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A New Generic Approach to the Pedestrian Fundamental Diagram

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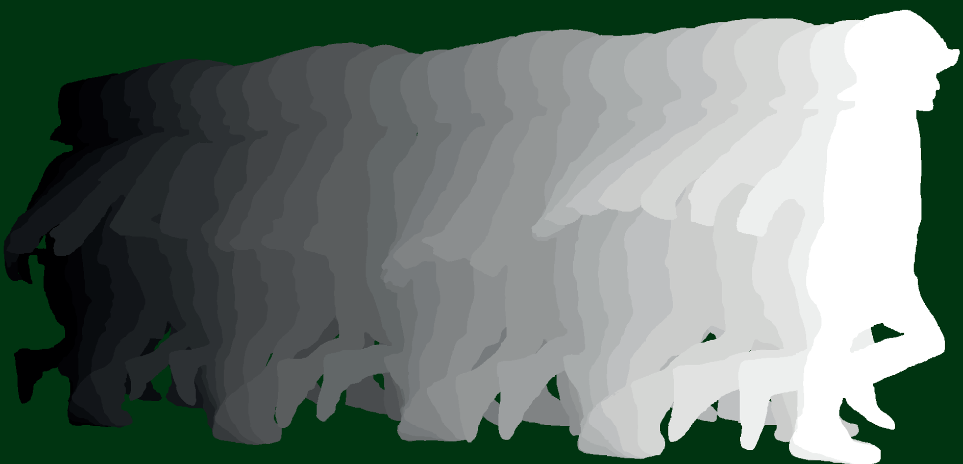

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A NEW GENERIC APPROACH TO THE PEDESTRIAN FUNDAMENTAL DIAGRAM

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ABSTRACT

The pedestrian fundamental diagram, which describes the relationship between speed, flow and density, is one of the key concepts for the design of pedestrian facilities. It allows to determine the capacity of facilities as well as to calculate estimated walking times, for example when changing trains. In the last decades, laboratory and field measurements have been conducted to obtain the fundamental diagram for different situations. Based on this it was revealed that the fundamental diagram differs significantly between different locations and pedestrian compositions. Various parameters which significantly influence the shape of the fundamental diagram curve have been determined. Thus, poor results might occur when using a general form of the fundamental diagram for design purpose. Still, only either fundamental diagrams measured in a single setting or ones aggregating these measurements are available. No comprehensive model was found which is able to describe the differences observed as well as being able to estimate fundamental diagrams for other pedestrian compositions. Currently, an estimation of a specific fundamental diagram without corresponding empirical data is not possible.

The idea of this thesis is to address this research gap by creating a generic model, which describes the main walking principles and the interaction between pedestrians. Using this model allows to generate situation specific fundamental diagrams. In addition, the underlying principles which determine the shape of the fundamental diagram are determined and the effect of different influence factors on human walking can be studied. By applying situation specific input parameter values, it shall be possible to generate situation specific fundamental diagrams useful for the design of pedestrian facilities.

The model creation was done in two steps. As a basis for the quantitative fundamental diagram model, a qualitative generic walking model was developed. A comprehensive overview of the basic principles of walking and the interaction of pedestrian was given in the generic walking model. This was done by combining individual findings available in literature. Starting from a simple case, where a pedestrian is walking alone at constant speed, the model is extended to include all relevant influences on a pedestrian.

The generic pedestrian walking model was then used as a basis for the fundamental diagram model. Here, a microscopic model was established where also the distribution of input parameter values can be simulated. Again, first a simple model was set up and complexity was added step by step. In the

end a model was created based on lane movement of pedestrians, where lane swapping is possible to enable overtaking.

For the model setup, a thoroughly literature review was performed at the beginning of this work. A special focus was laid on the pedestrian walking speed. The different influences on the free flow walking speed were collected and their effect was estimated. In addition, a definition of the fundamental diagram useful for this work and a detailed discussion on the time aspect of the Level of Service concept, which is closely linked to the fundamental diagram, was made in connection to the literature review.

For the calibration and validation of the model, empirical data already available from experiments and real-life measurements was used. This allowed to cover a wide range of different setting in the validation. In conclusion, the validation showed that the model is expected to provide adequately accurate and useful results for the expected scope of application.

Using the model it was possible to accept the research question stating that it is possible to create a generic pedestrian fundamental diagram model. This can be used to estimate specific fundamental diagrams. However, it was found that although the model is based strongly on the basic principles of walking, the estimation of the input parameters can be challenging. Still, for experienced users it is expected that the model will provide better results than general fundamental diagrams currently used.

The validated model is ready to be used to estimate situation specific fundamental diagrams. This was done for different scenarios, for example for the expected situation in 2050 or to determine the effect of the mixture of commuters and shoppers on the pedestrian flow. In the future scenario it was shown that the assumed trends result in reduced walking speeds, especially at higher densities. Here, the model allows for the first time to evaluate the effect of different changes and the simulation of fundamental diagrams for situations, where no empirical data is available.

ZUSAMMENFASSUNG

Das Fundamentaldiagram für den Fussverkehr beschreibt die Beziehung zwischen Gehgeschwindigkeit, Fussgängerdichte und Fussgängerfluss und ist als solches eines der wichtigsten Konzepte für die quantitative Dimensionierung von Anlagen des Fussverkehrs. Mit dessen Hilfe können etwa die Leistungsfähigkeit einer Fussgängeranlage oder die Gehzeiten auf einer Anlage, zum Beispiel für eine Umsteigebeziehung, berechnet werden. Zur Ermittlung des Fundamentaldiagrams für unterschiedliche Situationen wurden daher in den letzten Jahrzehnten diverse Labor- und Feldmessungen durchgeführt. Diese Messungen ergaben signifikante Unterschiede im Fundamentaldiagram zwischen verschiedenen Situationen, hervorgerufen durch eine Vielzahl von Einflussgrössen. Bei Verwendung einer allgemeinen Form des Fundamentaldiagrams können sich dadurch starke Abweichungen zum realen Gehverhalten ergeben, woraus eine mangelhafte Dimensionierung der Fussgängeranlagen entsteht. Nichtsdestotrotz konnte in der Literatur kein umfassendes Model gefunden werden, dass in der Lage ist, die beobachteten Unterschiede zu beschreiben und situationsspezifische Fundamentaldiagramme zu generieren. Es ist daher gegenwärtig nicht möglich, ein passendes Fundamentaldiagram ohne entsprechende empirische Daten zu berechnen.

Die dieser Arbeit zugrundeliegende Idee ist, dass es möglich sein sollte, anhand der Grundprinzipien des menschlichen Gehens ein generisches Model zu erstellen, mit dessen Hilfe situationsspezifische Fundamentaldiagramme erstellt werden können. Dieses Modell erlaubt ausserdem, die Auswirkungen und Zusammenhänge einzelner Aspekte auf den menschlichen Gang zu studieren. Durch die Verwendung situationsspezifischer Werte können spezifische Fundamentaldiagramme hergestellt werden, die einen Mehrwert für die Dimensionierung bieten.

Die Erstellung des Modells geschah in zwei Schritten. Als Grundlage für das quantitative Fundamentaldiagrammodel wurde ein generisches Modell zur qualitativen Beschreibung des Gehverhaltens erstellt. Für ersteres wurden Einzelerkenntnisse aus der Literatur zu einer umfassenden Beschreibung des menschlichen Gehens und der wichtigsten Einflüsse zusammengefasst. Beginnend mit dem einfachsten Fall, eine Person geht alleine mit konstanter Geschwindigkeit, wurde hier die Komplexität nach und nach erhöht.

Das generische Modell des menschlichen Ganges wurde dann als Grundlage für die Erstellung des Fundamentaldiagrammodells genutzt. Dieses Modell basiert auf einem mikroskopischen Ansatz, um auch den Einfluss der Streuung von Parameterwerten berücksichtigen zu können. Hierbei wurde wieder mit einem einfachen Model begonnen und die Komplexität nach und

nach erhöht. Das finale Modell basiert auf der Gehbewegung in Bahnen, wobei das Wechseln von Bahnen, und damit das Überholen von Personen, möglich ist.

Am Beginn der Arbeit wurde für die Modellerstellung eine umfassende Literaturübersicht über die relevanten Aspekte des menschlichen Gehens durchgeführt. Ein besonderer Fokus wurde hierbei auf die Gehgeschwindigkeit gelegt. Ausgehend von den Literaturangaben zur freien Gehgeschwindigkeit wurden die beschriebenen Einflussgrössen gesammelt und deren Auswirkungen auf die Gehgeschwindigkeit abgeschätzt. Zusätzlich beinhaltet die Literaturanalyse dieser Arbeit auch eine neue Definition des Fundamentaldiagrammes, die in weiterer Folge in dieser Arbeit genutzt wird, sowie eine detaillierte Diskussion des Zeitaspektes des Level of Service Konzeptes, das für die Dimensionierung eng mit dem Fundamentaldiagram verbunden ist.

Für die Kalibrierung und Validierung des Modells wurden verfügbaren Messdaten aus Experimenten und realen Situationen herangezogen. Dadurch war es möglich, eine Vielzahl unterschiedlicher Situationen und Fussgängerzusammensetzungen für die Validierung heranzuziehen. Die Validierung zeigte, dass das Modell für den gewählten Anwendungsbereich hinreichend genaue und nützliche Ergebnisse liefern kann.

Mit Hilfe des Modells konnte nun die Forschungsfrage bejaht werden. Diese stellte die Frage ob es möglich ist, ein Modell zu erstellen, dass, basierend auf den Prinzipien des Menschlichen Gehens und der relevanten Einflüsse, situationsspezifische Fundamentaldiagramme generiert. Das vorliegende Modell versucht das reale Gehverhalten möglichst genau abzubilden, es zeigte sich jedoch trotzdem, dass die Abschätzung der Werte für die Eingangsparameter nicht trivial ist. Es wird jedoch erwartet, dass erfahrene Nutzer mit Hilfe des Modells bessere Resultate erzielen als bei Anwendung eines allgemeinen Fundamentaldiagrams, wie es heutzutage verwendet wird.

Das validierte Model ist für die Berechnung situationsspezifischer Fundamentaldiagramme einsatzbereit. Als Anwendungsbeispiel wurden hierfür unterschiedliche Szenarien betrachtet, zum Beispiel ein Fundamentaldiagram für das Jahr 2050 oder die Abschätzung der Auswirkungen einer Mischung von Pendlern und Einkäufern auf den Fussgängerfluss. Hierbei wurde ermittelt, dass durch die angenommenen Trends in Zukunft eine Reduktion der Gehgeschwindigkeiten, insbesondere bei höheren Dichten, erwartet wird. Zum ersten Mal ist es somit möglich, die Auswirkungen von Veränderungen in der Fussgängerzusammensetzung oder Fundamentaldiagramme für Situationen ohne vorhandene empirische Daten zu berechnen.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND SYMBOLS

a	[m/s²]	Acceleration
a_{max}	[m/s²]	Maximum acceleration
C	[$m^{1/2}$/s]	Model parameter
C_s	[P/m s]	Specific capacity
D	[P/m²]	Pedestrian density
D_{max}	[P/m²]	Maximum density
d_B	[m]	Body depth
d_{back}	[m]	Backward distance for lane change
d_i	[m]	Intimate distance
E_0	[J/s kg]	Energy expenditure at $v = 0$
E_d	[kJ/km]	Energy expenditure per distance travelled
F_h	[P/h]	Hourly peak flow
F_s	[P/m s]	Specific flow
F_{step}	[Hz]	Step frequency
f_l	[−]	Lane width factor for overtaking
G	[kg]	Body mass
g	[m/s²]	Gravity
h	[m]	Headway
$h_{r,max}$	[m]	Maximum reaction headway
k	[V/m]	Vehicle density
L_l	[m]	Leg length
L_o	[m]	Observation length
L_s	[m]	Step length
L_{str}	[m]	Stride length
LOS		Level of Service
N_l	[−]	Number of lanes
P	[−]	Number of pedestrians
q	[V/s]	Vehicle flow
RMSE		Root mean square error
r_n	[%]	Random noise
S_{in}	[−]	Initial time steps with no lane change
S_s	[−]	Number of time steps used for speed calculation
SBB		Swiss Federal Railways

T	[s]	Time delay
T_{in}	[s]	Simulation time interval
T_{sim}	[s]	Simulation duration
t_d	[s]	Deceleration time
t_r	[s]	Reaction time
$t_{r,max}$	[s]	Maximum reaction time
t_{rd}	[s]	Reaction delay
t_s	[s]	Step duration
v	[m/s]	Walking speed
v_0	[m/s]	Free flow walking speed
$v_{5\,\%}$	[m/s]	5 % percentile walking speed
$v_{95\,\%}$	[m/s]	95 % percentile walking speed
v_d	[m/s]	Desired walking speed
v_i	[m/s]	Individual mean speed
$v_{l,max}$	[m/s]	Maximum lateral speed at standstill
v_{mean}	[m/s]	Mean walking speed
v_{min}	[m/s]	Minimum walking speed
v_{SD}	[m/s]	Standard distribution of walking speed
$v_{Stairs\ down}$	[m/s]	Walking speed for stairs (walking down)
$v_{Stairs\ up}$	[m/s]	Walking speed for stairs (walking up)
v_t	[m/s]	Time step speed
v_u	[m/s]	Upper speed limit
$v_{Walkway}$	[m/s]	Walking speed for walkways
$\bar{v}$	[m/s]	Mean speed
w_B	[m]	Body width
w_h	[m]	Head width for lane calculation
w_l	[m]	Lane width
$w_{lat,t}$	[m]	Lateral threshold for neighbours
w_s	[m]	Sway width
W_w	[m]	Walkway width
$\Delta v_{(t-\tau)}$	[m/s]	Speed difference at time $t-\tau$
$\Delta x_{(t)}$	[m]	Headway at time t
δ	[−]	Model parameter for the Kladek formula
γ	[−]	Model parameter
τ	[s]	Relaxation time

1

INTRODUCTION

A journey of a thousand li starts with a single step.
— Laozi

1.1 MOTIVATION

Walking is one of the most important steps in the evolution of humankind, as well as in the development of each human. Walking improves the health and wellbeing of people and produces significantly less emissions compared to motorized transport modes. Consequently, many cities and countries promote walking. In public transport trips, walking is also used to link the origin and destination to the next bus stop or train station. To provide adequate walking conditions, pedestrian facilities such as public transport stations or inner-city pedestrian zones should be designed in terms of quality and capacity. If they are not properly designed, crowding can occur and the functionality of the infrastructure is limited. In public transport, this might also affect the punctuality and reliability of the station and thus have negative impact on the total system.

In the future, the proper design of pedestrian facilities will gain importance. With an increase in the world population and the trend that people move into bigger cities, the population density in the cities rises. In addition, events in city centres (e.g. the Zürifäscht, the Streetparade in Zürich and spontaneous events organized using social media) have high requirements concerning the pedestrian infrastructure. New forms of threats and the consequently higher public awareness make escape situations in pedestrian areas more likely. In addition, the characteristics of the pedestrians will change due to the ageing society, resulting in more elderly people on pedestrian facilities. All these future trends will have an impact on the capacity and thus on the design of pedestrian facilities.

The capacity, or maximum flow, of a pedestrian facility can be calculated from the product of speed and density. The speed itself is dependent on the pedestrian density. At low densities, the walking speed is high. With a higher density and less space for each person walking, the speed decreases. At zero density as well as at the maximum density the flow is thus also zero. Consequently, the maximum flow is at a medium speed and density. These relationships are expressed in the pedestrian fundamental diagram. Apart from the flow, the quality of the pedestrian facility is also linked to the pedestrian density. Higher densities affect the quality by reducing the personal space. The design flow of pedestrian facilities is then done using the speed and density for a chosen quality level of the Level of Service scheme.

Until now, the design of pedestrian infrastructure is mainly done using a general form of the fundamental diagram. However, it is affected by several factors, like the cultural and social characteristics of a person. These influences change the shape of the fundamental diagram and consequently the capacity of the facility. Studies have been performed to determine the fundamental diagram based on different characteristics. Still, they cannot be used to derive a fundamental diagram for all situations needed.

In the last years, the quality of video and laser based pedestrian detection and tracking improved. Measurement techniques now allow to track individual pedestrians and to observe their characteristics. Especially in recent years various research projects and experiments were done to study different aspects of pedestrian walking and crowd behaviour. This can now be used to study situation specific characteristics of the fundamental diagram.

1.2 GOALS AND PURPOSE

The idea followed in this work is that different influences have an impact on the basic walking attributes. For example, depening on the age or gender a different desired walking speed or distance kept to others is maintained. Different attribute values will also lead to different fundamental diagram curves. Knowing the attribute values for each influence factor, the fundamental diagram could hypothetically be calculated for every situation needed.

The research gap addressed is that it is not possible to describe the differences obtained from measuring the fundamental diagram in different conditions using a comprehensive model. This work now aims at introducing a generic fundamental diagram model. Using equations describing the fundamental diagram, this model shall be able to provide an appropriate fundamental diagram for any specific situation.

If such a model can be created, this will strongly enhance the possibilities for the design of future pedestrian infrastructure. Changes in the pedestrian composition can be considered, leading to a more efficient design. This is especially important for future situations, where no measurement data and hence no suitable fundamental diagram exist.

In addition, as the model will be based on the known walking characteristics, this work will contribute towards a better understanding of human walking and the interaction between pedestrians. A detailed literature research will link the knowledge found from different disciplines to create a walking model, describing the interactions between pedestrians which then determine the fundamental diagram. As now most fundamental diagrams are directly based on measurement data of speed, density and flow, this generic approach will likely help to better understand the underlying principles.

As the model setup will require a thoroughly literature review, this work shall also provide a detailed overview of the current literature which can then be used as a basis for further research. Thus, a review of the literature on walking speed and on the fundamental diagram will be made.

Based on the same interaction principles, the Level of Service can be considered to be the other important design principle for pedestrian infrastructure. A minor part of this work will highlight this relation and discuss the possible implications of the findings to the Level of Service concept.

1.3 OUTLINE

This work is structured in chapters which correspond to the research progress, by first describing the literature and consequently derive the research questions. To answer them, the fundamental diagram model will be established and tested using existing data.

Parts of this dissertation have already been published, respectively are based on the following contributions:

- Ernst Bosina and Ulrich Weidmann (2016). Generic Description of the Pedestrian Fundamental Diagram. *Proceeding of Pedestrian and Evacuation Dynamics 2016*. Pedestrian and Evacuation Dynamics PED 2016. Ed. by Weiguo Song et al. Hefei, China: University of Science and Technology of China Press, pp. 548–555. DOI: 10.17815/CD.2016.11
- Ernst Bosina and Ulrich Weidmann (2017a). Defining the Pedestrian Fundamental Diagram. Traffic and Granular Flow TGF 2017. Washington, D.C.
- Ernst Bosina and Ulrich Weidmann (2017b). Die Geschichte des Fußgängers in der Verkehrsplanung. *Straßenverkehrstechnik* (12), pp. 860–866
- Ernst Bosina and Ulrich Weidmann (2017c). Estimating Pedestrian Speed Using Aggregated Literature Data. *Physica A: Statistical Mechanics and its Applications* 468, pp. 1–29. DOI: 10.1016/j.physa.2016.09.044
- Ernst Bosina et al. (2018). Defining the time component of the pedestrian LOS concept. Transportation Research Board 97th Annual Meeting. Washington, D.C.
- Ernst Bosina and Ulrich Weidmann (2018). Creating a generic model of the pedestrian fundamental diagram. 18th Swiss Transport Research Conference STRC. Monte Verità/Ascona: STRC. DOI: 10.3929/ethz-b-000263928

The paragraphs and chapters taken from these publications are marked at the beginning of the appropriate sections.

The current Chapter 1 serves as introduction to this dissertation and consists of the motivation, why the topic of this dissertation is relevant and useful, the purpose and goals of this work, the chapter outline as well as the limitations of the work.

The literature review is presented in Chapter 2. First, the historic background of the quantitative pedestrian research is highlighted. Then, the relevance of walking in history, the basic biomechanical principles of walking and interaction phenomena are discussed. A shortened version of the part on the historic background was published in a German magazine (Bosina and Weidmann, 2017b). In this chapter, the paper presented in Physica A on the pedestrian walking speed (Bosina and Weidmann, 2017c) is integrated into this thesis. Apart from a thoroughly literature review, this paper also aims at quantifying the influences on the walking speed. Then, the basics of the fundamental diagram as well as a new definition is presented. In the last part of Chapter 2, the relation between the fundamental diagram and the Level of Service concept can be found, which mainly consists of a paper presented at the annual meeting of the TRB (Bosina et al., 2018).

Based on the literature review, Chapter 3 presents the main research questions and the hypotheses of this work. Subsequently, the methods and approach necessary to answer the research question and hypotheses are described in Chapter 4.

In Chapter 5, the generic pedestrian walking model is presented, which describes the different influences on an individual pedestrian while walking. At the beginning, a single pedestrian walking undisturbed from others is considered, then more complex situations with interacting pedestrians are elaborated.

The fundamental diagram model created in this thesis is described in chapter 6. This model is divided into two parts. First, a model for lane movement is proposed; afterwards this model is extended for a unidirectional movement where overtaking is possible until a general unidirectional walking model is reached.

To test the fundamental diagram models, the data collection methods and data which will be used are discussed in Chapter 7. As in recent years various experiments and real-life observations were performed, no new data will be collected for this thesis, as the existing data will be used.

The model calibration and the test of hypotheses can be found in Chapter 8. In Chapter 10, the discussion and synthesis of this work is available. Also the conclusions drawn from this work and the strengths and weaknesses of the presented approach are discussed. In this chapter, a link to the Level of Service is made again to discuss the implications of the results to this concept. To conclude this work, perspectives for further research are described.

The bibliography of this work is located after the synthesis, followed by an appendix (Chapter A). The appendix includes the list of literature used in the paper on the pedestrian walking speed (Bosina and Weidmann, 2017c), which is also included as online appendix in the original publication. In addition, the reduced python code written for the fundamental diagram model is added as well as further tables and figures are provided.

1.4 LIMITATIONS

Although this thesis aims at covering all important aspects of human walking to provide a generic approach to the pedestrian fundamental diagram, several limitations still have to be applied in order to achieve the goals of this work within a single dissertation.

The work focusses on pedestrians walking on flat surfaces. Walking on stairs and other facilities shows to some extent a different behaviour and is therefore not included in this work. Transferring the results to other facility types should be done with caution.

In recent years a lot of literature was published focussing on pedestrians walking in groups. Although an impact on the walking characteristics and the specific fundamental diagrams can be expected, this behaviour is not further examined here for several reasons. Mainly, currently the appearance of groups cannot be estimated for future situations. Also, no automatic counting devices exist, able to detect the number of groups at a certain location. When planning and designing future infrastructure, it is thus not possible to reliably predict the number and types of groups appearing as well as estimating their impact. Here, further research is needed about the basics of group behaviour before the impact on the design can be estimated. Thus, the presence of groups is beyond the scope of this work.

For this thesis, only the presence of pedestrians able to walk freely without restrictions from disabilities is assumed. Even though their presence in transport facilities must be considered in the design to allow an independent lifestyle, the inclusion in the quantitative design is assumed to not be required unless a strong change of the design values is expected.

2

FUNDAMENTALS OF PEDESTRIAN TRANSPORT

Walking is man's best medicine.

— Hippocrates

A German version from parts of Chapter 2.1 and Chapter 2.2 were already published as:

Ernst Bosina and Ulrich Weidmann (2017b). Die Geschichte des Fußgängers in der Verkehrsplanung. *Straßenverkehrstechnik* (12), pp. 860–866

2.1 DEVELOPMENT OF PEDESTRIAN RESEARCH

2.1.1 *The roots of pedestrian research*

Like many other research disciplines, the research on pedestrian transport and the design of pedestrian facilities evolved over time. Pedestrian research today covers several sub disciplines, from the design of pedestrian areas to pedestrian routing and evacuation planning. Looking back in history, several milestones of the evolution of building rules and pedestrian research, from general considerations to specific research can be identified.

Already in ancient times rules and guidelines for the design of buildings were elaborated. In the code of Hammurabi a section describes the punishments for the builder of a house if the construction fails (Sommer, 1903). A building guideline is also written down in the bible, where it is recommended to build a battlement on the roof to prevent people from falling (Deuteronomy 22:8). Several building rules can be found in the Roman law (Vec, 2011). From this time, also first rules for traffic engineering are preserved. For example, the twelve tables state a minimum widths for roads of 2.4 m (Nasmith, 1890).

Vitruvius, a roman architect, proposed guidelines for building mainly based on an aesthetic viewpoint. For an optimal layout of temple stairs the tread should be 0.45 to 0.60 m, the riser 0.23 to 0.25 m (Morgan, 1914). These dimensions are not considered today. Several centuries later Blondel (1698) proposed a relationship between tread and riser dimensions based on ergonomic consideration, which are still in use today.

2.1.2 *First design criteria for pedestrian facilities*

Whereas in previous centuries only little research related to pedestrians is visible, the pedestrian research got more and more important in the 20^{th} century. In the beginning, mainly theoretical considerations on the capacity and design of pedestrian facilities were done. Measurements on the flow of people were conducted soon after (Predtečenskij and Milinskij, 1971). A reason for this might be the increase in car traffic. This made it necessary to separate transport modes and build sidewalks for pedestrians (Vogt, 1938). Since the beginning of the industrialisation also the world population and especially the number of people living in cities increased considerably. Among others, this might be an important reason for the rise in research activities.

The first design rules for walkways were based on the principles to allow a crossing of pedestrians without disturbance. For example, for sidewalks at main roads at least two pairs of pedestrians should be able to pass each other, resulting in an optimal walkway width of 4.5 m (Gerland, 1928). It was already proposed to provide bigger walkway widths for heavily used areas, such as living quarters for factory workers where high peak flows occur (Blum et al., 1921). Others derived the width of walkways based on theoretical considerations using an assumed walking speed of 0.5 m/s, a lane width of 0.75 m and a headway of 1 m (Brix, 1909). By adding 0.75 m of walkway width for standing passengers and another 0.75 m for overtaking pedestrians, the proposed 2.25 m of minimal walkway width for each of the two sides of the street are reached. Furthermore, a formula for the calculation of the walkway width W_w [m] based on the hourly peak flow F_h [P/h] is proposed:

$$W_w = 0.75 \cdot (2 + \frac{F_h}{3600}) \tag{2.1}$$

To improve the quality of the flow and to hinder pickpocketing an increase of the walkway width to 4 m is recommended. (Brix, 1909). Using the proposed formula will result in an extended pedestrian density for higher flow volumes, and thus a reduced quality of the flow.

The proposed walkway widths for main roads at this time were generally high compared to today's standards (Gerland, 1928; Stramentow, 1953), whereas the minimum walkway widths are similar. The minimum desired walkway width today is usually set at about 1.5 to 2.5 m, based on the human dimensions and distances kept to walls and the adjacent carriageway (AASHTO, 2001, 2004; Axelson et al., 1999; Department of Transport, 2011; FGSV, 2002; NACTO, 2013; Neufert et al., 2000; otak, 1997; VSS, 2009). Considerable higher widths are proposed for street sections with higher car or pedestrian volumes and obstacles on the walkway (FGSV, 2002; Grob and Michel, 2011).

The demand-driven design of pedestrian facilities first got important for railway and metro stations in cities. Apart from capacity and comfort, also the walking times have to be considered in these location and the pedestrian facilities have to be designed accordingly (Blum et al., 1921; Reimer, 1947).

In parallel to the design of streets and public transport stations for the demand of pedestrians, the building evacuation got more and more important. For example, the fires in the Opéra de Nice and the Ringtheater (Vienna) in 1881, causing hundreds of fatalities each, led to a considerable increase of efforts in fire protection ("Der Brand des Wiener Ringtheaters" 1881; Dieckmann, 1911; Mikoletzky, 1997). These incidents also led to new research and regulation concerning emergency exits and regulations. First experiments with different door widths were done to estimate the capacity of bottlenecks. It was revealed that the specific flow through doors with a small width ($< 1.0 - 1.1$ m) was considerably reduced due to crowding. At door widths smaller than 0.7 to 0.8 m the clogging phenomenon was observed, which was reproduced also in recent studies (Dieckmann, 1911; Helbing et al., 2005).

Regulations concerning the minimal width of doors, stairs and walkways for the building egress were already available at this time (Fischer, 1933). Depending on the building usage 1 m width was required for 80 to 125 persons. A similar range of values is used today, although in general the required widths are smaller. Variations in the requirements today are mainly based upon the total number of persons in the area and are differentiated for stairs and flat walkways (Bauministerkonferenz, 2014; Bundesministerin für Arbeit, Gesundheit und Soziales, 1999; VKF, 2017).

2.1.3 *The start of quantitative pedestrian research*

Beginning in the mid of the 20th century the research effort on pedestrians and the design of pedestrian facilities increased (Weidmann, 2012). First measurements on walking speeds for different pedestrian groups were made as well as pedestrian density and capacity values for different pedestrian facilities is available from this time (Evans, 1950; Reimer, 1947; Schmitz, 1946; Scholz, 1952). The flow on escalators and the flows during the boarding and alighting process were also measured and first empirical data got available (Evans, 1950; Reimer, 1949, 1950).

The first basic research on the pedestrian Level of Service scheme and the relation between density and walking speed was conducted during the 1960s (Fruin, 1970; Oeding, 1963). Using time lapse photography and other simple observation methods, the relationship between speed and density was described and the Level of Service scheme, which was known from car traffic, was adapted to the pedestrian traffic (Fruin, 1970, 1971a; Oeding, 1963).

2.1.4 *Current state of pedestrian research*

The Level of Service scheme and the fundamental diagram have been evaluated under different conditions and further developed in recent times. (Westphal, 1971). New and improved sensor technologies now enable more accurate and longer pedestrian data collection. This provided further information on human walking. Pedestrian behaviour models have been developed based on these data to simulate walking facilities (Daamen, 2004; Helbing and Molnár, 1995). Research on pedestrians and pedestrian infrastructure in the last years mainly focuses on the improvement of pedestrian models and simulation in special situations (bottleneck, corners, ...) (Bauer and Kitazawa, 2010; Daamen et al., 2005; Sahaleh et al., 2012; Zhang et al., 2011), the Level of Service for different pedestrian infrastructure such as elevators, escalators or open space with multidirectional flow (Hoogendoorn et al., 2011; Kretz, 2011; Weidmann et al., 2013) and the interaction with other transport modes (Muraleetharan et al., 2005; Weidmann, 1994, 1995). Other research focuses on crowd dynamics (Helbing and Mukerji, 2012; Johansson et al., 2008; Krausz and Bauckhage, 2012; Venuti and Bruno, 2007), evacuation (Hoskins and Milke, 2013; Nilsson and Frantzich, 2011; Peacock et al., 2010) and pedestrian safety.

Apart from the application in the field of transport, the research on pedestrian dynamics is mostly applied in building evacuation. Especially the width of emergency exits, the length of exit routes and the capacity of different facility elements are key factors, which influence the evacuation times. Here, the improvements made in the pedestrian research allow a better design. Especially in recent years, several guidelines based on recent findings in pedestrian research have been introduced for evacuation analyses (Department for Culture, 2008; IMO, 2007; RiMEA e.V., 2016). Similar as in pedestrian transport, the use of pedestrian simulation tools gained importance lately, as the computer performance increased and the models for pedestrian transport proved to be more and more suitable. In some countries, the use of computer simulations is already integrated in the corresponding standards (VKF, 2015).

2.2 PRINCIPLES OF HUMAN WALKING AND BEHAVIOUR

2.2.1 *Human walking motion*

Walking is done daily by most humans without difficulties, although the underlying principles are complex. The evolution of upright walking as it is done by modern humans took place in a timespan covering several millions of years. For each individual human, the development of his or her walking skills is also a process covering several years. It takes about one year for a child to learn to walk but another 4 to 5 years until the walking style is similar to an adult, with further development in the following years (Berger, 1984; Jung, 1984; Simoneau, 2010). Due to its importance, human walking was already studied in ancient times by Aristotle (1961). The first systematic studies on walking were done in the Renaissance, including the first biomechanical studies described by Borelli in the book De Motu Animalum (Borelli, 1685). The start of the modern scientific studies can be set to 1836, where Weber and Weber (1836) published their work on the walk cycle (Simoneau, 2010; Whittle, 2008).

2.2.1.1 *The evolution of human walking*

Upright walking is one of the first key factors in human evolution. In hominid history, bipedalism is considered to be the first considerable adaption, followed by the enlargement of the brain and the use of tools (Amato, 2004; Leakey and Hay, 1979; Weaver and Klein, 2006). The human ancestors originally showed quadrupedal walking and climbing on trees. The transformation to modern human walking was a process over millions of years showing different forms of walking. This transformation involved a considerable change in the geometry of muscles and bones (Lovejoy et al., 2009; Lovejoy, 1988).

In the middle Miocene, around 13.7 million years ago, first evidence of terrestrial locomotion in fossils from Kenyapithecus was found. The bone structures suggest that - apart from climbing - knuckle-walking, like it is performed by Chimpanzee today, was used (Senut, 2012).

The first evidences of hominin bipedalism, found in Orrorin tugenensis, can be dated back to about 6 to 7 million years ago (Pickford et al., 2002; Richmond and Jungers, 2008; Senut et al., 2001). The physiology of Orrorin tugenensis still shows remaining adaptions for climbing trees (Senut, 2012). An ongoing debate can be found in the scientific community, whether Orrorin is an ancestor of Homo (Pickford, 2012). During the evolution of bipedalism in human ancestors, a wide range of terrestrial walking types, from quadruple to bipedal walking, were developed. Only a few hominin genera established human-like bipedal walking (Harcourt-Smith and Aiello, 2004; McHenry, 2012; Senut, 2012).

Modern human like walking can be found about 3.7 million years ago (Crompton et al., 2012). From this age, fossil footprints were found in Laetoli in Tanzania showing fully upright bipedal walking. They are assumed to belong to Australopithecus afarensis (Leakey and Hay, 1979; Raichlen et al., 2010; White and Suwa, 1987). The genus Homo, including todays Homo sapiens, emerged about 2 to 2.5 million years ago. The first representative was Homo habilis, followed by Homo ergaster, which fossils indicate no big difference in bipedal walking to today's human. Before, still some features indicating apelike climbing behaviour were retained in fossils (Weaver and Klein, 2006).

Up to now, the reason for the development of bipedalism and the circumstances in which this process took place are unclear. Charles Darwin proposed that changes in the environment triggered the evolution of bipedal walking in human (Darwin, 1890). Since then, several theories are formulated, but no final conclusion can be drawn (McHenry, 2012; O'Higgins and Elton, 2007). Theories range from the ability to carry tools, children or food, the reduction of skin area to the sun to facilitate thermoregulation of the

FIGURE 2.1: Ancient step stones in the city of Pompeii (Xerti / Wikimedia Commons, CC0).

body, better overview of the surrounding due to a higher eye level, wading in water, higher long distance walking efficiency or the presentation of the upright body in conflict situations (Niemitz, 2010; Pontzer et al., 2014; Weaver and Klein, 2006). For a long time it was unclear in what kind of habitat the transition took place. Nowadays a forested location is assumed for this (Niemitz, 2010; Thorpe et al., 2007). Currently a combination of factors is considered to be the most likely hypothesis for the cause leading to the development of human bipedalism (Niemitz, 2010). It is further unclear if bipedalism developed once or multiple times in different environments and forms (Harcourt-Smith and Aiello, 2004).

In the last decades, newly found fossils provided more insights into the evolution of humans, human walking and the questions of, when, where and how this transition took place. Still evidence is lacking for several current hypotheses and some steps in the development of human walking are unknown.

2.2.1.2 *Walking as a means of transport*

The ability to walk is one of the distinct features of humans. It allowed migrating out of Africa and covering long distances for various reasons since then. Compared to most other animals, humans are excellent in long distance running but slow at short distances (Bramble and Lieberman, 2004). when walking, humans can also cover long distances. A high variation of average daily distance values exists in literature. Maximum walking distances of 33 to 50 km were proposed for daily trips (Buchner, 1853; Lindner, 1831; Mittler, 1830; Trapp and Wallerus, 2006; Voss, 1860). For the army of the Roman

FIGURE 2.2: Saxon milepost in Brück (Acf / Wikimedia Commons, public domain).

Empire a daily marching distance of 20 km for normal and 36 km for fast marches was planned. Without parts of the luggage usually carried, considerably longer trips, up to 90 km, were performed. For multiple days, the maximum daily distance possible is reduced to about 60 to 75 km. Around 1900, the military marching distances are similar; the maximum of single day marches was 70 km. A daily marching distance of 90 km can be considered as physical limit of humans (Riepl, 1972). Today, 32 km (8 hours at 4 km/h) are planned for military marches on paved roads. At night (3.2 km/h) and when walking off-road (day: 2.4 km/h; night: 1.6 km/h) the speed and hence the maximum distance is reduced (Department of the Army, 1990).

Distances covered by normal pedestrians in the classical antiquity without a heavy load were in the range of 30 to 40 km. Considerably longer distances were covered by mail carriers, who made daily distances up to 60 to 90 km per day. Around 1900, some postmen still had to walk up to 50 km on single days (Riepl, 1972).

Up until recent centuries, walking was the main means of transport. Ancient cities were designed based on the needs of pedestrian transport, including walkways and step stones for street crossing (Figure 2.1), as well as city dimensions representing acceptable walking distances (Schnabel et al., 2011). Horses, carriages, boats and other vehicles were used as well, but only after the construction of railroads the mode share of other transport means increased considerably.

Amongst others, the historic importance of walking can be seen by the fact that walking time and step length was frequently used as distance measurements (Figure 2.2). For example, the roman mile (mille passus) consists of 1 000 double steps (passus). The distance a pedestrian is able to walk was furthermore used as a measure of time, which is in several regions the basis for the unit "league" (Meyer, 1852). A compilation of distance measurements based on walking distances can be found in Table 2.1.

The dominance of walking can also be found in the planned distances to public facilities. Josef II, Holy Roman Emperor from 1765 to 1790, declared that new churches shall be erected to allow people to walk not more than one hour from home to the next church (Springer, 1996). Also the distribution of marketplaces in West Africa was found to correspond to a walking distance of not more than 8 to 16 km for all settlements to the next market (Hodder, 1965).

Even today, the walking distance can be found as a reference. For example, the distance covered by one hour of walking is used to determine the need for additional schools in rural areas (Burgenländischer Landtag, 2016; Tiroler Landtag, 2015; Vorarlberger Landtag, 2016).

Beginning with the constructions of railroads in the 19th century, the importance of pedestrian transport was strongly reduced and replaced by other transport means (Weidmann, 2012). Compared to the usage of railways for long distance trips, walking was considered less economical even for day labourers, as the time used for walking could have been used for working (List, 1833). The spreading of the automobile led to a transformation of cities and the street layouts. Some attempts were made to avoid the negative impact of automobiles, specifically accidents, emissions and space demand, as the whole streets were still used by pedestrians (Norton, 2007; Simonett, 1993). Soon, pedestrians were separated from vehicular traffic and sidewalks and traffic lights were installed.

Nevertheless, walking is still an important part of human transport. In addition to walking trips, walking also serves as a first and last mile, as well as an intermediate part, of public transport trips. In addition, other trips include a short walking section to and from the vehicle.

In the last decades, a lot of effort is done to increase the mode share of walking again. Due to the positive health effects, the space efficiency and the inexistent access barriers, walking is rediscovered as a sustainable transport mode, especially for cities.

TABLE 2.1: Historical distance measurements based on time demand for walking.

COUNTRY	DIMENSION	LENGTH [m]	SOURCE
-	Caravan hour	∼ 5 790	[4, 12]
Egypt	Egypt Diocta (Day travel)	∼ 50 050	[4, 7, 12]
Baden	Hour of rout	4 444	[2, 6, 12]
Batavia and Java	Hour	4 205	[8]
Bavaria	Hour of rout	3 707	[2, 8]
Bohemia	Great mile (2 hours of rout)	9 259	[6]
Burma	Day travel (10 Leongs)	33 959	[2]
Byzantine Empire	Emeresjos domos (Day travel)	47 225	[11]
England	Hour of rout	∼ 1 390	[4, 7]
Greece	Greek hour	5 654	[12]
Netherlands	Dutch hour	∼ 5 650	[7, 8, 12]
French India	Courosame	4 158	[2]
Saxony	Hour of rout	4 531	[9]
Spain	Hour of rout	5 010	[4, 7, 12]
Switzerland	Old Swiss hour of rout (Bern)*	5 279	[1, 3, 5, 10]
	Swiss hour of rout	∼ 4 890	[4, 7, 12]
	Old Swiss hour of rout (Zurich)	4 513	[3]
	New Swiss hour of rout**	4 800	[1, 2, 6]
Württemberg	Hour of rout	3 724	[2, 12]

[1] Baedeker (1859) [2] Buchner (1853) [3] Feer (1803) [4] Lindner (1831) [5] Malten (1830)
[6] Meyer(1852) [7] Mittler (1830) [8] Nelkenbrecher and Wolf (1842) [9] Schramm (1726)
[10] Staatskanzlei des Kantons Bern (1837) [11] Trapp and Wallerus (2006) [12] Voss (1860)
*110 Steps (0.8 m) per min
**100 Steps (0.8 m) per min

2.2.1.3 *Physiological principles of walking*

Walking is the most important form of daily locomotion for humans, followed by running, which is mainly relevant in sports (Kramers-de Quervain et al., 2008). It shows a highly repetitive pattern, whose basic element is a gait cycle (Figure 2.3). For each leg, a cycle consists of a stance phase, where the foot is in contact with the ground and a contact-free swing phase (Perry and Burnfield, 2010). On average, the stance phase represents 60 % of the gait cycle and the swing phase 40 %. This ratio depends on the walking speed, with an increase in swing time for higher walking speeds (Enoka, 2015). Between stance and swing phase there is a double support phase where both feet touch the ground, leading to two double support phases per gait cycle.

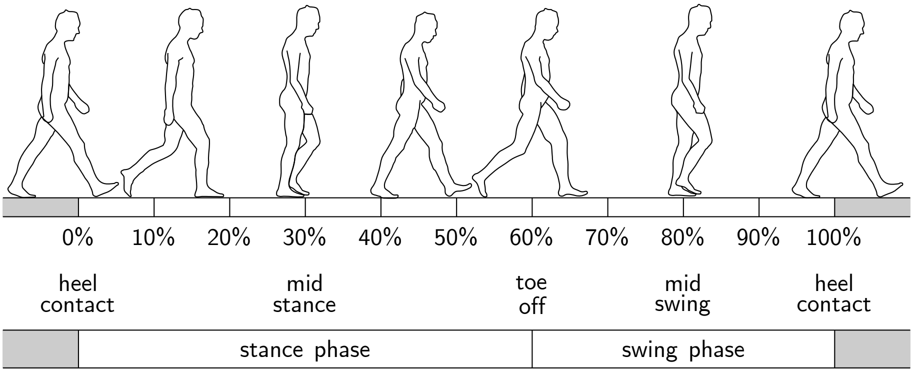

FIGURE 2.3: Gait cycle (silhouettes based upon Muybridge (1887)).

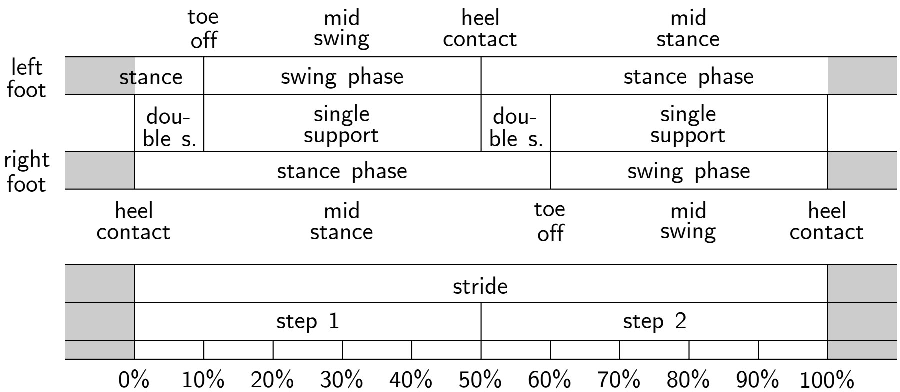

FIGURE 2.4: Left and right foot during the gait cycle.

Each gait cycle consists of one stride, which can be defined as the interval between a heel contact and the following heel contact with the same leg (Figure 2.4). The other foot follows the same pattern with an offset of half a gait cycle. A stride can then be further divided into two steps representing the interval between the heel contact and the next heel contact of the other leg (Enoka, 2015; Perry and Burnfield, 2010).

While walking, the body mass is constantly shifted from one leg to the other, so that one leg serves as support and the other leg moves forward to accept again the body load. The centre of mass of the human body is consequently moving in all three directions of space (Simoneau, 2010).

2.2.1.4 *Step length and frequency*

Walking speed can be determined by the product of stride length and stride frequency. In Table 2.2, average values for the most important walking para-

TABLE 2.2: Average range of walking parameter for adults (Kramers-de Quervain et al., 2008).

PARAMETER	UNIT	VALUE RANGE
Walking speed v	[m/s]	$1.20 - 1.50$
Stride length L_{str}	[m]	$1.30 - 1.50$
Step length L_s	[m]	$0.65 - 0.75$
Step frequency F_{step}	[Hz]	$1.75 - 2.16$

meters for adults are shown. Within the range of normal walking frequencies (1.3 to 2.0 Hz), stride length and frequency are simultaneously increased and decreased respectively to obtain a certain walking speed. Above, the leg length limits the stride length, thus mainly the frequency can be further increased. Only at very high walking speeds, above 2.0 m/s, a constant step length of about 0.95 m was observed (Scholz, 1952, 1953). Below this range more sideward movement is observed, as the rhythmic gait cannot be sustained any more (Kramers-de Quervain et al., 2008). This is in contrast to running, where for lower speeds mostly the stride length is changing and for high speeds the increase in speed is done by increasing step frequency (Enoka, 2015).

For walking speeds v [m/s] up to about 2.0 m/s the step length L_s [m] can be calculated by (Cavagna and Margaria, 1966):

$$L_s = 0.362 + 0.257 \cdot v \tag{2.2}$$

The step length and frequency highly depend on the human body characteristic. For example, at the same speed taller people use a lower step frequency on average. This relation is proportional to the square root of the leg length L_l [m] as described in the inverted-pendulum model for the maximum walking speed v_{max} [m/s] (Alexander, 1984; Hutchinson, 2011):

$$v_{max} = \sqrt{g \cdot L_l} \tag{2.3}$$

Using this model and a leg length of 0.90 m results in a maximum walking speed of 3.0 m/s. At this speed, people usually already changed their locomotion to running, which happens at about 2.0 to 2.5 m/s (Alexander, 1984; Enoka, 2015; Hreljac, 1995).

A linear dependency of step length and frequency on the walking speed can also be seen in real-life measurements (Hediyeh et al., 2015). For the intersection studied, a normal distribution for step length and frequency as well as for the walking speed was found.

2.2.1.5 *Energy demand*

Compared to other transport modes, walking is highly energy efficient. Only when riding a bicycle, less energy is used, as the benefit of wheels outweigh the additional mass of the bicycle. In walking, energy is mainly used to accelerate and decelerate the legs during a gait cycle and to move the centre of gravity up and down, as well as sideways. To reduce the energy demand, several optimisation strategies to transform between kinetic and potential energy and to reduce the displacement of the centre of gravity are applied (Whittle, 2008). In terms of vertical oscillation of the human body, an optimum amplitude of about 3 to 6 cm, depending on the walking speed, exists (Massaad et al., 2007). Although the body reduces the vertical displacement by three-dimensional leg movements and therefore the energy demand, a further decrease will again lead to an increase in the energy demand.

Kinetic energy is transformed to potential energy and back continuously while walking (Inman, 1966). At mid stance, the centre of mass is at its highest point, the potential energy is at maximum and the kinetic energy, thus also the walking speed, is at minimum. The opposite situation occurs during double limb support, where walking speed is highest and the centre of mass is at its lowest point (Simoneau, 2010). The difference between the maximum and minimum walking speed within a gait cycle is about 0.1 to 0.2 m/s for average walking speeds and increases with walking speed (Cavagna and Margaria, 1966; Orendurff et al., 2008). Human walking can thus be described by an inverted-pendulum model, which is in good accordance to experimental data for average walking speeds (Cavagna et al., 1976; Winter, 2009).

The energy demand while walking can be divided into the energy expenditure for standing upright and the energy demand for the additional muscle activities for walking. A higher walking speed results in a higher energy expenditure per time. Within the range of walking speeds, a hyperbolic curve proposed by Ralston (Ralston, 1976; Rose and Gamble, 2006) is found to best represent the relation between walking speed and energy expenditure (Figure 2.5) (Rose and Gamble, 2006). At about 2.4 m/s, where usually the transition from walking to running occurs, running also becomes more efficient than walking (Margaria et al., 1963).

By measuring the energy expenditure per distance, it was found that a minimum exists at a walking speed of about 1.30 to 1.33 m/s for normal adults (Abernethy et al., 2013; Bastien et al., 2005; Browning and Kram, 2005; Simoneau, 2010). At lower walking speeds, the basal energy demand becomes predominant, at higher walking speeds the disproportionately high increase in energy demand prevails. Also the muscular activation time is gait dependent and hence influence the energy demand (Stoquart et al., 2008). Several equations describing the relation between walking speed and energy expenditure per distance proposed in literature are shown in Table 2.3. The optimal speed value is in good accordance with the walking speeds observed for undistur-

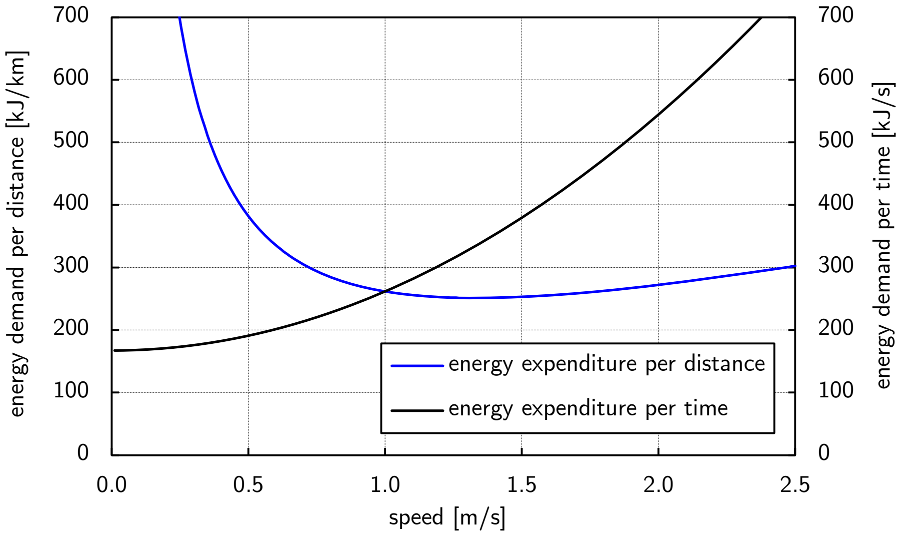

FIGURE 2.5: Relationship between walking speed and energy expenditure as proposed by Ralston (1976). dashed blue = energy expenditure per time [J/s], solid red = energy expenditure per distance [kJ/km].

bed walking (see Chapter 2.3 for a review of walking speed measurements). For each walking speed, a step frequency – step length combination exists with minimum energy expenditure. This is automatically adopted by the human body as well (Scholz, 1953; Simoneau, 2010; Zarrugh and Radcliffe, 1978). The efficiency of walking lies at about 0.20 to 0.25 (Ralston, 1976; Ralston and Lukin, 1969; Rose and Gamble, 2006). Here the efficiency is defined as the total positive work done while walking divided by the total metabolic energy expenditure, which also includes the basal energy demand. The predominant part of the energy is thus transformed to heat.

The relation between energy expenditure and walking speed depends on various human properties. For example, elderly people show a similar U-shaped curve for the energy demand per distance but at a higher energy level. It is supposed that the increase in energy demand is due to a reduction in muscle strength (Abernethy et al., 2013; Martin et al., 1992). Also gender (Wall-Scheffler, 2015), leg length (Leurs et al., 2011), inclination (Cotes and Meade, 1960), mass (Rose and Gamble, 2006) or terrain type (Pandolf et al., 1977) influence the energy – speed relation.

TABLE 2.3: Formulas from literature for calculating the energy expenditure E_d [kJ/km] per distance travelled.

SOURCE	ENERGY EXPENDITURE	
Ralston (1976)	$E_d = (\frac{8}{15 \cdot v} + 0.3 \cdot v) \cdot 4.1868 \cdot G$	
Ralston (1958)	$E_d = (\frac{29}{60 \cdot v} + 0.318 \cdot v) \cdot 4.1868 \cdot G$	
Zarrugh (1974)	$E_d = \frac{E_0}{(1 - \frac{v}{v_u})^2 \cdot v} \cdot G$	
Wall-Scheffler (2012)	$E_d = 132.9 \cdot v^2 \cdot -348.6 \cdot v + 453.8$	(Female)
	$E_d = 178.7 \cdot v^2 \cdot -517.8 \cdot v + 649.8$	(Male)
Browning and Kram (2005)	$E_d = (2.729 \cdot v^2 \cdot -7.256 \cdot v + 7.833) \cdot G$	(Normal)
	$E_d = (2.859 \cdot v^2 \cdot -7.137 \cdot v + 7.455) \cdot G$	(Obese)

G Body mass [kg]
v Walking speed [m/s]
E_0 Energy expenditure at $v = 0$ [J/s kg]
v_u Upper speed limit [m/s]

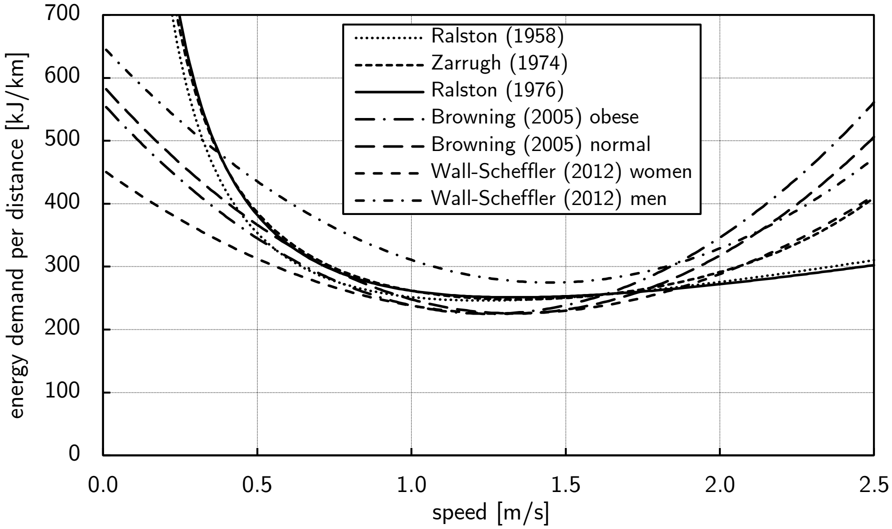

FIGURE 2.6: Energy demand per distance versus walking speed curves from literature; $G = 75$ kg, $E_0 = 1.975$ J/s kg, $v_u = 4.03$ m/s.

2.2.2 *Interactions in pedestrian flows*

2.2.2.1 *Introduction*

Walking in a traffic environment usually also involves the interaction with other pedestrians. In contrast to car traffic, where legal rules are needed to organize the traffic, pedestrian traffic mostly organizes itself without the need of dedicated rules. An exception of this might be the organization on escalators, where in most countries people are asked to stand on the right side and walk on the left.

In general, people adapt their walking speed and direction to avoid getting to close to or even touching each other. Especially the latter is dependent on the individual pedestrians and their characteristics, as exhibited by the differences in interpersonal distances between different cultures (Chattaraj et al., 2009). At higher densities, further self-organization phenomena can be observed.

2.2.2.2 *Lane formation*

In situations showing bi-directional flow a formation of lanes can be observed (Helbing et al., 2001; Hoogendoorn and Daamen, 2005b). These lanes can be stable for long times, especially in corridors without the need for crossing the opposing flow, but they can also form and dissolve within a short time interval.

The formation of lanes reduces the conflicts with the opposing slow, hence the necessity to change the walking speed or direction. The efficiency of the flow is increased by this self-organization phenomena (Helbing et al., 2005; Schadschneider et al., 2011). Using laboratory experiments it was revealed that the variation in desired walking speeds shows a strong influence on the stability of the lanes formed (Moussaïd et al., 2012).

Using computer simulations, a linear correlation between walkway width W_w [m] and average number of lanes N_l was found (Helbing and Molnár, 1995):

$$N_l = 0.36 \cdot W_w + 0.59 \tag{2.4}$$

With an increase in pedestrian density also the number of lanes is decreasing (Helbing, 1997). At high densities, often only two lanes remain.

2.2.2.3 *Pedestrians in groups*

In real-life scenarios, up to 70 % of all pedestrians walk in groups (Moussaïd et al., 2010). Contrary to single pedestrians, which try to avoid others, groups aim at keeping a short distance between the group members, independent of the surrounding pedestrian density (Helbing, 1997). In addition, groups also adapt their walking speed to other group members, hence reducing the walking speed (see Chapter 2.3.8.1). Therefore, the presence of groups also influences the pedestrian flow.

2.2.2.4 *Crowd behaviour*

At very high pedestrian densities, additional phenomena can be seen. In front of bottlenecks, stop-and-go waves can occur when the outflow is lower than the inflow. Similar to car traffic, an alternation between forward movement and backward gap propagation can be seen there (Helbing et al., 2007, 2006). Looking at the speed distribution at a constant density, stop-and-go waves show a double peak, one at about zero speed and the other at a low walking speed (Portz and Seyfried, 2011).

If strong physical contact exists between the pedestrians in crowds at even higher densities, crowd turbulence possibly happens (Helbing et al., 2007). Walking speed and direction is determined completely by the crowd at this stage. Single pedestrians cannot choose their walking speed and direction any more. This results in groups of people being pushed in different locations, visible as turbulences in the crowd. At this stage, it is usually impossible to influence the behaviour of the crowd any more. Hence, for safety reasons, such situations must be avoided. Otherwise, the pressure applied to the human bodies might exceed the resistance of the body and cause injuries and deaths due to suffocation, as well as falling pedestrians often cannot stand up again (Helbing and Mukerji, 2012; Schadschneider et al., 2011).

2.3 ESTIMATING PEDESTRIAN SPEED USING AGGREGATED LITERATURE DATA

This chapter was already published as:

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2.3.1 *Abstract*

For about 80 years, human walking speed is measured for different purposes. Since then the comparability of the results of these measurements is low, as the walking speed is influenced by a vast amount of parameters and no standardised measurement conditions exist.

This work aims at describing the most important influence factors based on existing literature and estimating their impact on the walking speed. For this purpose, a literature review was done, collecting all available walking speed

measurements. Using this data, the parameter values for different influences were computed.

As a result, the influences on the walking speed were grouped according to their strength, which enables to determine the most important parameters to consider in future walking speed measurements. In addition, standardised measurement conditions are proposed which will provide a comparability of future studies and therefore enhance their value.

2.3.2 *Introduction*

Engineers are interested in walking speed for the design of pedestrian facilities and the calculation of evacuation times. In medicine, walking speed is used as a measure for the health of human. Also in many other fields of research, walking speed is measured in combination with different influence factors. The walking speed of humans has often been measured under various conditions and for different purposes. This variety of purposes produced many measurements describing a vast amount of factors influencing the walking speed. However, as most of the measurements are performed in different settings and only once, the possibilities for comparison are poor. In addition, depending on the specific measurements, their results differ substantially. However, in pedestrian simulations, the walking speed is an important input parameter, which strongly influences the results. Each of the influences has usually only a small impact on the results, but in combinations they can generate considerable differences in the results, which are important especially for the design of pedestrian facilities. A better knowledge of the expected walking speed thus improves the reliability of the design.

In this study, the available data shall be consolidated to provide an overview of the available measurements. Here the influences and their correlations will also be systematically described. The next goal of this study is to extract best guesses based upon literature and to reduce the boundaries of parameters. By combining data from individual measurements, reasonable values can be provided. By analysing the data, the most important influence factors will be determined, too. Using the systematic description of the influences and the insights from the data analysis, potential research gaps, where measurement data is missing, can be identified. For future data collections, the paper also proposes standardised measurement conditions, which allow better comparability between measurements.

2.3.3 *Method*

2.3.3.1 *Approach*

The approach used in this work is based on a detailed data collection from literature. By systematically analysing existing literature, past walking speed measurements were identified and the results collected. This approach allows investigating measurement data from walking speed measurements in various settings and therefore having a broad overview about possible influences on the walking speed.

Compared to other approaches, this method has several advantages but also drawbacks that have to be considered. First, the analysis of available data is an efficient method. No new experiments or real-life measurements have to be done. To generate a similar amount of data already present in literature, a vast amount of resources has to be spent. It is therefore more resource efficient to first study existing data and try to get as much information as possible from this data. If this study reveals gaps in the available data, measurements that are more efficient can be done afterwards targeting these specific subjects.

On the other hand, the data available in literature is often lacking a detailed description of the precise conditions in which the measurements were performed. Statistical analyses and data comparisons are therefore strongly restricted. It also has to be noted that the study on influence factors often cannot be made under ceteris paribus conditions. Still, it is argued that the results of this study can produce benefit compared to existing data. At the moment, the values used for describing factors influencing the walking speed are either taken from single time measurements (Bornstein and Bornstein, 1976; Hankin and Wright, 1958; Navin and Wheeler, 1969) or are also based on literature studies but with a smaller data basis (Weidmann, 1993). A study providing consolidated values from as much available data as possible therefore still provides added value to the existing knowledge on walking speed. Other methods, such as experiments or real-life observations, also have shortcomings, which led to the decision to use a systematic literature review as the best suitable method. Apart from the resources needed for experiments, several influences, like the weather conditions, trip purpose or city size, cannot be tested in experiments with ceteris paribus conditions as well. In addition, pedestrians might react differently in the experimental context than under normal conditions. On the other hand, in real-life observations it can never be assured that the set of pedestrians observed is comparable in different situations. Hence, a mixture of experiments and real-life observations is needed to cover the whole range of potential influences, which leads to similar conditions as when using literature data. Especially cross correlations are complex to quantify, which is true for all possible methods.

2.3.3.2 *Literature review*

The literature review was done in a stepwise procedure. The first step was the determination of literature, which might include walking speed measurement data. For this, three approaches were used. By using literature already available in the author's own literature collection on pedestrian transport, citations potentially including walking speed measurements were selected and the corresponding literature was collected. In addition, literature databases (e.g. Google, Google Scholar, Microsoft Academic, Scopus, ScienceDirect and TRID) as well as journal, publisher and author websites identified by the literature already found were searched for relevant citations. For the database searches, keywords like "speed", "walking", "pedestrian" and "human" in German as well as in English were used in different combinations. The third approach to find relevant literature was to look for citations including speed measurements within the available papers. Identified literature was then obtained both offline and online and then checked again for citations until no new useful documents were found. At the end of the first step, 573 out of 661 documents potentially including speed measurements could be obtained.

In the second step, the literature was evaluated and the walking speed measurements were extracted into a database. This was done in a chronological order starting with the first available walking speed measurements in 1933 (Jahoda et al., 1933). This was done to ensure that the original sources were used and only new data was added to the database. In the end, 223 documents with unique measurement data were found.

As a third step, the influence factors considered in the following data extraction were determined. This was done by using the systematic developed by the authors in which they are categorised into four categories (Figure 2.7). According to this scheme, the influence factors considered during data extraction can be distinguished into endogenous and exogenous as well as static and dynamic influences. Especially the classification of static and dynamic depends on the scope, here static is considered to change in time intervals larger than for example a walking trip or a short-term observation. Within these categories, the influences can be grouped into physical pedestrian properties, emotional and cultural influences, facility properties and environmental influences. For some of them, the detailed mechanisms linking them to the walking speed are missing, thus the classification needs to be further developed when these links are determined.

In addition, the method used for the walking speed measurement and other parameters related to the observation as well as the aim of the measurement were considered as influence factors for the walking speed stated in the literature. These factors do not affect the walking speed per se, but they can influence the results of the measurements. Subsequently, a list of

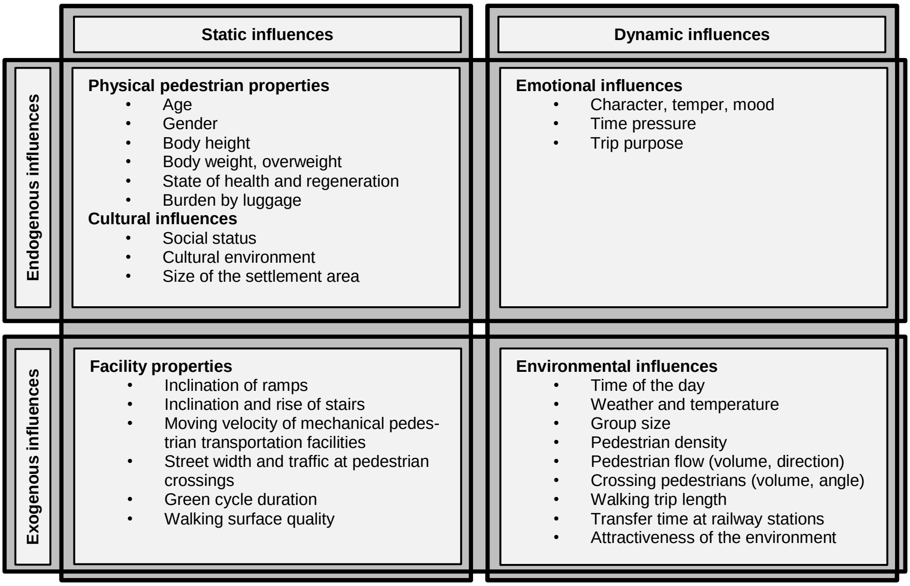

FIGURE 2.7: Influences on the pedestrian walking speed (own figure).

influence factors was created, which was used during data collection in the next step (Table 2.4).

As a fourth step, the data has been extracted from the literature. Based on the list of influence factors the corresponding values were determined for each measurement. Depending on the specific source, values for single measurements or mean values for a set of observations were available. It has to be noted that in most cases only a few influences were described for each study, hence the specific situation in which the measurements took place cannot be reproduced completely.

2.3.3.3 *Data analysis*

During data extraction, the first data analysis step was performed. Here, all literature was excluded which did not satisfy the requirements for data quality or comparability with other measurements. The most common criteria for exclusion were:

- The walking speed stated did not reflect the walking speed measured, but was for example already the result of a regression analysis.
- Only influences on walking speed were analysed which were not included in this study, for example different crossing types or the green cycle duration.

TABLE 2.4: List of influence factors used in the data analysis.

CHAP.	INFLUENCE	CHAP.	INFLUENCE
2.3.5	*Physical pedestrian properties*	2.3.8	*Environmental influences*
2.3.5.1	Gender	2.3.8.1	Group size
2.3.5.2	Age	2.3.8.2	Indoor/outdoor
2.3.5.3	Body height	2.3.8.3	Temperature
2.3.5.4	Body weight	2.3.8.4	Weather condition
2.3.5.5	Luggage	2.3.8.5	Year
2.3.6	*Emotional and cultural influences*	2.3.8.6	Month
2.3.6.1	Race	2.3.8.7	Day
2.3.6.2	Land use	2.3.8.8	Rush-hour
2.3.6.3	City size	2.3.8.9	Daytime
2.3.6.4	Country	2.3.8.10	Trip purpose
2.3.6.5	Continent	2.3.9	*Observation technique*
2.3.7	*Facility properties*	2.3.9.1	Measurement type
2.3.7.1	Inclination	2.3.9.2	Measurement method
2.3.7.2	Facility	2.3.9.3	Measurement length

- The measurement method was disputable, hence, the quality of the measurement could not have been assured.

One of the main influences on the walking speed is the pedestrian density as walking speed declines with increasing density. To eliminate this strong influence, only walking speed measurements at densities where pedestrians usually walk unimpeded were used for this study. In free flow or similar conditions, pedestrians do not react to the presence of other pedestrians, but freely choose their walking speed. This is often also reflected in the pedestrian fundamental diagram, where at low densities the walking speed is considered to be constant and only decreasing after a certain threshold, for example in Weidmann (1993). Also in experiments with single file movement it was found that the velocity is constant up to a certain spatial headway (Appert-Rolland et al., 2014). Still, even at low speeds pedestrians react to other pedestrians, especially because not all pedestrians walk at the same speed. However, as pedestrians do not walk in lines, they can also move sideways to pass other pedestrians. Hence, they do not have to reduce their walking speed for overtaking other pedestrians as long as the density is low enough. For this study, we therefore define the free flow speed as the speed where the pedestrian density does not influence the walking speed significantly. Based upon the data used for this study and theoretical considerations a pedestrian density of 0.5 P/m² was therefore used as the threshold value.

TABLE 2.5: Possible correlations between influences. Legend: ++ strong correlation, + correlation, o weak correlation, - no correlation expected.

	Gender	Age	Body height	Body weight	Luggage	Race	Land use	City size	Country	Continent	Inclination	Facility	Group size	Indoor/outdoor	Temperature	Weather condition	Year	Month	Day	Rush-hour	Daytime	Trip purpose	Measurement type	Measurement method
Age	+																							
Body height	+	++																						
Body weight	+	++	++																					
Luggage	○	-	-	-																				
Race	○	○	○	○	-																			
Land use	-	-	-	-	-	-																		
City size	-	-	-	-	-	-	++																	
Country	+	+	○	+	-	++	○	+																
Continent	+	+	○	+	-	++	○	+	++															
Inclination	-	-	-	-	-	-	-	-	-	-														
Facility	-	-	-	-	-	-	+	+	+	+	+													
Group size	○	○	-	-	-	-	+	-	-	-	-	-												
In-/outdoor	-	○	-	-	-	-	++	-	-	-	++	++	-											
Temperature	-	-	-	-	-	○	-	-	+	+	-	-	-	++										
Weather cond.	-	-	-	-	-	+	-	-	+	+	-	-	-	++	++									
Year	-	+	○	○	-	○	○	○	-	-	-	-	-	-	-	○								
Month	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-							
Day	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	○	-	-						
Rush-hour	+	++	-	-	○	-	-	+	-	-	-	-	++	-	-	-	-	○	○					
Daytime	○	+	-	-	○	-	-	-	-	-	-	-	++	-	+	+	-	-	-	++				
Trip purpose	+	++	-	-	++	-	++	+	-	-	-	○	++	+	-	○	○	○	○	++	++			
M. type	+	+	-	-	++	-	++	-	-	-	-	++	++	++	+	+	-	-	-	++	-	++		
M. method	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	++	
M. length	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	++	++

Next, the data points were aggregated to one average value for each situation with constant influence values. By applying this method, the differences in the aggregation level of the literature data as well as the influence of the different number of data points for a specific situation were eliminated. In general, more measurements will provide more reliable data, but this increase is nonlinear. As the amount of measurement values ranges from just a few to several thousand measurements, only the average value for each situation is used. This is done, as it is expected that the influence of different settings is more important, in terms of reliability of the results, than the amount of data collected in the same one.

For the data evaluation, each influence was analysed separately. On the one hand, this allows to evaluate each of them in a different way, which is a necessity considering the diverse influences. On the other hand, this approach assumes that the influence factors are independent, hence, no cross-correlation or bias between them occurs. In Table 2.5 possible correlations between the influence factors were estimated. For example, men are expected to be on average taller than women. It can be seen that several correlations exist which cannot be studied by the method used in this work. It will also not be possible to solve this issue completely by using other methods. As it might affect the results for some influences, it will be addressed in the further analysis. Still, it can be seen that most of the influence pairs can be considered uncorrelated. For these cases, the results are meaningful.

In addition, this work assumes that the strength of the individual influences is independent of other influences, for example, tall women react similarly to temperature as small men do. For the comparison of measurements in different settings, this assumption is crucial. Otherwise, it will never be possible to compare different measurements or generalise them, as it is impossible to generate exactly the same conditions twice. However, further research is indicated to determine and quantify these dependencies. Up to our knowledge, this was not done yet in a comprehensive way.

For this work, the individual influences were considered to reflect a percentage increase or decrease in walking speed compared to a reference condition. For example, women walking speed is considered to be 92 % of men's walking speed. The threshold for the significance was set at 0.05. The superposition of different influences will then be done by multiplying their effects.

In general, two different types of influences in relation to the available measurements can be determined. A few influences, such as gender and age of a person, vary within one data collection. Hence, they can be compared with each other in a setting, where all the other influences can be assumed to be constant. For example, to quantify the influence of the gender, the walking speed for men and women were compared in the same situation. Depending on the situation, the absolute value of the walking speed will be different when comparing with another situation, but it is assumed that the ratio between the walking speed for women and men will be constant. The quantification of the influence was therefore done by taking the ratio between the walking speed and the walking speed for a given reference scenario (e.g. men's walking speed).

Other influences, such as the observation technique, mainly differ between different studies, but usually do not change within a single study. Therefore, these influences can only be evaluated by using data from different measurements, which might have varying measurement conditions. Here, the absolute values are given, although the relative values are more meaningful and the level of the absolute values might be biased. Nevertheless, as the determination of a reference condition is not suitable for most of the influences, no reference conditions were introduced at this point and no normalisation was done. In the conclusions, a proposition to resolve this issue and to enhance comparability between different measurements can be found.

