the velocity $\vec{v}_i(t)$, speed $w_i(t)$, direction $\vec{e}_i(t)$, acceleration $\vec{a}_i(t)$ and jerk $\vec{\gamma}_i(t)$ of a pedestrian. Table 2.1 presents these basic microscopic variables and how they are derived.

Table 2.1 Basic microscopic variables for an individual pedestrian (Hoogendoorn, 2019a)

Variable	Quantity	Derivation	Unit
Position	$\vec{x}_i(t)$		(x, y)
Velocity	$\vec{v}_i(t)$	$\vec{v}_i(t) = \frac{d}{dt}\vec{x}_i(t)$	$(x, y)\ m \cdot s^{-1}$
Speed	$w_i(t)$	$w_i(t) = \|\|\vec{v}_i(t)\|\|$	$m \cdot s^{-1}$
Direction	$\vec{e}_i(t)$	$\vec{e}_i(t) = \frac{\vec{v}_i(t)}{w_i(t)}$	(x, y)
Acceleration	$\vec{a}_i(t)$	$\vec{a}_i(t) = \frac{d}{dt}\vec{v}_i(t) \quad or$ $\vec{a}_i(t) = \frac{d^2}{dt^2}\vec{x}_i(t)$	$m \cdot s^{-2}$
Jerk	$\vec{\gamma}_i(t)$	$\vec{\gamma}_i(t) = \frac{d}{dt}\vec{a}_i(t)$	$m \cdot s^{-3}$

To describe the interaction between several pedestrians, there are a few variables that describe how pedestrian i relates to another pedestrian j. The most important variables here are the time-headway $h_{i,j}(t)$, the area $A_i(t)$ per pedestrian and the local density $\rho_i(t)$.

The time-headway $h_{i,j}(t)$ shows the relation between two successive pedestrians i and j, which describes the difference in passage time at certain cross-section l between an individual pedestrian i and its predecessor j.

The area $A_i(t)$ per pedestrian reflects the available area for each participant i at time instant t, based on the study region Ω and other pedestrians j within this region. A well-known approach to compute the area $A_i(t)$ per pedestrian is the Voronoi tessellation, which is the partitioning of study region Ω into subregions $\Omega_i(t)$ based on the position $\vec{x}_i(t)$ of each pedestrian. The Voronoi tessellation method splits the area between all pedestrians exactly in the middle. The boundaries created by this method together form the boundary for area $A_i(t)$ to the point where they intersect with other boundaries. Figure 2.2 shows an example of a Voronoi diagram.

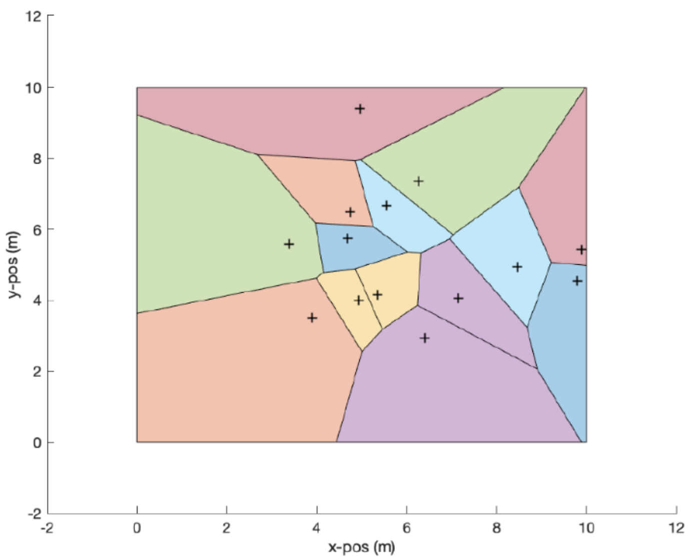


Figure 2.2 Example of a Voronoi diagram (Hoogendoorn, 2019a)

Based on the identified area $A_i(t)$, the local density $\rho_i(t)$ of each pedestrian can be computed, which gives an indication of the crowdedness per area. The microscopic interaction variables and how they are derived are presented in Table 2.2.

Table 2.2 Microscopic interaction variables (Hoogendoorn, 2019a)

Variable	Quantity	Derivation	Unit
Time-headway	$h_{i,j}(t)$	$h_{i,j}(t) = h_j(t_1 \mid l) - h_i(t_0 \mid l)$	s
Area	$A_i(t)$	$Voronoi\ tessellation$	$m^2 \cdot ped^{-1}$
Local density	$\rho_i(t)$	$\rho_i(t) = \frac{1}{A_i(t)}$	$ped \cdot m^{-2}$

Macroscopic variables

Macroscopic variables describe the dynamics of a flow on an aggregate level at a certain cross-section l or area Ω. Macroscopic variables are often used to determine the capacity, the level of service or level of crowdedness of a piece of infrastructure. The level of service concept will be discussed in section 2.3.

The equivalent of the microscopic local density $\rho_i(t)$ is the macroscopic (average) density $\rho(\vec{x},t)$ or $k(t)$, which is defined by the number of pedestrians n_Ω in the region Ω at time instant t and is expressed as number of pedestrians per area. In case the local densities $\rho_i(t)$ are calculated, the macroscopic density can also be calculated by averaging over the local densities.

The flow $q(\vec{x},t)$ or $q(t_0,t_1|l)$ describes the number of passengers N that passes a certain cross-section l with length L over a time period (t_0,t_1). Often, flow is used to express the capacity C of a certain piece of infrastructure.

The (space-mean) velocity $\vec{v}(\vec{x},t)$ is the average velocity of the considered pedestrians, and can be determined by averaging over the individual velocities $\vec{v}_j(t)$ of all pedestrians n located in area Ω. Notice that the velocity is a vector, indicating a direction, and that if we want to know the speed $u(t)$, we must take the absolute value of the velocity. Table 2.3 presents the macroscopic variables and how they are derived.

Table 2.3 Macroscopic variables (Hoogendoorn, 2019a)

Variable	Quantity	Derivation	Unit
Density	$k(t)$	$k(t) = \frac{n_\Omega(t)}{\Omega} \quad or$ $k(t) = \frac{1}{n} \cdot \sum \rho_i(t)$	$ped \cdot m^{-2}$
Flow	$q(t_0,t_1 \vert l)$	$q(t_0,t_1 \vert l) = \frac{N(t_0,t_1 \mid l)}{(t_1 - t_0) \cdot L}$	$ped \cdot m^{-1} \cdot s^{-1}$
Speed	$u(t)$	$u(t) = \vert\vert \frac{1}{n_\Omega} \cdot \sum_{\vec{x}_j(t) \in \Omega} \vec{v}_j(t) \vert\vert$	$m \cdot s^{-1}$

Fundamental diagram

In homogenous and stationary flow conditions, a fundamental relation exists between the macroscopic variables speed u, flow q and density k. The relation is defined as:

$$q = k \cdot u$$

In Figure 2.3, the fundamental diagram for the flow-density relation is given. Note that this is a conceptual representation, and that real experiments and field studies yield scatterplots (see examples in Figure 2.4 and 2.5). In the figure, both the uncongested conditions (left of capacity density) and the congested conditions (right of capacity density) can be seen. The slope in the diagram from the origin $(0,0)$ to a point in the graph indicates the corresponding speed u.

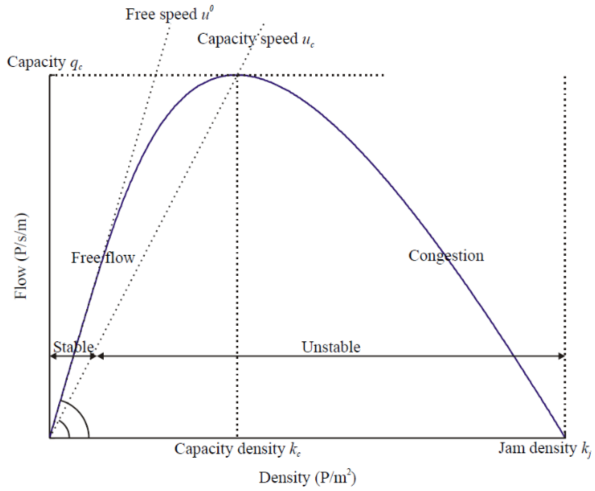


Figure 2.3 Conceptual flow-density relation for pedestrian traffic flows (Daamen, 2004)

In the fundamental diagram, a few traffic states can be distinguished. The traffic states are presented and briefly explained in Table 2.4.

Table 2.4 Traffic states within the fundamental diagram (Hoogendoorn, 2007)

Traffic state	Quantity	Explanation
Free speed	u^0	The maximum speed in an uncongested state (low flow/density)
Capacity	q_c	The maximum flow
Capacity density	k_c	The threshold density for an unstable flow (at q_c)
Capacity speed	u_c	The threshold speed for an unstable flow (at q_c)
Jam density	k_j	The maximum acceptable density

Stability of the fundamental diagram

Various handbooks, guidelines and experimental studies show significant differences in the fundamental diagram (Zhang, 2012), as shown in Figure 2.4. It is unclear whether these differences are caused by pedestrian flow properties or other factors. Also, different flow scenarios (e.g. uni- or bidirectional flows) yield different shapes of the fundamental diagram, as illustrated in Figure 2.5.

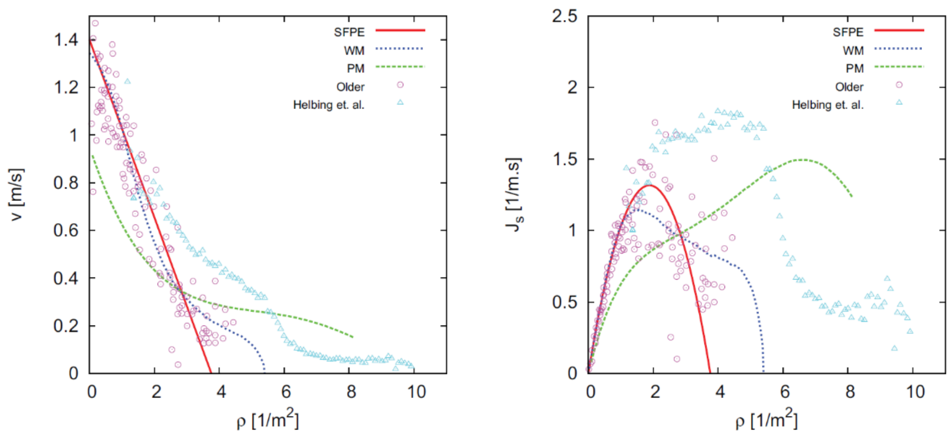


Figure 2.4 Differences in the fundamental diagram in various handbooks (Zhang, 2012)

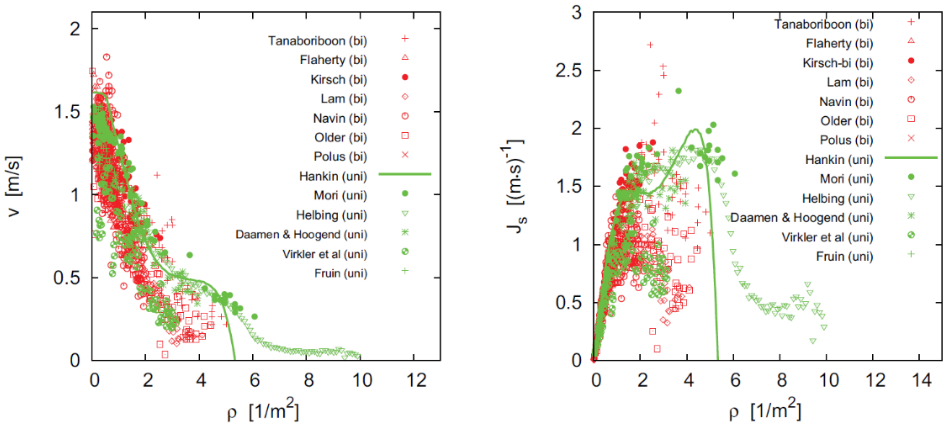


Figure 2.5 Differences in the fundamental diagram in various flow scenarios (Zhang, 2012)

Figure 2.6 displays an overview by Daamen (2004) of both personal as well as external factors that influence the fundamental diagram (based on various sources). These factors include socio-demographic factors such as age, gender and difference in culture, but also travel purpose and walkway attributes, such as the type of infrastructure.

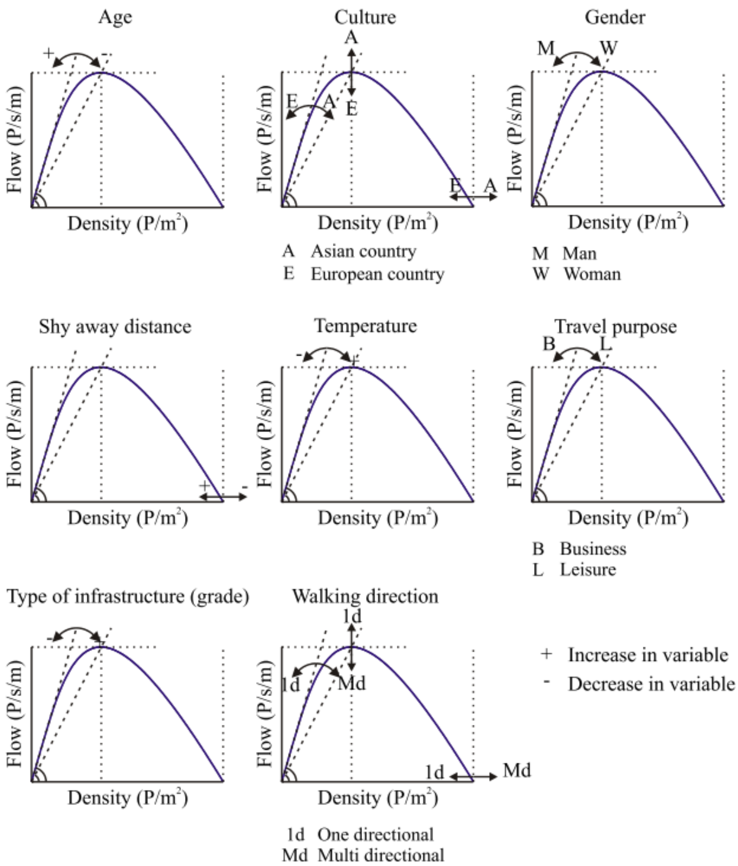


Figure 2.6 The influence of personal and external factors on the fundamental diagram (Daamen, 2004)

2.2 Factors influencing pedestrian dynamics

In this section we will discuss more in-depth how various factors influence pedestrian dynamics. Especially factors have been found that affect the walking speed $w_i(t)$ of a pedestrian, which in tum influences the flow on an aggregate level (and thus the flow capacity) as well (see Figure 2.6).

According to Buchmüller & Weidmann (2006), there are four main categories of factors that influence walking speed, which are presented in Table 2.5. In the remainder of this section we will look at the relation between walking speed and age and gender and between walking speed and travel purposes.

Table 2.5 Factors influencing walking speed (Buchmüller & Weidmann, 2006)

Physical characteristics	Cultural and racial differences
	Age
	Gender
	Body height/step length
	Handicaps
	Luggage
Travel purpose	Business
	Commuting
	Shopping
	Leisure
Environmental conditions	Temperature
	Weather
	Time of day
Walkway attributes	Inclination
	Stairways
	Escalators
	Moving walkways

Influence of age and gender on individual walking speed

Vanumu et al. (2017) compared the results of several studies about the relation between walking speed and age and gender. Figure 2.7 shows the variations in walking speed, ranging from approximately 0.9 to 1.6 m/s. As can be seen, not only significant differences are found between gender and age groups, also results vary among different studies. This could depend on multiple factors, including the chosen measurement method, the measurement accuracy, the cultural background of the study population, among others.

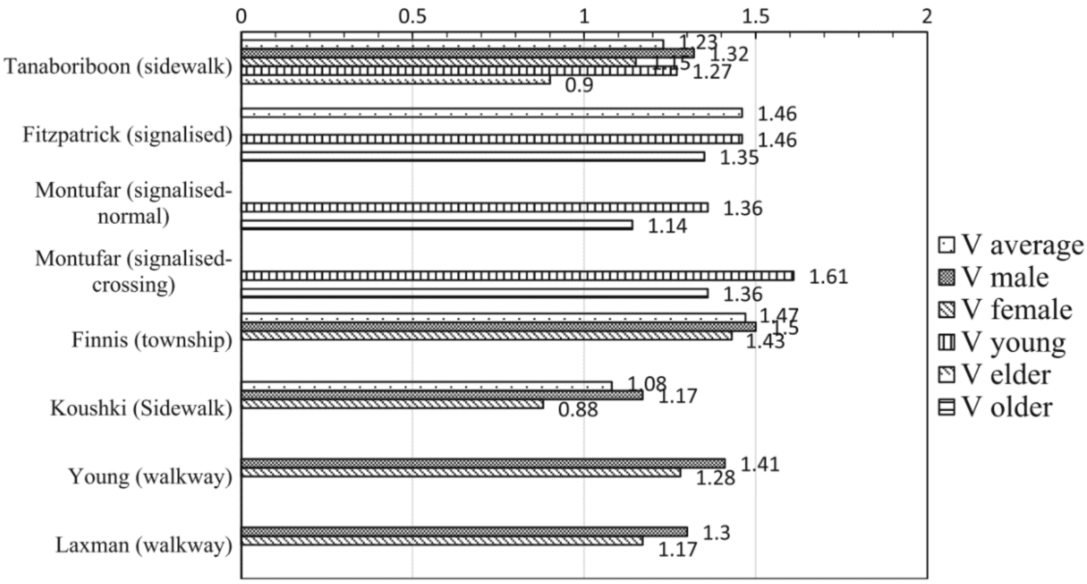


Figure 2.7 Walking speeds from various studies (Vanumu et al., 2017)

Influence of travel purpose on individual walking speed

Weidmann (1993) studied the relation between walking speed and travel purpose. Table 2.6 shows the different walking speeds resulting from his study, as well as the standardized values by Büchmuller & Weidmann (2006). It must be noted that the original values were based on a few measurements, and therefore the values were standardized to the mean value of 1.34 m/s. As can be seen, the highest walking speeds were observed for business purposes, followed by commuting, shopping and at last leisure. In other studies, free walking speeds of 1.50 and 1.75 m/s were observed for commuters and students respectively (Daamen, 2004). In case of pedestrian flows with mixed travel purposes, it has been found that the standard deviation in walking speeds increases to 0.5 – 1.0 m/s (Daamen, 2004).

Table 2.6 Walking speeds for different trip purposes (Buchmüller & Weidmann, 2006; Weidmann 1993)

Travel purpose	Walking speeds (m/s)	Standardized values (m/s)
Business	1.45	1.61
Commuting	1.34	1.49
Shopping	1.04	1.16
Leisure	0.99	1.10
Overall average	1.20	1.34

2.3 Level of service

The level of service is a qualitative measure to describe pedestrian traffic and is used for the dimensioning and evaluation of pedestrian facilities. The level of service concept was introduced by Fruin (1971), in which he proposed a model based on footpath capacity and pedestrian volume. He defined a six-level scale for the level of service of walkways and stairways, ranging from A to F, representing the best to the worst level respectively.

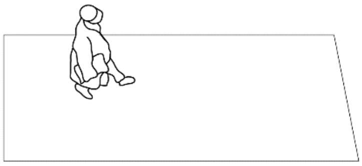
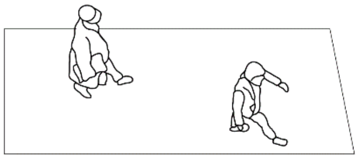
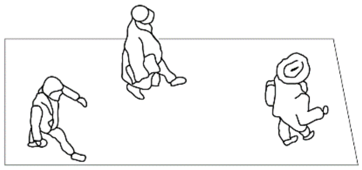
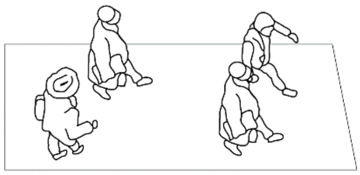
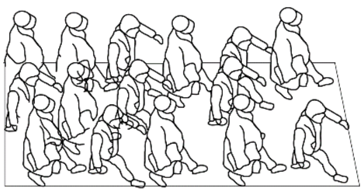
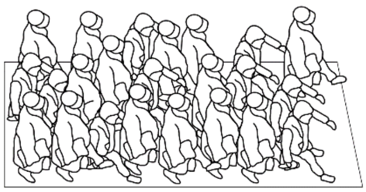
The levels provide guidance on acceptable or desirable standards, depending on the environment (e.g. shopping mall, sports stadium or public transport facilities). Generally, the level of service is expressed in either module (area per pedestrian) or in density (pedestrians per area). The description of the walkway conditions for each level of service and the corresponding values are represented in Table 2.7 (page 12).

Criticism on the level of service concept

With the introduction of his model, Fruin (1971) ignored other environment concerns. Since 1971, many researchers have suggested alternative approaches including measures such as comfort, safety, convenience, shade, greenery, among others. There has been much debate as to what should or should not be used.

Raad & Burke (2018) have systematically reviewed literature from 1971 to 2016 to identify the main approaches and to categorize the most common factors used. They found that over time, approaches use a much wider range of factors, but little consistency across the studies was observed. Collectively, the factors are categorized as: comfort, safety and mobility. The most observed factors were footpath width, obstructions to pedestrian flow, motor vehicle speeds and volumes, shoulder widths, and buffers such as on-street parking. Another important observation was that most of the factors have not been empirically studied.

Table 2.7 Description of the level of service and corresponding values for walkways (Fruin, 1971; Transportation Research Board, 2000)

Level of service	Description of walkway conditions		Density $ped \cdot m^{-2}$	Module $m^{2} \cdot ped^{-1}$
A	Select walking speed freely, bypass other pedestrians, no conflicts		< 0.31	> 3.3
B	Select normal walking speed, bypass other pedestrians in primarily same direction, minor conflicts with other directions		0.31-0.43	2.3-3.3
C	Speed restricted, bypass restricted, high probability of conflicts, reasonably fluid flow, but considerable friction and interaction		0.43-0.71	1.4-2.3
D	Speed restricted and reduced, bypass restricted, high probability of conflicts in multidirectional flows, frequent change in speed		0.71-1.11	0.93-1.4
E	Speed restricted and reduced, no bypass possible, reverse- and crossflow movements almost not possible, frequent stoppages and interruptions of flow		1.11-2.00	0.46-0.93
F	Speed extremely restricted and reduced, frequent conflicts, other flow directions not possible, rather queuing than a flow		> 2.00	< 0.46

2.4 Phenomena in pedestrian dynamics

In pedestrian dynamics several flow phenomena occur, including self-organization, bottleneck use, capacity drop and breakdown (Hoogendoorn, 2019c). Since narrow corridors (bottleneck use) or extreme densities (breakdown) are not considered in this research, we will only discuss the principles of self-organisation and the capacity drop, and their implications for this research.

Self-organisation

In many disciplines, self-organisation is the spontaneous emergence of (semi-) structured patterns. These emergent features result from interactions between multiple agents that follow their own local rules. A well-known example of self-organisation in the biological system is the flocking of birds, as illustrated in Figure 2.8.

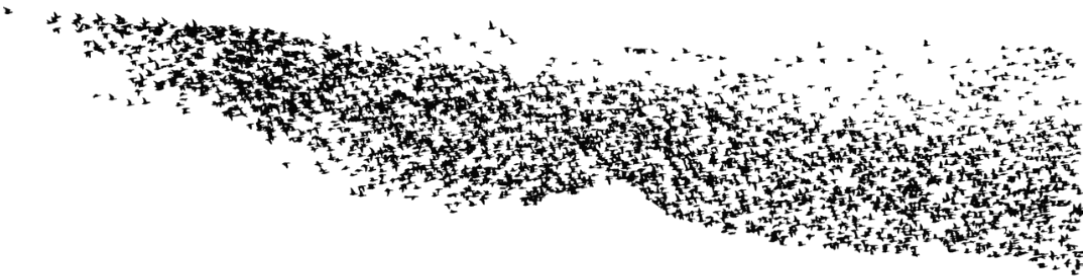


Figure 2.8 Flocking of birds (Johnson, 2019)

In pedestrian dynamics, lane formation is a common example of self-organisation, which is the formation of homogenous patterns in bidirectional and crossing flows. The underlying and determinant local rules are pedestrian objectives to keep a desired speed and direction (goal-oriented), and to keep distance from other pedestrians (collision avoidance).

Helbing et al. (2000) describes the lane formation mechanism as separation of a multidirectional flow to uniform lanes. It starts by pedestrians moving in different directions, which causes strong and frequent interactions. Since pedestrians (try to) avoid collisions, each interaction pedestrians move aside in order to pass each other. Repeating this movement tends to separate pedestrians in uniform lanes moving in uniform directions. For pedestrians this is a preferable state, as there will be very rare and weak interactions, which allows them to maintain their desired speed and direction as much as possible. An example of lane formation in bidirectional flows is shown in Figure 2.9 (left).

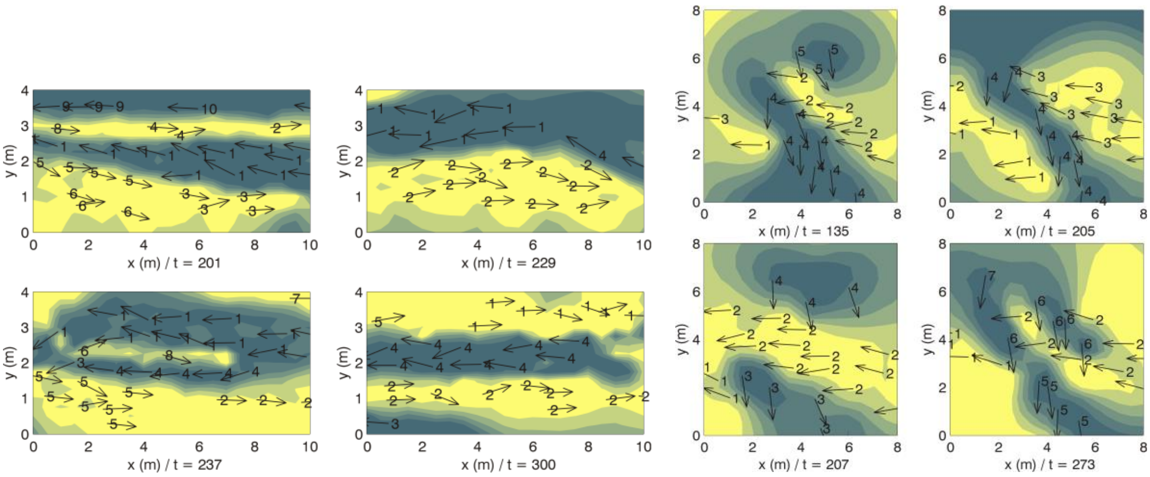


Figure 2.9 Formation of lanes (left) and diagonal stripes (right) (Hoogendoorn & Daamen, 2004)

However, it must be noted that lane formation is a dynamic process and that it depends on various flow conditions such as density and variations in speed and response times. This implies that the existence and number of lanes may vary over time. In general, high densities, homogenous conditions (mostly desired speed) and low response times enhance lane formation.

In crossing flows, patterns that are formed resemble diagonal stripes as illustrated in Figure 2.9 (right). As with lanes in bidirectional flows, stripes only occur when conditions are rather homogenous (same velocity).

An important note on self-organisation is that most the results are based on simulation and only limited empirical insights have been established (Hoogendoorn, 2019c). Homogenous conditions are easier to achieve in simulation environments in comparison to experiments or field studies. As can be seen in experiment results presented in Figure 2.9, lane and stripe formation vary significantly over 4 shots that were taken within 100-150 seconds. Hence, we expect more heterogeneity as well in this research and therefore less stable conditions for lane or stripe formation.

Capacity drop

The capacity drop (or the 'faster is slower effect') is the reduction of the flow capacity in case of increased haste or pressure (Hoogendoorn, 2019c). After a certain congested state, pedestrians maintain a larger headway compared to their headway before the onset of congestion. A conceptual visualization of the effect of the capacity drop on the flow-density diagram (in a vehicle traffic example) is presented in Figure 2.10. In vehicle related traffic research, capacity drop reductions of 1 to 15 percent, but also up to 30 percent have been observed (Hoogendoorn & Knoop, 2013). Examples in which the capacity drop was observed in pedestrian traffic was at infrastructural bottlenecks (and not crossing flow examples).