At first, influences were analysed where a comparison with otherwise constant conditions was possible. Successively the quantity of each influence was estimated and then the influence was eliminated from the dataset. This was done by calculating the corresponding walking speed for a reference scenario, where the examined influence has a fixed value.

Afterwards, the other influences were ordered to first evaluate the ones, which are considered strongly independent from the others. For example, the facility type is considered to have an impact on the walking speed independent from the country of the measurement. An uneven distribution of the measurements concerning the country is therefore not expected to affect the influence of the facility type. Otherwise, the walking speed in a specific country will be strongly influenced by the facilities on which the walking speed measurements are performed. Therefore, the facility type will be evaluated prior to the country. The order of influences used for the evaluation can be found in Table 2.6. It has to be noted that in some cases, the order can affect the results of the analysis, so that the effect of latter influences is reduced in favour of earlier ones. For example, the influence of body height might be already included in the gender, as male are on average taller than women. This issue will be further discussed in the respective sections.

For comparison, data from the literature study made by Weidmann (1993) and translated to English (Buchmüller and Weidmann, 2006) is used. This study on the walking speed was done more than 20 years ago using a considerable smaller database, but is still widely used as a reference for walking speed data (Daamen and Hoogendoorn, 2012; Galiza et al., 2011; Johansson and Kretz, 2012; Venuti and Bruno, 2007). Therefore, the results of this study are compared to the existing values and the differences are discussed.

TABLE 2.6: Order of influences for the analysis.

ORDER	INFLUENCE	CHAPTER	STUDIES	MEASUREMENTS
1	Gender	2.3.5.1	77	253
2	Group size	2.3.8.1	13	33
3	Age	2.3.5.2	67	665
4	Inclination	2.3.7.1	9	14
5	Facilities	2.3.7.2	202	844
6	Indoor/outdoor	2.3.8.2	195	777
7	Body height	2.3.5.3	23	24
8	Body weight	2.3.5.4	19	19
9	Luggage	2.3.5.5	23	37
10	Temperature	2.3.8.3	4	6
11	Weather condition	2.3.8.4	8	40
12	Year	2.3.8.5	202	663
13	Month	2.3.8.6	32	157
14	Day	2.3.8.7	13	64
15	Rush-hour	2.3.8.8	202	632
16	Daytime	2.3.8.9	21	96
17	Measurement type	2.3.9.1	202	616
18	Measurement method	2.3.9.2	202	615
19	Measurement length	2.3.9.3	76	311
20	Trip purpose	2.3.8.10	202	554
21	Race	2.3.6.1	202	533
22	Land use	2.3.6.2	202	533
23	City size	2.3.6.3	157	325
24	Country	2.3.6.4	189	189
25	Continent	2.3.6.5	191	191

2.3.4 *Data description*

2.3.4.1 *Literature groups*

The literature on walking speed measurements can be divided into different groups according to their research focus (Weidmann, 2012). In addition, the grouping of the literature available revealed further research focuses. The main groups researching walking speed can be found in Table 2.7.

The first measurements found were done in a sociographic study about Marienthal, a small city with a high rate of unemployment during the World Economic Crisis (Jahoda et al., 1933). Here the walking speed was used as a measure for the social status and their personal motivation. In the following decades several other publications were found, which correlate the walking speed with their cultural, economic and social status, formulated in the "pace of life" (Bornstein, 1979; Bornstein and Bornstein, 1976; Levine, 1988; Levine and Norenzayan, 1999; Morgenroth, 2008; Schmitt and Atzwanger, 1995).

In the middle of the 20th century the first literature concerning the capacity of pedestrian facilities were found (Daeves and Flachsbarth, 1952; Evans, 1950; Reimer, 1947; Scholz, 1952). Until now more and more measurements under different conditions were performed. Some literature concentrates on the capacity of pedestrian facilities, hence strongly considering the speed-density relation (Isobe et al., 2004; Müller, 1968; Navin and Wheeler, 1969; Oeding, 1963; Seyfried et al., 2005). A special focus is set here on the capacity and design of public transport stations (Cheung and Lam, 1997; Hankin and Wright, 1958).

In transportation research another aspect where the walking speed is required are pedestrian crossings. For the evaluation of the capacity and the design of traffic light cycle durations the expected walking speed is needed. Several literature is published investigating the walking speed for different crossing types and pedestrian characteristics (Hediyeh et al., 2014; Henderson and Jenkins, 1974; Kirsch, 1962).

Another engineering application for walking speed data is the building evacuation. Here often the walking speed on stairs is measured to determine the egress time (Boyce et al., 1999; National Bureau of Standards, 1935; Pauls, 1980; Peacock et al., 2011).

In the last decades several approaches for modelling pedestrian traffic were proposed (Daamen, 2004; Helbing and Molnár, 1995; Hoogendoorn et al., 2014; Løvås, 1994). To validate these models, data on pedestrian walking speed under defined conditions is needed (Liu et al., 2009; Parisi et al., 2009). Therefore several experiments were performed, also to evaluate human walking in different geometries, such as turns and bottlenecks (Hoogendoorn and Daamen, 2005a; Seyfried et al., 2006; Zhang and Seyfried, 2014).

Table 2.7: Different groups of walking speed measurements.

TOPIC/GOAL	MAIN STATEMENT	FIRST STUDIES	RECENT STUDIES	STUDIES USED
Social status, personal motivation	Successful and busy people walk faster	Jahoda et al. (1933)	Morgenroth (2008); Wiseman (2008)	18
Capacity of pedestrian facilities	Creation of fundamental diagrams, maximum capacity	1937 (Predtečenskij and Milinskij, 1971), Reimer (1947)	Nazir et al. (2014)	67
Pedestrian crossing	Pedestrians crossing speed, design speed	Evans (1950); Kirsch (1962)	Hediyeh et al. (2015)	42
Building evacuation	Walking speed for people in evacuation situations, capacity of bottlenecks	National Bureau of Standards (1935)	Almejmaj and Meacham (2014)	8
Modelling pedestrians	Human walking in predefined conditions for model evaluation	Daamen and Hoogendoorn (2003)	Daamen et al. (2014); Nikolić (2016)	23
Medicine/ human gait	Determination of the optimal walking speed in terms of energy consumption	Scholz (1952)	Ludlow and Weyand (2016); Weyand et al. (2013)	16
Medicine/ health	Walking speed as an indicator of health	Browning et al. (2006)	Studenski et al. (2011)	15

Parallel to the walking speed measurements done in the field of engineering, walking speed was investigated in medicine. First, the research focus was set at the understanding of human gait and the corresponding energy consumption (Dean, 1965; Ralston, 1958; Scholz, 1953; Weyand et al., 2010). Secondly, the walking speed was found to be a good indicator for the health of a subject. Therefore various literature was found investigating the influence of physical and mental disabilities to the walking speed (Browning et al., 2006; Studenski et al., 2011).

In all of these fields, also studies from recent years can be found, indicating that there is still research conducted in this field and further walking speed measurements are performed. In Table 2.7 relevant studies from recent years are mentioned as well as the number of studies per field used in the further analysis. It has to be mentioned that this number do not represent the total amount of literature in this field, as studies not relevant for further analysis are not stated.

2.3.4.2 *Number of measurements*

Most of the data obtained from literature is provided in an aggregated form. Whenever possible, the number of single speed measurements was recorded. When there was no information about the number available, each data point was recorded as one measurement. In total 342 576 measurements were retrieved from literature. Due to the broad literature review, it is expected that a considerable share of the total available data was obtained. Still, it has to be mentioned that measurements not published to a wider audience and sources in languages other than English and German might be missing.

Due to the possibility to perform long time video recordings and, in the last years, to extract speed data using automatic procedures, the amount of data increased within the last years (Figure 2.8). As can be seen in Figure 2.9, also the number of literature sources per year increased in the last decade but not proportional to the amount of data. Thus, the number of measurements per literature source increased.

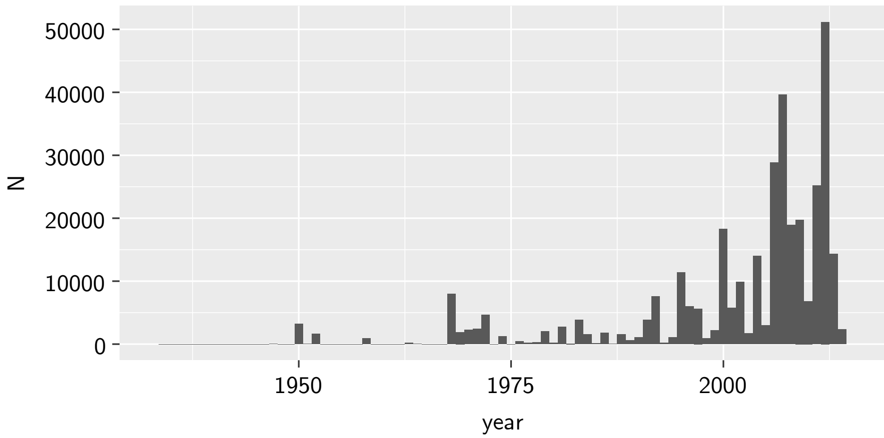

Figure 2.8: Number of measurements obtained by year of publication.

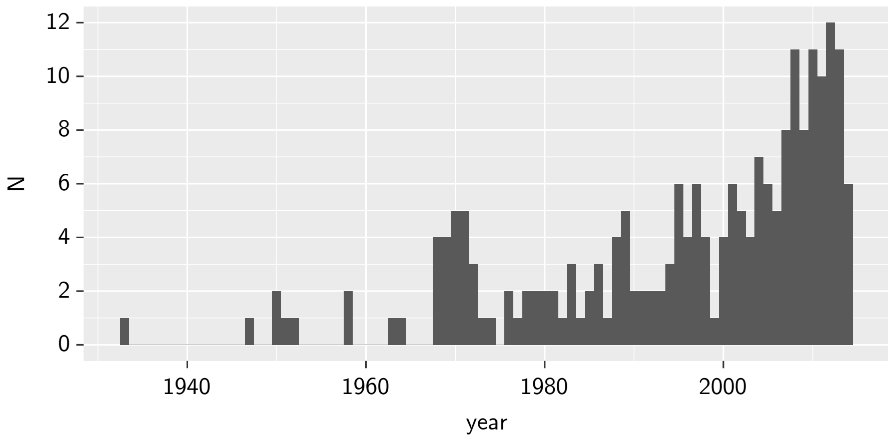

Figure 2.9: Number of literature sources by year of publication.

2.3.4.3 *General statistics*

The histogram of the speed measurements can be found in Figure 2.10. It can be seen that the walking speed for free flowing conditions varies between 1.0 and 1.6 m/s with some outliers above and below. The peaks in the histogram can be due to several reasons. For some data, only the mean value for a certain set of influences is provided, hence the distribution of the values is neglected. Also for some influence factors, some values might be overrepresented. For example, walking speed of only elderly people is often determined to obtain the walking speed reduction when getting older.

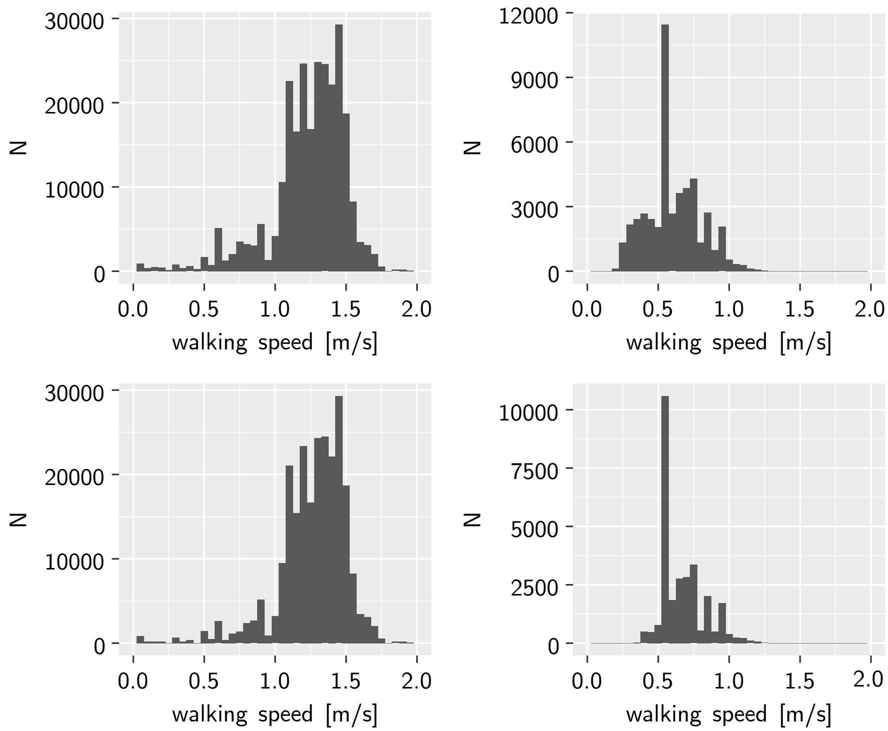

FIGURE 2.10: Histogram of all speed measurements obtained from literature (left = non-stair facilities, right = stairs, top = all densities, bottom = densities ≤ 0.5 P/m²).

One of the main influences to walking speed is the pedestrian density, as described in the fundamental diagram. For all the data, where the density could be obtained, Figure 2.11 (all data without stairs) and Figure 2.12 (data from stairs) show the relationship between speed and density. Where free flowing conditions were stated in the literature, a density of 0 P/m² was used. At low densities, the observed speed varies greatly. With an increase in density, the range of speed values observed reduces, mainly by the reduction of the maximum speed. Even at densities higher than 5 P/m² movement was measured. However, it has to be considered that only a few measurements are available for these high densities.

For comparison, the fundamental diagram curve from Weidmann (1993) for flat walkway respectively up- and downhill walking on stairs is added to the figures. These curves were obtained from a literature review and were calculated as the fundamental diagram for an average population. For flat surfaces, the curve is in a good fit at the upper part of the data, compared to the experimental data. For stairs, especially at low densities higher walking speeds were measured compared to the Kladek Formula. Considering the histogram for walking speed on stairs in Figure 2.10 it can be seen that the range of walking speed measurements is higher than expected, but the average is in well accordance to the curve from Weidmann.

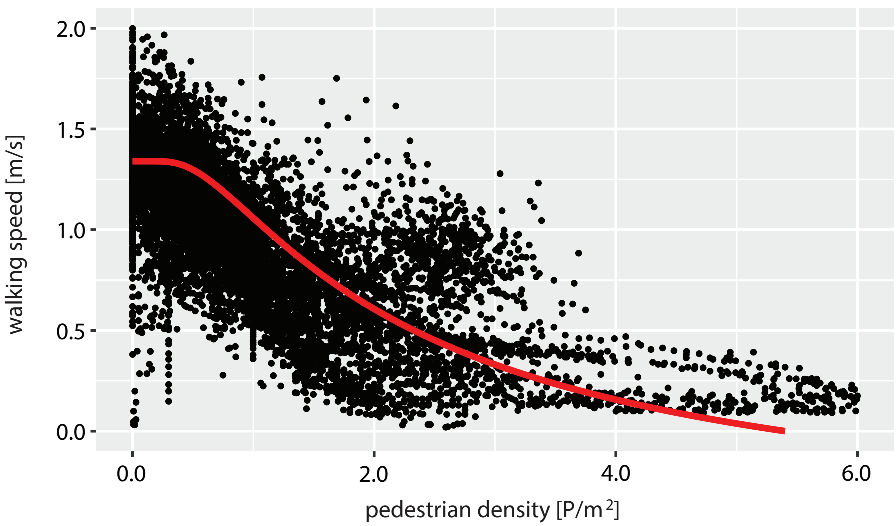

FIGURE 2.11: Speed-density relation for all literature data except data from stairs used compared to the Kladek Formula (Weidmann, 1993).

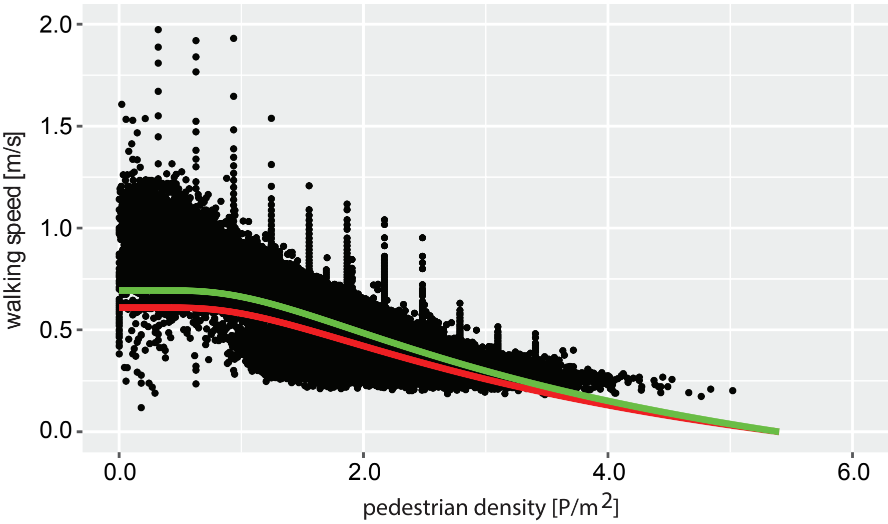

FIGURE 2.12: Speed-density relation for all literature data for walking speed on stairs used compared to the Kladek Formula for walking up- and downhill on stairs (Weidmann, 1993).

2.3.5 *Physical pedestrian properties*

2.3.5.1 *Gender*

To compare the influences of gender on the walking speed, data from observations were used, where only the gender differed. Using this method, 117 data pairs from 65 literature documents were used. For this data, the ratio of women walking speed to men walking speed was calculated. When plotting this ratio against the men walking speed, a linear correlation can be estimated, which indicates that the ratio is equal for all walking speeds (2.13). Therefore, no evidence was found that the difference in walking speed due to gender is affected by the density or other factors influencing the walking speed. The ratio between men's and women's walking speed ranges from 0.40 to 1.24 with an average of 0.92 (Figure 2.14), which means that in average the women's walking speed is 92 % of the men's walking speed. This is in good accordance to the value of 90 % found by Weidmann (1993). The difference between men's and women's walking speed was found to be significant.

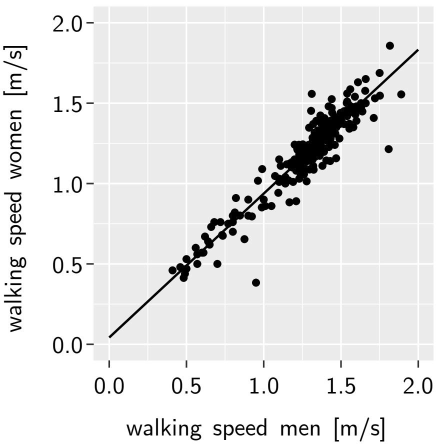

FIGURE 2.13: Correlation between walking speed of men and women in same situations.

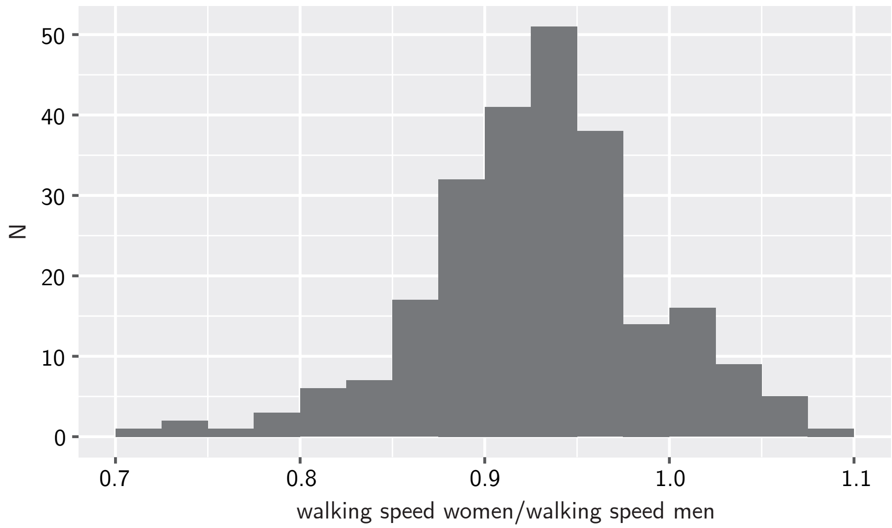

FIGURE 2.14: Histogram of the ratio between the walking speed of woman and men.

2.3.5.2 *Age*

Several references were found which clearly indicate the influence of age on the walking speed. The walking speed is considered to increase until the age of about 20 and then to decrease similar to the physical abilities (Weidmann, 1993).

To evaluate the influence of age based on the literature data, a reference curve obtained from Weidmann (1993) was used. This step was necessary for comparing speed values for different age classes. Based on the age class of each measurement, the corresponding speed value was obtained using the curve. To include the fact that the number of people in each age class is not the same, especially when considering elderly people, an estimate of the age distribution was used (UN DESA, 2013). As most of the literature used was from Europe and North America, the age distribution for these continents served as a reference. The results were then compared to the literature value to obtain the ratio between the literature value and the estimate based on the speed-age curve. To eliminate other influences, the average ratio for each set of measurements was computed and used to normalise the measurements. As a result, the deviation of the literature measurement to the initial curve was obtained. The mean deviation for all literature values can be found in Figure 2.15. It can be seen that the differences in walking speed between the age of 20 and 70 is found to be lower than in the reference data.

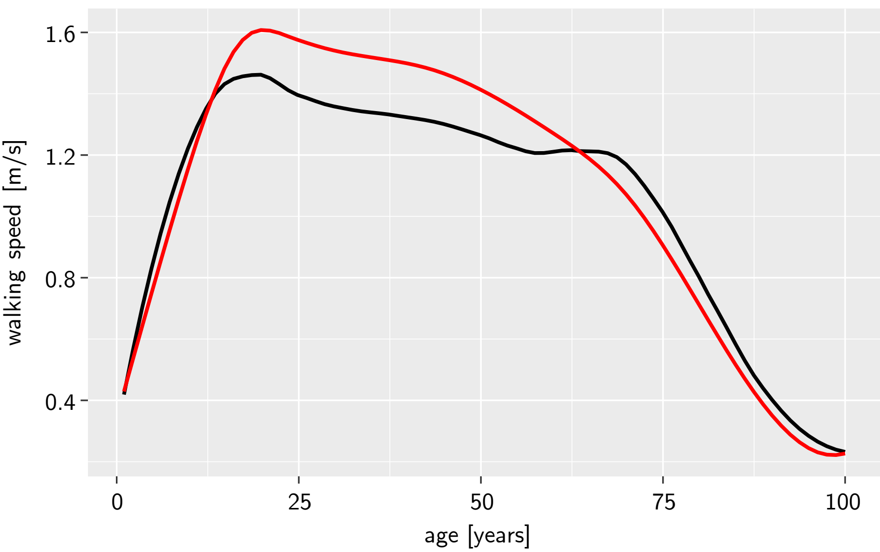

FIGURE 2.15: Influence of age on the walking speed (black: new data, red: Weidmann (1993)).

Most of the measurements were done either by estimating the age group of the pedestrian in field studies or by doing laboratory experiments. In these cases, people unable to walk are usually not considered. This group is relatively small in the younger age groups, but the group of old people include a higher amount of these people. In field measurements, also people are not measured who stay at home, because they are not able to cover longer distances or are too slow to cross the street at a reasonable amount of time. Therefore, it has to be considered that the speed values measured in the older age group do not represent the whole population.

2.3.5.3 *Body height*

Higher body height and therefore higher leg length is considered to be correlated to higher walking speed (Weidmann, 1993). In the literature data used for this study, only in some references the body height was stated. Among these, no source was found where the walking speed was measured with the body height as the only varying variable, usually also the age, gender or the body weight differs at the same time. Using a stepwise linear regression, speed measurements performed in several Swiss cities showed an increase in walking speed with increasing body height (Da Forno et al., 2011). Here, the body height was estimated using three height categories, hence no quantitative information about the actual body height-speed relation is available.

Contradicting the literature results, the data in Figure 2.16 show a decreasing trend in the walking speed with height. A possible explanation for this result is the small amount of data and the fact that there are several other parameters influencing the walking speed. Another effect might be that the range of body height in this study is narrow, hence differences in the energy expenditure for walking, which might influence the walking speed, are small and that pedestrians do not necessarily walk with their energetically optimal walking speed. Walking can be considered as a pendulum movement, thus body height positively correlates with speed by an increased step length due to longer legs, but is negatively correlated due to a reduced step frequency. For similar body heights, as present in the data, this effect almost eliminates the height effect. Still, for small people like children it is intuitive that the walking speed is reduced. It also has to be noted that the body height is strongly correlated with other influences such as gender and body weight, thus the reliability of this result is small. At least for the body height studied, it can be concluded that the influence of body height is statistically not significant, thus, if any, this influence is relatively small. As the amount of data available is small, the influence was not included in further analyses.

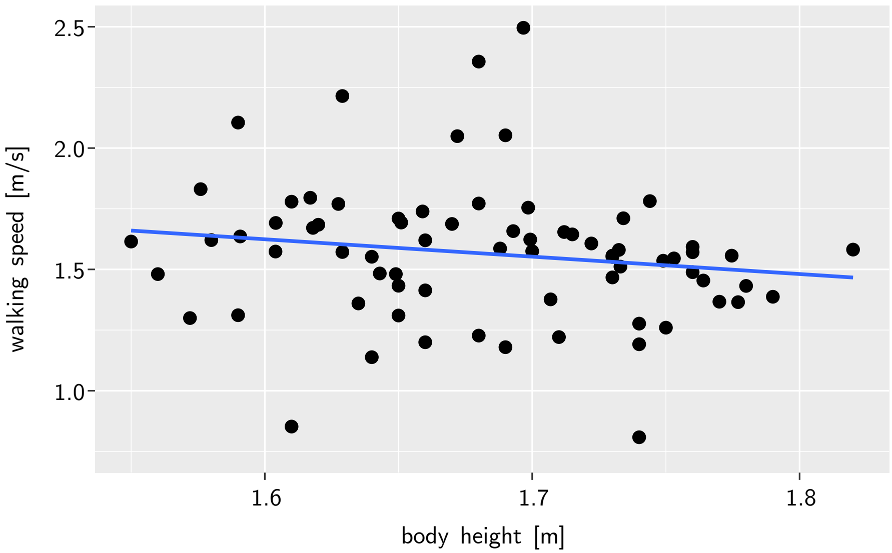

FIGURE 2.16: Height versus walking speed, normalised for age and gender ($y = -0.716 \cdot x + 2.769,\ R^2 = 0.026$).

2.3.5.4 *Body weight*

Similar to the body height, the body weight was usually measured in combination with age or gender. Using a linear model, the results in Figure 2.17 shows a slight decrease in walking speed with increasing weight, although this decrease is not significant. This is in accordance with some of the references (Da Forno et al., 2011) whereas other studies did not show any influence (Browning et al., 2006). Measurements on the energy consumption for walking show that the optimal walking speed in terms of energy is slower for heavier people (Browning et al., 2006). Still, the energy demand does not change strongly at slightly lower or higher walking speeds, therefore the influence of body weight on the walking speed can be smaller than it is reflected in the energy demand. It has to be added that the body weight also correlates with the body height. This correlation and its influence on the walking speed were not investigated in detail here.

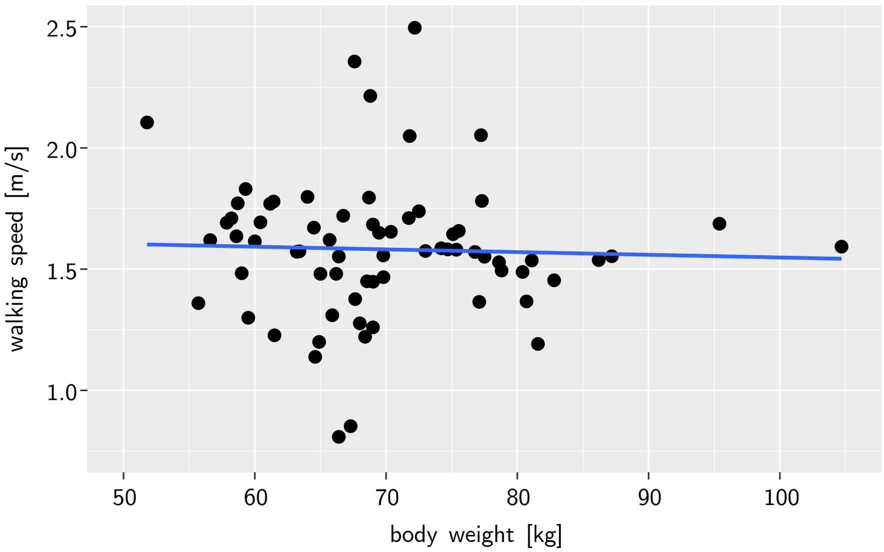

FIGURE 2.17: Body weight versus walking speed ($y = -0.001 \cdot x + 1.659,\ R^2 = 0.001$).

2.3.5.5 *Luggage*

Another influence factor is the luggage carried by the person. 13 references were found, which provided the walking speed for people carrying different kinds of luggage. For comparison reasons, only people with no luggage were compared to people with different kinds of luggage. As the different sources use different definitions of people carrying luggage or do not provide any definition, no further investigations were done. Comparing the influence of luggage carriage in different sources, no clear influence can be determined. The walking speed of people carrying luggage varies between 76 and 111 % of the walking speed of people carrying no luggage. As it is usually not expected that people carrying luggage walk faster than people with no luggage, the reason for this behaviour might be that the two groups differ in some other influence factor, which was not observed. On average, pedestrian carrying luggage were observed to walk at 95 % of the speed of people walking without luggage. Still, this difference was found to be not significant.

2.3.6 *Emotional and cultural influences*

2.3.6.1 *Race*

References were found indicating that the human race influences their walking speed (Da Forno et al., 2011). As there is no reason, why the race itself has an influence on the walking speed and the differences are not statistically significant, the race might serve as an indicator for other influences (Figure 2.18). For example, the personal characteristics or the trip purpose might be different for different groups. The differences between races observed in the data are therefore not considered relevant.

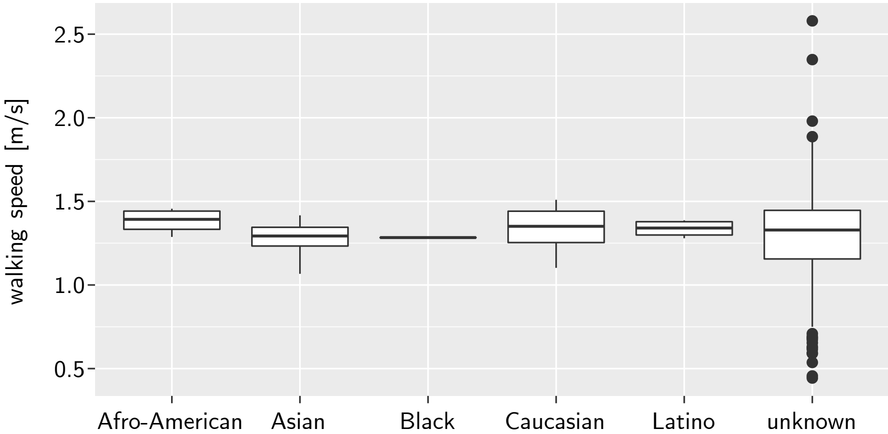

FIGURE 2.18: Race versus walking speed ($R^2 = 0.001$).

2.3.6.2 *Land use*

The influence of the land use can be due to two different factors. First, the surrounding land use can have a direct impact on the perception of the human and hence his walking speed. Second, the land use can serve as an indicator for the pedestrian's trip purpose, which is often not revealed in the studies. Central business districts therefore show the highest walking speeds (Figure 2.19), but only the land use categories school/university has a significant different average walking speed.

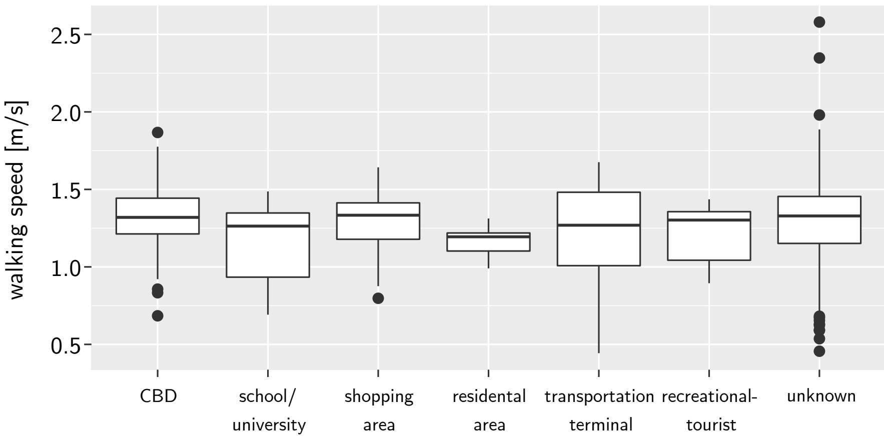

FIGURE 2.19: Land use walking speed ($R^2 = 0.029$).

2.3.6.3 *City size*

Several references found an influence of the city size on the pedestrian walking speed (Bornstein, 1979; Walmsley and Lewis, 1989). This influence is also visible in the available data, even though it is not significant and relatively small (Figure 2.20). The influence of city size is expected to serve only as a proxy for other influences, such as land use or trip purpose. Therefore, the fact that no or almost no influence was found in the data is not unexpected, even though it contradicts the references found. For cities with about 10 000 inhabitants the average walking speed is computed to 1.33 m/s whereas for cities with 1 000 000 inhabitants it is 1.35 m/s. Thus, due to the small absolute differences, the influence of city size can usually be neglected.

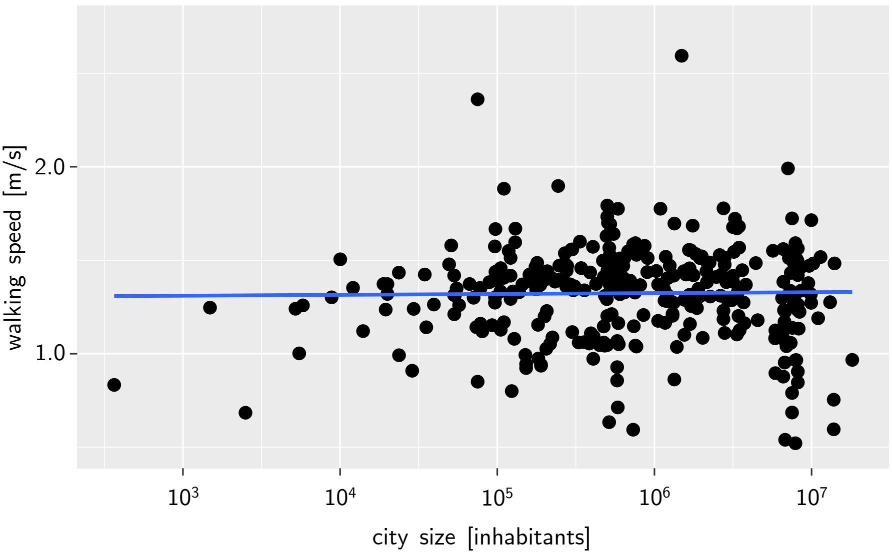

FIGURE 2.20: City size versus walking speed ($y = 0.017 \cdot log(x) + 1.264,\ R^2 = 0.003$).

2.3.6.4 *Country*

Differences in the walking speed of different countries can have various reasons. As for most of the influence factors, they can occur due to other influences not stated in the observations and therefore not included. However, there are also real reasons, for example variations in climate, wealth, or culture. Usually the personal characteristics invisible for an observer are not known, therefore, it is impossible to explain the differences observed (Table 2.8). Even though some of the differences are significant, no conclusion can be drawn if these differences are linked to the properties of the country.

2.3.6.5 *Continent*

Summarising the countries by continent, some differences between continents can be found which are not significant. The continent with the slowest average walking speed is Asia, the fastest South America (Figure 2.21). It has to be noted here that most of the measurements were done in Europe and North America, only a few measurements were obtained from Africa, South America and Australia.

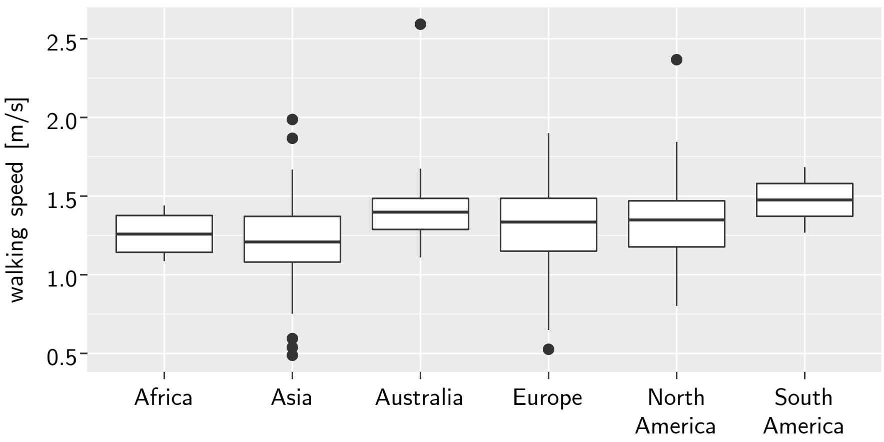

Figure 2.21: Continent versus walking speed ($R^2 = 0.044$).

TABLE 2.8: Average walking speed [m/s] in different countries (based on own calculations, $R^2 = 0.219$).

COUNTRY	SPEED [m/s]	COUNTRY	SPEED [m/s]
Australia	1.55	Kuwait	0.99
Austria	1.34	Malawi	0.59
Bahrain	1.06	Malaysia	1.42
Bangladesh	0.96	Malta	0.53
Brazil	1.38	Mexico	1.33
Bulgaria	1.25	Monaco	1.15
Canada	1.44	Netherlands	1.43
China	1.26	New Zealand	1.37
Costa Rica	1.36	Papua New Guinea	1.43
Croatia	1.54	Poland	1.48
Czech Republic	1.48	Romania	1.19
Denmark	1.73	Saudi Arabia	1.04
Egypt	1.32	Singapore	1.40
El Salvador	1.29	Slovenia	1.54
France	1.44	South Africa	1.26
Great Britain	1.25	South Korea	1.32
Germany	1.37	Spain	1.59
Greece	1.27	Sri Lanka	1.37
Hungary	1.32	Sweden	1.33
India	1.16	Switzerland	1.32
Indonesia	1.16	Syria	1.20
Ireland	1.54	Taiwan	1.29
Israel	1.14	Thailand	1.05
Italy	1.33	United Arab Emirates	1.28
Japan	1.36	USA	1.33
Jordan	1.23	Yemen	1.31
Kenya	1.44	Zimbabwe	1.35

2.3.7 *Facility properties*

2.3.7.1 *Inclination*

Several references include the effect of the inclination on the walking speed in their work. Based on the facility type, the inclination has to be divided into two different regimes. At higher inclinations, stairs can be found, whereas lower inclinations are usually connected to ramps. In Figure 2.22 the walking speed in dependency of the inclination can be seen. Using the available data, a linear regression analysis was done separately for the up- downhill direction as well as for stairs and ramps. As expected all four analysis show an influence of the inclination on the walking speed, although only the influence of the uphill direction is significant. In the uphill direction on ramps, the reduction in walking speed was found to be highest. The data for the uphill direction is in well accordance with the reference values, whereas the downhill values were found to be lower. Here also the variation in the data is bigger, thus the results are less meaningful. A possible explanation for the only small influence in the downhill direction is that the power demand for walking downhill is lower than for flat walking, but the energy optimal walking speed and the willingness to increase the walking speed does not change much. Only for steep surfaces the walking speed will be reduced due to difficulties while walking, therefore this is not visible in the data.

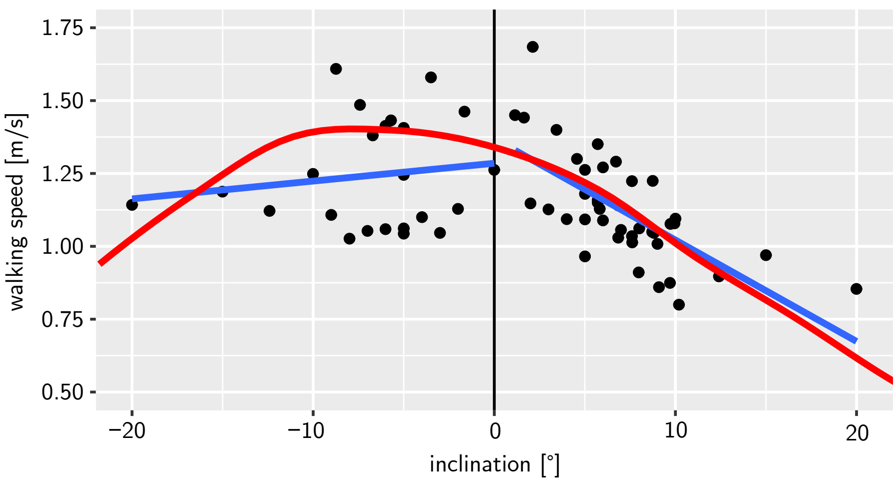

FIGURE 2.22: Influence of the inclination [°] on the walking speed, (blue: new data, red: Weidmann (1993)) (downhill: $y = 0.007 \cdot x + 1.289$, $R^2 = 0.021$, uphill: $y = -0.033 \cdot x + 1.357$, $R^2 = 0.470$).

2.3.7.2 *Facility*

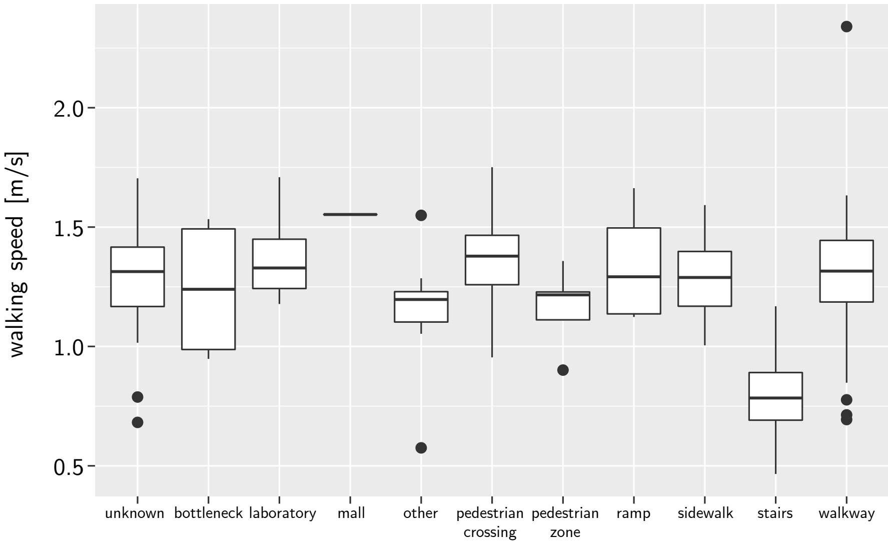

FIGURE 2.23: Walking speed on different facilities ($R^2 = 0.342$).

The type of walking facility can be seen as one of the strongest influences on pedestrians walking speed (Figure 2.23). Especially the presence of stairs leads to a considerable reduction in walking speed. Considering the limitations of the method used in this study, some of the differences in walking speed might also occur due to other influences. To increase the number of observations and therefore the stability of the results, the walking facilities were grouped by similar facility types (Table 2.9). Surprisingly, the highest walking speed was found to be in malls. Here the small amount of data for this facility might have influenced the result. When using walkways as a reference, the categories stairs, pedestrian crossings, pedestrian zones and other show a significant different walking speed.

TABLE 2.9: Average walking speed on different facilities.

FACILITY	SPEED [m/s]
Bottleneck	1.24
Laboratory	1.36
Mall	1.55
Other	1.16
Pedestrian crossing	1.43
Pedestrian zone	1.20
Ramp	1.46
Sidewalk	1.32
Stairs	0.76
Walkway	1.34

2.3.8 *Environmental influences*

2.3.8.1 *Group size*

By using the same methodology as for the gender, the influence of the group size was determined. A group is defined as people walking together, hence having the same walking speed and adapt their behaviour to the others. This distinguishes them from people walking at higher densities, where they might also have the same walking speed and walking direction, but do not intend to stay in the vicinity of the other group members. In contrast 19 observations from nine different sources were found, where the influence of the group size was determined. For comparison, the speed values for the different group sizes were put in relation to the speed at a group size of two. In Figure 2.24 it can be seen that an increase in group size decreases the walking speed. The highest reduction was observed between people walking alone and people walking in pairs, who have on average 90 % of the single pedestrian walking speed (Table 2.10). The difference between the walking speeds for single pedestrian walking compared to groups of two to six pedestrians is significant. An increase in walking speed for groups of six people compared to a group size of five can be observed. Nevertheless, this difference is not relevant, as only a single source was found including measurements for groups of six people.

2.3.8.2 *Indoor/outdoor*

When comparing indoor and outdoor locations, a significant difference was observed. The data show that people tend to walk about 16 % faster in out-

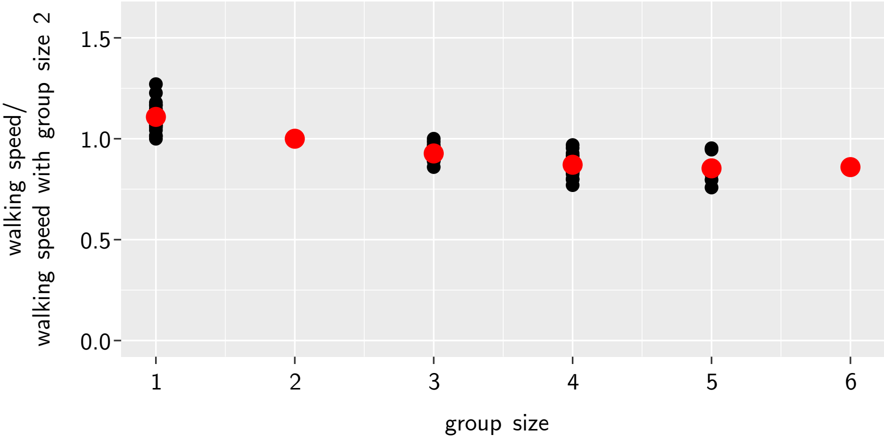

FIGURE 2.24: Comparison on group walking speed to walking speed of groups of 2 people.

TABLE 2.10: Average reduction in group walking speed.

GROUP SIZE	RATIO BETWEEN GROUP WALKING SPEED AND SINGLE PEDESTRIAN WALKING SPEED
1	1
2	0.90
3	0.84
4	0.79
5	0.77
6	0.78

door areas. This observation can have several reasons, for example the influence of different air temperatures and other weather conditions, which correlates with the location of the infrastructure (outside or inside). Another reason might be different activities taking place in these environments. An obvious explanation of a direct connection between walking speed and the location of the study site was not found. For comparison, the data was normalised to outdoor conditions.

2.3.8.3 *Temperature*

Only few data was found with information given about the air temperature at the time of measurement. Still, this data show a significant trend to lower walking speeds in higher temperatures (Figure 2.25), which is also in accordance with literature (Hoel, 1968; Monheim, 1980). This behaviour seems reasonable, as in cold temperatures, people tend to avoid spending too much time outside and movement in areas with high temperatures is more exhausting. In addition, the temperature regulation of the human body supports this behaviour. Walking in areas with cold temperature helps to keep the body temperature high and therefore reduces the bodies energy demand for heating whereas in hot temperature areas walking increases the body temperature and thus increases the cooling demand.

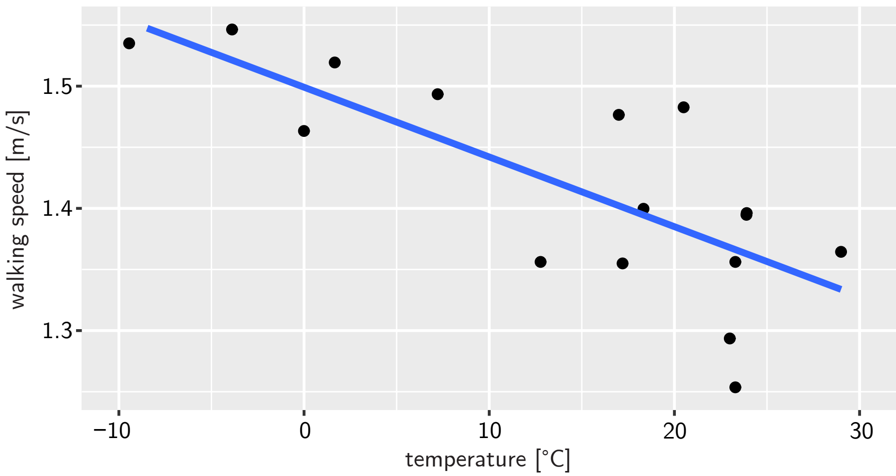

FIGURE 2.25: Temperature versus walking speed ($y = -0.006 \cdot x + 1.499,\ R^2 = 0.577$).

2.3.8.4 *Weather condition*

Similar to the temperature, also other weather conditions might influence the walking speed (Figure 2.26). Still, only a few references were found which do not allow making sound conclusions. As the differences are also not significant, the effect of the weather condition is not examined further.

2.3.8.5 *Year*

The year of measurement can be an indicator for several underlying influences. First, it is possible that the walking speed changed with time due to global trends not considered separately, for example the ageing society and the change in the social situation of the global population. Second, it might also show differences in the situations observed. As described in Chapter 2.3.4.1, the focus of the measurements shifted. A trend in the walking speed can therefore also show that not all parameters changing between these scopes are considered.

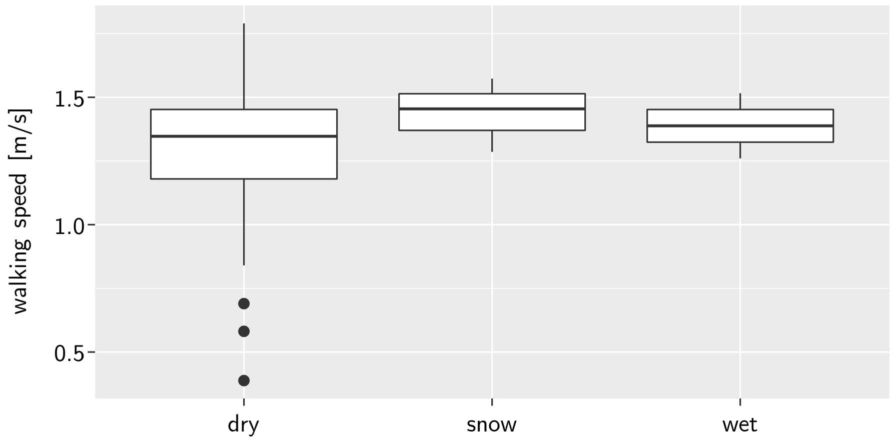

FIGURE 2.26: Weather versus walking speed ($R^2 = 0.025$).

The analysis showed almost no trend (0.000 6 m/s · *year*) which is also not significance (Figure 2.27). It can thus be concluded that there is no influence from the measurement year to the walking speed. When considering the historic sources about walking distances, also no trend in the walking speed can be determined. In comparison between the Roman Empire and modern armies the maximum daily distance is about the same (Department of the Army, 1990; Riepl, 1972). In former times, the walking speed was used in distance measurement units. The distance covered within one hour walking or within a day represents one walking hour or a daytrip. For one hour walking a distance of 3.7 to 5.7 km was assumed (Baedeker, 1859; Buchner, 1853; Feer, 1803; Lindner, 1831; Mittler, 1830; Nelkenbrecher and Wolff, 1842). These values are in good accordance with the estimate of hourly walking distances used for hiking (DAV and ÖAV, 2011; Schweizer Wanderwege, 2013).

This fact also supports the outcome concerning the influence of the body height. Within the last century the average body height in Europe increased about one centimetre per decade (Hatton and Bray, 2010). As there is no visible trend within this time, this supports the earlier finding that the effect of human height can be considered negligible.

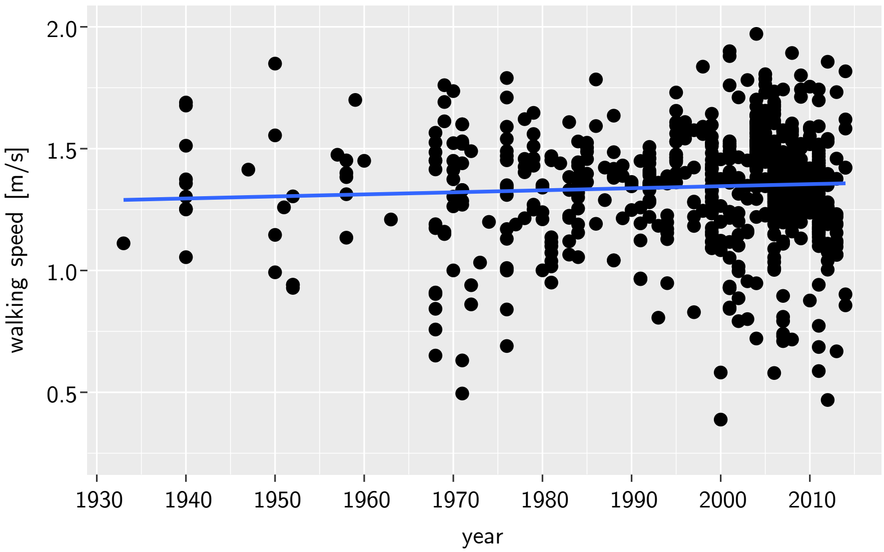

FIGURE 2.27: Year of measurement versus walking speed ($y = 0.00060 \cdot x + 0.1487,\ R^2 = 0.001$).

2.3.8.6 *Month*

The month of measurement can be used as an indicator for the weather. As the weather and temperature was not recorded for most of the datasets, it is expected that the influence caused by different weather conditions can still be observed comparing the different months. Still, the amount of data where the month of observation is stated is rather small. As most of the data was collected in Europe and North America, the temperature is highest between May and August and lowest in December to February. The analysis revealed that those months with warmer weather are related to a lower walking speed than the ones with cold weather, which is in good accordance with the expected outcome (Figure 2.28). As there was not a high amount of date available, some months, especially March and April, show different results.

2.3.8.7 *Day*

Surprisingly, the data indicates a considerable slower walking speed on Monday than on all other days (Figure 2.29). The range of walking speeds measured for Monday indicates that other influences are also reflected in the data, which were not recorded and hence were not considered in the data analysis. In addition, the overall number of literature data stating the day of measurement is low and for specific days of the week, only few measurements are available.

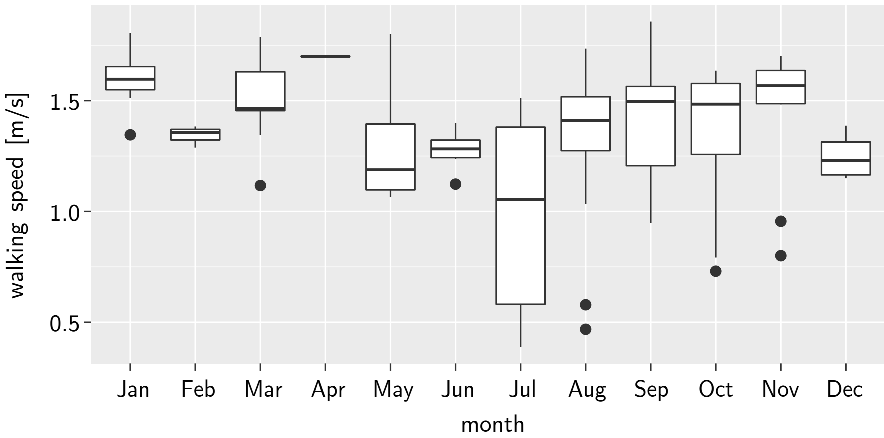

FIGURE 2.28: Month versus walking speed ($R^2 = 0.193$).

When comparing weekdays with the weekend, the average walking speed during weekend was found to be within in the same range as the walking speed during weekdays. Still, Saturday shows the lowest walking speed excluding Monday.

There is no obvious reason why the day of the week as such influences the walking speed but there are other influences, like the trip purpose, which is different for the days of the week. For example, during the weekend less people are expected to walk to work. It is therefore usually expected that the walking speed on the weekend is lower. When measuring pedestrian speed, the trip purpose and other influences are often not determined. To compare short-term measurements, it would therefore be better to use similar days to eliminate the influences, which are combined with the day of the week. Analogue to mobility surveys, working days between Tuesday and Thursday should be used for walking speed measurements.

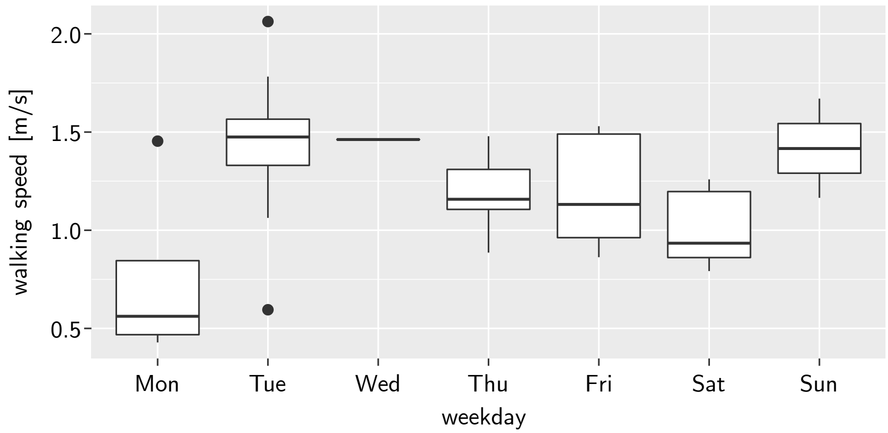

FIGURE 2.29: Day versus walking speed ($R^2 = 0.399$).

2.3.8.8 *Rush-hour*

Several references do not state the exact time, but indicate if the observations were made during rush hour or not. When comparing these two time types it can be seen that pedestrians tend to walk about 4 % faster during rush hours (Figure 2.30), but this difference is not significant. As an explanation for this, two different phenomena can be found. First, the physical capability of the human body changes during the day, having a maximum in the morning and the evening. Another factor is the differences in the set of pedestrians observed. Commuters consist of different age groups, but also have different trip purposes than the pedestrians observed outside rush hours.

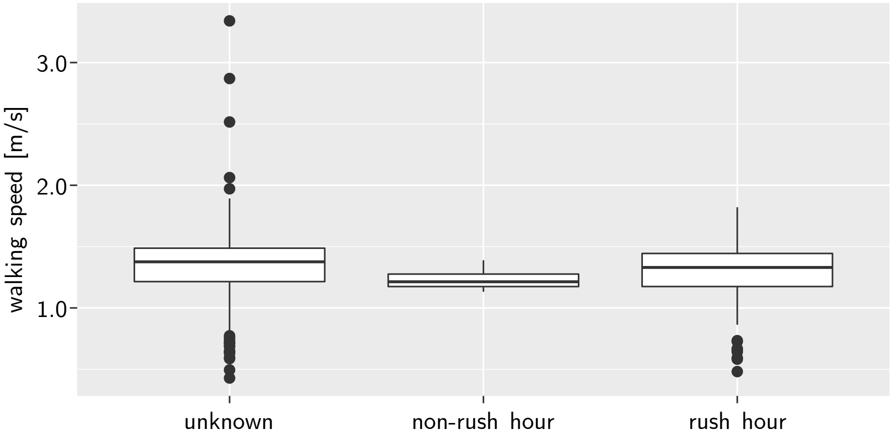

FIGURE 2.30: Rush hour/non-rush hour versus walking speed ($R^2 = 0.009$).

2.3.8.9 *Daytime*

As already described in the previous chapter, several influences change with the time of the day. In Figure 2.31, a decreasing trend in the walking speed throughout the day is visible. Nevertheless this trend is not significant. In addition, the scatter in the data is large, thus the influence of the linear trend is weak. A potential factor influencing the walking speed during the day is the physiological capability, which changes throughout the day (Weidmann, 1993). In addition, influences, such as differences in the trip purpose or the age distribution can have an influence on the observed behaviour. For example, strong differences in the walking speed during the day between working and non-working days have been observed (Brščić et al., 2014).

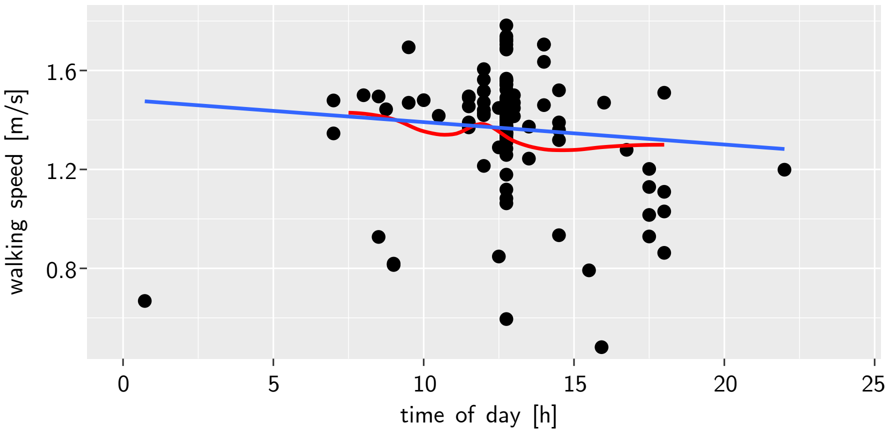

FIGURE 2.31: Time versus walking speed compared with the curve from Weidmann (1993).

2.3.8.10 *Trip purpose*

Depending on the trip purpose, people walk with different speeds. As can be seen in Table 2.11, business and commuter traffic is considered to have the highest walking speeds, leisure trips the lowest (Weidmann, 1993).

The data obtained are in good accordance with this, but in general the effects are smaller (Figure 2.32). Only leisure trips show unexpected high walking speeds. Otherwise, the range of walking speeds in this group is high, which might indicate that the group consists of several subgroups or that other influences are present as well. When comparing with commuting, only the trip purposes shopping and event have a significant different mean walking speed. For further evaluation, the average of event, leisure, shopping, education and commuting was used as reference.

TABLE 2.11: Average walking speed for different trip purposes (Weidmann, 1993).

TRIP PURPOSE	SPEED [m/s]
Commuting	1.49
Shopping	1.16
Business	1.61
Leisure	1.10
Average	1.34

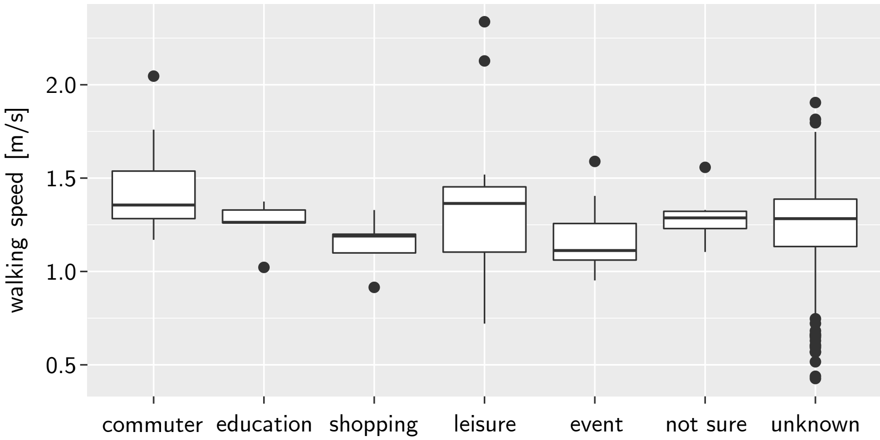

FIGURE 2.32: Trip purpose versus walking speed ($R^2 = 0.032$).

2.3.9 *Observation technique*

2.3.9.1 *Measurement type*

For data collection, different measurement settings can be used (Figure 2.33). The most important ones are laboratory experiments, walking speed tests with single persons and real-life observations. In comparison of these types, experiments have a slightly higher mean walking speed than real-life observations ($\sim 4\,\%$). Still, these differences are not significant. Some of this influence can be due to the different group compositions, which is partly already eliminated. In addition, the measurement setting itself can have an influence, as people might react different in real-life and experimental settings.

2.3.9.2 *Measurement method*

Apart from the measurement setting also the method, which is used to obtain the speed measurements can have an influence. In general, the speed can be

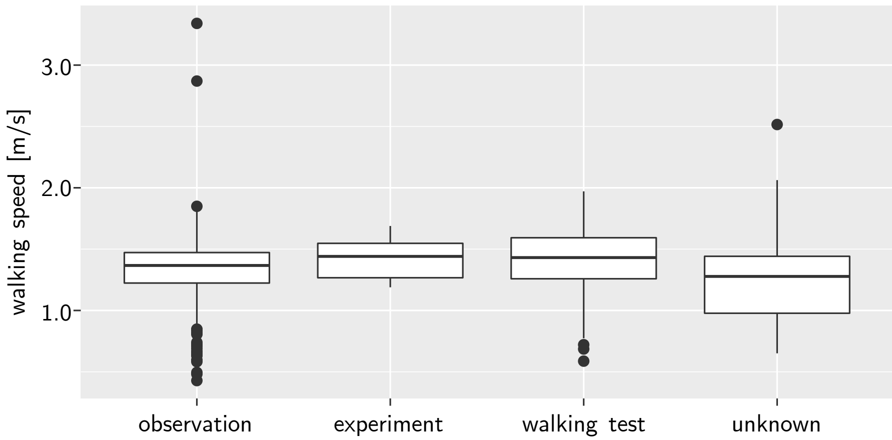

FIGURE 2.33: Measurement type versus walking speed ($R^2 = 0.009$).

measured directly by personal taking the time a pedestrian walks a certain distance. Another method often applied is to record videos on site and extract the walking speed from these recordings. This can then be done either manually or using automatic extraction algorithms. As the speed of video recordings can be adjusted, manual walking speed measurements from video recordings are generally the most accurate, but also most time consuming, method. They are therefore used as a reference scenario. It is reasonable that the measurement method has an influence on the walking speed measured, as they all have different error sources, but the magnitude and direction is not clear. In Figure 2.34 these differences can be seen, although only the mean walking speed of direct measurements and video recordings with automatic data extraction are significant different to video recordings with manual data extraction, which is used as reference.

2.3.9.3 *Measurement length*

Field measurements were performed for short length up to a few hundred metres. It is expected that the length of the measurement section mainly has an influence on the variation of walking speeds, but not on the average value. Pedestrian walking speed is not constant, but can vary in short time intervals. When observing pedestrians on longer stretches the variation is therefore reduced. Still the mean value should be constant. As expected, the available data do not show any significant influence on the walking speed by the measurement length (Figure 2.35).

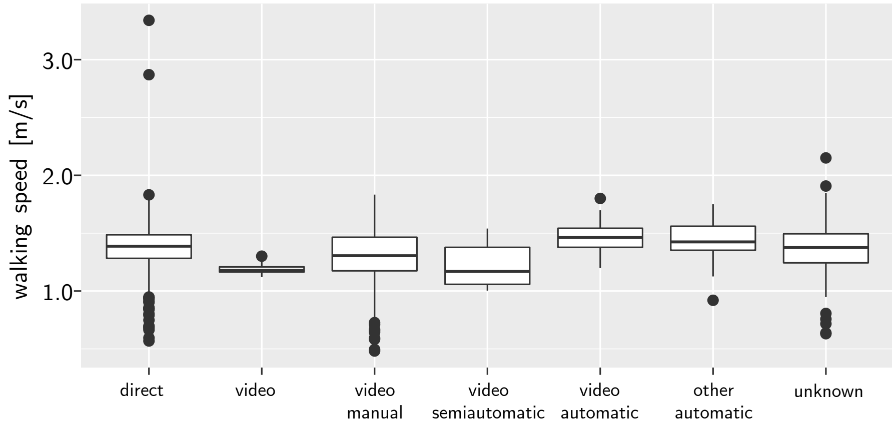

Figure 2.34: Measurement method walking speed ($R^2 = 0.038$).

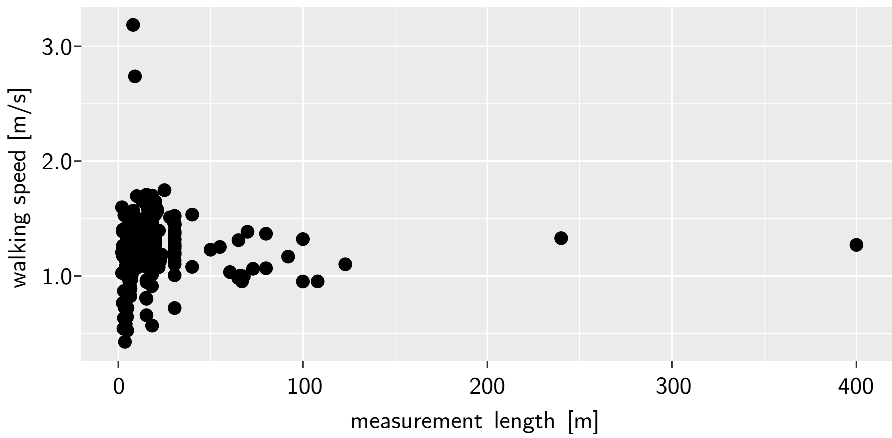

Figure 2.35: Measurement length versus walking speed.

2.3.10 *Synthesis and conclusion*

2.3.10.1 *Strength of influences*

The evaluation of the size of the different influences shows that they can be grouped according to their influence on the walking speed into four groups (A-D, Table 2.12). To describe the strength of the influences the range of mean values found for each influence was taken as a measurement. For example, 20-year-old pedestrians walk at an average speed of 1.6 m/s whereas people at the age of 90 to 100 years have an average walking speed of 0.2 m/s. Due to this big range of walking speeds age is classified in group A, having the strongest influence. These groups can be used to evaluate, which influences have to be considered, and hence described, when performing walking speed measurements.

The influences in group A have a strong impact on the result, thus their variation during the measurement period can have a stronger impact on the result than any other measurement, which should be evaluated. For one-time measurements, most of the influences in this group are usually constant, hence they have to be considered only when comparing different measurements. Otherwise, for example the age of the pedestrian is likely to be different when performing real-life measurements. The most important influence on the walking speed, which always has to be considered, is the pedestrian density. Among all others, the age is the most important one, with differences between the fastest and the slowest group of up to 90 % of the mean walking speed. Especially the occurrence of very young and very old pedestrians can have a strong impact on the total walking speed.

Group B summarises influences which are still important to consider, but whose effect on the walking speed is much smaller. Influences in group C have only a small impact on the walking speed, hence it is not as important to record them. Still, when considerable changes are expected between measurements, their values should be recorded. Group D contains all influences, where no effect on the walking speed was found or their effect is considered negligible.

The strength of the stated influences is not backed up very well in all cases. Depending on the amount of measurements available and their independence to others, there are several uncertainties occurring. In group A for example this is true especially for the influences country, day, daytime and month where other influences not considered might have a strong impact on the result.

TABLE 2.12: Strength of influences (influence strength: maximum range of values in % of the average free flowing walking speed).

INFLUENCE FACTOR	INFLUENCE	NUMBER OF STUDIES USED IN THE ANALYSIS
A (40 to 100 %)	Density	Not analysed
	Age	67
	Country	189
	Facility	202
	Inclination	9
	Day	13
	Daytime	21
	Month	32
B (10 to 25 %)	Group size	13
	Measurement method	202
	Trip purpose	202
	Continent	191
	Land use	202
	Indoor/outdoor	195
	Temperature	4
C (1 to 10 %)	City size	157
	Race	202
	Body weight	19
	Luggage	23
	Gender	77
	Measurement type	202
	Rush-hour	202
D (0 %)	Body height	23
	Measurement length	76
	Weather condition	8
	Year	202

2.3.10.2 *Limitations*

Throughout the study, several limitations and possibilities for bias in the results have to be considered. They can occur due to the data used in this study, the analysis of the data and the interpretation of the results.

LITERATURE DATA The data used in this study was obtained from literature available to the authors and in a language understandable for them. The availability of the literature restricts the data to data already published and available either online throughout inscriptions or freely available in the internet or as a hard copy available to the library system. The language restriction reduces the literature sources used to literature in English, German and some sources in other Indo-European languages.

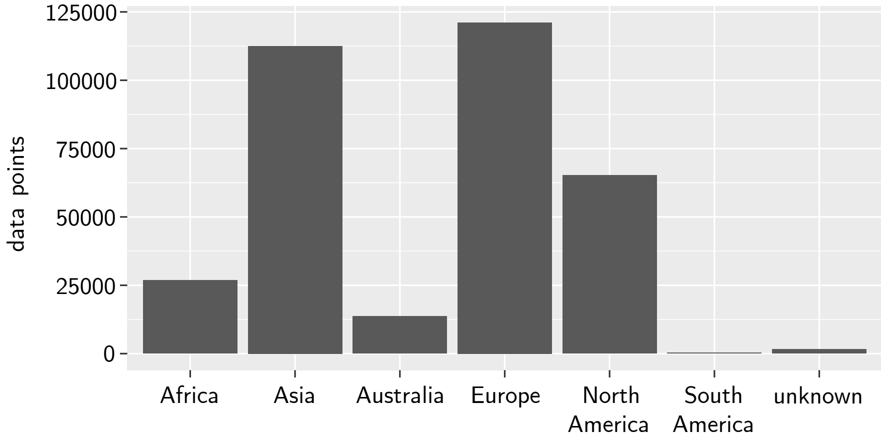

FIGURE 2.36: Data points per continent.

As neither the measurements nor the literature are evenly distributed among all possible influence values, for some influences far more data is available. In addition, the amount of measurement values differs strongly between different sources. As an example, Figure 2.36 shows the data points available per continent. It can be seen that most of the data was obtained in Asia and Europe and almost no data was available from South America.

The approach used in this study allows including data from various measurements done in the past to improve the knowledge about influences on the walking speed. Still, the use of data from literature has limitations to the results compared to data directly obtained from observations.

Depending on the specific source, the field surveys and laboratory experiments are described different, therefore often information irrelevant for the specific publication is not included. For this study, as detailed information as possible about the observation setting is important but missing. The differences between measurements can therefore also result from influence factors not stated in the literature.

The influence of the limitations related to the literature data to the results of the study is small compared to other limitations. The lack of data for all situations and the limitations in identifying suitable literature reduces the amount of data usable for the study and the parameters, which can be evaluated. As the amount of data is still relatively high compared to other studies, the influence of missing data is small. The main influence of this limitation is the higher uncertainty of the results, especially for influences with a limited amount of measurements. This leads to the fact that the deviation between measurements is still high, when all influences stated are brought to a reference scenario.

In this step, the main limitation is the missing description of influences in the study. This limits the comparability of different studies, as the speed differences observed might result from influences not stated in the studies. For future studies, it is therefore recommended to describe at least the states of the influences in group A and B according to Table 2.12.

DATA ANALYSIS An important limitation is the separate evaluation of each influence. This assumes independent parameters, which cannot be ensured in all circumstances. As described in the method section, the effect is taken into consideration for the evaluation order of the influence factors. For comparing single parameters, only this parameter should vary (ceteris paribus), whereas other influences are equal. This can only be guaranteed for a few situations, which makes this a major downside of this method. Still, as described previously, other potential methods will be affected by similar limitations.

As the data is often already aggregated, the variation of the walking speed cannot be evaluated using this method. In general, the variation in the data can be due to different influence factors or due to the variation within the same situation. For known influences, the variations of the mean value can be calculated with the proposed method. The effect of influences not described in the data and the variation in a specific situation cannot be evaluated here.

The limitation in the data analysis based on the data used for this study can strongly affect the results. To tackle these limitations, the influences analysed in this step were evaluated in a predefined order. This order aimed at ensuring that influences, which might have an impact on the results on the data analysis of other influences were examined before them. For example, the facility type was analysed before the continent as it was expected that different facilities influence the results for the continent stronger than vice versa. Here, also the amount of data for each influence was considered.

INTERPRETATION For the interpretation, the limitations of the validity of the results have to be considered. As described previously, the results might have a bias due to several assumptions and limitations made in this study. Especially when considering influences with smaller amounts of data available, the size of the influences is quite uncertain. In Table 2.13 an estimate was done to evaluate the reliability of the results of the influences considered in the study. It can be seen that for several influences the reliability is weak, thus further research is needed to quantify these influences.

TABLE 2.13: Reliability of results.

STRONG	MODERATE	WEAK
Gender	Body height	Luggage
Age	Body weight	Race
City size	Facility	Land use
Inclination	Indoor/outdoor	Country
Group size	Month	Continent
Temperature	Rush-hour	Weather condition
Year	Trip purpose	Day
	Measurement type	Daytime
	Measurement length	Measurement method

2.3.10.3 *Conclusion*

It was possible to describe the influences on the walking speed based on literature data. The results were compared with data from previous studies, showing that most of the influences can be reproduced. Considering the insights gained from this study, the average walking speed of 1.34 m/s proposed by Weidmann (1993) can be confirmed as a good estimation. Still, it has to be noted that providing an average walking speed is a difficult task, as for several influences (e.g. Land use, facility type, trip purpose, measurement method...) no average value and hence no average speed can be easily determined. This walking speed can thus be considered as an average of the walking speed measurements done in the past rather than a global average. It was further found that various influences have a relevant impact on the walking speed, hence, they should be considered in simulation and other applications. In addition, it was possible to reliably quantify several influence factors.

Still, it has to be noted that the differences of the mean walking speed between different measurements cannot be solely explained by the influences examined. One of the main reason for this are the different settings, which are used for the speed measurements and missing information in the literature concerning the detailed measurement setting. Therefore, several influence values are different between the measurements, but they are not described in literature. Hence, standard conditions are proposed in Table 2.14. Using this scheme, it will be possible to describe the measurements in a standardised way and thus enhance the comparability of different measurements. Information exceeding this scheme will further enhance studies on walking speed differences.

To further understand the underlying principles determining the walking speed, the correlations between different influences as well as their superposition has to be addressed. This can be done by applying multivariate statistics as well as by studying not only the influence factors but also the way they influence walking. For example, luggage increases the weight a person has to carry and hence the energy optimal walking velocity is shifted. If these connections are known for all the influences, correlations and dependencies can be better described. In addition, influences like country or continent can be determined, which only effect walking speed indirectly. For these, the direct influences can be identified.

TABLE 2.14: Proposed standard conditions (*italics*: reference attributes for comparison at different locations).

INFLUENCE	STANDARD CONDITION
Gender	*50:50* Comment: global average
Age	Age distribution, age group (1-, 5- or 10-year intervals) or: • Young: 1 - 10 • *Middle age: 10 - 70* • Elderly people: 70+ Comment: Before 10 and after 70 years of age the speed decreases strongly.
Body weight & body height	For laboratory tests: state values All other: *random choice at location*
Luggage	Division between people having heavier luggage (pushchair, suitcase, heavy and big bags or backpack) and *people without luggage or small luggage (small bags/backpacks, handbags)* Comment: Influence of luggage is especially important at places with a high share of people with heavy luggage (airports, shopping centres...).
Race	*Random choice at location*
Land use	Description of land use at location: • *Central business district* • Recreational/touristic area • Residential area • School/university area • Shopping area • Transportation terminal
City size	*State value*
Country	*State country of measurement*

TABLE 2.14: proposed standard conditions (*italics*: reference attributes for comparison at different locations).

INFLUENCE	STANDARD CONDITION
Continent	*Derived from country*
Facility – inclination	*Flat* Or state inclination and walking direction
Facility – type	Description of location: • Stairs • Laboratory • Bottleneck • Pedestrian crossing • Pedestrian zone • Walkway – next to car traffic • *Walkway – separate from car traffic*
Group size	*Alone* Or for each group size separate value
Indoor/Outdoor	Description of location: • *Indoor* • Outdoor
Temperature	State temperature (e.g. hourly average) *Standard: 15-25°C*
Weather condition	State condition: • Sun • *Cloudy* • Rain/precipitation • Snow
Time of measurement	State time of measurement: (year, month, day, time, rush-hour/non rush-hour) *Standard: Tuesday – Thursday, evening rush-hour (3 – 5 pm)*
Trip purpose	Estimation of main trip purpose: • *Commuting* • Shopping • Business • Leisure • Average

Table 2.14: proposed standard conditions (*italics*: reference attributes for comparison at different locations).

INFLUENCE	STANDARD CONDITION
Measurement type	State type: • *Real-life observation* • Walking test (single person walking) • Experiment
Measurement Method	State method: • Direct (manual timing) • Videotaping • *Manual data extraction* • Automatic data extraction • Semiautomatic data extraction • Other automatic data extraction technologies
Measurement length	State length *Standard: 5 m* Comment: Even though, no influence from the measurement length was found for the mean walking speed, it is likely that the variation of the walking speed will be influenced, and thus a standard length shall be set for comparison reasons. When measuring walking speed in different densities, a measurement length of 5 m also reflects the distance, where people react to the pedestrian density present (Tipakornkiat et al., 2012).
Pedestrian density	*Free flowing conditions* or state density in measurement area

Combining the data analysis done with the proposed standard conditions in Table 2.14, an estimate of reference values for the influence attributes can be given (Table 2.15). As a reference value, an average walking speed of 1.34 m/s was used. Using this table, it is possible to compare study results not measured using the same conditions. Future measurements using the standard condition scheme will ease comparability and further enhance the data basis for studying and understanding the pedestrian waking speed.

TABLE 2.15: Walking speed for the proposed standard conditions. A walking speed of 1.34 m/s is assumed for the reference attributes.

INFLUENCE (REFERENCE)	ATTRIBUTE VALUES**										SIGNIFICANCE
Gender (50 % men, 50 % women)	men* 104 % 1.39	women* 96 % 1.29									significant
Age (10 - 70 years)	1 - 10 66 % 0.88	10 - 20 109 % 1.46	20 -30 106 % 1.41	30 - 40 102 % 1.36	40 - 50 99 % 1.32	50 -60 93 % 1.24	60 - 70 92 % 1.24	70 - 80 75 % 1.00	80 - 90 43 % 0.58	90 - 100 21 % 0.29	not determined
Body height	no influence found										no significant influence
Body weight (average)	50 - 60 101 % 1.36	60 - 70 101 % 1.35	70 - 80 100 % 1.35	80 - 90 99 % 1.34	90 - 100 99 % 1.32						not significant
Luggage (no/small luggage)	no/small luggage 100 % 1.34	big luggage 97 % 1.30									not significant
Race	no influence found										no significant influence
Land use (central business district)	central business district 100 % 1.34	recreational/ touristic 92 % 1.23	residential area 88 % 1.19	school/ university area* 88 % 1.17	shopping area 97 % 1.30	transportation terminal 91 % 1.22					some significant differences
City size (10.000 inhabitants)	10 100 % 1.34	100 100 % 1.34	1.000.000 100 % 1.35	10.000.000 101 % 1.35							not significant
Country	see Table 2.8										some significant differences
Continent (Europe)	Asia 93 % 1.25	Australia 111 % 1.49	Europe 100 % 1.34	North America 103 % 1.38	South America 113 % 1.51						not significant

TABLE 2.15: Walking speed for the proposed standard conditions. A walking speed of 1.34 m/s is assumed for the reference attributes.

INFLUENCE (REFERENCE)	ATTRIBUTE VALUES**												SIGNIFICANCE
Facility - inclination (0 %)	15 % down 92 % 1.24	10 % down 95 % 1.27	5 % down 97 % 1.31	0 % 100 % 1.34	5 % up* 88 % 1.17	10 % up* 75 % 1.01	15 % up* 63 % 0.84						uphill: significant, downhill: not significant
Facility - type (walkway - separate from car traffic)	stairs* 57 % 0.76	laboratory 101 % 1.35	bottleneck 93 % 1.24	pedestrian crossing* 107 % 1.43	pedestrian zone* 90 % 1.20	walkway – on street 100 % 1.34	walkway – separated 100 % 1.34						some significant differences
Group size (1)	1 100 % 1.34	2* 90 % 1.21	3* 84 % 1.12	4* 79 % 1.05	5* 77 % 1.03	6* 78 % 1.04							significant
Indoor/outdoor (outdoor)	outdoor 100 % 1.34	indoor* 86 % 1.15											significant
Temperature (15 - 25°C)	-5 - 5°* 108 % 1.45	5 - 15°* 104 % 1.40	15 - 25° 100 % 1.34	25 - 35°* 96 % 1.28									significant
Weather condition (Dry)	dry (sun/cloudy) 100 % 1.34	rain/precipitation 108 % 1.45	snow 112 % 1.50										not significant
Time of measurement: year (2000)	1950 98 % 1.31	1960 98 % 1.31	1970 99 % 1.32	1980 99 % 1.33	1990 100 % 1.33	2000 100 % 1.34	2010 100 % 1.35						not significant
Time of measurement: month (Average)	Jan 116 % 1.55	Feb 97 % 1.30	Mar 110 % 1.47	Apr 123 % 1.65	May 93 % 1.24	Jun 93 % 1.25	Jul 71 % 0.95	Aug 99 % 1.33	Sep 103 % 1.38	Oct 98 % 1.31	Nov 107 % 1.43	Dec 91 % 1.21	not determined
Time of measurement: weekday (Tuesday)	Monday 52 % 0.69	Tuesday 100 % 1.34	Wednesday 100 % 1.35	Thursday 81 % 1.09	Friday 83 % 1.11	Saturday 69 % 0.93	Sunday 97 % 1.30						not determined

TABLE 2.15: Walking speed for the proposed standard conditions. A walking speed of 1.34 m/s is assumed for the reference attributes.

INFLUENCE (REFERENCE)	ATTRIBUTE VALUES**							SIGNIFICANCE
Time of measurement: daytime (3 - 5 pm)	7 - 9 am 109 % 1.47	9 - 11 am 107 % 1.44	11 am - 1 pm 105 % 1.40	1 - 3 pm 102 % 1.37	3 - 5 pm 100 % 1.34	3 - 7 pm 98 % 1.31	7 - 9 pm 95 % 1.28	not significant
Time of measurement: rush-hour (rush-hour)	rush-hour 100 % 1.34			non rush-hour 97 % 1.30				not significant
Trip purpose (commuting)	commuting 100 % 1.34	shopping* 81 % 1.08	leisure 96 % 1.28	education 88 % 1.18	event* 83 % 1.11			some significant differences
Measurement type (real-life observation)	real-life observation 100 % 1.34	walking test 103 % 1.38	experiment 106 % 1.42					not significant
Measurement method (video: manual data extraction)	direct: manual timing* 105 % 1.4	videotaping 92 % 1.23	video: manual data extraction 100 % 1.34	video: automatic data extraction* 113 % 1.51	video: semiautomatic 95 % 1.27	other automatic data extraction 110 % 1.47		some significant differences
Measurement length	no influence found							no significant influence
Pedestrian density	not investigated							-

*Attributes significantly different to the reference conditions ($p < 0.05$)

**% of reference walking speed (1.34 m/s) at otherwise reference conditions

2.4 FUNDAMENTAL DIAGRAM

Parts of Chapter 2.4.5 to 2.4.9 were already published as:

Ernst Bosina and Ulrich Weidmann (2016). Generic Description of the Pedestrian Fundamental Diagram. *Proceeding of Pedestrian and Evacuation Dynamics 2016*. Pedestrian and Evacuation Dynamics PED 2016. Ed. by Weiguo Song et al. Hefei, China: University of Science and Technology of China Press, pp. 548–555. DOI: 10.17815/CD.2016.11

Parts of Chapter 2.4.4 to 2.4.13 were already published as: Ernst Bosina and Ulrich Weidmann (2017a). Defining the Pedestrian Fundamental Diagram. Traffic and Granular Flow TGF 2017. Washington, D.C.

2.4.1 *Introduction*

The concept of the fundamental diagram originates from vehicular traffic. With an increase in car traffic congestions occurred, leading to a need for a better understanding of vehicle flow and to the development of the fundamental diagram. Several decades later, this concept was then applied to pedestrian traffic. Still, neither in car traffic nor in pedestrian traffic, a general definition and understanding of the fundamental diagram can be found. It can otherwise be observed that the term fundamental diagram is used for various different relations, without discussing the validity or limitations of the approach (Johansson, 2009b).

2.4.2 *Historical development*

In the 1920s the first studies were made to estimate the capacity of a single traffic lane (for a list see for example Evans (1950)). For example, a study on traffic flow was published in 1927, describing the problems connected to congestion in Manhattan (Lewis and Goodrich, 1927).

Greenshields was then the first to use a camera, a stopwatch and markers for the road distance, to photograph a street section in short time intervals (Greenshields, 1934). By using this method, it was possible to determine the vehicle speed, spacing and the traffic volume. This data allowed to propose mathematical formulations for the correlations between speed, flow and density, today called fundamental diagram (Greenshields, 1935). Thus, the work of Greenshields is usually considered the starting point of traffic flow theory and the fundamental diagram (Kuhne, 2011), even though the term fundamental diagram was only introduced several years later by Frank A. Haight for the relation between flow and density (Haight, 1963).

Each fundamental diagram can be divided into a stable region, where an increase in density will result in an increasing flow, and an unstable region, where it will lead to a decreasing flow and congestion occurs. The first fundamental diagrams were univariate, having a single formula for the stable and unstable region (FGSV, 2005; Kuhne, 2011). Later studies proposed two- and multi-variant models, where the stable and unstable regions are modelled using different formulae, showing a discontinuity at the maximum flow. The first two-variant model can be found at Edie (Edie, 1961).

In recent years the focus shifted to the description off different traffic states, to further understand the relations expressed in the fundamental diagram (Kim and Keller, 2001). Of special interest are also the details of the shift from stable to unstable flow conditions. If information about the probability of traffic breakdowns based on flow data of a certain section is available, different approaches were proposed to influence the flow, for example by reducing the speed limit, which is expected to keep the flow in stable conditions (FGSV, 2005).

2.4.3 *Definition of the fundamental diagram in vehicular traffic*

The traffic flow can either be modelled microscopically, where each individual vehicle is considered, or macroscopically, where average values over time or space are used (FGSV, 2005). For a macroscopic view, flow, speed and density are the most important parameter. The interdependence between these three variables can be seen in the fundamental diagram. The main goal of the fundamental diagram is the determination of the traffic volume (Leutzbach, 1994).

In general, the fundamental diagram is defined as the relation between vehicle flow q, vehicle density k and mean speed $\overline{v}$.

$$q = k \cdot \overline{v} \tag{2.5}$$

Still, different definitions of the exact meaning of the fundamental diagram can be found. Some define the fundamental diagram in a narrow sense as the relation between flow and density (Brilon, 2005; FGSV, 2005; Haight, 1963; Schnabel and Lohse, 1997; Wirth, 2010) or its graphical representation (Bischofberger, 1997; Leutzbach, 1972). The position vector of each point then describes the mean speed (Leutzbach, 1972). In a broader sense, the relations between flow and mean speed and between density and mean speed are named fundamental diagram (Botma, 1976; Knoop and Daamen, 2017; Wirth, 2010).

A mathematical formulation of the fundamental diagram was established by Edie (1963). He showed that the time-mean speed, where the mean is taken over time at the same location, is the harmonic mean of the space-mean speed, where the mean is calculated for a street stretch for the same time instance. The fundamental diagram is further defined based on a rectangle in the time-space diagram, resulting in the specification of the space-mean speed as the correct speed to be considered in the fundamental diagram.

Another aspect sometimes included in the definitions is the requirement that the fundamental diagram represents the steady state conditions of the traffic flow (Botma, 1976; Knoop and Daamen, 2017). As the real traffic flow is not constant, the considered time interval has a strong influence on the fundamental diagram. Long intervals reduce the variation of the data, short time intervals reduce the statistical meaning of the values (Coifman, 2014; Heidemann, 1989). Usually intervals between 1 minute and 1 hour are utilized in car traffic, from which 5 minutes are usually used for the fundamental diagram (FGSV, 2005). Another aspect for the appropriate time interval is the use of the fundamental diagram. For traffic operation short time intervals are useful, for planning long time intervals should be chosen (Lu et al., 2009).

To evaluate the correlation between density and flow, only stochastic variations of the flow, but no increase or decrease of the flow within the time interval considered are allowed (Sachse and Keller, 1992). To determine, whether the flow can be considered steady state, a cumulative curve of the vehicles versus the time can be plotted. For a constant flow, the curve has to follow a straight line, which can be tested using the Wilcoxon-test (Lenz, 1967). The parameters q, v and D are statistical limits. They can theoretically be only measured by averaging for an infinite long time or distance in stationary conditions (Wu, 2000).

Another definition of the fundamental diagram distinguishes between the fundamental diagram and other flow-density diagrams (Treiber and Kesting, 2010). Here, the fundamental diagram is the theoretical relation between density and flow for a homogeneous and stationary flow of identical vehicles in the equilibrium state, whereas flow-density diagrams show aggregated data from real-life measurements that usually do not show these properties.

Still, even if we achieve stationary and homogeneous conditions, the shape of the fundamental diagram will be different depending on the situation. Among others, the road conditions and geometry, the drivers' characteristics and the weather conditions will influence the vehicle flow and thus the shape of the fundamental diagram will change (Haight, 1963). Therefore, depending on the application and location, different fundamental diagrams must be used.

The fundamental diagram has several applications. It can be used in the planning and design phase of roads (determining the Level of Service and road capacity), for traffic flow control like ramp metering and dynamic speed limits, as well as to evaluate traffic related measures and their cost effectiveness (Botma, 1976; FGSV, 2005; Sachse and Keller, 1992; Schnabel et al., 2011). For the evaluation of the quality of the flow specific fundamental diagrams are in use depending on the share of trucks, the curvature of the road stretch and the inclination (FGSV, 2005).

2.4.4 *The introduction of the pedestrian fundamental diagram*

The first measurements of pedestrian density and walking speed were published in the 1960s (Oeding, 1963). It was already shown that variations in the trip purpose lead to different speed-density relations. In addition, several traffic conditions were proposed, which describe the quality of the flow based on the pedestrian density. Some years later, Fruin (1971b) published his work on the pedestrian speed-density relation and the Level of Service. The principles he developed are still used in pedestrian transport planning.

Even though the concept of the fundamental diagram was transferred from vehicular traffic, the first mentioning of the term "fundamental diagram" in the context of pedestrian transport can be found in Weidmann (1993). Often "speed-density relationship" or similar terms were used before. Sometimes also terms like "fundamental relationship" or "fundamental properties" can be found (Blue and Adler, 2001; Daamen and Hoogendoorn, 2003; TRB, 1985b). Still, it is unclear, whether the term is used synonymously for the fundamental diagram or if a differentiation is done consciously.

The fundamental diagram proposed by Weidmann (1993) is the most widely used one in pedestrian literature. It is based on pedestrian speed-density data from literature. This data is fitted to a formula derived for road traffic by Kladek (1966). In his work, Kladek concluded that existing linear and exponential speed-density curves failed in describing the relevant properties for a speed-density curve. He introduced a nonlinear curve showing a free flow speed at zero density, having zero speed at the maximum density and having a second derivative of zero at the free flowing section of the diagram. The curve was then applied to measurement data from two street sections (Kladek, 1966). Weidmann then found a good fit using this formula for the empirical pedestrian data. In his work, a general fundamental diagram for pedestrian transport was proposed for walkways and walking up- and downstairs (Weidmann, 1993):

$$v_{D,Walkway} = 1.34 \cdot \left[1 - e^{-1.913 \cdot \left(\frac{1}{D} - \frac{1}{5.4}\right)}\right] \tag{2.6}$$

$$v_{D,Stairs\ up} = 0.610 \cdot \left[1 - e^{-3.722 \cdot \left(\frac{1}{D} - \frac{1}{5.4}\right)}\right] \tag{2.7}$$

$$v_{D,Stairs\ down} = 0.694 \cdot \left[1 - e^{-3.802 \cdot \left(\frac{1}{D} - \frac{1}{5.4}\right)}\right] \tag{2.8}$$

In the last decades, many different fundamental diagrams have been measured and proposed in literature (Zhang, 2012; Zhang et al., 2014). Among others, the recent research in this field focused on the better understanding of the fundamental diagram for single file movement (Jelić et al., 2012b; Seyfried et al., 2007), the determinations of useful methods for calculating speed

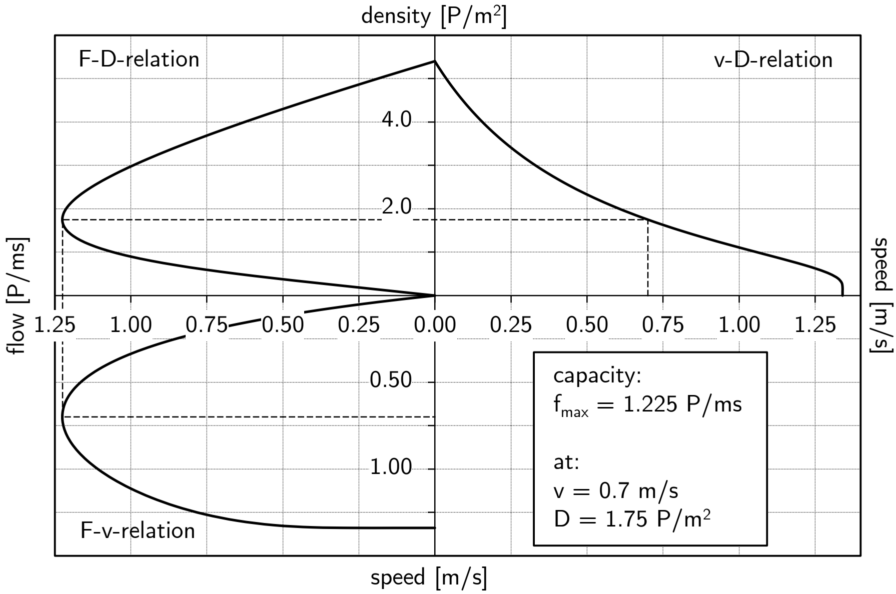

FIGURE 2.37: The pedestrian fundamental diagram as proposed by Weidmann (1993) (adapted from Buchmüller (2006)).

and density (Zhang et al., 2011), and the derivation of fundamental diagrams based on models (Flötteröd and Lämmel, 2015; Nikolić et al., 2016).

2.4.5 *Existing definition of the pedestrian fundamental diagram*

As for car traffic, the definitions of the pedestrian fundamental diagram found in literature vary considerably. The fundamental diagram is often solely described as the relation between density, flow and speed. Hence, a precise definition is missing. Nevertheless, as can be seen in car traffic, the differences between theoretical considerations and measurement data are significant and show the need of a proper description of the fundamental diagram.

Generally, the pedestrian fundamental diagram describes a relation between walking speed, pedestrian density and flow. Thus, the fundamental diagram consists of three relations (speed – density, speed – flow, flow – density), which all show the same information and hence can be derived from each other (Figure 2.37) (Seyfried et al., 2010a)). Still, it can be argued that not all such measurements can be used to determine the fundamental diagram, as it aims at describing the general relation between these three traffic properties. In literature therefore stationary and homogeneous conditions (Daamen, 2004; Hoogendoorn and Bovy, 2003; Nikolić et al., 2016), or a stationary flow

(Kaakai et al., 2007; Steffen and Seyfried, 2010) are mentioned as requirement. In addition, other factors like time and measurement area will influence the results.

Some other definitions specify the speed values needed. In the fundamental diagram, the average speed is considered (Blue and Adler, 1998; Seyfried et al., 2009a). Analogue to car traffic, a space mean speed (instantaneous mean speed) and a local mean speed exists. Here, the space mean speed shall be used for the fundamental diagram (Teknomo, 2002).

Daamen (2005) describes the fundamental diagram as a statistical relation under similar average conditions. It is assumed that on average, pedestrians behave the same if the average conditions are similar. Consequently, the fundamental diagram is sometimes considered as the averages of flow and density, compared to local values (Johansson et al., 2008). The fundamental diagram thus represents the macroscopic characteristics (Hoogendoorn and Daamen, 2009; Kaakai et al., 2007; Venuti and Bruno, 2009). On the other hand, others state that the fundamental diagram contains the local density (Bellomo et al., 2012; Parisi et al., 2009).

Summarising the literature, no satisfying definition for the pedestrian fundamental diagram was found. Different $v - D - F$ relations are named fundamental diagram although they have different scopes in term of time and space. Also the method used for calculating the density or the time intervals have a strong impact on the results. The possibility to compare different fundamental diagrams is therefore limited. Only a few authors provide a definition of the fundamental diagram, some of which are contradictory. A specific definition including a consistent discussion of the aim of the fundamental diagram and the corresponding essential properties of speed, flow and density is lacking.

2.4.6 *Aggregation levels*

2.4.6.1 *Classification*

For the classification of the fundamental diagram in term of the aggregation level used, two different approaches can be distinguished. First, the different levels can be divided based on the usage, hence the outcome. Second, they can be classified using the aggregation level of the model.

2.4.6.2 *Usage based classification*

For the usage based classification, the aggregation level of the result and the usage level of the outcome is relevant. The results can for example be provided on an individual pedestrian or on a flow level. This is reflected in the usage based classification. In general, a division between microscopic, macroscopic and mesoscopic can be made. A microscopic view provides data for the smallest unit, hence single pedestrians and a macroscopic approach shows only aggregated values. A mesoscopic level will provide certain aspects of both level.

To categorize the fundamental diagram in relation to other speed – density relations according to this logic, Table 2.16 shows different levels and their corresponding main properties. The fundamental diagram looks at pedestrian flows, hence a macroscopic aggregation, but at a cross-section location which can be considered microscopic in terms of space. Hence it is argued here that the classic fundamental diagram is mesoscopic according to common definitions (Hoogendoorn and Bovy, 2000). The behaviour of individual pedestrians cannot be described using this approach. But, as discussed further in Chapter 2.4.7.7, the fundamental diagram can be extended to show variations in the flow, supporting its mesoscopic nature.

The aggregation level of the output is always equal or higher than the model. The specific influences on individual speeds cannot be determined using a fundamental diagram model but only with microscopic models. On the other hand, microscopic models might be able to reproduce the fundamental diagram on the mesoscopic level. Similarly, fundamental diagrams can be used as a basis for modelling generalised macroscopic or network fundamental diagrams.

In car traffic, a speed-density model covering a street network is often called "macroscopic fundamental diagram" (Ambühl and Menendez, 2016; Geroliminis and Sun, 2011; Leclercq et al., 2014). It is argued here that two distinct speed-density relations exist at macroscopic level. It is thus proposed by the author to name the one at the pedestrian network level "network fundamental diagram".

2.4.6.3 *Model based classification*

In the model based classification, the aggregation of the model itself and not its output is considered. Analogue to the usage based classification, usually a differentiation between micro-, meso- and macroscopic models is made. In microscopic models, the individual behaviour of pedestrians and their individual characteristics are simulated using routines to describe the interaction between pedestrians and the environment. Macroscopic models use aggregated information; thus, the model framework considers aggregated features such as pedestrian flows or larger areas. In between, mesoscopic models show elements of both levels, thus certain aspects are modelled in aggregated form, whereas others are modelled disaggregated, for example by using a small space discretisation or by introducing stochastic variations in flow calculations. In this framework, the social force model is a microscopic model, the Kladek formula (Kladek, 1966) can be considered to be a macroscopic model.

TABLE 2.16: Usage based classification of speed-density relations at various levels.

LEVEL	NAME	PEDESTRIAN	SPACE	EXAMPLE
Macro	Network FD	Unknown no. of flows	Area / network	Hoogendoorn et al. (2011, 2018)
Macro	Generalised FD	Multiple ped. flows	Single situation	Daamen et al. (2015), Saberi and Mahmassani (2014)
Meso	Fundamental diagram	Pedestrian flow	Cross-section	Weidmann (1993)
Aggregated micro	Group $v-D$ relation	Individuals aggregated to groups	x-y position	
Micro	Individual $v-D$ relation	Individuals	x-y position	Blue and Adler (2001), Helbing and Molnár (1995)

The model based classification and the usage based classification are linked by the fact that the aggregation level of the model always has to be equal or lower than the results. Thus, a macroscopic model cannot be used to obtain individual speed-density relations, but a microscopic model can be used to obtain a classic fundamental diagram.

Until now, most fundamental diagrams are modelled using a macroscopic model, hence providing a mostly linear relation between average speed and density. Nevertheless, especially for the validation of models, also fundamental diagrams are calculated from microscopic models (Kretz et al., 2016). Still, no approach was found to explicitly model the fundamental diagram using a microscopic model.

2.4.7 *Defining the pedestrian fundamental diagram*

2.4.7.1 *Background*

As for this thesis, no suitable definition of the fundamental diagram exists in literature, a definition for the pedestrian fundamental diagram will be elaborated the following section. For this purpose, first the aim of the fundamental diagram must be defined. The pedestrian fundamental diagram is used to describe in aggregated form the pedestrian flow to allow the design of pedestrian facilities. For this purpose, the fundamental diagram is also strongly linked to the Level of Service concept (see Chapter 2.5).

To be useful for the design of pedestrian facilities, a basic definition of the fundamental diagram is needed which only reflects the pedestrian characteristics. It is thus independent from the measurement method used to obtain the fundamental diagram. It should consider the average situation, as individual measurements are usually not relevant for the design values. The fundamental diagram, compared to other speed – density relations, therefore does not represent the characteristics of individual pedestrians, as it is done in microscopic models.

Before providing a definition for the fundamental diagram, the following sections will discuss the requirements for flow, speed and density as well as for the time and space limits used to derive the fundamental diagram. For these, possible influences on the fundamental diagram will be shown and the correct approach will be defined to fulfil the goal of the fundamental diagram.

2.4.7.2 *Flow, speed and density*

In Chapter 2.4.6 it is argued that the classical fundamental diagram is mesoscopic, having a microscopic space extend and looking at the macroscopic flow. Other speed-density relations exist as well at different aggregation levels, but they serve different purposes out of the scope of this work. Now the classical (mesoscopic) fundamental diagram will be defined. For this, the flow, speed and density used in the fundamental diagram represent the average values of a flow rather than individual values.

It is commonly accepted that pedestrians react to pedestrians and obstacles in their vicinity by adapting their speed and walking direction, although the underlying concepts are still widely unknown. Especially the movement patterns in the transition phase between steady state flows are unclear. They are expected to be different for increasing and decreasing flows as well as compared to a steady state flow at the same density. To eliminate this phenomena, the first condition is that the flow has to be steady state, as it is already proposed in literature (Daamen, 2004; Hoogendoorn and Bovy, 2003; Kaakai et al., 2007; Nikolić et al., 2016; Steffen and Seyfried, 2010). Still, if a heterogeneous flow of people is considered, fluctuations of the flow will occur. Here, a distinction between changes in flow due to external factors, such as a reduction in pedestrian demand, and internal factors due the stochastic characteristics of the flow must be made. The first must be avoided; the latter is a substantial part of the fundamental diagram.

Different measurement methods for the pedestrian speed and density are available in literature providing significantly different results (Duives et al., 2015b; Seyfried et al., 2010a; Steffen and Seyfried, 2010). Depending on the averaging and aggregation over space and time, peaks and discontinuities will be flattened or strongly visible. The influence of space and time will be further discussed in the next chapters. It is argued that from the design perspective it should be possible to select the most appropriate methods. These methods either measure speed and density respectively exactly or as close as possible according to the definition. Here the definition of the fundamental diagram has include the relevant definition.

For the speed, the average speed for all pedestrian in an area is used (space mean speed, see Chapter 2.4.5). Else, when determining the speed-density relation for individual pedestrians, a wide scatter of walking speeds is expected. Although this scatter is important for studying the microscopic characteristics, it is not relevant for the macroscopic design of pedestrian facilities using the pedestrian fundamental diagram. From a design perspective the distribution of walking speeds at a given density might still be important. For example, to estimate walking times or to insert safety margins for the flow calculations different percentile values can be applied. In addition, only the speed in the global walking direction shall be considered, as the distance covered for overtaking other pedestrians or for sidesteps is irrelevant for design purposes.

In the fundamental diagram, the density serves as an indicator for the restriction in walking direction and speed. Up to now, it is unknown how the specific restrictions influence the microscopic walking characteristics, especially which area around the pedestrian is considered for the choice of walking speed and direction. Several assumptions for this can be found in literature, but it can be expected that this area is varying depending on the pedestrian characteristics and the distance to other pedestrians. Assuming that the pedestrian flow contains different pedestrians showing variations in their decision about speed and walking direction under the same circumstances, differences in local and global density can be expected, as it can be seen in real world data (Helbing et al., 2007). If the spacing between pedestrians is completely even, the density at a certain time will be independent of the size of the measurement area. However, for a heterogeneous set of pedestrians, the spacing will be uneven and therefore the local densities will show variations. Hence, two contradicting ideas of the fundamental diagram can be identified. If the fundamental diagram shall describe the average speed, which is chosen at a certain density, representing constrains experienced by a pedestrian, smaller areas must be used. If the area considered is increased, the density will describe the average density of the stream to a greater extend, including variations in the local densities observed. For the same situation, the first method will then show different density values whereas for the latter only a single global density will be used (Figure 2.38). This phenomenon can also be seen when using experimental data for computing micro- and macroscopic speed – density data (Cao et al., 2016b).

Given the fact that the exact dimensions of the influence area are unknown and most likely varying, the goal of the first method, namely describing the direct relation between speed and the restriction expressed in the density, cannot be fulfilled. As the fundamental diagram is also considered as a macroscopic expression, the second approach is used. Therefore, areas big enough to represent the average density of the total pedestrian flow must be used.

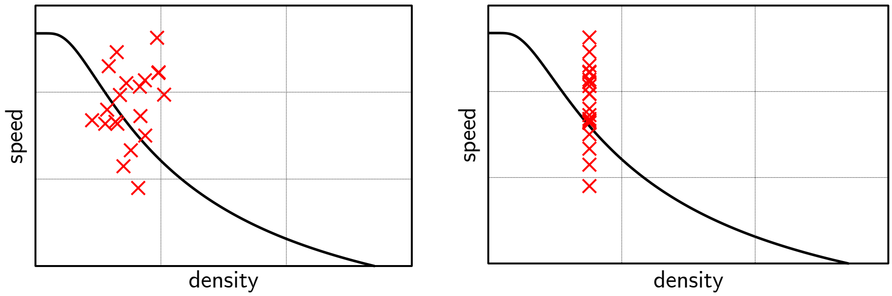

FIGURE 2.38: Artificial speed-density relations for small areas (left) compared to a single big area with a global density for all pedestrians (right) at a certain time step. Using a different size of the area will considerably change the speed density data obtained. In black the fundamental diagram proposed by Weidmann (1993) is presented. Figure source: Bosina and Weidmann (2016).

2.4.7.3 *Space*

The time interval and measurement area used can lead to different results. This is relevant especially when speed-density or speed-flow measurements are made to derive the fundamental diagram. Therefore, a definition is needed for these parameters to enable comparability across different settings.

In addition to the requirements described in the previous section, the measurement area, especially if it is small, will influence the results (Appert-Rolland et al., 2014; Zhang, 2012). For example, the fluctuation in density due to pedestrians entering or leaving the area and border effects has a great impact on the results (Steffen and Seyfried, 2010). Another important aspect for the area, which is used in the fundamental diagram are effects of boundaries. Next to obstacles and walls, as well as to opposing flows areas with a reduced flow rate can be observed (Bosina et al., 2016). As the effects of these areas vary in different situations, they shall be excluded from the fundamental diagram. In theory, these effects will not occur, if the flow of pedestrians has an infinite extend. To be independent from the shape of the facility and measurement area, the fundamental diagram therefore represents a situation without border, where the dimensions of the situation are irrelevant.

2.4.7.4 *Time*

Apart from space, the time interval used for the fundamental diagram has an important influence. The time interval can range from instantaneous, where speed and density will be calculated for a certain moment, to a long time period, where the measurements are averaged over the whole period. Like considering small areas, using the density at a moment in time will result in a high scatter of walking speeds for a certain density. This scatter also does not completely represent the reaction of walking speed to the density, as the human reaction is considered to show a certain time delay. Using a time interval similar to the human reaction time might be a promising idea, but this duration is not known exactly as well as it is expected to show variations depending on the person and the planned movement task. However, as the idea is to derive the fundamental diagram for a macroscopic stream and not for microscopic pedestrian properties, the more feasible approach is to extend the time interval to infinity to obtain the average walking speed. If the pedestrian fundamental diagram shall also include the variations of the walking speed and flow for a given density, the walking speed distribution can be used.

2.4.7.5 *Pedestrian characteristics*

The purpose of the pedestrian fundamental diagram is to describe the properties of a pedestrian flow for a cross-section, consequently at a mesoscopic level. Hence, the fundamental diagram will vary depending on the observed pedestrian characteristics (free flow walking speed, shy away distance...). For example, even if the average free flow walking speed is the same, differences in the walking speed distribution among the group (i.e. the standard deviation) might result in differences in the fundamental diagram (assuming otherwise similar conditions). By default, the fundamental diagram represents a situation with solely unidirectional flow.

2.4.7.6 *Definition*

If different or no definitions of the fundamental diagram are used, the comparison between resulting data is of limited value. Therefore, and to summarise the characteristics of the fundamental diagram and to distinguish it from other speed-density relations, a detailed definition of the pedestrian fundamental diagram for unidirectional flow is proposed:

The pedestrian fundamental diagram describes the (average) relation between speed, flow and density of a set of pedestrians with defined properties at constant global density for infinite time and space. The individual characteristics of the pedestrians might vary, but they are randomly distributed over space and time.

Using this definition, differences between pedestrian fundamental diagrams will still be visible but will only be based upon situational differences and not upon variations in the measurements. Based on this definition, the most suitable measurement methods can be selected for a specific situation (see Chapter 2.4.7.8).

2.4.7.7 *Stochastic variations in the fundamental diagram*

Usually, the fundamental diagram only shows the average relation between density and speed or flow. Still, even for the same constant setting and global density, stochastic variations will be visible. Individual pedestrians will not always react the same in the same situation, as well as variations between different pedestrians exist. In addition, the pedestrian composition within a flow is statistically distributed. Using the definition presented, these differences will lead to variations in the local density, which itself will also influence the speed and direction of individual pedestrian and therefore the global average speed and flow.

In Figure 2.39, an example for the influence of the stochastic variations on the fundamental diagram is shown. For this, it is assumed that the walking speed at a certain density shows a variation of $\pm 15\,\%$ around the mean value. For a given density, the fundamental diagram now shows a corresponding walking speed range as well as a range of flow values. Especially if the flow is known and it is in the range of the maximum average flow, this example will result in a wide range of corresponding densities.

The considerations regarding the stochastic variations in the fundamental diagram are especially important for the design of pedestrian facilities. Usually the design of facilities is not done for mean values, which would imply that $50\,\%$ of the time the design load is reached (assuming a normal distribution) the facility is overloaded. Here, an exceedance probability is applied to integrate the stochastic nature of the variables into the calculation. As a reference for suitable probability values, data from similar situations can be used. For the pedestrian crossing speed, often the 15th percentile is used as a reference value (Coffin and Morrall, 1995; Gates et al., 2006). To determine the design hourly volume of roads, the hourly value for the 30$^{(}$th) to 100$^{(}$th) yearly peak hour is used (Arnold et al., 2013; Sharma and Oh, 1989). In addition, it has to be considered, if the values are used for the design for quality or design for safety.

2.4.7.8 *Limitations in application*

Albeit the presented definition shall provide complete comparability between different fundamental diagrams, it is neither possible to measure nor to apply it in real-life scenarios, as for example the requirement of infinite time and space cannot be met. Nevertheless, as described previously the fundamental

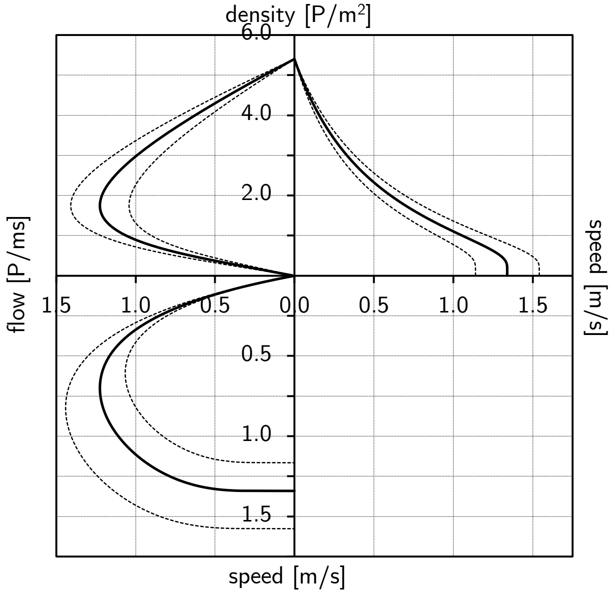

FIGURE 2.39: Influence of parameter variation on the fundamental diagram (Data: Weidmann (1993)).

diagram serves as a theoretical concept, useable for the macroscopic design of pedestrian facilities. For real-life measurements and experiments, the fundamental diagram can be used to generate data close to the theoretical definition, which will be highly comparable. For data collection, this leads to the goal to use large areas or time intervals showing the same pedestrian flow. In addition, measurement methods for density can be used to obtain data as close as possible to the theoretical model, (Duives et al., 2015b; Steffen and Seyfried, 2010).

For the design of pedestrian facilities, the presented definition of fundamental diagrams can be used as the calculations are usually done for pedestrian streams. Still, effects not considered in the fundamental diagram have to be considered, for example by reducing the effective width of a corridor to accommodate for wall effects and bidirectional flows (Bosina et al., 2016; Meeder et al., 2015). When applying the fundamental diagram to real conditions for the design of pedestrian facilities the usually highly variable flow regime must be considered. Here, methods have to be defined to account for phases with increasing or decreasing flow. It is also often needed to apply the fundamental diagram to intervals showing a variation in pedestrian flow having only average flow values. Even when assuming that no intervals with increasing or decreasing flows occur, it can be shown from the shape of the fundamental diagram that for an average flow the fundamental diagram differs.

For example, when assuming a non-linear speed-density curve, the average speed for one hour at a density of 1.5 P/s is different to the one for half an hour at 1.0 P/s and half an hour at 2.0 P/s (0.80 m/s versus 0.83 m/s). In general, this difference might be negligible, but it might be important for certain cases. If continuous measurements are available, several methods exist to determine, if constant conditions are present in a certain time interval (Liao et al., 2016).

As the definition of the fundamental diagram presented is strict, some of the requirements can be violated without a substantial influence on the results. Concerning time and space, a finite measurement time and space is possible without significant influence on the result. Small measurement areas can also be compensated using long observation times and vice versa.

2.4.8 *Range of the pedestrian fundamental diagram values*

Human walking, and therefore the fundamental diagram, is limited by several restrictions. Neither is it possible to walk at any given speed, nor can the pedestrian density reach unlimited high numbers. In a first step for describing the fundamental diagram, the physical limits of the speed-density relations of human walking shall be described.

The minimum pedestrian density can be set to zero, where a single pedestrian is walking in an infinite large area. In reality, where space is limited, often the pedestrian density for pedestrian walking freely is set to 0, as otherwise the calculated density will be solely dependent on the size of the measurement area. The human body dimensions restrict the maximum pedestrian density. For the determination of the space demand the human body is usually approximated by an ellipse, resulting in a space demand of 0.08 to 0.13 m^2/P (Buchmüller and Weidmann, 2006) or 12.5 to 7.7 P/m^2. Children and teenager have a lower space demand (0.04 to 0.09 m^2/P), whereas the presence of luggage can raise the space demand considerably (Predtečenskij and Milinskij, 1971). In addition, for the calculation of the maximum pedestrian density clothing and unusable space between pedestrians has to be considered as well (Kendik, 1986; Weidmann, 1993).

The potential walking speed of human lies within the range of standing pedestrian with a walking speed of 0 to the maximum walking speed determined by the human body. Considering the biomechanics of human walking and its energy demand it is obvious that human walking is limited to a certain maximum speed. Even before the theoretical maximum of walking speed human will start to run. Runing is a form of locomotion which needs less energy for higher speeds and allow to reach much higher speeds (Sentija and Markovic, 2009). The highest speed recorded for human locomotion is 12.4 m/s (DLV, 2010a). As this speed is obtained by running and only for a short distance (20 m average), reasonable values are much lower. Considering situations where fundamental diagrams are usually applied, it will be assumed for further discussions that only walking must be considered. Although it has to be mentioned that in real situations, also speeds of more than 5 m/s can be observed, which indicate that these pedestrians were running (Nikolić et al., 2016). Still, these high speeds do not occur very often, particularly not as average for a pedestrian flow, as it is represented in the fundamental diagram. Considering walking, the transition from walking to running occurs at about 2 m/s and the maximum walking speed using an inverted-pendulum model can be calculated to 2.9 to 3.0 m/s for an adult (Enoka, 2015; Minetti, 2000). In race-walking, higher speeds are observed (DLV, 2010b), nevertheless the movement in race-walking is different to normal walking.

In some studies, it was also observed that a minimum walking speed of about 0.45 to 0.50 m/s exists (Oeding, 1963). It is assumed that below this speed people prefer to stop completely for a short time (Johansson, 2009a). For higher walking speeds at lower densities, it can therefore be assumed that a minimum value exists. Only at higher densities lower walking speeds are observed. This can either be an average between pedestrians standing and walking pedestrians or it might be an indicator that slow walking occurs. Slow walking can be characterised as shuffling with a high proportion of sideways movement compared to walking freely. Measurement at high densities show a double peak speed distribution with a peak at about 0 m/s and another one at about 0.15 m/s (Seyfried et al., 2010b). This indicates that several pedestrians stopped completely, whereas others, if possible, walk at a slow walking speed.

Another limit of the pedestrian speed-density relation can be set using the space demand for walking. For each step a certain area is needed for placing the foot in front of the body in addition to the minimum body area (Weidmann, 1993). As it can be also observed in partner dances like Tango or Viennese Waltz, this additional space demand might also be further reduced by using the body space of other people. The human body has its highest space demand at the upper part of the body. Therefore, it is still possible to use this space for forward foot placement. In normal walking conditions, this behaviour is not expected to occur frequently. Only in highest density situation, it might influence the possible speed-density area. For higher densities, the step length – walking speed relation can thus be set as a limit. In addition to the physical space usually a time headway is observed, which is considered to account for the human reaction time (Johansson, 2009a).

It can be concluded that quite hard limits for the fundamental diagram exist, formed by the maximum walking speed and the human body space. There are also limits due to the dynamic space demand for walking and a lower walking speed limit due to the inefficiencies in human walking at low speeds. These limits are less strict and can be exceeded in certain situations.

2.4.9 *Main influences on the speed-density relation*

The fundamental diagram, as well as other speed-density relations, is mainly based upon the fact that pedestrians adapt their walking speed and direction due to the presence of other pedestrians in their vicinity as well as that their walking capabilities are limited. Depending on the density region within the speed-density relation, it is assumed that other factors are dominating the human walking characteristics. Whereas at low densities the physical properties of the humans are predominant, the interaction with others will gain importance with increasing density.

At low densities, where pedestrians walking without relevant interaction with other pedestrians, the determinant of walking speed is the human body and its biomechanical properties as well as the desired speed of the pedestrian. Due to the different characteristics of the individual pedestrians, differences in the walking speeds can be observed.

With an increase in density, conflicts with other pedestrians become more likely. Still, the available space allows solving these conflicts mostly by overtaking or by small changes in walking speed. However, as the walking path is extended due to the detour done when overtaking, the speed in the global walking direction, as it is usually shown in the fundamental diagram, is reduced.

A further increase in density will reduce the possibilities to pass other pedestrians. Hence, pedestrians reduce their speed according to the available space and to the walking speed of pedestrians in front of them.

Even if pedestrians try to avoid physical contact with other pedestrians, at highest densities these contacts will occur and increase with density. It is not possible anymore to keep a buffer space around one's body. Crowd phenomena like lock-step as well as stop-and-go waves and crowd turbulence will be observed (Helbing et al., 2007; Seyfried et al., 2005). Close to the maximum density, pedestrians therefore do not walk at a constant speed. Here, their walking is determined by the uneven distribution of available space. If no walking space is available, people will stop until a small walking space is present. Thus at high densities, the walking speed distribution shows two peaks, one at zero walking speed and one at a slow walking speed (Eilhardt and Schadschneider, 2015).

The variation of walking speeds is decreasing with an increase in density, which shows that the individual pedestrians have to adapt their walking speed to the movement of the pedestrian flow (Appert-Rolland et al., 2014; Oeding, 1963). Also the deviation of the minimum distance between two pedestrians is increased, indicating a more uniform flow (Johansson, 2009a).

2.4.10 *Proposed speed-density equations*

In literature, several speed-density equations have been proposed based on data from measurements (Table 2.17). Most of them use a linear correlation between density and speed. Nevertheless, the derived equations differ considerably due to the different setting in which they were measured.

Table 2.17: Speed-density equations proposed in literature.

SOURCE	TYPE	v [m/s]	D [P/m²]
Das et al. (2015)	Level walking	$v = 1.32 - 0.25 \cdot D$	
	Level walking	$v = 1.32 \cdot e^{-0.22 \cdot D}$	
	Level walking	$v = 1.37 - 0.42 \cdot D$	
	Level walking	$v = 1.38 \cdot e^{-0.36 \cdot D}$	
Fruin (1971b)	Level walking (unidirectional)	$v = 1.43 - 0.35 \cdot D$	
	Level walking (bidirectional)	$v = 1.36 - 0.34 \cdot D$	
	Stairs (up)	$v = 0.56 - 0.08 \cdot D$	
	Stairs (down)	$v = 0.65 - 0.10 \cdot D$	
Gerilla et al. (1995)	Level walking	$v = 1.39 - 0.39 \cdot D$	
Jia et al. (2009)	Level walking	$v = 1.69 - 0.59 \cdot D$	
	Stairs (up)	$v = 0.69 - 0.13 \cdot ln(D)$	
	Stairs (down)	$v = 0.94 - 0.18 \cdot D$	
Lam et al. (1995)	Level walking (indoor)	$v = 1.29 - 0.36 \cdot D$	
	Level walking (outdoor)	$v = 0.02 \cdot e^{4.47 - 0.572 \cdot D}$	
	Level walking	$v = 1.42 \cdot e^{-0.347 \cdot D^2}$	
	Level walking	$v = 1.67 \cdot e^{-0.5 \cdot D}$	
	Stairs (up)	$v = 0.89 - 0.17 \cdot D$	
	Stairs (down)	$v = 1.09 \cdot e^{-0.41 \cdot D}$	
	Stairs (up)	$v = 0.02 \cdot e^{3.89 - 0.2 \cdot D^2}$	
	Stairs (down)	$v = 0.02 \cdot e^{4.6 - D}$	
Laxman et al. (2010)	Level walking	$v = 1.37 - 0.41 \cdot D$	
	Level walking	$v = 1.39 - 0.41 \cdot D$	
	Level walking	$v = 1.48 - 0.42 \cdot D$	
	Level walking	$v = 1.44 - 0.32 \cdot D$	
	Level walking	$v = 1.38 - 0.53 \cdot D$	
	Level walking	$v = 1.35 - 0.53 \cdot D$	
	Level walking	$v = 1.40 - 0.33 \cdot D$	

TABLE 2.17: Speed-density equations proposed in literature.

SOURCE	TYPE	v [m/s]	D [P/m²]
Lee (2005)	Stairs (down)	$v = 0.77$	< 0.60
		$v = 0.87 - 0.16 \cdot D$	> 0.60
	Stairs (up)	$v = 0.68$	< 0.60
		$v = 0.77 - 0.14 \cdot D$	> 0.60
Mōri and Tsukaguchi (1987)	Level walking	$v = 1.48 - 0.20 \cdot D$	
Navin and Wheeler (1969)	Level walking	$v = 1.31$	< 1.07
		$v = 2.13 - 0.79 \cdot D$	> 1.07
Nazir et al. (2012)	Level walking	$v = 1.07 - 0.17 \cdot D$	
	Level walking	$v = 1.02 - 0.14 \cdot D$	
	Level walking	$v = 1.05 - 0.15 \cdot D$	
Nelson and MacLennan (1995)	Level walking	$v = 1.19$	< 0.54
		$v = 1.40 - 0.37 \cdot D$	> 0.54
	Stairs (down)		
	Riser = 19.0 cm,	$v = 0.85$	< 0.54
	tread = 25.4 cm	$v = 1.00 - 0.27 \cdot D$	> 0.54
	Riser = 17.8 cm,	$v = 0.95$	< 0.54
	tread = 27.9 cm	$v = 1.08 - 0.29 \cdot D$	> 0.54
	Riser = 16.5 cm,	$v = 1.00$	< 0.54
	tread = 30.5 cm	$v = 1.16 - 0.31 \cdot D$	> 0.54
	Riser = 16.5 cm,	$v = 1.05$	< 0.54
	tread = 33.0 cm	$v = 1.23 - 0.33 \cdot D$	> 0.54
O'Flaherty und Parkinson (1972)	Level walking	$v = 1.37 - 0.36 \cdot D$	
	Level walking	$v = 1.61 - 0.53 \cdot D$	
	Level walking	$v = 1.43 - 0.34 \cdot D$	
	Level walking	$v = 1.54 - 0.56 \cdot D$	
Older (1968)	Level walking	$v = 1.31 - 0.34 \cdot D$	
Pauls (1980)	Stairs (down)	$v = 1.26 - 0.33 \cdot D$	
Polus et al. (1983)	Level walking (1 regime)	$v = 1.31 - 0.27 \cdot D$	
	Level walking	$v = 1.27 - 0.12 \cdot D$	< 0.60
	(3 regimes)	$v = 1.62 - 0.73 \cdot D$	$[0.60, 0.75]$
		$v = 1.31 - 0.27 \cdot D$	> 0.75
Rastogi et. al (2013)	Level walking	$v = 1.58 \cdot e^{-0.33 \cdot D}$	
	Level walking	$v = 1.49 \cdot e^{-0.35 \cdot D}$	
	Level walking	$v = 1.34 \cdot e^{-0.39 \cdot D}$	
Sarkar and Janardhan (2001)	Level walking (unidirectional)	$v = 1.46 - 0.35 \cdot D$	
Tanaboriboon et al. (1986)	Level walking (bidirectional)	$v = 1.23 - 0.26 \cdot D$	

Table 2.17: Speed-density equations proposed in literature.

SOURCE	TYPE	v [m/s]	D [P/m²]
Tanaboriboon and Guyano (1989)	Level walking	$v = 1.21 - 0.22 \cdot D$	
Teknomo (2006)	Level walking (unidirectional)	$v = 1.02 - 0.36 \cdot D$	
	Level walking (bidirectional)	$v = 1.20 - 0.22 \cdot ln(100 \cdot D)$	
Virkler and Elayadath (1994)	Level walking	$v = 0.61 \cdot ln(4.32/D)$	≥ 1.07
		$v = 1.01 \cdot e^{-0.24 \cdot D}$	< 1.07
Weidmann (1993)	Level walking	$v = 1.34 \cdot [1 - e^{-1.913 \cdot (1/D - 1/5.4)}]$	
	Stairs (up)	$v = 0.61 \cdot [1 - e^{-3.722 \cdot (1/D - 1/5.4)}]$	
	Stairs (down)	$v = 0.69 \cdot [1 - e^{-3.802 \cdot (1/D - 1/5.4)}]$	
Ye et al. (2008)	Level walking (unidirectional)	$v = 1.44 - 0.45 \cdot D$	
	Level walking (bidirectional)	$v = 1.19 - 0.04 \cdot D - 0.08 \cdot D^2$	
	Stairs (down)	$v = 0.97 - 0.16 \cdot D$	
	Stairs (up)	$v = 0.69 - 0.14 \cdot D$	
Yeo and He (2009)	Level walking	$v = 1.29 - 0.11 \cdot D$	
	Stairs (up)	$v = 0.48 - 0.02 \cdot D$	
	Stairs (down)	$v = 0.57 - 0.02 \cdot D$	

In Figure 2.40 and Figure 2.41 the equations are compared with measurement data found in literature (Bosina and Weidmann, 2017c). At lower densities, the speed-density equations show a similar range as the measurement data. Most walkway fundamental diagram curves are close to each other at densities lower than 2.0 P/m². At higher densities, the differences in the equations are considerably bigger and they do not fit very well to the data any more. One of the reasons for this is that most of the data used for setting up the equations is recorded at low densities, hence, the speed–density curves at high densities are only extrapolations of the relations at lower densities.

2.4.11 *Capacity*

An important parameter for pedestrian facilities is the capacity, defined as the maximum flow. Similar to the speed-density equations, various values for the capacity of different pedestrian facilities exist (Table 2.18).

The specific capacity of walkways found in literature varies between 0.87 P/ms (Laxman et al., 2010) and 2.07 P/ms (Rastogi et al., 2013) with a mean value of about 1.40 P/ms. The corresponding densities show a range of 0.75 to

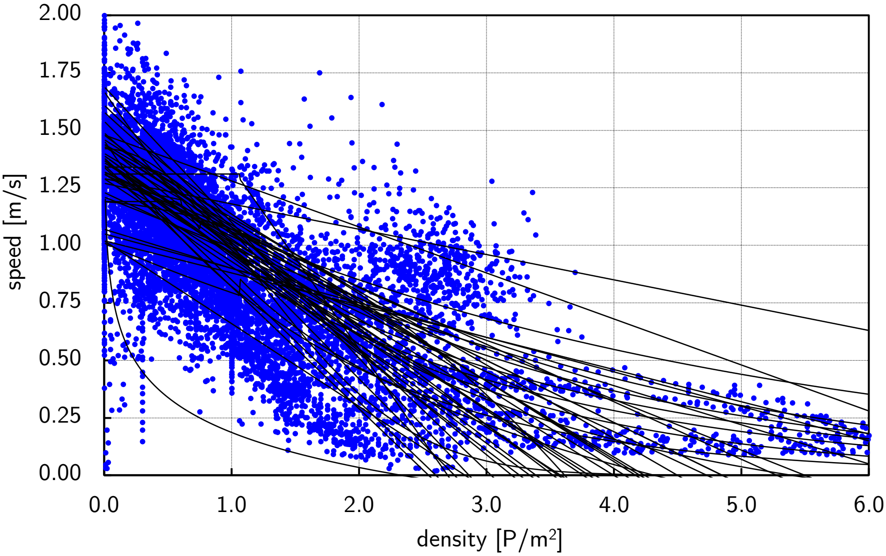

FIGURE 2.40: Fundamental diagram curves for level walking proposed in literature (see Table 2.17) in comparison with speed-density data found in literature (Bosina and Weidmann, 2017c).

3.70 P/m² and the walking speeds vary from 0.39 to 0.74 m/s. Still, it should be noted that the list of capacity values (Table 2.18) is neither complete nor is it a random selection of measurements. In experiments, also flow values of up to 4.3 P/ms were recorded (Oeding, 1963). However, as these experiments were specifically done to obtain the highest possible capacity, such values cannot be expected to occur in normal real-life situations.

No literature was found describing in detail the reasons for these differences, but some researchers made measurements at different locations showing different characteristics. It can therefore be assumed that, like the walking speed (see Chapter 2.3), several influences exist which influence the capacity of a pedestrian facility.

TABLE 2.18: Specific capacity C_s for level walking and stairs measured in literature.

SOURCE	TYPE	C_s [Ps/m]	v [m/s]	D [P/m²]
Al-Masaeid et al. (1993)	Level walking	1.00	0.67	1.49
Daly et al. (1991)	Level walking	1.43	0.60	2.38
	Stairs (up)	1.03	0.36	2.86
	Stairs (down)	1.14	0.56	2.04

TABLE 2.18: Specific capacity C_s for level walking and stairs measured in literature.

SOURCE	TYPE	C_s [P s/m]	v [m/s]	D [P/m²]
Fruin (1971b)	Level walking (commuter, unidirectional)	1.43	–	–
	Level walking (commuter, bidirectional)	1.35	–	–
	Level walking (shopping)	1.27	–	–
Gerilla et al. (1995)	Level walking	1.25	0.69	1.80
	Stairs	0.84	–	–
Graat et al. (1999)	Stairs	0.84	–	–
	Level walking	1.17	0.71	1.65
Jia et al. (2009)	Level walking	1.17	0.71	1.65
	Stairs (normal)	0.90	–	–
Khisty (1985)	Stairs (normal)	0.90	–	–
	Stairs (Emergency)	1.00	–	–
Lee and Lam (2006)	Stairs (up)	1.12	0.56	2.00
	Stairs (down)	1.32	0.68	1.94
Lam et al. (2003)	Level walking	1.13	0.72	1.58
	Level walking	1.25	0.68	1.83
	Level walking	1.53	0.61	2.50
	Level walking	1.47	0.60	2.45
	Level walking	1.43	0.60	2.39
Lam and Cheung (2000)	Level walking (outdoor)	1.36	0.52	2.63
	Level walking (outdoor)	1.07	0.46	2.34
	Level walking (indoor)	1.12	0.65	1.74
	Level walking (indoor)	1.03	0.39	2.65
	Level walking	1.27	0.58	2.19
	Level walking	1.34	0.69	1.95
	Level walking	1.45	0.36	4.06
	Level walking	1.21	0.39	3.09
	Stairs (up)	1.17	0.43	2.74
	Stairs (down)	1.33	0.60	2.22
	Level walking	1.53	0.61	2.50
	Stairs (up)	1.17	0.42	2.80
	Stairs (down)	1.22	0.57	2.14
	Level walking	1.47	0.60	2.45

TABLE 2.18: Specific capacity C_s for level walking and stairs measured in literature.

SOURCE	TYPE	C_s [P s/m]	v [m/s]	D [P/m²]
Laxman et al. (2010)	Level walking	1.15	0.69	1.68
	Level walking	1.18	0.69	1.70
	Level walking	1.32	0.74	1.78
	Level walking	1.59	0.72	2.22
	Level walking	0.87	0.69	1.30
	Level walking	0.87	0.67	1.29
	Level walking	1.46	0.70	2.09
Oeding (1963)	Level walking (commuter)	1.83	–	–
	Level walking (business)	1.50	–	–
	Level walking (shopping)	1.08	–	–
	Level walking (events)	1.50	–	–
Older (1968)	Level walking	1.28	0.64	1.94
	Level walking	1.71	0.53	3.23
Nazir et al. (2012)	Level walking	1.71	0.53	3.23
	Level walking	1.91	0.52	3.70
	Level walking	1.78	0.54	3.33
Rastogi et al. (2013)	Level walking	1.76	0.58	3.03
	Level walking	1.57	0.55	2.86
	Level walking	1.26	0.49	2.56
	Level walking (unidirectional)	1.33	0.59	2.27
	Level walking (bidirectional)	1.77	0.57	3.13
	Level walking (unrestrained)			
	Level walking (restrained)	1.57	0.55	2.86
	Level walking			
	Level walking	1.35	0.41	3.45
		2.07	0.70	2.92
		1.49	0.55	2.70
Sarkar and Janardhan (2001)	Level walking (unidirectional)	1.53	0.74	2.10
	Stairs	0.83	0.38	2.22
Shah et al. (2013)	Stairs	0.83	0.38	2.22
	Stairs	0.75	0.26	2.86
	Stairs	0.82	0.35	2.33
	Stairs	0.55	0.39	1.41
Shah et al. (2017)	Stairs (up)	1.35	0.35	3.85
	Stairs (down)	1.55	0.33	4.76
	Stairs (up)	1.27	0.27	4.76
	Stairs (down)	1.35	0.26	5.26

TABLE 2.18: Specific capacity C_s for level walking and stairs measured in literature.

SOURCE	TYPE	C_s [P s/m]	v [m/s]	D [P/m²]
Tanaboriboon et al. (1986)	Level walking (bidirectional)	1.48	0.58	2.54
	Level walking			
		1.68	0.62	2.71
Tanaboriboon and Guyano (1989)	Level walking	1.68	0.62	2.71
	Level walking (unidirectional)	1.38	$>$ 1.20	0.75
Ye et al. (2008)	Level walking (unidirectional)	1.38	$>$ 1.20	0.75
	Level walking (bidirectional)	$>$ 1.19	$>$ 1.20	$<$ 0.82
	Stairs (down)			
	Stairs (up)	$>$ 1.24	$>$ 0.92	$<$ 0.58
		$>$ 1.01	$>$ 0.75	$<$ 0.35

Surprisingly, no big differences can be found in literature regarding the capacity of stairs and other pedestrian facilities (Table 2.19). Whereas the capacity for walking upstairs is lower than for walking downstairs, both are within the range of capacity values for level walking. However, when using the average value from all capacity values found in literature, level walking shows a higher value. A reason for this is that the capacity values for level walking are measured in different situations with a varying pedestrian composition, hence the range of capacity values are larger. Still, in all guidelines found which state capacities for pedestrian facilities, different values for going upstairs, downstairs and level walking are proposed (Department for Culture, 2008; DIN, 2012; Gwynne and Rosenbaum, 2016; IMO, 2007). Compared to the capacity obtained from the fundamental diagrams proposed by Weidmann (1993), the measured capacity values are higher on average. For flat walking, the fundamental diagram yields a capacity of 1.225 P/m s, which is slightly lower than the average value found in literature. However, the capacity values for stairs (upstairs: 0.850 P/m s, downstairs: 0.975 P/m s) are lower than the corresponding minimum values.

TABLE 2.19: Range of specific capacity C_s [P/m²] from measurements found in literature.

TYPE	MINIMUM	MAXIMUM	AVERAGE	SOURCES
Level walking	0.87	2.07	1.40	51
Stairs (up)	1.01	1.35	1.16	7
Stairs (down)	1.14	1.55	1.31	7

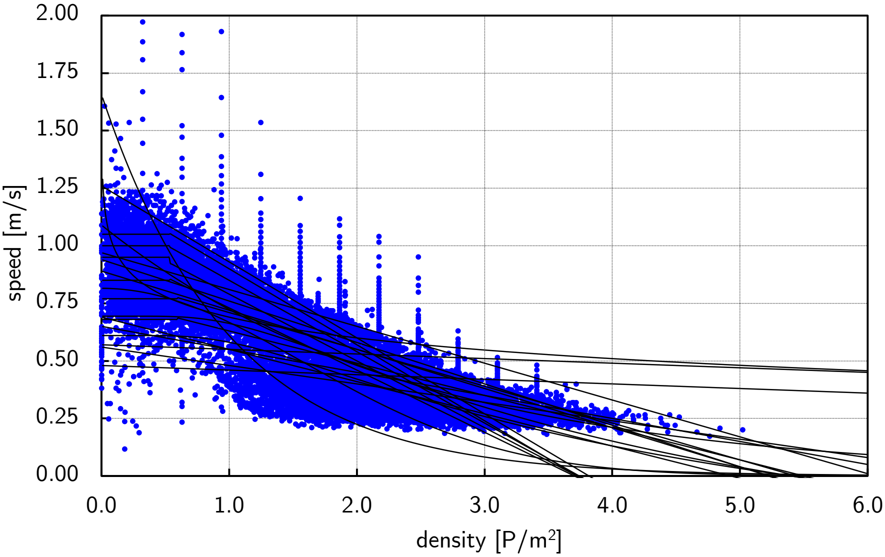

FIGURE 2.41: Fundamental diagram curves for stairs proposed in literature (see Table 2.17) in comparison with speed-density data found in literature (Bosina and Weidmann, 2017c).

The capacity value might also be influenced by the measurement method used. Usually the maximum flow observed or calculated using a speed – density curve is considered to represent the capacity. However, the time interval or the size of the measurement area can influence the maximum flow observed (Daly et al., 1991; Johansson et al., 2008). For vehicle traffic, different definitions for capacity exists, but in general the capacity is defined as a maximum for a set time period in certain conditions (Elefteriadou, 2014; TRB, 2010). For pedestrians, the Highway Capacity Manual (TRB, 2010) proposes a similar definition for the person capacity as for the vehicle capacity, which requires the capacity to be measured in prevailing conditions to obtain a reasonable expectancy. Still, a commonly accepted definition is missing.

Thus, it is recommended to specify the term capacity for pedestrian transport. In general, the capacity of a pedestrian facility represents the maximum flow, which can be sustained for a certain period and be used for design purposes. Short-term fluctuations and one-time measurements thus cannot be used as the capacity of a facility. As the usage is similar, the requirements concerning the measurements of the capacity are like the ones for the fundamental diagram. Likewise, the capacity not only depends on the facility but also on the set of pedestrians observed. For this work, the capacity will therefore be defined as the maximum flow expressed in the fundamental diagram (Johansson, 2009b; Seyfried et al., 2009b). Assuming a stochastic fundamental diagram, this implies that the capacity is a stochastic value, showing a mean and a certain probability distribution. The maximum a flow can reach under given conditions, for example at a certain Level of Service, will be named as "maximum flow".

2.4.12 *Influences on the fundamental diagram*

Not only the facility type but also several other factors can be determined to influence the fundamental diagram. First, it can be assumed that influences on the free flow walking speed (see Chapter 2.3 or (Bosina and Weidmann, 2017c)) will also have an effect on the shape of the fundamental diagram. Apart from variations in the free flow walking speed, mainly the maximum density and the distance kept to other pedestrians at a certain speed will influence the fundamental diagram. An influence factor can therefore influence the fundamental diagram in different ways (Daamen, 2004). For example, luggage can influence the free flow walking speed, but it will also increase the individual space demand and hence the maximum density. For general speed – density curves, the type of the flow and the measurement method will show a strong influence on the results (Cao et al., 2017).

In literature, only a few references can be found which propose different fundamental diagrams for different situation characteristics, mainly for different facilities, normal and emergency conditions, uni- and bidirectional flow and different trip purposes (Fruin, 1971a; Galiza et al., 2011; Oeding, 1963; Predtečenskij and Milinskij, 1971; Thompson et al., 2015; Venuti and Bruno, 2009). For different age groups, it was found that a group of young people has a higher walking speed and maximum specific flow than older pedestrians. Still, the lowest walking speeds at the same density were observed for mixed age groups, which is an indicator that the homogeneity of the group also influences the speed-density relation (Cao et al., 2016a). Apart from Daamen (2004), no work was found which aims at describing the influences on the fundamental diagram in a more conceptual way.

2.4.13 *Conclusions to the fundamental diagram literature*

Nowadays, the fundamental diagram concept is widely used to describe the relation between speed and density in pedestrian transport. Still, neither in car traffic, where the concept originates, nor in pedestrian transport, a commonly accepted definition beyond its three main properties, speed, density and flow, can be found in literature. This lead to the current situation, where a wide range of speed-density curves are named "fundamental diagram" which cannot be compared due to their differences in measurement and calculation processes.