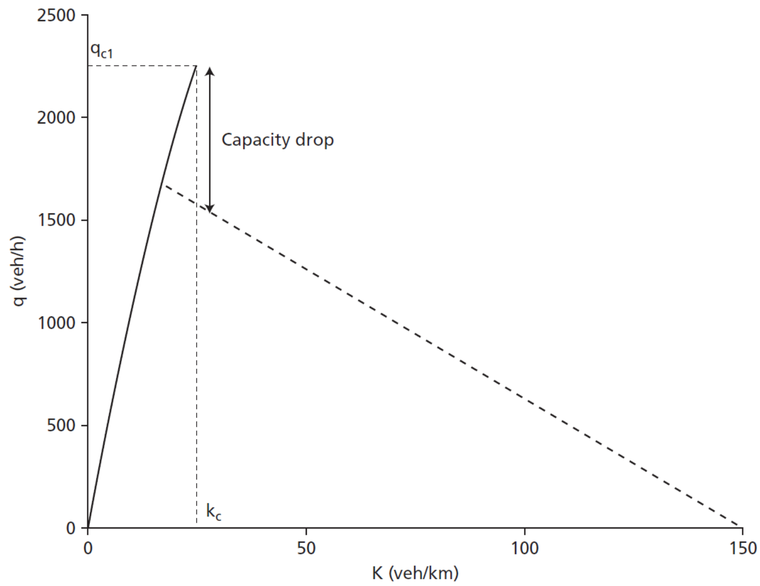


Figure 2.10. Conceptual visualization of the capacity drop in the flow-density diagram (Hoogendoom & Knoop, 2013)

2.5 Movement base case

In pedestrian crowd dynamics, several movement base cases can be distinguished (Duives, 2016). In this research we mainly look at intersecting flows, which is indicated in Figure 2.11 as (f), (g) and (h) respectively.

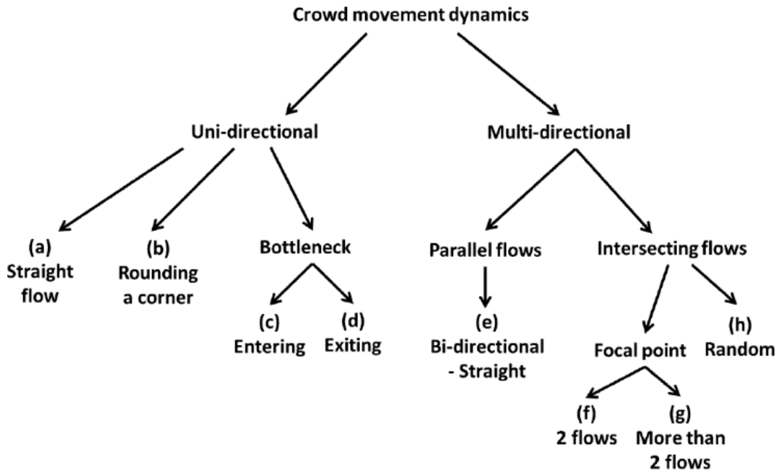


Figure 2.11 Taxonomy crowd movement base cases (Duives, 2016)

2.6 Studies regarding intersecting flows

In contrast to uni- and bidirectional flows, only a few studies have been performed with regards to intersecting flows and which have shown quantitative results (Plaue et al., 2011; Wong et al., 2010; Zhang & Seyfried, 2014; Hu et al., 2019). This section will summarize the main findings and insights found in these studies.

Wong et al. (2010) performed several experiments with two flows under an oblique intersection angle, varying from 0 and 180°. The experimental set-up is depicted in Figure 2.12 (left). They studied the impact of the density ratio (γ) and the intersection angles (ϕ) on the capacity of the area of intersection (region of interest), also called the crossing capacity. They did this for several densities and observed a maximum flow at a density of 2.6 ped/m2. The crossing capacity (i.e. the sum of both pedestrian flows) for different density ratios and intersection angles at a fixed density of 2.6 ped/m^2, resulting from the experiment, is presented in Figure 2.12 (right).

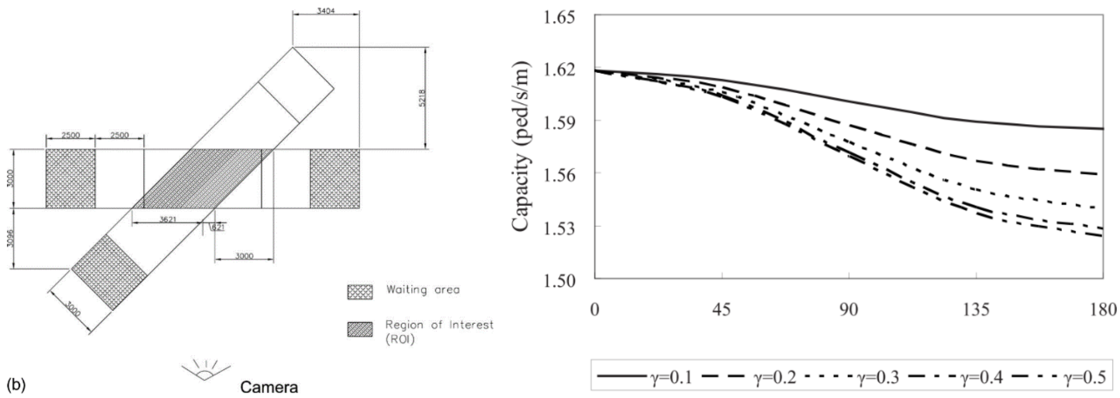


Figure 2.12 Experiment set-up (left) and relation capacity, intersecting angle and density split (right) (Wong et al., 2010)

As can be seen, a negative relation exists between the crossing capacity and intersection angle and density splits. Also, the researchers found a negative relation between the walking velocity and the angle of intersection. Hypothetically, this is due to an increase of the interaction effects between the two conflicting flows, which was caused by an increase in intersection angle.

Another observation was made at a crossing situation with a 90° angle. Here, pedestrians tend to wait to avoid collision (temporal avoidance), rather than to change direction (spatial avoidance). Also, they observed a non-linear relation between the walking velocity and the flow ratio. Here, the major flow tends to remain a higher walking speed in contrast to the smaller flow.

Plaue et al. (2011) conducted a series of experiments of intersecting pedestrian flows under controlled conditions. The experiment considered two flows at a 90° angle, in which one flow entered the intersection after ascending a staircase. The research was mainly focussed on trajectory extraction and the estimation of continuous density. No insights on capacity have been given. Figure 2.13 (left) depicts a snapshot of the experiment, in which the arrows stand for the direction and speed of the pedestrians. They found that pedestrians tend to speed upon exiting the intersection (longer arrows). They also observed a relation between average speed and local density, as can be seen in Figure 2.13 (right).

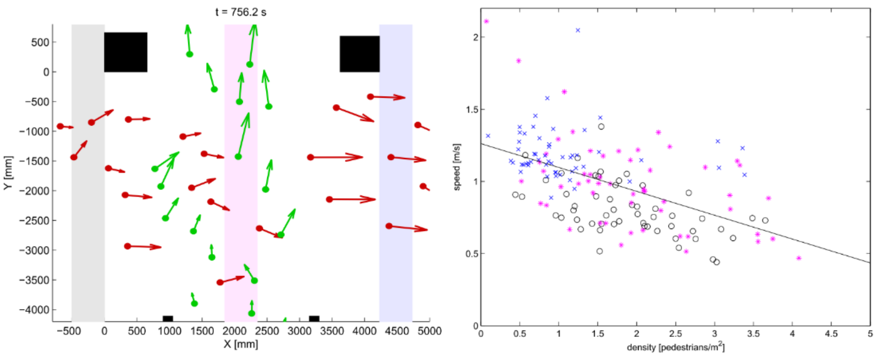


Figure 2.13 Speed and direction (left) and relation average speed and local density (right) (Plaue et al., 2011)

Zhang & Seyfried (2014) reviewed the same experiment as Plaue et al. (2011). They found that most arrows (the direction and speed of the pedestrians) point to upper left or lower right, as depicted in Figure 2.14 (left). This observation reveals the behaviour of pedestrians to walk against the flow while entering the intersection. They do this to avoid potential sudden conflicts. They also observed that once pedestrians entered the intersection, the trajectories become perpendicular (Figure 2.14, right).

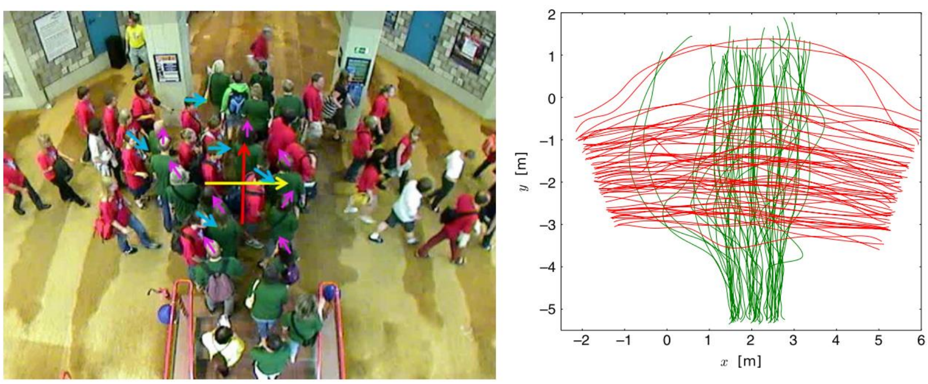


Figure 2.14 Snapshot experiment (left) and trajectories (right) (Zhang & Seyfried, 2014)

Another relevant insight from Zhang & Seyfried (2014) is the influence of the measurement area on density and velocity, which they observed for the range of 1 to 13 m^2. Furthermore, they applied the Voronoi method to illustrate the local densities and velocities.

Hu et al. (2019) recently performed an experimental study to the movement strategies of individuals in multidirectional flows. The experimental set-up is depicted in Figure 2.15 (left and middle). They did several runs with varying number of pedestrians in the experiment, ranging from 13 to 72 pedestrians. They observed typical pedestrian behaviours such as lane formation, detour-, follow-, waiting- and acceleration behaviour. Among the strategies, the straight strategy, in which pedestrians attempt to maintain the same direction while crossing the study area, was most popular (72%). About 2-15% chose the detour strategy, in which some chose it as only strategy and others after they initially chose the straight strategy but changed to a detour strategy as they were slowed down or stopped. It was found that in most cases, the detour strategy was most time efficient for a pedestrian to reach its destination. Despite this observation, it should be kept in mind that the efficiency of the strategy also depends on the strategy of other pedestrians.

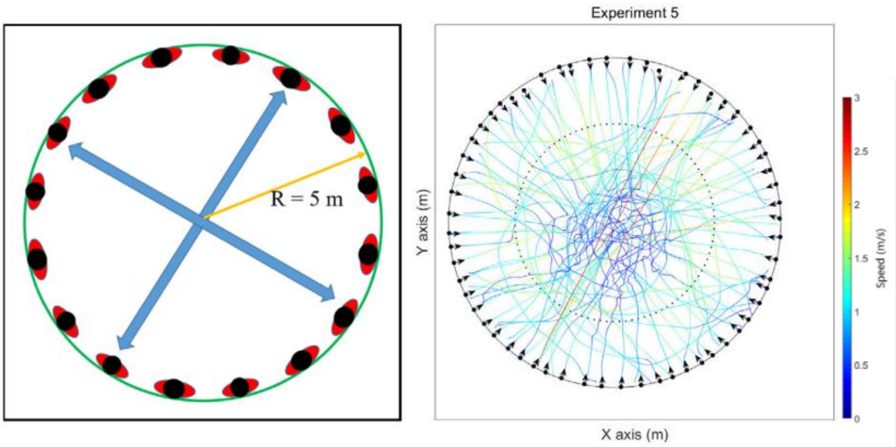


Figure 2.15 Schematic illustration of scenario (left) and trajectories and speed (right) (Hu et al., 2019)

Besides the typical pedestrian behaviours, also the trajectories where analysed (Figure 2.15, right). In the central area, where trajectories cross each other, low speed was observed. The length of walk path/displacement is proportional to the number of pedestrians in each run. The walking utility of pedestrian decreases with the increase of environment density. Stop phenomena appeared in high density and the stop time increases with the pedestrian number. The researchers graded the experiment results based on the movement time, length of walk path and detour decision time, which they labelled as key factors.

2.7 Capacity estimation methods

There are several approaches that can be applied to compute the capacity of a specific piece of infrastructure (Knoop & Hoogendoorn, 2013). The suitability of the approach depends on several factors, including the type of infrastructure, the type of data (individual/aggregate data) and time aggregation, the location of data collection (upstream of, in or downstream of the bottleneck) and the traffic conditions for which data are available (congestion, no congestion). In the remainder of this section, we will discuss three capacity estimation methods found in literature and their suitability for this research.

Cumulative curves

The cumulative curves method is a macroscopic approach and evaluates the capacity in terms of flow. The method determines the capacity by observing the outflow of bottleneck, which is to count the passengers passing a cross-section for a certain time period. After, the cumulative curves can be constructed, in which the slope of the (first order polynome of the) curve represents the average capacity (Hoogendoorn & Daamen, 2009; Van den Berg, 2009). Wierbos et al. (2019) performed a study to bicycle bottleneck capacity and extended the method with slanted curves, which is an elegant way to visualize capacity. This approach seems suitable to perform a capacity estimation for this research.

Composite headway model

The composite headway model method is a microscopic approach, in which the capacity is equal to the inverse of the mean empty zone. The mean empty zone is the mean of a distribution of desired (time) headways, which are subject to inter-personal (e.g. perception of comfort, walking purpose, kinematics such as step size and frequency) and intra-personal characteristics (i.e. individuals fluctuate around their desired minimum headway) (Hoogendoorn & Daamen, 2005). This approach is used to estimate the capacity of a narrow corridor or other situations in which lane formation occurs.

In this research, the bottleneck is a crossing flow, rather than a narrow corridor. The composite headway model approach assumes lane or layer formation, as it is needed to determine time headways. In case of a crossing flow, lane formation may take place, but it is more likely to be interrupted compared to the corridor example. Hence, it this method may not be suitable to apply in this research. It might be possible to adjust the method, for example to consider the (free) area between pedestrians.

Gap acceptance model

The gap acceptance model is a microscopic approach and considers the (remaining) capacity of a nonprioritized crossing flow. This method originates from vehicle traffic and has not been applied to pedestrian studies. Therefore, if a microscopic approach is considered, the suitability of this method should be explored.

2.8 Conclusions

In this chapter, a wide variety of aspects regarding pedestrian flow theory and intersecting flows has been presented, which addresses the corresponding research question:

What is the current state-of-the-art knowledge with respect to pedestrian flow theory and intersecting flows?

The literature study has showed that, regardless of the context (e.g. flow scenario, location, composition of study population, type of study, etc.), pedestrian dynamics can be described by macroscopic and microscopic traffic variables. These variables are generic and are fundamentally related. Despite the fundamental relation between these variables, it is questionable whether the results of a study are specific or can be generalized to a certain extent. The literature study showed that many factors influence pedestrian dynamics, in which the presence and strength of the factors is determined by the context of the study. Since the context of each study is quite specific, this literature study shows that performing research in pedestrian flow theory is quite complex, and that results are often specific and difficult to compare or to generalize.

It must be noted that this literature study is limited, since more aspects regarding pedestrian theory can be considered. Nevertheless, this chapter aims to give a basic understanding and addresses, to the knowledge of the author, the most relevant aspects for this research. The literature study will be a starting point for the theoretical framework (chapter 3), in which we will incorporate insights from previous studies and practice to construct a theoretical overview of this research and its context.

3 Theoretical framework

This chapter presents the theoretical framework for pedestrian intersections at railway stations, which is based on insights from literature (chapter 2) and practice. The aim of the theoretical framework is to give an overview of the research topic and the related variables that describe the context of this research. Basically, it attempts to draw the full picture of the considered situation. In general, a theoretical framework is meant to be used as a tool to scope the research and to verify and identify the strength of the relations.

This study mainly focusses on the construction of the framework and does not elaborately attempt to verify all relations in it. Section 3.1 will elaborate on the construction of the theoretical framework and section 3.2 aims to answer the following research question:

Which variables should be included in the theoretical framework and how do they relate?

3.1 Theoretical framework

The theoretical framework is presented in Figure 3.1 (page 21) and shows the hypothesized causal relations between the research topic and several variables. The research topic in this framework is the intersection capacity, which is expressed as flow. The other variables included in the theoretical framework are collected from the literature study (chapter 2) and practice, which describe the context of a pedestrian intersection at the railway station. It is assumed that these variables (indirectly) influence the intersection capacity to a certain extent. The variables and their relation to the research topic will be discussed in the following subsections.

Microscopic and macroscopic variables

Often, multiple variables are used to describe traffic flow conditions, including macroscopic variables *flow*, *density* and *velocity*. These are mainly determined by microscopic variables *velocity*, *position* and *headway*. The microscopic velocity influences the aggregate velocity as well as the microscopic position, which influences the headway. In turn, the headway influences the aggregate density. The aggregate density and velocity influence the aggregate flow, which is the measure used to express the research topic, the intersection capacity. The organisation of microscopic and macroscopic variables is based on existing and verified relations (Duives et al., 2015a). This provides a solid foundation for expanding the theoretical framework.

Intersection variables

There are several properties that distinguish intersecting flows from uni- and bidirectional flows. This includes the *intersection angle*, which is not 0 (unidirectional) or 180 (bidirectional) degrees. Research by Wong et al. (2010) showed that the intersection angle does influence the flow capacity of an intersection. Another property studied in the same research was the *flow ratio* (they called it density ratio), which is the ratio between the flows that intersect. It was shown that the flow capacity was lower for more balanced flows. The last variable, *dimensions area*, considers the length, width, size and shape of the intersection area. It is assumed that the dimensions influence the occupation of space and thus could increase or decrease the flow. It is assumed that the intersection variables indirectly influence the flow (and thus intersection capacity) through other variables which will be discussed in the next subsections.

Pedestrian objectives, abilities and behaviour

In the literature study (chapter 2), several factors were identified to influence pedestrian behaviour. Section 2.4 shows how pedestrian objectives such as *goal orientation* and *collision avoidance* influence the emergence of phenomena such as *lane formation*. Also, the ability of pedestrians to locate themselves in or to navigate through an environment are important elements that influence their behaviour. This includes the *spatial knowledge* (i.e. is the pedestrian familiar in the area), *orientation* (i.e. can the pedestrian locate itself) and *navigation* (i.e. does the pedestrian knows where to go). In section 2.6, studies report how intersecting flows enhance *deceleration*, *acceleration*, *stopping* and *detour* behaviour. In these examples, the circumstances (e.g. the density or variation in speed) and flow scenario (i.e. the intersection variables) are determinative. To summarize, it is assumed that the combination of macroscopic variables, the intersection variables and the pedestrian objectives and abilities, determine pedestrian behaviour. The relations are indicated with arrows in Figure 3.1.

From a microscopic perspective, pedestrian behaviour can be expressed in variables speed, position and headway. For instance, for lane formation a short headway must be maintained and the velocity of one pedestrian should be similar to his predecessor. A detour can be identified in trajectory analysis, which is based on the positions during a period. Acceleration, deceleration and stopping behaviour can be retrieved from the speed of a pedestrian and its deviations in speed. Hence, it is assumed that pedestrian behaviour is directly related to the microscopic variables (Figure 3.1).

Other factors

Besides pedestrian behaviour, also other factors were mentioned in the literature study (chapter 2) to influence microscopic variables. Section 2.2 presents several factors which were verified to influence pedestrian speed (and thus position and headway as well). These factors are categorized as *physical characteristics* (e.g. age and gender), *travel purposes* (e.g. commuting and leisure), *environmental conditions* (e.g. temperature and time of day) and *walkway attributes* (e.g. staircase and escalator). As learned from practice, it is also assumed that the *trip state at the station* (i.e. arriving, departing, transferring and waiting) influences the pedestrian speed and therefore has been added to the framework as well.

3.2 Conclusions

Based on verified relations and insights from literature and practice, a theoretical framework has been constructed for pedestrian intersections at railway stations. This allows us to answer the following research question:

Which variables should be included in the theoretical framework and how do they relate?

The starting point for the framework is the research topic intersection capacity, which is expressed as flow. The foundation of the framework consists of microscopic and macroscopic traffic variables that are used to describe traffic conditions (including the intersection capacity). The context is described by several factors relating directly or indirectly to the traffic variables. It is assumed that the flow scenario (intersection variables), the traffic conditions (macroscopic variables) and pedestrian objectives and abilities together determine pedestrian behaviour. Pedestrian behaviour and other factors, such as physical characteristics and travel purpose, directly influence microscopic variables such as velocity and headway. In turn, these microscopic variables determine the aggregate conditions (macroscopic variables), and thus the intersection capacity. In this research we will use the framework as an overview and as a tool to interpret the results of the data analysis in chapter 9. In chapter 10, we will discuss the generalizability of the theoretical framework to other contexts and to other flow scenarios.

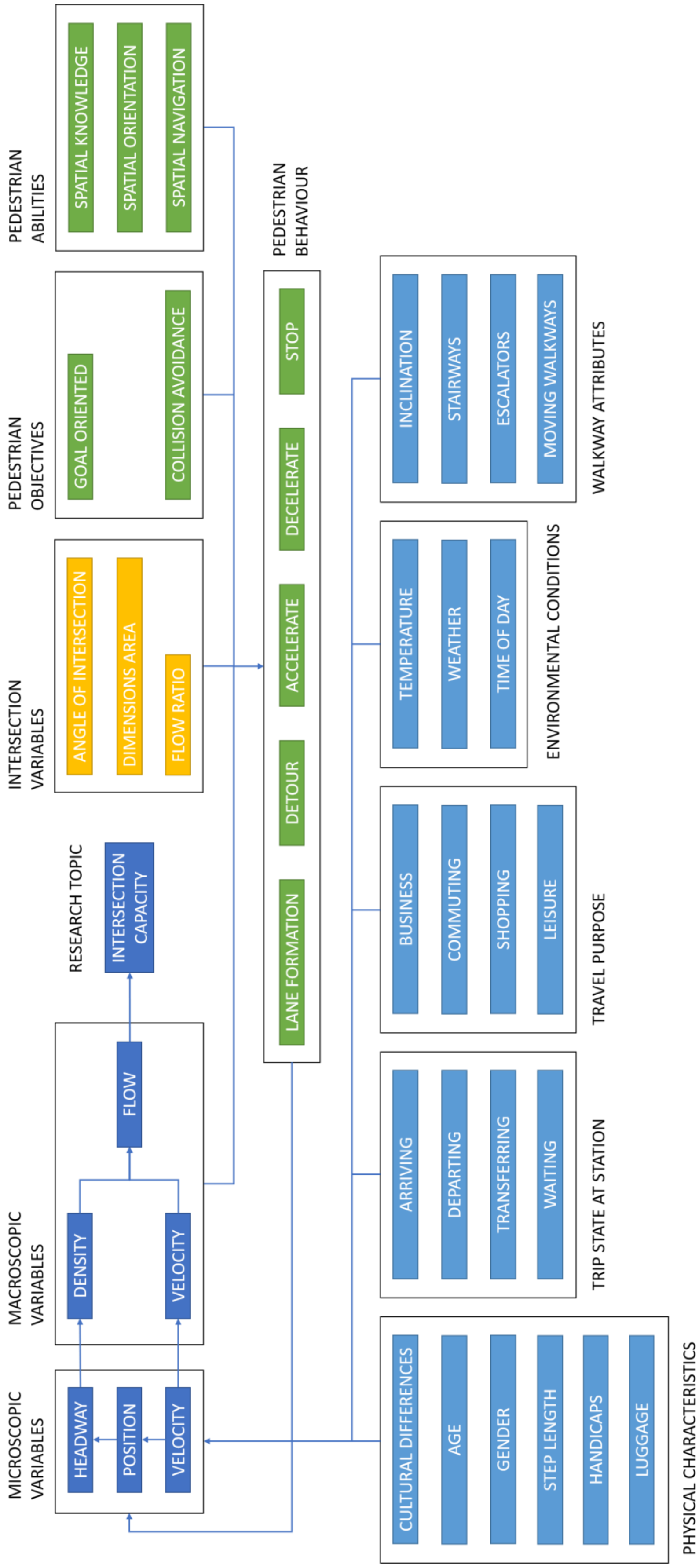


Figure 3.1 Theoretical framework

4 Static analysis

The objective of the static analysis is to compare the theoretical capacity of certain cross-sections with its demand, and thus to give insight into potential bottlenecks with a low effort and thus quick calculation. This analysis allows us to answer the following research question:

Which cases of intersection flows within our case study are interesting for further analysis?

For this analysis, detailed trajectory data is left aside, and only smartcard data will be used to do the calculations. Smartcard data is easier to access and enables quick calculations for a larger scope both spatially as well as temporally.

The next section will elaborate on the use of smartcard data for this analysis. In section 4.2 we will analyze the capacity and demand for different cross-sections at our case study Utrecht Centraal station. The analysis will be concluded in section 4.3, where we will present potential bottlenecks.

4.1 Smartcard data

For this analysis, two datasets of smartcard data are used. Both datasets only consider weekdays, since these are familiar for regular peaks and high demands.

For computing the origin-destination (OD) matrix of Utrecht Central station, smartcard data for all travels within the Netherlands is used. With this data it can be estimated how many passengers have departed, arrived or transferred at Utrecht Central station and at which platform(s) they have been. For this analysis, the most recent OD matrix will be used, which is based on 2017 smartcard data. Since it is only based on smartcard data, no estimations can be made for the demand between the entrances of the station. Hence, there is no information about pedestrians that only pass the station.

Furthermore, smartcard data at Utrecht Central station gives insight into the demand at each entrance and the distribution across its gates. For this analysis, smartcard data of 65 weekdays in April, May and June 2019 is used.

It must be noted that there is a difference between data of 2017 and 2019, which may affect the conclusion drawn from this analysis. For this analysis, a trade-off had to be made between the availability of the data and the inclusion of the development of Utrecht Centraal station and its surroundings[1]. The most recent OD-matrix dates from 2017, while the most recent developments around the station's entrances are taken into account in the 2019 entrance/gate data. According to NS, the proportions in the OD-matrix will only vary slightly, since the demand between platforms is rather stable and not influenced by changes around the station. Furthermore, to overcome the difference in overall

[1] Utrecht Centraal and the area around it (including other public transport facilities, a food court and a shopping mall) is currently in a rebuilding process, which started in 2011 and is due in 2030. Since the opening of the current station hall, in December 2016, several changes have been made in the direct environment. By 2016, the busses at the Centrum side (east) already moved to the Jaarbeurs side (west). In the second half of 2019, a bus and tram station will be opened at the Centrum side. Developments that took place from 2017 onwards (and possibly influenced differences in the datasets) include the opening of the bike storage at the Centrum side in the summer of 2017, which offers 12500 places compared to 4200 at the Jaarbeurs side. In February 2018, the public square at the Centrum side finished, increasing the accessibility between the city center and the station. Both changes may have influenced travelers to choose a different entrance over time.

passenger growth between years, we will use percentages mostly to express how passengers are distributed at the station.

4.2 Cross-sections, capacity and demand

Before we start, we will specify three types of cross-sections to analyze. Looking at the physical scope of this research, the main hall, we are mainly interested in the places where passengers enter and leave, and which corridors they use within.

In this case, the majority of the passengers either enters/exits the main hall through one of the few entrances, consisting of OVCP ("OV-Chipkaart en Poortjes") gates, and through the staircases/escalators that connect the main hall with the platforms. Also, other facilities (e.g. shops, office building) along the main hall and the elevators that connect the main hall to the platforms can be considered as entrances that are used often by passengers, but these will be left out of scope.

For the static analysis, the following type of cross-sections will be analyzed:

- Entrances and gates (subsection 4.2.1-4.2.2)
- Staircases and escalators (subsection 4.2.3-4.2.4)
- Corridors (subsection 4.2.5-4.2.6)

4.2.1 Capacity entrances and gates

Figure 4.1 shows a map of the main hall, tunnel and platforms of Utrecht Centraal station. Also, its entrances are indicated on this map.

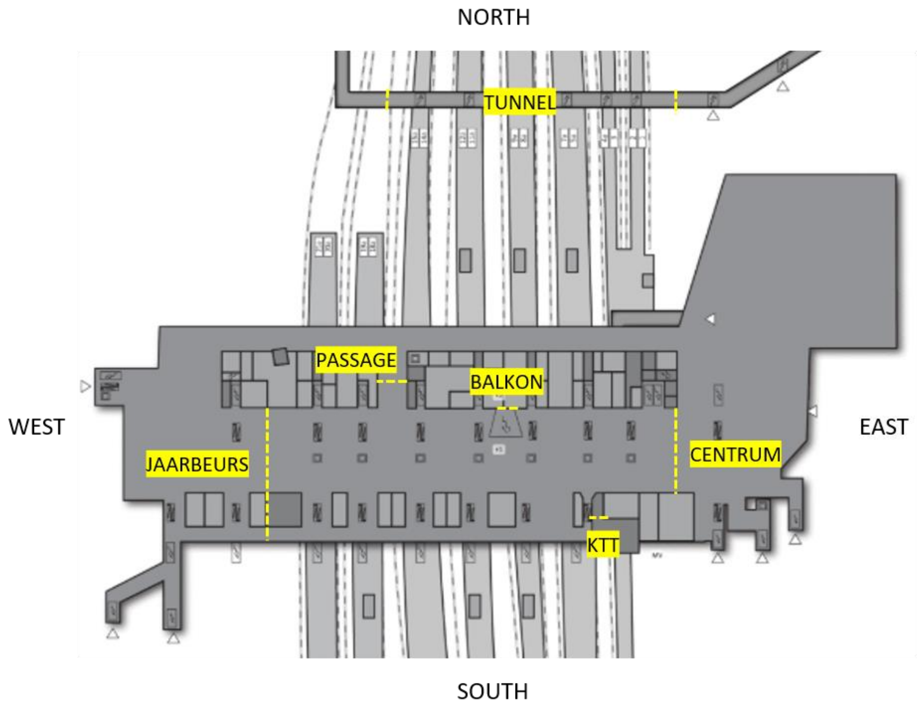


Figure 4.1 Map of Utrecht Centraal station and its entrances

There are 5 entrances towards the main hall, each containing several gates. There are two main entrances, 'Centrum' located east and 'Jaarbeurs' located west. Another smaller entrance 'Passage' is located north, heading to the passage/corridor which runs parallel to the main hall. Also located north and one level up is the entrance 'Balkon', leading to a food corner. South there is an entrance 'KTT' towards an office building. Besides the entrances towards the main hall, there is also a tunnel 'Noordertunnel' or 'Tunnel' north of the main hall, connecting most of the platforms and two other entrances.

The entrances, the number of gates per entrance for each direction and the theoretical capacity per entrance is presented in Table 4.1. The capacity per gate is determined at 24 passengers per minute for unidirectional flows, and 10 passengers per minute for bidirectional flows (NS & ProRail, 2017a). It must be noted that, besides the gates designated for either check-in or check-out, there are also undirected gates. Therefore, the capacity for check-in and check-out is actually higher, but since it can be used in either direction at any time, there is no guarantee on the amount of extra capacity.

Table 4.1 Number of gates per direction and theoretical capacity (NS & ProRail, 2017a; NS, 2019a)

Entrance	Gates check-in	Capacity (p/min)	Gates check-out	Capacity (p/min)	Gates undirected	Capacity (p/min)
Centrum	9	216	11	264	7	70
Jaarbeurs	11	264	11	264	6	60
Passage	2	48	3	72	1	10
Balkon	-	-	-	-	2	20
KTT	-	-	-	-	2	20
Tunnel	5	120	7	168	7	70
Total	27	648	32	768	25	250

4.2.2 Demand entrances and gates

Table 4.2 presents the average demand of passengers per weekday for each entrance and the maximum demand that passes an entrance in a certain minute.

Table 4.2 Average demand per weekday and recorded peak demand in one minute (NS, 2019a)

Entrance	Check-in (p/day)	%	Peak (p/min)	Check-out (p/day)	%	Peak (p/min)
Centrum	41,255	38.2	131	43,657	40.7	163
Jaarbeurs	50,551	46.8	194	49,123	45.8	243
Passage	4,943	4.6	28	4,586	4.3	29
Balkon	847	0.8	10	858	0.8	11
KTT	987	0.9	8	1,320	1.2	11
Tunnel	9,215	8.5	64	7,378	6.9	45
Total	107,798	99.8		106,920	99.8	

As can be seen by comparing Table 4.1 with Table 4.2, the peak demand for each entrance is not exceeding the theoretical capacity. However, the demand is not distributed equally over all gates at each entrance. When looking closer at the smartcard data and at each individual gate, 4 out of 84 gates exceed the capacity limit of 24 passengers per minute per gate, and 3 gates operate at 90% of the capacity level. Besides, it should be noted that this data is disaggregated from either 1 hour or 15 minutes to 1 minute, and therefore within 1 hour or 15 minutes the demand may vary, and thus higher peaks can occur.

Table 4.3 presents the distribution of demand over gates at the entrances Centrum and Jaarbeurs. The gates are split up in 3 or 4 parts, which correspond with the corridors in the main hall (Figure 4.3). As can be seen, the distribution for check-in or check-out is quite different. Especially at the Centrum entrance there is a high demand for check-in at the A corridor. Since the main entrance of the building is located north, the inflow towards the gates passes the A corridor first, resulting in a higher demand at these gates. At the Jaarbeurs side the demand is distributed more equally. Here, most demand is transferring from/to the bus station, which is located parallel to the platforms with staircases/escalators aligned in the same way (staircases/escalators visible on map in Figure 4.1).

Table 4.3 Distribution of demand over gates at entrances Centrum and Jaarbeurs (NS, 2019a)

Corridor	Centrum check-in (%)	Centrum check-out (%)	Jaarbeurs check-in (%)	Jaarbeurs check-out (%)
A	76.5	32.6	35.5	26.0
B	16.6	41.9	17.2	25.2
C	6.8	25.5	38.4	38.4
D	-	-	8.9	10.4
Total	100	100	100	100

4.2.3 Capacity staircases and escalators

Figure 4.2 shows the 13 staircases and 13 escalators of Utrecht Centraal station connecting the main hall to 16 platforms. As can be seen, all staircases and escalators serve at least two platforms at the same time. At Utrecht Centraal station, the width of an escalator is 1 meter (for one direction) and the width of a staircase is 3.5 meters (for both directions).

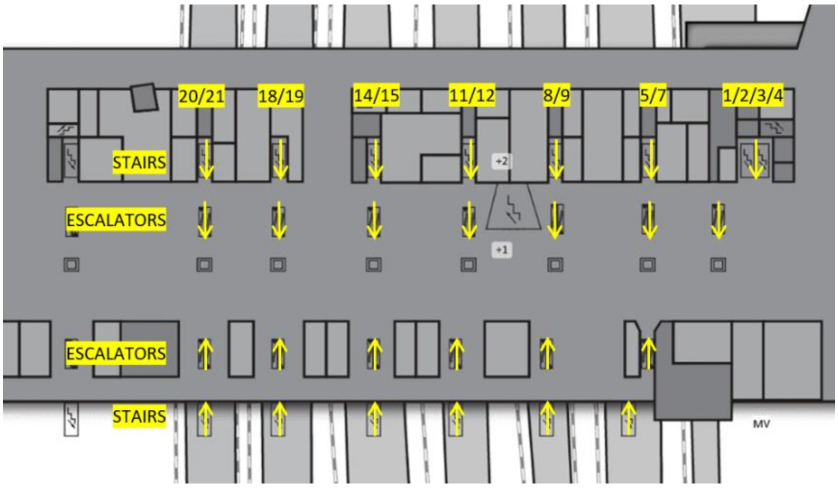


Figure 4.2 Staircases and escalators at Utrecht Centraal station

The theoretical capacity of a staircase is determined for ascending/descending separately and can be derived from the maximum flow rates. Considering a walking speed of 0.38 m/s for ascending and 0.44 m/s for descending, Buchmüller & Weidmann (2006) found a maximum flow rate of 0.85 p/m/s and 0.98 p/m/s respectively. Considering a width of 3.5 meter, this implies a capacity of 2.9 p/s or 178.5 p/min for ascending and 3.4 p/s or 205.8 p/min for descending. Since the staircases at Utrecht Centraal serve both directions at the same time, this capacity will be considered as the maximum capacity and is assumed to be lower in most cases. According to NS & ProRail (2017b), the design capacity for staircases is set at 120 p/min (for a width of 3.5 meter) in both directions, which is indeed lower than the capacities according to Buchmüller & Weidmann (2006).

The theoretical capacity for an ascending/descending escalator can be calculated based on the speed and dimensions of the escalator. The velocity of the escalators operated by NS is 0.65 m/s, which is equal to 1.63 steps/s (NS & ProRail, 2017b). The escalator has a net width of one meter, and according to NS, not more than one passenger will occupy a step. This implies a theoretical maximum flow of 1.63 p/s, which is equal to 97.8 p/min. This is in line with standards defined by the Deutsches Institut für Normung

(2005). Since often passengers leave more space in between, the actual capacity is assumed to be lower. According to NS & ProRail (2017b), the design capacity for escalators is set at 80 p/min (for a width of 1 meter) in both directions, which is indeed lower than the theoretical capacity.

4.2.4 Demand staircases and escalators

To estimate the demand at the staircases and escalators, we look into the OD (origin-destination) matrix of the main hall. The OD matrix is presented in Table 4.4 and shows the proportional demand between all entrances and platforms. As can be seen, the platforms are combined, which means that in most cases two platforms are served by two staircases and two escalators. As explained in section 4.1, the demand between the entrances is unknown.

Table 4.4 Proportional demand (in %) per weekday at Utrecht Centraal (NS, 2017)

O ↓ / D →	Balkon	Centrum	Jaarbeurs	Passage	KTT	Tunnel	1-4	5-7	8-9	11-12	14-15	18-19	20-21	**Departures**
Balkon							0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.1**
Centrum							1.5	1.9	1.6	2.7	1.0	2.2	0.6	**11.5**
Jaarbeurs							1.7	3.7	2.7	5.0	1.6	3.8	0.8	**19.4**
Passage							0.1	0.1	0.1	0.3	0.1	0.3	0.1	**1.1**
KTT							0.1	0.1	0.1	0.1	0.0	0.1	0.0	**0.4**
Tunnel							0.8	0.8	0.4	2.3	0.6	1.2	0.2	**6.3**
1-4	0.0	1.5	1.7	0.2	0.1	0.8	0.1	0.7	0.6	0.6	0.5	0.4	0.3	**7.3**
5-7	0.0	2.8	5.5	0.1	0.0	1.5	0.6	1.1	1.2	0.0	0.1	0.4	0.4	**13.8**
8-9	0.0	1.8	2.7	0.1	0.1	0.3	0.6	0.6	0.9	1.2	0.3	0.9	0.2	**9.5**
11-12	0.0	2.0	3.2	0.3	0.1	0.8	0.6	0.2	0.8	1.1	0.9	1.1	0.3	**11.4**
14-15	0.0	1.3	1.9	0.2	0.1	0.5	0.1	0.5	0.5	0.2	0.0	0.2	0.2	**5.7**
18-19	0.0	1.7	3.3	0.2	0.0	0.8	0.8	1.6	0.6	0.3	0.0	0.2	0.3	**10.0**
20-21	0.0	0.6	0.8	0.1	0.0	0.2	0.3	0.3	0.3	0.5	0.2	0.5	0.0	**3.6**
Arrivals	**0.1**	**11.7**	**19.1**	**1.1**	**0.3**	**4.8**	**7.2**	**11.6**	**9.7**	**14.3**	**5.2**	**11.2**	**3.4**	

As retrieved from Table 4.4, Table 4.5 shows the proportional demand on the staircases and escalators for each combination of platforms per weekday. As can be seen, the demand for departures and arrivals is highest for platform 5-7 and 11-12, followed by platform 18-19. Hence, it is expected that the staircases/escalators at these platforms serve the highest demands.

Table 4.5 Proportional demand departures and arrivals over all platforms per weekday (NS, 2017)

Platform →	1-4	5-7	8-9	11-12	14-15	18-19	20-21	Total
Departures (%)	11.9	22.5	15.5	18.6	9.3	16.3	5.8	100
Arrivals (%)	11.5	18.5	15.5	22.8	8.3	17.8	5.5	100

Based on the smartcard data, the demand at individual staircases/escalators cannot be measured. Considering there are 4 staircases/escalators for each platform, in an equal case the demand is split exactly in 4, implying that 25% of the demand for that platform goes to each stair/escalator. However, it depends on multiple factors how the demand is distributed, including where the train stops along the platform, and which (side of the) entrance passengers enter the main hall (i.e. which corridor they use). But also, the personal preference for, or ability to use the escalator/stairs play a role.

4.2.5 Capacity corridors

The main hall of Utrecht Centraal station has three main corridors (A, B, C) connecting its two main entrances Centrum (east) and Jaarbeurs (west), with all platforms. One sub corridor (D) located south of the main hall connects one entrance, Jaarbeurs, and most of the platforms. The corridors are shown in Figure 4.3, as well as the two main entrances.

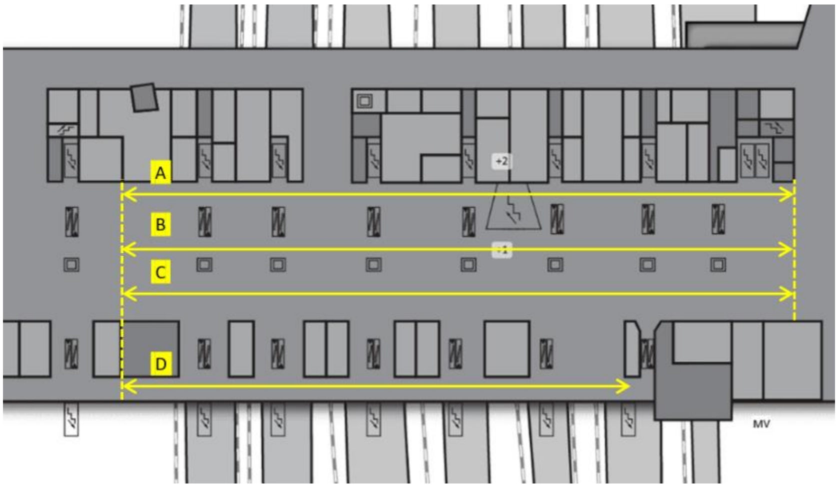


Figure 4.3 Main and sub corridors at Utrecht Centraal station

The theoretical capacity of a corridor depends on the maximum level of density that is desired. At NS, a distinction is made between the capacity that indicates self-reliance ("zelfredzaamheid") and comfort. Capacities have been determined for both uni- and bidirectional flows and can found in Table 1.1 (chapter 1). Table 4.6 presents the width and theoretical capacity (based on Table 1.1) for each corridor in passenger per meter per minute.

Table 4.6 Width and theoretical capacity for each corridor

Corridor	Width (m)	Self-reliance unidirectional (p/m/min)	Self-reliance bidirectional (p/m/min)	Comfort unidirectional (p/m/min)	Comfort bidirectional (p/m/min)
A	5.5	363	308	269.5	231
B	5	330	280	245	210
C	13	858	728	637	546
D	6	396	336	294	252

4.2.6 Demand corridors

The demand through the corridors can be estimated based on the OD matrix (Table 4.4) in combination with the distribution of demand over individual gates at the entrances (Table 4.3). In theory, we can draw cross-sections at different locations to estimate the demand that is passing that line. However, in practice, passengers can easily interchange corridors between platforms as they move through the station hall. Therefore, estimations become more unreliable further away from the entrance (where we can show precisely how many passengers entered/exit each corridor).

By looking only at Table 4.3, we can say that at the Centrum entrance the demand is highest at corridor A (especially check-in), followed by B (especially check-out). At the Jaarbeurs entrance, most demand is found in corridor C for both check-in and check-out, followed by corridor A and B.

Since corridor A and B are significantly smaller (5 and 5.5 m) in contrast to corridor C (13 m), we can conclude that corridor A and B are most likely to reach their capacity. It must be noted that corridor D has a similar width to corridor A and B, however, this corridor only serves one of the main entrances and has a small share of demand at this entrance (Table 4.3). Therefore, corridor D is considered less likely to meet its capacity.

4.3 Conclusions

In the last sections we have analyzed the capacity and the demand of three types of cross-sections: the entrances and gates, the staircases and escalators, and the corridors. Combining the insights from these sections allows us to identify six potential bottlenecks for further analysis, which answers the following research question:

Which cases of intersection flows within our case study are interesting for further analysis?

In subsection 4.2.2 we have seen that most passengers enter or leave the main hall either at the entrances Centrum (east) and Jaarbeurs (west). At the Centrum entrance, most passengers enter corridor A and leave corridor A and B. At the Jaarbeurs entrance most passengers enter and leave corridor C, followed by corridor A and B.

From subsection 4.2.4, we can conclude that most passengers depart and arrive at platform 5/7 and 11/12 followed by platform 18/19. The four staircases/escalators for each of these platform combinations are expected to serve the highest demand, however, the demand at individual staircases and escalators is unknown.

In subsection 4.2.6 we assume that the capacity is most likely to be met in corridor A and B, since they are substantially smaller compared to corridor C.

Combining these insights, we initially identify six intersections as potential bottlenecks that are interesting for further analysis: corridor A and B intersecting with platform 5/7, 11/12 and 18/19. For each platform, corridor A intersects with a staircase and corridor B intersects with two escalators (one for each direction). As found in subsection 4.2.3, their capacity and thus the expected outflow differs, and this makes it interesting to compare the two corridors. To conclude, the six intersections (also depicted in Figure 4.4) selected for further analysis are:

1. Corridor A and the staircase of platform 5/7
2. Corridor B and the escalator of platform 5/7
3. Corridor A and the staircase of platform 11/12
4. Corridor B and the escalator of platform 11/12
5. Corridor A and the staircase of platform 18/19
6. Corridor B and the escalator of platform 18/19

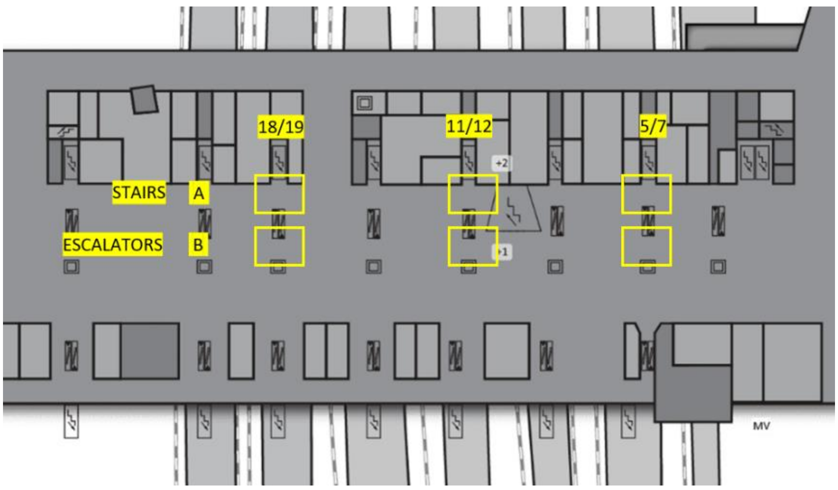


Figure 4.4 Selected intersections (6) for further analysis

5 Selected intersections

In the previous chapter, six intersections have been proposed for further analysis. These intersections are expected to have the highest demand at the main hall of Utrecht Centraal station. According to Table 4.5, the highest flows are expected at platform 5/7 and 11/12, followed by platform 18/19. As will be explained in the next chapter, there is only trajectory data available for the intersections of platform 5/7 and 18/19. Therefore, the intersections of platform 11/12 will not be considered in this research. Hence, the following four intersections (as depicted in Figure 5.1) are selected for further analysis:

Intersection 1 Corridor A and the staircase of platform 5/7
Intersection 2 Corridor B and the escalator of platform 5/7
Intersection 3 Corridor A and the staircase of platform 18/19
Intersection 4 Corridor B and the escalator of platform 18/19

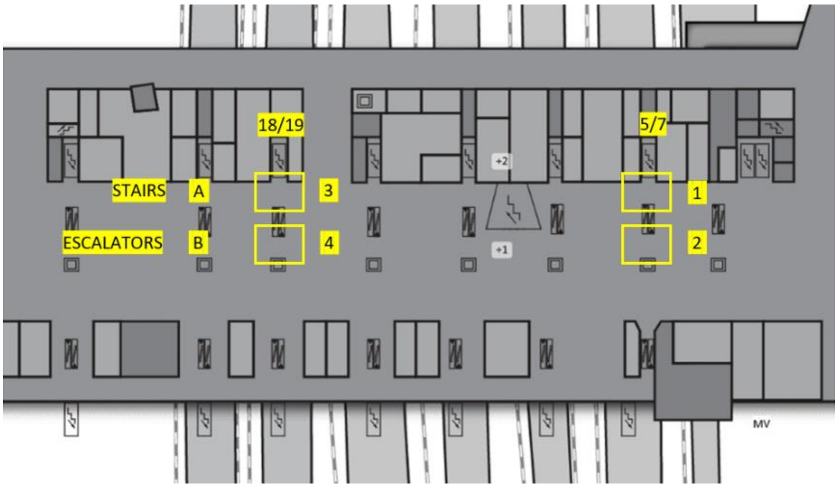
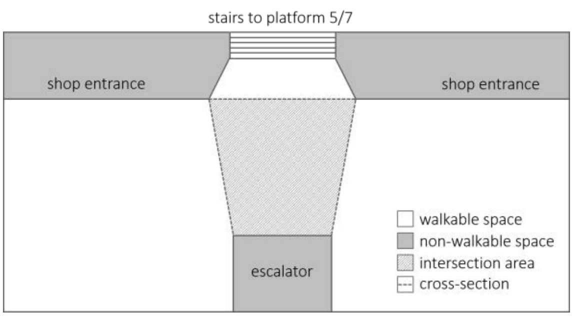


Figure 5.1 Selected intersections (4) for further analysis

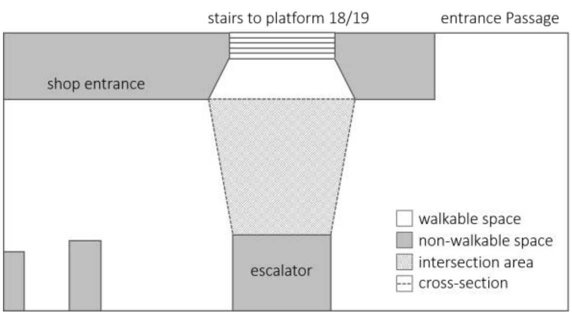
Section 5.1 presents the specifications of the intersections and section 5.2 describes the flow scenario. Based on this information, several variables from the theoretical framework (as presented in chapter 3) will be selected (section 5.3) to scope the analysis and to help interpret the results in chapter 9.

5.1 Specification of the intersections

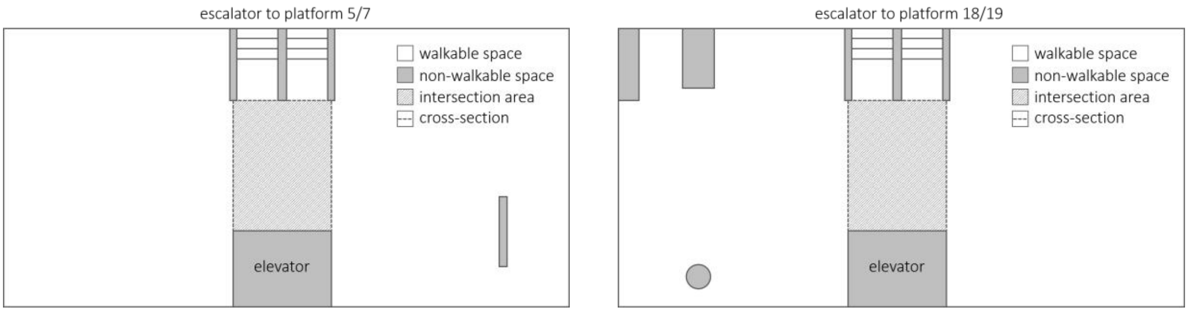
A detailed map of the intersections is presented in Figure 5.2. The intersection area, the cross-sections, but also objects (benches/screens) and (shop) entrances are indicated on the map. All intersections have three cross-sections for passengers to enter or exit the intersection and there is one physical boundary.



a. Intersection 1



b. Intersection 3



c. Intersection 2 **d.** Intersection 4

Figure 5.2 Detailed map of the selected intersections

The respective length, width and area of the intersection, and length of the cross-sections are presented in Table 5.1. As can be seen, intersection 1 and 3 are similar in shape and size, and the same goes for intersection 2 and 4. Also, they share the same type of vertical infrastructure; a staircase (intersection 1 and 3) or an escalator (intersection 2 and 4).

Table 5.1 Specification of the intersections

Intersection	Length	Width	Area of intersection	Length of cross-section	Type of vertical infrastructure
1	$5.5\,m$	$4-6\,m$	$27.5\,m^2$	$17.2\,m$	stairs
2	$4.75\,m$	$3.75\,m$	$17.8\,m^2$	$11.4\,m$	escalator
3	$5.5\,m$	$4-6\,m$	$27.5\,m^2$	$17.2\,m$	stairs
4	$4.75\,m$	$3.75\,m$	$17.8\,m^2$	$11.4\,m$	escalator

Figure 5.3 shows a view on each intersection to give an impression of the size and its surroundings. The station hall has a permanent roof and both natural light as well as artificial light define the light conditions in the hall. The temperature is close to the outdoor temperature, which varies with the seasons[2]. Located above the intersections, information signs show the platform numbers, the travel information for the respective platforms and a clock. At intersection 1 and 3, a guideline for visually impaired pedestrians is located in the center of the corridor and located right towards the staircase (black line on the floor in Figure 5.3).

a. Intersection 1 **b.** Intersection 3

[2] The climate in the Netherlands is a moderate maritime climate, meaning there are mild winters and cool summers. Between 1981-2010, the average lowest temperatures throughout the year varied between 0.2-12.8 °C and the average highest temperatures varied between 5.6-22.8 °C (KNMI, 2011).

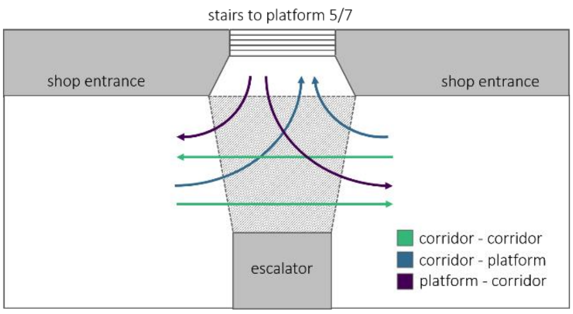
c. Intersection 2

d. Intersection 4

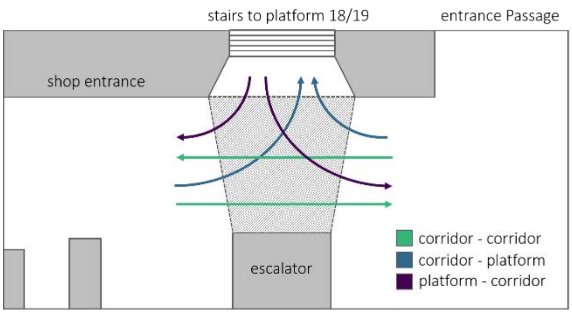
Figure 5.3 View on the selected intersections

5.2 Flow scenario

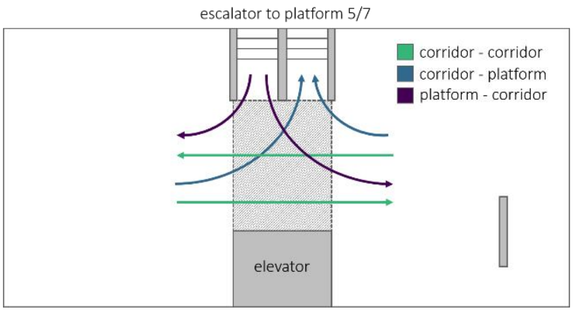
Figure 5.4 presents the flow scenario at the intersections. It consists of a bidirectional flow through the corridor and perpendicular to it a bidirectional crossing/merging flow between the corridor (in both directions) and the platform. It must be noted that in practice, not all pedestrians keep right as is indicated in the figure.



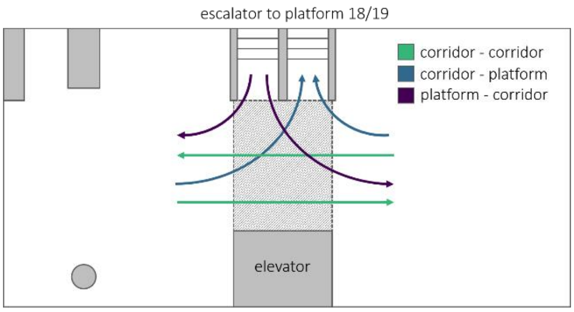
a. Intersection 1



b. Intersection 3



c. Intersection 2



d. Intersection 4

Figure 5.4 Flow situation at the selected intersections

It has been observed that the flow to the platform is distributed rather equal over time. The flow might increase as the departure of a train at the respective platform is happening soon. In contrast, the flow from the platform to the corridor is distributed over short waves, which correspond to the offloading of an arriving train at the respective platform. As was mentioned in chapter 4 (static analysis), the corridor itself is used by pedestrians to depart or arrive by train, to transfer between trains/busses, to visit the shops/facilities in the corridor or to simply pass the station. Hence, the flow through the corridor varies between a constant flow and waves of passengers that have arrived by trains at other platforms.

In the remainder of this research, a distinction will be made between the flow through the corridor and the flow between the corridor and platform and vice versa. We refer to a main flow and crossing flow respectively (see Table 5.2). Note that the crossing flow is essentially a mix between a crossing and a merging flow, depending on the direction in which the flows meet (see arrows in Figure 5.4).

Table 5.2 Categorization of main and crossing flow

Origin/Destination	Corridor	Platform
Corridor	Main flow	Crossing flow
Platform	Crossing flow	x

5.3 Selected variables from the theoretical framework

In the previous sections, a detailed description of the intersections and flow scenario has been given. Based on this knowledge, the following variables from the theoretical framework are selected:

Table 5.3 Selected variables from the theoretical framework and their use in this research

Measure	Estimate	Fixed	Varied
Flow	Intersection capacity	Angle of intersection	Dimensions area
Density		Time of day	Stairs/escalators
Travel time (velocity)			
Flow ratio			

Figure 5.5 (page 33) displays the theoretical framework as proposed earlier, in which the selected variables are highlighted. The variables are selected for several reasons, which will be explained below.

Movement base case

The chosen movement base case is a bidirectional main flow and perpendicular to it a bidirectional crossing flow. This means that the *angle of intersection* is fixed at 90 degrees. However, the proportion between the main and crossing flow can vary, and thus influence of the *flow ratio* on the intersection flow capacity can be measured and evaluated.