Thus, a definition of the fundamental diagram for unidirectional flow was established for this work. It is based on the aim and application purposes found in literature. Based on this definition it shall also be possible to derive fundamental diagrams in different situations which can be compared in a meaningful way.

As for example the reaction of pedestrians to similar situation can vary, the fundamental diagram has some stochastic variations. The proposed definition thus allows an extension from a fundamental diagram representing the mean values to a stochastic fundamental diagram, which also includes these variations. Especially for the design of pedestrian facilities, this can enhance the quality of the results.

The speed-density curves found in literature were shown in this chapter. Although the differences in the creation pose difficulties for their comparison, they form a clear area within the speed-density plot. It can also be concluded that the widely used fundamental diagrams proposed by Weidmann (1993) can still serve as an approximation of the mean curves. Using theoretical considerations about the physical properties of pedestrians, the range of the pedestrian fundamental diagram values can be narrowed down.

However, especially at the capacity values obtained from literature, considerable variations can be found. Apart from variation in the measurement settings, this can also reflect the walking behaviour found in different setting. Here, like for the walking speed, several influences can be identified.

2.5 LEVEL OF SERVICE CONCEPT

2.5.1 *Background*

Closely related to the fundamental diagram and another key concept for the design of pedestrian facilities is the Level of Service concept, which is used to describe the quality perceived by the users. First it was introduced in the Highway Capacity Manual 1965 for road traffic. There it was also stated that the LOS should be applied to a section of a roadway, which can have varying characteristics. Still, this assumption was rarely considered, as up to now, in most cases the LOS concept is applied to uniform facilities (Roess and Prassas, 2014).

Soon after its introduction it was transferred to pedestrian traffic. Here, the pedestrian density is used to distinguish different service levels. Already before, it was concluded that the pedestrian density shall be in a range which is comfortable, even if this leads to a lower specific flow (Schmitz, 1946). In Figure 2.42 and Table 2.20 different LOS schemes proposed for walkways and other facilities are shows. Similar to road traffic, uniform pedestrian facilities are usually used for the calculation of the LOS. Thus, the fundamental diagram can be applied to determine the density which relates to a specific LOS.

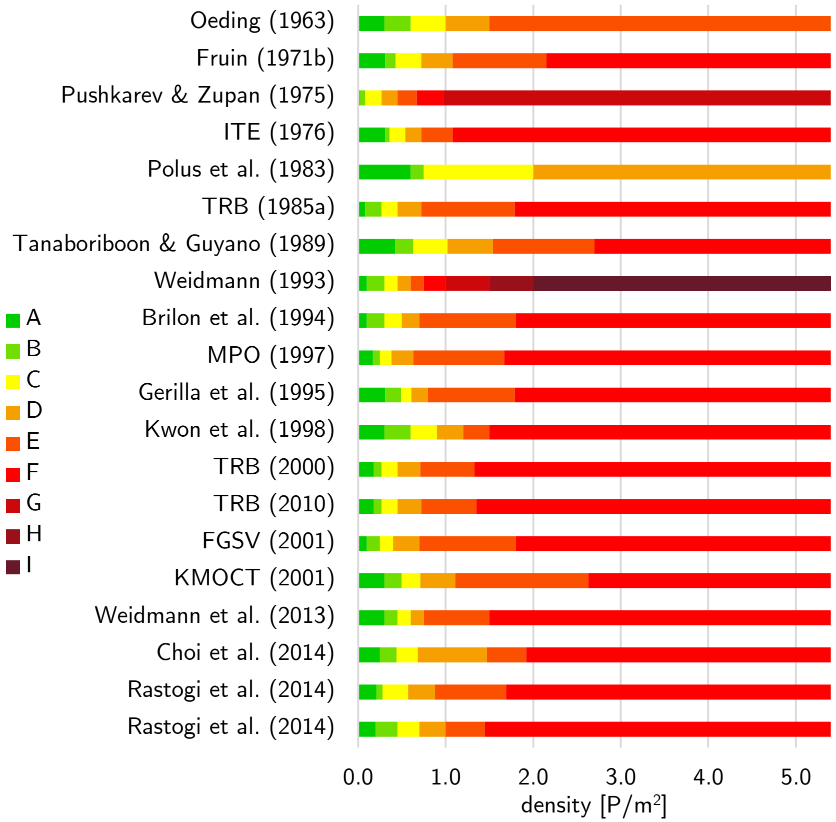

FIGURE 2.42: LOS schemes for walkways proposed in literature.

TABLE 2.20: LOS limits for platoons on walkways, stairways, waiting areas and other facilities from literature (upper limits) [P/m²]. Schemes that use a different notation than letters have been converted for better readability. Subclasses are omitted.

SOURCE	A	B	C	D	E	F	G	H	I
Walkway (platoons)									
Davis and Braaksma (1987)	0.59	0.77	1.00	1.25	1.43	> 1.43			
TRB (2000)	0.02	0.13	0.25	0.50	1.00	> 1.00			
Stairways									
Fruin (1971b)	0.54	0.72	1.08	1.54	2.69	> 2.69			
ITE (1976)	0.54	0.63	0.90	1.35	2.15	> 2.69			
Weidmann (1993)	0.20	0.60	0.75	0.90	1.15	1.65	2.15	2.60	5.40
Brilon et al. (1994)	0.10	0.30	0.50	0.70	1.80	> 1.80			

TABLE 2.20: LOS limits for platoons on walkways, stairways, waiting areas and other facilities from literature (upper limits) [P/m²]. Schemes that use a different notation than letters have been converted for better readability. Subclasses are omitted.

SOURCE	A	B	C	D	E	F	G	H	I
TRB (2000)	0.53	0.63	0.91	1.43	2.00	> 2.00			
TRB (2010)	0.54	0.63	0.90	1.35	2.15	> 2.15			
Weidmann et al. (2013)	0.60	0.80	1.00	1.15	2.15	>2.15			
Queues and waiting areas									
Fruin (1971b)	0.83	1.08	1.54	3.59	5.38	> 5.38			
TRB (1985a)	0.83	1.08	1.54	3.59	5.38	> 5.38			
Brilon et al. (1994)	1.00	2.00	3.00	4.00	6.00	> 6.00			
TRB (2000)	0.83	1.11	1.67	3.33	5.00	> 5.00			
FGSV (2001)	1.00	1.50	2.00	3.00	6.00	> 6.00			
Weidmann et al. (2013)	0.90	1.20	1.50	2.00	4.00	> 4.00			
Waiting areas (safety relevant)									
Weidmann et al. (2013)	0.55	0.75	0.95	1.25	2.50	> 2.50			
Crosswalk									
Lam and Lee (2001)	0.26	0.46	0.71	1.25	1.92	> 1.92			
Elevator									
Weidmann et al. (2013)	0.95	1.30	1.65	2.20	4.50	> 4.50			
Escalator									
Weidmann et al. (2013)	0.65	0.80	1.00	1.25	2.40	> 2.40			
Crossings, Places									
Weidmann et al. (2013)	0.15	0.25	0.35	0.45	0.80	> 0.80			

2.5.2 *Abstract*

The following section (Chapter 2.5.2 to 2.5.7) was already presented as:

Ernst Bosina et al. (2018). Defining the time component of the pedestrian LOS concept. Transportation Research Board 97th Annual Meeting. Washington, D.C.

For pedestrians, a number of density-based Level of Service (LOS) schemes exist in the literature. Although their values differ substantially, several common principles can be identified as necessary assumptions of this LOS concept. From these assumptions follows the importance of the time aspect of the LOS. Pedestrian flows are typically characterized by strong, often short-term, fluctuations. The LOS thus depends strongly on the chosen measurement interval. This link is highly relevant when designing infrastructures, as time-aggregated pedestrian counting data are often used in practice. Despite this fact, the time-dependency of LOS is hardly discussed in the literature.

This paper attempts to provide a conceptual basis for the pedestrian LOS based on a comprehensive review of the literature. With the increasing availability of continuous counting data, the time component of the pedestrian LOS concept can be examined in more detail. A case study described in this paper, together with a recently published LOS concept, illustrates the influence of flow variations on the LOS and the perceived quality of the flow. Results show that the time interval can be incorporated into an LOS scheme in a meaningful way, although certain limitations remain. It is furthermore argued that facility design should be based on ensuring a certain minimum LOS for a defined share of users, provided that detailed continuous counting data is available. Such an approach would best enable the construction of cost efficient as well as comfortable pedestrian facilities.

2.5.3 *Introduction*

When designing pedestrian infrastructures several aspects have to be taken into account. The most important parameter is the demand, which determines the pedestrian flow and density on the facility. One of the further requirements is the level of comfort that should be offered to travellers, which requires a scheme for determining traffic flow quality as a function of the measured or expected demand. The so-called Level of Service (LOS) concept is widely used for this purpose, having become a key factor in the design of pedestrian transportation facilities since its introduction in the 1960s. The pedestrian density is often used as a proxy for the traffic quality, as higher densities restrict movements and thus reduce the quality of the flow.

Although the density-based LOS has been applied in praxis for several decades, some of its basic assumptions and considerations are not well described in literature. It is for example widely known that the pedestrian demand exhibits high fluctuations and therefore the chosen time interval for determining the LOS will strongly affect the results. However, the implications of this fact are rarely discussed.

The first part of this paper will review and discuss the literature about existing pedestrian LOS schemes will be reviewed and discussed in terms of the main assumptions that underlie density-based LOS concept. These assumptions are then needed to evaluate the time component of the LOS, as they will lead towards the question of the most useful time interval. In the second part, the connection between time interval and LOS will be analysed based on data from two railway stations. The results are then compared to a newly developed LOS scheme (Weidmann et al., 2013) which attempts to address the issue of the missing time component. Lastly, new insights concerning the time component of the LOS will be presented and discussed.

2.5.4 *Literature review*

Given enough space and an unlimited budget, there would be no reason not to design spacious pedestrian facilities that always offer comfortable densities. Since engineers and planners usually work under restrictions, they must be able to compromise between the cost-effectiveness and quality level of a project. Pedestrian density is commonly used as a criterion because of its measurability. Rather than one density value for all purposes, a scale with different levels is used, since individual infrastructures can differ greatly in both function and expected flow characteristics over time.

It should be noted that besides density, other aspects of the pedestrian experience like safety, quality of surroundings and surface quality, are not covered by density-based LOS schemes. The approach is therefore mostly relevant for the design and operation of heavily used infrastructures, like railway stations or airports, where densities are actually high enough to be perceived as uncomfortable. Ironically, situations with very few pedestrians can also be perceived as low quality because of a felt lack of security or liveliness. This aspect is obviously not reflected in the density-based LOS, either.

2.5.4.1 *Development of the pedestrian Level of Service concept*

The LOS concept was first introduced for motorized traffic in the 1960s in the Highway Capacity Manual (Highway Research Board, 1965). It is based on the assumption that low traffic volumes correlate with higher perceived quality by the driver. To determine the LOS, the operating speed and the service volume to capacity ratio were used. Based on these criteria, six levels, from A to F, were distinguished.

During the same period, a LOS concept for pedestrians was developed. A first, but widely unnoticed, approach for a description of traffic quality was suggested by Oeding (1963). Based on pedestrians' freedom to choose their walking speed, walk side to side or overtake others, he proposed four quality levels plus a crowded state. Several years later, Fruin developed his LOS concept for pedestrians based on the LOS principles for motorized traffic from the Highway Capacity Manual (Fruin, 1970). In addition to the criteria developed by Oeding, he introduced the probability of conflicts for cross-flow traffic as a determinant of the LOS (Fruin, 1971a). Apart from walkways, he also developed LOS parameter for stairways and queues (Fruin, 1971b). Fruin's LOS levels are still used as reference values in many applications today.

Following Fruin, the LOS concept for pedestrians was further developed and adapted to different situations. Pushkarev and Zupan researched pedestrian platoons and the right time interval for determining LOS (Pushkarev and Zupan, 1975). They concluded that situations with predominantly platoon flows require a time interval of 15 to 30 minutes, corresponding with the observed cyclical variation. As the work of Fruin was based on flow characteristics typical for the United States, several publications focused on transferring the concept to different locations (Polus et al., 1983; Tanaboriboon and Guyano, 1989). Another LOS classification based on the number of conflicts was proposed by Schopf (1985) who researched the space demand in various walking situations. The LOS is then determined based on the walkway width and the traffic volume. This concept assumes that the width needed for an encounter follows a certain distribution.

The concrete mechanisms that underlie the influence of density on the perceived quality were long underrepresented. In an attempt to address this, Weidmann (1993) used existing literature to compile a list of eight criteria that can be used to distinguish the different LOS levels:

1. Possibility to freely select walking speed
2. Frequency of forced speed changes
3. Necessity to react to other pedestrians
4. Frequency of forced direction changes
5. Hindrances when crossing a pedestrian flow
6. Hindrances when walking in opposing direction
7. Hindrances when overtaking
8. Frequency of unintentional physical contact

Some scholars have suggested using alternative parameters like delay time or the number of conflicts with other traffic as a measure for quality, rather than density (Kretz, 2011; Milazzo II et al., 1999; Virkler, 1996). Indeed, the perceived quality does not solely depend on restrictions imposed by other pedestrians. To account for this, other quality concepts were developed which are widely applied today. They consider for example attractiveness of surroundings, motorized traffic volumes, safety aspects or network parameters (Christopoulou and Pitsiava-Latinopoulou, 2012; Kadali and Vedagiri, 2016; Khisty, 1994; Mōri and Tsukaguchi, 1987; Sarkar, 1993; Stangl, 2012). This branch of LOS schemes overlaps with the idea of walkability (Frank et al., 2010; Saelens and Handy, 2008), which focuses more holistically on the quality of the walking experience. Lastly, in recent years researchers have increasingly focused on developing multimodal LOS concepts (Dowling et al., 2008; Scherer et al., 2009; TRB, 2010).

2.5.4.2 *Existing density-based Level of Service limits*

Several LOS schemes based on pedestrian density can be found in the literature. A comparison of LOS for walkways is presented in Table 2.21. For different situations and infrastructures like platoons on walkways (Davis and Braaksma, 1987; TRB, 2000), stairways (Brilon et al., 1994; Fruin, 1971b; ITE, 1976; TRB, 2010; Weidmann, 1993; Weidmann et al., 2013), queues and waiting areas (Brilon et al., 1994; FGSV, 2001; Fruin, 1971b; TRB, 1985a, 2000; Weidmann et al., 2013), crosswalks (Lam and Lee, 2001), places (Weidmann et al., 2013) and mechanical pedestrian infrastructure (Weidmann et al., 2013), separate LOS schemes were proposed in literature. In accordance with the original LOS concept proposed in the Highway Capacity Manual (Highway Research Board, 1965), most LOS schemes have levels ranging from A to F.

Table 2.21: LOS limits for walkways from literature (upper limits) [P/m²]. Schemes that use a different notation than letters have been converted for better readability. Subclasses are omitted.

SOURCE	A	B	C	D	E	F	G	H	I
Oeding (1963)	0.30	0.60	1.00	1.50	> 1.50				
Fruin (1971b)	0.31	0.43	0.72	1.08	2.15	> 2.15			
Pushkarev and Zupan (1975)	0.02	0.08	0.27	0.45	0.67	0.98	5.38		
ITE (1976)	0.31	0.36	0.54	0.72	1.08	> 2.15			
Polus et al. (1983)	0.60	0.75	2.00	> 2.00					
TRB (1985a)	0.08	0.27	0.45	0.72	1.79	> 1.79			
Tanaboriboon and Guyano (1989)	0.42	0.63	1.02	1.54	2.70	> 2.70			
Weidmann (1993)	0.10	0.30	0.45	0.60	0.75	1.00	1.50	2.00	5.40
Brilon et al. (1994)	0.10	0.30	0.50	0.70	1.80	> 1.80			
MPO (1997) quoted in: Shafabakhsh et al. (2013)	0.17	0.25	0.38	0.63	1.67	> 1.67			
Gerilla et al. (1995)	0.31	0.49	0.61	0.80	1.79	> 1.79			
Kwon et al. (1998)	0.30	0.60	0.90	1.20	1.50	> 1.50			
TRB (2000)	0.18	0.27	0.45	0.71	1.33	> 1.33			
TRB (2010)	0.18	0.27	0.45	0.72	1.35	> 1.35			
FGSV (2001)	0.10	0.25	0.40	0.70	1.80	> 1.80			
KMOCT (2001) quoted in Choi et al. (2014)	0.30	0.50	0.71	1.11	2.63	> 2.63			
Weidmann et al. (2013)	0.30	0.45	0.60	0.75	1.50	> 1.50			
Choi et al. (2014)	0.25	0.44	0.68	1.47	1.92	> 1.92			

TABLE 2.21: LOS limits for walkways from literature (upper limits) [P/m²]. Schemes that use a different notation than letters have been converted for better readability. Subclasses are omitted.

SOURCE	A	B	C	D	E	F	G	H	I
Rastogi et al. (2014)	0.21	0.28	0.57	0.88	1.69	> 1.69			
Rastogi et al. (2014)	0.20	0.45	0.70	1.00	1.45	> 1.45			
FGSV (2015)	0.10	0.25	0.60	1.30	1.90	> 1.90			

The different values of the LOS vary considerably. For example, the upper limit for LOS A ranges between 0.02 to 60 P/m². As it is unlikely that such big differences can be explained by local or cultural factors alone, it can be assumed that the underlying principles for determining the limits are not consistent between schemes.

2.5.4.3 *Assumptions and complications*

LOS concepts for pedestrians aim to provide a measure of the quality of the flow as perceived by the user, which in turn can be described as the degree of interference between individual road users (VSS, 1998a). Upon careful examination of the density-based LOS concept, several assumptions can be identified that have to be fulfilled in order for the concept to be a viable measure for quality. By understanding these assumptions, one might gain more insight into of the density-based LOS approach and its limits:

1. The perceived quality is based upon the amount of hindrances experienced while walking.
2. Hindrances are mainly the possibility of freely selecting the walking speed, walking direction and the distance to others.
3. The perceived quality is similar for different sets of pedestrians in the same circumstances.
4. The number of hindrances and thus the available choices depend on the number and location of pedestrians in the vicinity.
5. The number and location of pedestrians can be adequately described by the pedestrian density in an area around the pedestrian. The pedestrian density can thus be used as a proxy for the perceived quality.
6. The quality depends on the average perception within a certain time interval, though high densities will always represent poor qualities.

If pedestrian flow values are used, these values have to be transformed to densities. Here, the fundamental diagram can be used, considering that it is not intended for unsteady flows (Bosina and Weidmann, 2016).

Explicitly writing down these assumptions reveals several weaknesses of the concept. For example, different groups of pedestrians might have a different perception of the same situation. Furthermore, the composition of a group is likely to have an influence on the type and number of mutual hindrances. For the concept to be usable, these deviations must be within an acceptable range (Assumption 3).

Perhaps the most important assumption is the correlation between pedestrian density and the perceived quality (Assumption 5). One possible weakness of density as an indicator is that pedestrians walking in front will have a stronger impact on a person's perceived walking quality than pedestrians walking behind the subject in question. A further complication is caused by the various methods that can be used to determine the density (Steffen and Seyfried, 2010). When the density is calculated in the most basic way, as the number of pedestrians within a certain area, the size of the area is relevant. To a certain degree, smaller observation areas will improve the correlation between density and the perceived quality, as it can be assumed that the quality mainly depends on pedestrians in close vicinity. However, at the very least an area must include all relevant pedestrians to describe accurately the assumed relation between the experienced restrictions and the density. This minimum has so far not been systematically determined. A more fundamental problem of density as an indicator is the fact that individual locations of pedestrians are not represented. Other density measurement methods, such as the Voronoi density (Steffen and Seyfried, 2010), have similar shortcomings. Surely, the size of the measurement area used to determine the LOS should cover the relevant influence area of a pedestrian, but further research is needed to find the optimal size and to link the area to the perceived quality. Overall, it can be assumed that the pedestrian density correlates only with the average perceived quality. In other words, ensuring a certain LOS cannot guarantee a minimum perceived quality, it only provides an average value.

A less fleshed out aspect of LOS is the time component, tied to the large fluctuations that are typical for pedestrian traffic. This problem has only been addressed in the literature to a certain degree, for example by introducing an LOS for platoon flow (Davis and Braaksma, 1987; Pushkarev and Zupan, 1975). If longer time intervals are used to determine the LOS, the correlation between the average density and the quality perceived by individual pedestrians is weaker, because their "felt" density deviates more from the mean. For this reason, caution is advised when comparing LOS values that stem from measurements over different time spans. For example, an hourly flow might have LOS B on average, whereas the busiest 2-minute time interval within the same hour might yield a value in LOS E.

A further complication of the time aspect of LOS is the fact that for individual pedestrians, densities will change considerably during a walk. If LOS should reflect the quality of the flow perceived within a certain time interval, it is unclear whether each individual perceives an averaged quality, a momentary impression, or some other influence like the worst experienced quality. No literature was found on the relation between time interval, density variation and perceived quality. Some researchers conducted interviews to relate the density to the perceived quality level, but they only asked for instantaneous impressions or about situations that just occurred (Choi et al., 2014; Lam and Lee, 2001; Lee et al., 2005).

Without further knowledge, it has to be assumed that the perceived quality corresponds to the average experience in a certain time interval. This is partly confirmed by the research on the measurement of subjective well-being. Kahneman and Krueger (2006) suggest a U-index, defined as the fraction of time spent in an unpleasant state, meaning that the most intense feeling reported for that episode is a negative one. At the same time, specific occasions of being in a negative mood (such as the stress caused by a short experience of very high density) do not seem strongly related to a person's general well-being. Relatedly, Glass and Singer (1972) write that stress has no immediate influence on task performance. They did however find a decrease in performance on tasks carried out in the period after a short, acute, stressful situation. For this reason, highly crowded situations might lead to poor perceived qualities, irrespective of the duration. For a LOS concept this means that the quality of a route can be calculated by averaging over the time spent in each quality class, as long as the density does not exceed a certain threshold. This threshold might be different in different situations. For example, the acceptable range of densities when leaving a football stadium is different from that for a Sunday outing in a park.

In summary, the underlying assumptions of the LOS concept show that the relation between pedestrian density and perceived quality is far more complex than often assumed. The pedestrian density and therefore the quality changes continuously during a walk. How well the average corresponds to the perceived quality is largely unknown because of the absence of data linking rapidly changing traffic situations with human perception.

2.5.5 *Basic principles of a time oriented Level of Service concept*

To be able to capture the large volume fluctuations typical for pedestrian infrastructures, the measurement window should be relatively small. A typical value used in praxis is two minutes (FGSV, 2015; Weidmann et al., 2013). Count data for even shorter intervals is generally not available. Since even such short aggregation periods might have varying underlying distributions, the time dependency of flow and LOS will be further examined in the following case study. The used counting data was made available by SBB (Swiss Federal Railways) and city of Zurich, supplemented by own measurements. The SBB data were collected at the railway stations Zurich Stadelhofen, an inner-city rapid transit hub, and Bern, an important national network node, both exhibiting suitably high pedestrian volumes. Railway stations are good case studies for the application of the density-based LOS, as the high traffic demand necessitates good design, and causes the type of large, short-term flow fluctuations that are of interest. Furthermore, continuous and high-resolution counting data is not yet widely available. The main goal of the case study is to determine the counting periods that result in suitable peak values for the design of pedestrian infrastructures. Secondly, an existing time-based LOS scheme is tested using the same data.

2.5.5.1 *Determining the peak values*

Although it is common practice in pedestrian transport to design for the peak hourly volume, a formal method to determine the peak hour was not found in the literature. Pedestrian demands are commonly obtained from short manual counts or estimated based on simulations. Only recently have automatic counts enabled long-term measurements. Since such measurements also include rare peaks, a design for the absolute peak hour might lead to oversized and expensive infrastructures.

For motorized traffic the 30^{th} to 100^{th} highest hourly flows per year are used for design purposes, which correspond to the 98.86^{th} to 99.66^{th} percentiles (TRB, 2000; VSS, 1998b). The authors propose using the same range for pedestrian traffic, as the additional costs of designing for even higher values would likely outweigh the additional benefits for the road users (Highway Research Board, 1950). Flows in the highest percentile are mainly caused by rare events, like accidents or big events (Bernard and Axhausen, 2008).

The principle of using a particularly busy peak hour, while not using the absolute highest peak, is illustrated in Figure 2.43, showing the 95^{th} to 100^{th} percentile of hourly pedestrian volumes as measured at a number of locations. For this figure, data from the city of Zurich, covering different counting sensors found throughout the city (1 year, 15-min intervals), as well as data from SBB (4 weeks, 1-min intervals) for several cross sections within the railway stations Zurich Stadelhofen and Bern are used. It highlights the 98.86th to 99.66th percentile range mentioned above, which would result in a design volume of about 3 to 13 times the average annual hourly traffic. When determining the hourly flow used for facility designing, two additional points have to be considered. First, high flows can lead to undesirable crowding, which might pose a safety issue. These situations should be avoided, even for only a few hours per year. Otherwise, alternative safety measures must be implemented. As noted previously, the safety aspect is not included in the LOS and has to be considered separately. Second, the design flow for car traffic

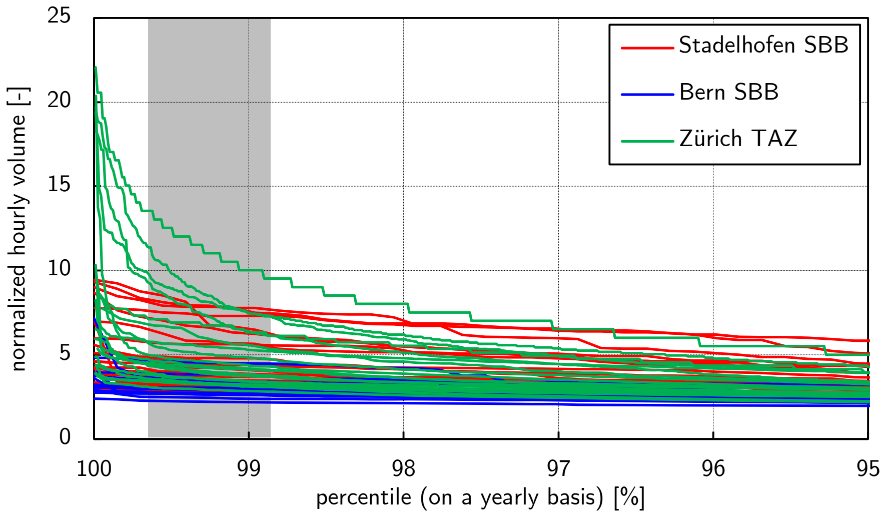

FIGURE 2.43: Hourly pedestrian volume as a share of the average annual hourly pedestrian volume, sorted from highest to lowest. The dark grey area shows the 98.86th to 99.66th percentile, corresponding to the 30th to 100th yearly highest hourly flow. Green = Data from 2016 for different locations within the city of Zurich (Data: data.stadt-zuerich.ch), Red = Zurich Stadelhofen, Blue = Bern (Data: SBB).

is intended to determine the capacity of the road, not the quality of the flow. Therefore, it might be possible to choose a lower percentile and still provide a good quality for the majority of the pedestrians.

2.5.5.2 *Flow fluctuations*

As mentioned above, available count data is usually aggregated to at least one-minute intervals. The available data therefore does not support measurement intervals that are short enough to account for the specific situations to which pedestrians react. On the other hand, considering the size of an infrastructure element, pedestrians spend a certain time within its extents. Individuals' perception of quality differs as well. It thus seems reasonable to use an average flow value for designing facilities, as long as the measurement interval roughly corresponds to the individuals' duration of stay on a particular infrastructure element.

Even when choosing relatively short measurement intervals in the range of 1 to 2 minutes, a considerable amount of the flow variation might be lost in the aggregation. To demonstrate this, counting data was collected for a daily two-hour peak at the entrance of the Zürich Hardbrücke station, another important rapid transit stop, for an aggregation interval of 15 seconds

(Meeder et al., 2015). The data show a mean value of 0.41 P/s and a standard deviation of about 0.40 P/s for the 15-second interval values (Figure 2.44). Fluctuations become considerably smaller for aggregation intervals greater than 10 minutes compared to shorter intervals. Most of the information about flow variations is already lost at that point. Even when measuring the commonly seen 2-minutes peak interval, the corresponding 15-second peak flow can be almost double the size. One important conclusion from this is that designing for LOS E, for example in a 2-minute peak, does not provide LOS E for all pedestrians, but only on average. This should be considered for when designing infrastructures, especially when platoons dominate the pedestrian flow. On locations where short peak flows can result in unsafe situations, such as crowding on railway platforms, smaller time intervals than 2 minutes should be used.

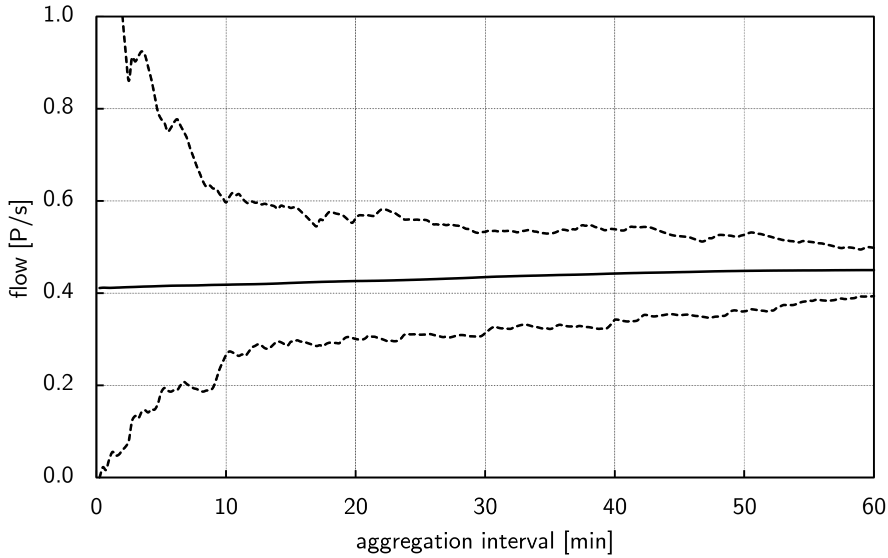

FIGURE 2.44: Mean, minimum and maximum flow for different aggregation intervals. Average flow = 0.41 P/s, standard deviation (15 s interval) = 0.40 P/s. Count data from Hardbrücke rapid transit station previously published by Meeder et al. (2015).

2.5.5.3 *Determining the relevant time interval for facility design*

The only comprehensive time concept for LOS present in the literature was proposed by Weidmann et al. (Weidmann et al., 2013) who links each LOS to a defined time interval. For example, LOS B is considered acceptable within the peak hour, whereas LOS E corresponds to the 2-minutes peak (LOS C: 30 min, LOS D: 15 min). For locations where pedestrian volumes fluctuate sharply, thus exhibiting higher peak flows, this will result in LOS E being the determinant level. For more even flows, LOS B is more likely to be relevant. This approach aims at offering a good LOS for the majority of the pedestrians and an acceptable LOS for the short-time peaks. For the used count data, the peak values for each of these time intervals can be determined and compared to the design values, determining the time interval that should ideally be used for design purposes for each location (Figure 2.45). For the data used, this shows that in most situations, the 60 minute peak is most relevant. Since high but short peaks are expected within railway stations, this indicates that, using this approach, only in exceptional cases shorter time intervals are expected to be relevant.

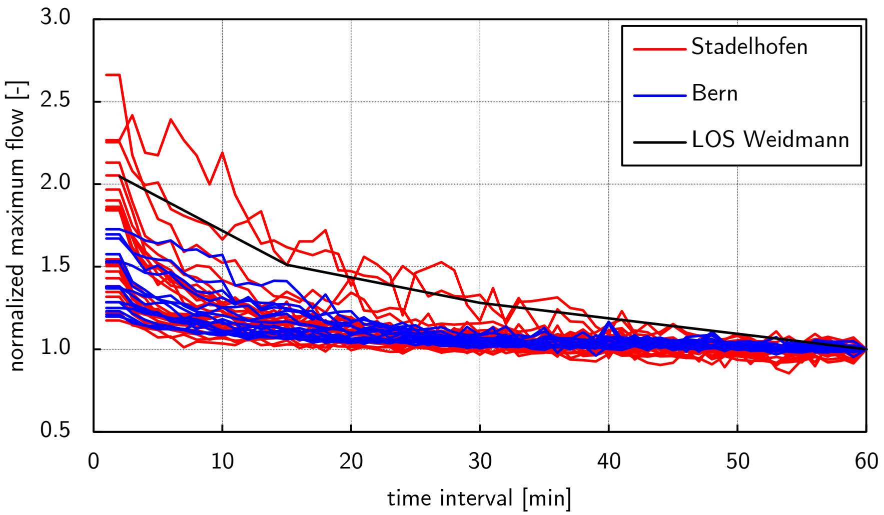

FIGURE 2.45: 99.66th percentile flow (normalized to hourly flow) per time interval (1 to 60 min) in comparison to the LOS values from Weidmann et al. (2013) (black curve, 2 min, 15 min, 30 min and 60 min values) when designing for LOS B for the peak flow. Red = Zurich Stadelhofen, Blue = Bern (Data: SBB).

2.5.5.4 *Perceived Level of Service*

Without further knowledge about the density distribution, it can be assumed that the median and mean value are roughly equivalent. This means that if the average density value corresponds to a certain LOS limit, about 50 % of the time at least this LOS is available. Nevertheless, as higher pedestrian densities in the uncongested regime also mean higher flows and thus more pedestrians, less than 50 % of the pedestrians will be provided with this LOS. Different flow patterns will result in different numbers of people served with the desired LOS level. In general, a more uneven load will result in less pedestrians experiencing a good LOS for the same average density.

Using the 99.66th percentile flow as design load and designing solely according to the LOS concept by Weidmann et al. (2013) allows to determine the LOS values experienced. In Figure 2.46, this is done using the 1-minute count data for Zurich Stadelhofen and Bern. The data shows a higher variability in the share of pedestrians experiencing each LOS. For example, at least LOS B is reached for 50 to 93 % of the pedestrians and LOS E for 82 to 100 %. It can be also seen that cross sections with higher demand generally show better LOS. It has to be noted here that no other design criteria, such as a minimal width or safety issues are considered. Thus, these cross sections are likely to have a higher width than based on this calculation and hence will also show better LOS.

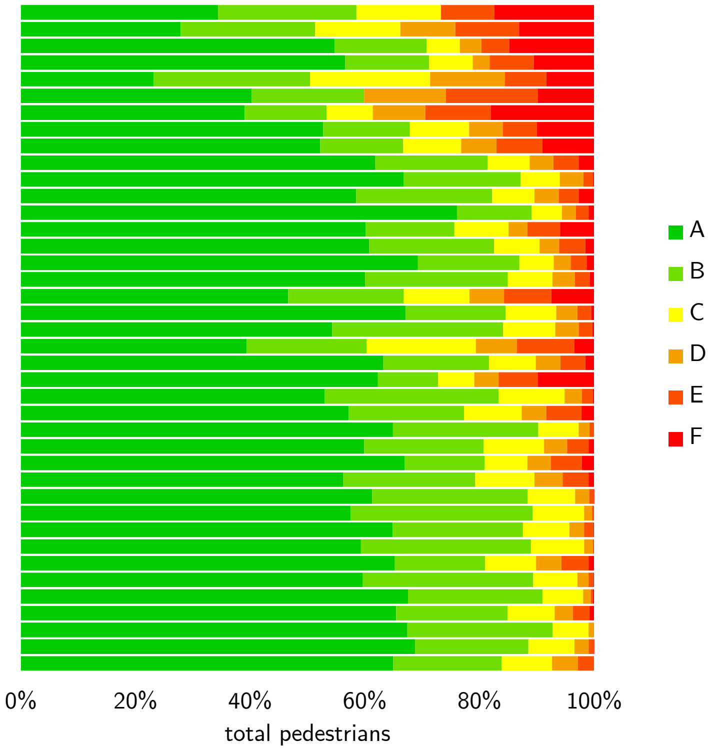

FIGURE 2.46: LOS experienced by all pedestrians passing a measurement location, when the design concept by Weidmann et al. (2013) is applied. The 99.66th percentile flow is used for the design. The bars represent the individual measurement locations, sorted by the total number of pedestrians in ascending order (Data: SBB).

Although the share of pedestrians experiencing minimum LOS differs significantly between different locations, this approach is generally considered useful, as the design also has to include the cost efficiency. When considering only the observed cross sections showing higher flows, the experiences LOS are nevertheless in the same range. In addition, complete counting data is often not available, for which the concept allows to design pedestrian infrastructure using limited data.

Summarizing the considerations about the quality distribution and the timescales shows that the aim of the LOS concept, which is to provide a certain quality for a defined share of pedestrians can be achieved by optimizing the LOS limits and the design load used. If complete data is available, the design approach can be further extended to define a minimum share of pedestrians experiencing each LOS. This could enable similar quality levels for different facilities while simultaneously achieving a high cost efficiency. For example, it might be decided that 80 % of all pedestrians should experience at worst LOS B, 90 % LOS C, 95 % LOS D and 99 % LOS E.

2.5.6 *Conclusion*

The research presented in this paper provides sufficient evidence that a time-based LOS concept can be applied to provide a satisfactory transport quality for the majority of users and at the same time meet the requirements of building cost-efficient and compact pedestrian facilities. Steps were made toward finding the appropriate time-intervals for designing efficient, high-quality pedestrian infrastructures. If facility design is based in the 99.7th percentile flow (or density) values, an acceptable compromise between comfort and economic values can be achieved. Applying the time-oriented LOS system suggested by Weidmann et al. (2013) to real world data of flows in train stations, it was shown that in the majority of cases 60 minutes is the most suited counting interval for determining the dimensions of pedestrian infrastructures. In situations where more pronounced peaks in the pedestrian volume over time occur, a 2-minute interval is usually needed.

Furthermore, it is important to stress that in order for an LOS concept to fulfil its goals, the focus needs to be on the quality as perceived by the individual users. Although LOS is often described in terms of the efficiency of the pedestrian flow, the original meaning has always been a description of the transport quality experienced by pedestrians. Therefore, finding the time interval that best takes into account the relevant peak(s) in the flow can be helpful, as it enables the estimation of the shares of pedestrians that at least experience the various LOS bands. If detailed counting data are available, the LOS can be further developed by setting minimum LOS values for a share of pedestrians rather than a time interval.

One area in which the time-based LOS concept is still lacking is the relation between density and the perceived quality. Although intuitively this connection seems to make sense, and although a density-based quality scale is suggested in various rules and regulations worldwide, there is very little data supporting this concept, let alone providing the best-suited limits for the different LOS bands (A-F). Based on literature from the social sciences on subjective well-being, one possible approach could be surveys aimed at finding out at what densities negative emotions start to be the dominant ones. More research in this area is undoubtedly needed.

2.5.7 *Acknowledgements*

The authors wish to thank the Swiss Federal Railways (SBB) for providing data for this study and the City of Zurich, for making pedestrian counting data available on their open data platform.

2.5.8 *Level of Service and the fundamental diagram*

Due to its relation to the pedestrian density and its macroscopic characteristic, the LOS concept is closely linked to the fundamental diagram. Even though the fundamental diagram only shows the average density, the curve is to a great extend determined by interference of walking paths, which also is considered the determinant of the perceived quality. A change in the fundamental diagram, for example due to differences in the accepted minimal distance, will also change the perceived quality at the same density. Focusing on the number and types of conflicts and interactions will provide new insights into the basics of the fundamental diagram as well as the LOS concept.

Considering the differences in the fundamental diagrams produced in different situations also shows that it cannot be recommended to use the same densities for the LOS levels everywhere. At the same density, depending on the characteristics, less conflicts, consequently higher walking speeds and a better perceived quality can occur. In this situation, a higher density for the same quality level can be applied. The LOS limits thus should always reflect the specific situation where they are applied. Still, it can be possible to determine global parameters based on the hindrance criteria presented in Chapter 2.5.4.1, which ensure the same meaning of each LOS level throughout the different schemes. Nevertheless, it can be expected that apart from the measurable number and type of conflicts, also the perception might differ, which need to be reflected in the specific LOS levels.

In real-life applications, similar to the fundamental diagram, the time-based variation of the demand is an important aspect, which up to now bears a high uncertainty. Strictly speaking, the fundamental diagram is only valid for steady state situations, which rarely occur in reality. Also in the LOS concept, the variation of the flow introduces uncertainties. It is unknown how to best link the flow to the perception in this situation and the relation between the flow and density using the fundamental diagram is uncertain.

Most of the LOS schemes proposed do not explicitly differ between unidirectional and bidirectional flow. Nevertheless, based on the differences in the fundamental diagram and the flow situation, a variation in the perceived quality can be expected. Using a stated-preference survey, a study in Hong Kong aimed at determining the influence of the bi-directional flow on the perceived quality (Lee et al., 2005). It was concluded that the quality of the minor flow at the same density, especially at flow ratios smaller than 0.4 to 0.3, was considered worse than for the main flow. The resulting LOS values considering the flow ratio can be seen in Figure 2.47.

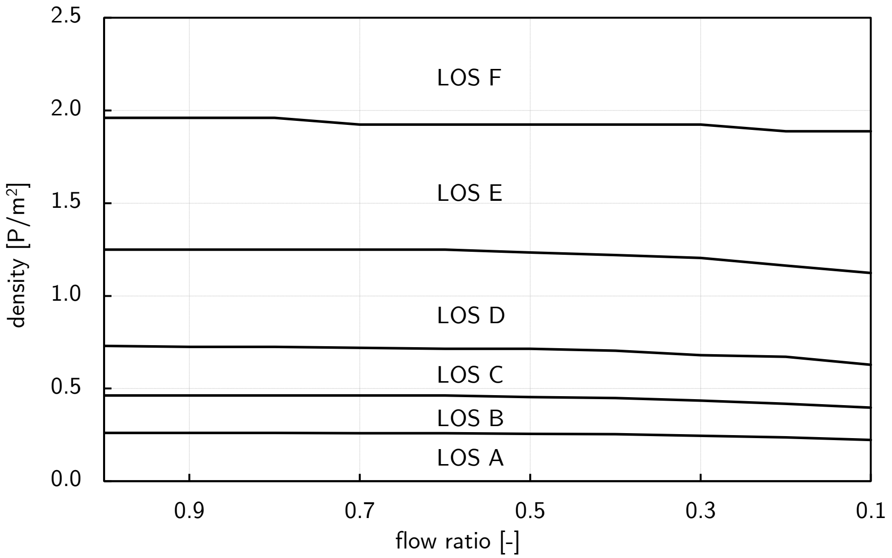

FIGURE 2.47: LOS for signalised crossings in Hong Kong considering the flow ratio (Lee et al., 2005).

2.5.9 *Level of Service at different aggregation levels*

The LOS concept, as it is used and presented in this chapter, can be characterised either as macroscopic or mesoscopic, depending on the scale used. Nevertheless, it is assumed that a similar concept can be applied at microscopic and at network level.

At microscopic level, each individual user is simulated, hence also an individual LOS scheme can be established or the data can be aggregated to a higher level. At an individual level, the cascade of assumptions needed to link the pedestrian density to the perceived quality is not needed to its full extend, but the amount and type of hindrances can be directly measured. For design purposed, the individual quality measurements can then be aggregated over time and space as needed, to obtain a detailed overview of the LOS within a pedestrian facility.

At network level, the overall LOS of a facility can be determined using the network fundamental diagram. For this, the density might not be a suitable proxy for the perceived quality, as within a network the density will vary strongly and thus have limited value. Here, other parameters, such as the total time delay, might be a better indicator for the current quality. Similar to car traffic, a network based approach might be useful to provide information about the current state of the system. Until now, no literature was found applying a network based LOS concept for pedestrian transport.

Analogue to the fundamental diagram, the LOS concept can be extended to different aggregation levels. Although not applied yet, it might be worth studying as it is expected to provide useful information for different purposes.

3

RESEARCH QUESTION AND HYPOTHESES

All truly great thoughts are conceived while walking.
— Friedrich Nietzsche, Twilight of the Idols

Based on the findings from literature a research question and four hypotheses were formulated for this work.

3.1 RESEARCH QUESTION

Is it possible to derive a generic model for the pedestrian fundamental diagram based on the principles of human walking and its relevant influences, so that it can be adapted to every specific situation?

Existing approaches to generate fundamental diagrams are mainly based on measurements of specific situations. The aim of this research is to provide a framework which can be used to provide also specific fundamental diagrams for situations where no measurements exist. This shall be done using the knowledge about human walking and the interactions while walking, hence being as close as possible to the physical and psychological principles determining the fundamental diagram.

3.2 HYPOTHESIS 1: BASIC PRINCIPLES OF HUMAN WALKING

H1: A generic description of human walking can be made, which integrates the principles of interaction with other humans. Based on this, the main principles of walking can be identified in different situations.

A vast amount of literature exists describing different aspects of human walking. Still, this knowledge is usually spread among different disciplines. For example, the walking motion is described in the field of biomechanics, the psychological and social aspects in the respective research fields, and crowd and interaction phenomena are studied by the pedestrian dynamic research. In this work, these different approaches to human walking shall be combined to get a more detailed concept of the main walking principles at all levels.

3.3 HYPOTHESIS 2: INFLUENCE ON WALKING

H2: Several influence factors affect the pedestrian speed and density relation. These influence factors can be expressed by different attribute values used in the generic description of the basic walking principles.

While the main aspects of walking are the same for most pedestrians, each individual pedestrian and situation shows aspects, which influence walking and the interaction among humans while walking. Using the generic description of walking developed to study hypothesis 1, it shall be possible to study the individual aspects by introducing the individual properties into the model.

3.4 HYPOTHESIS 3: DESCRIPTION OF THE FUNDAMENTAL DIAGRAM

H3: By using the approach presented in this work it will be possible to derive a model for the fundamental diagram based on the principles of human walking.

The fundamental diagram, as it is discussed in Chapter2.4, is a model for the design of pedestrian facilities. It describes the relation between speed and density which strongly depends on the principles of human walking. It is therefore expected that it is possible to generate the fundamental diagram by combining the principles of human walking in a generic model.

3.5 HYPOTHESIS 4: PARAMETER VARIATION

H4: The changes in the fundamental diagram due to different pedestrian compositions can be simulated.

Using the generic fundamental diagram model, it should be possible to use the specific pedestrian and situation characteristics to obtain a more specific fundamental diagram. This allows to generate fundamental diagrams for situations without the need of prior measurements.

4

RESEARCH CONCEPT

The one who follows the crowd will usually go no further than the crowd. Those who walk alone are likely to find themselves in places no one has ever been before.
— Francis Phillip Wernig

4.1 INTRODUCTION

Based on the literature review, the research questions and hypotheses have been formulated, which aim at the creation of a generic fundamental diagram model and a better understanding of the principles of human walking. For this, a research concept was developed, which will be described in this chapter and follows the steps needed for the creation of a computer model (ISO, 2015).

In Figure 4.1, the research steps needed to answer the research questions and hypotheses and the corresponding chapters are shown. First, the conceptual model will be developed by analysing reality and making useful simplifications (Chapter 5 and Chapter 6). Then, the conceptual model will be transferred to a computer model (Chapter 6). After the computer model is set up, it will be tested to ensure the right implementation of the conceptual model (Chapter 8). This is done using empirical data described in Chapter 7. Then it will be calibrated and validated to prove that the model is accurate enough to be useful. After answering the research question and hypothesis the model can be applied to several situation to show the usefulness of the model.

4.2 MODELLING REQUIREMENTS

The background of this work is the design of pedestrian facilities, thus looking at pedestrians from an engineering perspective. Nevertheless is walking a complex matter involving different disciplines from psychology, physiology and medicine, social sciences and engineering. To be able to model pedestrians and the interactions while walking, knowledge is needed from various disciplines focussing on different questions concerning walking. The literature review is therefore essential to provide an overview about the current knowledge which can then be compiled together in a model.

The literature review in Chapter 2 revealed several research gaps and contradicting information. Therefore, to address these shortcomings considerati-

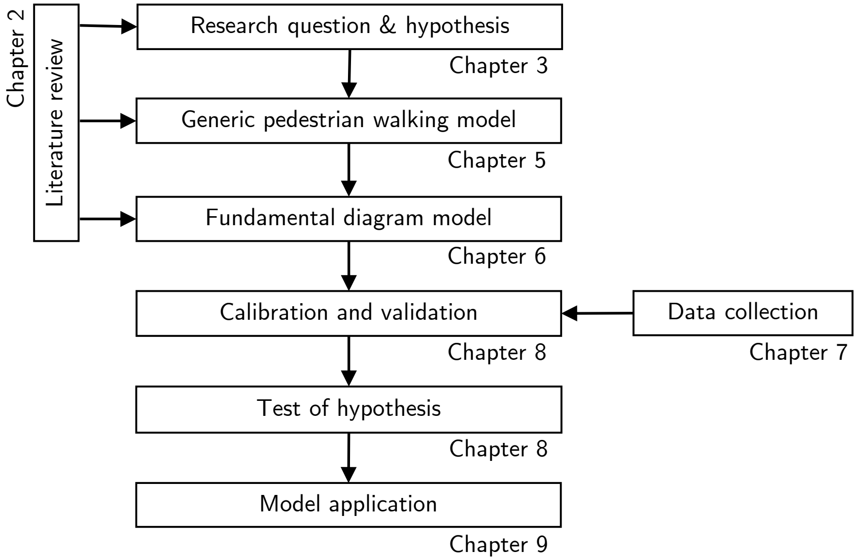

FIGURE 4.1: Research steps and corresponding chapters.

ons needed for this work were discussed during literature review . Specifically, the influences on the pedestrian walking speed were analysed and new values were computed based on existing literature; a definition of the fundamental diagram was proposed which is needed for its modelling and some aspects of the LOS concept were discussed.

4.3 MODELLING APPROACH

To answer the research question, a generic model is needed which includes all important aspects of human walking. It should be as close as possible to the real human walking behaviour and be able to reproduce a situation specific fundamental diagram. Therefore, the model input needs to be adaptable based on different pedestrian characteristics.

Based on the literature review it can be concluded that no appropriate model exists which can directly be used to answer the research question and hypotheses. Thus, a new model will be created from scratch. As the detailed description of human walking and the generation of a specific fundamental diagram are different tasks, the model will be split into two parts. First, a generic pedestrian walking model will be introduced. This model aims at describing the most important influences and interactions in human walking from the point of view of an individual pedestrian. This will be a conceptual model which primarily focuses on the qualitative description of the interactions. In a second step, a fundamental diagram model is proposed. Based on the insights gained from the human walking model, this model will be able to generate situation specific fundamental diagrams. This model will provide quantitative results which can then be compared with measurements for validation and be used to generate fundamental diagrams for design purposes.

For the model setup, a literature-based approach was used. To answer the research question several other approaches involving data-driven models or analogies are feasible. Still, several considerations resulted in the creation of a literature-based model:

- A vast amount of studies can be found focusing on different aspects relevant for human walking. Using the knowledge and data available is an efficient method also allowing to consider different aspects and situations which cannot be covered alone.
- In literature, no literature-based approach to describe the fundamental diagram was found. Hence, this work can serve as a proof of concept. This approach seems feasible as especially in recent years an increasing amount of literature was published in the relevant fields.
- Using available measurement data to set up a data-driven model is considered challenging, as this data is usually gathered for other purposes and some relevant information could be missing. Hence, they might not be very well suited for the specific research question. Therefore, measurement data were only used for relations for which they are specifically measured and to prove the applicability of the model.
- Collecting own measurements is a promising method, as they can be designed to measure exactly the information which is needed for the model setup. However, this approach is resource intensive and it is not possible to study a high number of different situations.

Naturally, this approach has some shortcomings. As the work found in literature is not in alignment with each other, several aspects are described in detail there, whereas for other parts little to no information is available.

4.4 Calibration and Proof of Model Applicability

After the model setup and calibration, it is necessary to prove that the model can reproduce the fundamental diagram and its variation with sufficient accuracy. For this, the model will be verified and validated. This is done using several complementary methods which are determined to be most suitable for the specific modelling purpose.

One main aspect which has to be shown is the agreement between the model results and observation data. The necessary data can either be obtained by own measurements, either in laboratory settings or in real-life situations, or by using existing data. Similar to the model setup it was decided to rely on existing data, as already measurement data is available from several sources. Even though the existing data might be lacking some information useful for the model validation, it is considered suitable for the specific purpose.

4.5 SIMPLIFICATIONS AND ASSUMPTIONS

As the reality, especially in the field of pedestrians, is complex and sometimes still not completely understood, the planned model cannot and do not need to include all possible aspects. As the main purpose is to estimate the influence of different pedestrian compositions on the fundamental diagram and hence the flow when designing pedestrian facilities, only relevant influences for this purpose have to be considered.

To be able to answer the research question, therefore several simplifications and assumptions were made for the fundamental diagram model:

- The parameters will be set to cover the range of the most frequently occurring values. Outliers and special events, where an exceptional pedestrian composition can be found or the pedestrian behaviour differs considerably from the norm, will be outside the scope of this model.
- Children, people with disabilities, pedestrians walking in groups and waiting pedestrians are not considered.
- Only unidirectional walking without any disturbance from crossing flows, walls or obstacles is included, in accordance to the definition of the fundamental diagram established in Chapter 2.4.7.6.

5

GENERIC PEDESTRIAN WALKING MODEL

Solvitur ambulando, St. Jerome was fond of saying. To solve a problem, walk around.

— Gregory McNamee

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5.1 OVERVIEW

In literature, various studies exist, focusing on specific aspects of human movement or the interaction between pedestrians. The generic pedestrian walking model now aims at combining these data to a coherent model, which describes pedestrian walking and its influences. In literature only one study, published after the creation of this chapter, was found which aims at providing a similar conceptual walking model (Duives et al., 2015a). As the processes involved in the pedestrian speed-density relation are complex and sometimes detailed knowledge is lacking, a stepwise modelling approach was used. Starting from the simplest scenario, a pedestrian walking undisturbed at constant speed, the complexity of the model was increased (Figure 5.1).

5.2 SINGLE PEDESTRIAN WALKING MODEL

5.2.1 *Model description*

At first, a single pedestrian will be modelled. No interaction with other pedestrians or obstacles occur, it is assumed that the pedestrian walks undisturbed. Therefore, walking is only influenced by the properties of the pedestrian itself.

5.2.2 *Constant speed*

In the first step, a model for a single pedestrian walking undisturbed at constant speed is created. Hence, the pedestrian walks at his free flow speed. In

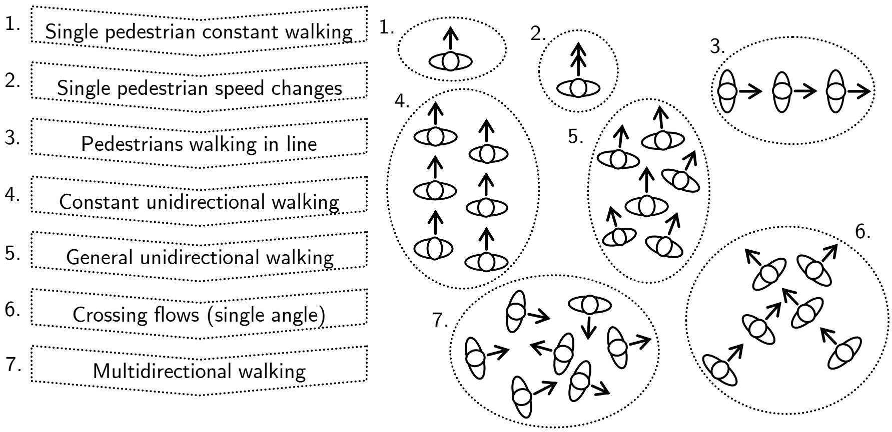

FIGURE 5.1: Model Steps used for the generic model of pedestrian walking.

literature, it is often assumed that a pedestrian, if undisturbed, walks at a speed, which is optimal in terms of energy expenditure (Ralston, 1958; Srinivasan, 2009). The energy demand per distance walked follows a U-shaped curve, producing an energy optimal walking speed of about 1.0 to 1.5 m/s. At low walking speeds, the basal energy demand dominates, thus the energy demand per walking distance is high whereas at high walking speed the additional energy demand for walking increases disproportionately (see Chapter 2.2.1.5). In different situations, pedestrians choose a different, energetically suboptimal, walking speed. Different free flow speeds hence result from other determinants. For this, two additional determinants for the free flow walking speed are proposed (Figure 5.2).

First, depending on the duration of the work, the maximum power a pedestrian can produce is limited. This limit may apply to the total body but also to certain muscles. Usually, walking is expected to be done at a power level, which can be sustained for long terms. The maximum instantaneous power calculated for a 100 m sprint was 2 619 W, whereas for ordinary fit men steady state power output values ranging from about 200 to 400 W can be found in literature (Avallone et al., 2007; Gómez et al., 2013; Morton, 1990; Wilkie, 1960). Still, the power usable for a certain activity depend on its muscles and movements involved (Harrison, 1970). For walking, a factor of 0.20 to 0.25 can be assumed between the metabolic expenditure and the power output produced (Ralston, 1976).

A good measurement for the work capacity of a human is the maximal aerobic capacity $VO_{2\ max}$ (Perry and Burnfield, 2010). For longer walks, pedestrians limit the rate of energy consumption to around 45 % $VO_{2\ max}$, for walks longer than 3 hours it is further limited to 35 % $VO_{2\ max}$ (Bastien et al., 2005). Activities with a level of less than 50 % of an individual $VO_{2\ max}$ can

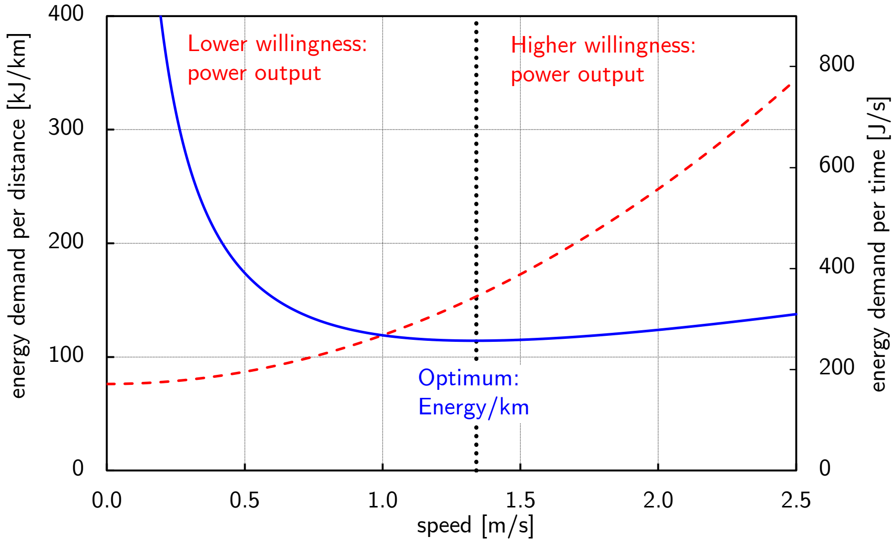

Figure 5.2: Main determinants of the walking speed.

be sustained for long durations without exhaustion (Waters et al., 1988). In laboratory conditions it was also found that people selected their fast walking speed close to the threshold of anaerobic metabolism (Perry and Burnfield, 2010). This indicates that the maximum power and the physical capabilities of an individual influences the range of walking speeds selected. Especially people with disabilities or bad health conditions might therefore choose their walking speed according to their physical capabilities (Waters and Mulroy, 1999). Also, older people, who usually show a lower maximum capacity, tend to decrease their walking speed to keep a certain submaximal reserve (Malatesta et al., 2004).

Additionally, people might increase their walking speed and hence spend more power, up to the maximum, to reach their destination at their desired arrival time. Otherwise, if time is unlimited, a slower pace might be selected to reduce the power output. This behaviour is summarised in the proposed third influence on the free flow walking speed, the willingness to spend power.

Energy expenditure can be calculated either per distance or per time. Whereas the first is considered to be optimised when choosing the energy optimal walking speed, the latter is usually kept at a moderate level. It was for example found that people with motor disabilities compared to healthy subjects show higher energy expenditure per distance covered but similar energy expenditure per time (Ralston, 1976).

Thus, for grouping the influences on human walking speed, three mechanisms (maximum power, energy optimal walking speed and willingness to spend power) are proposed (Figure 5.3). These three sub models then determine the free flow walking speed, as well as the step frequency and the step length used. The energy optimal walking speed is determined from the energy demand for walking which itself consists of the energy demand for standing and the additional energy demand for walking. Whereas the first is constant over time, the second is dependent on the walking speed.

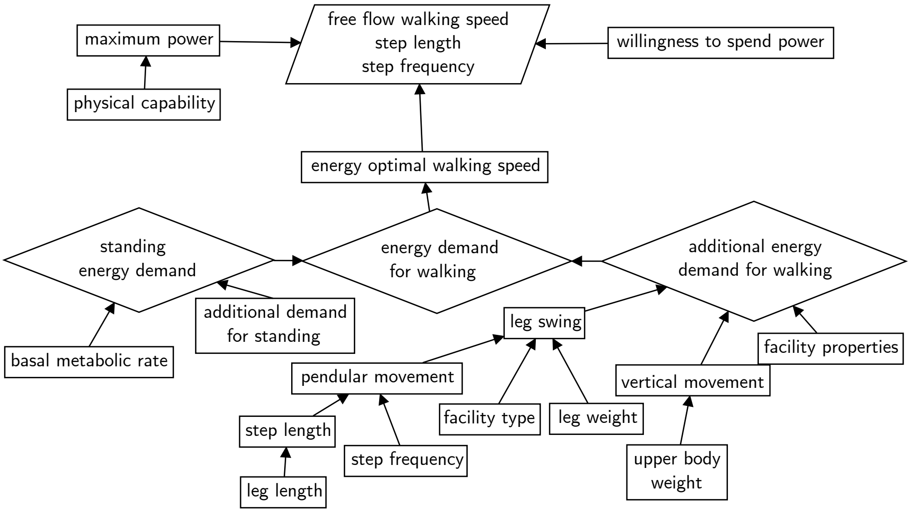

FIGURE 5.3: Single pedestrian constant walking model determining the free flow walking speed. (adapted from (Bosina and Weidmann, 2016)).

The model describing free flow walking speed (Figure 5.3) can now be used to link the influences on the walking speed (see Chapter 2.3 or (Bosina and Weidmann, 2017c)) to their point of influence (Figure 5.4). The energy optimal walking speed and the maximum power are mainly dependent on the human physical capabilities. In addition, the facility type influences the additional energy demand for walking by its inclination, surface quality and type. All other environmental and emotional influences are expected to influence only the willingness to spend power. Still, the actual free flow walking speed achieved might then also depend for example on the maximum power output. Using the proposed model it is now possible to study the influences in more detail.

For example, as men and women show various differences in their body's physical structure, the gender also influences the free flow walking speed. In addition, the energy demand curve for women is flatter at the optimal walking speed, thus a change in walking speed requires less additional energy compared to men (Wall-Scheffler, 2012). In addition, the willingness to spend power is different. It was found that women reduce the power production at high-rate activities such as inclined walking or walking with loads, and

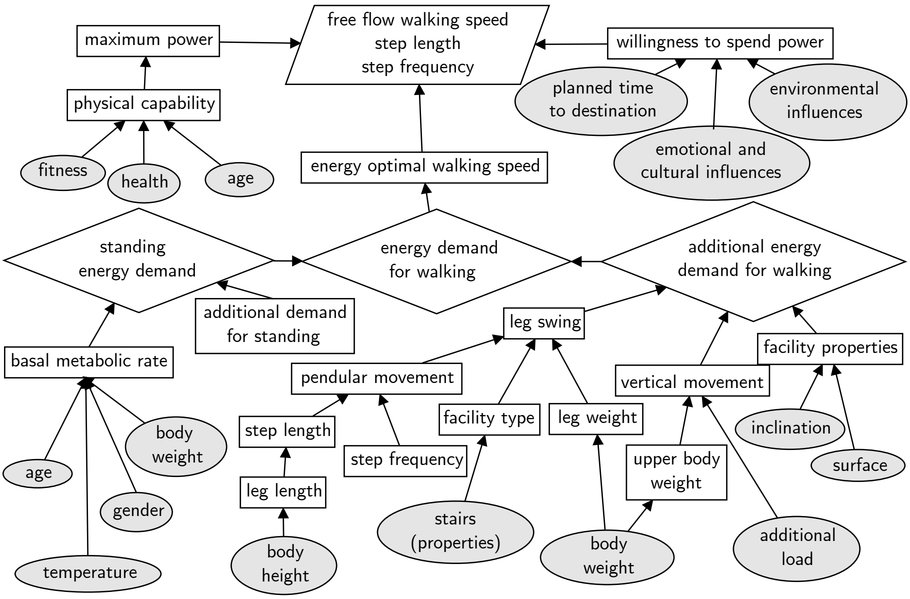

FIGURE 5.4: Influences on the free flow walking speed in the single pedestrian constant walking model. The circles represent influences on the walking speed at their point of influence. (Bosina and Weidmann, 2016).

thus their walking speed, presumably to reduce the heat production (Wall-Scheffler, 2015; Wall-Scheffler and Myers, 2013).

The effect of age on the walking speed is due to different influences. For children, increasing age correlates to an increase in body height, which influences the energy optimal walking speed. In higher age groups, starting at about 30 years of age, age also relates to a decrease in muscle strength, which increases the energy demand for walking (Martin et al., 1992).

Surface inclination also acts at different levels on the free flow walking speed. For walking uphill, the energy demand is increased, as potential energy is added to the body. When walking downhill at slopes up to about 5.2°, less muscle force is needed due to the decrease in potential energy (Margaria, 1968). In addition to the change in minimal energy, people walking downhill at higher grades prefer a more stable and hence slower walking speed compared to the energy optimal walking speed (Hunter et al., 2010). Thus, the inclination influences the energy demand for walking but also the willingness.

Other influences, such as the trip purpose or the group size do not influence the gait directly, but they can be considered as a determinant of the desired speed. The attractiveness of the environment may change the desired speed, whereas the biomechanics stay the same.

Carrying a load increases the energy expenditure, but the energy optimal walking speed is not changed. Considering the energy expenditure per distance per mass, the curve is about the same as in unloaded conditions, as the energy expenditure increases linearly with mass. Still, the additional energy expenditure per time is higher at higher walking speeds for a constant load (Bastien et al., 2005). For frontal loads, a decrease in the energy optimal walking speed was found (Wall-Scheffler and Myers, 2013).

As a result of the single pedestrian walking model, the free flow walking speed and the corresponding step length and frequency are obtained.

5.2.3 *Update cycle*

Influences, like obstacles, surface changes or other pedestrian often result in a reaction of the pedestrian concerning his walking parameters. Due to processing times within the human body and the time to make the reaction decision, a delay occurs between the input and the reaction in terms of walking speed or direction. In addition, some changes are difficult to detect, for example small walking speed differences, hence also a certain time is needed to obtain the information.

In general, the minimum time between the information occurrence and the resulting movement is determined by the motor control of the neuromuscular system, which can be described as an information-processing model (Abernethy et al., 2013). First, the information has to be received by the human and then processed to obtain a desired reaction. This results in a muscle contraction, which then leads to a movement. The latency of the response depends on the type of reaction, which can be divided into short-latency, medium- and long-latency as well as voluntary reactions (Shinya et al., 2016).

For voluntary reactions, it takes on average at least about 200 ms for a human to react to a sudden change in conditions (Abernethy et al., 2013; Le Runigo et al., 2005; McLeod, 1987). If the reaction follows an expected signal, the reaction times can be lower. At 100 m sprint races, reaction times of about 150 ms were measured (Helene and Yamashita, 2010). In more complex situations, where more than one response alternative are available, the reaction times increase (Abernethy et al., 2013).

Automatic muscle reactions can be faster. Short-latency reactions have a response time of about 40 to 50 ms (Sinkjaer et al., 2001). For medium-latency responses, the reaction time in walking or running is between 60 to 90 ms (Berger et al., 1984; Stacoff et al., 1996). Long-latency responses have longer response times but do not always occur (Sinkjaer et al., 2001). These muscle reactions usually occur after disturbances in walking which can for example occur on uneven surfaces. For the reaction to other pedestrians, they are usually not relevant. There, voluntary reactions take place.

When walking, pedestrians normally have several possibilities how to react. In addition, the information is usually not as explicit as a gunshot at the start of a race, but can be for example a slight change in walking speed of the pedestrian in front. Therefore, the reaction times in real-life are expected to be larger. For example in laboratory experiments, an average reaction time of 0.6 seconds was calculated (Degond et al., 2015).

Another aspect relevant for the reaction time in walking is its stepwise procedure. Within a walking cycle, changes in walking speed and direction can mainly only take place once every step. Indications exist that each step is planned ahead while the information during the execution of the step is only of secondary importance (Hollands and Marple-Horvat, 1996). Walking can thus be simulated by discrete decisions about the length and time interval of the next step (Seitz et al., 2016).

5.2.4 *Speed changes*

In real-life situations, a considerable amount of walking is done while accelerating or decelerating. For example, video observations done at a pedestrian crossing in Japan revealed that for about 18 % of all steps the speed was varied (Robin et al., 2009).

Compared to its average speed, humans show high acceleration capabilities. Sprinters can for example reach accelerations up to 10 to 15 m/s^2 (Helene and Yamashita, 2010; Margaria, 1976). When walking, lower acceleration values are expected. Nevertheless, real-life observations and laboratory measurements show that it is possible to reach the desired walking speed from standing within one to two steps (Fugger et al., 2000; Jian et al., 1993).

Several studies were conducted also measuring the observed accelerations. For normal walking, accelerations of 1.5 to 3.0 m/s^2 were measured, for fast walking 2 to 5 m/s^2 (Ahlgrimm et al., 2009). Other studies, determining the average acceleration for the first metre starting from standstill, measured values from 0.25 to 2.77 m/s^2 for walking, depending on age and gender. For fast walking, a range of 0.72 to 3.56 m/s^2, for running values between 1.28 to 5.56 m/s^2 were calculated (Bartels and Erbsmehl, 2014). Usually, higher acceleration values were found for men.

Another study, focusing on the acceleration and deceleration at stopping points, determined that the acceleration and deceleration curves are quite similar (Bauer and Kitazawa, 2010). Here, average acceleration values up to 0.6 m/s^2 were measured. Almost all of the speed change took place within the first two metres, which is in good accordance with other observations, where the maximum speed was reached 1.82 m from the start (Brogan and Johnson, 2003). For turning manoeuvres, accelerations up to about 1.0 m/s^2 were recorded. In real-life observations at intersection, acceleration values of 1.37 ± 0.88 m/s^2 were recorded for starting pedestrians (Fugger et al., 2000).

Another factor influencing the acceleration and deceleration values is the desired comfort. If pedestrians are asked to stop as fast as possible, the peak values are significantly higher than when they stop comfortably (Tiemann, 2012). In general, higher desired walking or running speeds also lead to higher accelerations when starting (Bartels and Erbsmehl, 2014; Mayer and Krechetnikov, 2012; Tiemann, 2012).

Also for stopping, higher speeds lead to longer stopping distances (Zhang et al., 2009). Stopping movement can take place within one or two steps. At comfortable walking speed, it was observed that a signal before mid-stance resulted in a stop at the footfall of the swing leg (Hase and Stein, 1998). Otherwise, a second step was needed to stop completely.

Changes in walking speed are also performed within a few steps. In experiments, the acceleration from 1.0 to 1.4 m/s was done within one step, the opposing deceleration within two steps (Orendurff et al., 2008). This study revealed also that the acceleration and deceleration measured was caused by a change in the sagittal ankle movement starting in the early single limb phase at about 15 % of the gait cycle.

In laboratory experiments, the acceleration a_t from standing to walking at the desired speed v_d was found to follow the equation (Liu et al., 2017; Ma et al., 2010; Moussaïd et al., 2009):

$$a_t = \frac{v_d - v_t}{\tau} \tag{5.1}$$

In Table 5.1, the parameter values obtained from experiments in France (Moussaïd et al., 2009) and China (Liu et al., 2017; Ma et al., 2010) are listed.

TABLE 5.1: Desired velocity v_d $[m/s]$ and relaxation time τ $[s]$ for calculating the acceleration using formula (5.1).

v_d [m/s]		τ [s]		SOURCE
MEAN	SD	MEAN	SD	
1.29	0.19	0.51	0.05	Moussaïd et al. (2009)
1.51	0.15	0.71	0.10	Ma et al. (2010)
1.54	0.15	0.66	0.11	Liu et al. (2017)

Based on the findings from literature, the acceleration and deceleration movement can be integrated into the pedestrian walking model (Figure 5.5). For each of them, a maximum value can be computed based on the properties of the human body and the period of the gait cycle. Usually, a lower desired acceleration or deceleration value is used. This value is based on the situation and is limited by the achievable maximum.

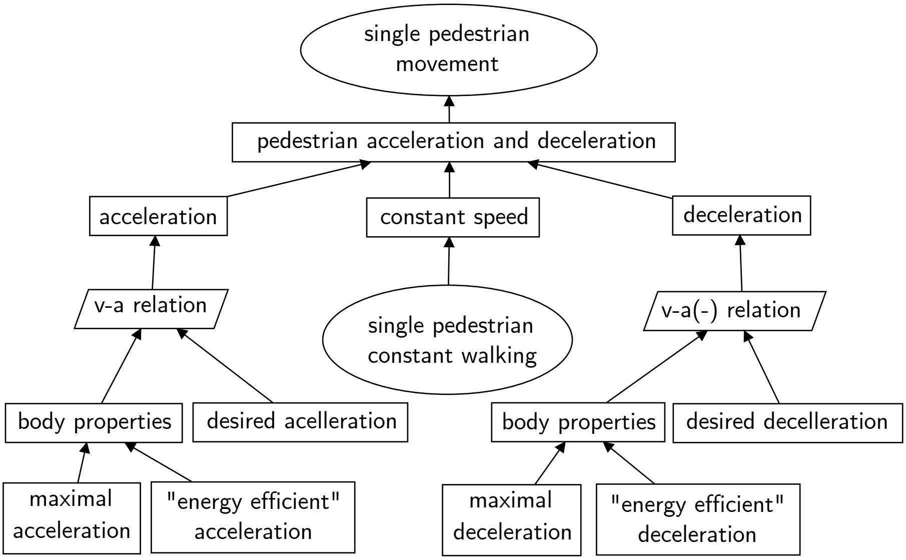

Figure 5.5: Model for single pedestrians walking.

5.2.5 *Turning movement*

In daily walking activities, between 8 and 50 % of all steps recorded were done during turning movements (Glaister et al., 2007). Thus, the properties of these movements have to be considered when describing pedestrian walking.

Similar to speed changes, also turning movements show reaction times and delays. In an experiment, people were unable to change the walking direction by 60° when the signal was given only one step ahead (Patla et al., 1991). This indicates that the change of direction involves a deceleration of the forward movement, a body rotation and walking in the new walking direction For turning around 180° it was found that two turning strategies exist, spin and step turns (Hase and Stein, 1999). Spin turns involve turning on the ball of one foot, whereas in step turns the turning movement involves turning on both feet while stepping still occurs. The choice of strategy was observed in the experiment to be dependent on the phase within the gait cycle. In real-life observations, only step turns were observed (Glaister et al., 2007).

Considering the trajectories of turning movements, it was found that minimum jerk and minimum snap (first derivative of jerk) models showed the best fit (Pham et al., 2007). Thus it can be assumed that pedestrians tend to follow a smooth trajectory when turning (Multon and Olivier, 2013). Concerning the walking speed, a considerable reduction was found during turning movements (Orendurff et al., 2006). In experiments, also a speed dependency of the maximum turning angle was found (Seitz et al., 2015).

5.3 UNIDIRECTIONAL MOVEMENT

5.3.1 *Model description*

After the completion of the single pedestrian walking model, the next step to increase the complexity of the model is the unidirectional movement. Here, three different modelling steps are done. First, only the walking direction is considered in the model for pedestrians walking in line. As a second step, unidirectional walking with pedestrians showing the same properties is investigated. Here, the speeds for all pedestrians are the same. The focus of this model is hence on the interpersonal distances. The last step describes the general unidirectional walking, where also overtaking takes place, due to different speeds.

5.3.2 *Pedestrians walking in line*

Experiments and models using pedestrians walking in line are widespread among literature (Cao et al., 2016b; Chattaraj et al., 2009; Jelić et al., 2012a; Jezbera et al., 2010; Seyfried et al., 2005). In this setting, pedestrians walk in a row without overtaking each other. Ideally, the walking speed is thus independent of the lateral extend of the pedestrians and the walking area, thus it is the simplest case for pedestrian flows. In most cases, it is assumed that the walking speed is solely adapted to the pedestrian in front. Anyway, simulations show that at least the pedestrian behind also has an influence on the movement, whereas the influence of pedestrians further away is minimal (Kretz et al., 2016).

When walking, pedestrians try to keep a certain distance to other pedestrians. If the distance to the pedestrian in front is below a certain threshold, the walking speed is reduced to avoid getting too close to the next pedestrian or even get in physical contact. The minimum space required by a single pedestrian corresponds to its body depth. As in this situation physical contact exists between all pedestrians, it is usually not reached. Data from Germany state for example a median chest depth of 22.5 cm for adult men and 19.0 cm for adult women, which results in a maximum line density of 4.4 to 5.3 P/m (DIN, 2005). Measurements in other countries show a median chest depth between 17.0 and 28.5 cm for men (DIN, 2013; Pheasant, 2006). When considering the whole body depth, average values ranging from 21.7 to 32.5 cm can be found (DIN, 2013; Still, 2000). In addition to these values, the clothing and luggage has to be added to the physical space demand.

The distance, pedestrian usually keep to others, can be divided into the intimate, personal, social and public zone (Hall, 1966). Each of these zones was further divided into a close and a far distance (Table 5.2). Depending on the relationship, another person is allowed to enter a specific zone without feeling uncomfortable. Each zone represents a different kind of possible interactions and perceptions, for example the possibility to touch the person or to see the face details. Further studies in recent years showed differences in the zone dimensions based on the personal characteristics (Fujiyama, 2005). When applying this concept to pedestrians walking, it can be assumed that pedestrians reduce their walking speed to avoid others to intrude in their intimate or personal distance. Therefore, in addition to the desired buffer distance kept while standing an additional distance is required to react and reduce the walking speed.

Table 5.2: Personal distances [m] according to Hall (1966).

zone	close phase		far phase	
	from	to	from	to
Intimate distance		0.15	0.15	0.20
Personal distance	0.46	0.76	0.76	1.22
Social distance	1.22	2.13	2.13	3.66
Public distance	3.66	7.62	7.62	

In experiments, the expected decrease in walking speed with decreasing headway can be found Table 5.3. Data covering the whole range of pedestrian headways indicate three distinct sections in the speed-density(headway) data: a free flowing regime, a weakly constrained regime and a strongly constrained regime (Appert-Rolland et al., 2014). For large headways (> 3 m), the walking speed was independent on the headway, hence the pedestrians walked at their preferred speed without visible reaction to other pedestrians. Between 3.0 and 1.1 m, a range corresponding roughly to the social distance, the speed is slightly lowered by the smaller headway. At lower headways, a strong relation between walking speed and headway was observed. This finding was partly reproduced by similar experiments in China, where the division between the weakly and strongly constrained regime was also at 1.1 m but the free flow regime was measured until 2.8 to 1.1 m (Cao et al., 2016b).

Models using real-life observations from a walkway in Bangkok found an influence length of pedestrians in front on the walking speed of 5 to 9 m (Tipakornkiat et al., 2012). Hence, compared to the previously described experiments, the influence area was found to be considerably larger.

The acceleration of following pedestrian was found to be dependent on the walking speed differences, the distance between the two and a time delay, which represents the time needed to assess the velocity of the predecessor (Appert-Rolland, 2015). A model formulation for this was proposed as:

TABLE 5.3: Relation between walking speed v [m/s] and headway h [m] for single-file movement experiments.

SOURCE	EQUATION	REGIME	COUNTRY
Seyfried et al. (2005)	$h = 0.36 + 1.06 \cdot v$		Germany
Chattaraj et al. (2009)	$h = 0.22 + 0.89 \cdot v$		India
	$h = 0.36 + 1.04 \cdot v$		Germany
Jelić et al. (2012b)	$h = 0.45 + 0.75 \cdot v$	$v < 0.80$	France
Cao et al. (2016b)	$h = 0.25 + 0.69 \cdot v$	$h < 1.10$ (students)	China
	$h = 0.25 + 1.31 \cdot v$	$h < 1.10$ (mixed)	China

$$a_{(t)} = C \cdot \frac{\Delta v_{t-T}}{(\Delta x_t)^{\gamma}} \tag{5.2}$$

Where:

		Parameter values (Appert-Rolland et al., 2014)
$a_{(t)}$	Acceleration at time t [m/s²]	-
Δv_{t-T}	Speed difference at time $t-T$ [m/s]	-
$\Delta x_{(t)}$	Headway at time t [m]	-
T	Time delay [s]	0.658 ± 0.45
C	Model parameter [$m^{1/2}/s$]	0.809 ± 0.355
γ	Model parameter [$-$]	0.5

Data from experiments also show that a higher variation in walking properties influences the speed-density relation in the single-file movement (Cao et al., 2016b; Yanagisawa et al., 2013; Zhang et al., 2016).

Compared to the previous model, the reaction to other pedestrians is introduced (Figure 5.6). Here, two different regimes can be distinguished. If the distance to the pedestrian in front is large enough, the walking speed is independent from the person in front and determined by the model for single pedestrian movement. At closer distances, the walking speed is adapted to the distance and walking speed of the pedestrian in front. This adaption is dependent on the physical characteristics like walking speed, body space and distance, as well as on psychological characteristics such as the minimum accepted distance to others (von Sivers and Köster, 2015).

In addition to the physical constraints and requirements for walking, the interaction between pedestrians can be described as driven highly by the human perception and psychology.

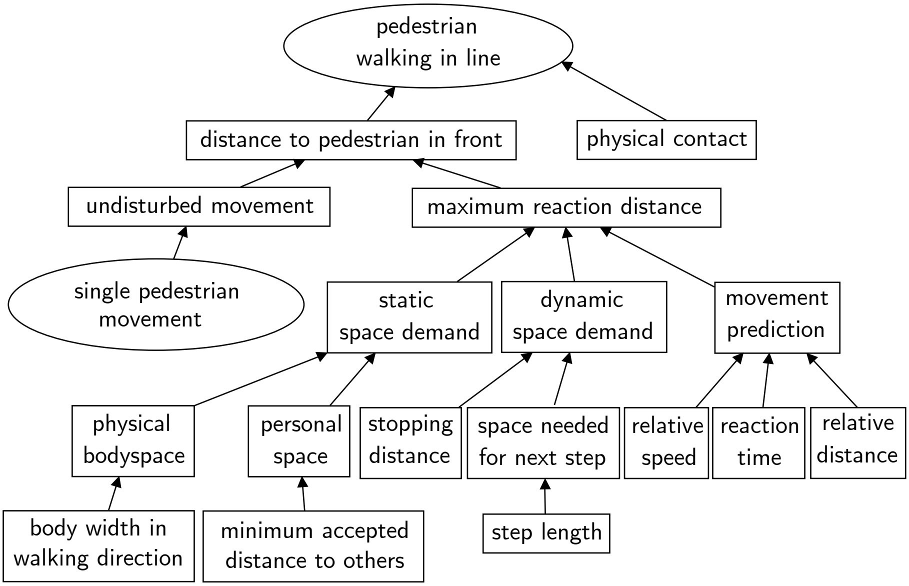

FIGURE 5.6: Model for pedestrians walking in line (adapted from: Bosina and Weidmann (2016)).

5.3.3 *Constant unidirectional walking*

In this model step, the flow of pedestrians is increased from walking in line to a flow of people in the same direction. Otherwise, the pedestrian characteristics and hence the walking speeds are assumed to be the same for all pedestrians. Therefore, mainly the lateral influences of other pedestrians are introduced.

Similar to the frontal distances in the single-direction, the distances in lateral direction can be divided into the body area and the desired distance between pedestrians. This distance can also be divided into the space needed for walking and the buffer distance to other pedestrians.

The human body in the transverse plane can be approximated by an ellipse (Buchmüller and Weidmann, 2006). The lateral size of the human body is determined by the shoulder width, which shows median values for adults between 33.0 to 48.6 cm (DIN, 2013; Pheasant, 2006). Including the average luggage burden observed, the mean width was calculated to 69 cm (Schopf, 1985).

As walking includes also lateral movement, additional space is required to allow walking. Within a standard gait cycle, the body moves about 4 to 6 cm in lateral direction at normal gait (Murray et al., 1964; Simoneau, 2010). In laboratory measurements a negative correlation between swaying amplitude and walking speed leading to high amplitudes at low walking speed was found (Hoogendoorn and Daamen, 2005a). When also the deviation from a straight line is included, the lateral sway increases additionally. For a 85 % confidence interval, the lateral movement is up to 28.2 cm (Schopf, 1985).

Using time-lapse photography, Fruin (1971b) determined average lateral and longitudinal spacing between pedestrians at different pedestrian densities. At about 0.5 P/m², an average headway of 1.5 m was found in lateral direction between the centres of mass and a distance of 1.0 m in lateral direction. It was also observed that at higher densities, the longitudinal distance was stronger reduced than the lateral one. At a density of about 2.2 P/m², the spacing can almost be represented by a circle with a diameter of 0.6 m.

Based on experiment data, it is assumed that pedestrians keep a constant net-time headway of about 0.5 s to a pedestrian in front in order to avoid collision (Johansson, 2009a). Other studies however show higher headways for slower walking older pedestrians (Thompson et al., 2015).

Considering the dependency of the distance to the next person on its direction shows that the influence depends on the angle to the next pedestrian (Johansson et al., 2007). As the visual field is also restricted to about 170° to 180°, without turning their head, pedestrians will mainly perceive information about pedestrians walking in front of them (Cristiani et al., 2014). It is also assumed that pedestrians mainly observe the closest pedestrians in front (Goffman, 1971). Other pedestrians obstructed by others or further away are disregarded.

As in the proposed model it is assumed that all pedestrians show the same properties, a grid-based distribution of pedestrians can be expected. This grid will allow pedestrians to keep the desired distance to others for a given speed while minimizing the space demand. While standing at maximum density possible and assuming elliptical bodies, the optimal solution can be found using the arrangement showing the highest packing density.

If a situation is considered, where the body buffer zone is respected, the highest density depends on the shape of this zone. Here, different forms of the body buffer zone can be used. From a distance point, either a circular shape around the centre of body mass or an elliptical shape similar to the body ellipse can be used. Otherwise, it can also be argued that the visual perception has a strong influence, which will concentrate the body buffer to the front of the body.

Otherwise, the area needed for walking is expected to have a strong forward orientation. Pedestrians walking to the frontal side therefore might be accepted at a much shorter distance than directly in front. The required walking space can further be divided into a zone required for the foot placement and a sensory zone for the perception and reaction (Fruin, 1971b).

The space demand for lateral movement is thus based upon three aspects in the model (Figure 5.7). First, the personal distance, which is dependent

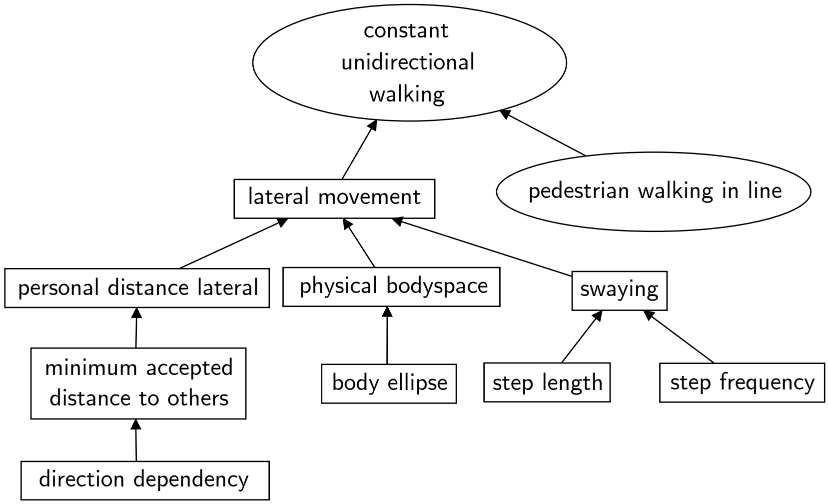

FIGURE 5.7: Model for constant unidirectional walking.

on psychological factors, second the physical body space and third the space demand for walking, namely the lateral swaying.

5.3.4 *General unidirectional walking*

The model for general unidirectional walking includes all decisions and characteristics relevant for determining the speed-density relation in unidirectional flows, and hence for calculating the fundamental diagram. In addition to the adaption of walking speed described in the previous models, the overtaking of other pedestrians is added. For this, the most important aspect is the decision if a person is passing another pedestrian and/or is reducing its speed due to the limited space, which is mainly dependent on the relative position, the speed and heading of the pedestrian (Knorr et al., 2016).

To pass another pedestrian, a gap in the flow is needed for the overtaking pedestrian whereas when reducing the speed, the space demand reduces. When overtaking, pedestrians keep a certain distance to the other pedestrian or obstacles, depending on the current angle (Gérin-Lajoie et al., 2006). This behaviour can be expected to be similar to the distances kept when walking next to each other without overtaking, and can be approximated by a parabola. In laboratory experiments it was also revealed that the personal space when circumventing an obstacle, which can be assumed to be similar to a pedestrian, is side dependent (Gérin-Lajoie et al., 2008). Towards lateral both sides show the same distances to the obstacle, but towards the front the right side showed a more streamlined and shorter area of personal space. This study also found no differences in the distance behaviour when circumventing obstacles for different walking speeds, which anyway might just be based on the experimental setting.

Under experimental conditions no general preference for a passing side when overtaking was found, but individual pedestrians did show a side preference (Daamen et al., 2014). On the other hand, in real-life observations a side preference is visible (Zanlungo et al., 2014a). The side preference in real-life situations might also result from the fact that overtaking was measured in a bidirectional flow. As in this case each direction usually is shifted towards one direction, overtaking usually takes place towards the centre, similar to car traffic on a highway.

The decision, if a pedestrian is overtaking or reducing his speed is likely not only dependent on the available space. It can be argued that pedestrians will adapt their speed to the pedestrians in their vicinity to reduce the number of conflicts and hence improve the capacity of the flow (Fu et al., 2016). Otherwise, slow pedestrians will produce gaps. They will subsequently be used by faster pedestrians for overtaking resulting in suboptimal flows (Moussaïd et al., 2012).

The space demand can also be reduced by body rotations, especially at higher densities. To reduce the space needed in lateral direction, a pedestrian can turn the body and make a better usage of the available space. This behaviour might lead to a higher stability of the flow (Feliciani and Nishinari, 2016).

The model for general unidirectional walking is extended from the model for constant unidirectional walking by the possibility to overtake other pedestrians (Figure 5.8. The decision, whether to overtake a pedestrian or reducing the speed and stay behind, is based on the physical space demand as well as it is highly dependent on the human perception and psychology.

5.4 GENERAL WALKING MODEL

5.4.1 *Model description*

As walking is not restricted to unidirectional flow, pedestrians also developed strategies to negotiate conflicts with pedestrians from different directions. The general walking model therefore includes the principles of pedestrians crossing. Applying the principle "from simple to complex", first bidirectional flows is modelled, where only the flow at an angle of 180° is added. In a second step, the flow directions are generalised, allowing all possible crossing angles. In the last step a model for multidirectional walking, as it is done for example at crossings or public places, is developed.

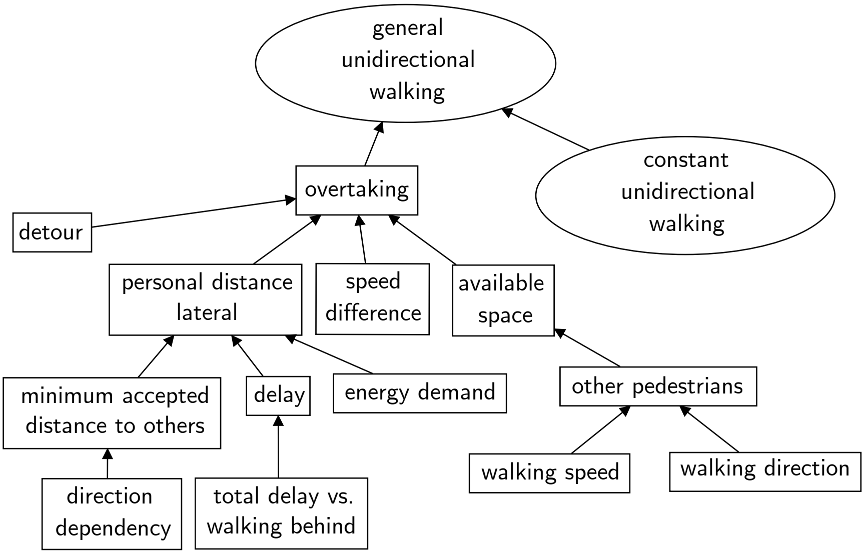

FIGURE 5.8: General unidirectional walking model (adapted from: Bosina and Weidmann (2016)).

5.4.2 *Bidirectional flows*

In addition to the unidirectional flow model, pedestrians walking in the opposite direction are integrated into the model. This mainly results in a new conflict type, which can be described as head-on collision. Contrary to overtaking, where the person behind mainly has to react in order to avoid the collision, both pedestrians are likely to react.

Generally, the decision possibilities for a pedestrian in a head-on collision are similar to overtaking. If a conflict approaches, one or both involved pedestrian can change the walking direction and speed. A solely reduction of speed is usually not desired, as this will result in stopping for both pedestrians.

In contrary to overtaking, where no side preference was found, a clear side preference, depending on the culture, is visible (Fujiyama and Tyler, 2009; Zanlungo et al., 2012). If the two desired walking paths do not meet exactly but are shifted towards one side, the crossing side will also be strongly influence (Yuan et al., 2017). In general, pedestrians tend to walk on one side of a corridor or walkway whenever possible. This behaviour is also considered to lead to a strong reduction in the number of conflicts and higher walking speeds (Yuan et al., 2017).

When crossing, pedestrians also tend to keep a certain distance to each other. The mean shoulder distance between two pedestrians while crossing without space restrictions was found to be 21 cm, 85 % of the encounters were closer than 27.5 cm (Schopf, 1985).

Laboratory experiments, where enough space was available, showed only a direction change but no speed reduction while crossing (Huber et al., 2014). This change started at 2.1 to 2.7 m, depending on the walking speed. For lower walking speeds, smaller distances were observed. The distances are in good accordance with models based on real-life data, where 2.5 m was determined as the starting point for sideward movement (Ma et al., 2016).

In real-life situations, the visual perception of the environment by the pedestrian is important. Using information about the presence of other pedestrians, the potential conflicts and the conflict time have to be identified and solved by adapting walking speed and direction (Ondřej et al., 2010). To reduce the number of conflicts, self-organized lane formation usually takes place in bidirectional flows (see Chapter 2.2.2.2).

5.4.3 *Crossing flows*

Compared to the bidirectional flow, crossing conflicts are more complex, as the path planning has more options. In head-on conflicts, the main choice is to evade towards right or left, or to keep straight as the opponent already walked far enough to one side. In crossing flows at other angles, the movement prediction of the opposing passenger is much more important. Apart from the direction change, often also a speed adaption is done.

In general, the crossing of two pedestrians can be characterised by three phases: observation, reaction and regulation (Olivier et al., 2012). In the observation phase, a potential crossing conflict is detected and a resolution strategy is developed. In the next step, a reaction is performed to resolve the conflict and allow a crossing while maintaining an accepted minimum distance. The regulation phase then consists of a short time interval (approximately 0.8 s) before the crossing, where the conflict is solved and the minimum crossing distance is maintained.

In a laboratory setting, where the test person had to cross the path of another person, who did not change his walking speed and direction, at an angle of 90°, showed a clear crossing strategy in this setting (Basili et al., 2013). In almost all test runs, the test person only adapted its walking speed without altering the direction and passed after the interfering person. This finding can be confirmed by results from another experimental study, where only 5.9 % of the participants made a detour to solve the crossing conflict (Lv et al., 2015). In this study, most of the crossing conflicts were solved by one pedestrian accelerating while the other was decelerating.

Another study, focusing on crossing conflicts at 60° and 90°, otherwise showed a mixed path and speed adjustment behaviour (Knorr et al., 2016). The results of this study indicate that each individual pedestrian show a predefined crossing strategy. Considering multiple crossing angles from 45° to 80° also showed a mixture of speed and path adjustment (Huber et al., 2014). Whereas the lateral movement distance was almost constant for all angles, the speed adjustment was higher for smaller crossing angles.

The distance, where the turning manoeuvre is started was found to be dependent on the crossing angle (Huber et al., 2014). The longest distance was observed at an angle of 180°, hence at a head-on conflict. For 45°, this distance was reduced to 1.5 to 2.2 m. For the transfer to real-life condition it has to be noted that these experiments consisted of a participant doing the detour and a non-responsive person walking at constant speed. In another experiment, where a pedestrian was walking straight and another pedestrian served as an obstacle which the walking pedestrian had to circumvent, the distance where a direction change was initiated was mostly between 0.9 and 2.0 m (Lv et al., 2013).

At high densities, space becomes limited, hence the conflict resolution methods observed in two pedestrian experiments might not be feasible any more. In this case, another conflict resolution type, stopping completely, is visible (Parisi et al., 2016). Still, as long as enough space is available, changing the walking direction is far more favourable.

5.4.4 *Multidirectional walking*

The increase in complexity between crossing flows and multidirectional walking is mainly based on the increased cognitive and conflict resolution task. No new conflict type or physical walking attribute is needed.

At lower densities, multidirectional walking can be described by a series of crossing flows, where one conflict is solved after another. With an increase in the pedestrian density, several conflicts have to be solved at the same time. It can be expected that for this, similar phenomena and techniques are applied, namely the formation of lanes and at high densities, stopping for the conflict resolution.

6

FUNDAMENTAL DIAGRAM MODEL

Wanderer, there is no path, the path is made by walking.
— Antonio Machado, Campos de Castilla

An adapted version of this chapter was already presented as:

Ernst Bosina and Ulrich Weidmann (2018). Creating a generic model of the pedestrian fundamental diagram. 18th Swiss Transport Research Conference STRC. Monte Verità/Ascona: STRC. DOI: 10.3929/ethz-b-000263928

6.1 OVERVIEW

6.1.1 *Aim of the model*

In contrast to the pedestrian walking model in Chapter 5, the fundamental diagram model aims at providing a generic description of the fundamental diagram for unidirectional walking. The model shall describe the relation between the average density and speed according to the definition of the fundamental diagram proposed in Chapter 2.4.7. In addition, it is based on the principles of human walking presented in the generic pedestrian walking model. The aim of the model is to be able to simulate different pedestrian properties and to obtain corresponding fundamental diagrams. C, microscopic model results do not have to show a high accuracy, but the mesoscopic fundamental relation shall be consistent with existing data to be useful for the design of pedestrian facilities. Obviously, as the model itself will be microscopic and generic, the model aims at sufficiently describing pedestrian walking.

Several microscopic model approaches exist in literature for the simulation of pedestrian flows (see for example Duives et al. (2013) or Reda (2017)). Among these, most models use analogies or otherwise do not aim at modelling the walking behaviour, as it shall be done here in the fundamental diagram model. For example, the widely used social force model (Helbing and Molnár, 1995) uses the analogy of forces to calculate the accelerations while walking and thus the walking behaviour. But other models, such as the Follow-The-Leader model (Degond et al., 2015), the optimal step model (Seitz and Köster, 2012), visual based models (Kang and Han, 2017; Moussaïd et al., 2011) or energy based models (Guy et al., 2010) are aiming at directly describing at least parts of the walking principles. These models will be used as a starting point for the model setup.

As the interaction between pedestrians is complex, the fundamental diagram model will also be developed starting with simplifications and gradually increasing the complexity. In Table 6.1, the list of models created for this work and their main characteristics are shown, which provides an overview about the main modelling steps. The complexity of modelling the pedestrian flow is mainly based on two aspects.

Table 6.1: List of models created and their main properties.

MODEL	SPACE	UPDATE	DECISION	ASPECTS ADDED
Model A	Single lane	each time step / deterministic	instantaneous	
Model B	Single lane	const. walking step duration	one step ahead	
Model C	Single lane	individual step length	decision time before step change	acceleration limitation, random noise
Model D	Single lane	individual step length	prediction for time of step change	
Model E	parallel lanes	individual step length	prediction for time of step change	switching lanes
Model F	continuous 2D	individual step length	prediction for time of step change	side movement
Model G	continuous 2D	individual step length	prediction for time of step change	headway adaption

First, the flow can show differences in the number of walking directions and the width of the flow. For the fundamental diagram in this work, the flow is defined to be unidirectional and shows an unlimited extend, hence no border effects apply. Multidirectional flows will not be considered. To start with the simplest first step possible, the flow can be assumed to be based on single lanes not interacting with each other (Chapter 6.2.4). By defining a lane width for each lane, a unidirectional fundamental diagram can be calculated. This model will then be further elaborated to include the most relevant aspects visible in the fundamental diagram. In Chapter 6.3.3, a fully unidirectional movement model is derived, where overtaking is possible and pedestrians can move continuously in space.

The second aspect is the variation of the pedestrian properties. In reality, pedestrians will show individual properties, which influences walking and thus the fundamental diagram. For the least complex situation, these properties can be set to be equal for all pedestrians, which makes it easier to calculate the fundamental diagram, at least for a simple case. Again, this assumption will be dropped to also study the influence of variations in the pedestrian composition.

6.1.2 *Modelling approach*

Only for the first modelling step, Model A of the lane-based models, the steady state condition can be obtained directly using the formula without the need of iterations. All other models are based on a time-step approach and are microscopic. For each global density, a set of pedestrians is generated and initial speeds and positions are determined. Then, the simulation is done for a defined number of time-steps, until steady state conditions are expected. The model parameters are descibed in the following section (Chapter 6.1.3) as well as for the model calibration (Chapter 8.4), where the model parameters are grouped into simulation, input and calibration parameters. The main structure of the model selected (Model E) is presented in Chapter 6.5.

The simulation area is modelled as infinite loop, where pedestrians reaching the end of the track start again at the beginning of the track. Also, the lateral limits of the area are connected, hence people leaving the area on one side will enter on the other side. Thus, the size of the simulation area is only relevant for the modelling, no wall effects occur in the model.

The model is implemented in Python (version 3.6.4), the code is available in the Appendix A.2. The model results are usually presented as shown in the example in Figure 6.1. Here, not only the average walking speed is shown, as it is done in the regular fundamental diagrams but also the range of walking speed measurements. The dark grey area indicates the speed distribution computed using the average individual walking speed, hence one average value per person. The light grey area shows the distribution of the instantaneous walking speeds. For comparison, the fundamental diagram from Weidmann (1993) is also added to the figure.

6.1.3 *Model parameters*

For the basic model variables, literature data is available which allows to estimate the range of their values (Table 6.2). For the deceleration time it was assumed that the deceleration needs one to two steps, independent on the walking speed (see also Chapter 2.2.1.4) and that these steps are done at the full walking speed chosen. For the pedestrian composition parameters either a minimum, maximum, average or uniform distribution is used for the model setup. For the minimum and maximum variable compositions extreme values are used, so that for the minimum composition the lowest speed at a certain density and for the maximum composition the highest speed is obtained. Thus, for example the minimum composition consists of the minimal desi-

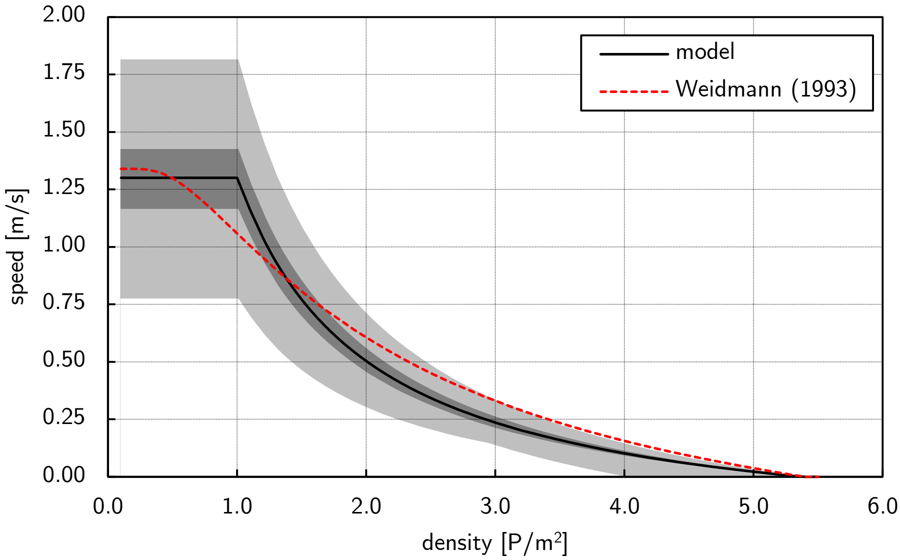

FIGURE 6.1: Example of the fundamental diagram plot from the model result. Black curve: average speed; dark grey: range of individual walking speeds over a longer time period; light grey: instantaneous walking speeds; green: fundamental diagram from Weidmann (1993).

red walking speed but the maximal body width. The uniform and average composition are both based on the range of values presented.

In addition to the basic pedestrian properties, several other simulation parameters were introduced. These are shown in Table 6.3 and will be further described when they are introduced into the model.

TABLE 6.2: Range of values for the pedestrian characteristics used for modelling the fundamental diagram. The minimum and maximum values in the range of values are set, so that the minimum will result in a minimum walking speed for a given density and the maximum for a maximum speed.

	VALUE RANGE			
VARIABLE	MIN.	MAX.	CHAP.	SOURCE
Desired walking speed v_d [m/s]	1.00	1.60	2.3.4.3	Bosina and Weidmann (2017c)
Body width w_B [m]	0.49	0.33	5.3.3	DIN (2013), Pheasant (2006)
Sway width w_S [m]	0.06	0.04	5.3.3	Murray et al. (1964), Simoneau (2010)
Body depth d_B [m]	0.29	0.17	5.3.2	DIN (2013), Still (2000)
Intimate distance d_I [m]	0.20	0.15	5.3.2	Hall (1966)
Reaction time t_r [s]	0.80	0.40	5.2.3	Degond et al. (2015), Ma et al. (2010), Moussaïd et al. (2009)
Deceleration time t_d [s]	1.02	0.49	2.2.1.4	Hediyeh et al. (2015)

TABLE 6.3: Simulation parameters and default values used for the model creation.

PARAMETER	DEFAULT		FIRST IN
Number of pedestrians P	1 000		Model A
Simulation time interval T_i	0.1	s	Model A
Simulation duration T_{sim}	10 000	s	Model A
Number of time steps used for speed calculation S_s	1 000		Model A
Random noise r_n	10	%	Model C
Step formula	Cavagna		Model C
Maximum acceleration a_{max}	0.6	m/s²	Model C
Reaction delay t_{rd}	$0.2 - 0.4$	s	Model C
Maximum reaction time $t_{r,max}$	1	s	Model C
Minimum walking speed v_{min}	0	m/s	Model C
Number of lanes N_l	10		Model E
Backward distance for lane change d_{back}	3	m	Model E
Initial time steps with no lane change S_{in}	100		Model E
Maximum reaction headway $h_{r,max}$	4	m	Model E
lateral threshold for neighbours $w_{lat,t}$	1	m	Model F
Lane width factor for overtaking f_l	1.1		Model F
Maximum lateral speed at standstill $v_{l,max}$	0.1	m/s	Model F
Head width for lane calculation w_h	0.2	m	Model G

6.2 LANE-BASED MODELS

6.2.1 *Model description*

For the lane-based models, walking is simulated as a one-directional movement, where pedestrians walk in predefined lanes without interaction between lanes. Thus, no side movement exists. In this case, it can be assumed that each pedestrian is only reacting to the pedestrian directly in front. In addition, the only reaction possibility is the change of walking speed, as no sideward evasion is possible. To obtain a two-dimensional fundamental diagram for this situation, a lane width has to be defined, which is described in Chapter 6.2.3.

As the pedestrians cannot overtake each other, faster pedestrians have to reduce their walking speed when approaching a slower pedestrian in front. As the fundamental diagram definition used requires steady state conditions, this will only be reached if all pedestrians show the same (slowest) walking speed. Therefore, the linear model cannot be used to determine the influence of different desired walking speeds, but an average walking speed has to be used for the model to be useful. At higher densities, overtaking is expected to be less relevant and all pedestrians will walk at speeds lower than desired. In this case, the missing possibility of overtaking will not influence strongly the results.

6.2.2 *Model layout*

In Chapter 6.2.4 to 6.2.7, four models (Model A to Model D) will be presented. The models are based on their predecessors and will step by step add features which will improve the consistency of the model with the human walking principles. One important aspect addressed in the model improvements is the time and amount of possible speed changes and the time, when the next speed is decided (Table 6.4). In Model A, every time step a speed update is possible, which is based on the information currently available. For the last model (Model D), a speed change is only possible at the end of a step. In addition, this change is done on a prediction based on the situation a certain time interval before the end of the step.

Each model can be run using different simulation parameter values. In Table 6.5, the values for the simulations presented in the figures of this chapter are shown. As overtaking is not possible in the lane-based models, the uniform distribution is computed without a free flow speed distribution. Otherwise, as the model runs until steady state conditions are reached, everyone would align behind the slowest pedestrian, who will determine the average walking speed. Therefore, the average walking speed is used for all pedestrians for the uniform distribution. Only Model D.5 uses a speed distribution

TABLE 6.4: Speed change and time of speed change procedure for the different lane based models.

MODEL	SPEED CHANGE	TIME OF SPEED DECISION
Model A	Every time step / deterministic	Instantaneous
Model B	Global walking step duration	One step ahead
Model C	Individual step length	Certain time before step change
Model D	Individual step length	Prediction for time of step change

to compare the effect to Model D.2. For all parameter values not shown, the default values from Table 6.3 are used.

6.2.3 *Lane width*

To obtain a two-dimensional density based on a lane-based model it is necessary to define a lane width for each lane. In real-life situations it was observed that at higher densities the average lateral and longitudinal spacing is reduced (Fruin, 1971b). The lateral distance between pedestrians is also depending on the lateral shy away distance and the direction angle.

When assuming a random distribution of pedestrians, the spacing between pedestrians will be equal in lateral and longitudinal direction. At higher densities, where the distance in front is less than the required headway for the desired walking speed, pedestrians can either reduce their speed or move sideways where no pedestrian is closely in front. As the required distance in longitudinal direction is considered to be larger than in lateral direction, it can be assumed that an increase in density will first result in a decrease in lateral distance before the speed is reduced.

TABLE 6.5: Simulation parameter values used for the lane-based models in this chapter.

MODEL	T_i [s]	DISTRIBUTION	r_n [%]	STEP FORMULA	a_{max} [m/s²]	t_{rd} [s]	FIGURE
A.1-3	-	Min/max/av	-	-	-	-	Figure 6.4
B.1	0.45	Uniform	-	-	-	-	Figure 6.6 Figure 6.8
B.2	0.50	Uniform	-	-	-	-	Figure 6.7 Figure 6.9
C.1	0.10	Uniform	0	Cavagna	2.0	0.2	Figure 6.11
C.2	0.10	Uniform	0	Cavagna	2.0	0.2 – 0.4	Figure 6.12
C.3	0.10	Uniform	0	Jelić	2.0	0.2 – 0.4	Figure 6.13
C.4	0.10	Uniform	0	Cavagna	0.6	0.2 – 0.4	Figure 6.14
C.5	0.10	Uniform	0	Cavagna	0.3	0.2 – 0.4	Figure 6.15
C.6	0.10	Uniform	10	Cavagna	0.6	0.2 – 0.4	Figure 6.16
D.1	0.10	Average	10	Cavagna	0.6	0.2 – 0.4	Figure 6.19
D.2	0.10	Uniform	10	Cavagna	0.6	0.2 – 0.4	Figure 6.18 Figure 6.21
D.3	0.10	Maximum	10	Cavagna	0.6	0.2 – 0.4	Figure 6.19 Figure 6.20
D.4	0.10	Minimum	10	Cavagna	0.6	0.2 – 0.4	Figure 6.19
D.5	0.10	Uniform	10	Cavagna	0.6	0.2 – 0.4	Figure 6.21

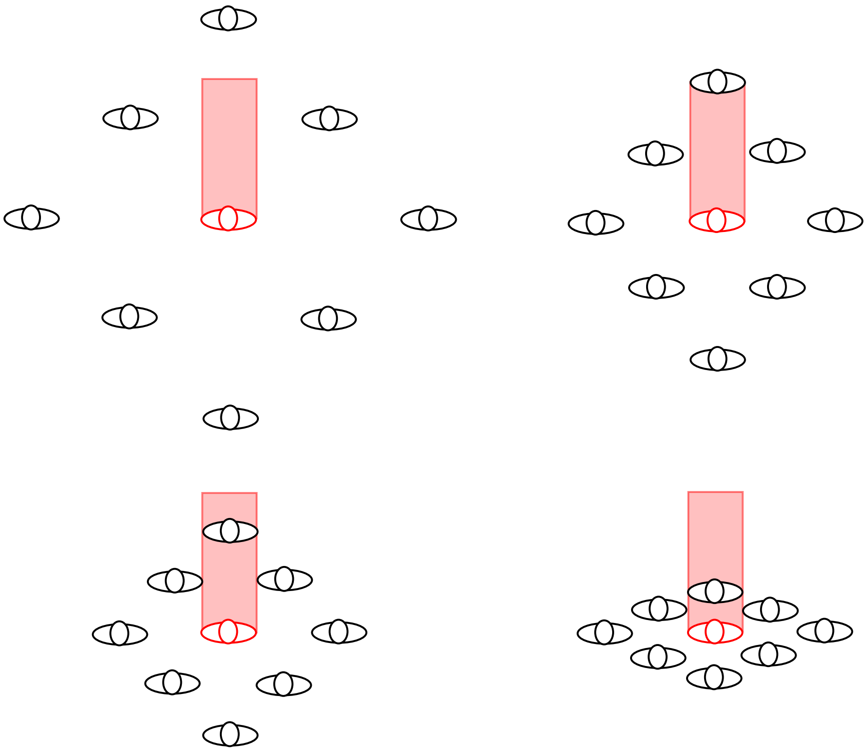

FIGURE 6.2: Grid based concept for the distribution of pedestrians at different densities (light blue area = minimum headway at desired walking speed). Top left: lowest density, bottom right: highest density (no movement).

The easiest configuration to study this effect is, when uniform distances among all pedestrians are assumed (Figure 6.2). At low densities, the distances between pedestrians are assumed to be isotropic. An increase in density will lead to a situation, where the minimal headway in longitudinal direction is reached. A further increase in density will thus be reached by reducing the lateral distances until the minimal distances in lateral direction occur. Then, again the longitudinal distances will be reduced, until the minimal space demand, hence the highest density and no movement, appears. Based on the concept presented in Figure 6.2, the headway is calculated using different formulas:

$$if: \quad D < \frac{2}{((d_B + d_i) + (t_r + t_d) \cdot v_d)^2} \qquad h = \sqrt{\frac{2}{D}} \tag{6.1}$$

$$elseif: \quad D < \frac{1}{((d_B + d_i) + (t_r + t_d) \cdot v_d) \cdot w_l} \qquad h = (d_B + d_i) + (t_r + t_d) \cdot v_d \tag{6.2}$$

$$else: \quad D \geq \frac{1}{((d_B + d_i) + (t_r + t_d) \cdot v_d) \cdot w_l} \qquad h = \frac{1}{D \cdot w_l} \tag{6.3}$$

Where:

D	Pedestrian density [P/m²]
d_B	Body depth [m]
d_I	Intimate distance [m]
h	Headway [m]
t_r	Reaction time [s]
t_d	Deceleration time [s]
v_d	Desired walking speed [m/s]
w_l	Lane width [m]

Using the assumed spacing behaviour in Figure 6.2, it can be seen that a reduction in walking speed is only observed, when the lateral distance between the lanes reaches its minimum value, which is estimated to be represented by the body width plus the body sway. A simple assumption is that the lane width can be calculated using Equation 6.3 for the whole density range, as the difference between this and the previous model is solely the calculation of the headway at low densities, which are not relevant for the determination of the fundamental diagram. For the lane-based models the lane width is therefore assumed to equal the average body and sway width.

6.2.4 *Model A: basic lane model*

6.2.4.1 *Uniform pedestrians*

The simplest form, where a fundamental diagram can be calculated, is a single lane of pedestrians showing the same properties. For this model, it is assumed that constant conditions exist. Hence, delays in reaction and other factors which might produce variations at stable conditions are lacking. Also, no speed differences will occur at constant densities. The resulting fundamental diagram solely depends on the speed, a pedestrian keeps at a certain distance to the pedestrian in front, and the width of each lane.

The speed-distance relationship can be further divided into speed independent components and speed dependent ones. Speed independent components and thus constant are the body depth and the intimate distance, which is considered to be also respected while standing at the closest comfortable distance. The reaction distance and the deceleration distance are speed-dependent. The lane width can be calculated using the body width and the gait cycle sway.

At low densities, the desired walking speed is determining the chosen walking speed, at a certain density, the walking speed can be set to zero, as the limited space does not allow further movement. In between, the walking speed depends on the pedestrian density. For the single-file movement, for each speed, a headway needed can be calculated. This headway consists of constant parts, the body depth d_B and the intimate distance d_i, and of speed dependent parts, namely the reaction and deceleration distance (Figure 6.3).

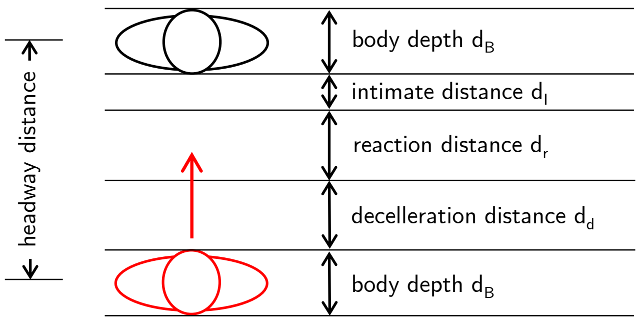

FIGURE 6.3: Headway distance in single-file movement.

The pedestrian density can then be obtained using the calculated headway and the lane width. The lane width w_l itself can be calculated using the body width w_B and the gait cycle sway w_s:

$$w_l = w_B + w_s \tag{6.4}$$

As described in Chapter 6.2.3, the headway will be calculated using Equation 6.4. When summarising the influences, the following equation can be derived, describing the density dependent walking speed:

$$v = v_d \qquad for:\ D > \frac{1}{((d_B + d_i) + (t_r + t_d) \cdot v_d) \cdot w_l} \tag{6.5}$$

$$v = \frac{h - (d_B + d_i)}{(t_r + t_d)} \qquad for:\ D > \frac{1}{((d_B + d_i) \cdot w_l} \tag{6.6}$$

Where:

D	Pedestrian density [P/m²]
d_B	Body depth [m]
d_i	Intimate distance [m]
h	Headway[m]
t_r	Reaction time [s]
t_d	Deceleration time [s]
v	Walking speed [m/s]
v_d	Desired walking speed [m/s]
w_l	Lane width [m]

The range of the fundamental diagrams calculated using the presented formula and the range of variables can be seen in Figure 6.4. The fundamental diagram for walkways presented by Weidmann (1993) is well within this range. Still, as the model assumes uniform pedestrian characteristics, it is expected that a general unidirectional fundamental diagram shows lower walking speeds for the same densities, as pedestrians have to adapt themselves to the pedestrian in front.

6.2.4.2 *Lane movement with single property variation*

When walking in line, pedestrians cannot overtake each other. Thus, pedestrians showing a higher desired walking speed have to slow down and adapt to the pedestrian in front, resulting in a walking speed corresponding to the slowest pedestrian in front. In addition, the pedestrian characteristics, such as body depth or reaction time might vary between pedestrians. This results in different headways required to keep a certain speed. As the speed shall be the same for all pedestrians, different headways will be established, depending on the pedestrian characteristics.

In this model extension, each property is varied between the maximum and minimum values obtained from literature and presented in Table 6.2. This allows to discuss the individual effects on the fundamental diagram.

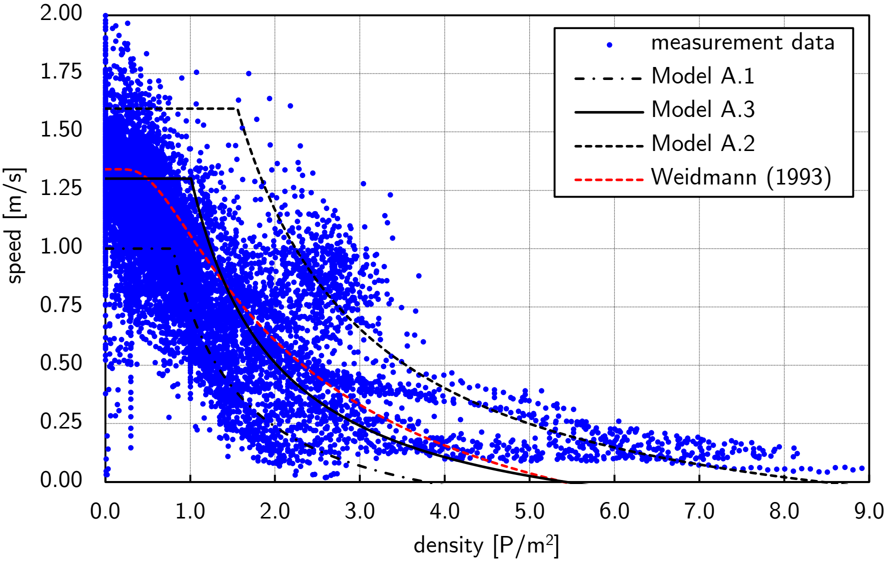

FIGURE 6.4: Model A.1-3: range of calculated fundamental diagrams compared with the fundamental diagram from Weidmann (1993) and the speed-density data from Bosina and Weidmann (2017c).

When the model is extended to allow a distribution in the body depth and/or the intimate distance, it can be seen that only the average values influence the fundamental diagram, the distribution of these values has no influence. In the current model, for a given density, the walking speed is equal for all pedestrians, as overtaking is impossible and no fluctuations are considered. Hence it is assumed that the headway for each pedestrian is optimised, so that all pedestrians have the minimum headway for the highest speed possible. Therefore, people showing larger body depth or intimate distance will have higher headways than other pedestrians, resulting in the same speed for everyone. In the fundamental diagram model, the body depth and intimate distance can thus be substituted by their average values to calculate the speed for a given density.

As overtaking is impossible in the lane movement situation considered, the slowest walking speed determines the walking speed of all pedestrians in steady state conditions. Thus, also the slowest desired walking speed has to be considered when determining the fundamental diagram curve.

The width of each lane is determined using the body width and the sway width. In a first approach it can be expected that here the average value is determining the lane width.

Similar to the body depth and the intimate distance, also for the reaction distance and the deceleration distance, only their average values are relevant.

It can be concluded that using these simple models, no variations are visible in the fundamental diagram. Hence, the fundamental diagram does neither show any stochastic variations nor changes with differences in the variation of the input parameters. Still, experiments described in literature indicate that also the variation has an influence on the resulting fundamental diagram (Cao et al., 2016b; Zhang et al., 2016).

6.2.5 *Model B: introducing step duration*

6.2.5.1 *Introduction*

An additional aspect relevant for the pedestrian flow is the time delay. The reaction of pedestrians to visual perceptions is not immediately but shows a certain time delay. In the previous models, this was modelled assuming a reaction time corresponding to a certain distance kept to the person in front. In addition to this, also the acceleration and deceleration starts with a certain delay. To also include this in the model, Model B separates the action point, where the change in walking speed occurs, and the decision point, where the decision for the next walking speed is made (Figure 6.5).

Figure 6.5: Model B: modelled point of decision and action for a single step.

Based on the literature findings in Chapter 5.2.3 and Chapter 5.2.4 the influence of the reaction delay will be refined in the next model step. For this step, the model cannot further be exclusively based on deterministic formulas. Therefore, a model framework is established in python, simulating individual pedestrians. For each density considered, a simulation is done until quasi-steady state conditions are reached, which are represented in the fundamental diagram. This approach also allows to study the distribution of walking speeds present at a certain global density.

6.2.5.2 *Step length delay*

The simplest possibility to introduce the reaction delay is to assume a constant delay for all pedestrians. In a first step, this is done by using the distance between two pedestrians from the previous time step to calculate the current speed instead of assuming an instant reaction to the distance as it was done in the previous models. From literature, it can be concluded that in general, an acceleration or deceleration movement is always initiated in the same phase of the walking cycle (see Chapter 5.2.3 and Chapter 5.2.4). Thus, the walking speed can mainly be adapted once for each step. The update cycle of the model shall therefore correspond to the step duration.

Combining the assumption of a single speed update each step and a reaction delay, the situations some time (the reaction delay) before the next step is considered to determine the next speed. As the update of the walking speed is done in parallel for all pedestrians in this model, the situations one walking step ahead equals the situation at the decision time, as long as the reaction delay is equal or smaller than one step.

As additional boundary condition it is assumed that the pedestrians are not compressible, hence their minimal distance corresponds to the body depth. Nevertheless, due to the reaction delay, the intimate distance can be violated in this model.

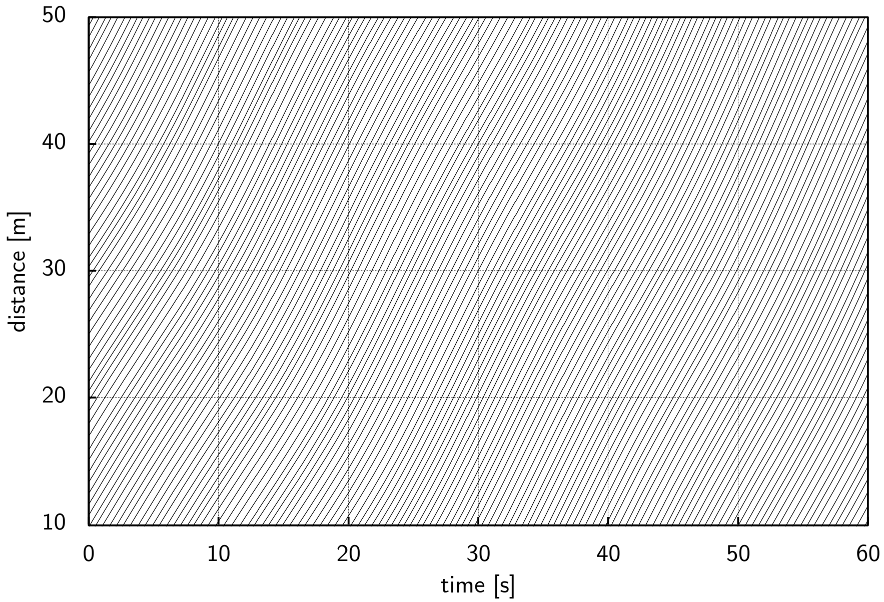

FIGURE 6.6: Model B.1: space-time diagram for a density of 2.0 P/m² and a simulated time interval of 0.45 s.

From literature, an average step frequency of 1.75 to 2.16 Hz can be found at free flow walking speed (Kramers-de Quervain et al., 2008). This corresponds to a duration of 0.46 – 0.57 s0.46 to 0.57 s between two consecutive step initiations. Calculating the fundamental diagram based on this model and an update interval corresponding to one step reveals two distinct situations. For intervals shorter than 0.47 s, a homogeneous flow can be observed (Figure 6.6). For longer time intervals, stop-and-go waves are produced (Figure 6.7). In single-file movement experiments, stop-and-go waves were also observed, but only at linear densities of more than about 1.7 P/m (Portz and Seyfried, 2011; Ziemer et al., 2016). Although this behaviour is not expected at this global density, the simulation results indicate that the reaction delay influence the resulting flow and thus the fundamental diagram.

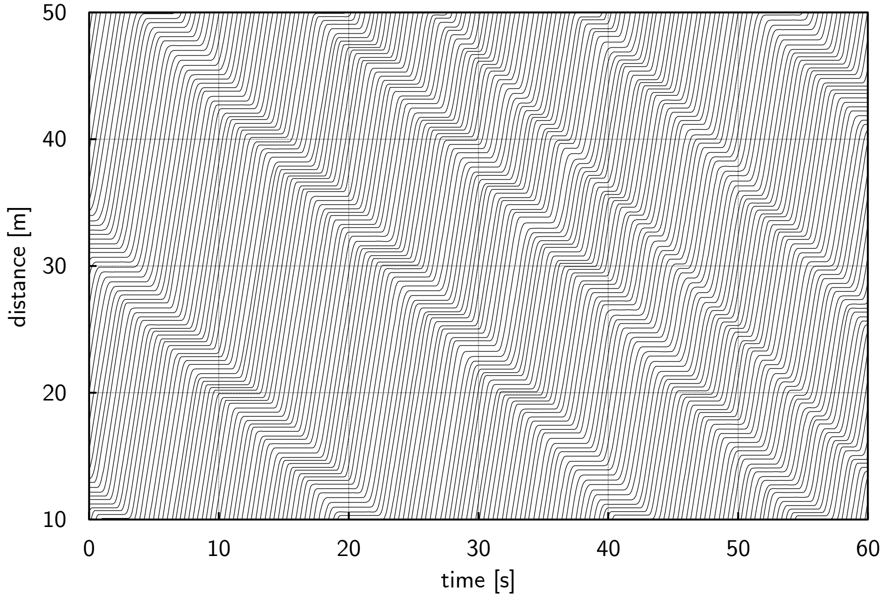

FIGURE 6.7: Model B.2: space-time diagram for a density of 2.0 P/m²and a simulated time interval of 0.50 s.

For short intervals, the obtained fundamental diagrams are the same as in the first model (Figure 6.8). The speed distribution shown does show some variations, which is assumed to be due to the fact that the pedestrians in the model do have a reaction delay which will lead to a variation in the instantaneous speeds. The average individual speeds are otherwise close to the global average speed.

For the time interval of 0.50 s, a slight change in the fundamental diagram is visible (Figure 6.9). The mean speed at densities between 1.0 and 1.5 P/m² is slightly lower, whereas at higher densities, the speed is higher. Also, a slightly higher maximum density was found.

Whereas the distribution of average individual speeds is similar, the instantaneous speed shows a considerably stronger distribution. Starting with a density of about 1.0 P/m², the instantaneous speed values vary between standing pedestrians and pedestrians walking at the free flow speed which is linked to the stop-and-go waves visible in the space-time diagram shown in Figure 6.7.

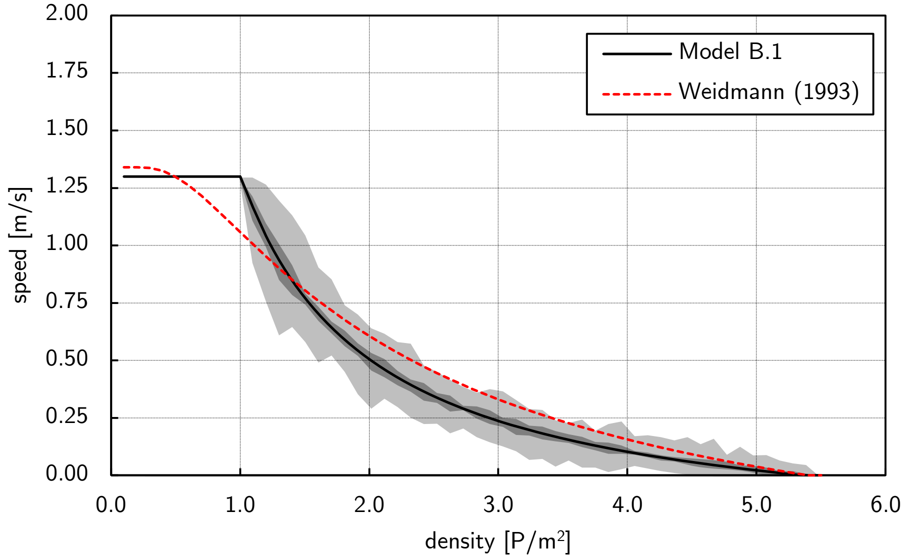

FIGURE 6.8: Model B.1: fundamental diagram for a simulated time interval of 0.45 s.

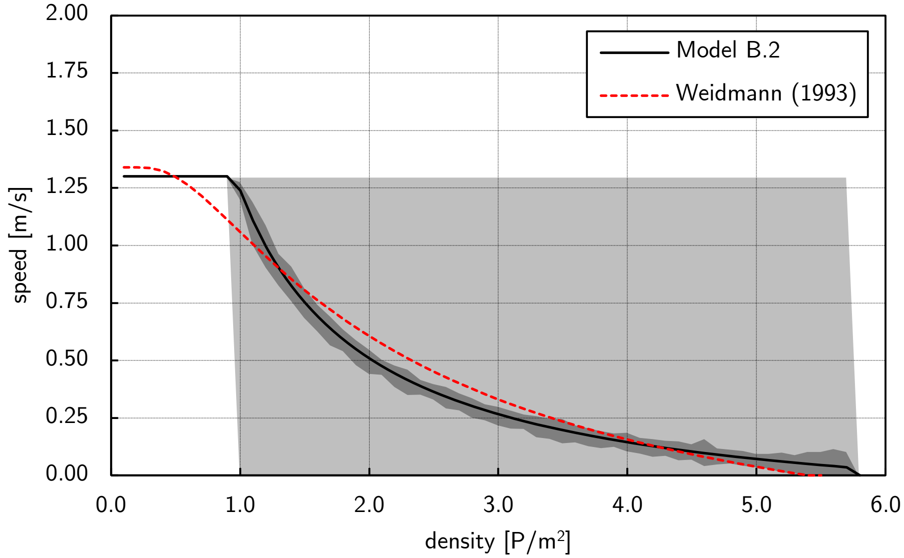

FIGURE 6.9: Model B.2: fundamental diagram for a simulated time interval of 0.50 s.

6.2.6 *Model C: individual step length*

6.2.6.1 *Introduction*

At higher walking speeds the step frequency increases, hence the walking cycle length decreases. Therefore, the constant time interval between speed adaptions as present in the previous model can be adapted to be dependent on the walking speed. Using the formula from Cavagna and Margaria (1966) (Chapter 2.2.1.4), the step duration t_s can be calculated using the walking speed v by:

$$t_s = \frac{0.362}{v} + 0.257 \tag{6.7}$$

To include the fact that at low walking speeds only few data exists and speed changes are also possible within a gait cycle, a maximum step duration is set at 1.0 s.

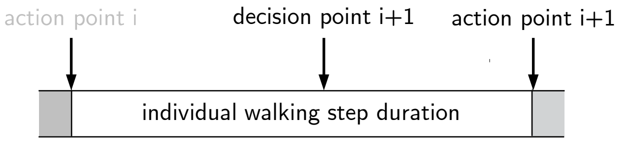

Figure 6.10: Modelled point of decision and action for a single step.

In the previous model, the decision for step $i+1$ was done at the start of step i. Now the model is adapted, so that these two points are separated in time (Figure 6.10). This reflects the fact that a certain time is needed to obtain information, process it and initiate an action as it is discussed in Chapter 5.2.3. Thus, the decision is made at a certain time interval before the action point, corresponding to the minimum time interval possible to update the movement. Until this time, a decision might be updated if new information is available. Afterwards, no update, which can be applied at the action point, is possible. Still, also within a step, changes in speed and direction are possible, but as they involve higher effort and are not expected to take place regularly, these are omitted in this model.

6.2.6.2 *Reaction delay*

As no information on the reaction time tr between decision point and action point was found in literature, a value of 200 ms and a range between 200 and 400 ms is used as a first estimation. This conforms to the minimum of 200 ms presented in Chapter 5.2.3.

The results for both model runs do not show strong differences between these two reaction times (Figure 6.11 and Figure 6.12). At walking speeds higher than 2.0 P/m², the higher reaction times lead to slightly higher walking speeds and to higher maximum density (5.3 P/m² compared to 5.9 P/m²).

However, the biggest differences can be seen in the speed distribution. Whereas stop-and-go behaviour is only visible for densities higher than 2.0 P/m² in Model C.1, it can be already seen at densities slightly higher than 1.0 P/m² in Model C.2, when keeping the free flow speed is not possible any more. As discussed previously, this does not correspond to the expected pedestrian behaviour. Still, the fundamental diagram curve is not considered to be influenced strongly by this model behaviour. Therefore, no changes were made to the model parameters to determine, if this happens for all parameter combinations. As this is an intermediate model stage, the occurrence of stop-and-go waves will be discussed in a later model stage, if they are then still visible.

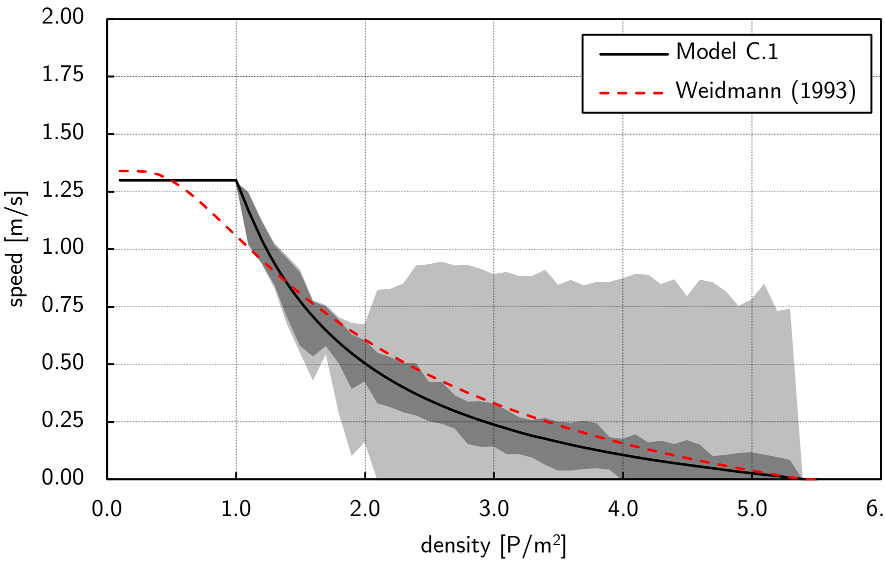

FIGURE 6.11: Model C.1: fundamental diagram for a reaction time $t_r = 0.2$ s; Step duration calculated from Cavagna and Margaria (1966).

6.2.6.3 *Step duration*

For the calculation of the step duration, various formulas exist in literature. For comparison, and to study its effect, a different formula is used as well (Jelić et al., 2012b):

$$t_s = \frac{0.065}{v} + 0.720 \tag{6.8}$$

When comparing the fundamental diagram curves in Figure 6.12 and Figure 6.13, which have the same input data except the step length formula,

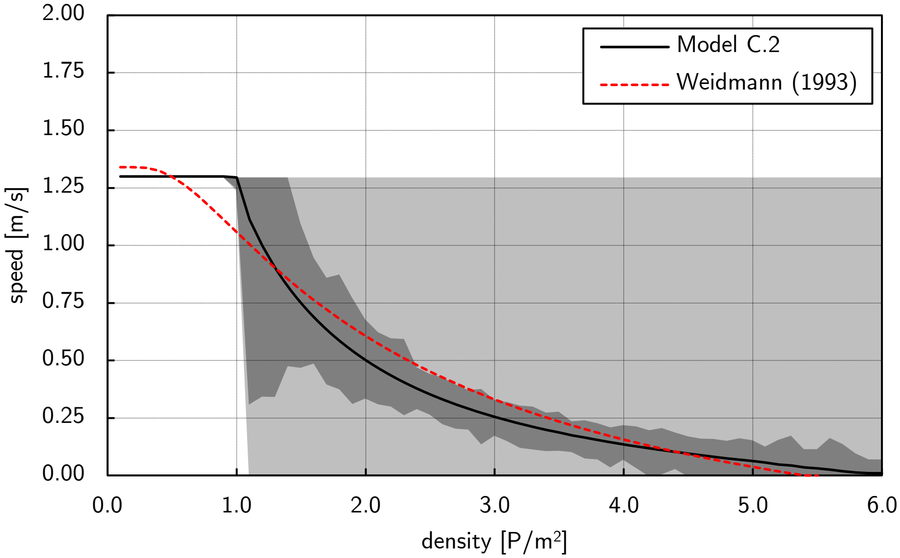

FIGURE 6.12: Model C.2: fundamental diagram for a reaction time $t_r = 0.2 - 0.4\,\mathrm{s}$; Step duration calculated from Cavagna and Margaria (1966).

only small differences are visible. Also, the range of instantaneous walking speeds is similar, only the average individual walking speed differ, but they are in a similar range.

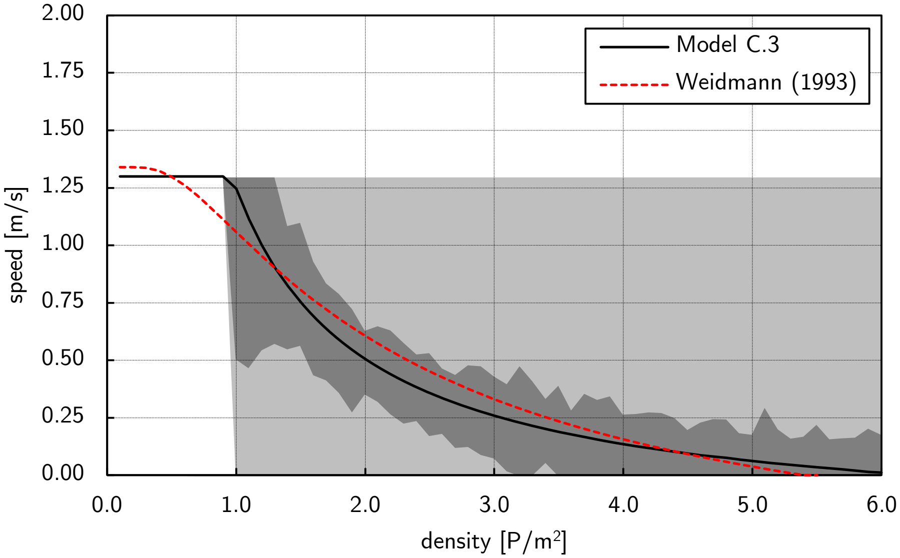

FIGURE 6.13: Model C.3: fundamental diagram for a reaction time $t_r = 0.2 - 0.4$ s; Step duration calculated from Jelić et al. (2012b).

6.2.6.4 *Acceleration limitation*

Up until now, the model allows all speed changes to happen within one step, as no limit to the possible acceleration is set in the model. However, in reality maximum values exist which can be achieved due to physical constraints. But also lower values can be found in literature which are based on comfort considerations of the pedestrians (see Chapter 5.2.4).

The previous model showed an unexpected stop-and-go behaviour, which might occur due to strong acceleration and deceleration movements. Therefore, a maximum acceleration value of 0.6 m/s² is set based on the literature study in Chapter 5.2.4. This value is relative low, but allows to see if the limitation of the acceleration will influence the model results. Even when introducing the acceleration limitation, stop-and-go waves dominate the pedestrian flow in the model (Figure 6.14). The maximum acceleration was further lowered to 0.3 m/s², still similar results were obtained (Figure 6.15). Compared to the previous model (Model C.4), the highest density, at which an average free flow speed occurs, is lower but at densities higher than about 2.4 P/m², Model C.5 shows again higher walking speeds. Nevertheless, the fundamental diagrams obtained are well within the range of expected values.

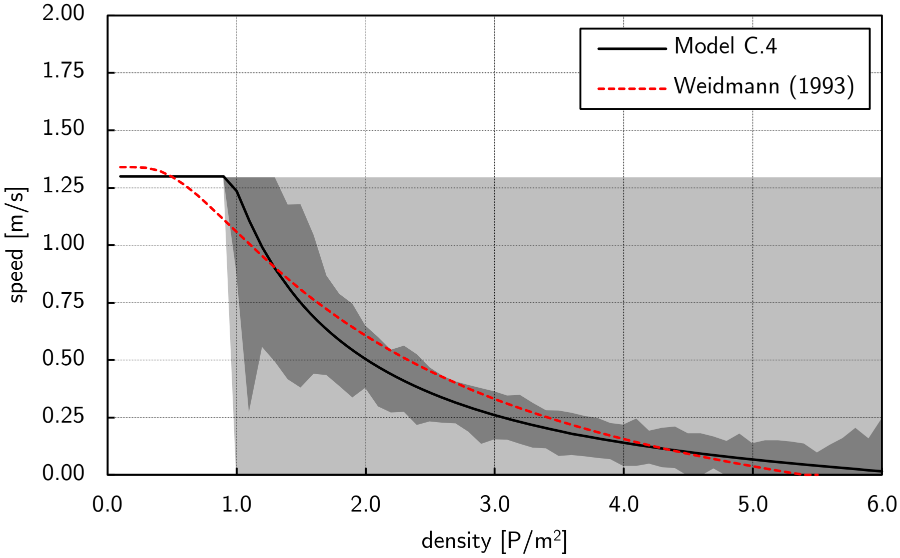

Figure 6.14: Model C.4: fundamental diagram for a maximum acceleration of 0.6 m/s^2.

6.2.6.5 *Random noise*

Another model addition for the fundamental diagram based on lane movement is the introduction of a random noise. The model does not include all aspects likely to influence the pedestrian walking characteristics. Individual pedestrians also do not react the same even in the same conditions. To simply include these influences, a random noise is added to the model. The value for each speed update is calculated and a random noise, showing a standard distribution of 10 % of the individual speed value, is added. This allows to study the effect of random variations on the fundamental diagram (Figure 6.16). In general, the average speed-density curve, as well as the speed distribution for a single time step, is similar to the previous model. Only at the free flow speed a speed distribution is visible, which did not occur previously.