Infrastructure

The infrastructure of the chosen intersections has several properties, including the *dimensions of the area* and the presence of a *staircase or escalator*. Two pairs of intersections share the same properties, which means that the influence of these variables on the intersection flow capacity can be compared.

Capacity estimation methods

In order to determine the *flow capacity of the intersection*, three methods are proposed in this research. For these methods, macroscopic variables *flow*, *density* and microscopic variable velocity will be measured, in which the velocity is derived to *travel time* (velocity is approximately equal to distance divided by the travel time). An elaborate description of the methods is presented in section 8.3.

Traffic conditions

In order to do a capacity estimation, congested conditions are necessary. Since peak hours are known for its high demand, the *time of day* in this research will be fixed. The selection for the morning and evening peak also implies that the population mostly consists of *commuters*. However, since this information is explicitly available, it cannot be considered as a fixed variable and is therefore not highlighted in the framework.

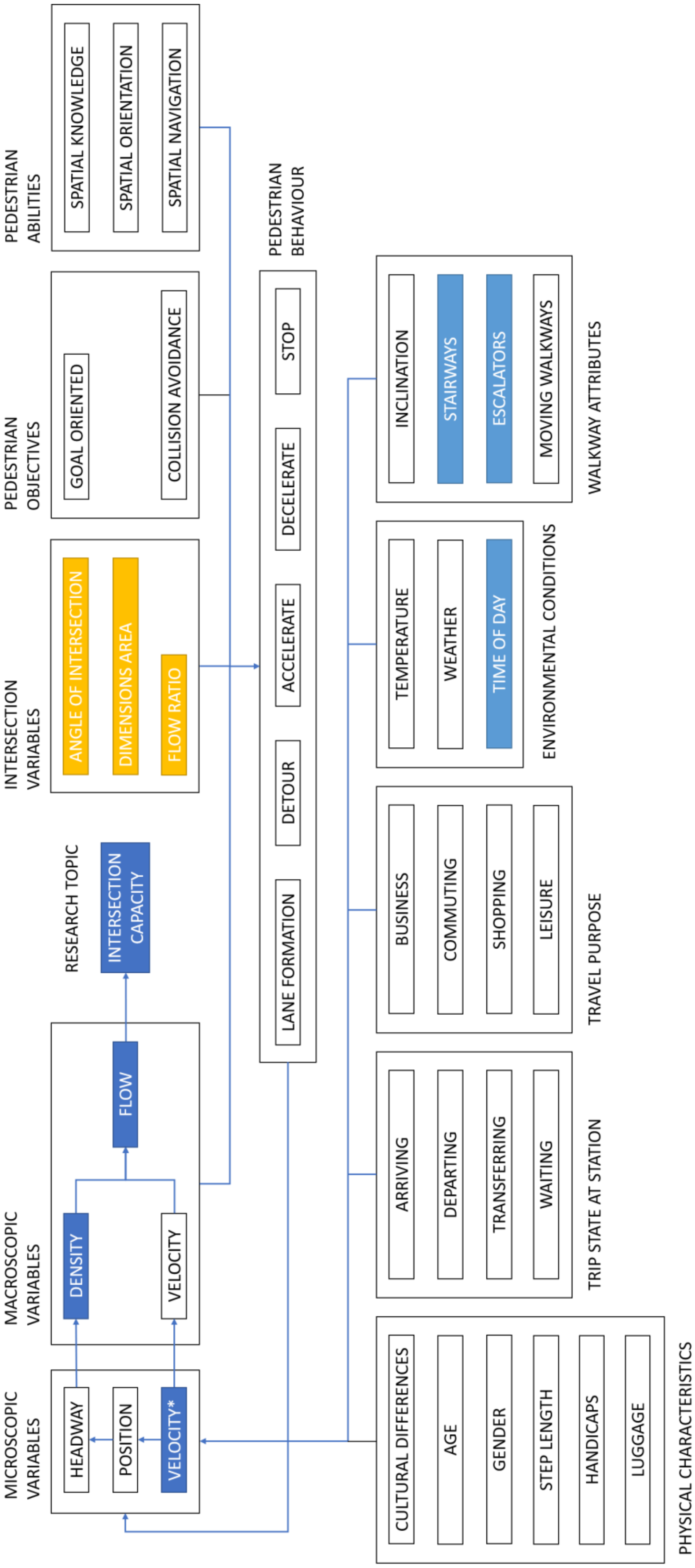


Figure 5.5 Theoretical framework and selected variables

6 Data collection method

In this chapter, the data collection method is presented. First, several data systems currently in use by NS are presented and several of their advantages and disadvantages with respect to this study are discussed (section 6.1). Section 6.2 gives a brief description of the technology of the chosen data system, and section 6.3 describes what the data looks like.

6.1 Data systems at NS

NS has several data systems to record pedestrian movements, including SMART station, ROCKT, GOTCHA, OV-chipkaart (smart card) data and counting agencies. Table 6.1 gives an overview of the data systems, their characteristics and their purpose. Each data system has a different purpose, measurement method and level of detail with respect to pedestrian movement and occupation of infrastructure. This makes them more or less suitable for this study. The advantages and disadvantages of these systems are discussed at the end of this section.

Table 6.1 Description and purpose of several data systems currently in use by NS

System	How	What	Purpose
SMART station	Wi-Fi tracking (by BlipTrack)	To track passenger route and activity location-choice behaviour	To document movement patterns of pedestrians in the station to increase efficiency
	Overhead sensors (Pedestrian Analytics System by ASE)	1. To count pedestrians in predefined areas or passing cross-sections 2. To measure the trajectory of pedestrians within sensor	To determine demand or occupancy level for certain pieces of infrastructure, and to analyse local pedestrian flows
ROCKT (Reizen OV-ChipKaart per Trein)	An algorithm that links train service data with OV-chipkaart (smartcard) data	To assign passengers to routes/trains based on the passenger's origin and destination, time of check-in/-out and train schedule	To determine when and where pedestrians are in the station
GOTCHA	Measuring points in railway tracks to measure the weight of a train	To measure weight of cargo and passengers (payload weight) on top of a train's empty weight	1. For infrastructure manager: to assign track usage costs to cargo train accordingly to its weight 2. For passengers: to indicate the occupancy level of a carriage, to make the seat/carriage occupancy distribution among the train more efficient by directing

			passengers to empty seats
OV-chipkaart (smartcard) data	Registration of smartcard use per gate	To collect check-in/-out per gate/entrance	To gather information with regards to the distribution of demand over gates and entrances (and is used for ROCKT, see second row of this table)
Cameras	Recording footage	To count passengers	To analyse passenger numbers near access gates at Utrecht Centraal station (NS, 2019b)
Counting agencies	Staff of agencies counting manually	Pedestrians at specific areas or passing cross-sections	To gather information on the occupancy level of a certain piece of infrastructure, this is often applied for small studies, for which it is not worth (e.g. in terms of money, effort) to install sensors that would have the same purpose

Privacy statement

With respect to several privacy issues exposed by personal smartcard data, personal devices and sensor/camera footage, NS has set up an elaborate privacy statement, which can be found at www.ns.nl/en/privacy. Regarding the privacy in and around the station with respect to the data systems as described above, the following measures are summarized:

- For WiFi tracking, personal MAC addresses are used. At the moment of collection, the address is immediately hashed (i.e. converted into a series of characters). This series is changed twice again, with a certain level of randomness, to avoid that the series can be traced to an individual.
- The footage recorded by the PAS sensors is not saved on the sensor, which means there are no images to identify individuals.
- The images recorded by cameras are blurred as soon as possible to make passengers unrecognizable.

Advantages and disadvantages of the data systems

We want to check whether the data systems at NS are suitable for this study with respect to their properties and capabilities. In Table 6.2, several properties of the data systems are checked, including but not limited to: the ability to do local measurements (i.e. measure at specific areas or cross-sections), the ability to retrieve certain information and the ability to measure macroscopic variables and microscopic traffic variables.

Table 6.2 Advantages and disadvantages of NS data systems

System	Advantages	Disadvantages
SMART station (Wi-Fi tracking)	- Ability to track passenger route and activity location through a station - Information available w.r.t. origin/destination at station	- No local measurements possible (e.g. when to pass a certain cross-section, speed of pedestrian, trajectory)
SMART station (Overhead sensors, PAS)	- Local measurement possible: ability to precisely count pedestrians in specific areas or passing specific cross-sections - High level of detail in measurements (e.g. trajectory, speed) - Ability to retrieve both microscopic and macroscopic variables	- No information available w.r.t. origin/destination at station
ROCKT (Reizen OV-ChipKaart per Trein)	- Information available w.r.t. origin/destination at station	- No local measurements possible (e.g. when to pass a certain cross-section, speed of pedestrian, trajectory)
GOTCHA	- Estimate distribution of demand across train - Estimate distribution of demand across stairs/escalators at platform	- No local measurements possible (e.g. when to pass a certain cross-section, speed of pedestrian, trajectory) - No information available w.r.t. origin/destination at station
OV-chipkaart (smartcard) data	- Estimate distribution across entrances/gates - Estimate demand corridors - Information available w.r.t. origin/destination at station	- No local measurements possible (e.g. when to pass a certain cross-section, speed of pedestrian, trajectory)
Cameras	- Ability to precisely count pedestrians in specific areas or passing specific cross-sections (depending on camera position)	- Intensive labour - Higher exposure to measurement error (depending on the position of the camera)
Counting agencies	- Ability to precisely count pedestrians in specific areas or passing specific cross-sections (depending on camera position)	- Intensive labour - Higher exposure to measurement error (depending on the position and workload of the staff)

Conclusions

The PAS technology (SMART station) is well suited for this study for two reasons. The level of detail in the data enables to derive both microscopic variables (i.e. travel time), as well as macroscopic variables flow and density. Moreover, since this study deals with rather small areas (see dimensions of the selected intersections in section 5.1), it is essential to be able to measure precisely. In case of PAS, time can be measured in deciseconds, and distance can be measured up to millimeters.

6.2 Overhead sensors/Pedestrians Analytics System

In this study, datasets will be analysed that were collected by NS using advanced pedestrian counting technology, Pedestrian Analytics System (PAS), provided by Swiss company ASE. PAS is capable of tracking individual pedestrians anonymously by overhead sensors, by accurately measuring their path (trajectory). In turn, the trajectory data enables the researcher to asses walking speeds and directions, densities and flowrates. Furthermore, the technology is capable of filtering out non-pedestrian objects such as shadows and smaller objects (e.g. luggage). As illustrated in Figure 6.1, multiple sensors can be combined to track pedestrians across a longer stretch of infrastructure.

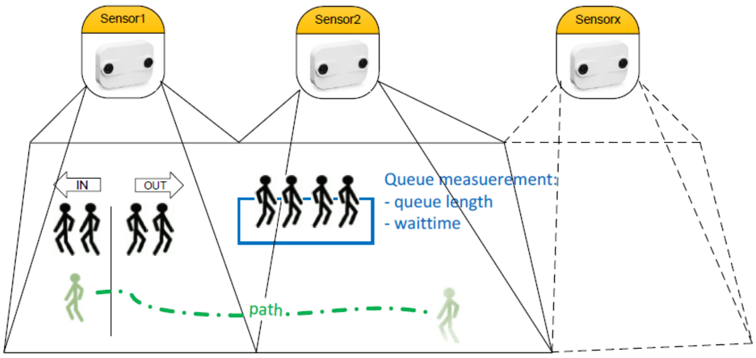


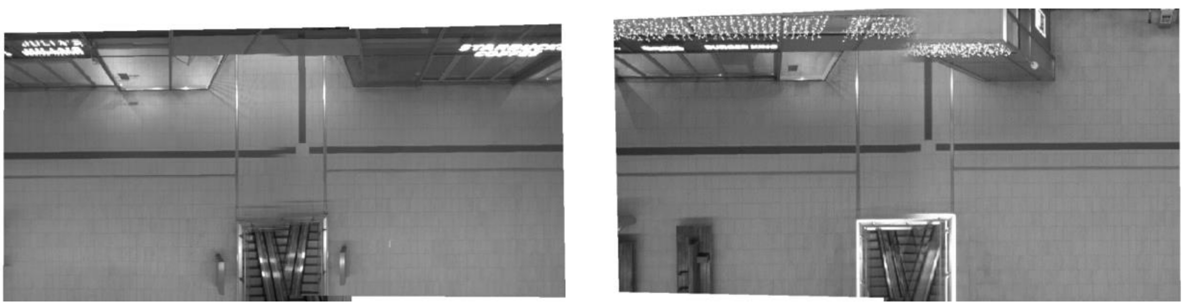
Figure 6.1 PAS sensors (Heuvel, 2017)

The data is collected and saved to the PAS database. The data can be accessed in raw data format or in a processed and aggregated format. The latter provides densities and flowrates for pre-defined areas and cross-sections respectively. This enables the researcher to perform a quick analysis with a low computational effort. The disadvantage of the processed PAS data is that only little (macroscopic) information can be collected (flow and density), without the flexibility to adjust the areas and cross-sections after collecting the data. Moreover, the size of the smallest measurement period is limited to one minute.

In previous studies, PAS has been applied to analyse pedestrian flows at platforms at Dutch and Swiss railway stations, where they assessed the platform safety risks (Heuvel et al., 2017) and the use of danger zones at platforms (Thurau et al., 2017).

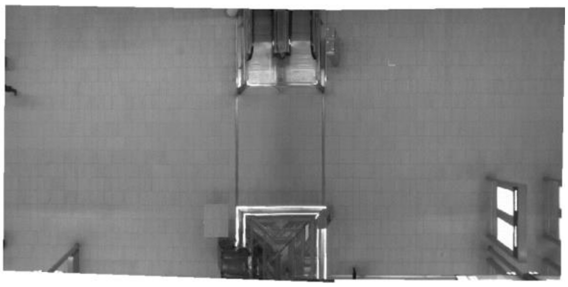
Within the Netherlands, overhead sensors are placed in several stations, including Utrecht Centraal, Amsterdam Centraal, Amsterdam Zuid, Amsterdam Bijlmer, Schiphol and ‘s Hertogenbosch. The sensors are placed above platforms, entries of stairs/escalators and at OVCP (“OV-Chipkaart en Poortjes”) gates. At platforms, NS wants to assess the occupation of platforms and safety risks. At entries of stairs/escalators, NS wants to assess the in- and outflow of the vertical infrastructure, and the queuing in front of escalators at platforms. At OVCP gates, NS wants to assess the pedestrian flows (Amsterdam Zuid) and safety risks at the outflow of an escalator (Amsterdam Centraal) (Schakenbos, 2018).

Figure 6.2 shows the sensor ranges of the four selected intersections at Utrecht Centraal station. NS has collected data since June 2017 for intersection 1 and 2 and from September 2018 for intersection 3 and 4.

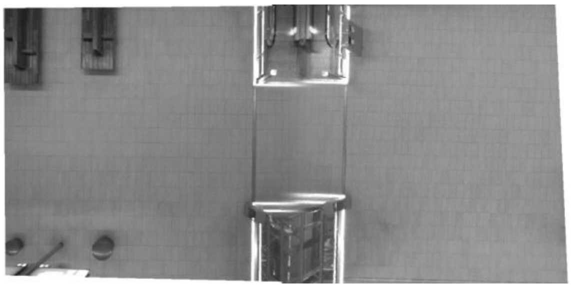


a. Intersection 1

b. Intersection 3



c. Intersection 2



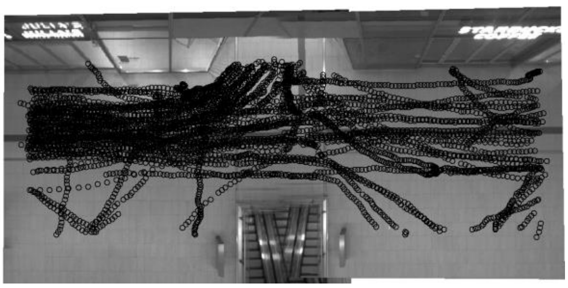
d. Intersection 4

Figure 6.2 Sensor range of the selected intersections at Utrecht Centraal station

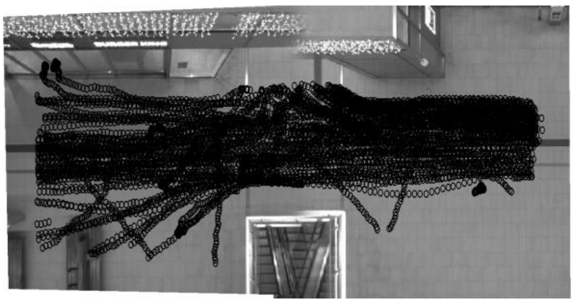
6.3 Description of the data

In the datasets produced by PAS, one data entry represents the location of one pedestrian at one intersection at one specific time step. Every time step of 0.1 second, the (x, y) coordinate is saved for each pedestrian that is located within the range of the sensor. For the sensors at the intersections 1 and 3 and intersections 2 and 4, this results respectively in approximately 9 and 14 million data entries for each busy weekday per intersection, which is equivalent to 75.000-110.000 pedestrians. Besides the time step, the object (pedestrian) ID and its coordinate, also the sensor ID is saved to the dataset. Figure 6.3 shows an example of the trajectories of 100 pedestrians per intersection.

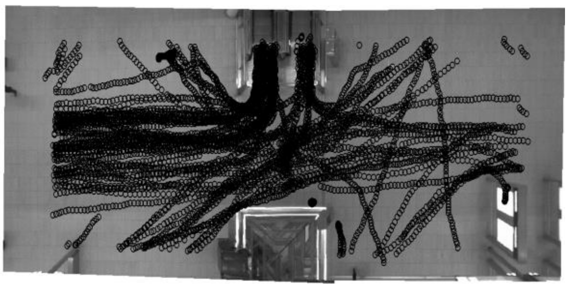
The level of detail of these datasets has a big advantage. That is, it captures the movement of pedestrians at a high level of detail, and thus contains a lot of information. This enables researchers to derive many microscopic as well as macroscopic variables, for very specific locations and time frames. The drawback of this level of detail is that the analysis can become a computationally extensive task due to the size of the comprehensive dataset. To both maintain the possibility to add a high level of detail to the analysis (without losing information) and to limit the computational burden, an efficient selection process is essential. The following chapter will elaborate on the selection process that was set up for this study.



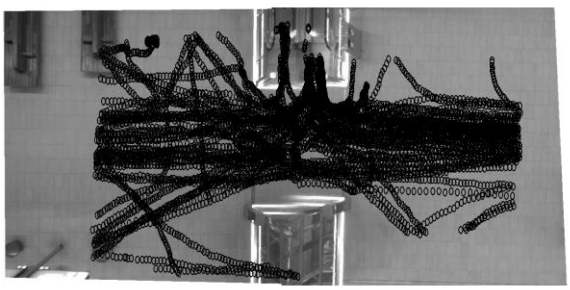
a. Intersection 1



b. Intersection 3



c. Intersection 2



d. Intersection 4

Figure 6.3 Trajectories of 100 pedestrians at the selected intersections

7 Data processing method

In this chapter, the data processing method is presented. Data processing is important, because it avoids the researcher to analyze all data (which is computationally heavy), and it offers the possibility to select samples based on specific conditions (e.g. time of day).

Figure 7.1 presents the research flow chart, which shows the research steps for the preparation of the data for the analysis (chapter 7 and 8), and the relation (input/output) to the other chapters. This chapter describes the steps to select and retrieve samples for each intersection from the processed PAS data (as described in section 6.2). This data is more aggregated, which yields a lower computational effort, and still gives a good insight into the observations in terms of flow. After samples for each intersection have been selected, the raw PAS data (i.e. trajectory data) will be used for the actual data analysis.

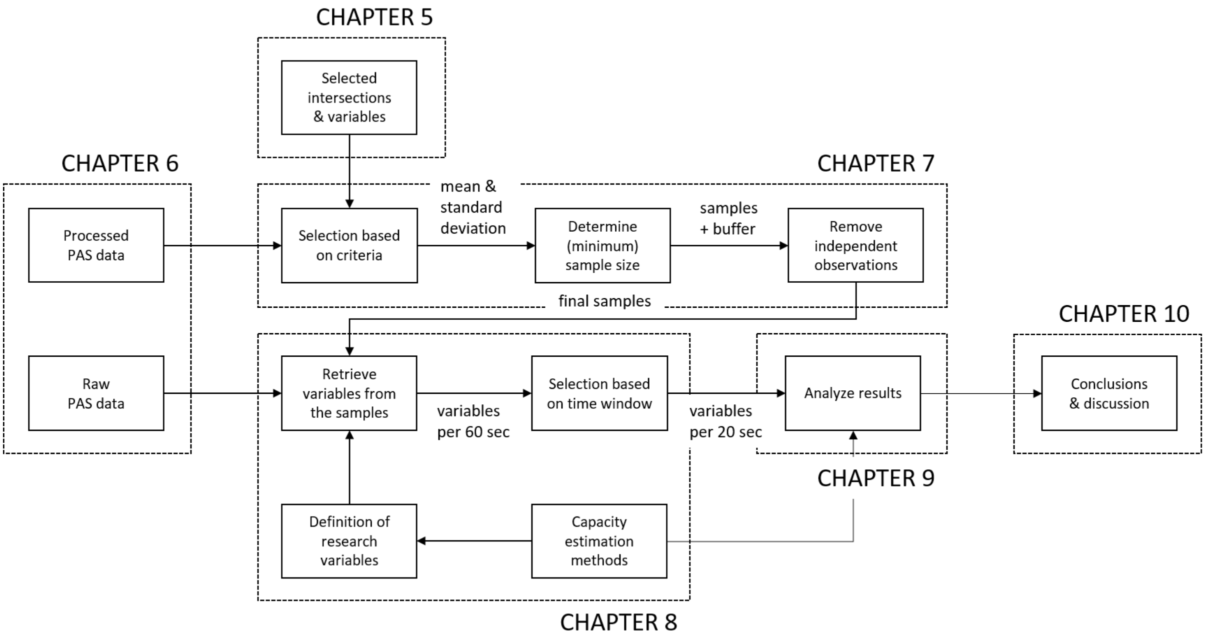


Figure 7.1 Research flow chart describing the research steps

Section 7.1 describes the selection criteria for the data samples and section 7.2 presents a method to determine the minimum sample size and its results. Also, to ensure that the observations within the samples are independent and therefore yield reliable results, a procedure is proposed to remove dependent observations from the selected samples (section 7.3)

7.1 Selection criteria

In order to estimate the intersection flow capacity, it is important to look at the busiest moments in terms of the outflow of the intersection. Therefore, the main selection criteria for the samples is that they should contain observations with the highest flows. With respect to the processed PAS data, the smallest observation size in terms of time is one minute.

As explained in chapter 3 (theoretical framework), the selection process will apply to (commuters in) peak hours, which is chosen to minimize the effect of several differences between travel purposes and time of day, and to consider the busiest periods (and thus the highest flows) at the station on a regular basis. Therefore, the selection is based on peak hours (07:00-09:00 and 16:00-18:00) on weekdays

(Monday to Friday) for one year of PAS data (01-10-2018 till 30-09-2019). A year of data is observed to cover for busy months (trends) within one year. The most recent data is used in order to minimize the influences of the rebuilding process of Utrecht Centraal station and its surroundings. The following holidays and a public transport strike (OV-staking) have been excluded from the list of potential candidate days, because they might not be representable for (commuters in) peak hours:

- Tuesday 25-12-2018 (Christmas Day)
- Wednesday 26-12-2018 (Second Day of Christmas)
- Tuesday 01-01-2019 (New Year's Day)
- Friday 19-04-2019 (Good Friday)
- Monday 22-04-2019 (Eastern Monday)
- Tuesday 28-05-2019 (OV-staking)
- Thursday 30-05-2019 (Ascension Day)
- Monday 10-06-2019 (With Monday)

Excluding these days does not influence the sample selection itself, since the flows at these days at the station are significantly smaller than the flows on regular weekdays and peak hours, and only the highest flows are selected. However, excluding these days does influence the standard deviation of the first selection of all weekdays and peak hours with respect to the flow, which affects the minimum sample size that is discussed in the next section.

7.2 Method to determine minimum sample size

This section aims to determine a sample size per intersection for two reasons. The sample should be small enough to limit the computational burden of the analysis, but more importantly, the sample should be big enough to ensure that the results are statistically valid[3]. In this case that means that the samples should represent the population correctly with 95% certainty.

There are several methods to determine the minimum sample size, depending on the information that is known about the considered population. When the standard deviation of the population is known, it can be used to determine the minimum sample size n. Let σ be the standard deviation of the population and let d be the level of accuracy of 0.05, which is multiplied with the mean μ. For a 95% confidence interval z_a becomes 1.96. The sample size n can be obtained by the formula:

$$n \geq \frac{z_a^2 \cdot \sigma^2}{d^2}$$

Table 7.1 shows the values and minimum sample sizes for the four intersections.

Table 7.1 Calculation of the minimum sample size

Intersection	z_a	σ	d	n
1	1.96	2.21	0.24	325
2	1.96	2.79	0.29	367
3	1.96	1.92	0.22	291
4	1.96	2.61	0.26	376

[3] In this case, we select a sample based on the highest flows. This means that the sample is not an average representation of the population. It is questionable whether the results yielded from a sample that is not randomly selected is statistically valid as the method implies.

7.3 Independent observations assumption

To ensure that the samples yield reliable results, all observations must be independent. This is a statistical assumption that is called the *independent observation assumption*. It means that two observations cannot show the same event, as the event will be counted twice. In our samples, this means that a peak in flow occurring in one minute, should not be partly present in another minute. If dependent observations are kept and one peak is counted twice, it yields biased and thus unreliable results. To ensure independency in the samples of this research, a simple procedure is proposed.

Before removing the dependent observations (i.e. remove one of the two), a buffer of 100 observations is added to the initial sample (as presented in Table 7.1), to ensure that the final sample meets the minimum sample size criteria.

It has been observed that peaks in the outflow of the intersection last for about 5 to 10 seconds and that they resolve within 30 seconds. Since each observation has a length of one minute, independency can be guaranteed if a minimal gap of one minute is maintained between each observation in the sample.

This procedure iterates through the time-sorted observations one by one, looking only at the observation and its first adjacent neighbor. In case two observations are adjacent in time within the initial sample, the observation with the lowest flowrate is removed from the list. In case both observations have the same flowrate, the first observation is removed. This may affect the final sample when there are more than two time-adjacent observations with the same flowrate, as in that case multiple adjacent observations will be removed (e.g. three out of three observations are removed), whereas using another procedure (e.g. that only removes the middle observation out of three) yields a (slightly) different sample selection. It can be considered as the drawback of this procedure. However, since it is uncommon to end up with an initial selection (0.5-1.0% of all observations) that has more than two time-adjacent observations with the exact same flowrate, the effect of the procedure is assumed to be rather small and therefore accepted.

Table 7.2 shows for each intersection the minimum sample size, the added buffer and the removed observations after the execution of this procedure and the final sample size, which will be used for the remainder of this research.

Table 7.2 From minimum sample size to final sample size

Intersection	**1**	**2**	**3**	**4**
Minimum sample size	325	367	291	376
Add buffer	+ 100	+ 100	+ 100	+ 100
Remove dependent observations	- 100	- 81	- 49	- 39
Final sample size	325	386	342	437

7.4 Insights/Evaluation

It must be noted that, however assumed otherwise, not all trajectory data was available for the final samples due to several reasons. This resulted in (slightly) smaller samples and the violation of the minimum sample requirement of intersection 1 by 3 observations.

The following figures give insight into the samples regarding the selected months (Figure 7.2), days (Figure 7.3) and morning/evening peak (Figure 7.4) of the final sample per intersection. Since some trajectory data is missing, the overviews are a bit biased.

The busiest months are expected to be from September to November, which is somehow confirmed by looking at intersection 1 and 2. It is assumed that these months are busier due to the share of students in the population of commuters, which is higher at the beginning of the academic year and decreases as the year progresses.

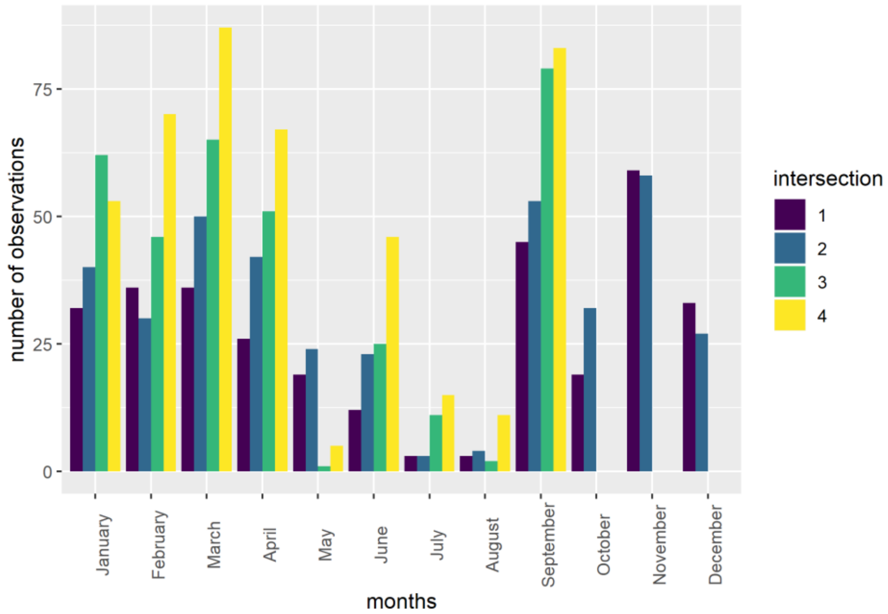


Figure 7.2 Number of observations per month per intersection

As can be seen, the busiest days during the week are Tuesday and Thursday for all intersections. This is probably because part-time workers often plan their free days right before or after the weekend (Monday or Friday) or in the middle of the week (Wednesday). Also, parents might plan their free day at Wednesdays, since children at Dutch primary schools are free during these afternoons.

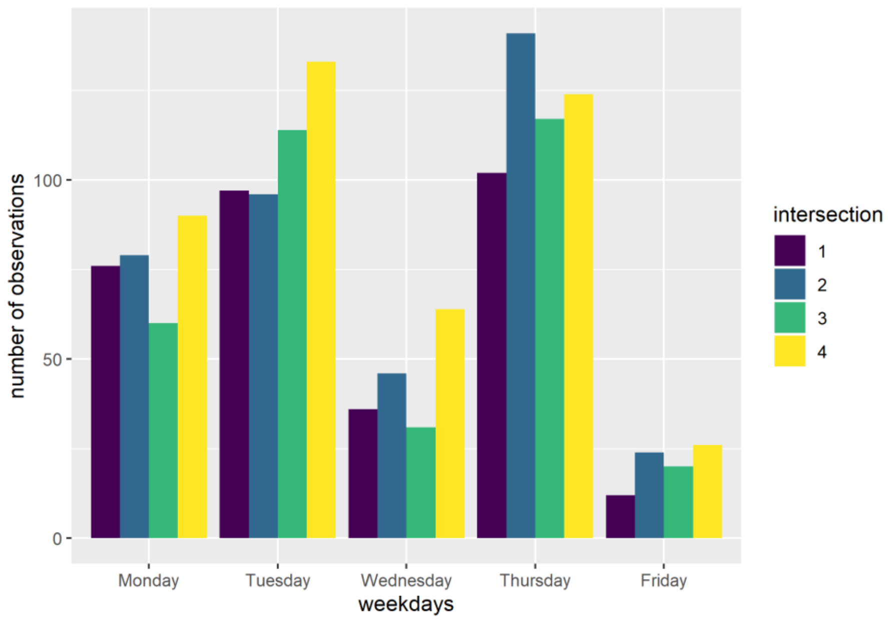


Figure 7.3 Number of observations per weekday per intersection

For intersection 1 and 2, the highest flows occur in the morning peak, whereas for intersection 3 and 4 this is more balanced.

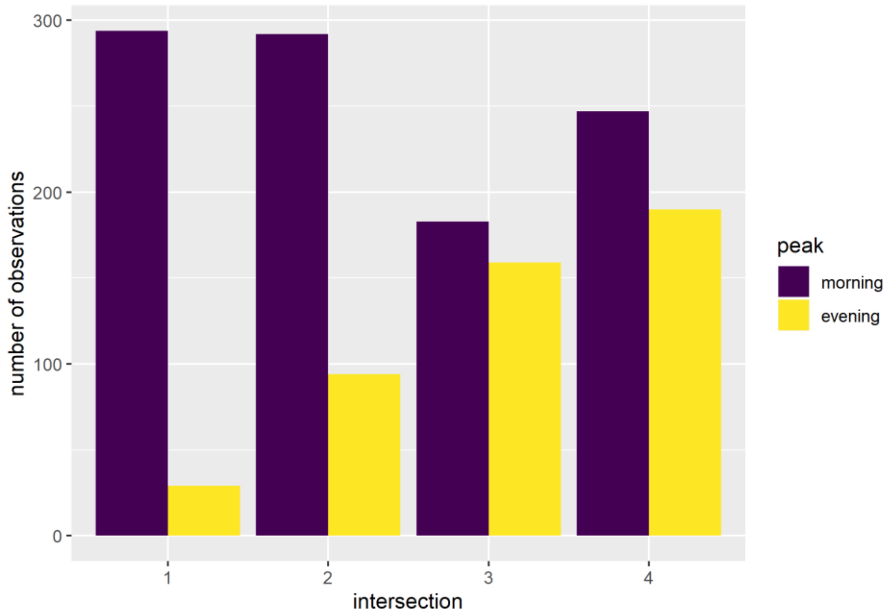


Figure 7.4 Number of observations per morning/evening peak per intersection

8 Capacity estimation methods

This chapter presents three capacity estimation methods that are tested in this study. Since these intersections in combination with the flow scenario are specific and, to the knowledge of the author not studied before, no statements can be made yet on the suitability of an (existing) capacity estimation method. Therefore, this study proposes and tests three capacity estimation methods, based on previous research and general pedestrian traffic engineering principles. Chapter 9 presents the results yielded by these methods and in chapter 10 (conclusion, discussion), the methods will be compared, and their suitability will be discussed.

The previous chapter concluded with a sample selection for each intersection for further analysis. This sample selection was based on processed PAS data. For the remainder of this research, unprocessed PAS data (i.e. trajectory data as described in section 6.3) will be used. This data is more detailed and allows to derive both microscopic and macroscopic variables, for specific locations and time frames.

Section 8.1 gives the definition of the research variables, section 8.2 elaborates upon the influence of different time windows and the selection thereof for the analysis, and section 8.3 presents the capacity estimation methods.

8.1 Definition of the research variables

The three capacity estimation methods (which will be explained in detail in section 8.3) require the measurement of traffic variables; flow q, density k and travel time tt. Furthermore, the flow ratio γ will be measured to analyze its influence on the intersection capacity. These four variables were also presented in the selection of variables from the theoretical framework in section 5.3. The following paragraphs elaborate upon the definition of each variable in more detail.

Flow

The flow q is generally quantified by the number of pedestrians n that pass a cross-section with length l during a time period Δt. In this study, the cross-section is indicated by the three dashed lines per intersection in Figure 5.2. For intersection 2 and 4, half of the dashed line that separates the escalators with the intersection is used, since these cross-sections can only be used in one direction. The length of the cross-section per intersection is presented in Table 5.1.

The flow consists of the outflow of the intersection, meaning that only pedestrians passing the cross-section in the direction from inside the intersection outwards are counted. Flow counts into the intersection (the inflow) are not counted.

Furthermore, the flow is normalized in two ways. To overcome the difference in length of the cross-sections of intersection 1 and 3 and intersection 2 and 4, the flow is normalized to flow per *meter* per minute (i.e. the flow is divided by the length of the cross-section), which is also the most commonly used unit to express flow.

Instead of normalizing the flow to the length of the cross-sections, the flow could also be normalized to the area of the intersection. The length of the cross-section can be equal, and still the area can be larger or smaller (this is because the length of the physical boundary is not considered in the cross-section). Hence, normalizing the flow to the area might give a better representation of the intersection, since it can cover for its size. However, the author has not studied this option in detail and opted early in the process of the data analysis for the normalization step by length of the cross-section. For future research, it could be interesting to study the difference between normalization to length or area and its effects on the results.

Moreover, if the measured period Δt is not one minute, then the flow should be normalized to flow per meter per *minute* by dividing 60 over Δt (Δt is always expressed in seconds). To conclude, the flow [p/m/min] is formulated as follows:

$$q_l = \frac{n_l \cdot \frac{60}{\Delta \mathrm{t}}}{l}$$

Flow ratio

The flow ratio γ represents the proportion of the main flow q_{main} and the crossing flow q_{cross}. The main flow and crossing flow for this research are specified in section 5.2 (flow scenario). The flow ratio is expressed as a value between [0,1], in which 1 represents a 100% share of the main flow and 0 represents 100% of the crossing flow.

It must be noted that the flow ratio only covers a part of the total flow measured in the observation. In case pedestrians are already within the intersection, their origin (the cross-section they pass when they enter the intersection) is unknown and therefore no category can be assigned. The same goes for pedestrians that have not left the intersection at the end of the measurement (they have no destination within the measurement). The flow ratio is retrieved as follows:

$$\gamma_{main} = \frac{q_{main}}{q_{main} + q_{cross}}$$

Density

There are several measures to quantify the density or level of crowdedness. A comprehensive overview by Duives et al. (2015b) presents a review of 9 measures, including but not limited to the grid-based, X-T, range-based and Voronoi measure. In this study, the density is defined by a grid-based assessment, which is chosen to limit the computational efforts.

In the grid-based method, the pedestrians located within the grid are included in the measurement. In this study, the grid is equal to the intersection area (as presented in Figure 5.2). This method has three limitations which can be solved by using other methods: 1) pedestrians on the border of the grid (the intersections) might not be counted, 2) the density depends on the time and exact placement of the measuring area, which may result in discontinuous estimations over space and time, and 3) the experience of crowdedness by the pedestrians may not be in line with the measurement, since the crowdedness can be located more centrally or to the border of the grid (Duives et al., 2015b). Nevertheless, this method has been chosen for the practical reason of a low computational effort.

The density k is defined as the average number of pedestrians n in area A during time period Δt, calculated per time step t. Density is expressed in pedestrians per square meter. In this case, each time step t lasts 1 second, hence the average is taken of the sum of pedestrians counted in each second within time period Δt. Besides the average density, also the minimum, maximum or median density could be used to express the level of crowdedness. Since we are interested in the flow situation over a period Δt (see time windows, section 8.2) rather than high or low peaks, the average density is a better representation of the flow situation compared to maximum or minimum values that could only last for a very short time.

Similar to the flow, the density is normalized to pedestrians per *square meter* to overcome the differences in size between the intersections (i.e. the number of pedestrians is divided by the area). The density [p/m^2] is formulated as follows:

$$k_A = \frac{1}{\Delta t \cdot A} \cdot \sum_{\Delta t} n_A$$

Travel time

Regarding the travel time, both the average travel time $\overline{tt}$ as well as the minimum travel time $tt_{\min}$ will be measured. The average travel time gives insight into the differences between all pedestrians of the observations, which likely yields reliable results (e.g. observed trends are more trustworthy). The minimum travel time gives insight into differences between the fastest pedestrian of the observations, which could yield less reliable, but instead clearer results.

The average travel time $\overline{tt}$ is defined as the average time spend in the intersection area by pedestrians of the main flow q_{main}. This measure is irrelevant for the crossing flow q_{cross}, since the paths travelled vary in length significantly, whereas the path for the pedestrians in the main flow is rather the same (mostly equal to the width of the intersection). The average travel time is the average taken of the sum of the time difference $tt = t_D - t_O$ of each pedestrian from q_{main}, measured between the cross-section of their origin and destination (so, either enter/exit the corridor left/right and vice versa).

The minimum travel time $tt_{\min}$ is calculated in the same way, except that the smallest time difference $tt = t_D - t_O$ is selected, which represents one pedestrian.

Both the average and minimum travel time are expressed in seconds to one decimal place. Similar to the flow ratio, this variable only covers a part of the total flow, since not all pedestrians have both a cross-section of origin and destination during the measurement, and even a smaller group is part of the main flow. To conclude, respectively the average and minimum travel time [s] are formulated as follows:

$$\overline{tt}_{main} = \frac{1}{n_{main}} \cdot \sum_{n_{main}} tt$$

$$tt_{\min,main} = \min\left(tt_{1,main} : tt_{n,main}\right)$$

8.2 Time window selection method

In chapter 7 (data processing), the process to retrieve samples from the data is based on the processed PAS data, which shows the observed flow per minute. Figure 8.1 illustrates an observation of one of the samples based on the (unprocessed) trajectory data, which is the flow per second within one minute. As can be seen, the flow varies significantly throughout the minute, showing both peaks and troughs, implying that peaks are averaged out if only the whole minute is observed.

To account for averaged flows, both a sliding and a smaller time window can be considered. A sliding time window searches for the maximum flow for a certain time window by iterating through a larger time window. In chapter 7 (data processing), the observations are based on processed PAS data, thus clock minutes, meaning that the observation only begins on the start of the minute (i.e. 08:00:00 and not 08:00:23). By looking at a larger time window (i.e. by taking one minute before and after the observation), 120 iterations can be made, if iterations are separated by one second. Chances are likely to find a higher flow in one of the other 119 iterations compared to the initial observation.

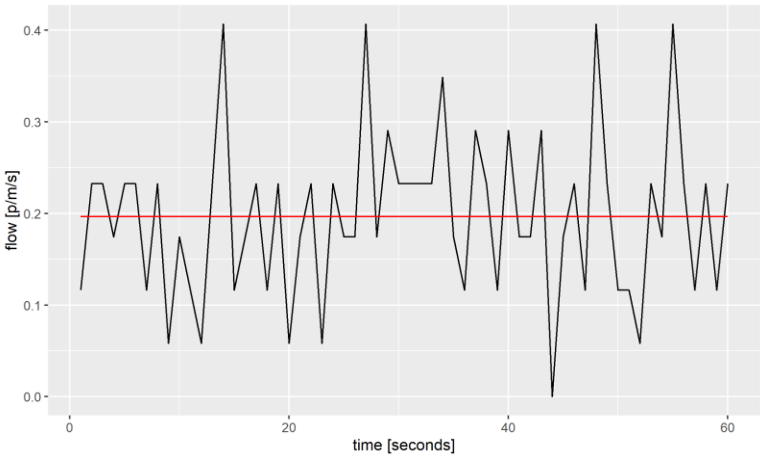
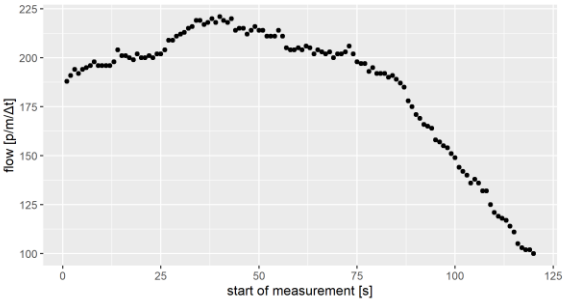
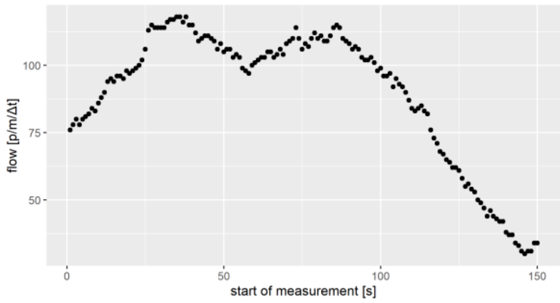


Figure 8.1 Flow per second and average (red line) within one observation

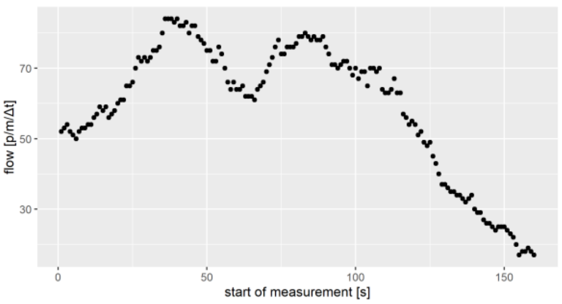
Furthermore, a smaller (sliding) time window can be considered to capture less averaged peaks. Figure 8.2 illustrates the effect of both sliding time windows (comparison of clock minutes and sliding minutes) and of smaller time windows within the same minutes. As can be seen, more variation and higher maximum flows occur if a smaller time window is selected.



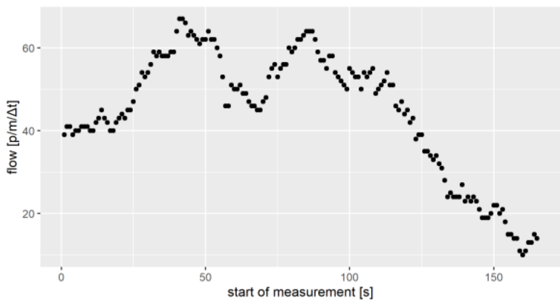
a. Time window Δt of 60 seconds



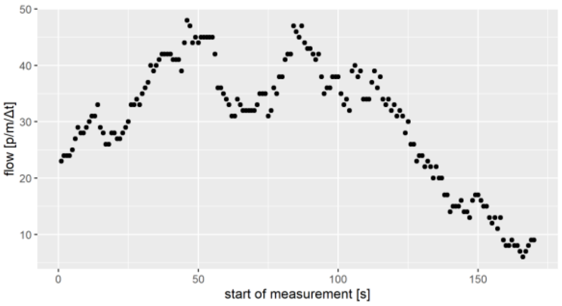
b. Time window Δt of 30 seconds



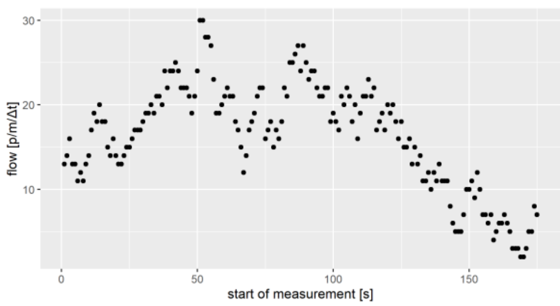
c. Time window Δt of 20 seconds



d. Time window Δt of 15 seconds



e. Time window Δt of 10 seconds



f. Time window Δt of 5 seconds

Figure 8.2 Effect of sliding time windows for various lengths of time window Δt

Figure 8.3 shows the maximum observed flows (normalized to flow per minute) for each time window with a length Δt between 1 and 60 seconds for 100 observations of one intersection (the red line represents the average). For this, within one minute[4] the time window iterates through the respective minute and only considers the highest flow measured through the iterations. Note that the number of iterations decreases as the time window increases (a time window of 1 second has 60 iterations and a time window of 60 seconds only has 1 iteration).

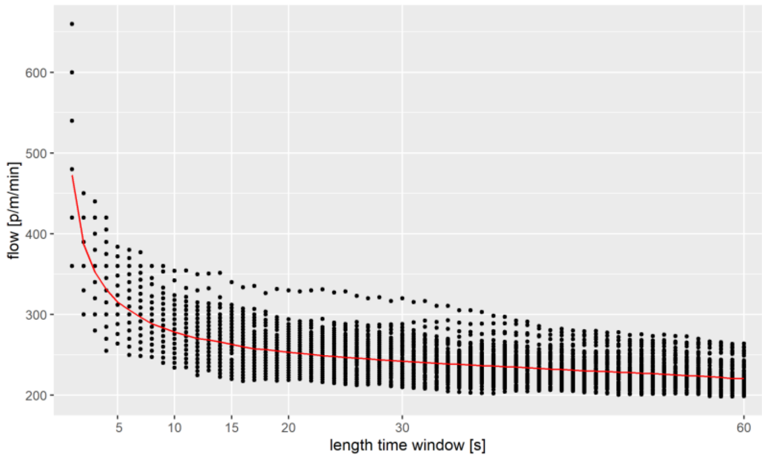


Figure 8.3 Variation in length time window and the corresponding observed maximum flow

The selection of a suitable time window is based on a trade-off between a good representation of busy periods (i.e. peaks) and a good representation of the system (which consists of on- and offloading of peaks as well). This section has shown that a time window of 60 seconds might be too large, as the actual peaks only last for 5 to 10 seconds (Figure 8.1). However, a time window of 5 or 10 seconds might be too short as it only shows one peak, which is not representable for the system that includes the on- and offloading of the peak.

Therefore, to the knowledge of the author, time windows between approximately 15 and 30 seconds all seem reasonable time windows. For the remainder of this study, a time window of 20 seconds has been selected. It is recommended for further research to study the effect of time window lengths on the results (e.g. on the variables and their relations as defined in section 8.1 and 8.3) in more detail.

8.3 Capacity estimation methods

Capacity is often defined as the maximum possible flow passing a certain cross-section l over a time period Δt. This is the most straightforward way to look at the capacity of a piece of infrastructure, on the condition that the demand is high enough to reach the capacity threshold.

In experimental studies, the demand can be controlled and often increased, which enables researchers to push the demand to a capacity level. In a field study like this, it could be that the capacity is never met. Hence, other variables such as the density or delay in terms of travel time, should be incorporated into the analysis to verify that the capacity is met.

[4] In the explanation of Figure 8.2 a large time window of three minutes was considered, in Figure 8.3 only the respective observation of one minute is considered as the larger time window. Due to the independent observation assumption (as explained in section 7.3), the observations in the samples are separated by at least one minute. Therefore, the larger time window cannot be larger than one minute, since the new observations (by using sliding time windows) could overlap and become dependent.

Since we study capacity conditions with respect to intersecting flows, we are interested in the influence of the flow ratio on the flow capacity of the intersections. This will be included in the results (chapter 9).

The following paragraphs describe for each method how the capacity flow q_c is achieved, and which conditions should be met to verify that the capacity threshold is reached.

Method 1: Maximum flow

The first method is most straightforward. It states that the capacity flow q_c is equal to the maximum flow q_{max} within the observed sample of size N and is determined by:

$$q_{max} = \max(q_{n=1} : q_{n=N})$$

This method lacks the possibility to verify that the capacity flow is met, therefore no condition is presented to do so. However, this method can indicate the minimum capacity that can be handled by the infrastructure.

Method 2: Density – Flow

This method is based on the fundamental diagram (as described in section 2.1) and visualizes the relation between the density k and the flow q. The relation is visualized by a curve (as derived from the results, which initially is a scatterplot), in which the flow increases as the density increases to capacity density k_c and decreases between the capacity density and the jam density k_j, indicating free and congested traffic conditions respectively (see Figure 2.3).

In this method, the curve indicates the capacity flow q_c at the highest point (k_c,q_c), on the condition that the curve has a parabolic shape[5]. This condition is met if the observations n within the sample of size N show both an increasing trend as well as a decreasing trend. In order to indicate the capacity flow q_c, the majority of observations must comply with:

$$q_n < q_c \quad \wedge \quad k_n < k_c \quad n \in N \quad (increasing\ trend)$$

$$q_n > q_c \quad \wedge \quad k_n > k_c \quad n \in N \quad (decreasing\ trend)$$

Method 3: Density – Travel time

The third method hypothetically states that the capacity flow q_c is met at the threshold at which the travel time increases, and passengers start to experience delay. In this case, an increase in delay is expected after a certain threshold in density (according to Fruin, see Table 2.7). It is debatable whether a certain delay (increase in travel time) is acceptable, which could yield a higher capacity density (and thus a higher capacity flow).

After determining the capacity density, subsequently the flow capacity can be determined from the density-flow relation as was studied in method 2. Since the flow-density relation is initially a scatterplot, the chosen capacity density yields a range of capacity flows. It should be kept in mind that each decision for a capacity standard within this range yield consequences of under or over dimensioning of the infrastructure to a certain extent. Under dimensioning happens if a low capacity flow is selected from the range (the risk increases that the demand exceeds the capacity more often), and over dimensioning

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[5] This condition suggests that the flow-density relation is defined as a parabolic shape. In fact, there are many models that define different shapes of the fundamental diagram, including the Greenshields or triangular diagram, in which the first is a parabolic shape and the other (as the name suggests) triangular. Also, a discontinuous shape could represent the relation (see capacity drop, Figure 2.10). Regardless of the shape, the increasing/decreasing trends are most important to this condition, which are present in any shape.

happens if a high capacity flow is selected. The decision maker can decide (per intersection) on a certain flow capacity within this range.

In this method we look at the relation between the density k and average travel time $\overline{tt}$ of the pedestrians that cross the intersection during time period Δt. We do the same comparison for the density k and the minimum travel time $tt_{\min}$.

The capacity density k_c is met if a trend occurs in which the *minimum* average travel time $\min\,(\overline{tt})$ for a certain density k_i increases (with x percent, in which x is the accepted level of delay as determined by the decision maker). Here, subset I represents bins i of densities k within the sample of size N. The same condition applies to the comparison with the minimum travel time. The condition is met if from a certain density bin k_i the observations comply with:

$$\min\left(\overline{tt}(k_i)\right) - \min\left(\overline{tt}(k_{i=1}) : \overline{tt}(k_{i=I})\right) > 0 + x \quad i \in I \quad (average\ travel\ time)$$

$$\min\left(tt_{min}(k_i)\right) - \min\left(tt_{min}(k_{i=1}) : tt_{min}(k_{i=I})\right) > 0 + x \quad i \in I \quad (minimum\ travel\ time)$$

9 Results

In this chapter, the results of the data analysis according to the capacity estimation methods in chapter 8 are presented. First, a trend analysis is performed with respect to the research variables (section 9.1). Section 9.2 presents and discusses the results of the three capacity estimation methods. In this chapter, the theoretical framework (section 5.3) will be used to interpret the results.

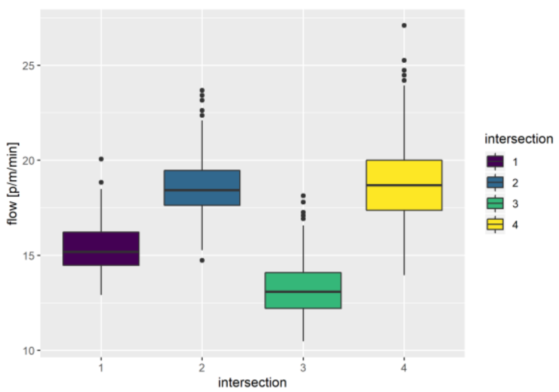
9.1 Trend analysis

In this section, research variables for each intersection are presented and several trends will be highlighted. The research variables, as defined in section 8.1, are summarized in Table B.1 (Appendix B) and in Figure 9.1. Note that the time window Δt for all measurements is set at 20 seconds (section 8.2). Therefore, with respect to flow, the measured values are multiplied by 3 to normalize to flow per meter per *minute*.

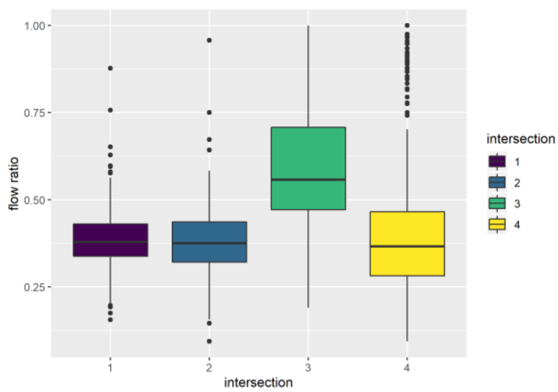
Flow

The highest flows occur at intersection 2 and 4. It is assumed that this is caused by the presence of the escalators at these intersections (instead of the staircases at intersection 1 and 3). In case of an escalator, the inflow to the intersection (located downstream the escalator) is rather equal to the inflow to the escalator (located upstream of the escalator), with the exception that some pedestrians will walk while others stand still. While exiting the escalator, the pedestrians cannot anticipate on the traffic situation at the intersection by stopping, simply because the escalator is moving (in case it operates as an escalator). In case of exiting a staircase, pedestrians can adjust to the traffic situation at the intersection, by waiting or forming a queue at the staircase and therefore (temporarily) decreasing the inflow to the intersection. This means that the less controllable and therefore higher outflow of an escalator and thus the higher inflow to the intersection, is expected to yield a higher outflow of the intersection as well (until capacity is reached).

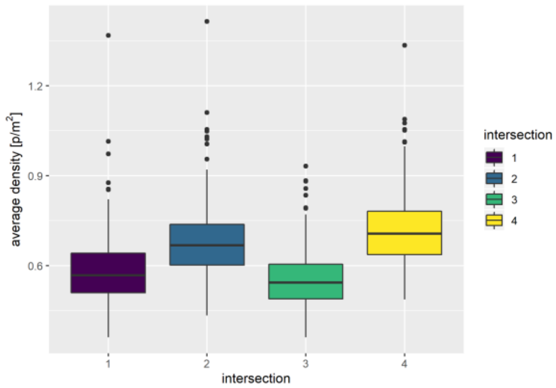
Another assumption that could explain the higher flows at intersection 2 and 4 are the dimensions (i.e. the shape and the size) of the intersection, which are similar for intersection 2 and 4 and similar for intersection 1 and 3. It is assumed that the different dimensions yield a different occupation of space in terms of pedestrian paths, which could influence the flow dynamics. However, since this research has no insight in the occupation of space on a microscopic level (e.g. trajectory or speed changes), more research including microscopic variables is required to measure this effect.