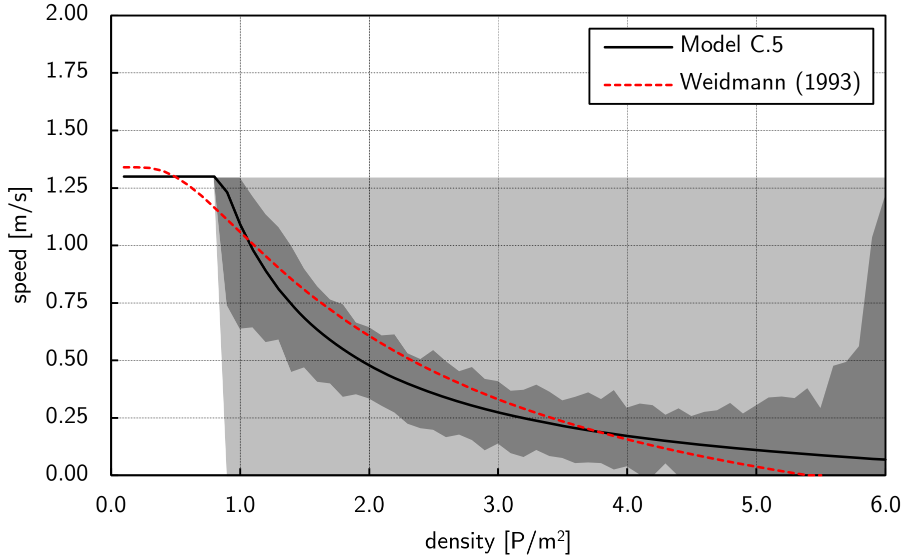

FIGURE 6.15: Model C.5: fundamental diagram for a maximum acceleration of 0.3 m/s².

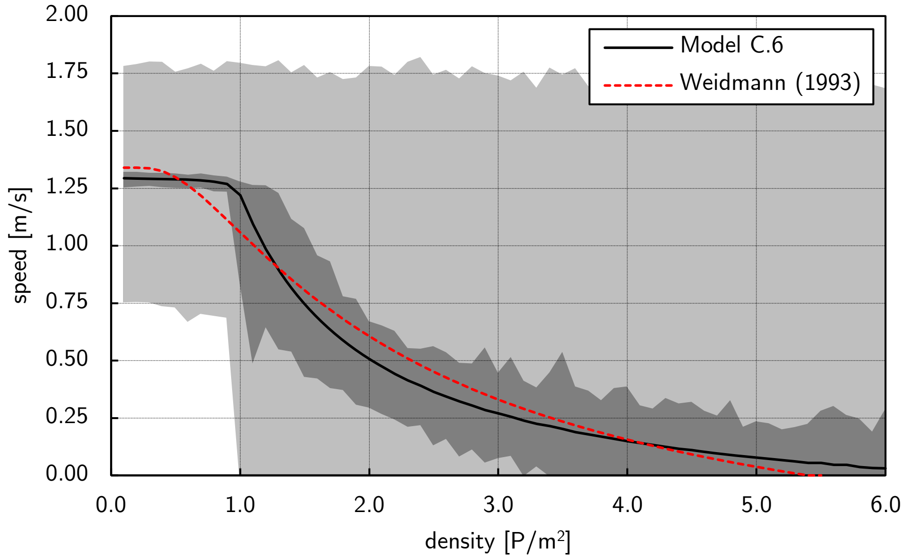

FIGURE 6.16: Model C.6: fundamental diagram with a random noise of 10 %.

6.2.7 *Model D: movement prediction*

6.2.7.1 *Introduction*

As the human perception and the corresponding reaction takes some time, the movement decision is always based on outdated information. This is reflected in the previous model by introducing a reaction time, which separates the decision point from the action point. However, pedestrians, especially at steady state conditions, more or less move in a predictable manner. Thus, based on the information on its surrounding, a pedestrian can predict the movement of the other pedestrians and adapt its walking behaviour accordingly. To also reflect this in the model, Model D introduces a movement prediction (Figure 6.17). At the decision point, the current speed is used to predict the position of the other pedestrian at the next action point, hence the beginning of the next step. This information is then used to determine the speed for the next step.

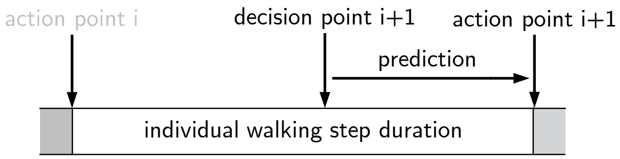

Figure 6.17: Model D: modelled point of decision and action for a single step.

6.2.7.2 *Model results*

In Figure 6.18, the fundamental diagram for a uniform pedestrian distribution generated using Model D.2 can be seen. Compared to the previous model with the same parameter (Model C.6, Figure 6.16), lower average walking speeds at higher densities are visible. The curve of this model is again similar to the first models (Model A.2, Figure 6.4). The only visible difference is the small speed drop at densities lower than 1.0 P/m², which in Model A was always at the free flow speed until the curve changed abruptly.

In the speed distribution shown in the graph stopping pedestrians only appear at densities higher than 3.0 P/m². Thus, stop-and-go waves are not present any more at low densities, as they were in the previous models. The distribution of average pedestrian speeds is only in a small range around the mean value. The instantaneous speed distribution gets narrower for higher walking speeds.

In Figure 6.19, the model simulations were done using the same model parameter as for Figure 6.18 but with different pedestrian populations. Similar to the results form Model A (Figure 6.4), the range of speed-density values is in the same range as the fundamental curves from the pedestrian populati-

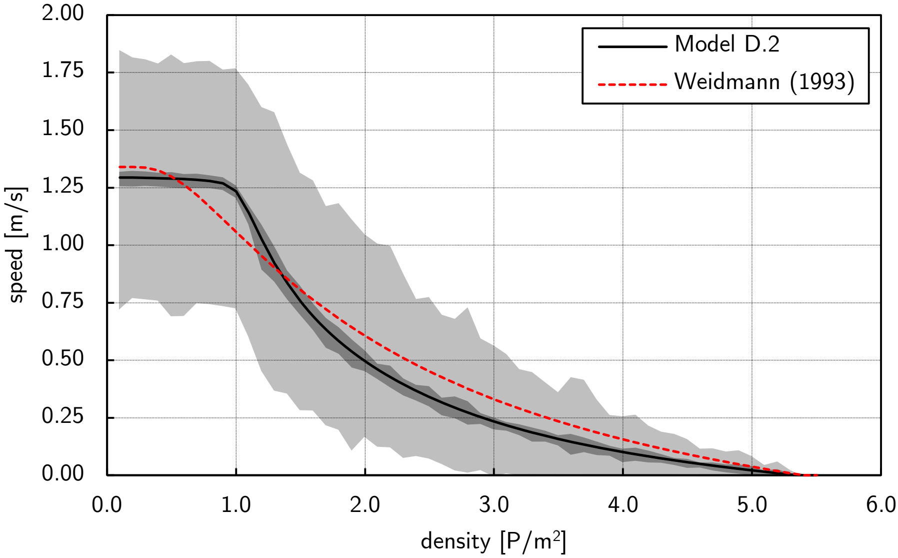

FIGURE 6.18: Model D.2: fundamental diagram for a uniform pedestrian composition.

ons using the minimum and maximum values. In comparison to the results from Model A, a visible difference only exists for the maximum distribution, where Model D.3 shows higher speed values at higher walking speeds and a higher maximum density. The reason for this can be seen in Figure 6.20, where also the speed distribution is computed. In contrast to the other simulations using Model D, stop-and-go waves are visible. Here, also the average pedestrian speeds are widely distributed.

Still, a direct comparison between the calculated fundamental diagrams and the speed-density values from literature has to be made with caution. First, the speed density values are often disaggregated values, whereas the model results are the mean from all pedestrians in steady state conditions. Second, the model is still based on a lane-movement approach.

6.2.7.3 *Free flow speed*

Up until now, the uniform distribution uses only the average free flow walking speed, as otherwise the fundamental diagrams calculated would be only determined by the slowest person. To visualise the effect of the distribution of the free flow speed, Figure 6.21 compares the fundamental diagrams obtained from Model D.2 and Model D.5. Whereas in Model D.2, an average free flow walking speed is used for all pedestrians, a uniform speed distribution exists in Model D.5. As expected, these two models are only different at densities lower than 1.2 P/m², where the average walking speed is higher than 1.0 m/s in Model D.2.

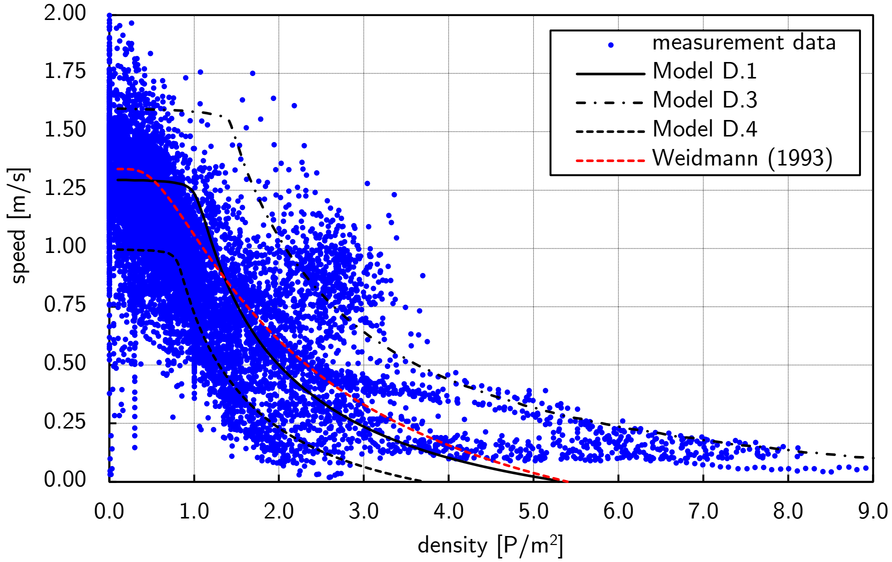

FIGURE 6.19: Model D.1, D.3, D.4: fundamental diagrams with different pedestrian compositions (average, maximum, minimum). As a reference fundamental diagram from Weidmann (1993) and the speed-density data from literature compiled in Bosina and Weidmann (2017c) are shown.

6.2.8 *Model comparison*

To compare all lane-based fundamental diagram models presented, Figure 6.22 shows a comparison of the results from the different models until now. For each model, a simulation was selected having the same parameter values. The comparison shows that the model results are quite similar for all models, hence the model extensions made did not change the results strongly. Nevertheless, the results from last model (Model D.2) do show certain improvements. The transition from the free flow phase to the restricted phase at about 1.0 P/m² is not as abrupt as in the first models. In addition, for most parameter values, stop-and-go waves are only visible at high walking speeds, which corresponds to the microscopic behaviour also visible in real-life situations.

To extend the linear model to a speed-density model and to allow the calculation of two dimensional fundamental diagrams, a lane width was calculated. By running the model only for single lanes, the speed-density relation for single-file movement can be calculated.

The first comparison with literature data and the fundamental diagram from Weidmann (1993) shows that the range of fundamental diagrams obtained from the model correspond to the expected range. To validate this model,

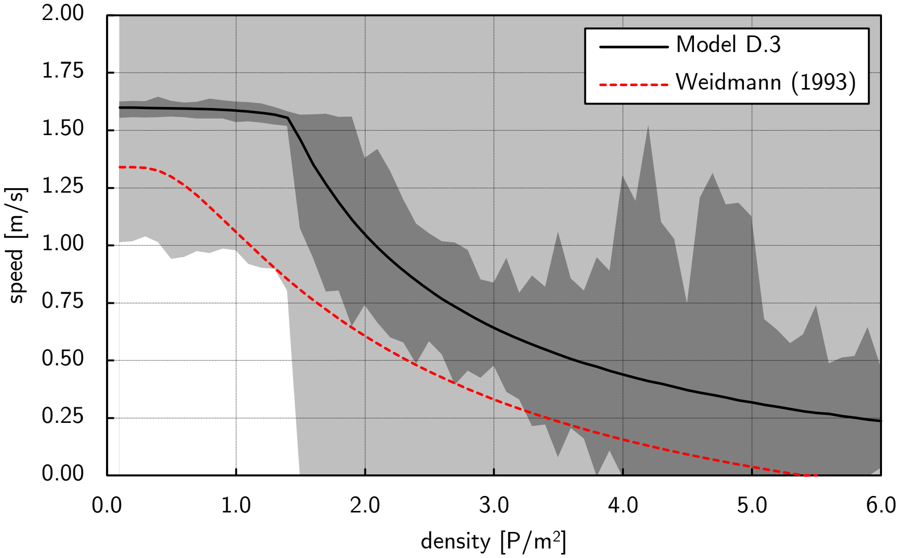

FIGURE 6.20: Model D.3: fundamental diagram for a maximum pedestrian composition.

it will be compared to data from lane movement experiments (see Chapter 8). In addition, the model results can be compared to unidirectional fundamental diagrams to see, if this model is already able to reproduce the difference observed also in this case.

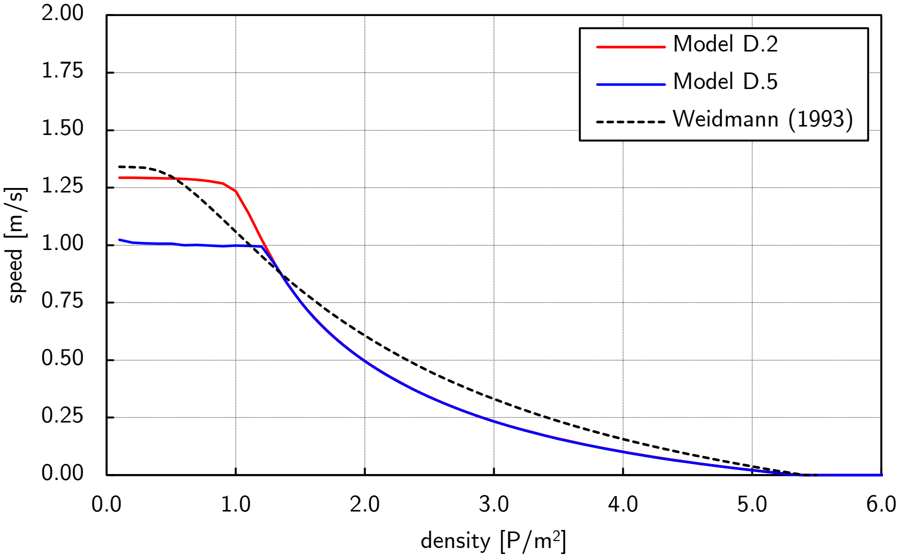

Figure 6.21: Model D.2 and D.5: fundamental diagrams for a uniform pedestrian composition with an average (Model D.2) and a uniform (Model D.5) desired walking speed distribution.

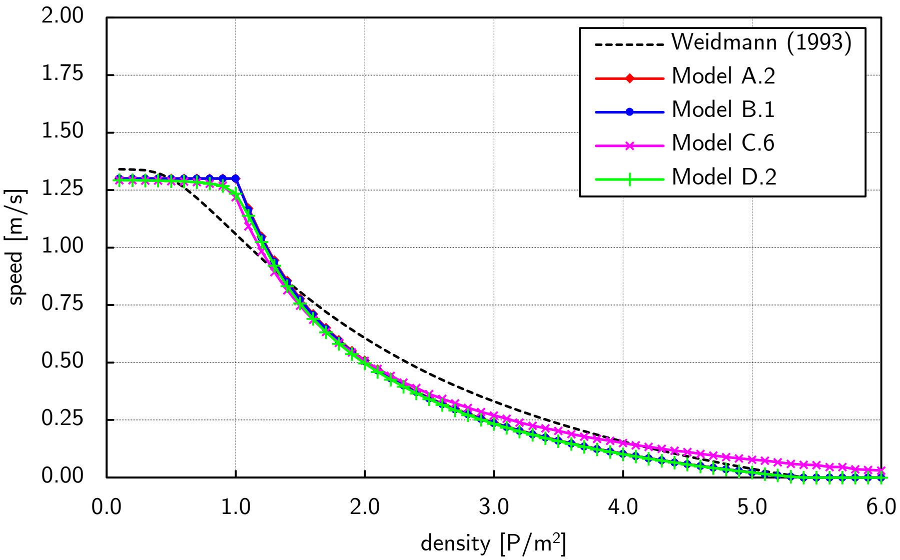

Figure 6.22: Model A.2, B.1, C.6, D.2: comparison of the fundamental diagram curves for the different lane-based models and the fundamental diagram proposed by Weidmann (1993).

6.3 LANE-CHANGE MODEL

6.3.1 *Model description*

Although the results of the lane-based models are within the range of expected values, they are not capable of adequately describe the influence of the free flow speed distribution, as overtaking is not possible. To tackle this problem, a model extension is made, which allows the pedestrians to change from one lane to a neighbouring one. The pedestrians are still walking in lanes, but, if enough space is available, swapping lanes is possible. This allows to walk past slower pedestrians. As no side preference as well as walking on a specific side is implemented, the pedestrians will stay in the new lane until a further lane change is made.

6.3.2 *Model layout*

To integrate the lane-change behaviour into the existing model, a simple lane-changing model will be established. For this, several lanes as they are modelled in Model D will be run simultaneously. At each time step, a routine will be introduced, which will first determine, if a pedestrian wants to change the lane and then move the pedestrian from one lane to the other.

The decision, if a pedestrian in changing a lane is considered to be based on the current walking speed and the headway. If the current walking speed is lower than the desired walking speed and the headway is smaller than the same position in a neighbouring lane, a lane change is desired. In addition, a backward free space is set for the neighbouring lane to avoid conflicts with other pedestrians. Another threshold value is set for the maximum headway to the pedestrian in front. If the headway is higher than this value, no lane change is made, as enough space is available to increase the speed.

The lanes are again aligned in a circle; hence all lanes have two equal neighbours. If both neighbouring lanes fulfil the requirements for a lane change, the one providing a longer headway is used for changing to.

A pedestrian can change the lane at the beginning of each step. As the model is kept simple, the lane change decision is based on the current distances at this time and is done immediately. In reality it would be expected that also the decision on the lane change is done beforehand and that the lane-change procedure needs some time in which both lanes are blocked to some extent. On the other hand, the walking speed is not updated when changing lanes, hence the walking speed calculated from the lower previous headway is used.

The initial positioning of the pedestrians and the initial speed is set randomly, hence also bigger gaps can occur. To avoid lane changes based on the initial conditions, lane-changing is only allowed after a defined number of time steps. Otherwise it might be possible, that pedestrians move to another lane due to the initial conditions and then cannot move away any more when the initial gaps are closed.

To study the effect of different parameter settings on the simulation results, several simulation runs were made (Table 6.6). First, different pedestrian distributions were simulated. Then, the minimal distance to pedestrians in the back was varied, to see the influences on the results.

Table 6.6: Simulation parameter values used for the lane-change models in this chapter.

MODEL	P	T_{sim} [s]	DISTRIBUTION	d_{back} [m]	S_{in}	$h_{r,max}$ [m]	FIGURE
E.1	100	1 000	Average	3.0	100	4	Figure 6.37
E.2	100	1 000	Uniform	3.0	100	4	Figure 6.23 Figure 6.25
E.3	100	1 000	Max	3.0	100	4	Figure 6.37
E.4	100	1 000	Min	3.0	100	4	Figure 6.37
E.5	100	1 000	Uniform	3.0	100	4	Figure 6.24 Figure 6.25
E.6	100	1 000	Uniform	2.0	100	4	Figure 6.25
E.7	100	1 000	Uniform	1.0	100	4	Figure 6.25
E.8	100	1 000	Uniform	0.5	100	4	Figure 6.25

6.3.3 *Model E: results*

For simulations without variations in the free flow speed, the results are similar to the ones obtained using Model D. In Figure 6.23 the resulting fundamental diagram and speed distribution from Model E.2 can be seen. In comparison to the results from Model D.2 (Figure 6.18), where the same parameter values were used, only a slight increase in the speed variations is visible. This also corresponds to the expectations. At low densities, where free flow speed is simulated, no need to overtake is present, as everyone has the same free flow walking speed. At high walking speeds, no big enough gaps exist which will make a lane-change possible in the model. In addition, the distribution of the other parameters seems not to be big enough to trigger lane-change behaviour also at medium densities.

In the previous model, a distribution of free flow speeds lead to an average walking speed of the minimum free flow speed at low densities. As can be seen in Figure 6.24, the possibility to change lanes allows to walk past slower pedestrians, which leads to higher walking speeds in this density region. Still, the walking speed is not as high as the walking speed for Model E.2,

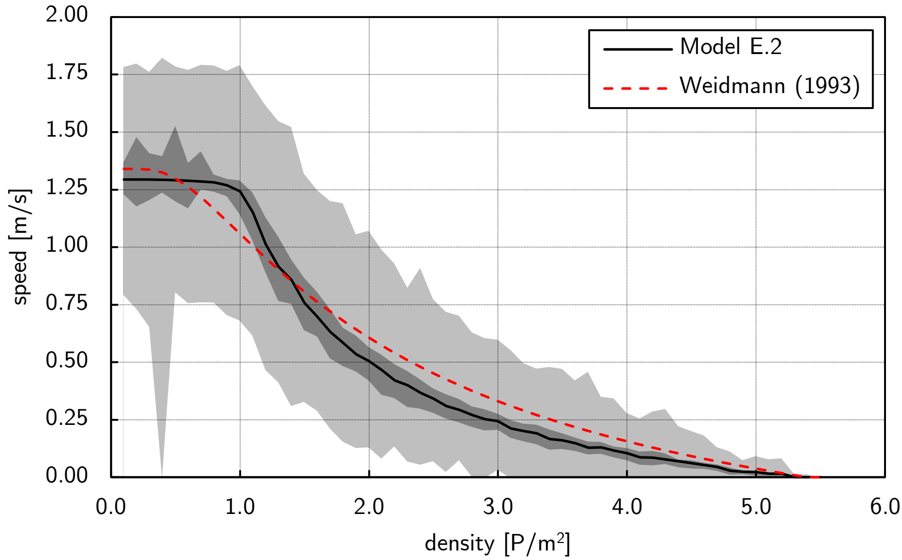

FIGURE 6.23: Model E.2: fundamental diagram for a uniform pedestrian composition without variations in the desired walking speed.

which has an average free flow walking speed for all pedestrians. For higher densities, the two fundamental diagram curves do not show any differences. The free flow speed distribution can also be seen in the walking speed distribution, where a higher range can be seen for a distributed free flow speed.

The possibility to overtake is strongly determined by the parameter which determines the minimal backwards distance to be allowed to change to another lane. The bigger the value is, the more space is needed for the lane-change, hence the less overtaking occurs. Otherwise, if the minimal backwards distance is reduced, it becomes more likely for pedestrians from the back to be forced to slow down as they will otherwise collide with the pedestrian who changed from one lane to another. The resulting fundamental diagrams from simulations with different parameter values are visible in Figure 6.25. A slight increase in the mean walking speed for shorter minimal backward distances can be seen, but the differences are small.

Due to the lane change behaviour, the pedestrian characteristics and potentially also the number of pedestrians in not equal for all lanes. Therefore, small differences in the walking speed can be seen (Figure 6.26). This corresponds to the expected behaviour, as also in reality, varying mean walking speed might be observed in similar settings. It also shows, that the variation is higher at lower densities, resulting in slightly different steady state conditions for the same parameter values. To obtain more precise results, more lanes or several model runs should be done to obtain an average value. Still, due

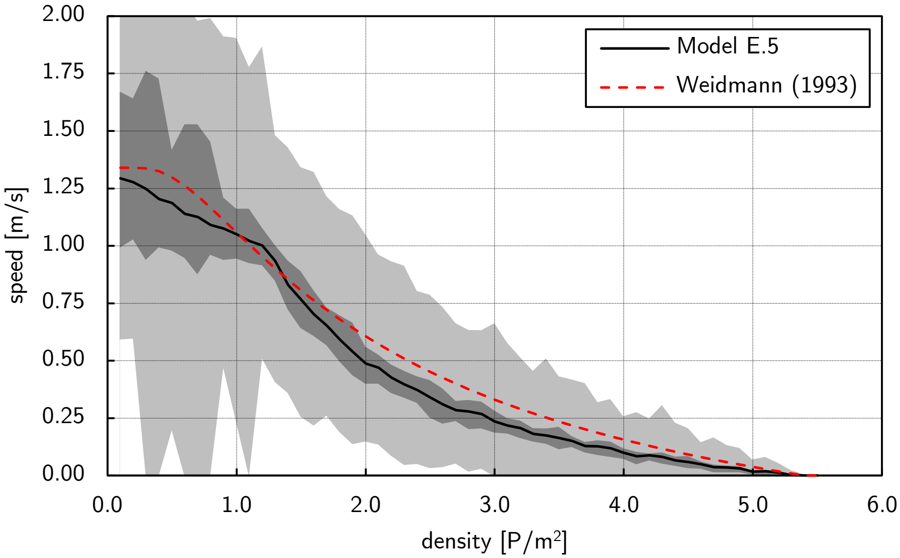

Figure 6.24: Model E.5: fundamental diagrams for a uniform pedestrian composition with a uniform desired walking speed distribution.

to longer simulation times and the only minor influence on the results, the simulation parameters are not changed for further simulations.

The first model results for Model E show that the model is able to include the overtaking procedure in the fundamental diagram calculations by establishing a lane change procedure. The model results suggest that distributed free flow speed values lead to slower walking speeds compared to a single free flow speed for all pedestrians at otherwise the same parameter values.

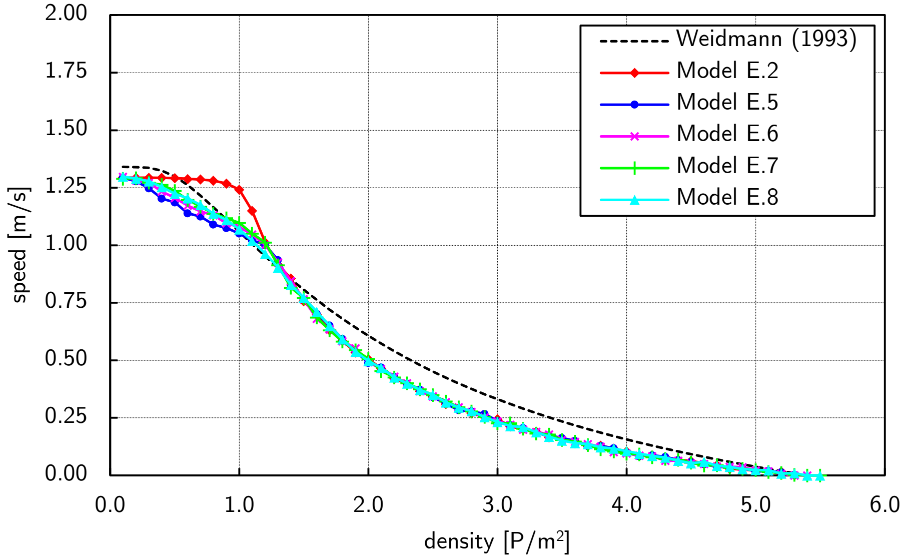

FIGURE 6.25: Model E.2 and Model E.5 to E.8: influence of a different minimum backward distance for lane change on the fundamental diagram. For comparison, Model E.2 shows the results for a single free flow speed for all pedestrians.

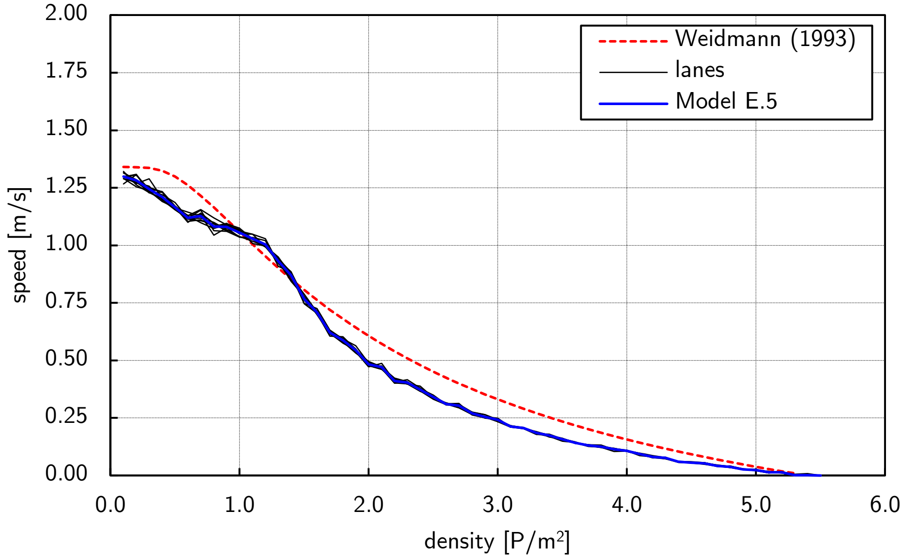

FIGURE 6.26: Model E.5: speed-density diagrams for the individual lanes simulated.

6.4 FULLY UNIDIRECTIONAL MODELS

6.4.1 *Model description*

In the previous lane-change model it was possible to overtake other pedestrians by changing lane and walking past them. Still, frontal walking was modelled by lanes and lateral movement was done by an instantaneous lane-change. In the fully unidirectional movement model, the lateral movement will also be modelled continuously, hence the lateral position can be chosen freely. On contrary to the lane-based model, overtaking and adapting the lateral distance to others is now possible. For the creation of this model, the final lane movement model derived in Chapter 6.2.7 will be used and extended to include routines for lateral movement.

As this model does not consist of lanes any more, also the frontal movement routines have to be adapted. This is done by a redefinition of the headway, which then allows to follow the same speed calculation as in the lane-based models. For the lateral movement, two principles are introduced. First, it is assumed that pedestrians keep a certain distance to others, hence increase their lateral distance when walking too close to each other. Second, people will react to pedestrians in front to be able to overtake them.

Similar model parameters are used to compare the results with the previous models. In Table 6.7, the parameters used for the simulations in this chapter are shown.

TABLE 6.7: Simulation parameter values used for the fully unidirectional models in this chapter. For parameters not shown, the default values from Table 6 are used.

MODEL	P	T_{sim} [s]	DISTRIBUTION	FIGURE
F.1	200	500	Uniform	Figure 6.33, Figure 6.34
G.1	200	500	Uniform	Figure 6.36

6.4.2 *Headway*

Similar to the lane movement model it is assumed that pedestrian adapt their speed based on the distance to the pedestrian in front. To determine, which pedestrian is considered to be the one directly in front of the pedestrian and hence is determining the available headway, an approach based on the space demand for walking is used. It is assumed that a pedestrian needs a lateral distance determined by the body width plus the sway width. The next pedestrian in front is therefore defined as the one which has the shortest headway within the defined lateral distance. In Figure 6.27, the pedestrian in front is shown for different pedestrian positions. The first situations are similar to the model for pedestrians walking in line, hence the pedestrian in front is straight ahead. Also, if a pedestrian is only partially within the lateral distance, he will be considered. If another pedestrian is entering the walking space from the side, he will become the front pedestrian, to whom the current pedestrian adapts its walking speed and the available headway is calculated.

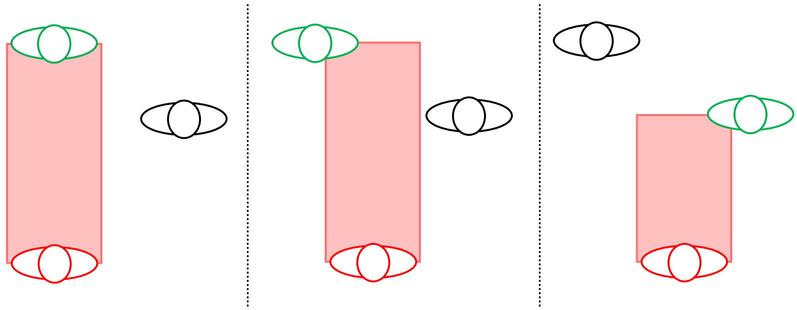

FIGURE 6.27: Determination of the pedestrian in front (green) based on the space demand for walking.

6.4.3 *Nearest neighbour and lateral movement*

It is assumed that pedestrians perform a lateral movement due to two reasons. First, to avoid collisions with pedestrians in front, lateral movement is needed to overtake others.Second, people are expected to maintain a certain distance to others when walking side by side. It is assumed that pedestrians will try to keep the lateral distances to the left and right neighbour about equal, as long as they are close. In addition, as described in Chapter 5.3.3, the visual field limits the perception mainly to pedestrians in front and it was also observed that attention is paid mainly to the closest pedestrians. Therefore, the lateral movement is calculated based on the distance to the nearest neighbours. For this, in addition to the nearest neighbour in front two other pedestrians, one on each side, are defined (Figure 6.28). The nearest side neighbour is considered here to be the closest pedestrian in lateral direction between the centre point of the pedestrian considered and its closest pedestrian in front. In the example shown, the nearest neighbour to the right is closer to the walking space of the pedestrian considered than the one to the left.

In the model approach, the lateral movement is based on the position of the nearest pedestrians. Overtaking is not modelled directly, but is enabled by lateral movement to evade the pedestrian in front. Depending on the position of the three nearest neighbours defined before, different movement strategies are applied. For the lateral and the frontal distance different threshold values are defined. These values correspond to the maximum distance to other pede-

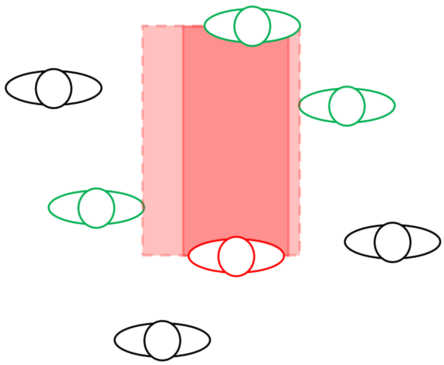

Figure 6.28: Definition of the nearest neighbours (green) used for modelling the side movement.

strians where a lateral reaction might occur. For longer interpersonal distances no reactions are assumed.

Table 6.8: Side movement depending on position of nearest neighbours (1 closer than threshold, 0 further away than threshold).

	nearest neighbour			
case	front	left	right	action
CASE 1	0	0	0	No movement
CASE 2a	0	1	0	Move to right
CASE 2b	0	0	1	Move to left
CASE 3	0	1	1	Move to middle
CASE 4	1	0	0	Move to other side
CASE 5a	1	1	0	Move to right
CASE 5b	1	0	1	Move to left
CASE 6	1	1	1	Move to middle

In Table 6.8 and Figure 6.29, the different distance cases and the resulting movements are shown. In general, the movement is assumed to be in the direction without side neighbour. No side preference was included in the model as a unidirectional flow is considered and the literature does not provide a clear picture (see Chapter 5.3.4). For a first approach the reaction of the pedestrian was independent of the walking speed of the pedestrian in front and the pedestrian considered. In a refined approach, a lateral movement in case 4 was only modelled, when the walking speed of the pedestrian in front is lower than the desired walking speed of the pedestrian, hence he might be willing to overtake in order to reach the desired speed.

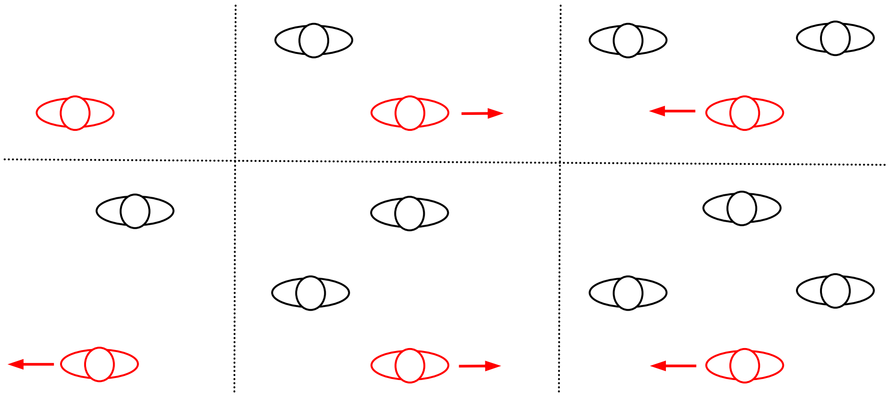

FIGURE 6.29: Side movement depending on position of nearest neighbours.

Apart from the movement direction also the desired distance has to be computed. In general, it is assumed that the desired distance corresponds to the distance necessary to reach the lateral distance threshold or that the pedestrian in front is not within the walking space and hence is not considered as next pedestrian in front any more. If there are pedestrians closer than the threshold on both sides, the pedestrian in the middle will aim at keeping the same distance to both sides. In addition to the desired lateral location, a maximum lateral speed is set, limiting the movement. Similar to the frontal movement, the lateral movement is then calculated for each step. Within one step therefore either the lateral position goal is reached or the maximum sideward movement speed is applied. The lateral movement is modelled to be constant for a single step.

To test the model applicability, a simulation run with a single pedestrian walking and another pedestrian standing in front was performed (Figure 6.30). As desired, the pedestrian walks to the side and overtakes the standing pedestrians without a visible speed reduction. Still, it was observed that when other parameter values are used, like a smaller maximum reaction headway, a reduction of the walking speed can be observed (Figure 6.31). This can be explained by the fact that if the lateral movement is not finished, the standing pedestrian is still within the assumed walking space and the frontal distance might get smaller than the free flow headway, hence a speed reduction is applied.

Another test was done for two pedestrians walking close to each other to study the effect of the lateral movement due to neighbours on the right or left side (Figure 6.32). As expected, the two pedestrians move away from each other, until their desired minimum lateral distance is reached. For this

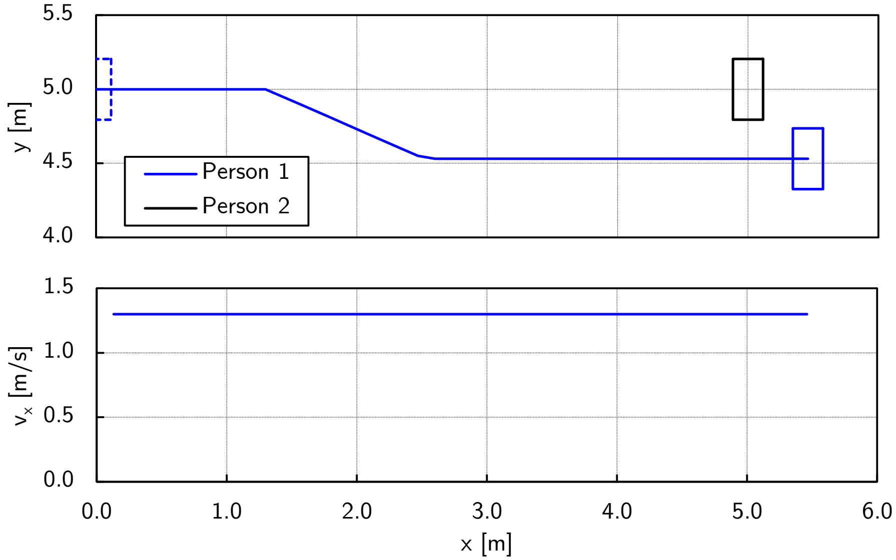

FIGURE 6.30: Person overtaking a standing pedestrian. Maximum reaction headway $h_{r,max} = 3.5\,\text{m}$.

simulation, two pedestrians having the same property values are generated and no stochastic term was used, hence they both show identical but inverse walking paths.

6.4.4 *Further model adaptions*

To study the effect of the assumptions made, further parameters were introduced into the model which are considered to possibly reflect human walking behaviour. First, the lane width which determines the lateral distance when overtaking was varied using an additional parameter. Initially the person overtaking only moves sideward until the distance corresponds to the lane width, thus the body width plus the sway width of both pedestrians. Using this parameter, also wider overtaking distances can be studies. Especially when walking side by side, also pedestrians slightly behind might influence the behaviour. Therefore, a parameter was introduced to consider also pedestrians at a defined distance behind the pedestrian as potential side neighbours. These parameters were varied to see the impact on the results. However, these changes were found to not strongly influence the preliminary model results.

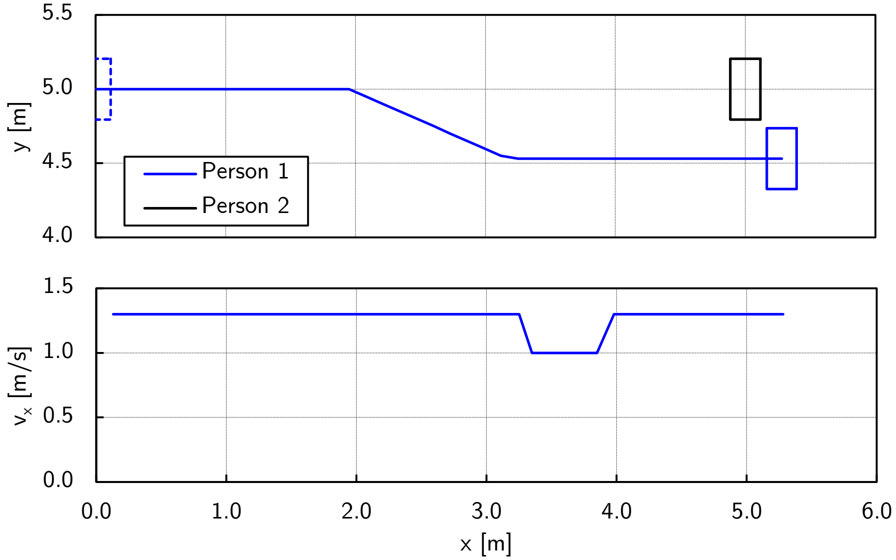

FIGURE 6.31: Person overtaking a standing pedestrian. Maximum reaction headway $h_{r,max} = 3.0\,\text{m}$.

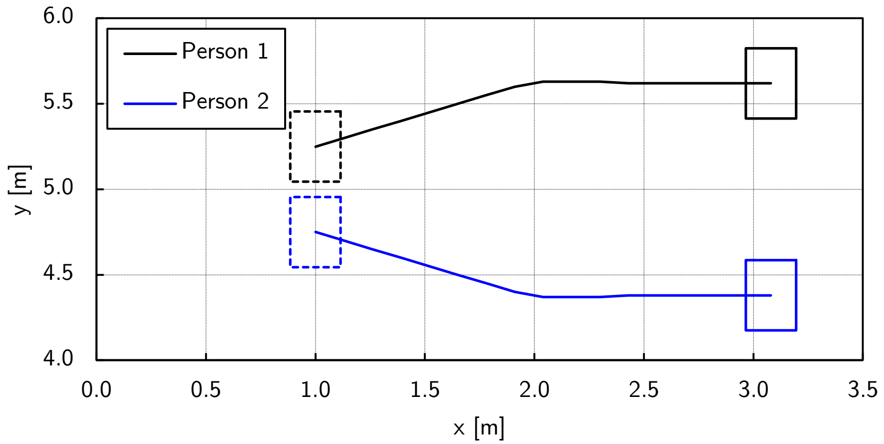

FIGURE 6.32: Two persons walking side by side. Initial lateral distance = 0.5 m, desired lateral distance = 1.0 m, maximum lateral speed = 0.5 m/s.

6.4.5 *Model F: model results*

6.4.5.1 *Fundamental diagram*

Compared to the simulation results using the previous models, the results of Model F were found to be low and did not correspond to the range of expected fundamental diagram values (Figure 6.33). At almost free flow conditions, the model results correspond to the desired speed distribution used, which was a uniform distribution between 1.0 and 1.6 m/s. But already at rather low densities the average walking speed is strongly reduced, resulting in a non-realistic speed density curve. As can be seen from the instantaneous speed percentile values, already at very low densities, standing pedestrians and stop-and-go waves are observed in the model. Variations within the range of expected parameter values also did not change the results fundamentally, hence in can be concluded that this model will not be able to generate realistic fundamentals diagrams without considerable adaptions.

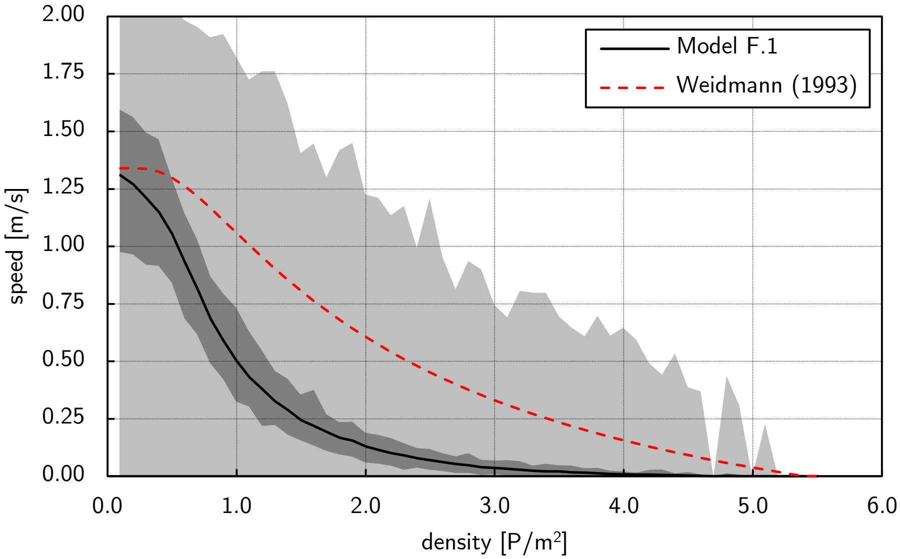

FIGURE 6.33: Model F.1: results of the unidirectional movement model.

6.4.5.2 *Neighbours*

The lateral movement in this model is determined based on the presence of neighbouring pedestrians in the vicinity. For this, different cases were introduced, which can be seen in Table 6.8. After a simulation run it can be determined, which situation predominates at each density (Figure 6.34). The results show that at very low densities mainly Case 1 is present, where no pedestrians are close enough to be considered neighbours. At low densities up to about 0.7 P/m², the share of Case 1 is reduced rapidly, whereas all other neighbour cases can be found. This might be an indication that the existing model underestimates the speed in these situations, as it might still be possible to overtake the pedestrian in front without speed reduction. At medium densities up to about 2.0 P/m², Case 4 to Case 6 have similar shares, whereas all other cases do not exist anymore. This means that all pedestrians do have someone in front whereas a lateral movement is often still possible. But as the model calculates the headway only in the global walking directions, a speed reduction is applied here. At higher densities, Case 6 becomes the predominant case, which means that neighbours are present on all three sides.

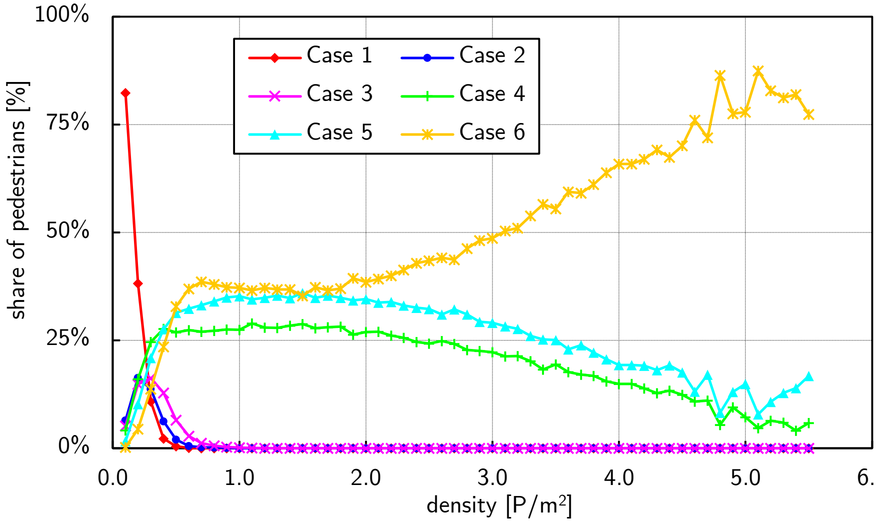

FIGURE 6.34: Model F.1: position of nearest neighbour at different densities. See Table 6.8 for a description of cases. Lateral threshold = 1.0 m, frontal threshold = 4.0 m.

The existence of pedestrians in front is even more visible in Figure 6.35, where all cases with pedestrians in front are combined. Whereas at a density of 0.1 P/m² only 10 % of the pedestrians have a pedestrian in front, this number increases to 90 % at 0.5 P/m². At a density of 1.0 P/m², all pedestrians have a neighbour in front. Otherwise, the presence of one or two pedestrians on the side is roughly constant at densities higher than 0.3 P/m². Only at densities higher than 2.0 P/m², an increase of situations with pedestrians on both sides is visible. Nevertheless, at these densities the model does show only small movements any more.

It has to be noted, as the model is neither validated nor verified, the data of the neighbouring pedestrians only provides information about the model

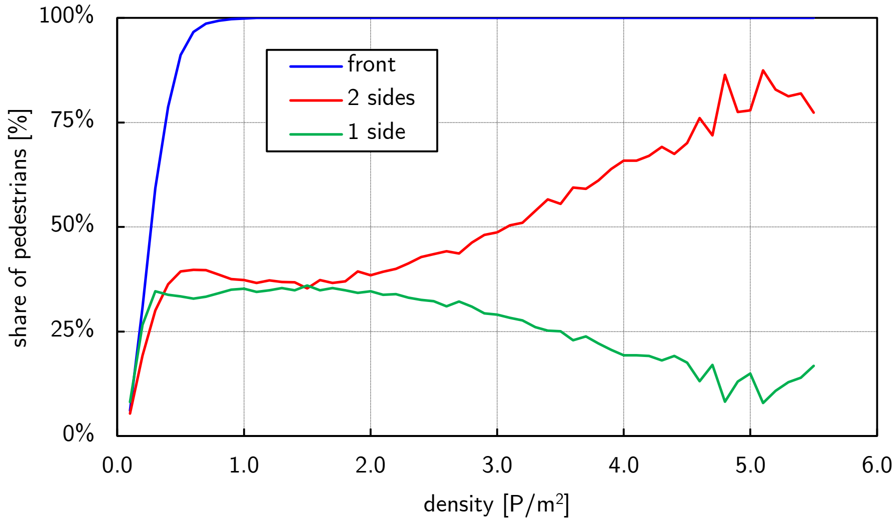

Figure 6.35: Presence of neighbouring pedestrians at different densities. Lateral threshold = 1.0 m, frontal threshold = 4.0 m.

itself. Still, it can give some indications about the real-life situation, as long as no ordering in the spatial pedestrian behaviour is visible. Obviously, the results also heavily depend on the thresholds chosen for the neighbour distance which is now done only based on some rough assumptions.

6.4.5.3 *Possible improvements*

The unidirectional model, as it is presented here was found to provide model results which do not correspond to the expected range of values. A reason for this might be that the model aims at being as simple as possible, which seems to be too simple to adequately describe unidirectional movement. Thus, some future model adaptions are proposed:

- At the moment, the pedestrians are modelled as squares, having a defined body width and body depth. In reality, the human body in a horizontal plane can better be described by an elliptic or a complex shape. This adaption will reduce the occupied space for each pedestrian and hence will likely increase the simulated walking speeds.
- The current model calculates the headway, which is then used to determine the walking speed, only in frontal direction. Thus, if space is available on one side but the headway is closer than the minimum headway for the desired speed, a speed reduction applies. In reality it can be expected that in these situations no speed reduction is visible. Using other methods to determine the headway will likely impact the results.

- In certain situations, it can be observed that pedestrians do not walk exactly behind each other, but slightly shifted, so that it is possible to see past the pedestrian in front. This behaviour can also be linked to faster walking speed. Nevertheless, this is not implemented in the model, where the headway is always calculated to the pedestrian in front, independently of the amount of overlap. Here, a model improvement to obtain a more realistic walking behaviour is indicated.

Apart from certain more complex pedestrian behaviour, which is not included in the current model, it can also be concluded that several aspects of the human movement in unidirectional flow are still unknown. For example, information about the decision whether to overtake or to stay behind another pedestrian or which are the most important pedestrians for the movement decisions is scarce. In addition, whereas experiments for single-file movement are done regularly, unidirectional movement experiments are assumed to be more resource intensive and are more complex to perform. For example, a high number of pedestrians is needed to roughly obtain steady state conditions. Also, real-life situations with unidirectional flow are scarce.

6.4.6 *Model G: head-based headway*

To test the effect of a simple model extension, a head-based headway calculation is introduced. Instead of determining the lane width based on the full body with, only an assumed head width is used. Only pedestrians in front which bodies overlap with the head zone in the centre are considered frontal neighbours. The planned walking speed will be based on the distance of a pedestrian which overlap more and hence is more likely to block the walking path. Still, the full body width will be used to determine the lateral movement as well as for the collision avoidance. This is expected to be in a better agreement with the real-life situation, as pedestrians further away will also be in in the visual field and small body overlaps can be negotiated by small lateral movements or the turning of the body, which is not modelled here.

In Figure 6.36, the fundamental diagram simulated using Model G.1 can be seen. In comparison with Model F.1, the walking speeds are slightly higher but still considerably lower than the expected values. The used approach to provide a unidirectional model does not seem to be promising without a fundamental change of the model.

6.5 MODEL SELECTION

Based on the models created, a model has to be selected. This model has to be considered promising to be able to be useful for answering the research

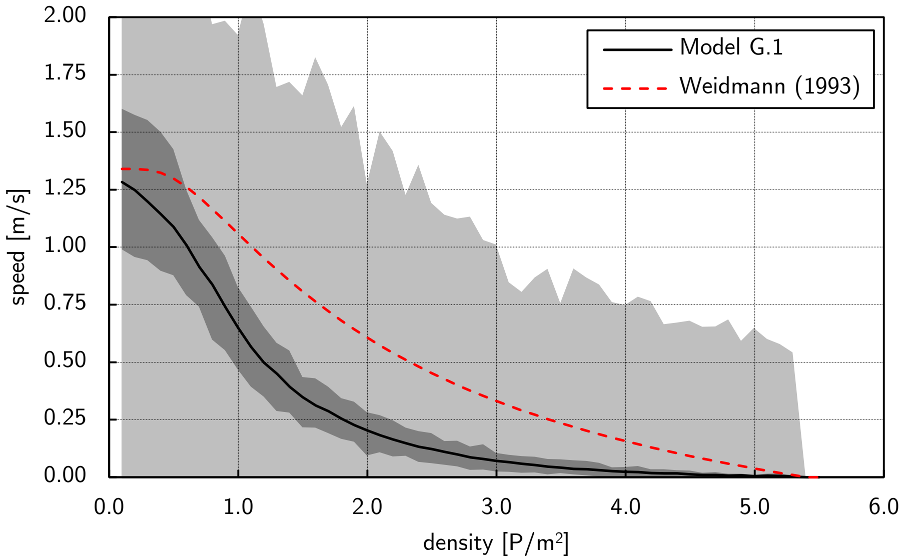

FIGURE 6.36: Model G.1: uUnidirectional movement model with a head-based headway.

hypotheses. For the goal of this work, the model shall be able to provide situation specific fundamental diagrams based on the specific pedestrian characteristics.

The fully unidirectional models, which are the most complex ones created, show a high discrepancy between the preliminary simulation results and the expected ones. This indicates that in reality, the pedestrians behave differently or that the model is based on assumptions which do not describe the real walking behaviour well enough. Thus, it is expected that a more complex model and more knowledge about the interaction processes in unidirectional walking is needed to create a functional model.

Still, the lane-change and lane-based models were already able to reproduce fundamental diagrams close to the expected values. Therefore, either a lane-based or a lane-change model will be selected. Both are expected to be sufficient for answering the research questions. As the lane-change model (Model E) is also able to simulate overtaking behaviour and to study the effect of different free flow speed distributions, this model will be selected for this work. Nevertheless, the lane-based models all result in similar fundamental diagram curves. If simulation time is an issue, it might be useful to test, if this model is also able to fulfil the requirements. However, this is not done in this work as one model is sufficient to answer the research questions.

In Figure 6.38, the main modelling steps are shown. The model runs for several loops. For each density the model runs for the number of timesteps specified. The main formulas were presented in this chapter and are referenced in the figure.

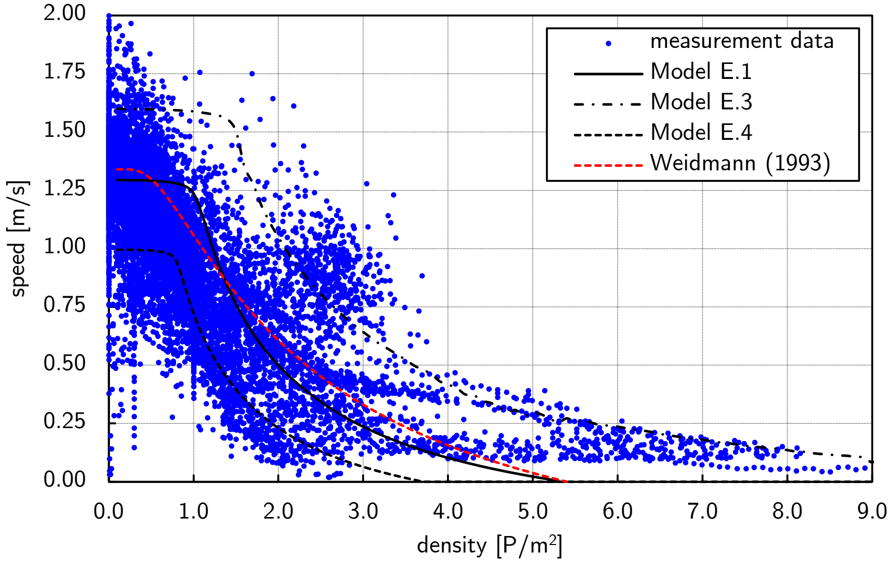

FIGURE 6.37: Model E.1, E.3, E.4: fundamental diagrams with different pedestrian compositions (average, maximum, minimum). As a reference fundamental diagram from Weidmann (1993) and the speed-density data from literature compiled in Bosina and Weidmann (2017c) are shown.

Figure 6.37 shows the fundamental diagram curves for different pedestrian compositions to estimate the resulting range. The results correspond to the estimated range which indicates that Model E can be useful for answering the research questions. Therefore, in the next step, the model will be calibrated, verified and validated.

```
procedure MODEL(pedestrian parameter, model parameter)
    lane width ← mean(body width + sway width)
    for all densities D do
        track length ← D/lane width
        current position ← random distribution within track length
        current speed ← random distribution within track length
        action point ← f(current speed, step formula)    ▷ Equation 6.8 or 6.7
        decision point ← action point−reaction delay
        for all time steps t do
            for all pedestrians do
                if t ← decision point then
                    predicted position ← linear interpolation(current position)
                    next speed ← f(predicted position, pedestrian parameters, current speed)
                if t ← action point then
                    current speed ← predicted speed
                    action point ← f(current speed, step formula)
                                                       ▷ Equation 6.8 or 6.7
                    decision point ← action point−reaction delay
                walking distance ← min(speed × interval, headway)
                current position ← current position + walking distance
                if t > timestep with no lane change then
                    lane swap ← f(current speed, current positions)
procedure SPEED(positions, pedestrian parameter, current speed)
    speed ← Equation 6.5 and Equation 6.6
    speed ← min(speed,minimum speed)
    speed ← speed ∗ normal distribution(1,random noise)
    speed ← min(current speed+max. acelleration/step length, speed)
    speed ← max(current speed−max. acelleration/step length, speed)
procedure LANE SWAP(positions, pedestrian parameter, current speed)
    if current speed < desired speed and headway <reaction headway then
        for left lane and right lane do
            if headway side > headway front then
                if back distance side >min. back distance then
                    change lane ← yes
        if change lane == yes then
            lane swap side ← max(headway left, headway right)
```

FIGURE 6.38: Main modelling steps in the final model. Input parameters are set in roman.

7

DATA COLLECTION

Everywhere is walking distance if you have the time.
— Steven Wright

7.1 INTRODUCTION

For the model validation and the test of hypotheses data is needed for comparison to the model results. This chapter now presents the data sources and the fundamental diagrams calculated from the empirical data. In Chapter 8 they will then be compared to the fundamental diagrams obtained from the model results.

As described in the research concept in Chapter 4, it is planned to use existing data for this purpose. This is done because laboratory experiments as well as real-life observations are resource intensive and it is not possible to obtain the same range of pedestrian compositions as it is already present in literature. This chapter now presents the different available data and calculate speed-density values which will then be used in the next chapter.

For different purposes, different data is needed. In general, data sources were preferred which are openly available and provided raw data. Using raw data instead of already calculated speed-density curves allows to estimate the fundamental diagram based on the definition presented in Chapter 2.4.7 and therefore enhance the comparability between different sources. Although the measurement data show different aggregation levels and measurement methods a calculation method is selected which shall ensure the best comparability possible. Similar to the values computed in the model creation in Chapter 6, a mean speed value and the range of walking speed at a given density are computed. The complete results of the speed calculations are available in the Appendix A.3.

In accordance with the definition of the fundamental diagram used, the global density is used. For single-file movement experiments, the number of pedestrians inside the circle and the track length is used to determine the linear density. For unidirectional flows, an area with an assumed constant global density is used. The measurement area used is further described in the sections for each data source.

For the speed values at each density, the mean value is computed. If possible, also the 5 % and 95 % quantiles of the instantaneous and average individual walking speeds are computed. These quantiles were selected to provide an information about the range of walking speed and simultaneously removing extreme values and model and measurement errors which are likely to produce outliers.

As the resolution differs between different data sources, high resolution data was aggregated to 1 s intervals. This allows a better comparison between different sources. In addition, this reduces the influence of speed variations potentially resulting from the stepping procedure. As they are not modelled in the fundamental diagram model presented, this will also enhance the comparability between the measurement data and the model.

7.2 SPEED-DENSITY DATA

7.2.1 *Fundamental diagram from Weidmann (1993)*

As described in Chapter 2.4.4, the fundamental diagram from Weidmann (1993) is one of the first but still the most used one for pedestrian transport. The fundamental diagram curve presented is based upon data from 25 references and aims at providing an average fundamental diagram. The empirical relation presented was then approximated using the Kladek formula (Figure 7.1).

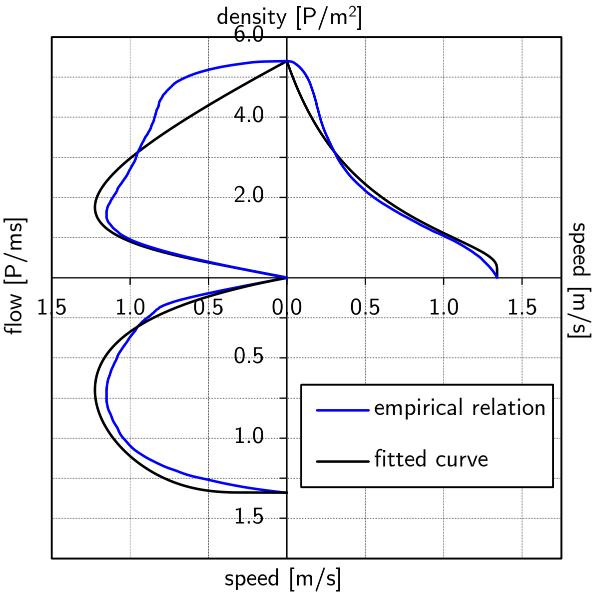

FIGURE 7.1: Fundamental diagram by Weidmann (1993), empirical relation and curve fitted using the Kladek formula.

Although several other fundamental diagrams were proposed in the meantime and different speed-density data is available, no similar general fundamental diagram was proposed in literature (Table 7.1). Especially the version using the Kladek formula is often used for comparison with model results and was in general found to be useful as an average fundamental diagram. Therefore, this fundamental diagram will be used in this work for similar purposes.

Table 7.1: Data characteristics for the fundamental diagram by Weidmann (1993).

Dataset name	Fundamental diagram from Weidmann (1993)
Date	1993 (data from before)
Location	Various
Data type	Fundamental diagram curve
Measurement technique	Literature data
Literature source	Weidmann (1993)
Data description	Average pedestrian fundamental diagram

7.2.2 *Other speed-density formulas*

As presented in Chapter 2.4.10, also various other equations describing the relation between speed and density can be found (Table 7.2). In contrast to the fundamental diagram by Weidmann (1993), these equations were usually derived based on measurement data for specific situations. Hence, they cannot be used as a global average but to estimate the range of possible fundamental diagrams or for comparison with a defined pedestrian composition. Nevertheless, often the detailed pedestrian characteristics and the method used to obtain the speed-density curves is missing, or is considerably different to the definition used for this work.

Table 7.2: Data characteristics for the speed-density formulas.

Dataset name	Speed-density equations from literature
Date	Various
Location	Various
Data type	Speed-density equations
Measurement technique	Various
Literature source	See Chapter 2.4.10
Data description	Speed-density equations for different situations

7.2.3 *Speed-density data from Bosina and Weidmann (2017c)*

For the publication on the pedestrian walking speed (Chapter or Bosina and Weidmann (2017c)) speed-density data was collected from literature (Table 7.3). This data, although the measurement techniques differ considerably, can be used to estimate the expected speed-density range and for comparison with model results. For this purpose, the original data collected was aggregated so that each data point corresponds to one measurement location and one density interval. The density was rounded to one decimal place. As not for all data the location was provided, not all data points represent one location measurement, but the aggregation was done to match this aim as close as possible. Further discussions on the limitations on the data used is done in Bosina and Weidmann (2017c) (see Chapter 2.3).

TABLE 7.3: Data characteristics for the speed-density data from literature (Bosina and Weidmann, 2017c).

Dataset name	Speed-density data from literature
Date	Various
Location	Various
Data type	Speed-density data
Measurement technique	Various
Literature source	Bosina and Weidmann (2017c)
Data description	Speed-density data for different situations

Under the assumption that the speed-density values can be used to estimate a general fundamental diagram and a range of speed values, two different calculations were made. First, a fundamental diagram curve was calculated by fitting the data to the Kladek formula (Kladek, 1966) for comparison to the Kladek curve presented by Weidmann (1993). Second, the mean as well as the range of walking speed values (5 % and 95 % percentile) were computed.

It has to be noted that the speed-density data available is a mixture of individual values as well as aggregated ones. The data is also not evenly distributed among different situations, hence a bias in the data can be expected. Nevertheless, the fundamental diagram curves as well as the range of walking speed are expected to provide useful information about the range and mean value of walking speed for each density.

In Table 7.4, the parameter values for the new fit to the Kladek formula are shown. The fit was done using the SciPy.optimize package curve_fit, which uses a Levenberg-Marquardt algorithm for optimization without setting boundary values for the parameters (SciPy community, 2017). The mean value of the walking speed shows a good correspondence with the new Kladek curve up to densities of about 6.0 P/m² (Figure 7.2). At higher densities,

Table 7.4: Parameter values for fitting the speed-density data from literature for flat walking (Bosina and Weidmann, 2017c) to the Kladek formula (Kladek, 1966). For comparison, the values from Weidmann (1993) are stated.

parameter	new (n = 1 395)	weidmann (1993)
v_0	1.32	1.34
D_{max}	18.55	5.4
δ	1.34	1.913

the new Kladek curve is higher than the measured values, but it has to be noted that at these densities only little measurements were available. As the Kladek formula only has three parameters and most values are below 4.0 P/m², a good fit at lower densities was obtained at the cost of a too high maximum density. The value of 18.55 P/m² obtained from the model fit is thus more a mathematical effect. In reality, a lower maximum density is expected, although the maximum density of 5.4 P/m² as proposed by Weidmann (1993) might be too low. When comparing the newly drawn Kladek curve with the one from Weidmann (1993), a good fit up to 2.0 P/m² can be seen. At higher densities, a higher walking speed can be seen in the new curve as well as in the literature data used.

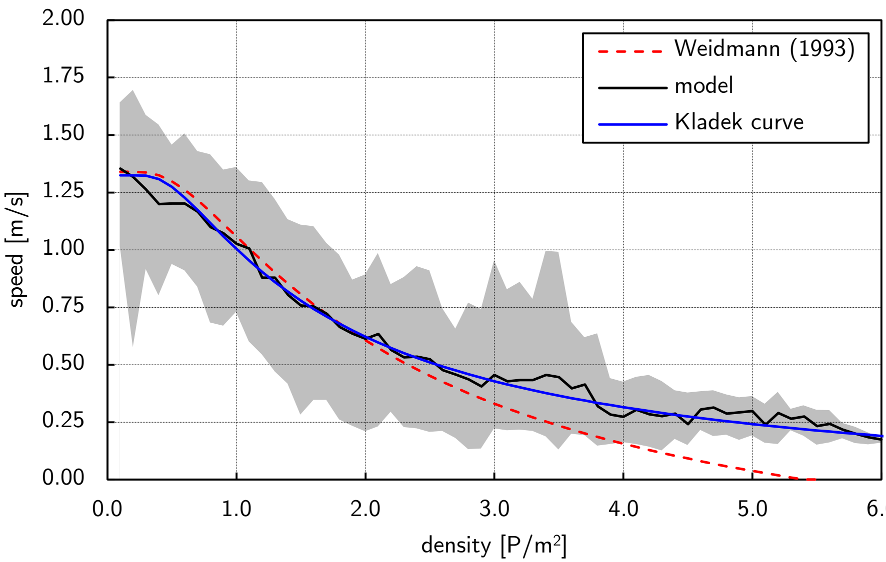

Figure 7.2: Mean, and range of speed density values calculated using the dataset from Bosina and Weidmann (2017c) and the Kladek curve fitted to these data. For comparison, the fundamental diagram from Weidmann (1993) is shown.

The range of values and the fit to the Kladek formula can also be done for walking on stairs (Table 7.5 and Figure 7.3). Here, considerably less data and especially no data for densities higher than 5.0 P/m² is available, the results should therefore be used with caution. Still, the data indicate that the walking speed on stairs is generally slightly higher than shown in the Kladek curves from Weidmann (1993).

TABLE 7.5: Parameter values for fitting the speed-density data from literature for stair walking (Bosina and Weidmann, 2017c) to the Kladek formula (Kladek, 1966). For comparison, the values from Weidmann (1993) are stated.

	UPSTAIRS		DOWNSTAIRS	
	NEW ($n = 193$)	WEIDMANN (1993)	NEW ($n = 166$)	WEIDMANN (1993)
v_0	0.73	0.61	0.89	0.694
D_{max}	9.57	5.4	9.96	5.4
v_0	2.61	3.722	2.22	3.802

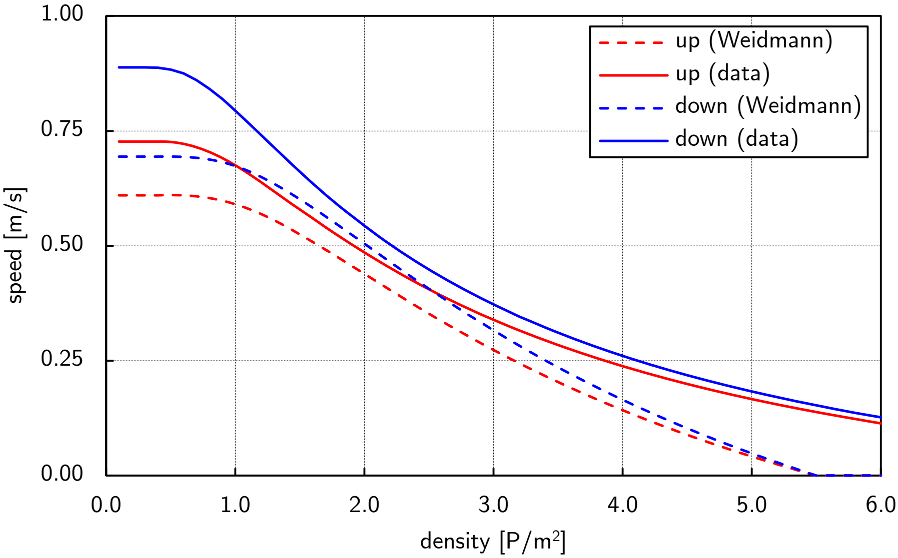

FIGURE 7.3: Kladek curves calculated using the dataset from Bosina and Weidmann (2017c) in comparison with the fundamental diagrams from Weidmann (1993) for walking up- and downstairs.

7.3 SINGLE-FILE MOVEMENT

7.3.1 *Overview*

In the last decade, several single-file movement experiments were performed, which can be used to determine the speed-density relation. During the experiments, the pedestrians are walking in an oval shaped corridor build using chairs, ropes or other material to prevent sideward evasion and to keep the circle length constant. Different numbers of pedestrians are then let into the circle to obtain different global densities.

The division "Civil Security and Traffic" at the Forschungszentrum Jülich (FZ Jülich) did perform several single-file movement laboratory experiments in the past and also made detailed data thereof available on their website (Forschungszentrum Jülich, 2018). The experiments are recorded using video cameras. Afterwards, trajectory data is extracted using the software PeTrack (Boltes and Seyfried, 2013).

Apart from the data available at the PED data archive of FZ Jülich, results of single-file movement experiments can be found in literature. Depending on the aim, this data can also be used for comparison with simulation results.

7.3.2 *Single-file movement, Rotunde (FZ Jülich)*

Published in 2005, the single-file movement experiment performed by the Research Centre Jülich is the first of this kind found in literature (Table 7.6). For this experiment, students as well as staff members were chosen as participants. The data collection was done manually from video recordings of a 2 m stretch at the straight section of the oval setup. The description of the measurements can be found in Seyfried et al. (2005).

TABLE 7.6: Data characteristics: single-file movement, Rotunde (FZ Jülich).