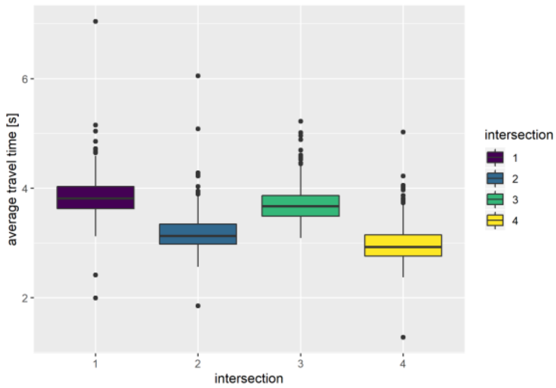
a. Boxplot flow



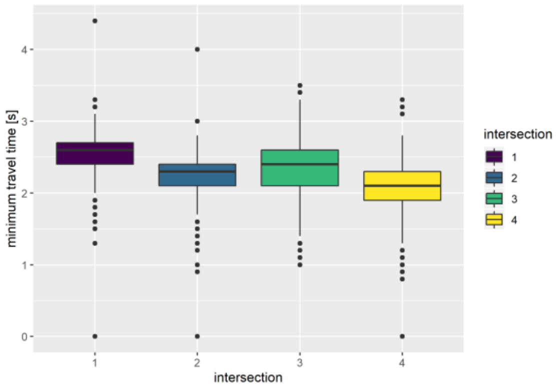
b. Boxplot flow ratio



c. Boxplot density



d. Boxplot average travel time



e. Boxplot minimum travel time

Figure 9.1 Summary research variables

Flow ratio

With regards to flow ratio, three observations stand out. All intersections have an average flow ratio around 0.40/0.60 (40% main flow and 60% crossing flow or vice versa). This either implies that higher flows are yielded because pedestrian traffic is handled more efficiently at rather balanced flow ratios (e.g. due to the effect of self-organization), or it is the result of the demand pattern at the intersection, which means that the flow ratio is determined by the demand.

The second observation shows that the flow ratio at intersection 1 and 2 is more clustered, whereas for intersection 3 and 4 this is more widespread and shows more observations with higher shares (75-100%) of the main flow. It seems most likely that this is the result of different demand patterns, which could depend on the different locations of the intersections in the station. For example, a high production/attraction around intersection 3 and 4, could yield a higher main flow.

The third observation that stands out is that intersection 3 has an average share of main flow of approximately 60%, compared to the other intersections for which this is approximately 40%. If this difference would be caused by the dimensions of the intersection or the presence of a staircase/escalator, a similar result would appear at intersection 1, which is not the case. Again, it seems likely that this difference is caused by the demand pattern at this location. Here, also the high share of main flow could be caused by the absence of a high share of crossing flows, which could depend on the distribution of flow from platform 18/19 towards the main hall. If the demand at the platform is structurally distributed unevenly over the vertical infrastructure, for example due to the stop location of the train, it could yield structurally a low share of crossing flow at intersection 3.

Density

Similar to the flow, the highest densities occur at intersection 2 and 4. According to literature (section 2.1), it is assumed that flow and density correlate, and thus it is assumed that the density is also influenced mostly by the presence of the escalator (or by the dimensions of the intersections, see explanation of the flow). Table 9.1 presents the densities categorized to level of service. As can be seen, for all intersections LOS C has the highest share (53-90%). For intersection 2 and 4, also LOS D has a large share (34-47%). Occasionally (<1%), LOS E is reached. However, if a smaller time window is considered, this share is expected to increase, meaning that for short time periods (less than 20 seconds) it can be more crowded (LOS E or even LOS F).

Table 9.1 Distribution of level of service (LOS) per intersection (in %)

Intersection	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
1	0	2.8	88.5	8.4	0.3	0
2	0	0	65.8	33.7	0.5	0
3	0	0.5	87.7	7.0	0	0
4	0	0	52.9	46.9	0.2	0

Average travel time

The average travel time of the population is lower at intersection 2 and 4. This is in line with expectations, since the length of the walking paths of the main flow, which are assumed to be approximately the same length as the widths of the intersections (see Table 5.1), are smaller.

If the average travel time is converted to speed (which is approximately equal to the distance/width of intersection divided by the travel time), this would yield approximately:

Table 9.2 Estimated average speed main flow (in m/s) per intersection

Intersection	**1**	**2**	**3**	**4**
Estimated average speed	1.30	1.18	1.35	1.26

Hence, it seems that there is a higher speed in the A corridor (intersection 1 and 3) and a higher speed at platform 18/19 (intersection 3 and 4). Since the width of intersection 1 and 3, and thus the path of the main flow, can vary quite a lot (between 4-6 meters, in contrast to 5 meters for intersection 2 and 4), it is tricky to draw conclusions about speed. However, the difference between intersections around platform 5/7 and 18/19 can be addressed.

Two assumptions regarding the difference between speeds around platforms can be made. The first assumption is the presence of the bus station at the Jaarbeurs side of the station (close to platform 18/19), which could yield a higher speed for passengers that need to make a transfer between train and bus and vice versa within a short transfer time. The second assumption is that there are more transfer passengers between trains passing platform 18/19 than passing platform 5/7.

Minimum travel time

The minimum travel time is equal to the fastest pedestrian for each observation. These pedestrians take approximately 0.90-1.40 seconds less travel time compared to the average pedestrian. If the average minimum travel time is converted to speed (as was done similarly in the previous subsection), this would yield:

Table 9.3 Estimated minimum speed main flow (in m/s) per intersection

Intersection	1	2	3	4
Estimated minimum speed	1.98	1.70	2.15	1.80

This results in similar trends, hence the same assumptions regarding the average travel time applies to the minimum travel time as well.

Conclusions

To conclude, a few trends can be identified:

- Both a higher flow and density is observed for intersection 2 and 4. It is assumed that the escalators at these intersections cause a higher inflow into the intersection, which yields a higher outflow of the intersection (until capacity is reached). According to pedestrian traffic flow theory, flow and density correlate, which explains that the trend occurs in both variables. Another factor that could explain the difference, are the different dimensions of the intersections. It is assumed that the dimensions influence the occupation of space and thus the flow dynamics. However, since this research has no insight in the occupation of space on a microscopic level (e.g. pedestrian paths, individual speed), more research including microscopic variables is required to measure this effect.

- For all intersections an average flow ratio of around 0.40/0.60 is observed. This either implies that higher flows are yielded because pedestrian traffic is handled more efficiently at these (balanced) flow ratios, or it is the result of the demand pattern at the intersection. It also has been observed that the flow ratio at intersection 1 and 2 is more clustered, and that intersection 3 and 4 shows more observations with higher flow ratios of 0.75-1.0. It is assumed that these differences are caused by different demand patterns, which depend on the location of the intersections (e.g. higher production/attraction around the intersection).
  At last, it is observed that intersection 3 has an average flow ratio of 0.60 compared to 0.40 at the other intersections. It is assumed the higher share of the main flow is the result of reduced crossing flows, which can be caused by an uneven distribution of demand from the platforms over the vertical infrastructure to the main hall (e.g. due to the stop position of the train along the platform).

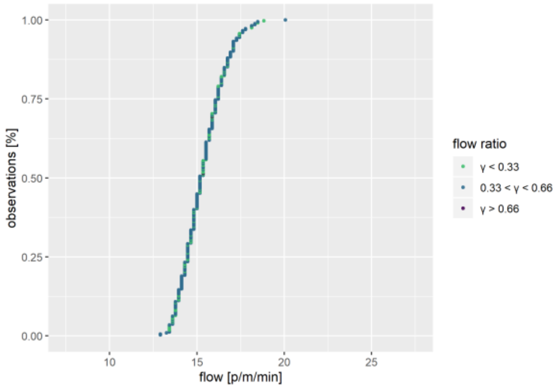
- Higher average and minimum travel times of the main flow are observed for intersection 1 and 3. This is in line with expectations, since the distances travelled, which are almost equal to the width of the intersections, are larger. More interestingly, lower travel times, thus higher speeds, are observed at intersection 3 and 4. It is assumed that higher speeds at these intersections are the result of a larger share of transfer passengers that need to make a connection between train and bus or train and train within a short amount of time.

9.2 Results capacity estimation methods

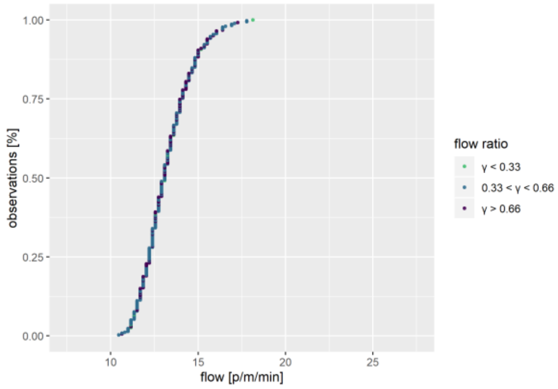
In the previous section, research variables were analyzed individually, and several trends could be identified. In the following subsections, the results yielded by the methods (as presented in section 8.3) will be analyzed, which is in all cases a combination of the previously studied variables. In the first two methods the influence of the flow ratio γ on the flow and density will be studied. For each method, we will check if the capacity is met according to its definitions.

Method 1: Maximum flow

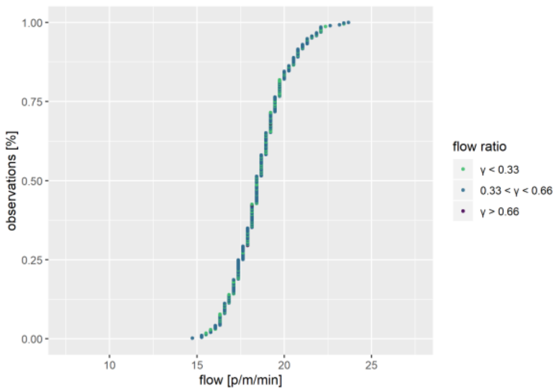
The first method states that the capacity flow q_c is equal to the maximum flow q_{max}. This method lacks the condition to verify that the actual capacity of the infrastructure is measured. However, it can measure the minimum flow capacity which the infrastructure can handle. Figure 9.2 illustrates the observed flows per intersection in increasing order, and in addition the flow ratio (colored) is shown. By looking only at the flow, a steady trend through the plot and a nod can be observed. This nod seems to represent some exceptional high flows.



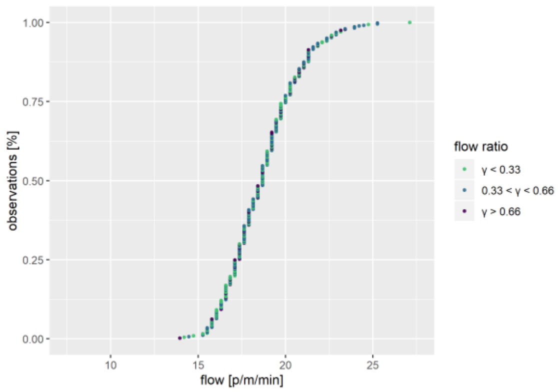
a. Intersection 1



b. Intersection 3



c. Intersection 2



d. Intersection 4

Figure 9.2 Maximum values for flow (q)

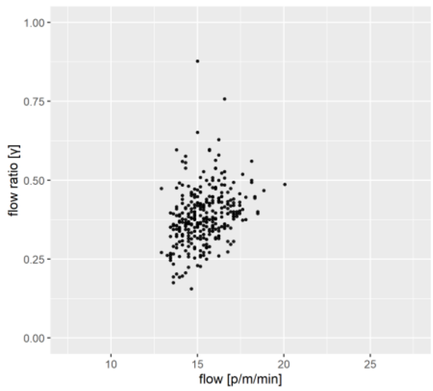
The flow ratio is categorized into three groups, a main flow between 0 and 33% $(\gamma < 0.33)$, a main flow between 33 and 66% $(0.33 < \gamma < 0.66)$ and a main flow between 66 and 100% $(\gamma > 0.66)$. By looking at the figure, the flow ratio seems scattered along the plot for all intersections, implying that the share of the main and crossing flow have no significant impact on decreasing/increasing the flow (at least not in these observations). Another observation that stands out is the different combination of flow and flow ratio at intersection 3 compared to the other intersections. As was pointed out in section 9.1, it seems that a demand pattern with a high share of crossing flow (i.e. lower flow ratio) yields a higher demand (due to the offloading of a train) and therefore a higher outflow. Hence, it is assumed that the demand pattern at intersection 2 and 4 are rather similar and differs between 1 and 3.

Table 9.4 presents the mean and standard deviation of the flow accordingly to the flow ratio bins. As can be seen, the middle bin contains the highest flows (except for intersection 1) and highest variation. This implies that a rather balanced share of both flows yields a higher outflow (which could be the result of the demand pattern).

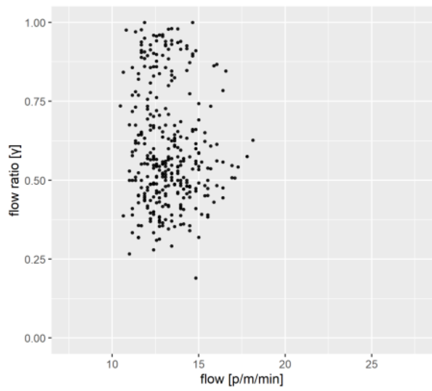
Table 9.4 Mean and standard deviation flow (q) for several bins of flow ratio (γ)

Intersection	$\gamma < 0.33$		$0.33 < \gamma < 0.66$		$\gamma > 0.66$	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	14.76	0.97	15.55	1.22	15.78	1.11
2	18.08	1.47	18.84	1.57	18.07	1.19
3	12.77	1.42	13.39	1.44	12.89	1.30
4	18.09	1.87	19.30	2.08	18.46	1.84

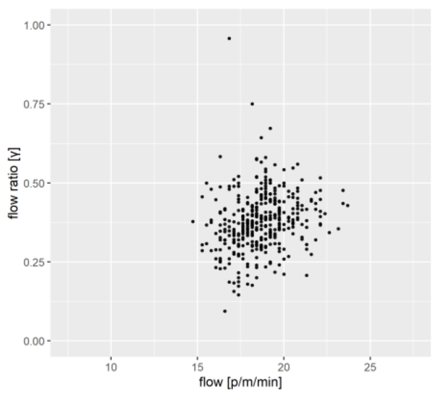
Figure 9.3 shows the relation between the flow and the flow ratio for all intersections. With respect to intersection 1 and 2, the highest flows seem to be centered around a flow ratio of 0.40 (40% share of main flow), which is quite in line with the observation in Table 9.4. In contrast to Figure 9.2, this either implies a trend (flow is handled more efficiently at a certain flow ratio) or as said earlier, it is the result of the demand pattern. However, the trend is quite vague, especially at intersection 3 and 4. Therefore no further conclusions will be drawn with respect to the influence of the flow ratio on the flow.



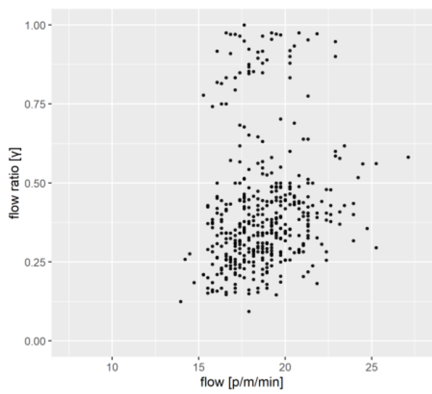
a. Intersection 1



b. Intersection 3



c. Intersection 2

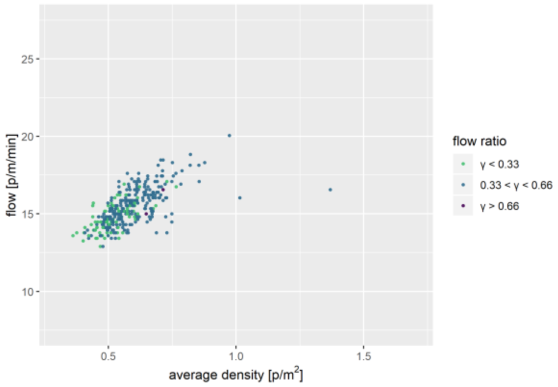


d. Intersection 4

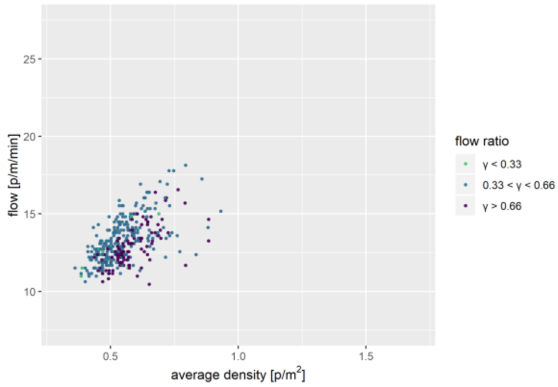
Figure 9.3 Relation between flow (q) and flow ratio (γ)

Method 2: Density – Flow

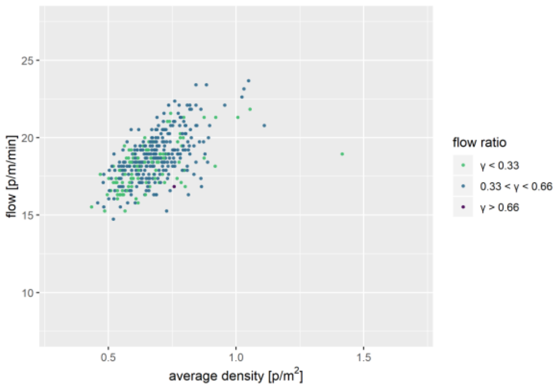
The second method is based on the capacity definitions of the fundamental diagram and states that the capacity flow q_c can be identified if both free flow and congested conditions are measured. Figure 9.4 show the flow-density relation per intersection, and in addition the flow ratio (colored) is shown. As can be seen, the flow and density are related, and a strong increasing trend and a slight decreasing trend can be observed. However, since there are almost no observations that confirm the decreasing trend (i.e. congested conditions), it is uncertain if the top of the flow-density curve can be identified. Hence, we conclude that the capacity flow cannot be identified in these measurements.



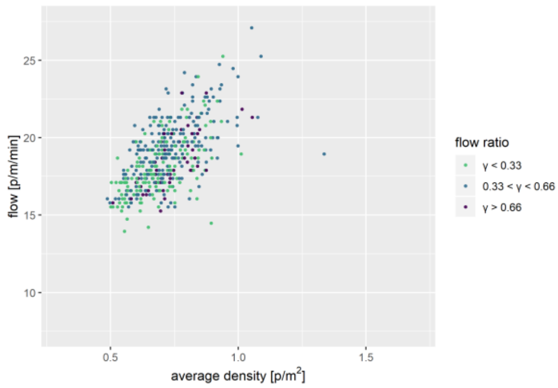
a. Intersection 1



b. Intersection 3



c. Intersection 2



d. Intersection 4

Figure 9.4 Relation between density (k) and flow (q)

Table 9.5 presents the mean and standard deviation of the density accordingly to the flow ratio bins. For each intersection the density increases as the flow ratio increases. This means that a higher share of main flow results in more pedestrians at the intersection. This could imply that the space at the intersection is used more efficiently for a high share of main flow (e.g. due to efficient self-organization, in which lane formation yield smaller headways).

Table 9.5 Mean and standard deviation density (k) for several bins of flow ratio (γ)

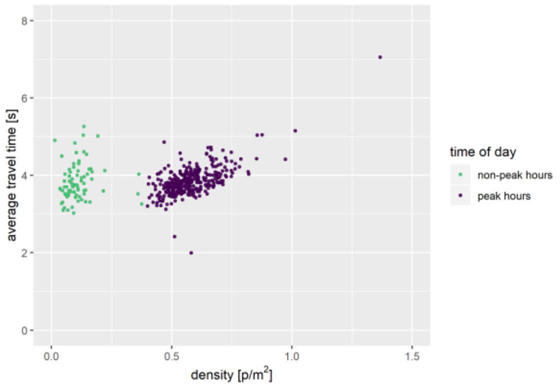
Intersection	$\gamma < 0.33$		$0.33 < \gamma < 0.66$		$\gamma > 0.66$	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	0.52	0.08	0.60	0.11	0.68	0.05
2	0.65	0.13	0.69	0.10	0.71	0.08
3	0.50	0.10	0.55	0.09	0.59	0.09
4	0.69	0.10	0.73	0.12	0.74	0.10

Method 3: Density – Travel Time

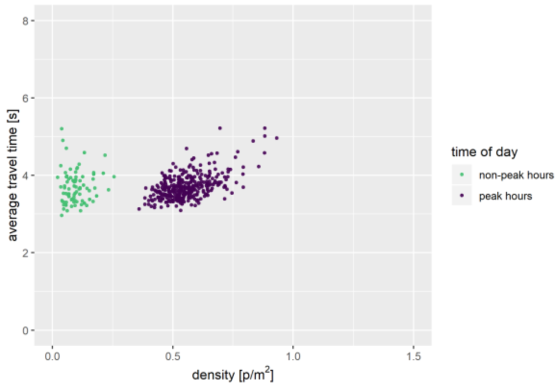
The third method hypothetically states that the capacity flow q_c is met at the threshold at which the travel time increases, and passengers start to experience delay. In this case, an increase in delay is expected after a certain threshold in density, which is defined as the capacity density (which is not necessarily the same capacity density as defined in Figure 2.3/Table 2.4). It is debatable whether a certain delay is acceptable (a certain acceptable delay yields a higher capacity density). Subsequently, the flow capacity can be determined from the density-flow relation (as presented in the results of method 2 in the previous subsection).

Both the average travel time of the pedestrians in the main flow, as well its fastest pedestrian (minimum travel time) is analyzed. Figure 9.5 presents the relation between the density and the average travel time and Figure 9.6 presents the density in relation to the minimum travel time. In addition, 100 observations outside peak hours are added to both figures to compare the potential differences in travel time between peak hours and non-peak hours (and thus between a population with assumed mostly commuters or others).

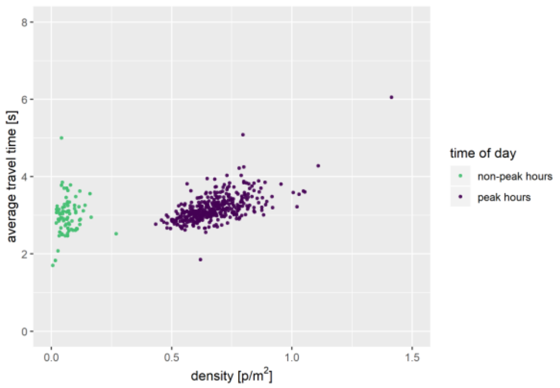
As can be seen in Figure 9.5, the observations showing the lowest average travel times slightly increase as the density increases. This trend is especially visible at intersection 1, 2 and 3 from a density of around 0.70 p/m^2 (at intersection 4 this seems to be around 0.90 p/m^2). This is in line with the description of level of service D by Fruin (1971), which states that the speed is restricted and reduced at a density of 0.71 p/m^2 or higher. The non-peak hours show a similar travel time at low densities in peak hours.



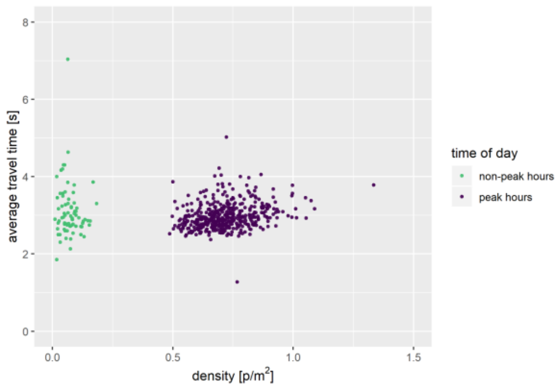
a. Intersection 1



b. Intersection 3



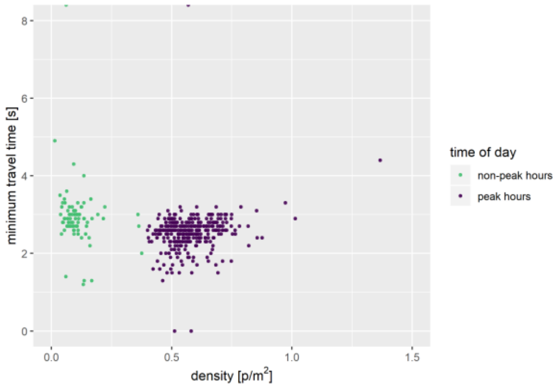
c. Intersection 2



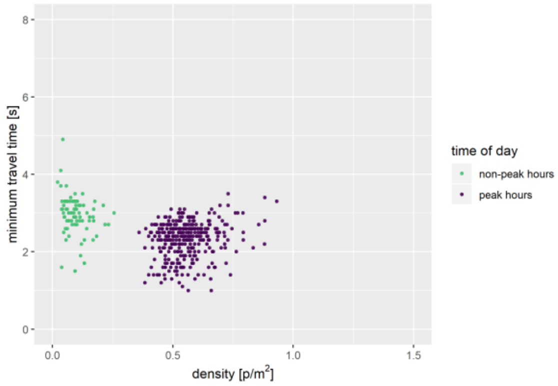
d. Intersection 4

Figure 9.5 Relation between density (k) and average travel time $(\overline{tt})$

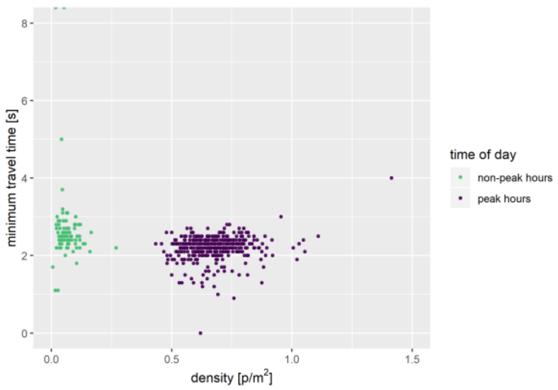
Figure 9.6 presents the minimum travel time (or fastest pedestrian) per observation in relation to the density. In this figure too, a trend is visible that the minimum travel time increases as the density increases. For intersection 1 and 3 this threshold seems to be around 0.70 p/m^2 and for intersection 2 and 4 it seems to be round 0.80 or 0.90 p/m^2. Compared to Figure 9.5, there is a clear difference between the fastest travel times within peak and non-peak hours, which could be due to the commuters who are known for travelling at a higher speed (see section 2.2).



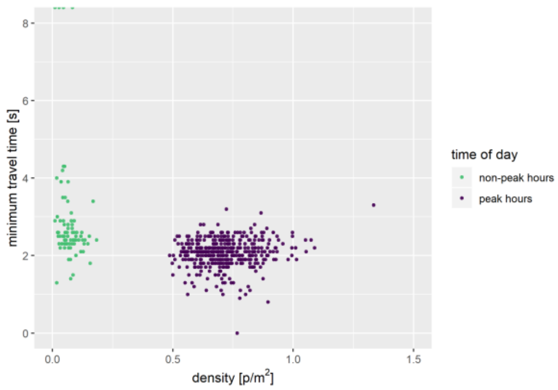
a. Intersection 1



b. Intersection 3



c. Intersection 2



d. Intersection 4

Figure 9.6 Relation between density (k) and minimum travel time ($tt_{\min}$)

For example, if no delay is accepted, the capacity density is determined at 0.70 p/m^2 for intersection 1, 2 and 3, and 0.90 p/m^2 for intersection 4. Subsequently, according to this method, the flow capacity can be retrieved from the flow-density relation (as presented in the results of method 2, previous subsection). This would approximately yield the following flow capacity range per intersection:

Table 9.6 Approximate capacity density and flow capacity range per intersection for $x = 0$

Intersection	**1**	**2**	**3**	**4**
Approximate capacity density (p/m^2)	0.70	0.70	0.70	0.90
Approximate flow capacity range ($p/m/min$)	13.5-17.5	16.5-21.5	12.5-16.0	20.0-25.0

The decision maker can decide (per intersection) on a certain flow capacity within this range. It should be kept in mind that each decision for a capacity standard within these ranges yield consequences of under or over dimensioning to a certain extent (as explained in section 8.3).

Conclusions

In the last section, the three capacity methods were evaluated. Accordingly, the influence of the flow ratio on the flow and density has been studied. A few conclusions can be drawn:

- The first method requires the measurement of flow. The capacity could not be identified, since this method lacks the condition to verify that the capacity is met. However, the measured flow could indicate the minimum flow capacity of the infrastructure.

- The second method requires the measurement of flow and density. This method is based on the capacity definitions of the fundamental diagram and states that the capacity can be identified if both free flow and congested conditions are measured. In this study, congested conditions have not been measured, which means that the flow capacity could not be identified. However, the flow-density relation was clearly visible, implying that this method is suitable for capacity estimations in this context/flow scenario.

- The third method requires the measurement of flow, density and travel time. This method states that the flow capacity of the infrastructure is met if a certain level of delay in terms of travel time is observed at a certain density threshold. It is debatable whether a certain delay is acceptable. In this study, it has been observed that the travel time increases from a density of approximately 0.70 p/m^2, which is in line with expected reductions in speed (or increase in travel time) at level of service D, as defined by Fruin (1971).

- Regarding the influence of the flow ratio on the flow and density, two conclusions can be drawn. The flow ratio and the flow seem to be determined by the demand pattern. This makes it difficult to study the relation between flow ratio and flow. A rather clear trend was identified in the relation between the flow ratio and the density, in which an increase in flow ratio means an increase in density. This could be explained by the fact that a high share of main flow (high flow ratio), means mainly a high share of bidirectional flow in the corridor, with little interference of a crossing flow. In case of a bidirectional flow, it is expected that more efficient self-organization takes place (e.g. lane formation), yielding lower headways and thus higher densities.