Dataset name	Single-file movement, Rotunde
Date	2005
Location	Forschungszentrum Jülich, Germany
Data type	Speed-headway data
Measurement technique	Standard video recordings
Literature source	Seyfried et al. (2005)
Link to data	ped.fz-juelich.de/db/doku.php?id=corridor1
Data description	Speed-headway data for different number of pedestrians in the experiment. Extraction was done manually from video recording by determining the entrance and exit time for a 2 m measurement area.

The dataset consists of walking speed measurements for five different global linear densities. The resulting mean speeds and range of walking speeds can be seen in Figure 7.4. In addition, Seyfried et al. (2005) determined the free flow walking speed using manual and automated procedures, averaging at 1.24 and 1.37 m/s, respectively.

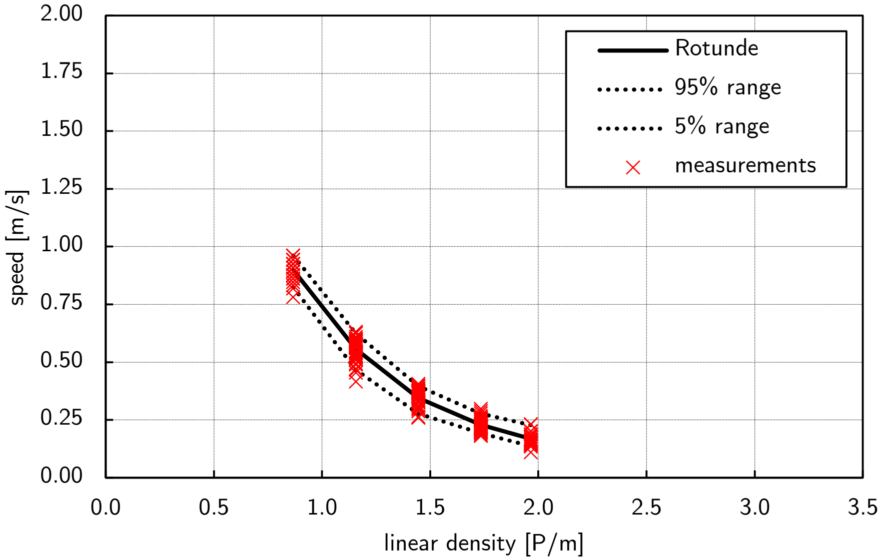

FIGURE 7.4: Dataset: single-file movement, Rotunde (FZ Jülich). Linear speed-density equation and the range of walking speeds observed.

7.3.3 *Single-file movement, Casern (FZ Jülich)*

Funded by the DFG (DFG-Grant No. KL 1873/1-1 and SE 1789/1-1) single-file experiments were made by FZ Jülich with soldiers at the Bergische Kaserne Düsseldorf (Table 7.7). The experiment was filmed from above and the participants were equipped with head marker to enable an automatic extraction of trajectories (Boltes et al., 2010). Trajectory data is available extracted from two top-mounted cameras.

Table 7.7: Data characteristics: single-file movement, Casern (FZ Jülich).

Dataset name	Single-file movement, Casern
Date	2006
Location	Bergische Kaserne Düsseldorf, Germany
Data type	Trajectory data from measurement section
Measurement technique	Video camera with tracker marks on hats
Literature source	Seyfried et. al (2010a,b), Boltes et al. (2010)
Link to data	ped.fz-juelich.de/db/doku.php?id=corridor2
Data description	Individual trajectory data for different number of pedestrians

To determine the range of walking speed measurements and the average speeds the speed values were calculated from the trajectory data. The trajectories were visually checked for consistency and data showing unsteady behaviour at the beginning and end of the data was excluded from the analysis to obtain data which is considered to represent the steady state conditions. In addition, a maximum acceleration threshold was used to remove individual speed values which are suspected to be due to measurement errors. In Figure 7.5, the resulting speed-density curve can be seen. This curve is in close agreement with the results from the Rotunde experiment (Figure 7.4), but covers a higher density range. Remarkably, the walking speeds at a linear density of 0.85 P/m (22 pedestrian in the circle) are slightly lower than at 0.96 P/m. (25 pedestrian). The reason for this is not obvious from the data, but as it is not considered relevant for the further use of the data, no detailed studies were made.

7.3.4 *Single-file motion of pupils (FZ Jülich)*

In 2015, experiments were made at two schools in Wuppertal (Germany). For each of the two schools, experimental data from two circles is available (Table 7.8). For each school, runs were made for two different age groups and a mix of both. General information about the experimental setup can be found in von Krüchten and Schadschneider (2017), Wang et al. (2018a) and Wang et al. (Wang et al., 2018b).

For the generation of speed – linear density diagrams, the global density was calculated using the number of people in the circle and the track length. The track length was determined by fitting two straight sections, one for each long side, and a half circle on each end to the data. The length is therefore expected to roughly represent the average length walked by the participants. This fit shows that at higher densities the circle length slightly increases on average. Still, the differences in the resulting densities compared to a fixed

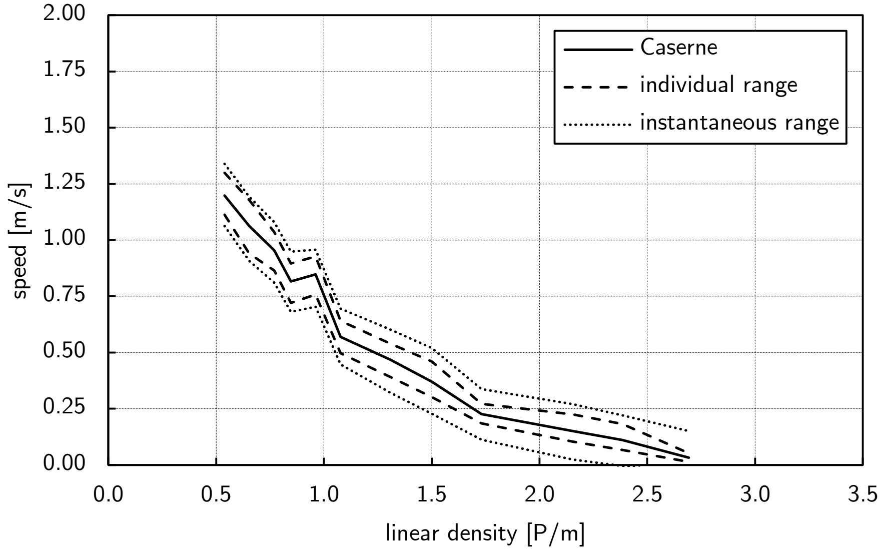

FIGURE 7.5: Dataset: single-file movement, Casern (FZ Jülich). Linear speed-density equation and the range of walking speeds (individual mean speeds and instantaneous speeds) observed.

length are small. For runs where pedestrians are walking unrestricted a density of 0 P/m is set.

For the analysis of the walking speeds, data from two metres long straight sections on both long sides of the experimental circle were used. Similar to the analysis of the previous experiment, data at the beginning and at the end as well as other data showing disturbances was excluded. The resulting average speed-linear density values for each experimental run can be seen in Figure 7.6. In general, the speed values calculated are in the same range as the ones from the previous experiments considered. Still, especially in the mid-density region they are slightly higher.

7.3.5 *Chattaraj et al. (2009)*

The first study found in literature to measure the influence of different pedestrian compositions on the single-file movement repeated the study from Germany made by FZ Jülich (see Chapter 7.3.2) in India (Chattaraj et al., 2009) (Table 7.9). Here, higher speeds were measured in the Indian experiment at the same headway. This is linked to cultural differences between these two countries. In general, people from middle-eastern cultures are expected to have smaller personal distances. In addition, in the experiment in India only men were participating, whereas in Germany a mixed gender population was used, which might also have an impact on the results.

Table 7.8: Data characteristics: single-file motion of pupils (FZ Jülich).

Dataset name	Single-file motion of pupils
Date	2015
Location	Gymnasium Bayreuther Straße, and Wilhelm-Dörpfeld-Gymnasium, Wuppertal Germany
Data type	Trajectory data and videos of experiment
Measurement technique	Video camera system with tracker marks on hats
Literature source	von Krüchten and Schadschneider (2017), Wang et al. (2018a,b)
Link to data	http://ped.fz-juelich.de/db/#single-file_motion_of_pupils
Data description	Individual trajectory data for 4 circles (2 per school)

Table 7.9: Data characteristics: single-file movement (Chattaraj et al., 2009).

Dataset name	Single-file motion of students (India)
Date	2008
Location	India
Data type	Individual speed headway data
Measurement technique	Video camera
Literature source	Chattaraj et al. (2009, 2013)
Data description	Speed-headway data for different number of pedestrians in the experiment. Extraction was done manually from video recording by determining the entrance and exit time for a 2 m measurement area

Based on the data, Chattaraj et al. (2009) calculated a linear speed-headway regression for the experiment in Germany and India:

$$h = 0.36 + 1.04 \cdot v \tag{7.1}$$

$$h = 0.22 + 0.89 \cdot v \tag{7.2}$$

7.3.6 *Song et al. (2013)*

Single-file movement experiments with college students were conducted at two universities in China (Song et al., 2013) (Table 7.10). A camera at the straight part of the experiment circle was used to record the pedestrians. The experiment description and the results are available in the article, especially

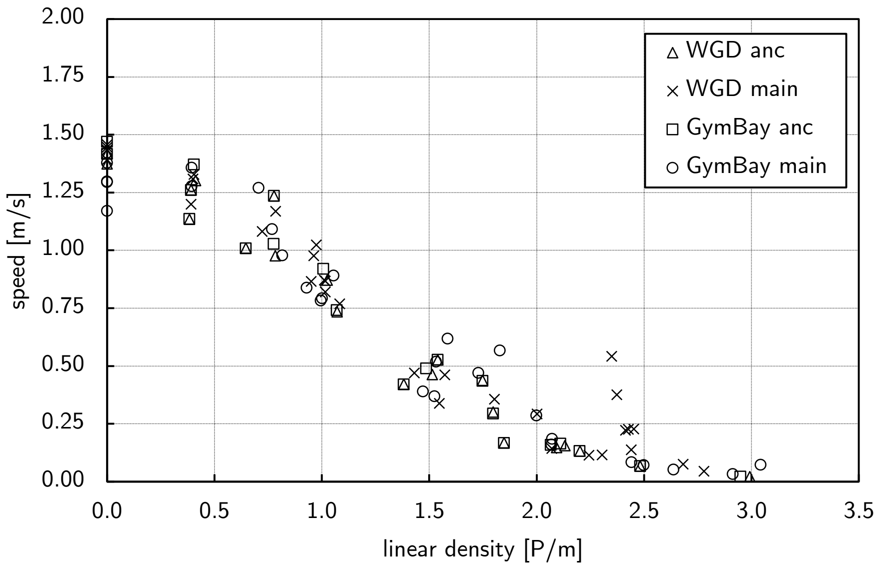

FIGURE 7.6: Dataset: single-file movement of pupils (FZ Jülich). Linear density versus mean walking speed per experiment run.

the average speed stated for each number of pedestrians in the circle can be useful for the model test. The speed-density data provided can be seen in Figure 7.7.

TABLE 7.10: Data characteristics: single-file movement (Song et al., 2013).

Dataset name	Single-file motion of students (China)
Date	2008 & 2010
Location	Hefei and Baoji, China
Data type	Mean speed for each number of pedestrians
Measurement technique	Video camera
Literature source	Song et al. (2013)
Data description	Mean speed values for each run for similar experiments at two locations.

7.3.7 *Cao et al. (2016a)*

To study the effect of different age compositions, Cao et al. (2016a) made single-file movement experiments with groups of young and old pedestrians as well as a mixed group with members of both ages (Table 7.11). It was

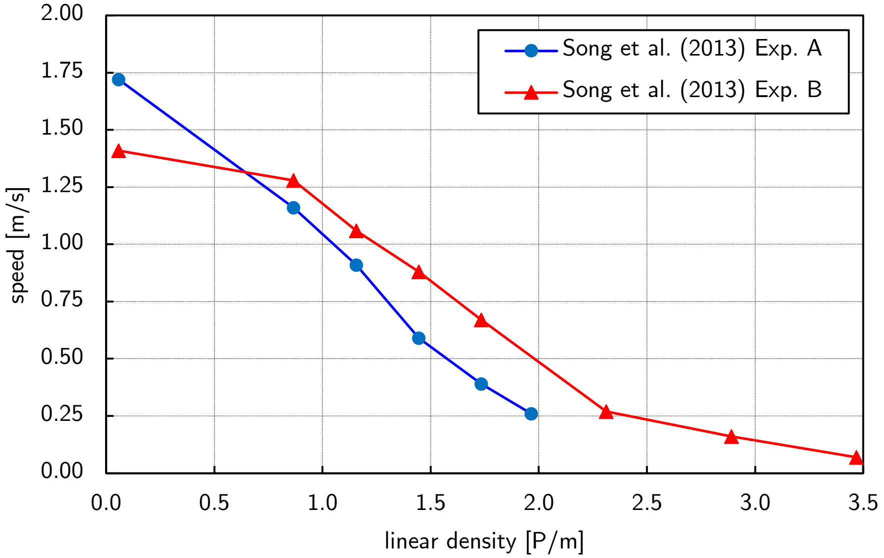

FIGURE 7.7: Global linear density versus mean walking speed per experiment run, Data from Song et al. (2013).

shown that in situations with smaller headways, the mixed group showed the slowest walking speed. Although no data is available which allows to estimate the fundamental diagram or a speed-headway relation according to Chapter 2.4.7.6, the data from this paper can be used to study, if similar findings can be reproduced using the derived model.

TABLE 7.11: Data characteristics: single-file movement (Cao et al., 2016a).

Dataset name	Single-file motion with different age compositions
Date	2015
Location	Tianshui Health School, Gansu, China
Data type	Local speed-headway values
Measurement technique	Video camera with tracker marks on hats
Literature source	Cao et al. (2016a,b)
Data description	Different graphs describing the speed-headway relation for the different age compositions.

7.4 UNIDIRECTIONAL MOVEMENT

7.4.1 *Overview*

Similar as for single-file movement experiments, the PED Data Archive of FZ Jülich provides data from experiments for unidirectional movement (Forschungszentrum Jülich, 2018). In the projects HERMES and BaSiGo, experiments with unidirectional flow in corridors were conducted, which can be used for comparison with the results of the fundamental diagram model.

7.4.2 *HERMES: corridor experiments*

In the project HERMES, experiments were conducted with different geometries at the Esprit-Arena Düsseldorf and the Messe Düsseldorf (Keip and Ries, 2009) (Table 7.12). At the latter, two setups with unidirectional flow in a corridor were tested. One experiment was done in an oval setting similar to the ones used for single-file movement (experiment UG), but with a higher width to enable overtaking. The second one was a straight corridor with different entrance and exit as well as corridor widths (experiment OG).

TABLE 7.12: Data characteristics: unidirectional movement HERMES.

Dataset name	HERMES, UG & UO
Date	2009
Location	Messe Düsseldorf, Germany
Data type	Trajectory data
Measurement technique	Video camera system with tracker marks on hats
Literature source	Keip and Ries (2009), Zhang et al. (2011), Zhang (2012)
Link to data	http://ped.fz-juelich.de/db/#unidirectional_flow_open_boundary_condition_2d http://ped.fz-juelich.de/db/#unidirectional_flow_closed_boundary_condition
Data description	Trajectory data extracted with the software PeTrack (Boltes and Seyfried, 2013)

For the experiment UG, trajectory data for one straight section and a part of the half-circle on both sides is available. For the data analysis, the corrected trajectories as they were made available by FZ Jülich on their website were used. In addition, videos of these experiments are provided, which allow to observe the pedestrian behaviour during the experiment. The circle layout was adapted for different simulation runs by using three different walkway widths. The straight section, from which the trajectory data is available, is created using wall elements, whereas the curves are made using lower boxes and traffic cones. Participants can lean over the boxes and cones but cannot do this at the area of the wall elements. This causes a small narrowing effect and some disturbances at the transition. It was therefore chosen to use the average density within the measurement section in the straight part of the circle, instead of the total density. The measurement section was set at the 4 m in the middle of the straight part, which is 6 m in total. The resulting speed-density curves can be seen in Figure 7.8. At higher densities, the speeds are similar for all three corridor widths, whereas for low densities a higher variation can be seen. The videos of the experiments also show that at a width of 1.0 m, two lanes are formed at the run with the highest number of pedestrians, at 1.4 m two to three pedestrians walk side by side and at 1.8 m mostly three to four. This indicates that the lane width roughly corresponds to 0.5 m.

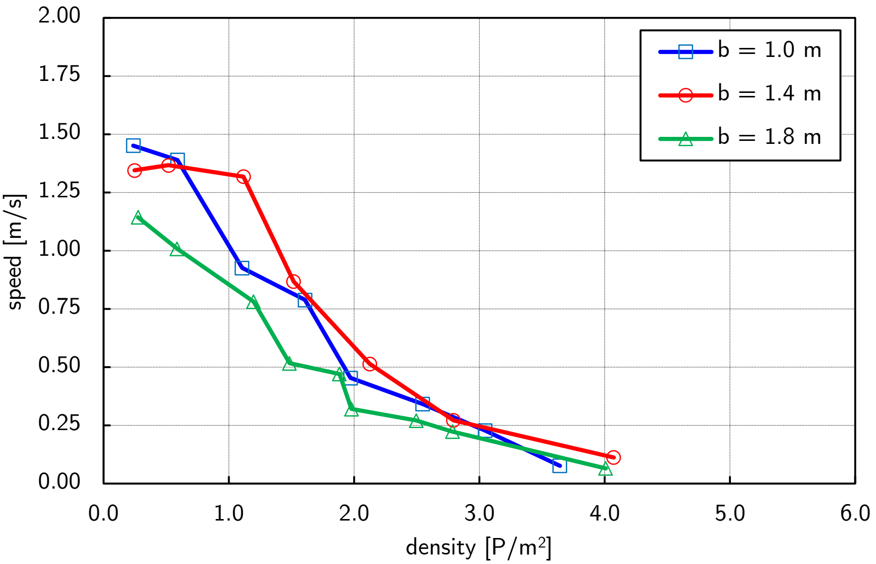

Figure 7.8: Speed-density curves for each of the walkway widths, Data from the HERMES experiment UG.

The second unidirectional experiment within the HERMES project (experiment UO) consists of a straight corridor, which width was set at three different values (1.8, 2.4 and 3.0 m). In addition, a bottleneck was located in front of the corridor to limit the inflow and one at the end of the corridor to limit the outflow. Different flows were established by changing the widths of each element.

To determine speed-density values from this experiment for this work, a time and space interval with near steady state conditions was selected for each experiment. Based on the data, a 4.0 m corridor stretch in the middle of the corridor was selected. Each experiment starts with an inflow phase, where the experimental setting is filled, a near-constant phase, where time wise steady state conditions can be assumed and an outflow phase where not the whole area is filled anymore. The time interval considered was therefore set to the steady state phase in the middle, which was selected based on the number of people and average walking speed in the measurement section. Although different numbers of pedestrians took part in different simulation runs, it was observed that the inflow- and outflow widths had a stronger impact on the flow (Keip and Ries, 2009).

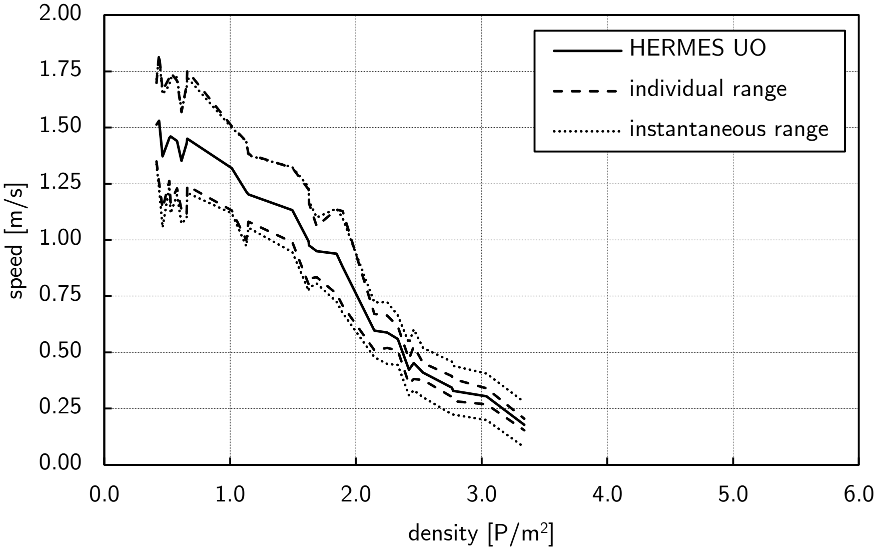

FIGURE 7.9: Dataset: HERMES experiment UO (FZ Jülich). Speed-density curve and the range of walking speeds (individual mean speeds and instantaneous speeds) observed.

In Figure 7.9, the resulting speed-density curve is shown. At lower densities, experiments with limited inflow are located, whereas at high densities, the experiments with a limited outflow and hence queueing inside the measurement area. This can also be seen at the range of walking speed, where a higher range is visible for the experiments with limited inflow. The speed density curves are similar for all three corridor widths (Figure 7.10). In comparison with the experiment UG, higher walking speeds in the medium density range are calculated.

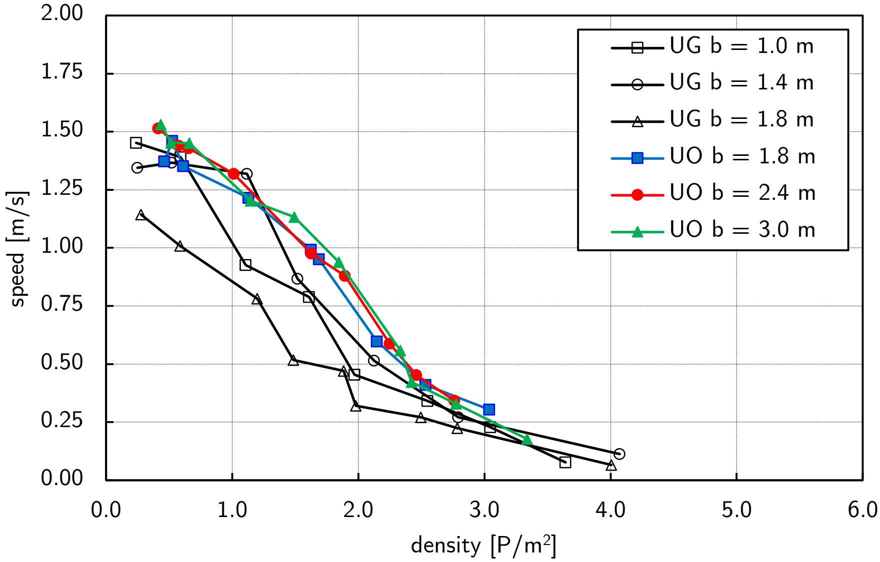

Figure 7.10: Speed-density curves for each of the corridor widths (experiment UO) in comparison with the data from experiment UG, Data from the HERMES experiment.

7.4.3 *BaSiGo: corridor experiments*

Within the framework of the research project BaSiGo (Bausteine für die Sicherheit von Großveranstaltungen) a large scale experiment with about 2000 participants was conducted (Holl, 2016) (Table 7.13). The participant composition can be characterized as homogeneous, although most of the participants were students. For the data extraction, an automated method to extract the trajectories and person IDs on their hats was used (Mehner et al., 2015).

Among others, also a setting with unidirectional flow in a corridor was examined. The experiment was conducted several times with different entrance and exit widths, the corridor itself had a constant width of 5.0 m.

In Figure 7.11, the resulting range of walking speed can be seen. Here, almost a linear speed-density curve is produced, but high and low densities are not covered.

Table 7.13: Data characteristics: unidirectional movement BaSiGo.

Dataset name	BaSiGo: UNI_CORR_500
Date	2013
Location	Messe Düsseldorf, Germany
Data type	Trajectory data with pedestrian characteristics
Measurement technique	Video camera system with tracker marks on hats
Literature source	Holl (2016)
Link to data	ped.fz-juelich.de/db/#corridor_unidirectional_flow
Data description	Trajectory data and pedestrian characteristics which can be linked using individual head marks.

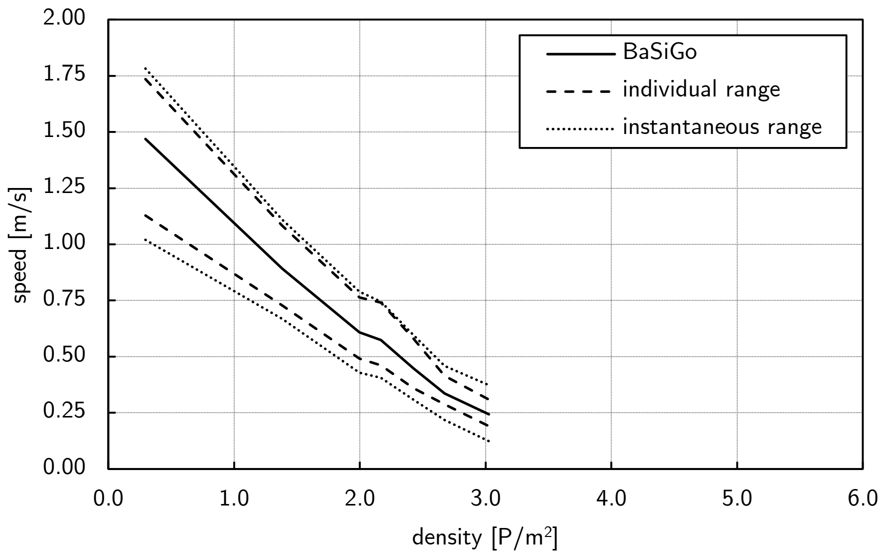

Figure 7.11: Dataset: BaSiGo experiment UNI_CORR_500 (FZ Jülich). Speed-density curve and the range of walking speeds (individual mean speeds and instantaneous speeds) observed.

7.5 REAL-LIFE DATA - SBB

7.5.1 *Overview*

Unidirectional flow in real-life situations only occur in specific situations, usually when the directions are separated, for example at certain railway or underground stations. Therefore, only unidirectional real-life data is available which can be used for comparison with the model results. For design purposes, it is often recommended, to apply a certain capacity loss, depending on the share of the two opposing flows (Navin and Wheeler, 1969; Weidmann, 1993; Weidmann et al., 2013). Thus, for certain tasks it is also feasible to use bidirectional data for comparison with the model results.

For this work, two different data sources were found. First, tracking data from two shopping and business centres in Osaka (Japan) are available online from the Intelligent Robotics and Communication Laboratories (IRC) of the Advanced Telecommunications Research Institute International (ATR). The main characteristics for these data can be found in Table 7.14. Second, tracking data was provided for this work from the Swiss Federal Railways (SBB). This data has similar properties as the first dataset but from a Swiss railway station. As the background of this work is the design of pedestrian facilities, which is especially important in railway stations, it was decided to use the SBB-dataset for this work.

TABLE 7.14: Data characteristics: real-life Data IRC.

Dataset name	DIAMOR, ATC
Date	2010, 2012 & 2013
Location	Diamor shopping centre and ATC (Asia and Pacific Trade Center) shopping and business centre in Osaka, Japan.
Data type	Trajectory data
Measurement technique	3-D range sensors
Literature source	Brscic et al. (2013), Zanlungo et al. (2015, 2014b)
Link to data	`www.irc.atr.jp/crest2010_HRI/ATC_dataset/` `www.irc.atr.jp/sets/groups/`
Data description	Corridor tracking data including pedestrian height

7.5.2 *Description: SBB dataset*

For different purposes, SBB has pedestrian counting and tracking devices in their railway stations. Pedestrian tracking is conducted using overhead

TABLE 7.15: Data characteristics: real-life Data SBB.

Dataset name	PU Bern SBB
Date	2018
Location	Bern railway station, Switzerland
Data type	Trajectory data
Measurement technique	Stereo cameras with automatic data extraction based on depth information.
Literature source	Hool (2018)
Data description	One month of tracking data including pedestrian height

stereo cameras which provide depth information in their field of view. This data is then used to automatically track pedestrians. The system is currently installed at two platforms, one in Bern and one in Zurich Hardbrücke as well as in the main underground passage of Bern railway station. The latter will be used for this work, as bidirectional flow is mainly present there. The data, as well as the data description is not publicly available, but was provided by SBB for this work (Table 7.15).

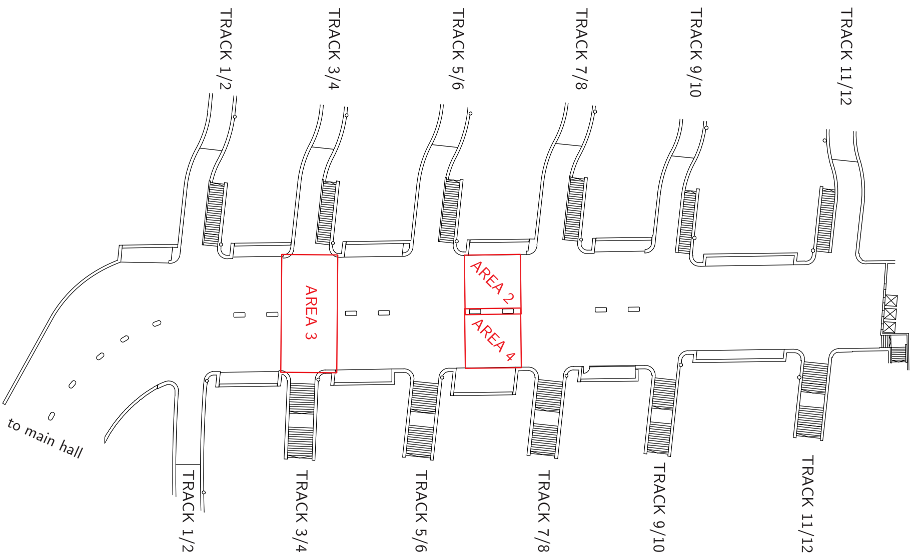

FIGURE 7.12: Location of measurement areas in the main underground passage of Bern railway station.

7.5.3 *Data processing*

Further figures covering the processing steps can be found in the Appendix A.4.

In comparison to experimental settings, real-life data shows a higher number of behaviours, for example standing pedestrians and pedestrians walking in different directions, which are not part of the fundamental diagram definition and will thus influence the results. In addition, the pedestrian flow is not constant, hence steady state conditions are hard to reach. It is important to analyse the data to ensure that the data used reflects the desired behaviour as close as possible.

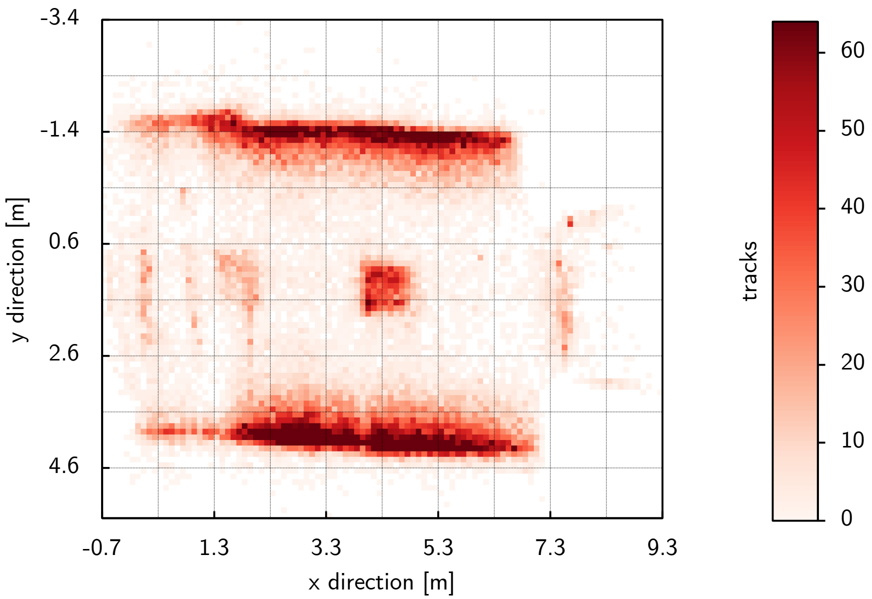

FIGURE 7.13: Day: 12.05.2016; Area 2; Endpoints of pedestrian trajectories.

For this, different processing steps were made. First, as about 8 data points per second were available with varying intervals, one data point was selected per second and person. This was done by selecting the first value in each second. For the last second of each track, the last value was used instead of the first one to cover the complete length of the track. As the timestamps are different for different tracks, in contrary from the video data used in the experiment data, the data do not reflect the situation at one exact point in time.

Then, the area used for the further analysis was selected. This was done based on the location of the start and endpoints of the pedestrian trajectories, the average walking direction and the average density. The values were aggregated for 0.1 m cells.

In Figure 7.13, the endpoints of the pedestrian trajectories for one day are shown. Most of the trajectories end at the edge of the sensor range. It is also visible that most pedestrian move in the main walking direction along the y-axis. Still, in the middle of the area ($x = 4.2$; $y = 1.0$), a cluster of ending trajectories is visible. As the Area 2 consists of a set of four sensors aligned in a rectangle, it is assumed that this cluster is located in the overlapping area of these four clusters. Here, the merging of the sensor data does seem to produce a split in the trajectories for a certain number of pedestrians. This is also visible when the start points are considered, where a higher amount of trajectory starts are visible around this cluster.

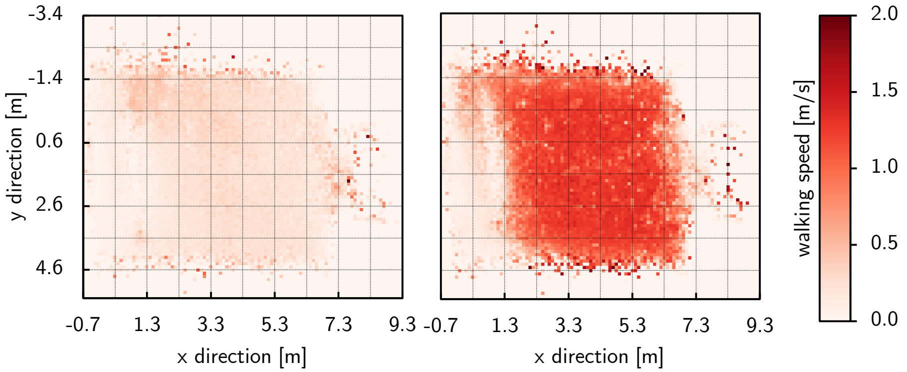

FIGURE 7.14: Day: 12.05.2016; Area 2; average walking speed in x and y (main walking) direction.

To determine the main walking direction, the average walking speed in x and y direction was computed for each 0.1 m grid cell (Figure 7.14). The walking speed in y direction, the main walking direction of the underpass, is considerably higher than in the lateral direction. This also indicates that only limited lateral movement exist in Area 2, . The other two measurement areas show similar behaviour (see Appendix A.4.2).

To determine a measure for the average density, for each grid cell, the number of measurement points within a day was computed (Figure 7.15). Whereas for the middle part of Area 2 an even distribution is visible, the right part does show a considerably higher accumulation of data points. This can be explained by the fact that on the side of the corridor a takeaway is located, which queue is visible in the sensor range.

Based on the three evaluation parameters (trajectory start- and endpoints, directional walking speed, distribution of data points), Area 2 was selected for the fundamental diagram estimation. From this sensor area, a $3.5 \cdot 3.5$ m area in the middle was selected (Sensor area: x: $2.7 - 6.2$ m; y: $-0.3 - 3.2$ m).

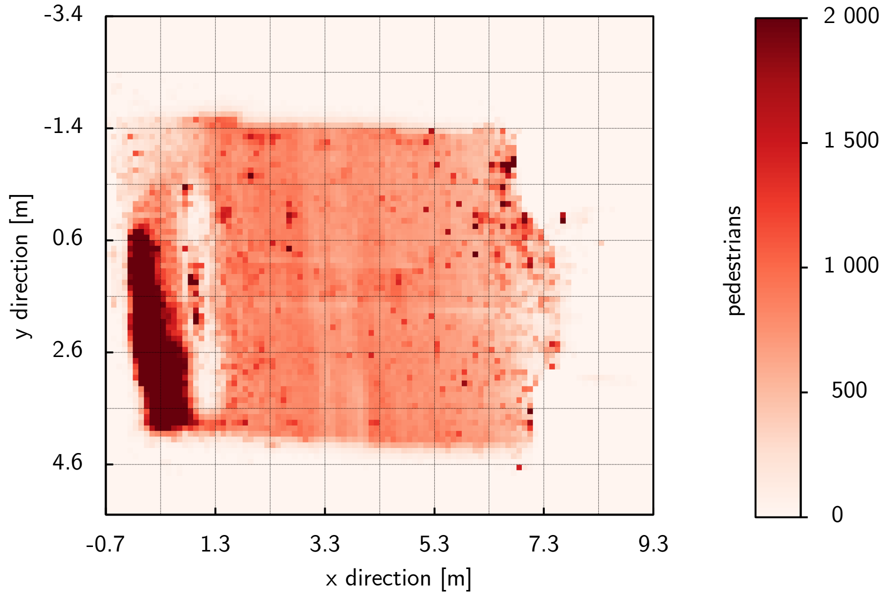

FIGURE 7.15: Day: 12.05.2016; Area 2; number of pedestrians per grid cell.

In the next step, the available data covering 77 days (09.05.2016 – 24.07.2016) was processed. For this, the following procedure was applied:

- Selecting the first data point per second for each pedestrian.
- Calculating the walking speed in x and y direction. The data will be assigned to the time and space midpoint of each interval.
- Selecting the data points within the evaluation area.

In the end, 6 366 386 data points from 2 521 112 trajectories were extracted and used for the further calculations. In Figure 7.17 and Figure 7.16, the histogram of the walking speeds in x and y direction are shown. In x direction, a distribution around $v = 0\,\mathrm{m/s}$ is visible, indicating that the lateral walking direction is dominated by the side movement of people walking along the corridor and thus the influence of people crossing the main flow is small. Still, the visible peak suggests that two distributions are superposed in this graph, one with a very high peak and small deviation and another less pronounced peak with a larger deviation. If only data points with absolute walking speeds of less than $0.25\,\mathrm{m/s}$ are considered, only the high peak values remain, showing that this peak belong to standing pedestrians, while the more even peak corresponds to pedestrians walking. For the y direction, three peaks can be distinguished, one for standing pedestrians around the speed of zero and one peak for each walking direction (Figure 7.17). In total 558 230 data points (8.8 % of total) show walking speeds lower than 0.25 m/s.

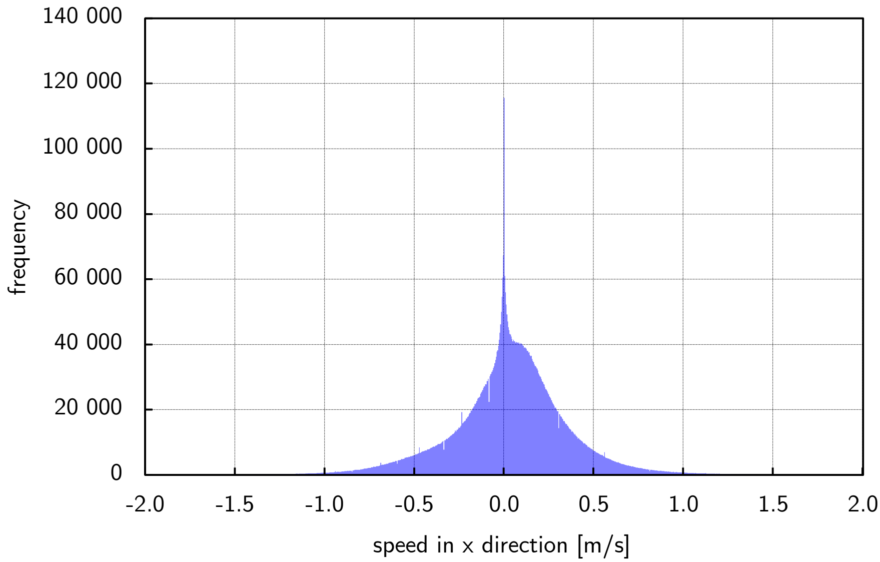

FIGURE 7.16: Time: 09.05.2016 – 24.07.2016; Area 2, analysis region; histogram of walking speeds in x-direction.

To determine if a higher share of people walking laterally is visible, Figure 7.18 shows the number of data points for each $v_x - v_y$ combination. Here, two peaks for each walking direction and another one for standing pedestrians are visible. It is clear that no pronounced lateral walking exists, the walking direction is along the y-axis.

In a next step, the data points of each track were aggregated and an average speed in x and y direction was calculated to obtain the average values for each pedestrian (for figures see Appendix A.4.5). The results are similar to the ones for individual data points, only the share of low walking speeds is reduced. Now, about 1.7 % of all trajectories show a mean speed value lower than 0.25 m/s. It is concluded that waiting pedestrians are expected to not strongly influence the results. Still, the data show a relative high share of trajectories with no movement (5 771 out of 42 417 trajectories with $v \leq 0.25$ m/s). This might be due to measurement or data processing errors. But as they correspond only to a small fraction of all trajectories (0.2 %), no further investigations were made.

In conclusion, the data show a distinct walking direction with only a small fraction of people with strong lateral movement or pedestrians standing in the measurement area. Still, it was not possible to determine the quality of the data, although similar measurement setting on railway platforms were

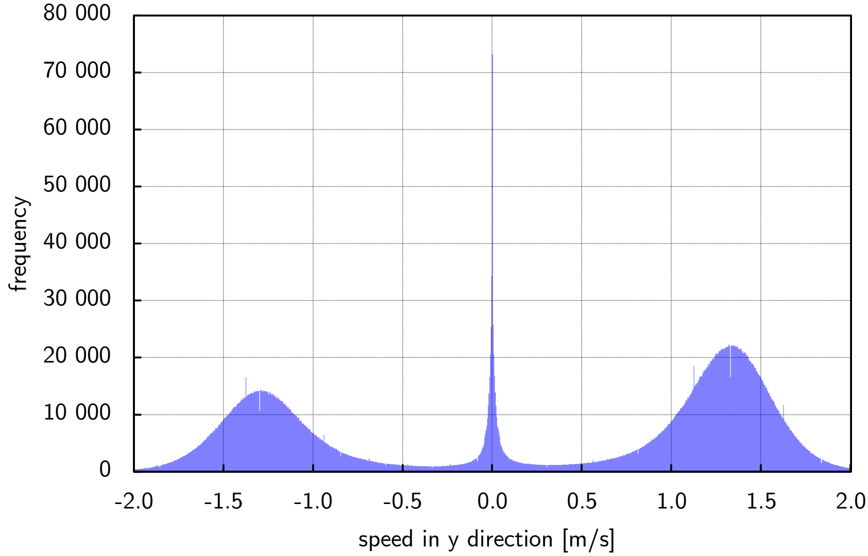

FIGURE 7.17: Time: 09.05.2016 – 24.07.2016; Area 2, analysis region; histogram of walking speeds in y-direction.

found to show a high data accuracy. Here, also the stitching of trajectories was found to fail in some cases.

7.5.4 *Density estimation*

According to the definition of the fundamental diagram proposed in Chapter 2.4.7.6, the density used shall reflect the global density. As the data only covers a small area, the calculation of a global density is not possible for each time step. In addition, the conditions in the fundamental diagram are supposed to be steady state, which in reality happens only for short time intervals.

Thus, for the evaluation of the real-life data, a method has to be determined to estimate the steady state density. Here the use of the Voronoi density (Steffen and Seyfried, 2010) and methods to determine steady-state conditions as well as changes in the density can be used (Basseville and Nikiforov, 1993; Liao et al., 2016). Still, the calculation of the Voronoi density is only possible if tracking data is also available for the area around the measurement area, which cannot be guaranteed due to the limited sensor area. In addition, the instantaneous density shows a high fluctuation due to the size of the measurement area, hence the determination of changes in the density is difficult. By also considering the fact that the focus of this data evaluation is not the exact estimation of the fundamental diagram but to provide a reference values, a simpler method was chosen.

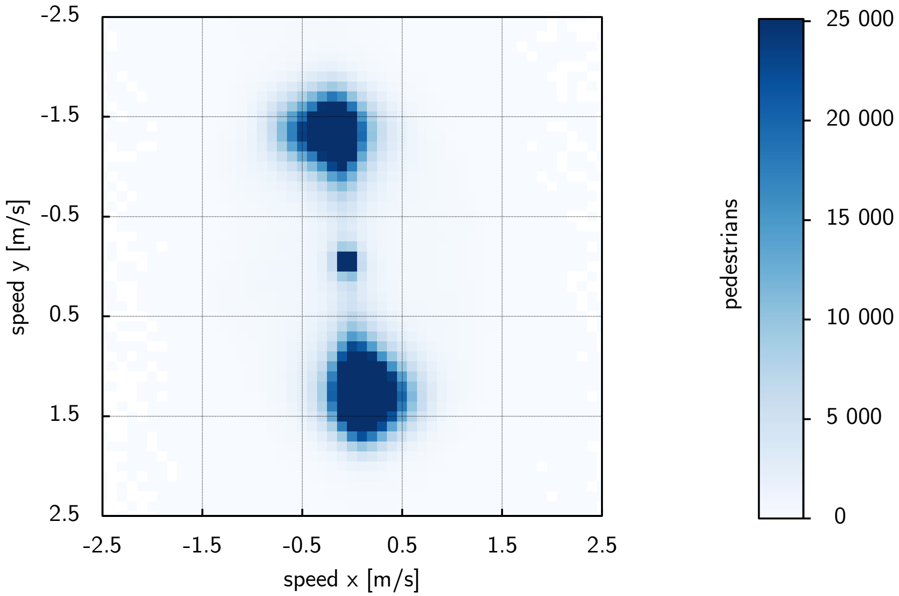

FIGURE 7.18: Time: 09.05.2016 – 24.07.2016; Area 2, analysis region; number of data points for each $v_x - v_y$ combination, colour map cut at 20 % of the maximum value.

Data is available for 77 days, thus limitation in the data processing can be to some extend covered by the amount of data. Thus, a moving average approach was used to estimate the density for each time step. For a constant global density, the average density of a small area for a longer time interval tends towards the global average. Therefore, this method will provide a good estimate for the global density in this case. When the global density changes, this method will result in an average density, thus evening out the change. Methods using change detection would result here in a distinct jump in density. Still, considering the perception of humans while walking, it is unclear which method is closer to the perception during walking in steady state condition. Another possibility is to remove intervals where the change in density is higher than a certain threshold from the data, but this approach was not studied further.

When using a moving average to determine the instantaneous density, the length of the averaging window is the most important parameter. When walking along the corridor, the pedestrians will experience the density in their close vicinity. Hence a value was chosen to roughly correspond to this time interval. Otherwise, small time intervals will increase the influence of the size of the measurement area. Here, a time interval of 15 s was chosen to estimate the density.

7.5.5 *Fundamental diagram*

Using the calculated density and the walking speeds in x direction, the fundamental diagram can be calculated. Most data recorded is from intervals with low densities. More than 99 % of the data shows a density lower than 1.0 P/m², values higher than 1.5 P/m² are almost never observed. Consequently, the speed density curve at densities higher than this, up to the maximum density of 2.1 P/m², shows high fluctuation and should be ignored for further analysis.

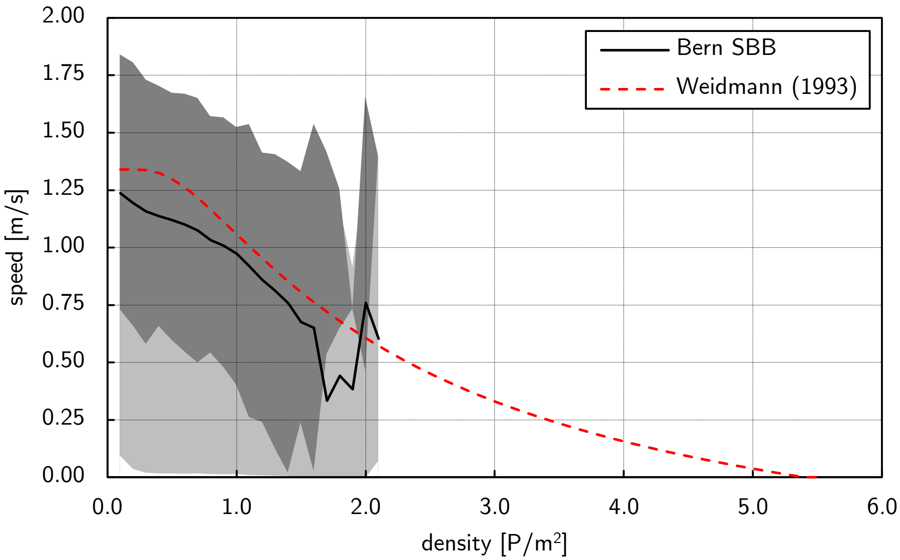

FIGURE 7.19: Dataset: SBB, Bern railway station. Speed-density curve and the range of walking speeds (individual mean speeds and instantaneous speeds, 5 % and 95 % percentile) observed.

In general, the resulting speed-density curve is similar to the curve from Weidmann (1993), although the walking speeds are slightly lower (Figure 7.19). In addition, a high range of walking speed for each density is visible. This can be partly explained by the fact that these real-life measurements also contain flow disturbances, such as stopping and standing pedestrians, which are not present in laboratory experiments and in the fundamental diagram. This can also be seen in Figure 7.20, where the distribution of instantaneous walking speeds is shown for a density of 0.5 P/m². Here two peaks, one in the region of the mean walking speed and another one at $v = 0$ is visible. This clearly suggests that the small walking speeds are due to undesired influences in the data, especially as stopping pedestrians are not expected at these densities.

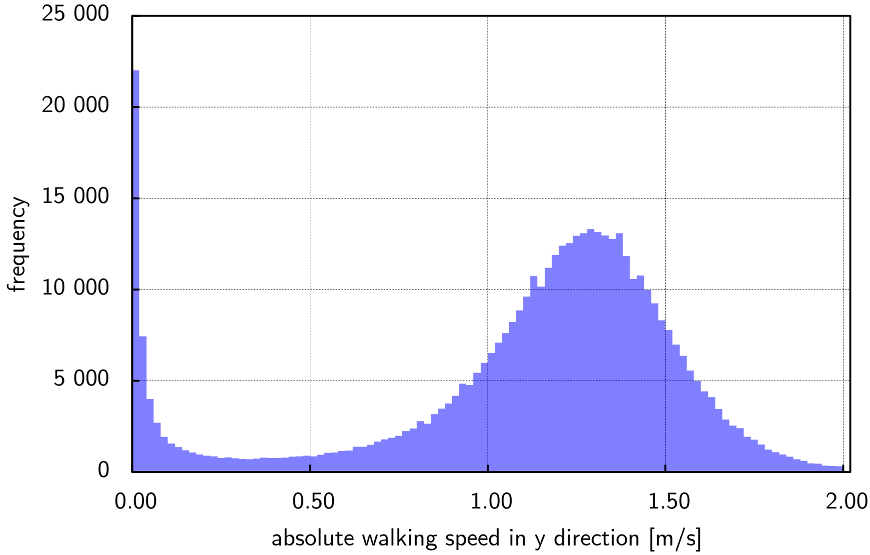

FIGURE 7.20: Dataset: SBB, Bern railway station. Distribution of walking speeds at D = 0.5 P/m²

To eliminate some of this noise, stopping pedestrians (identified using a walking speed threshold of 0.25 m/s) were removed from the data for the walking speed calculations (Figure 7.21). Here, a slightly higher overall walking speed and a smaller range of walking speeds is visible. As the removal of slow speeds from the data better reflects the behaviour expected in the fundamental diagram, these results are further used as estimation of the fundamental diagram in this setting.

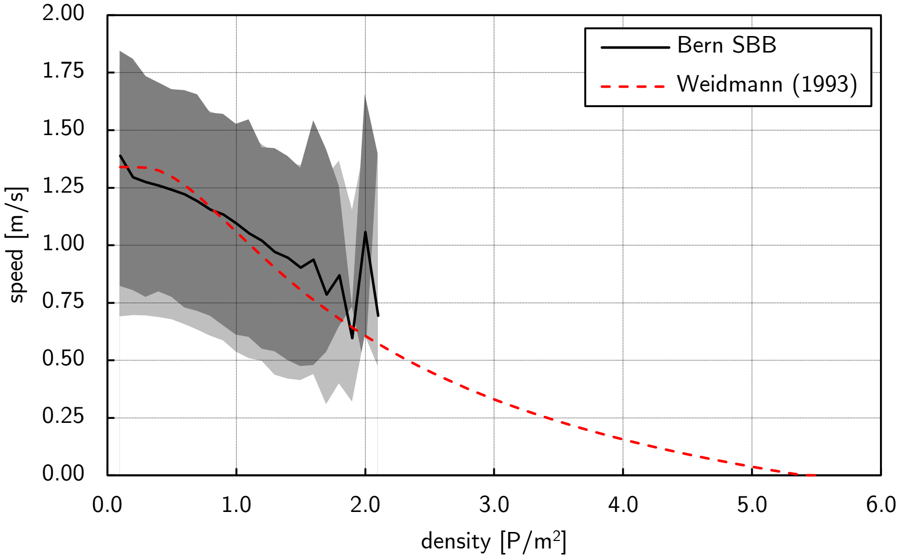

FIGURE 7.21: Dataset: SBB, Bern railway station. Speed-density curve and the range of walking speeds (individual mean speeds and instantaneous speeds, 5 % and 95 % percentile) observed. $v < 0.25\,\mathrm{m/s}$ (standing pedestrians) removed from speed calculation.

7.6 OVERVIEW

Throughout the data collection, speed-density curves for different situations were calculated. For comparison, all single-file movement curves are shown in Figure 7.22 and all unidirectional curves in Figure 7.23.

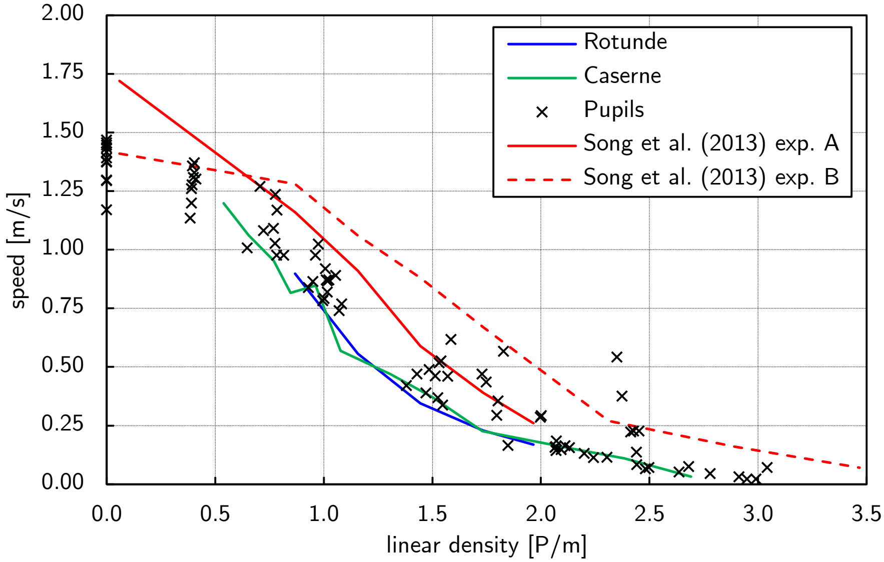

FIGURE 7.22: Linear speed-density curves computed from literature data.

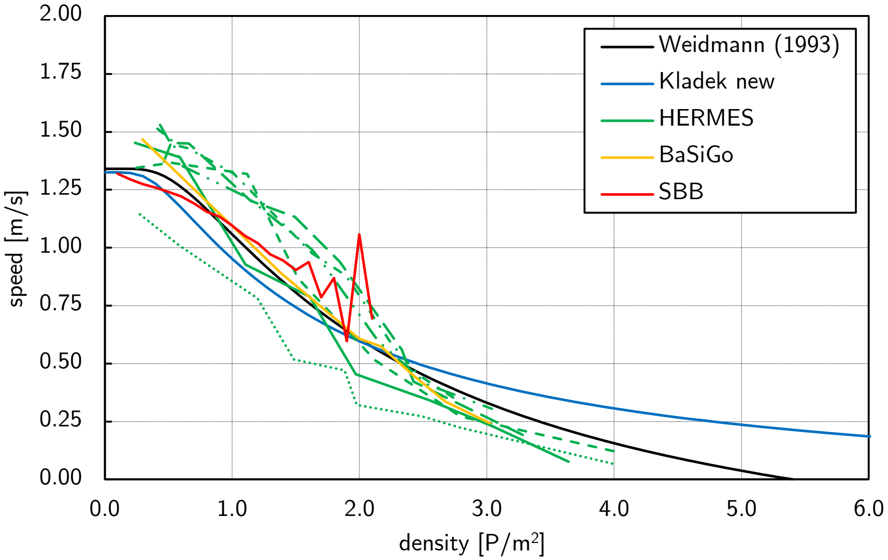

FIGURE 7.23: Unidirectional speed-density curves computed from literature data.

8

MODEL CALIBRATION AND TEST OF HYPOTHESES

Wer geht sieht mehr, als wer faehrt. (The one who walks sees more than the one who drives)
— Johann Gottfried Seume, Mein Sommer

8.1 INTRODUCTION

In Chapter 6.5, Model E was selected to be used for answering the research questions. Therefore, this model will now be calibrated, verified and validated (Figure 8.1). This will ensure that the model is useful and is accurate enough to answer the research question and to test the hypotheses.

In this chapter, first the verification of the model will be discussed. Afterwards the model will be calibrated using real-life data. Then, the validation is performed to determine the quality of the model. This then allows to describe the usability and limits of the model. In the last part of this chapter, the research questions will be answered.

In literature, several definitions of the terms validation and verification exist (Kleijnen, 1995). For this work, the model verification will be defined as the examination that the model implementation was done without errors and that the simulations are working as expected, hence that the model assumptions are correctly implemented into the computer code (Carson, 2002; ISO, 2015; Law, 2015). The model validation is described as the comparison between the model and the real-life system to determine if it provides sufficiently accurate results.

8.2 MODEL VERIFICATION

The model verification according to the definition used aims at ensuring that the model implementation is done correctly, hence the model is behaving as intended and as specified in the contextual model (Sargent, 2007). For this purpose, multiple techniques can be used (Kleijnen, 1995), wherefrom different methods were selected according to the model type. After the model verification no indication was found that the model is not implemented correctly.

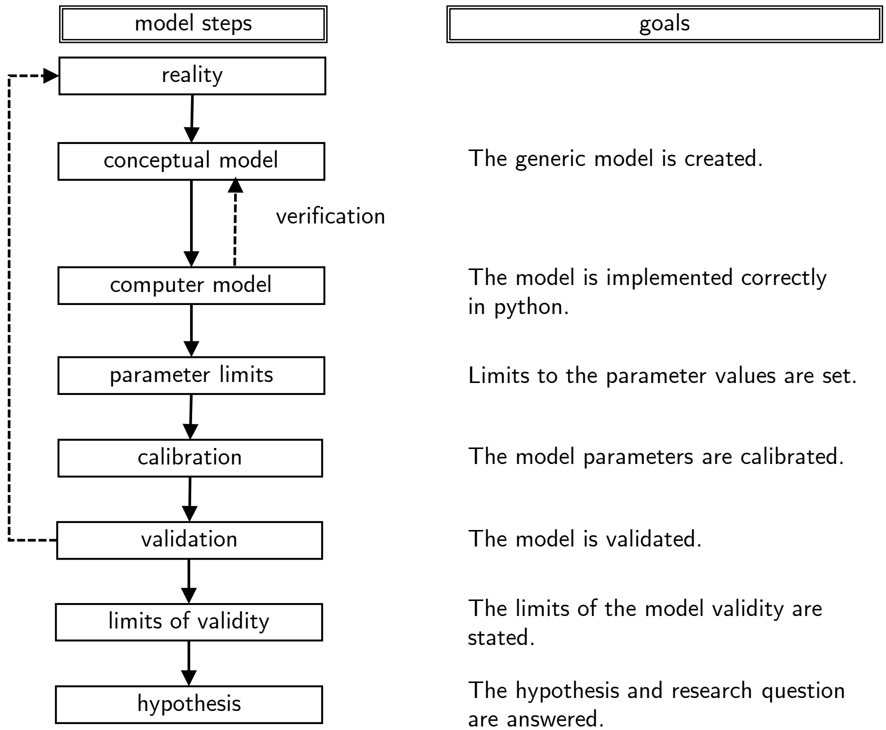

FIGURE 8.1: Steps performed for model testing.

8.2.1 *General programming practice*

Several techniques exist for writing software to minimise errors in the code (Sargent, 2007). For the model implementation the programming language python and the integrated development environment Spyder was used. To ensure the readability of the code, the code was commented and it was checked using the PEP 8 style guide for python (van Rossum et al., 2016). Standard debugging procedures were applied to detect errors in the code. Several final and intermediate results and variable values were checked for plausibility.

8.2.2 *Stepwise implementation*

The model was implemented in accordance with the modelling steps presented in Chapter 6. Thus, for each step, which also increased the model complexity, the model behaviour and intermediate results can be analysed. For the first steps this also allows a direct comparison of the model results with the analytical calculations. As the model parts are added one after another, implementation errors can be identified easier. In addition, by setting certain values or by commenting out parts of the code, complex models can be made identical to previous model steps. This allows to check if the implementation of additional features caused problems in previously existing parts of the code.

8.2.3 *Observation of flow characteristics*

By observing certain microscopic flow characteristics, a proper implementation can be checked. For this, especially the speed-distance diagram and the resulting fundamental diagram were used. For this model verification step, especially the collision-free movement and the free flow speed were observed. When walking in line, no overtaking is possible, hence everyone has to walk behind each other without collisions. This was checked using the time-space diagram at different densities (Figure 8.2). The correct implementation of the free flow speed was verified by comparing the walking speed at the lowest pedestrian density (0.1 P/m²) to the desired speed in the input variables. In addition, parameter variations were made to compare the expected model behaviour with the model results. The observation of flow characteristics in this validation step did not show any unexpected behaviour.

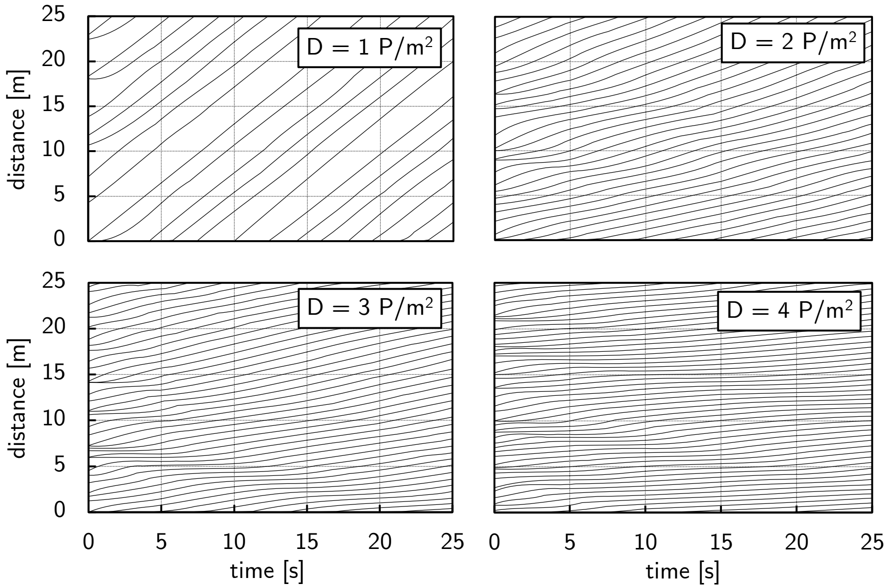

FIGURE 8.2: Time-space diagram for different global densities (1, 2, 3 and 4 P/m²). Model E.2 with only one lane.

8.2.4 *Test cases*

In addition to the observation of the flow characteristics during and after simulation, specific test cases were established. In literature, several test cases are proposed, whereof similar ones can be derived to test the fundamental diagram model created (IMO, 2007; RiMEA e.V., 2016; Song and Fu, 2016)

- Constant speed: a single pedestrian should walk constantly, or on average if a random variation is introduced, at its desired walking speed.
- Stopping pedestrian: if a pedestrian is standing at a certain point, a pedestrian approaching from behind has to stop without touching or intersecting with the standing pedestrian (Figure 8.3).
- Overtaking: same setting as for stopping pedestrians but with a second empty lane. The pedestrian should change lane and pass the standing pedestrian (Figure 8.4).
- Parameter change: changing a parameter value (e.g. desired walking speed) during the simulation will lead to a visible behaviour change (Figure 8.5). For all test cases, the expected results were observed, thus no indications of implementation errors were found.

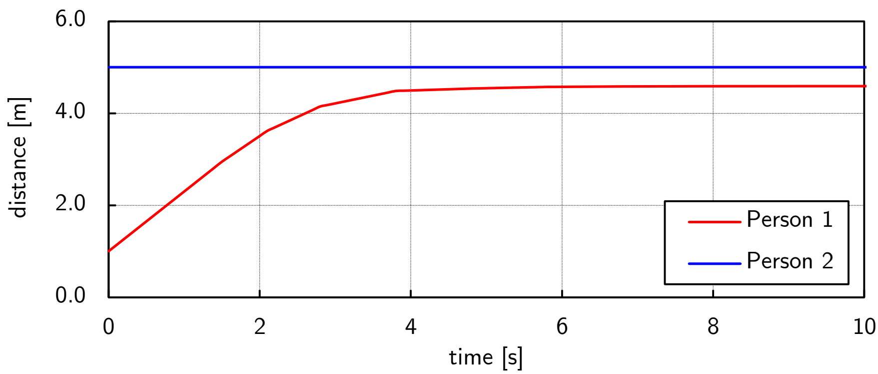

FIGURE 8.3: Time-space diagram for a pedestrian approaching a standing pedestrian and stopping behind.

8.3 RANGE OF PARAMETER VALUES

Every model is made for a specific purpose, which also determines which simplifications are made. It is important to specify the purpose as well as the

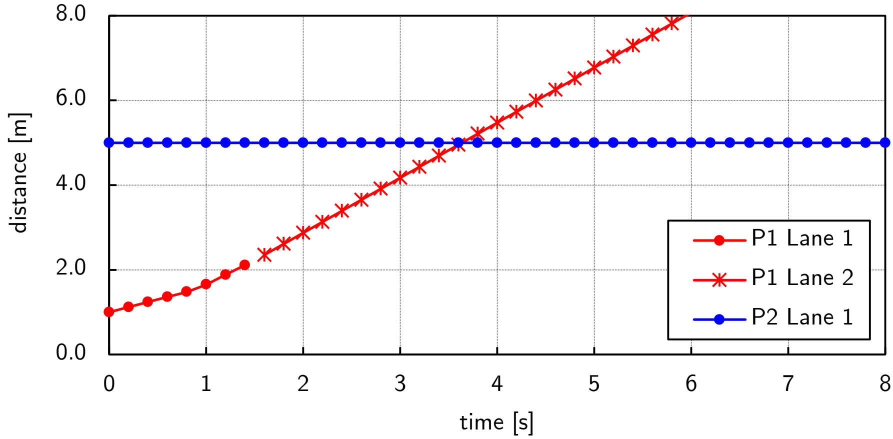

Figure 8.4: Time-space diagram for a pedestrian approaching a standing pedestrian and overtaking using another lane, where no one is walking.

limits, in which the model can be applied. If another usage is planned, or the limits shall be extended, the model has to be validated again to prove that it is also suitable for the changed requirements. Thus, the model shall cover the whole range of parameter values, which are usually used as design values. In a first step, the model parameters are limited to a range of values which excludes rare events and special situations. The model validation will then be done for this range to prove the validity of the model. Then, in Chapter 8.5.5, the limits of the model validity are stated.

In Table 8.1, the model parameters of Model E and their defined range of values are shown. Some parameters are based on physical pedestrian characteristics, such as the body depth and width. These can be limited using measurement data representing the average adult. Other parameters are well described in literature, here the values stated will be used to determine the range of values used in this model. As some parameter values cannot be taken from literature, the range of these values will be determined based on own assumptions. To respect the set limits when generating the pedestrian properties in a model run using a normal distribution, the distribution was truncated to these limits.

Especially the reaction and deceleration times are expected to strongly influence the results. For the model creation, these two parameters were set based on the assumption that a pedestrian is able to stop without contact to the pedestrian in front. Particularly for laboratory experiments this assumption might not hold true. Therefore, the value range of these parameter was enlarged.

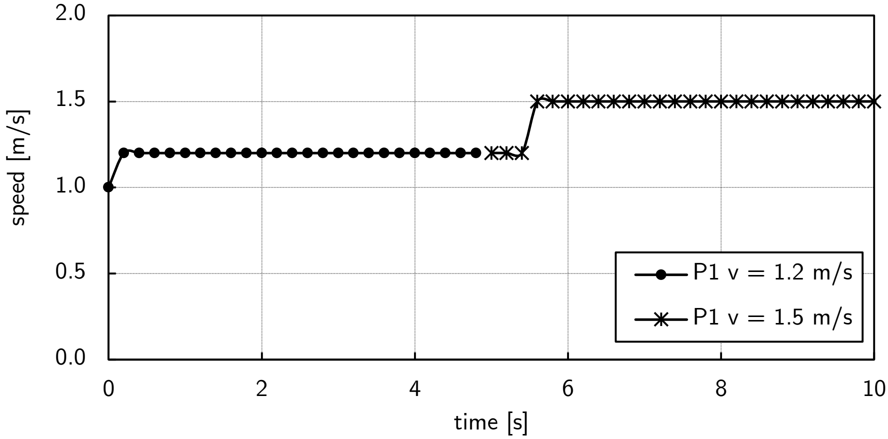

FIGURE 8.5: Time-space diagram for a single pedestrian experiencing a change in its desired speed at time step 50 ($v_1 = 1.2\,\text{m/s},\ v_2 = 1.5\,\text{m/s}$).

8.4 MODEL CALIBRATION

8.4.1 *Calibration parameters*

As the model aims at being based upon a generic description of human walking, also the parameters used are supposed to be measurable from observations and hence can be considered input values. Still, as some parameters are based on simplifications, they cannot easily be measured, thus they will be fixed. These parameter values will be determined in the model calibration. Nevertheless, as these parameters are depending on the pedestrian characteristics, it might be useful to adapt them if a different pedestrian composition is expected. Additional calibration parameters might be needed to minimise the deviation of the model results from the calibration data.

The model parameters are split into different groups (Table 8.2). The first group consists of simulation parameters. These are generally fixed for all simulation runs to ensure comparability. They mainly contain parameters to reach steady state results while minimising the calculation time. The second group consists of parameters, which will be calibrated. Although they mostly reflect properties of human behaviour theoretically can be measured, they are usually hard to estimate. Still, if detailed data is available, the use of other parameter values than the one from the calibration might be useful. In the third group the input parameters are located. They will be set based on the pedestrian composition for each simulation run.

TABLE 8.1: Range of parameter values used for the model validation and the scope of the variation.

PARAMETER		MIN.	MAX.	CONSTANT FOR
Reaction delay t_{rd}	[s]	0.10	0.50	Individual step
Desired walking speed v_d	[m/s]	1.00	1.90	Individual
Body width w_B	[m]	0.30	0.50	Individual
Sway width w_s	[m]	0.04	0.06	Individual
Body depth d_B	[m]	0.15	0.35	Individual
Intimate distance d_I	[m]	0.15	0.20	Individual
Reaction time t_r	[s]	0.30	0.80	Individual
Deceleration time t_d	[s]	0.30	1.10	Individual
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	individual
Random noise r_n	[%]	0	20	Model run
Step formula		Cavagna; Jelic		Model run
Backward distance for lane change d_{back}	[m]	0.50	5.00	Model run
Maximum reaction headway $h_{r,max}$	[m]	2.00	6.00	Model run
Maximum reaction time $t_{r,max}$	[s]	0.50	1.50	Constant
Minimum walking speed v_{min}	[m/s]	0.00	0.50	Constant

8.4.2 *Calibration approach*

For an optimal calibration of the model, the input data as well as the real-world results are needed. For the fundamental diagram model created, this data is not completely available. Nevertheless, the available information can be used to estimate the input parameters as well as to calculate the resulting fundamental diagram. Based on the data sources presented in Chapter 7, the data from the HERMES experiment UO ($b = 2.4$ m) will be used (Appendix A.5.1). This data covers a high range of walking speeds as well as detailed information about the participating pedestrians is available, which makes it suitable for the model calibration. Based on the documentation of the experiment and related papers (Keip and Ries, 2009; Zhang et al., 2010), the input parameters for this experiment are estimated and shown in Table 8.3. For the physical parameters German population data for the age and height distribution were used (DIN, 2005). For other parameter values it was assumed that the participants were mainly young people who, in an experimental setting, pay highly attention while walking and hence do react quicker and allow less space than in other settings.

Table 8.2: Model parameter groups and their respective parameters.

GROUP	PARAMETER
Simulation parameters	Initial time steps with no lane change S_{in}
	Number of lanes N_l
	Number of pedestrians P
	Number of time steps used for speed calculation S_s
	Simulation duration T_{sim}
	Simulation time interval T_{in}
Calibration parameter	Backward distance for lane change d_{back}
	Maximum reaction headway $h_{r,max}$
	Maximum reaction time $t_{r,max}$
	Minimum walking speed v_{min}
	Random noise r_n
	Reaction delay t_{rd}
	Step formula
Input parameter	Body depth d_B
	Body width w_B
	Deceleration time t_d
	Desired walking speed v_d
	Intimate distance d_i
	Maximum acceleration a_{max}
	Reaction time t_r
	Sway width w_s

For the determination of the calibration parameters, a trial-and-error approach was used. This simple calibration method was used to reduce the calculation time needed for the calibration and due to the uncertainties in the available reference data also more elaborate calibration methods were not expected to improve the results. In addition, by manually selecting the parameter for each simulation run, a better understanding of the model behaviour is reached.