10 Conclusions, discussion and recommendations

This chapter is split up in three parts. First, the main findings are presented and the answer to the main research question is formulated (section 10.1). Second, the limitations of this research will be discussed, and the results will be put into perspective (section 10.2). At last, recommendations for science and practice are given (section 10.3).

10.1 Conclusions

The objective of this research is twofold: to gain insight into how the flow capacity of a pedestrian intersection at a railway station is influenced by several factors and to explore methods that can estimate the flow capacity of a pedestrian intersection. To structure the research, the following research question is posed:

Which factors theoretically influence the flow capacity of a pedestrian intersection at a railway station, and how can the flow capacity of a pedestrian intersection be estimated?

The literature study concluded that many factors influence pedestrian dynamics (and thus the flow capacity) and that the presence and strength of these factors depend on the context of the study (e.g. location, type of flow situation, composition of study population, type of study, etc.). Since the context in each study is quite specific, studies are often complex and difficult to compare.

To gain insight into how the flow capacity of a pedestrian intersection at a railway station is influenced by several factors, this study proposes a theoretical framework describing these relations based on the insights from other studies and practice. Since the context for each study differs, the relations within this framework are hypothesized and thus not yet verified. The framework is a starting point for this and future research regarding pedestrian intersections at railway stations and should be used as a tool scope the research and to verify and identify the strength of the relations.

The theoretical framework is presented in Figure 3.1 (page 21) and shows the hypothesized causal relations between the research topic - intersection flow capacity - and several variables that describe the context of this study (including pedestrian traffic, the flow situation, the infrastructure, pedestrian behaviour, trip purpose, trip state at the station, among others). In this research, the theoretical framework is mainly used to interpret the results of the field study.

In this study, three capacity estimation methods were proposed to estimate the flow capacity of a pedestrian intersection. To test their suitability, a field study was conducted at four intersections in the main hall of Utrecht Centraal station. The flow scenario at these intersections consist of a bidirectional main flow through the corridor connecting the main entrances and the platforms, and perpendicular to it a bidirectional crossing flow connecting the corridor with the platform through vertical infrastructure (either a staircase or escalator).

According to the field study, the second and third method both seem suitable for capacity estimations, even though the intersection flow capacity (according to the traffic flow principles) could not be estimated in this study. Depending on the accepted level of delay, the third method was able to determine a range of capacity flows at a certain capacity density. Both methods seem suitable for capacity estimations, because they have conditions to verify that the capacity is met. This is lacking in the first method; however, the first method could give an indication of the minimum flow capacity which the infrastructure is able to handle. Furthermore, the second method shows a clear flow-density relation, implying that it should be able to estimate the intersection flow capacity if congested conditions are measured.

In addition to testing these methods, the flow ratio was measured to study its effect on the intersection flow capacity. Implicit in the formulation of the knowledge gap (section 1.2), we asked the question; how is the flow capacity of a pedestrian intersection different from, for example, a corridor (i.e. unidirectional and bidirectional flows)? Since the intersection flow capacity (according to traffic flow principles) has not been measured, instead the flow-flow ratio relation and the density-flow ratio relation was studied.

No clear relation could be identified between the flow and the flow ratio. The flow ratio and the flow seemed to be strongly determined by the demand pattern around the intersection, which excludes the possibility to study its effect on the flow. However, a rather clear trend was observed in the density-flow ratio relation, in which an increase in flow ratio means an increase in density. It is expected that a high share of main flow (i.e. a high share of bidirectional flow in the corridor) and thus little interference with the crossing flow yield more efficient self-organization (i.e. due to lane formation, lower headways and thus higher densities are achieved).

10.2 Discussion

In this section, several aspects of this research will be discussed, and the research will be put into a broader perspective. The topics for discussion include a reflection on the theoretical framework, the chosen capacity estimation methods, decisions regarding data processing and limitations of computational power.

Generalization of the theoretical framework

The theoretical framework proposed in this research regards the flow capacity of a pedestrian intersection in the context of a railway station. To which extent can this framework be used in other railway stations and other contexts (e.g. at a shopping mall, street, event)?

This framework mainly describes general relations between pedestrian traffic, pedestrian behaviour, and environmental factors, which could be found in any context. In each context, the most general variables within the framework will be present to a certain extent, and it is assumed that the causal relations do not vary (e.g. the age of a pedestrian directly influences the individual speed in any context). Therefore, the framework can be applied to pedestrian intersections with a similar flow scenario in other contexts as well, including other intersections at Utrecht Centraal station, other stations within and outside the Netherlands, but also in a shopping mall, a street or an event.

Also, the intersection variables allow for different flow scenarios of intersecting flows (section 2.5). However, for both other contexts as well as flow scenarios, the researcher must critically look at the factors that are (not yet) included and which factors apply to the context of the respective study.

The typical factor for a railway station is the *trip state at the station*, which includes *arriving, departing, transferring and waiting*. Especially *transferring and waiting* applies to transfer ('knooppunt') stations, or stations with transfer connections to other public transport services and will not be present in stations with only a production/attraction function. The trip state at the station factor does not apply to another context, but then other factors might be important and need to be included (e.g. floor type, sound or lighting).

Furthermore, this framework does not include variables to describe pedestrian flows interfering with other traffic, such as bicycles or motorized vehicles. Hence, currently the framework is not applicable to mixed traffic intersections.

Suitability capacity estimation methods

As was mentioned in the conclusions (section 10.1), the main advantage of the second and third method is that they can verify that the capacity is met, and thus they are both suitable for capacity estimations.

The third method can be regarded as an extension of the second method, since they both measure the flow and density. The disadvantage of the third method is that it requires to measure travel times of individual pedestrians as well, which is a microscopic variable and demands more extensive calculations. However, this method does allow to determine capacity standards based on the performance indicator delay, which may be a more suitable performance indicator for a train station rather than capacity standards based on traffic flow principles.

Despite the fact that the first method lacks the ability to do capacity estimations, the main advantage of this method is that it only requires to measure the flow, which means that it is quite suitable for quick calculations for the evaluation of a piece of infrastructure or for determining its minimal capacity.

Improvement capacity estimation methods

For the testing of the capacity estimation methods in this study, the selection criterion for the samples was the highest flows (data processing, chapter 7). This is a suitable criterion for the first method, since it only considers measuring the flow.

For both the second and especially the third method, (additionally) a selection based on the highest densities could possibly give more valuable insights for capacity estimations, since it reveals the congested conditions. This study concluded that the flow capacity (according to traffic flow principles) could not be identified. If a capacity drop (section 2.4) would have been typical for the intersections analyzed in this study, selecting on congested conditions could show this effect. However, it is not likely that this was the case in this study due to the rather low densities.

Measuring the effect of the flow ratio on the flow capacity

In this study it was difficult to evaluate the relation between flow and flow ratio, since they both seem to be determined by the demand pattern. To properly study the influence of the flow ratio on the flow (capacity), the research variables should be controlled.

Wong et al. (2010) did a similar, but experimental study, hence they were able to control the research variables. The density was fixed and the flow ratio (they called it density ratio) was varied. They were able to measure the intersection capacity for several flow ratios and intersection angles.

It should be possible in a field study as well to measure the effect of the flow ratio on the flow (capacity). However, it requires to search for the same set of flow situations (with specific combinations of densities, flow ratios, etc.) as would be produced by an experiment. The main drawback of a search method would be that it requires the analysis of a lot of data for these combinations of variables before selecting them. This might be a heavy computational task. Also, if certain level of densities or flow ratios are not present in the field data, the dataset might not be complete to do a proper evaluation.

Excluding the limits of computational power or time

As was mentioned in section 5.3, the high level of detail in the data results in a lot of data available for this research. Since this study was restricted by time and computational power, a selection process in the data processing method preceded the data analysis. The drawback of a selection process is that valuable information may be left out of the selection. If there was no constraint regarding computational power or time, how would the data processing be different, and could this have yielded different results?

The data processing could be different in multiple ways. If we would consider the same context (i.e. weekdays, peak hours) for the same year, for the first selection approximately 61.200 one-minute observations per intersection could be studied, compared to 300-400 observations in the original study. If the analysis is proceeded in the same way, this would most likely result in a wider range of flows, densities, travel times and flow ratios. Also, it is likely that higher flows would be measured, since the highest flows within 20 seconds are not necessarily stored within the highest flows for one-minute observations. In this way, the results could reveal more information, including (potentially) the intersection flow capacity (based on either method 2 or 3).

Also, with no computational limit, a more elaborate analysis could be performed to study the effect of the flow ratio on the flow (capacity). As was described in the previous study, this would require a search method for combinations of the research variables in which the datasets of an experimental study can be mimicked.

10.3 Recommendations

In this section, several recommendations for both science and practice will be given. These recommendations are based on the conclusions and discussion of this chapter and on questions that arose during this project.

Recommendations for science

- **Selection criteria:** For the application of the second and third method it is necessary to measure congested conditions as well. Observations based on the highest densities should be included in addition to the highest flows.

- **Computational power and sample size:** If computational power or time is no constraint, it is recommended to avoid a preselection based on aggregate data to prevent removing valuable information. Instead of determining a (minimum) sample size, as was done in this research, the samples could also be selected by selecting all observations with a certain flow and density level and higher. Depending on the research objective (e.g. studying commuters), part of the preselection maintains (e.g. selecting only peak hours).

- **Pedestrian dynamics on a microscopic level:** This research mainly studied pedestrian dynamics on a macroscopic level. In the literature study, many insights were obtained by looking at the pedestrian dynamics on a microscopic level. To increase the understanding of pedestrian dynamics at intersections, it is recommended to obtain insight into pedestrian behaviour (e.g. lane formation, decelerating, accelerating, stopping and detour behaviour). For this, trajectories and individual speeds should be studied.

- **Flow scenario:** In this study, six origin-destination pairs (see arrows in Figure 5.4) at the selected intersections were categorized to either a main flow (bidirectional flow in the corridor) or a crossing flow (flow from/to platform merging with the main flow). As Wong et al. (2010) showed, different angles of intersecting flows yield different capacities. It is expected that there is a different impact on the flow dynamics by flows that merge or cross with the main flow. Hence, for further research it is recommended to distinguish between crossing and merging flows and study their influence on the flow dynamics at the intersection separately.

- **Time windows:** It could be interesting to perform a sensitivity analysis with regards to the length of the time window. As mentioned in section 8.2, the selection of a suitable time window is based on a trade-off between a good representation of congested conditions and a good representation of the system (which includes the on- and offloading of peaks as well). Based on this knowledge, a selection of time windows with a length between 15 and 30 seconds remained to choose from and eventually a time window of 20 seconds was selected. It is unclear how, for example, 15 or 30 seconds might have yielded different results and thus a sensitivity analysis is recommended to obtain these insights.

- **Capacity estimation method 4:** The methods in this study only regard the outflow of the intersection. Hence, information on the demand pattern (the inflow) was left out. In this study, the demand pattern was assumed to be a determinative factor in the level of measured outflow at the intersections. Therefore, it is recommended to look into the relation between the demand pattern and the outflow. This relation can be studied by the cumulative curves method (as explained in section 2.7), in which the cross-sections can be studied separately as well. It is recommended for both future research as well as NS to evaluate this method. Based on the insights yielded by this method, potentially NS can predict the handling of flow or the intersection capacity based on the expected demand pattern (which can be estimated in advance by a static analysis).

Recommendations for practice

- **Expand the static analysis with route choice information:** A static analysis is a useful tool for NS to identify potential bottlenecks in their stations. The static analysis in this study was based on smartcard data. Only the estimations for the demand close to the entrances were expected to be rather accurate, since information was available on the check-ins/outs per gate. To identify potential bottlenecks more accurately, the static analysis could be expanded with insights into route choice from models such as SMART station. In this way, other potential bottlenecks than the intersections between the corridors and platforms can be identified. This could reveal other flow situations to be worth researching, for example intersections between corridor and (popular) shops or intersections at corridors and a path through the area (especially if the main/transferring flow is delayed by these intersections).

- **Experimental or simulation study:** In field studies like these, it could occur that the demand is never high enough to do enough measurements for a proper capacity estimation. It could be valuable to perform or find an experimental or simulation study for a similar flow situation, in which the demand can be pushed until capacity level. In this way, capacity estimations can be made for the flow situation at the station. Another advantage of an experimental/simulation study is that variations in the lay-out of the experimental set-up can provide insights into the differences between the intersections at Utrecht Centraal station and other stations, and thus provide insight into the generalizability of the results. A drawback of comparing field and experimental/simulation studies, is that often it is difficult to exactly mimic the real situation. Not all factors that have a significant influence are directly visible and could be left out of scope accidentally. Also, both an experimental and simulation study are costly and time consuming.

Currently, at NS a distinction is made between the capacity that indicates self-reliance ("zelfredzaamheid") and comfort, which indicates the level of crowdedness for acceptable safety risks and the level of crowdedness in which pedestrians can walk undisturbed respectively (see section 1.1).

Depending on the chosen performance indicator to evaluate a station's capacity, the second method of this research is more suitable if it is desired to define capacity standards based on traffic flow principles, and the third method is more suitable if it is desired to define capacity standards based on the accepted level of delay. Are these methods suitable for the self-reliance and comfort standards currently in use at NS?

- **Standards for self-reliance:** Regarding safety risks, generally standards are based on acceptable level of densities. However, it depends on the distribution of the density across the (intersection) area if safety issues arise. Safety issues are expected to arise when congestion (higher densities) is closer to the vertical infrastructure, especially when it is close to the outflow (downstream) of an escalator. Therefore, self-reliance capacity standards for intersections, especially in combination with vertical infrastructure, should be based on the local densities at an intersection (rather than the average density). It is recommended to gain insight into the local densities and study its relation to the average density. If an accepted level of local densities yields at most a certain average density, this average density could be used as a standard with a corresponding capacity flow.

- **Standards for comfort:** Regarding situations in which pedestrians can walk undisturbed, the third method of this research could be a suitable method or starting point. In this study, the method only regards the travel time of the pedestrians of the main flow. The method could be expanded by looking at the travel times of the crossing/merging flows. Also, the performance indicator 'in which pedestrians walk undisturbed' could be expressed by pedestrian detour, decelerating and stopping behaviour (per origin-destination pair) at the intersection. For this, the speed and trajectories of the pedestrians should be studied for several flow/density conditions at the intersections.

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Appendix A Scientific paper

Estimating the Flow Capacity of Pedestrian Intersections at Railway Stations

A field study at Utrecht Centraal station

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Abstract

Understanding pedestrian traffic is essential to design for safe and reliable pedestrian infrastructures, facilities and operations. For the assessment and design of pedestrian transfer areas at stations capacity standards for uni- and bidirectional flows are applied. It has been observed that, at railway stations, also other configurations of flows occur, such as intersecting flows at different angles (e.g. intersections between transfer areas and stairs/escalators or shops). In contrast to uni- and bidirectional flows, for which many researches have quantitively studied the pedestrian flow characteristics, only little research has been done to intersecting flows.

The purpose of this research is to gain insight into how the flow capacity of a pedestrian intersection at a railway station is influenced by several factors and to explore methods that can estimate the flow capacity of a pedestrian intersection. A theoretical framework has been constructed that shows the hypothesized causal relations between the research topic - intersection flow capacity - and several variables that describe the context of this study. Furthermore, three capacity estimation methods were proposed to estimate the flow capacity of a pedestrian intersection. According to the field study, the second and third method both seem suitable for capacity estimations, even though the intersection flow capacity (according to the traffic flow principles) could not be estimated in this study. Several recommendations have been made for future research, including points of improvement regarding the the studied methods, directions for research focus and the usability of the findings in this study.

I. Introduction

For the assessment and design of pedestrian transfer areas in stations, Dutch railway operator NS ("Nederlandse Spoorwegen") applies capacity standards for uni- and bidirectional flows. These standards regard the flow capacity and is expressed as maximum flow or throughput, which is the number of pedestrians that pass a certain cross-section within a certain time frame.

It has been observed that, at railway stations, also other configurations of flows occur, including two or more flows that intersect at different angles. The current capacity standards at NS, based on the fundamental traffic flow relations for uni- and bidirectional flows, are not applicable to intersecting flows. Hence, using these standards result in unreliable capacity estimations. Without reliable capacity estimations, a certain performance of the transfer area, mostly defined and measured by the level-of-service (LOS), cannot be guaranteed. In response to this problem, NS has expressed the need for capacity estimations at transfer areas in their stations where flows intersect, in order to determine reliable capacity standards.

In contrast to uni- and bidirectional flows, for which many researches have quantitively studied the pedestrian flow characteristics, only little research has been done to intersecting flows (Duives, 2016). The purpose of this research is to gain insight into how the flow capacity of a pedestrian intersection at a railway station is influenced by several factors and to explore methods that can estimate the flow capacity of a pedestrian intersection. For this purpose, both a literature study as well as a field study will be conducted.

This paper is structured as follows. In section II a literature study is given, which is followed by the construction of a theoretical framework. In section III, the methodology of the field study is described, and the capacity estimation methods are proposed. The results of the field study are presented in section IV. In section V conclusions will be drawn and recommendations for future research will be given.

II. Literature study: Theoretical framework

Literature study

Regardless of the context (e.g. flow scenario, location, composition of study population, type of study, etc.), pedestrian dynamics can be described by macroscopic and microscopic traffic variables. These variables are generic and are fundamentally related. Figure A.1 shows a conceptual representation of the fundamental diagram for the flow-density relation, in which both the uncongested conditions (left of capacity density) and the congested conditions (right of capacity density) can be seen.

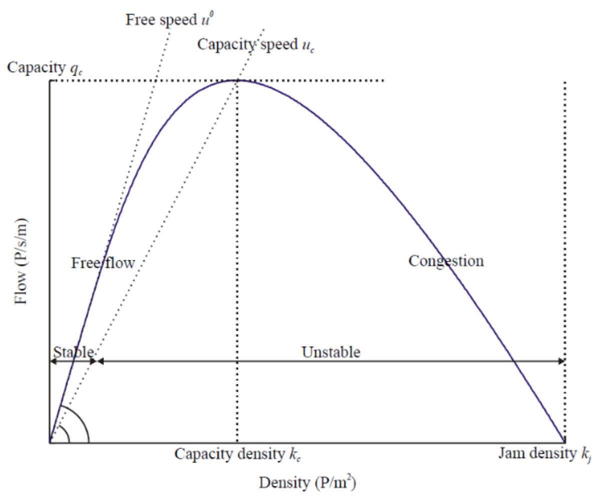


Figure A.1 Conceptual flow-density relation for pedestrian traffic flows (Daamen, 2004)

Despite the fundamental relation between these variables, it is questionable whether the results of a study are specific or can be generalized to a certain extent. Literature (Buchmüller & Weidmann, 2006; Daamen, 2004; Hu et al., 2019; Plaue et al., 2011; Vanumu et al., 2017; Weidmann 1993; Wong et al., 2010; Zhang, 2012; Zhang & Seyfried, 2014) shows that many factors influence pedestrian dynamics, in which the presence and strength of the factors is determined by the context of the study.

Figure A.2 (page 71) displays an overview by Daamen (2004) of both personal as well as external factors that influence the fundamental diagram (based on various sources). These factors include socio-demographic factors such as age, gender and difference in culture, but also travel purpose and walkway attributes, such as the type of infrastructure.

It must be noted that this literature study is limited, since more aspects regarding pedestrian theory can be considered. Nevertheless, it aims to give a basic understanding and addresses, to the knowledge of the author, the most relevant aspects for this research.

Theoretical framework

Based on verified relations and insights from literature and practice, a theoretical framework has been constructed for pedestrian intersections at railway stations. The aim of the theoretical framework is to give an overview of the research topic and the related variables that describe the context of this research. Basically, it attempts to draw the full picture of the considered situation. In general, a theoretical framework is meant to be used as a tool to scope the research and to verify and identify the strength of the relations.

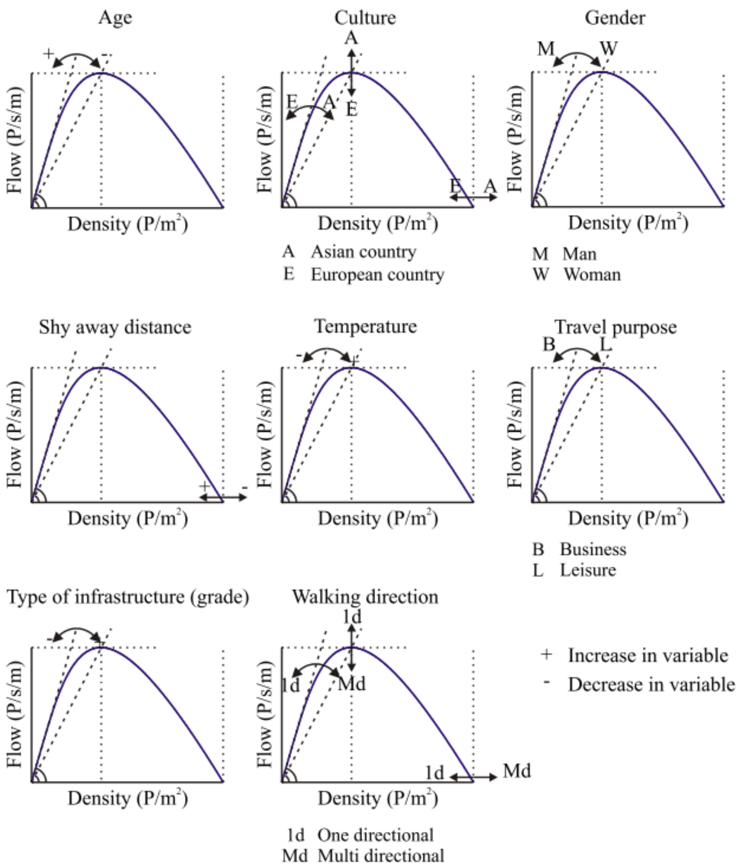


Figure A.2 The influence of personal and external factors on the fundamental diagram (Daamen, 2004)

The theoretical framework is presented in Figure A.3 (page 72) and shows the hypothesized causal relations between the research topic and several variables. The research topic in this framework is the intersection capacity, which is expressed as flow. It is assumed that the other variables in the theoretical framework (indirectly) influence the intersection capacity to a certain extent, as indicated by arrows.

The foundation of the framework consists of microscopic and macroscopic traffic variables that are used to describe traffic conditions (including the intersection capacity). The context is described by several factors relating directly or indirectly to the traffic variables. It is assumed that the flow scenario (intersection variables), the traffic conditions (macroscopic variables) and pedestrian objectives and abilities together determine pedestrian behaviour. Pedestrian behaviour and other factors, such as physical characteristics and travel purpose, directly influence microscopic variables such as velocity and headway. In turn, these microscopic variables determine the aggregate conditions (macroscopic variables), and thus the intersection capacity.

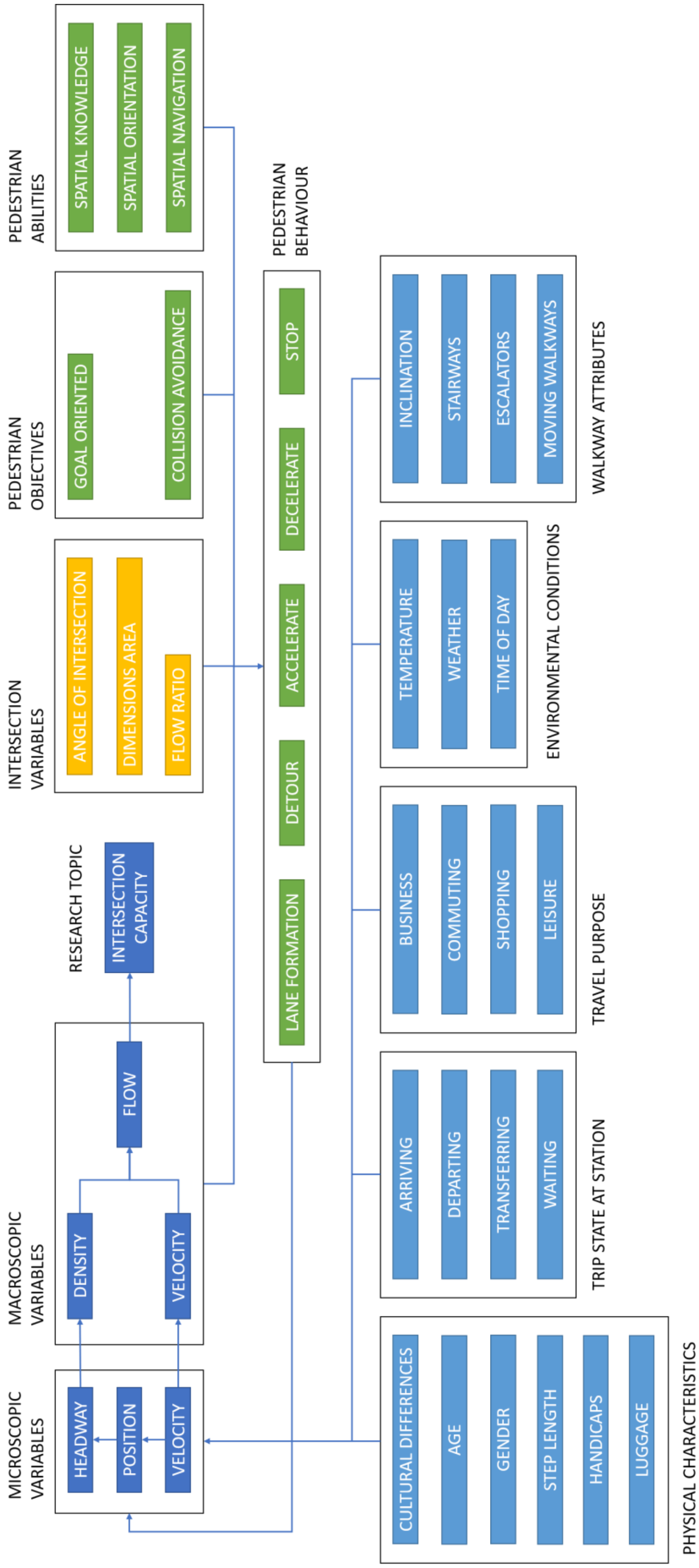
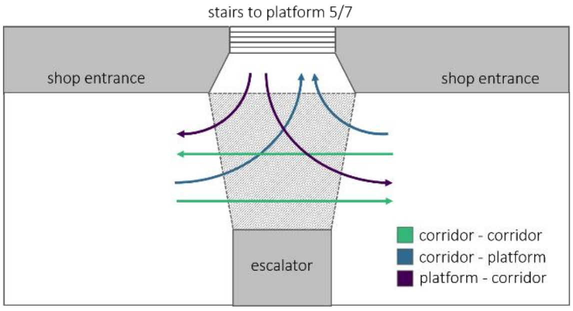


Figure A.3 Theoretical framework

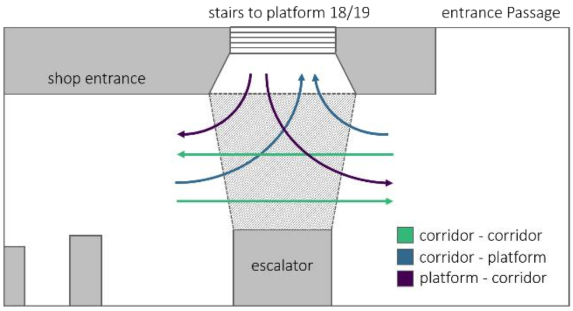
III. Field study: Capacity estimation methods

Selected intersections

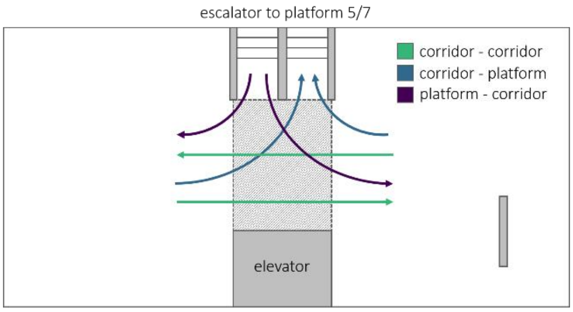
In this study, three capacity estimation methods were proposed to estimate the flow capacity of a pedestrian intersection. To test their suitability, a field study was conducted at four intersections in the main hall of Utrecht Centraal station. The flow scenario at these intersections consist of a bidirectional main flow through the corridor connecting the main entrances and the platforms, and perpendicular to it a bidirectional crossing flow connecting the corridor with the platform through vertical infrastructure (either a staircase or escalator). The selected intersections and the flow scenario are shown in Figure A.4.



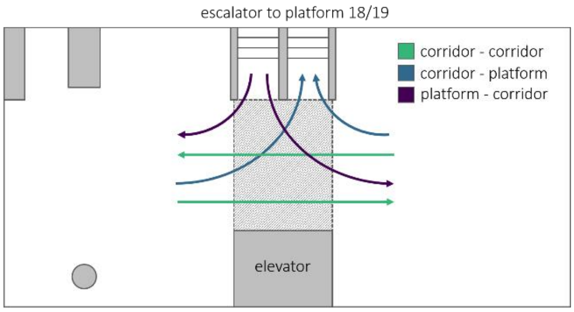
a. Intersection 1



b. Intersection 3



c. Intersection 2



d. Intersection 4

Figure A.4 Flow situation at the selected intersections

Data collection method

In this study, datasets were analysed that were collected by NS using advanced pedestrian counting technology, Pedestrian Analytics System (PAS), provided by Swiss company ASE. PAS is capable of tracking individual pedestrians anonymously by overhead sensors, by accurately measuring their path (trajectory). In turn, the trajectory data enables the researcher to asses walking speeds and directions, densities and flows.

The datasets have a high level of detail, which has a big advantage. That is, it captures the movement of pedestrians at a high level of detail, and thus contains a lot of information. This enables researchers to derive many microscopic as well as macroscopic variables, for very specific locations and time frames. The drawback of this level of detail is that the analysis can become a computationally extensive task due to the size of the comprehensive dataset. To both maintain the possibility to add a high level of detail to the analysis (without losing information) and to limit the computational burden, an efficient selection process is essential.

Data processing method

The selection process applies to peak hours, which is chosen to minimize the effect of several differences between travel purposes and time of day, and to consider the busiest periods (and thus the highest flows) at the station on a regular basis. Therefore, the selection was based on peak hours (07:00-09:00 and 16:00-18:00) on weekdays (Monday to Friday) for one year of PAS data (01-10-2018 till 30-09-2019).

Figure A.5 presents the research flow chart, which describes the research steps for the preparation of the data for the field study. The flow chart describes the steps to select and retrieve samples for each intersection from the processed PAS data. This data is more aggregated, which yields a lower computational effort, and still gives a good insight into the observations in terms of flow. After samples for each intersection have been selected, the raw PAS data (i.e. trajectory data) was used for the actual data analysis.

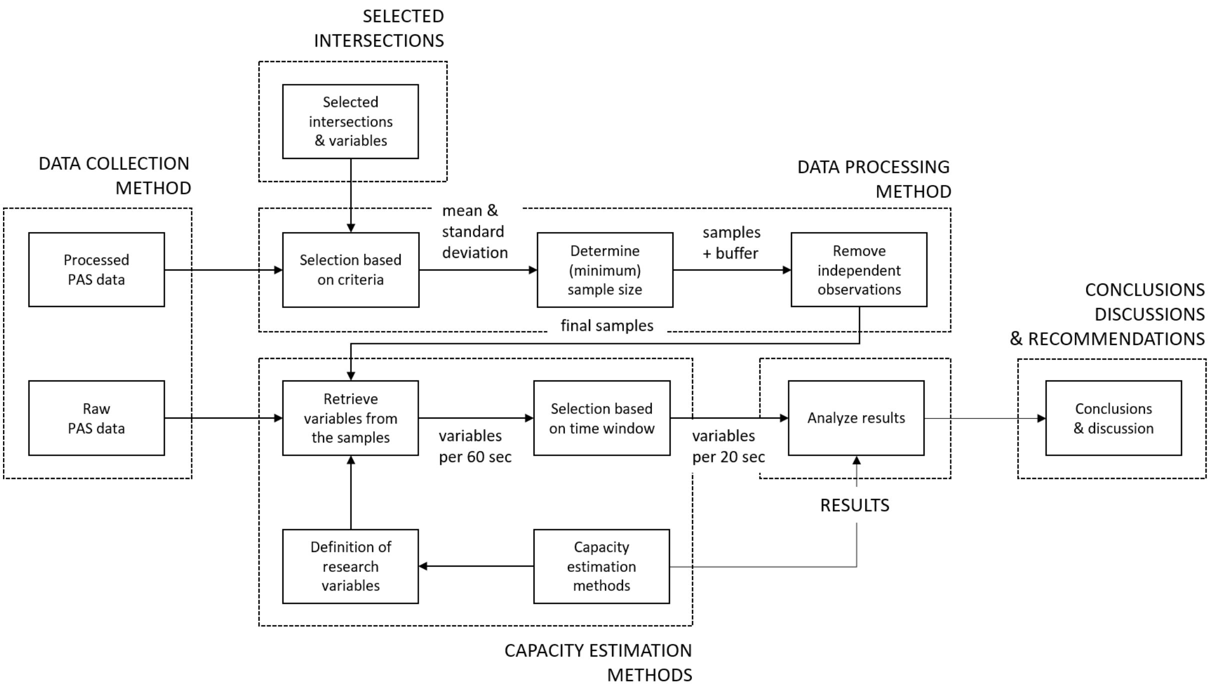


Figure A.5 Research flow chart describing the research steps

Capacity estimation methods

The three capacity estimation methods proposed in this study are based on previous research and general pedestrian traffic engineering principles. The methods describe how the capacity flow q_c is achieved, and which conditions should be met to verify that the capacity threshold is reached.

Method 1: Maximum flow

The first method is most straightforward. It states that the capacity flow q_c is equal to the maximum flow q_{max} within the observed sample of size N and is determined by:

$$q_{max} = \max(q_{n=1} : q_{n=N})$$

This method lacks the possibility to verify that the capacity flow is met, therefore no condition is presented to do so. However, this method can indicate the minimum capacity that can be handled by the infrastructure.

Method 2: Density – Flow

This method is based on the fundamental diagram (as illustrated in Figure A.1) and visualizes the relation between the density k and the flow q. The relation is visualized by a curve (as derived from the results, which initially is a scatterplot), in which the flow increases as the density increases to capacity density k_c and decreases between the capacity density and the jam density k_j, indicating free and congested traffic conditions respectively (see Figure A.1).

In this method, the curve indicates the capacity flow q_c at the highest point (k_c,q_c), on the condition that the curve has a parabolic shape. This condition is met if the observations n within the sample of size N show both an increasing trend as well as a decreasing trend. In order to indicate the capacity flow q_c, the majority of observations must comply with:

$$q_n < q_c \quad \wedge \quad k_n < k_c \quad n \in N \quad (increasing\ trend)$$

$$q_n > q_c \quad \wedge \quad k_n > k_c \quad n \in N \quad (decreasing\ trend)$$

Method 3: Density – Travel time

The third method hypothetically states that the capacity flow q_c is met at the threshold at which the travel time increases, and passengers start to experience delay. In this case, an increase in delay is expected after a certain threshold in density (according to Fruin, 1971). It is debatable whether a certain delay (increase in travel time) is acceptable, which could yield a higher capacity density (and thus a higher capacity flow).

After determining the capacity density, subsequently the flow capacity can be determined from the density-flow relation as was studied in method 2. Since the flow-density relation is initially a scatterplot, the chosen capacity density yields a range of capacity flows. It should be kept in mind that each decision for a capacity standard within this range yield consequences of under or over dimensioning of the infrastructure to a certain extent. Under dimensioning happens if a low capacity flow is selected from the range (the risk increases that the demand exceeds the capacity more often), and over dimensioning happens if a high capacity flow is selected. The decision maker can decide (per intersection) on a certain flow capacity within this range.

In this method we look at the relation between the density k and average travel time $\overline{tt}$ of the pedestrians that cross the intersection during time period Δt. We do the same comparison for the density k and the minimum travel time $tt_{\min}$.

The capacity density k_c is met if a trend occurs in which the *minimum* average travel time $\min(\overline{tt})$ for a certain density k_i increases (with x percent, in which x is the accepted level of delay as determined by the decision maker). Here, subset I represents bins i of densities k within the sample of size N. The same condition applies to the comparison with the minimum travel time. The condition is met if from a certain density bin k_i the observations comply with:

$$\min(\overline{tt}(k_i)) - \min(\overline{tt}(k_{i=1}) \colon \overline{tt}(k_{i=I})) > 0 + x \quad i \in I \quad (average\ travel\ time)$$

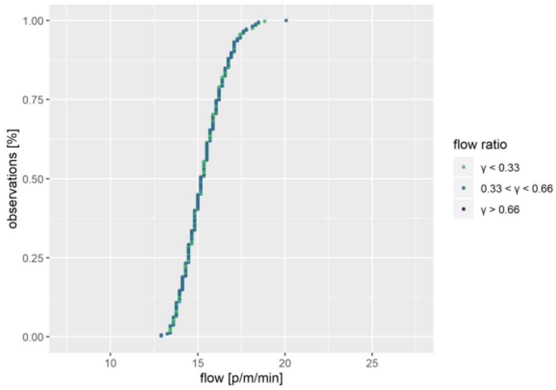
$$\min(tt_{min}(k_i)) - \min(tt_{min}(k_{i=1}) \colon tt_{min}(k_{i=I})) > 0 + x \quad i \in I \quad (minimum\ travel\ time)$$

IV. Results

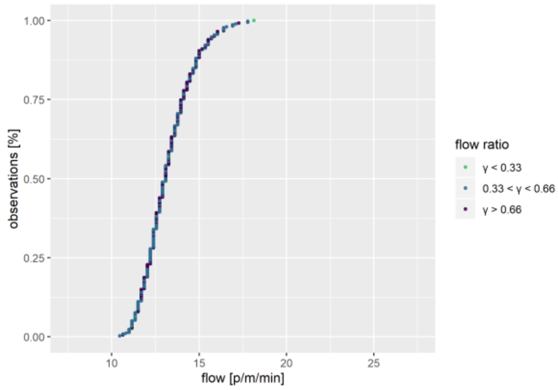
The results yielded by the methods (as presented in section II) are presented in this section. In addition, an analysis of the influence of the flow ratio γ on the flow and density can be found at the end of this section. For each method is checked if the capacity is met according to its definitions.

Method 1: Maximum flow

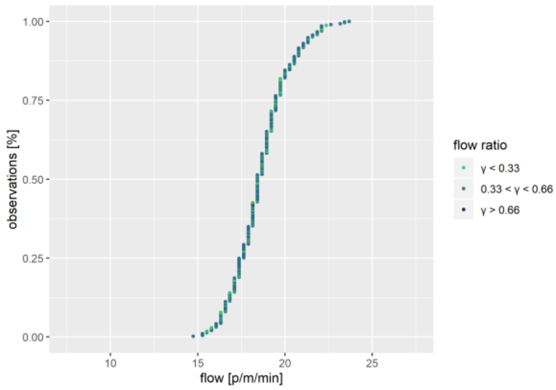
Figure A.6 illustrates the observed flows per intersection in increasing order, and in addition the flow ratio (colored) is shown. By looking only at the flow, a steady trend through the plot and a nod can be observed. This nod seems to represent some exceptional high flows. The capacity could not be identified, since this method lacks the condition to verify that the capacity is met. However, the measured flow could indicate the minimum flow capacity of the infrastructure.



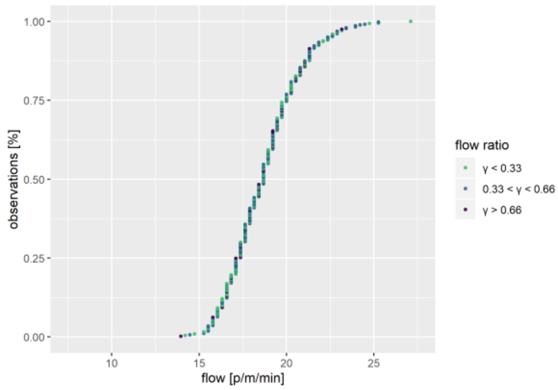
a. Intersection 1



b. Intersection 3



c. Intersection 2

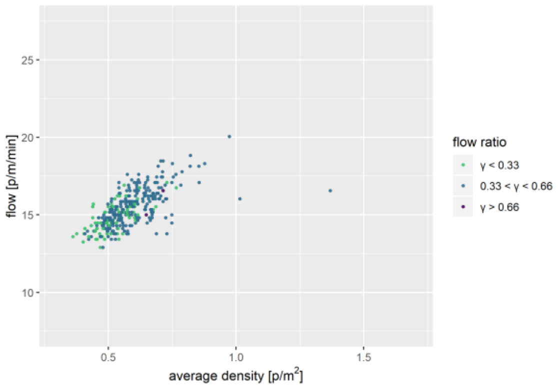


d. Intersection 4

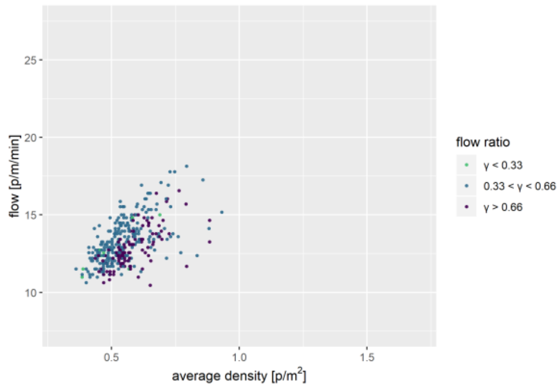
Figure A.6 Maximum values for flow (q)

Method 2: Density – Flow

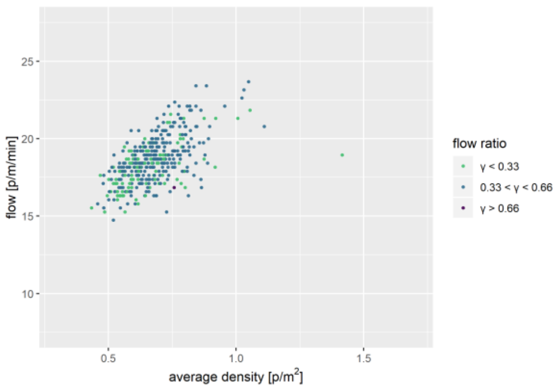
Figure A.7 show the flow-density relation per intersection, and in addition the flow ratio (colored) is shown. As can be seen, the flow and density are related, and a strong increasing trend and a slight decreasing trend can be observed. However, since there are almost no observations that confirm the decreasing trend (i.e. congested conditions), it is uncertain if the top of the flow-density curve can be identified. Hence, we conclude that the capacity flow cannot be identified in these measurements. However, the flow-density relation was clearly visible, implying that this method is suitable for capacity estimations in this context/flow scenario.



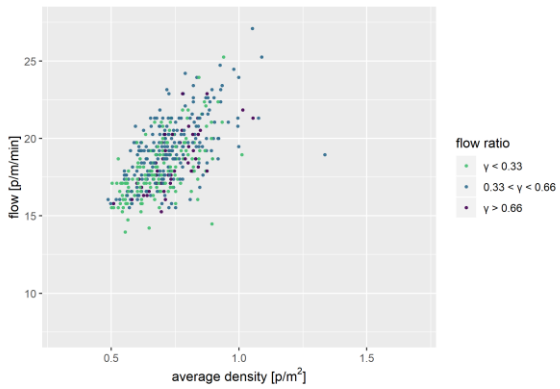
a. Intersection 1



b. Intersection 3



c. Intersection 2



d. Intersection 4

Figure A.7 Relation between density (k) and flow (q)

Method 3: Density – Travel time

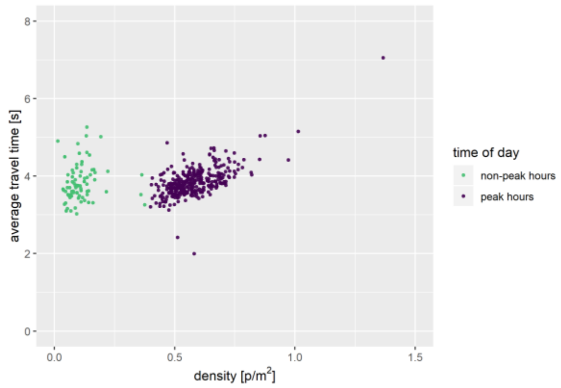
Figure A.8 presents the relation between the density and the average travel time and the density in relation to the minimum travel time. It can be observed that the travel time increases from a density of approximately 0.70 p/m^2, which is in line with expected reductions in speed (or increase in travel time) at level of service D, as defined by Fruin (1971).

For example, if no delay is accepted, the capacity density is determined at 0.70 p/m^2 for intersection 1, 2 and 3, and 0.90 p/m^2 for intersection 4. Subsequently, according to this method, the flow capacity can be retrieved from the flow-density relation (as presented in the results of method 2). This would approximately yield the following flow capacity range per intersection:

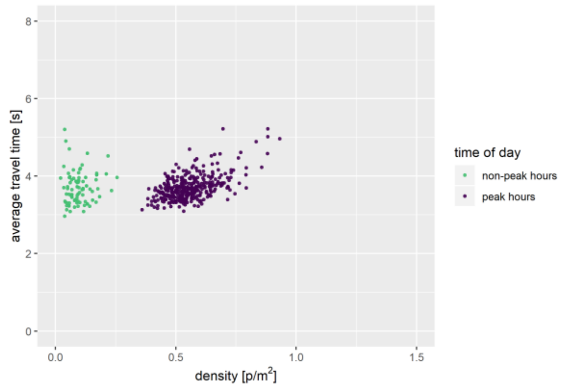
Table A.1 Approximate capacity density and flow capacity range per intersection for $x = 0$

Intersection	**1**	**2**	**3**	**4**
Approximate capacity density (p/m^2)	0.70	0.70	0.70	0.90
Approximate flow capacity range $(p/m/min)$	13.5-17.5	16.5-21.5	12.5-16.0	20.0-25.0

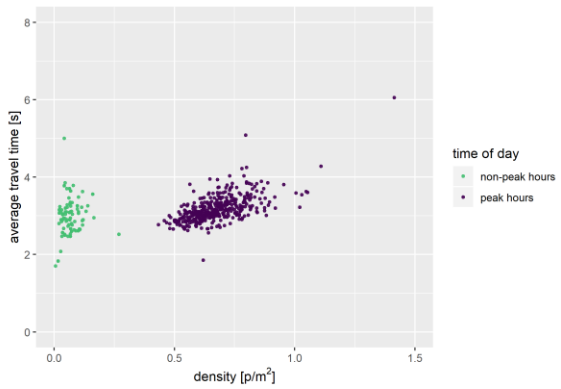
The decision maker can decide (per intersection) on a certain flow capacity within this range. It should be kept in mind that each decision for a capacity standard within these ranges yield consequences of under or over dimensioning to a certain extent (as explained in section III).



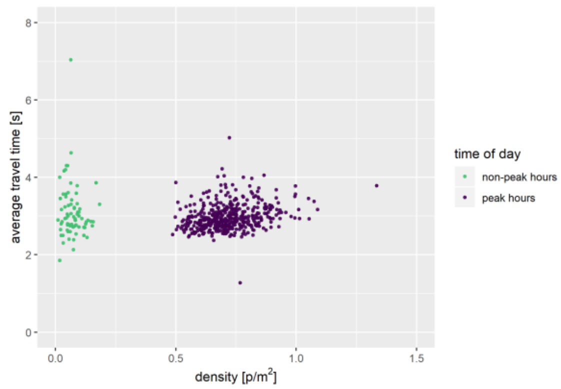
a. Intersection 1($\overline{tt}$)



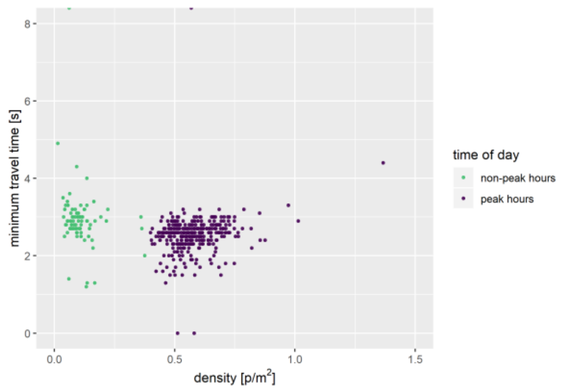
b. Intersection 3 ($\overline{tt}$)



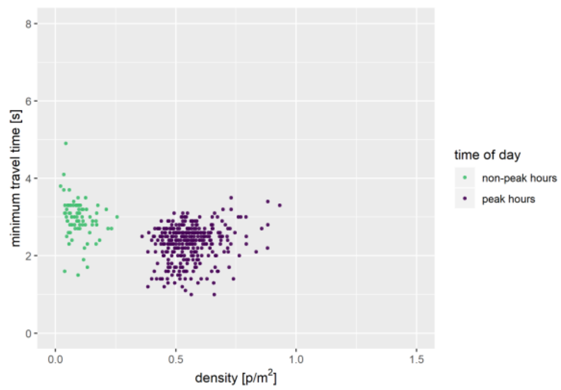
c. Intersection 2($\overline{tt}$)



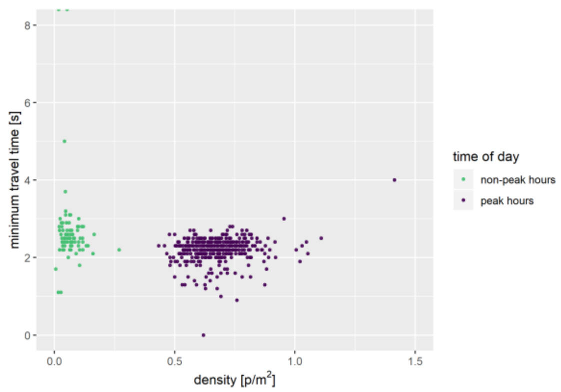
d. Intersection 4 ($\overline{tt}$)



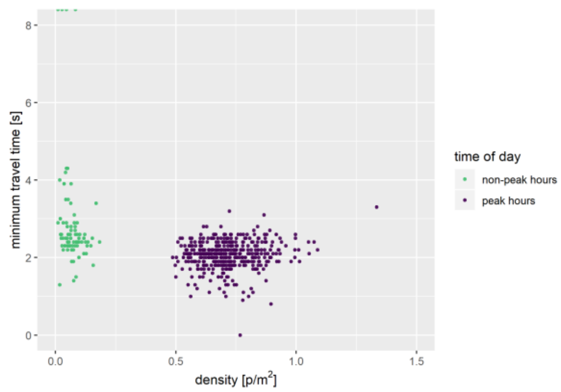
e. Intersection 1(tt_{min})



f. Intersection 3 (tt_{min})



g. Intersection 2(tt_{min})



h. Intersection 4 (tt_{min})

Figure A.8 Relation between density (k) and average travel time ($\overline{tt}$) / minimum travel time (tt_{min})

Influence flow ratio on flow and density

Table A.2 presents the mean and standard deviation of the flow accordingly to the flow ratio bins. As can be seen, the middle bin contains the highest flows (except for intersection 1) and highest variation. This implies that a rather balanced share of both flows yields a higher outflow (which could be the result of the demand pattern).

Table A.2 Mean and standard deviation flow (q) for several bins of flow ratio (γ)

Intersection	$\gamma < 0.33$		$0.33 < \gamma < 0.66$		$\gamma > 0.66$	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	14.76	0.97	15.55	1.22	15.78	1.11
2	18.08	1.47	18.84	1.57	18.07	1.19
3	12.77	1.42	13.39	1.44	12.89	1.30
4	18.09	1.87	19.30	2.08	18.46	1.84

Table A.3 presents the mean and standard deviation of the density accordingly to the flow ratio bins. For each intersection the density increases as the flow ratio increases. This means that a higher share of main flow results in more pedestrians at the intersection. This could imply that the space at the intersection is used more efficiently for a high share of main flow (e.g. due to efficient self-organization, in which lane formation yield smaller headways).

Table A.3 Mean and standard deviation density (k) for several bins of flow ratio (γ)

Intersection	$\gamma < 0.33$		$0.33 < \gamma < 0.66$		$\gamma > 0.66$	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1	0.52	0.08	0.60	0.11	0.68	0.05
2	0.65	0.13	0.69	0.10	0.71	0.08
3	0.50	0.10	0.55	0.09	0.59	0.09
4	0.69	0.10	0.73	0.12	0.74	0.10

Regarding the influence of the flow ratio on the flow and density, two conclusions can be drawn. The flow ratio and the flow seem to be determined by the demand pattern. This makes it difficult to study the relation between flow ratio and flow. A rather clear trend was identified in the relation between the flow ratio and the density, in which an increase in flow ratio means an increase in density. This could be explained by the fact that a high share of main flow (high flow ratio), means mainly a high share of bidirectional flow in the corridor, with little interference of a crossing flow. In case of a bidirectional flow, it is expected that more efficient self-organization takes place (e.g. lane formation), yielding lower headways and thus higher densities.

V. Conclusions and recommendations

The objective of this research is twofold: to gain insight into how the flow capacity of a pedestrian intersection at a railway station is influenced by several factors and to explore methods that can estimate the flow capacity of a pedestrian intersection.

Conclusions

To gain insight into how the flow capacity of a pedestrian intersection at a railway station is influenced by several factors, this study proposed a theoretical framework describing these relations based on the insights from other studies and practice. Since the context for each study differs, the relations within this framework are hypothesized and thus not yet verified. The framework is a starting point for this and future research regarding pedestrian intersections at railway stations and should be used as a tool scope the research and to verify and identify the strength of the relations.

In this study, three capacity estimation methods were proposed to estimate the flow capacity of a pedestrian intersection. To test their suitability, a field study was conducted at four intersections in the main hall of Utrecht Centraal station. According to the field study, the second and third method both seem suitable for capacity estimations, even though the intersection flow capacity (according to the traffic flow principles) could not be estimated in this study. Depending on the accepted level of delay, the third method was able to determine a range of capacity flows at a certain capacity density. Both methods seem suitable for capacity estimations, because they have conditions to verify that the capacity is met. This is lacking in the first method; however, the first method could give an indication of the minimum flow capacity which the infrastructure is able to handle. Furthermore, the second method shows a clear flow-density relation, implying that it should be able to estimate the intersection flow capacity if congested conditions are measured.

In addition to testing these methods, the flow ratio was measured to study its effect on the intersection flow capacity. Since the intersection flow capacity (according to traffic flow principles) has not been measured, instead the flow-flow ratio relation and the density-flow ratio relation was studied. No clear relation could be identified between the flow and the flow ratio. The flow ratio and the flow seemed to be strongly determined by the demand pattern around the intersection, which excludes the possibility to study its effect on the flow. However, a rather clear trend was observed in the density-flow ratio relation, in which an increase in flow ratio means an increase in density.

Recommendations

For both the second and especially the third method, (additionally) a selection based on the highest densities could possibly give more valuable insights for capacity estimations, since it reveals the congested conditions. It is recommended to include observations in the samples based on the highest densities should be included in addition to the highest flows.

The methods in this study only regard the outflow of the intersection. Hence, information on the demand pattern (the inflow) was left out. it is recommended to look into the relation between the demand pattern and the outflow. This relation can be studied by the cumulative curves method.

In field studies like these, it could occur that the demand is never high enough to do enough measurements for a proper capacity estimation. It could be valuable to perform or find an experimental or simulation study for a similar flow situation, in which the demand can be pushed until capacity level. In this way, capacity estimations can be made for the flow situation at the station.

To increase the understanding of pedestrian dynamics at intersections, it is recommended to obtain insight into pedestrian behaviour (e.g. lane formation, decelerating, accelerating, stopping and detour behaviour). For this, trajectories and individual speeds should be studied.

Currently, at NS a distinction is made between the capacity that indicates self-reliance ("zelfredzaamheid") and comfort, which indicates the level of crowdedness for acceptable safety risks and the level of crowdedness in which pedestrians can walk undisturbed respectively. Self-reliance capacity standards for intersections, especially in combination with vertical infrastructure, should be based on the local densities at an intersection (rather than the average density). Hence, the methods tested in this study are not suitable for estimating this capacity standard. Regarding situations in which pedestrians can walk undisturbed, the third method of this research could be a suitable method or starting point (since it only evaluates the travel time of the pedestrians of the main flow).

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Appendix B Summary research variables

Table B.1 Summary research variables

Research variables		Intersection			
		1	2	3	4
Flow (q) $ped \cdot m^{-1} \cdot min^{-1}$	Min.	12.91	14.74	10.47	13.95
	1st Qu.	14.48	17.63	12.21	17.37
	Median	15.17	18.42	13.08	18.68
	Mean	15.36	18.62	13.22	18.74
	3rd Qu.	16.22	19.47	14.08	20.00
	Max.	20.06	23.68	18.14	27.11
Flow ratio (γ) $[0,1]$	Min.	0.16	0.09	0.19	0.09
	1st Qu.	0.34	0.32	0.47	0.28
	Median	0.38	0.38	0.56	0.37
	Mean	0.39	0.38	0.60	0.41
	3rd Qu.	0.43	0.44	0.71	0.47
	Max.	0.88	0.96	1.00	1.00
Density (k) $p \cdot m^{-2}$	Min.	0.36	0.43	0.36	0.49
	1st Qu.	0.51	0.60	0.49	0.64
	Median	0.57	0.67	0.54	0.71
	Mean	0.58	0.68	0.56	0.72
	3rd Qu.	0.64	0.74	0.60	0.78
	Max.	1.37	1.42	0.93	1.33
Average travel time ($\overline{tt}$) sec	Min.	1.99	1.85	3.09	1.27
	1st Qu.	3.63	2.98	3.49	2.76
	Median	3.81	3.13	3.67	2.92
	Mean	3.85	3.19	3.71	2.98
	3rd Qu.	4.03	3.34	3.87	3.15
	Max.	7.05	6.05	5.22	5.02
Minimum travel time ($tt_{\min}$) sec	Min.	0.00	0.00	1.00	0.00
	1st Qu.	2.40	2.10	2.10	1.90
	Median	2.60	2.30	2.40	2.10
	Mean	2.52	2.21	2.33	2.08
	3rd Qu.	2.70	2.40	2.60	2.30
	Max.	4.40	4.00	3.50	3.30