Hence, at first an initial set of parameter values and a possible range of values was defined representing the expected values (Table 8.4). Then, the calibration parameters were varied to obtain a close agreement between the model results and the fundamental diagram obtained from the measurement data. First, each value was varied over a wide range independently and then the best values for each parameter were determined to generate a new set of parameter values. Again, the parameters were varied, but the range of values

TABLE 8.3: Input parameter for the model calibration, estimation for dataset HERMES UO $b = 2.4$ m.

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.23	0.31	0.26	0.02	Normal
Body width w_B	[m]	0.40	0.49	0.44	0.03	Normal
Deceleration time t_d	[s]	0.30	0.80	0.50	0.05	Normal
Desired walking speed v_d	[m/s]	1.25	1.85	1.55	0.18	Normal
Intimate distance d_i	[m]	0.14	0.20	0.16	0.01	Normal
Maximum acceleration a_{max}	[m/s²]	0.50	0.70	0.60	0.05	Normal
Reaction time t_r	[s]	0.30	0.60	0.45	0.05	Normal
Sway width w_s	[m]	0.04	0.06	0.05	0.01	Normal

were narrowed down. It was observed that the model results differ slightly for the same parameter values. This can be explained by the stochastic nature of the model, especially due to random lane change processes, which influences the number of pedestrian per lane and hence the average lane walking speed (see Chapter 6.3.3). To estimate the resulting range some calibration runs were done a few times. The parameters used for the calibration runs can be found in the tables in Appendix A.5.2.

TABLE 8.4: Input values and value range for the calibration parameter before model calibration.

PARAMETER		RANGE OF VALUES		START
		MIN.	MAX.	VALUE
Backward distance for lane change d_{back}	[m]	0.5	5.0	3.0
Maximum reaction headway $h_{r,max}$	[m]	2.0	6.0	4.0
Maximum reaction time $t_{r,max}$	[s]	0.5	1.5	1.0
Minimum walking speed v_{min}	[m/s]	0.0	0.5	0.0
Random noise r_n	[%]	0	20	10
Reaction delay t_{rd}	[s]	0.2	0.4	0.2 – 0.4
Step formula		Cavagna; Jelic		Cavagna

The comparison between the model output and the real-world results will be done using the calculated fundamental diagrams and the range of walking speeds for each density. The quality of the fit will be determined by calculating the root-mean-square error (RMSE) of the speed values for each density.

Here, density steps of 0.1 P/m² for densities between 0.1 and 2.8 P/m² will be used. The experimental data used for the calibration does not show these increments, hence the speed values will be linear interpolated for the desired densities. For the the free flow speed, the value of 1.55 ± 0.18 m/s stated for this expermient by Zhang et al. (2010) will be used. The RMSE will be calculated for the mean as well as for the 5 % and 95 % quantile speeds. For the calibration, primarily the RMSE of the mean speed will be considered, the error of the range of walking speeds is of second order.

8.4.3 *Calibration results*

Based on the model purpose a maximum error of ±10 % for the mean speed is considered sufficiently accurate. This requirement is met already at the first calibration run, which shows a RMSE of 0.080 m/s at an average walking speed of 1.02 m/s for the calibration data (Figure 8.6). Also, the range of walking speeds as well as the curve fit is acceptable, although the deviation is significantly higher.

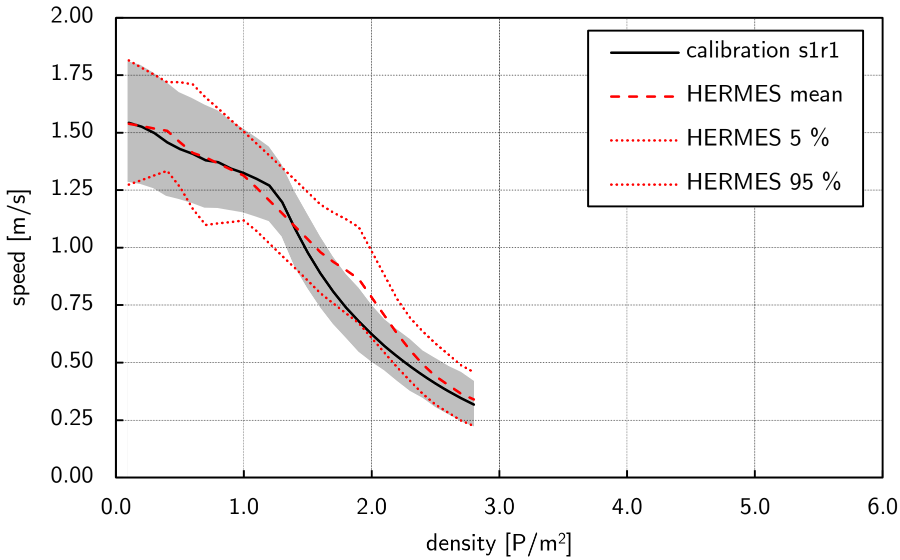

FIGURE 8.6: Initial calibration run (Set 1, Run 1): Fundamental diagram and the range of instantaneous walking speeds (5 to 95 % percentile) from the model and the reference data calculated from the HERMES experiment. $RMSE\ (v_{mean}) = 0.080$ m/s.

Starting from the initial parameters, the trial-and-error approach for the model calibration was performed until good parameter values were obtained. The parameter values used for the calibration runs and the resulting RMSE are provided in the Appendix A.5.2. The variation of the parameter values showed that the calibrations parameters do not strongly influence the results. Therefore, only a slight reduction in the RMSE was reached at the end of the calibration process. As the results do not differ strongly, the value for the minimum walking speed was set to zero for the later calibration runs. This was done because it did not strongly influence the calibration results, but will result to stopping pedestrians at higher densities, which is not considered realistic. For the best set of values (Set 4, Run 18), an average RMSE of 0.072 m/s was determined. The final values for the calibration parameters are shown in Table 8.5. In Figure 8.7, the corresponding fundamental diagram is presented. Here, only minor changes to the fundamental diagram of the initial run are visible.

In conclusion, the calibration only provided a small improvement of the model results. It was observed that the model is much more sensitive to the input parameters than to the calibration parameters.

TABLE 8.5: Calibration parameter: final values (from Set 4, Run 5).

PARAMETER		INITIAL VALUE	FINAL VALUE
Backward distance for lane change d_{back}	[m]	3.0	3.5
Maximum reaction headway $h_{r,max}$	[m]	4.0	4.0
Maximum reaction time $t_{r,max}$	[s]	1.0	0.6
Minimum walking speed v_{min}	[m/s]	0.0	0.0
Random noise r_n	[%]	10	7
Reaction delay t_{rd}	[s]	0.2 – 0.4	0.3
Step formula		Cavagna	Cavagna

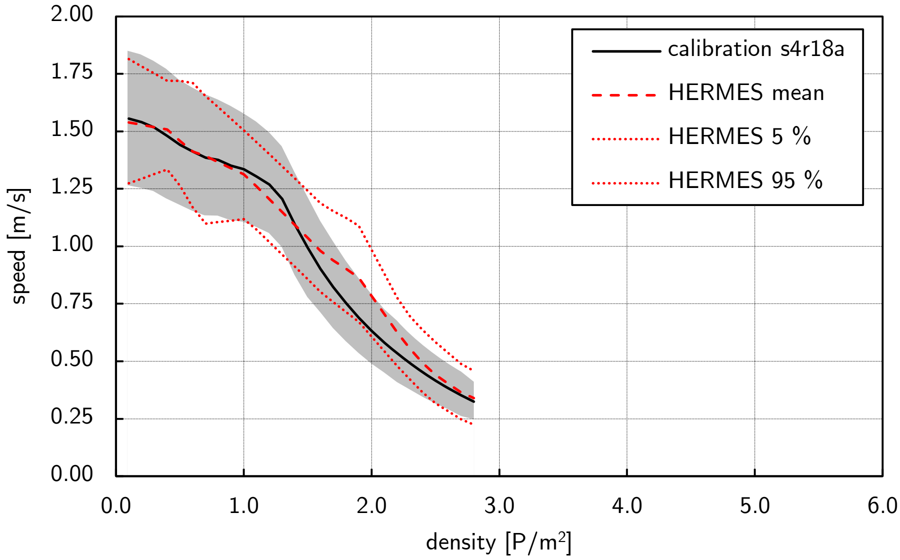

FIGURE 8.7: Final calibration values (Set 4, Run 18a): Fundamental diagram and the range of instantaneous walking speeds (5 to 95 % percentile) from the model and the reference data calculated from the HERMES experiment. *RMSE* $v_{i,mean} = 0.070$ m/s.

8.5 MODEL VALIDATION

8.5.1 *Validation concept*

After the model verification, the model validation aims at proving that the model is an accurate representation of the real-world system for the specific purpose. Apart from the comparison between model results and real-world data for the same input parameters, different other techniques exists (Carson, 2002; Law, 2015; Song and Fu, 2016). Especially for parts of the model, where no real-world data is available, other tests are needed. Again, a combination of methods was used to validate the model and hence to show that the model is useful for the defined purpose, hence to provide situation specific fundamental diagrams for designing pedestrian facilities (Figure 8.8).

Some model validation is already done during model verification. Especially when observing flow characteristics during the simulation runs. Here, the examination of the model behaviour ensures that the implemented model behaves as specified in the model setup. But as the model behaviour corresponds to a real behaviour, this step is also part of the model validation.

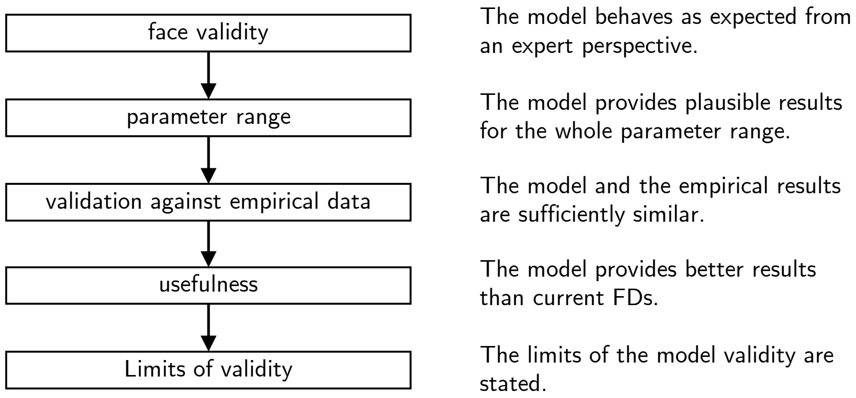

FIGURE 8.8: Validation steps performed.

8.5.2 *Face validity*

A model has face validity if the simulation results and the model behaviour correspond to the system behaviour as it is expected from experts (Law, 2015). The comparison of the model behaviour with expert opinions was already done during the phase of model creation. Here, the different model sets (Model E.1 to Model E.8) can be used to determine the face validity. During the model verification, additional scenarios were created which can be used to prove the face validity. Based on the observed model behaviour several conclusions can be drawn which support the face validity of the model:

- The model results cover the same range of speed-density values as the data obtained from literature (Figure 6.37)
- The shape of the resulting fundamental diagram is as expected and similar to existing fundamental diagram curves.
- Changes in parameter change the shape of the fundamental diagram as expected.
- Behaviour similar to stop-and-go waves can be seen in the data at higher densities, where short time stopping was observed (Figure 8.2).
- Realistic lane change and stopping behaviour was observed (Figure 8.3 and Figure 8.4).

Another aspect which can be tested for the face validity is the application validity (Bossel, 1992). Apart from proving that model and real system show the same behaviour and results, the model has to be useful for the design purpose and the intended users. The aim of the presented model is to be useful for answering the research question and hypotheses from Chapter 3. For this, the model has to determine a fundamental diagram based on the pedestrian characteristics. The model is ready to be applied, but good knowledge about pedestrian transport and programming knowledge is needed, which can be expected from the intended user. Based on the considerations made, nothing was found opposing the face validity of the model.

8.5.3 *Parameter range*

In the next step, the validity of the model will be tested for the intended range of the input parameter values, as they are stated in Table 8.1. Here, different sets of input parameter values will be used to determine qualitatively, if the model provides reasonable results for the whole value range. At first, the minimum, maximum and average input parameter values as well as a uniform distribution was used similar to the ones created during the model creation process. Then, an average normal distribution was estimated for all parameters. This parameter set was then varied by setting each parameter individually to a high and low distribution and studying the effect on the results. In Appendix A.6 the parameter values used are show, in Figure 8.9 the resulting fundamental diagrams are presented.

The results are all within the expected range derived from the empirical data. They do not show any indication that a certain parameter range results in unnatural model behaviour. It can be seen that if only one parameter is varied, the resulting fundamental diagrams are in a narrow speed range, especially at higher densities. In contrary, the two simulations using a maximum and minimum parameter combination do show strong differences to the other simulations. Here, the simulation run with the highest walking speeds do show a wide speed distribution and stopping pedestrians at a density of about 0.5 P/m^2. Still, when considering the parameter set and the resulting fundamental diagram, the results can be accepted as valid.

For a second test to evaluate the parameter range 30 simulations were done with randomly generated input parameter distributions within the defined parameter range (Figure 8.10). Two of these combinations did show an unexpected high range of walking speeds, although plausible mean values were obtained. All other simulations did not show any irregularities. It is therefore expected that the model is valid for the whole parameter range.

8.5.4 *Validation against empirical data*

8.5.4.1 *Approach*

To compare the simulation results against empirical data, and hence show that the resulting fundamental diagrams are similar for the real system and

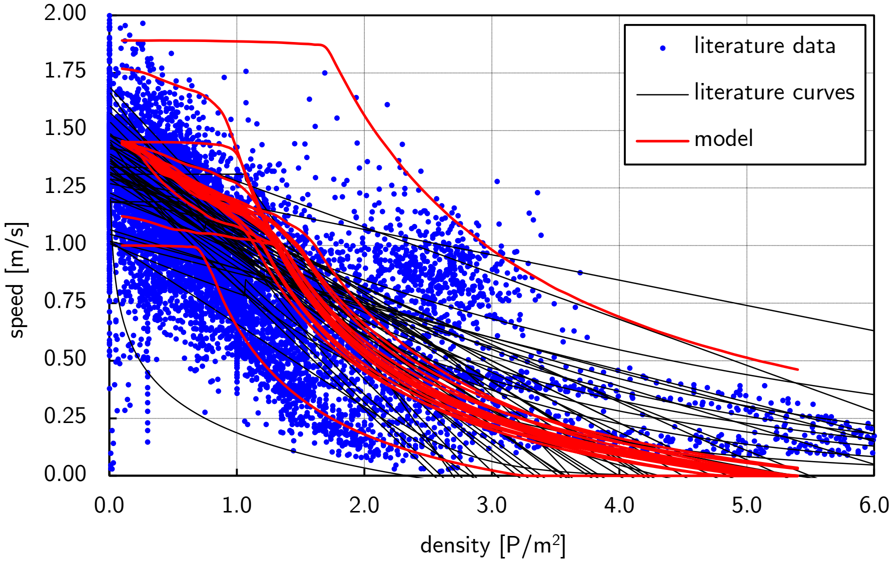

FIGURE 8.9: Resulting fundamental diagrams for studying the model validity for the whole input parameter range in comparison with literature data (Figure 2.40).

the model, the data sources presented in Chapter 7 will be used. For comparison, again the RMSE will be calculated for the density range covered by the empirical data.

Some of the input parameter values are not available from the empirical data. Therefore, they have to be estimated based on the knowledge about the expected value range and the description of the data collection setting.

First, the validation will be done for the movement in a single lane without overtaking. Hence, the model will be reduced to only compute the headway, which can then be compared to the empirical data of the single-file movement experiments. Then general fundamental diagrams will be compared to the model results to determine if model results can reproduce the average speed-density curve. In the final step, situation specific fundamental diagrams will be compared to also show that the model is able to reproduce the changes due to specific influences.

One of the main goals of the model is to be able to reproduce a situation specific fundamental diagram and hence improving the quality of the fundamental diagram estimation. It has to be better at predicting the fundamental diagram compared to the simpler general models available. Otherwise, the application of the complex model created provides no benefit. For this purpose, the Kladek curve proposed by Weidmann (1993) is considered, which is widely used as a general reference curve. In addition, the Kladek curve is also

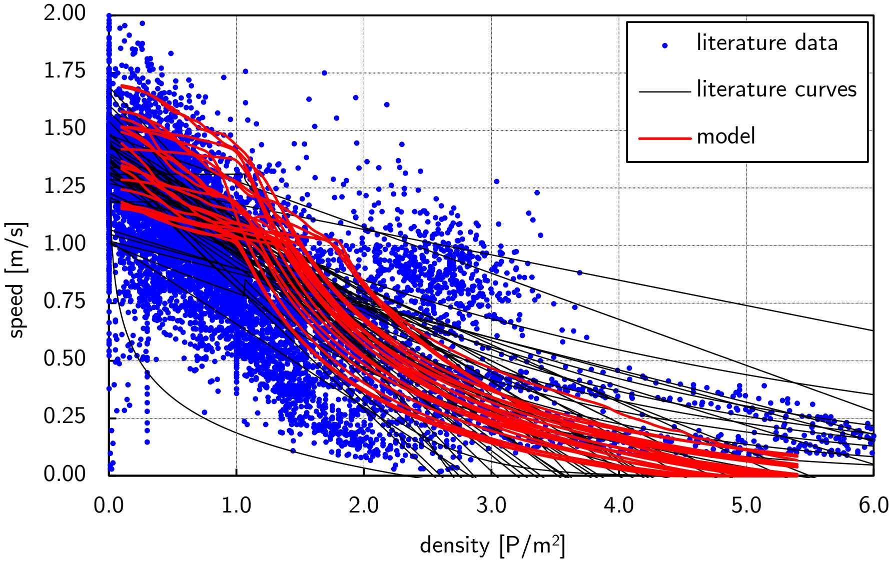

FIGURE 8.10: Resulting fundamental diagrams for studying the model validity for 30 randomly generated parameter distributions in comparison with literature data (Figure 2.40).

adapted to the situations by changing the free flow speed but otherwise using the same parameters. To calculate the curve for the single-file movement data, a lane width of 0.46 m was assumed. This value corresponds to the average lane width in this work. The comparison between the model fit of the original Kladek curve, the adapted Kladek curve and the model results then allows to determine the usefulness of the model.

8.5.4.2 *Rotunde (Forschungszentrum Jülich)*

The Rotunde experiment was performed with students and staff of the Central Institute for Applied Mathematics of the Research Centre Jülich (Seyfried et al., 2007). In addition, it is expected that the attention of pedestrians during experiments is higher than in real-life situations. Therefore, lower reaction and deceleration times are assumed. The estimated input parameters can be found in Table 8.6.

In Figure 8.11, the model results as well as the fundamental diagram calculated from the empirical data is shown. Here, a very good agreement between the mean value of the data and the model can be seen. Also, the RMSE of the speed range showed a good model fit, whereas the Kladek curve shows a considerably worse fit to the data (Table 8.7).

TABLE 8.6: Input parameter: single-file movement, Rotunde (FZ Jülich).

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.15	0.35	0.20	0.03	Normal
Deceleration time t_d	[s]	0.30	1.10	0.50	0.05	Normal
Desired walking speed v_d	[m/s]	–	–	1.24	–	None
Intimate distance d_i	[m]	–	–	0.15	–	None
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	0.60	0.05	Normal
Reaction time t_r	[s]	0.30	0.80	0.50	0.05	Normal

TABLE 8.7: Single-file movement, Rotunde: RMSE for the model, the Kladek curve and the adapted Kladek curve.

	$RMSE\ v_{i,mean}$	$RMSE\ v_{i,SD}$	$RMSE\ v_{i,5\%}$	$RMSE\ v_{i,95\%}$	$RMSE\ v_{t,sd}$	$RMSE\ v_{t,5\%}$	$RMSE\ v_{t,95\%}$
	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
Model	0.030	0.011	0.036	0.035			
Kladek	0.153				0.037	0.235	0.066
Kladek adapted	0.123				0.043	0.216	0.031

8.5.4.3 *Casern data (Forschungszentrum Jülich)*

The casern experiment shows similar characteristics as the Rotunde experiment. However, the participants were all soldiers. The input values were estimated to be the same as for the Rotunde experiment, but the standard distribution was reduced (Table 8.8).

For the Casern data, a good fit of the model was determined (Figure 8.12 and Table 8.9). Also the range of walking speeds is similar, although a stronger difference between the model results and the experimental data is visible. Still, the model fit is considerably better for the model results than for the Kladek formula.

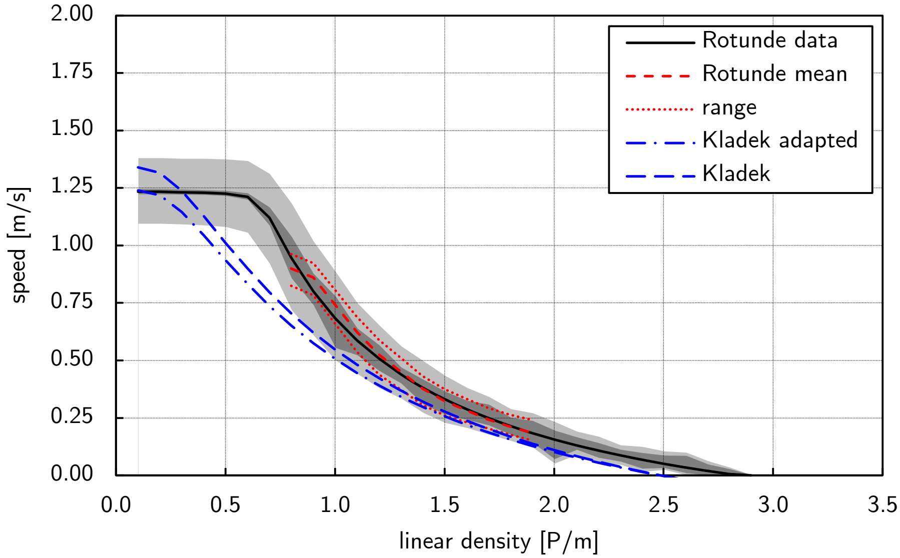

FIGURE 8.11: Single-file movement, Rotunde: linear fundamental diagram and the range of walking speeds (instantaneous and individual, 5 to 95 % percentile) from the model and the reference data. $RMSE\ v_{i,mean} = 0.030\,\mathrm{m/s}$.

TABLE 8.8: Input parameter: single-file movement, Casern (FZ Jülich).

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.15	0.35	0.20	0.01	Normal
Deceleration time t_d	[s]	0.30	1.10	0.50	0.01	Normal
Desired walking speed v_d	[m/s]	–	–	1.24	–	None
Intimate distance d_i	[m]	–	–	0.15	–	None
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	0.60	0.01	Normal
Reaction time t_r	[s]	0.30	0.80	0.50	0.01	Normal

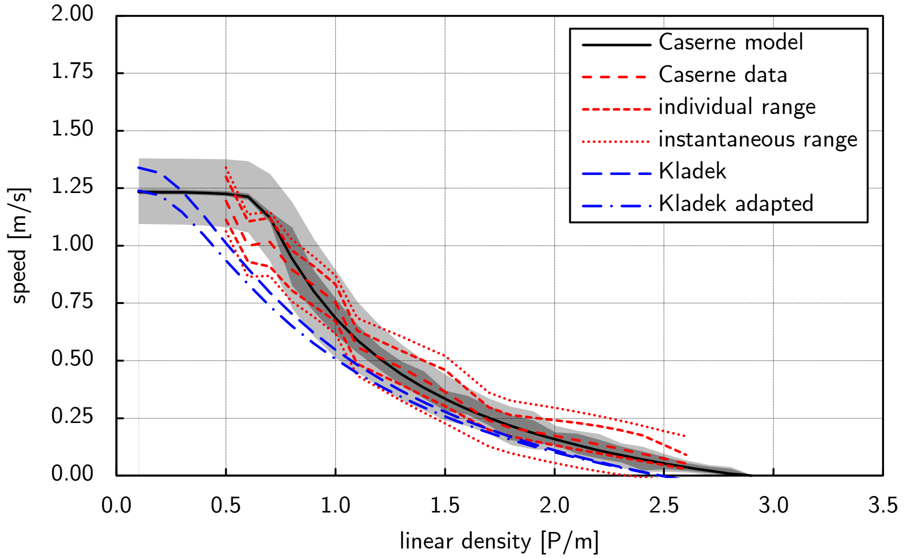

FIGURE 8.12: Single-file movement, Casern: linear fundamental diagram and the range of walking speeds (instantaneous and individual, 5 to 95 % percentile) from the model and the reference data. $RMSE\ v_{i,mean} = 0.058\,\mathrm{m/s}$.

TABLE 8.9: Single-file movement, Casern: RMSE for the model, the Kladek curve and the adapted Kladek curve.

	$RMSE\ v_{i,mean}$ [m/s]	$RMSE\ v_{i,SD}$ [m/s]	$RMSE\ v_{i,5\%}$ [m/s]	$RMSE\ v_{i,95\%}$ [m/s]	$RMSE\ v_{t,sd}$ [m/s]	$RMSE\ v_{t,5\%}$ [m/s]	$RMSE\ v_{t,95\%}$ [m/s]
Model	0.058	0.023	0.077	0.057	0.033	0.060	0.094
Kladek	0.117				0.055	0.184	0.128
Kladek adapted	0.148				0.052	0.204	0.147

8.5.4.4 *Pupils (Forschungszentrum Jülich)*

During the experiments in the two schools of the pupils dataset, experiment runs with different pedestrian compositions were made (Wang et al., 2018a). For the model validation, the input parameters were estimated to represent an average experimental composition (Table 8.10). Hence, all data were compared against one simulation run.

TABLE 8.10: Input parameter: Single-file movement, pupils (FZ Jülich).

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.15	0.35	0.16	0.02	Normal
Deceleration time t_d	[s]	0.30	1.10	0.45	0.10	Normal
Desired walking speed v_d	[m/s]	–	–	1.39	–	None
Intimate distance d_i	[m]	–	–	0.15	–	None
Maximum acceleration a_{max}	[m/s^2]	0.20	0.80	0.50	0.10	Normal
Reaction time t_r	[s]	0.30	0.80	0.40	0.10	Normal

In total, a RMSE for the mean speed of 0.122 m/s was calculated for the model (Figure 8.13). As expected, this value is slightly higher than for the previous experiments due to the use of the mean values for each experiment and the differences in the pedestrian composition. Nevertheless, the RMSE is considerably lower than the one computed for the Kladek formula (0.224 m/s) and the adapted Kladek formula (0.210 m/s).

8.5.4.5 *Chattaraj et al. (2009)*

In Chattaraj et al. (2009), a comparison is made between the Rotunde experiment and a similar experiment made in India. In this experiment, only men were participating and a small intimate distance was mentioned in the paper. Based on the experiment description it can also be concluded that physical contact might have also occurred. Therefore, the input parameters were adapted accordingly and an intimate distance lower than the parameter range set for the model was used (Table 8.11).

Chattaraj et al. (2009) provided linear speed-headway equations for both experiments. Here, the fundamental diagram model is able to reproduce the differences observed (Figure 8.14). Only at low densities, where the linear equations do not produce a maximum walking speed, a strong difference is visible. Consequently, the linear equations were limited to the maximum walking speed as stated in the paper.

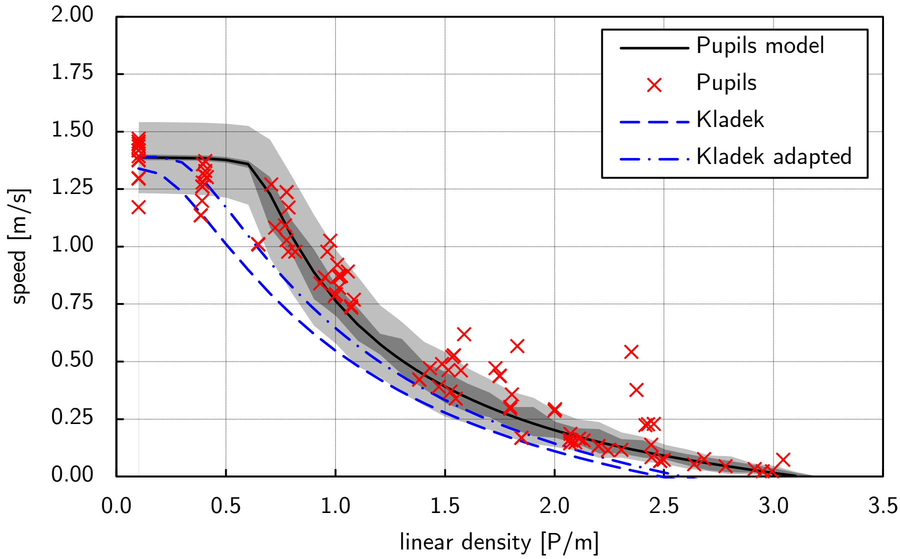

FIGURE 8.13: Single-file movement, Pupils: linear fundamental diagram and the range of walking speeds (instantaneous and individual, 5 to 95 % percentile) from the model and the reference data. *RMSE* $v_{i,mean}$ = 0.122 m/s.

TABLE 8.11: Input parameter: Single-file movement, India (Chattaraj et al. (2009)).

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.15	0.35	0.15	0.01	Normal
Deceleration time t_d	[s]	0.30	1.10	0.40	0.05	Normal
Desired walking speed v_d	[m/s]	–	–	1.27	–	None
Intimate distance d_i	[m]	–	–	0.10	–	None
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	0.70	0.05	Normal
Reaction time t_r	[s]	0.30	0.80	0.35	0.05	Normal

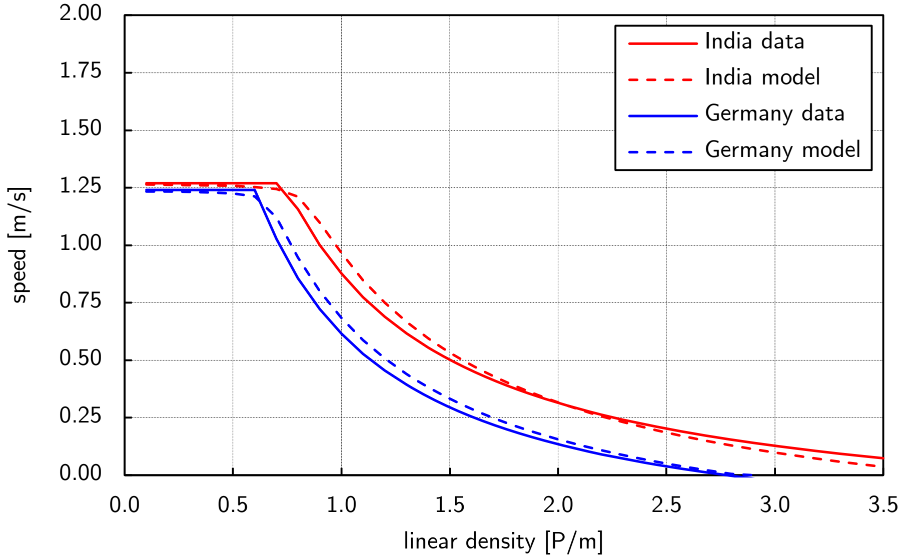

FIGURE 8.14: Single-file movement, Chattaraj et al. (2009): linear fundamental diagram from the model and the reference speed headway equations (Equation 7.1 and Equation 7.2).

8.5.4.6 *Cao et al. (2016a)*

The experiment using different age compositions described in Cao et al. (2016a,b) are used to test whether the model is able to replicate the observed changes in the speed-headway relation when old and young people are mixed. It is mentioned that the young people are familiar with each other and form a homogeneous group. For the old pedestrian group, less detailed information is available.

TABLE 8.12: Input parameter: Cao et al. (2016a), young pedestrian group.

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.15	0.35	0.15	0.01	Normal
Deceleration time t_d	[s]	0.30	1.10	0.35	0.05	Normal
Desired walking speed v_d	[m/s]	–	–	1.23	–	None
Intimate distance d_i	[m]	–	–	0.10	–	None
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	0.70	0.05	Normal
Reaction time t_r	[s]	0.30	0.80	0.35	0.05	Normal

The first estimate of the input parameter values did provide a good fit for the young pedestrian group but too low walking speeds for the old pedestrian group. As the aim of this validation step is to compare the results for the mixed age group, another parameter estimate was done for the old age group (Table 8.12 and Table 8.13). For the mixed pedestrian group, the two other groups were merged alternately, as it is described in the experiment documentation. No other changes in the pedestrian parameters were made.

TABLE 8.13: Input parameter: Cao et al. (2016a), old pedestrian group.

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.15	0.35	0.18	0.02	Normal
Deceleration time t_d	[s]	0.30	1.10	0.60	0.15	Normal
Desired walking speed v_d	[m/s]	–	–	0.95	–	None
Intimate distance d_i	[m]	–	–	0.15	0.01	Normal
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	0.50	0.10	Normal
Reaction time t_r	[s]	0.30	0.80	0.50	0.10	Normal

For comparison with the model results, the linear headway velocity estimates from Cao et al. (Cao et al., 2016b) are used (Figure 8.15). It can be seen that the model is not able to reproduce the experiment results for the mixed group. In the model, the resulting speed-density curve for the mixed group is between the two other groups whereas in the experiment, a lower walking speed was found for a medium density range. Data from higher densities are not available for the old pedestrian group. Two reasons might lead to these results. First, as it is also discussed in the paper, the pedestrian behaviour might have changed in the mixed group. Therefore, the solely merging of the two input parameter sets does not reflect the expected behaviour in the mixed group. For example, it is described that the mean walking speed is higher than expected, hence the older pedestrians walked faster, and the pedestrians tended to keep longer headway between each other's to better avoid collisions. Second, the mixture of pedestrians with strongly different properties might generally lead to a behaviour not included in the model. Thus, further investigations are indicated to better understand the behaviour of pedestrians in mixed settings.

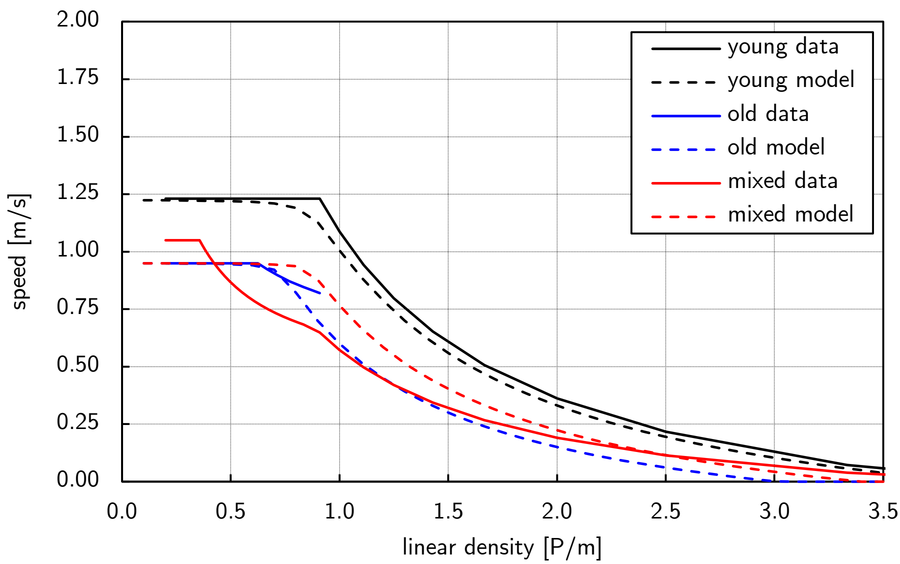

FIGURE 8.15: Single-file movement, Cao et al. (Cao et al., 2016b): Linear fundamental diagram from the model and the reference curves.

8.5.4.7 *Weidmann (1993)*

To compare the average unidirectional fundamental diagram to literature data, the fundamental diagram proposed by Weidmann (1993) is used. In Table 8.14, the corresponding input parameter values used for the model are stated.

TABLE 8.14: Input parameter estimates for Weidmann (1993).

PARAMETER		RANGE OF VALUES				DISTRIBUTION
		MIN.	MAX.	μ	σ	
Body depth d_B	[m]	0.15	0.35	0.25	0.03	Normal
Body width w_B	[m]	0.30	0.50	0.41	0.04	Normal
Deceleration time t_d	[s]	0.30	1.10	0.75	0.12	Normal
Desired walking speed v_d	[m/s]	1.00	1.90	1.34	0.26	Normal
Intimate distance d_i	[m]	0.15	0.20	0.17	0.01	Normal
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	0.50	0.15	Normal
Reaction time t_r	[s]	0.30	0.80	0.60	0.10	Normal
Sway width w_s	[m]	0.04	0.06	0.05	0.01	Normal

The model results show a good agreement to the empirical fundamental diagram, although the modelled walking speeds are slightly lower at higher densities (Figure 8.16). The RMSE for the mean walking speed was calculated to 0.075 m/s (Table 8.15). Otherwise, the range of walking speed is considerably higher for the Weidmann curve.

As the Weidmann curve does not reflect a specific setting or pedestrian composition. A direct comparison is difficult. Especially the range of walking speeds provided represents a mixture of situations and is based only on a limited amount of data, whereas the model only provided the range of walking speeds expected for a specific setting. Still, for validation purposes it can be concluded that the model seems to be able to provide a similar average fundamental diagram as it is available in literature.

TABLE 8.15: RMSE for the comparison with the fundamental diagram from Weidmann (1993).

	RMSE $v_{i,mean}$ [m/s]	RMSE $v_{i,SD}$ [m/s]	RMSE $v_{i,5\%}$ [m/s]	RMSE $v_{i,95\%}$ [m/s]	RMSE $v_{t,sd}$ [m/s]	RMSE $v_{t,5\%}$ [m/s]	RMSE $v_{t,95\%}$ [m/s]
Model	0.075				0.103	0.110	0.168

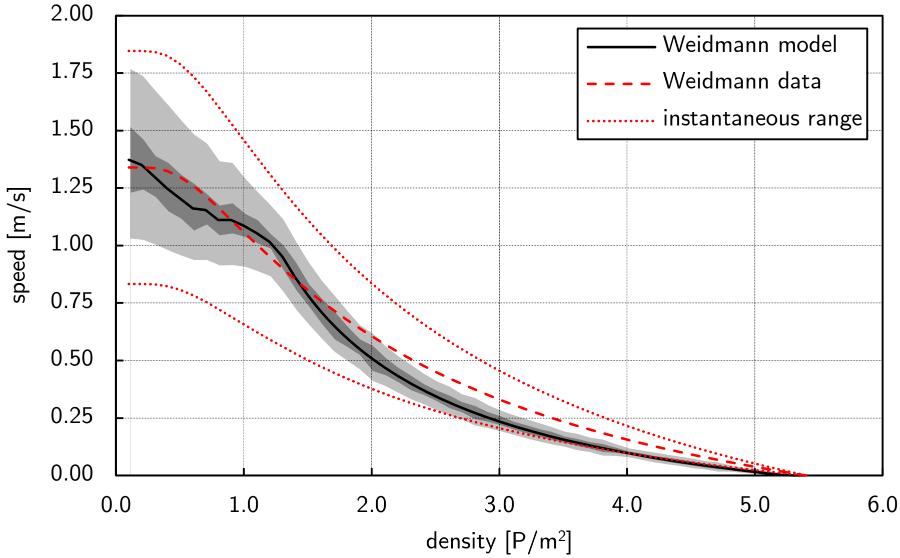

FIGURE 8.16: Fundamental diagram and the range of walking speeds (instantaneous and individual, 5 to 95 % percentile) from the model and the fundamental diagram from Weidmann (1993). $RMSE\ v_{i,mean} = 0.030\,\text{m/s}$.

8.5.4.8 *BaSiGo*

The data from the BaSiGo experiment UNI_CORR_500 can be used to validate the model based on a specific pedestrian group. The participants of the experiment are mainly students, hence based on the experimental description similar values than for the HERMES experiment, which was used for calibration, are estimated (Table 8.16).

Also for this experiment, a good fit between the fundamental diagram obtained from the empirical data and the model was found (Figure 8.17). The range of walking speeds is again lower for the model than the empirical data. Using the Kladek curve resulted in a similar RMSE (Table 8.17). Remarkably, the adapted Kladek curve with a higher desired walking speed shows a worse fit compared to the original curve as proposed by Weidmann (1993).

TABLE 8.16: Input parameter estimates for BaSiGo UNI_CORR_500.

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.15	0.35	0.26	0.02	Normal
Body width w_B	[m]	0.30	0.50	0.44	0.03	Normal
Deceleration time t_d	[s]	0.30	1.10	0.55	0.10	Normal
Desired walking speed v_d	[m/s]	1.00	1.90	1.50	0.20	Normal
Intimate distance d_i	[m]	0.15	0.20	0.17	0.01	Normal
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	0.60	0.10	Normal
Reaction time t_r	[s]	0.30	0.80	0.50	0.10	Normal
Sway width w_s	[m]	0.04	0.06	0.05	0.01	Normal

TABLE 8.17: BaSiGo experiment: RMSE for the model, the Kladek curve and the adapted Kladek curve.

	$RMSE\ v_{i,mean}$	$RMSE\ v_{i,SD}$	$RMSE\ v_{i,5\%}$	$RMSE\ v_{i,95\%}$	$RMSE\ v_{t,sd}$	$RMSE\ v_{t,5\%}$	$RMSE\ v_{t,95\%}$
	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
Model	0.063	0.089	0.151	0.135	0.033	0.095	0.092
Kladek	0.049				0.021	0.107	0.088
Kladek adapted	0.084				0.040	0.053	0.228

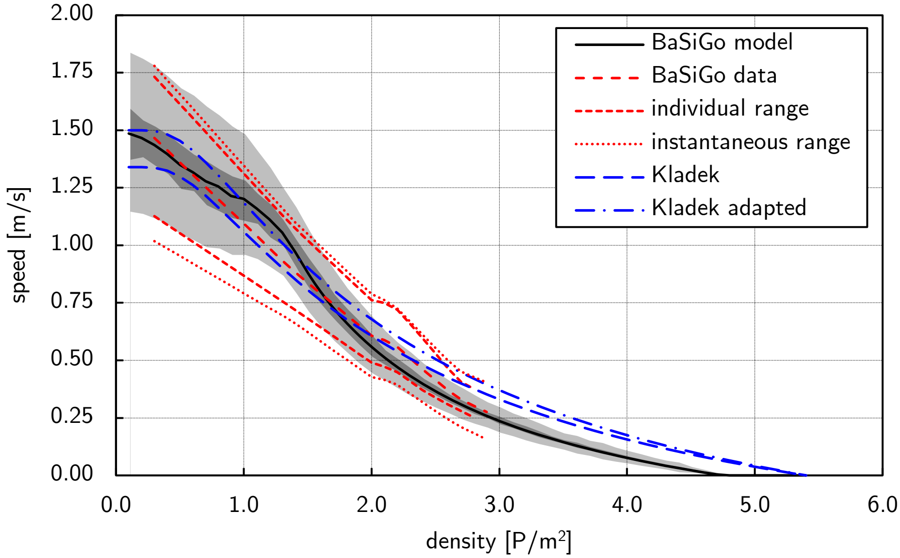

FIGURE 8.17: Fundamental diagram and the range of walking speeds (instantaneous and individual, 5 to 95 % percentile) from the model and the reference data calculated from the BaSiGo experiment. $RMSE\ v_{i,mean} = 0.063\,\mathrm{m/s}$.

8.5.4.9 *Bern SBB*

The real-life data obtained from SBB for the Bern railway station mainly consist of railway passengers. The data are recorded during the whole day as well as on weekdays and weekends. Although different sets of pedestrians are recorded at this location, it will be assumed that the majority of users are regular commuters. The estimated pedestrian composition is therefore shifted slightly towards faster reactions and less personal space (Table 8.18).

TABLE 8.18: Input parameter estimates for the SBB dataset.

PARAMETER		RANGE OF VALUES				DISTRI-
		MIN.	MAX.	μ	σ	BUTION
Body depth d_B	[m]	0.15	0.35	0.25	0.03	Normal
Body width w_B	[m]	0.30	0.50	0.41	0.04	Normal
Deceleration time t_d	[s]	0.30	1.10	0.65	0.15	Normal
Desired walking speed v_d	[m/s]	1.00	1.90	1.30	0.20	Normal
Intimate distance d_i	[m]	0.15	0.20	0.16	0.01	Normal
Maximum acceleration a_{max}	[m/s²]	0.20	0.80	0.70	0.20	Normal
Reaction time t_r	[s]	0.30	0.80	0.55	0.15	Normal
Sway width w_s	[m]	0.04	0.06	0.05	0.01	Normal

For the comparison between the empirical data and the model results, only densities up to 1.7 P/m² are considered, as higher densities almost never occurred. In this density range, a good fit of the model to the data was obtained for the mean value (Figure 8.18). In Table 8.19, the RMSE values are shown. The model as well as the Kladek curve do show an acceptable RMSE for the mean value. For the range of walking speeds a better fit is provided using the Kladek curve and the standard deviation of 19.3 % as proposed by Weidmann (1993).

8.5.4.10 *Conclusion*

Based on the validation against empirical data it can be concluded that the model is able to reproduce the fundamental diagrams for all situations studied accurately enough to be a useful tool for the design of pedestrian facilities. Only when replicating the results from Cao et al. (2016b) it was not possible to obtain similar curves to the mixed pedestrian group. However, it is not clear if the differences are due to weaknesses in the model or due to the specific experiment situation.

When comparing the model results to the results obtained from applying the Kladek formula, similar results can be obtained in most cases. Yet in general, the fundamental model presented shows a better fit for the fundamental

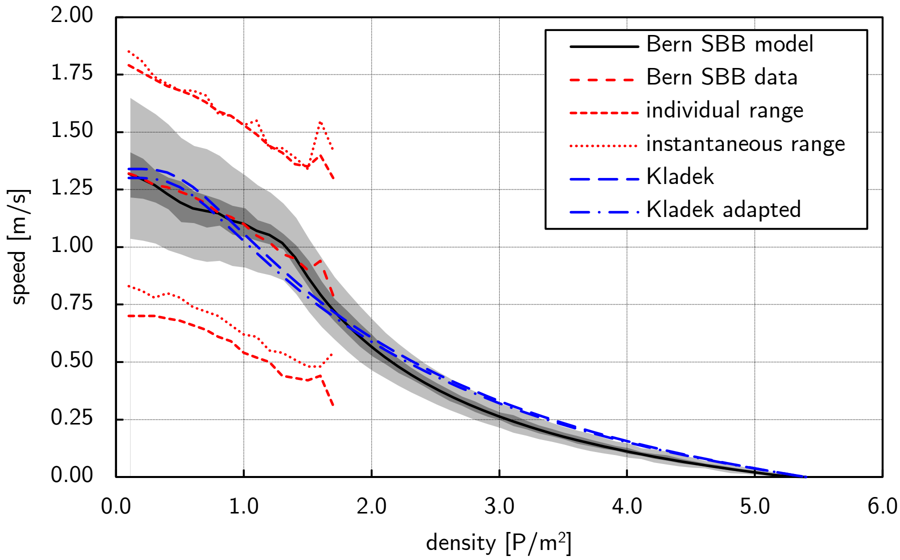

FIGURE 8.18: Fundamental diagram and the range of walking speeds (instantaneous and individual, 5 to 95 % percentile) from the model and the reference data calculated from the SBB dataset of Bern railway station. $RMSE\ v_{i,mean} = 0.047\,\mathrm{m/s}$.

diagram curve. For the walking speed distribution at a single density, a good fit is rarely reached. This is expected to result from the fact that the model represents steady state conditions as well as it contains some simplifications which might impact the speed distribution. Hence, the comparison between the model results and the empirical data is difficult.

Although a good fit of the model was reached for the different data, it was revealed that the estimation of the input parameter is complex. It is not possible to use the same input parameters for the model as in reality, because usually only descriptive data about the pedestrian composition is available. The input parameter values thus have to be set by the model user. As the model parameters are based on the walking principles, these parameters can be estimated in different ways. For some parameters, for example the free flow walking speed, data is available from the experiments. For the physical properties general measurement data based on the specific pedestrian compositions can be used. Other parameter values are currently unavailable. Still, they can be theoretically measured or estimated based on existing knowledge. By applying the model to different empirical data, information about good parameter sets for a given pedestrian composition is provided. Consequently, this knowledge can then be used for the parameter estimation of new pedestrian compositions.

TABLE 8.19: SBB dataset: RMSE for the model, the Kladek curve and the adapted Kladek curve.

	$RMSE\ v_{i,mean}$ [m/s]	$RMSE\ v_{i,SD}$ [m/s]	$RMSE\ v_{i,5\%}$ [m/s]	$RMSE\ v_{i,95\%}$ [m/s]	$RMSE\ v_{t,sd}$ [m/s]	$RMSE\ v_{t,5\%}$ [m/s]	$RMSE\ v_{t,95\%}$ [m/s]
Model	0.047	0.271	0.466	0.405	0.181	0.238	0.290
Kladek	0.071				0.111	0.036	0.196
Kladek adapted	0.081				0.117	0.029	0.213

8.5.5 *Limits of the model validity*

8.5.5.1 *Model purpose*

A model is never a perfect representation of the real system, but it is designed according to the specific model purpose. It is thus necessary to specify the model aims and which limits apply to the parameter values used and the scenarios, in which the model is expected to provide useful results. For all other purposes and situations, first the applicability of the model has to be determined or, if needed, model extensions have to be made. Otherwise the quality of the model cannot be guaranteed.

The primary purpose of the model can be derived from the research question and hypotheses in Chapter 3 and is to provide a tool to estimate the fundamental diagram for design purposes. Therefore, the intended accuracy of the model shall be better than existing fundamental diagrams and should show an acceptable error. This was proven in the model validation by comparing the model results to the Kladek formula proposed by Weidmann (1993). The overall accuracy in comparison to empirical data was usually within the range of $\pm 10\,\%$. This can be accepted in facility design; especially as more precise data is unavailable. Still, a higher accuracy cannot be expected from the model, especially as uncertainties also exist for the input data.

8.5.5.2 *Valid input parameter values*

The model is validated for input parameter values within the range stated in Table 8.20. Within this range, all parameter combinations are expected to produce relevant and accurate results. For parameter values outside this range caution should be applied, as the validity of the results was not tested. However, during the validation against empirical data a lower intimate distance was used with good results. Although not all tests were made to estimate the model validity, no contraindication was found that useful results can also be obtained from the model outside this parameter range.

For single file movement experiments it also seems that the intimate distances are lower than for a unidirectional flow. This can be explained by the fact that pedestrians might not walk straight behind each other but slightly shifted. This behaviour might increase the lane width in this situation compared to the assumed lane width in the model.

Table 8.20: Validated value range for the selection of input parameter.

PARAMETER		RANGE OF VALUES	
		MINIMUM	MAXIMUM
Body depth d_B	[m]	0.15	0.35
Body width w_B	[m]	0.30	0.50
Deceleration time t_d	[s]	0.30	1.10
Desired walking speed v_d	[m/s]	1.00	1.90
Intimate distance d_i	[m]	0.15	0.20
Maximum acceleration a_{max}	[m/s²]	0.20	0.80
Reaction time t_r	[s]	0.30	0.80
Sway width w_s	[m]	0.04	0.06

8.5.5.3 *Model boundaries*

Based on the goals set, the model is intended to only include unidirectional walking behaviour. It is not possible to study bidirectional or multidirectional flows. Also, situations showing boundary effects from walls or obstacles and other influences have to be considered using other methods. Nevertheless, the model can also be useful in these settings as part of a more complex design method.

The parameter values, where the model is expected to provide useful results, cover all standard design situations. However, this does not include extreme pedestrian compositions or settings which considerably deviate from normal situations. For example, panic situations, small children or persons with walking disabilities or military marches cannot be studied with this model, unless the model is revalidated beforehand for these situations. In conclusion, the model boundaries include the relevant situations which are within the scope of this work.

8.6 test of hypotheses

8.6.1 *Introduction*

The model validation did not show any indication that the model results are not valid. Therefore, the research question and hypotheses can now be answered based on the model created.

8.6.2 *Hypothesis 1: basic principles of human walking*

H1: A generic description of human walking can be made, which integrates the principles of interaction with other humans. Based on this, the main principles of walking can be identified in different situations.

In Chapter 5, a generic pedestrian walking model was created based on the available literature. It can be concluded that most aspects of human walking were described in literature, although a comprehensive model of human walking, which includes all relevant principles, was missing. It was possible to integrate the existing knowledge into the human walking model. Here, it was revealed that some interaction principles for complex flows are not known well yet. Still, the hypothesis can be accepted.

8.6.3 *Hypothesis 2: influence on walking*

H2: Several influence factors affect the pedestrian speed and density relation. These influence factors can be expressed by different attribute values used in the generic description of the basic walking principles.

The created pedestrian walking model also allows to study the influence of individual characteristics on the speed density relation. As the model only qualitatively shows the influences, the study of different attribute values is not possible. However, quantitative studies can be made based on the literature study on the pedestrian walking speed (Chapter 2.3 or Bosina and Weidmann (2017c)) or by setting different parameter values for the fundamental diagram model. Thus, this hypothesis can be accepted. Nevertheless, further studies on the different influences are needed to study their specific impact.

8.6.4 *Hypothesis 3: description of the fundamental diagram*

H3: By using the approach presented in this work it will be possible to derive a model for the fundamental diagram based on the principles of human walking.

The corresponding fundamental diagram model was created in Chapter 6 and validated in Chapter 8.5. This hypothesis can therefore be accepted.

8.6.5 *Hypothesis 4: parameter variation*

H4: The changes in the fundamental diagram due to different pedestrian compositions can be simulated.

This hypothesis can be verified based on the model validation. It was shown that the fundamental diagrams from different experiments can be reproduced using the established model, hence the effect of different pedestrian compositions can be reproduced. Nevertheless, during validation some deviations were found which show that a further evaluation of this hypothesis is indicated.

8.6.6 *Research questions*

Is it possible to derive a generic model for the pedestrian fundamental diagram based on the principles of human walking and its relevant influences, so that it can be adapted to every specific situation?

Yes, it was possible to derive a generic fundamental diagram model for unidirectional pedestrian flow. Still, it has to be noted that although the input parameters are based on physical pedestrian characteristics or are measurable properties, most of the parameter values are usually not available. They have to be estimated, which adds uncertainties to the model results. In addition, the model is restricted to the limits of the model validity discussed in Chapter 8.5.5. However, it is expected that the model covers the most important design situations.

9

MODEL APPLICATION

It is far better to foresee even without certainty than not to foresee at all.
— Henri Poincaré, The Foundations of Science

9.1 INTRODUCTION

In this chapter, the validated model will be applied to calculate the fundamental diagram for different scenarios. First, an average pedestrian composition will be modelled in order to derive a standard fundamental diagram. This can contribute to the existing average fundamental diagrams and can serve as a baseline and design tool, if no information is available on the pedestrian composition. Daamen (2004) estimated the effect of different pedestrian characteristics on the fundamental diagram. Using the fundamental diagram model, it is now possible to simulate the changes and compare the model results with the estimates from Daamen. In addition, three scenarios were made showing particular pedestrian compositions. The model will be applied for these settings to obtain situation specific fundamental diagrams.

The input parameters for the models presented are available in the Appendix A.7. For the body dimensions, the data presented in DIN (2013) and DIN (2005) are used as a basis.

9.2 STANDARD FUNDAMENTAL DIAGRAM

The standard fundamental diagram aims at representing the speed-density relation for a global average pedestrian composition (Figure 9.1). Interestingly, the model results show a distinct peak in the flow-density relation, which is located at the transition from the free flow phase to the restricted phase. At this point, all pedestrians in the model reduce their walking speed. There are several reasons possible for the shape of the curve. First, the model represents a steady state and a well distributed pedestrian composition. In addition, almost no random events are present in the model, which in combination results in a quite uniform flow. In reality, also in near steady state conditions, some events might occur, which still have an influence on the fundamental diagram. This distinct peak is also proposed by several authors for vehicular traffic, indicating that it might be also present in the pedestrian fundamental diagram (Coifman, 2014; Knoop and Daamen, 2017). In summary, it is unclear whether this distinct peak occurs due to the steady-state conditions of the model or some simplifications made. Thus, further research is needed on this topic.

For the free-flow region of the fundamental diagram, an almost linear curve is obtained from the model. For the quality based design of pedestrian facilities using the Level of Service, only this region is relevant. Therefore, it seems feasible to use a linear approximation of the fundamental diagram. This can reduce the complexity of the calculations.

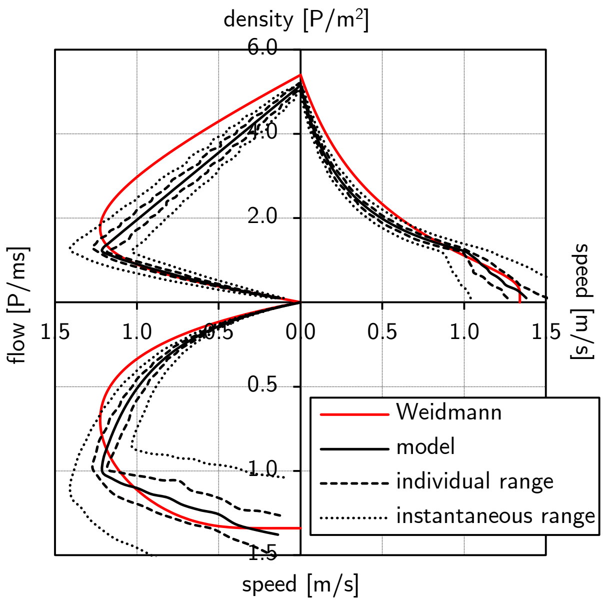

FIGURE 9.1: Simulated fundamental diagram for an estimated global average pedestrian composition.

9.3 INFLUENCE OF INDIVIDUAL PEDESTRIAN CHARACTERISTICS

9.3.1 *Introduction*

Daamen (2004) made some theoretical considerations about the shape of the fundamental diagram for different pedestrian compositions. For these pedestrian groups, the parameter values of the model will be estimated and the model results will be compared to the proposed outcome. The estimated input parameter values are shown in Appendix A.7.

9.3.2 *Age*

As it is described in Chapter 2.3.5.2, the free flow walking speed is heavily dependent on the age of the pedestrian. The walking speed strongly increases until the age of about 20 and then decreases again. For comparison of the fundamental diagram for different age groups roughly the age groups of 20 to 30 years and 70 to 80 will be compared. For these two groups, the input parameters will be estimated. Apart from the differences in the desired speed it is assumed that younger pedestrians react quicker and keep a smaller intimate distance. Also, the body depth is slightly different according to the data.

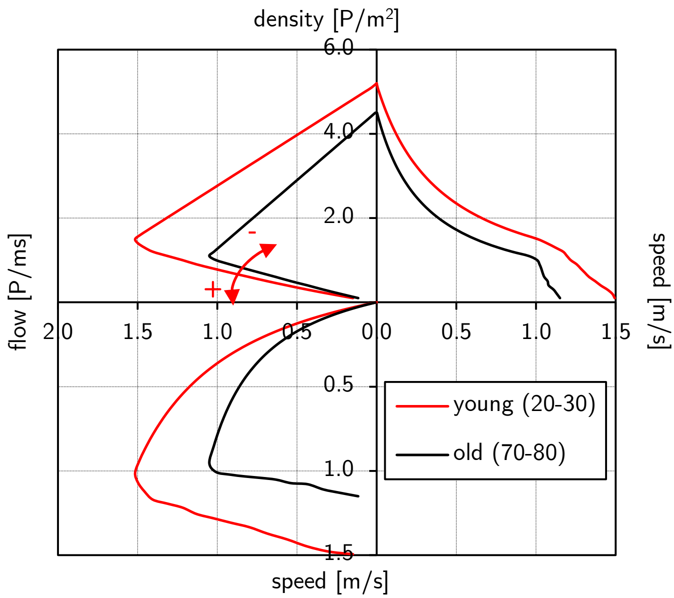

Figure 9.2: Comparison between the calculated fundamental diagram for an old and a young age group. Arrows indicate the expected curve behaviour according to Daamen (2004), colour shows the agreement.

The resulting fundamental diagrams for these two groups differ considerably (Figure 9.2). In contrary to the estimates from Daamen (2004), the increase in flow is steeper for the young pedestrian group. Still, as the influence of age on the free flow walking speed and other pedestrian properties is linear, a comparison between children and adult pedestrians would lead to a different result. Here, no further description is available in Daamen (2004). In addition, a significant higher maximum flow at a slightly higher density was simulated. The maximum densities are also expected to be higher for the young pedestrian group.

9.3.3 *Culture*

Among others, Chattaraj (2009) showed in his work that cultural differences in the walking behaviour exist between different regions. This is partly because of the differences in the body size, but also the dimensions of personal space differ between cultures (Hall, 1966). These observations were integrated into the input parameters for these two groups.

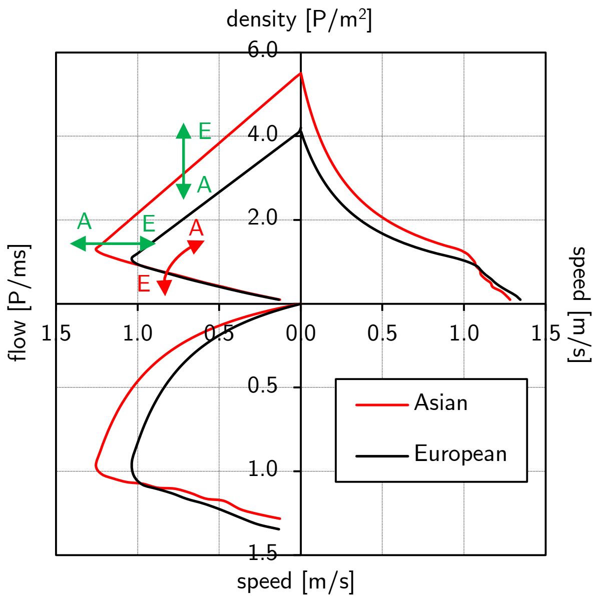

FIGURE 9.3: Comparison between the calculated fundamental diagram for Asian and European people. Arrows indicate the expected curve behaviour according to Daamen (2004), colour shows the agreement.

In Figure 9.3, the model results are shown. Apart from the slope of the flow curve in the free flow regime, where no clear difference is visible, the results correspond to the expected behaviour. Still, in comparison to the expected results, the estimate for the European group at high densities seems to be too low. In general, a higher maximum density would be expected here.

9.3.4 *Gender*

At the free flow walking speed, a clear difference between the genders is visible in most situations (Chapter 2.3.5.1). But also, the other input parameters are estimated to differ slightly between men and women. As expected, these differences are also visible in the fundamental diagram, although the differences are small (Figure 9.4). Here, the higher desired walking speed of men is also visible. Nevertheless, almost no difference in the pedestrian flow at low densities exist. At higher densities and for the maximum flow, higher flow values are visible for women due to their smaller body space.

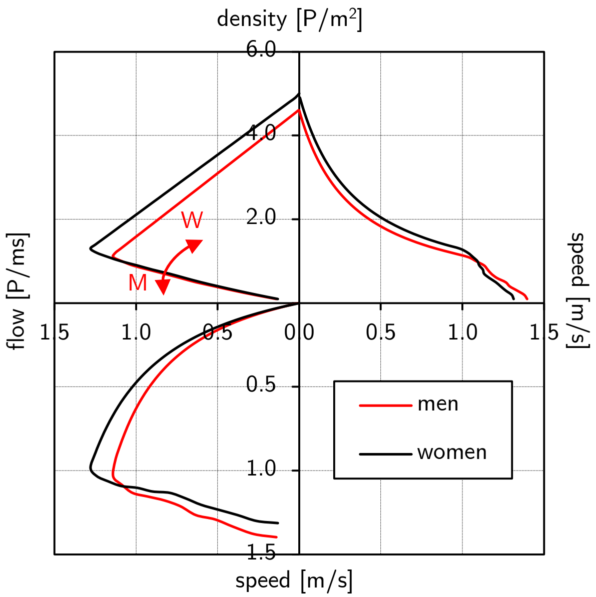

FIGURE 9.4: Comparison between the calculated fundamental diagram for men and women. Arrows indicate the expected curve behaviour according to Daamen (2004), colour shows the agreement.

9.3.5 *Temperature*

An influence of temperature is mainly expected for the free flow walking speed, which is in general higher for lower temperatures. In addition, it was assumed that pedestrians at lower temperatures have slightly lower reaction times and accelerate faster. Still, the results indicate that the influence of the temperature on the fundamental diagram is low (Figure 9.5). Only at low densities the higher walking speed for low temperature is visible, whereas otherwise the differences are minimal.

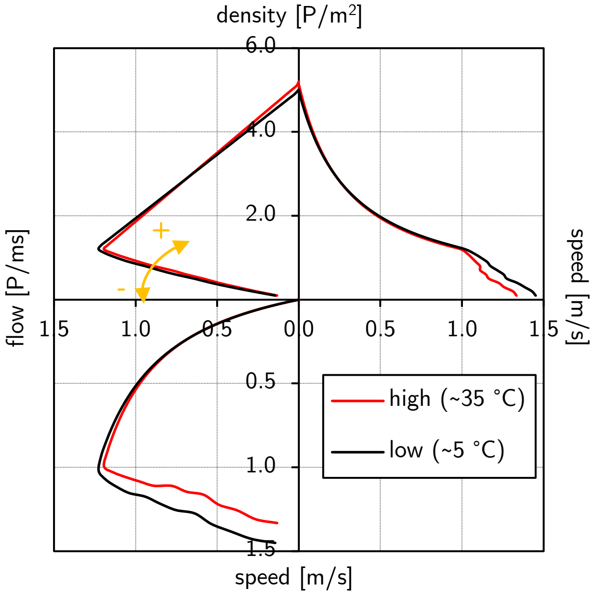

FIGURE 9.5: Comparison between the calculated fundamental diagram for cold and warm temperatures. Arrows indicate the expected curve behaviour according to Daamen (2004), colour shows the agreement.

9.3.6 *Travel purpose*

Also the travel purpose was addressed by Daamen (2004). Pedestrians walk slower on average during leisure trips than in business trips (Figure 9.6). It was additionally assumed that pedestrians react quicker and have a smaller intimate distance in business trips. This results in a fundamental diagram showing a considerably higher maximum flow, as well as generally higher flow values than for leisure trips.

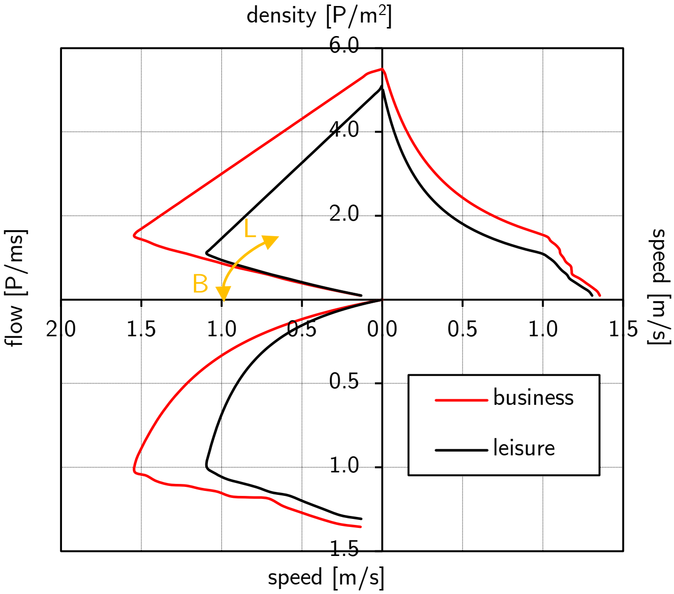

Figure 9.6: Comparison between the calculated fundamental diagram for commuters and leisure travellers. Arrows indicate the expected curve behaviour according to Daamen (2004), colour shows the agreement.

9.4 railway station: commuters and leisure travel

In railway stations, commuter flows, which are usually expected to be fast and goal-oriented, are more and more mixed with pedestrians visiting the station for shopping or leisure. It is expected that these two groups have different characteristics and hence also show significant differences in the fundamental diagram.

Therefore, in this scenario the effect of a mixture between commuters and people going shopping is studied. For this, three simulations were made, one for each group separately and one where pedestrians from both groups were mixed randomly (Figure 9.7). As expected, a clear difference between the commuters and the shoppers can be seen. Interestingly, the mixture of the two groups resulted in a fundamental diagram curve closer to the lower curve of shoppers. This indicates that a mixture of different pedestrian groups, which will also lead to a wider distribution of parameter values, does have a negative influence on the pedestrian flow.

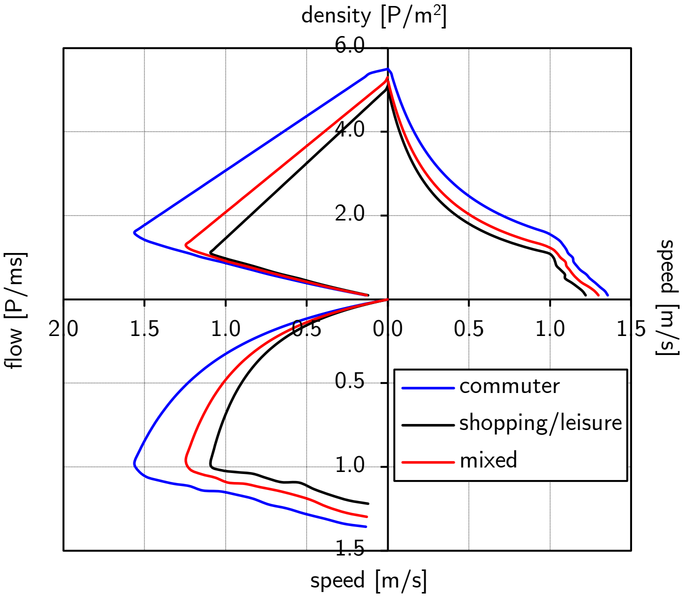

FIGURE 9.7: Comparison between the calculated fundamental diagram for commuters and leisure/shopping travellers and a mixture of both groups.

9.5 FESTIVALS

Festivals and other big outdoor events can attract a very high amount of people in locations, which are often not designed specifically for this purpose. In addition, the pedestrian composition is considerably different from the average. For this purpose, now a fundamental diagram for festivals is estimated (Figure 9.8). The main assumptions here are that mostly young pedestrians will attend and they are not in a hurry. Hence, low walking speeds and slow reactions, but lower variations and smaller intimate distances are assumed. This then also leads to lower pedestrian flows throughout the whole density range.

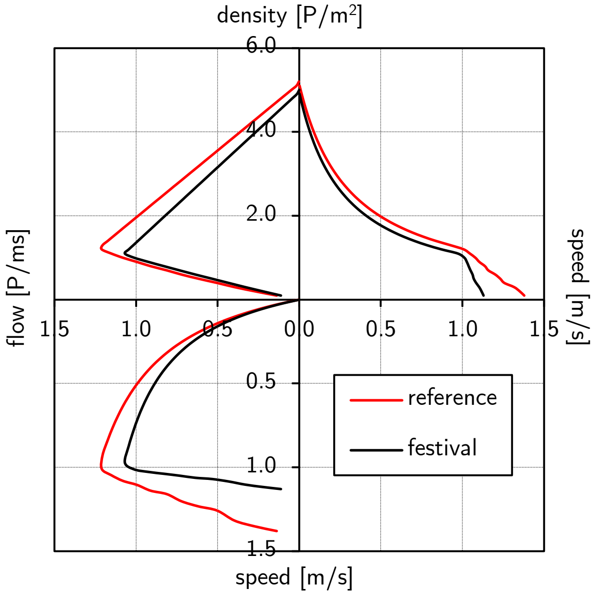

FIGURE 9.8: Simulated fundamental diagram for festivals.

9.6 FUNDAMENTAL DIAGRAM 2050

One of the main reasons why a generic fundamental diagram is useful is that pedestrian compositions can be simulated for situations, where no measurement data is available. Thus, this scenario aims now at estimating the changes of the fundamental diagram due to the expected trends and generate a fundamental diagram for the year 2050 in a European context.

Different trends are postulated which influence the pedestrian characteristics, sometimes also in opposite direction:

- In most countries the average age as well as the share of older people is rising, which leads to more pedestrians with lower walking speeds.
- People are getting taller, which increases the average walking speed.
- The average body weight increases which also influences the body width and depth.
- Indications exist that people are getting more and more individualistic, which might also have an influence on the distances kept while walking.
- Distraction from smartphones or other electronic devices might rise, increasing the reaction times.

- Further optimizations in public transport reliability and information technologies might increase the stress level for working people, which will be visible in the pedestrian characteristics.

Based on these trends a new set of input parameter values was estimated and the fundamental diagram was determined (Figure 9.9). Based on these assumptions, especially in the higher density ranges, a decrease in the flow values is visible. At lower densities, only minor changes occur. This indicates that, in addition to the increase in the demand, facilities should also be designed for a decrease in the flow values in the fundamental diagram.

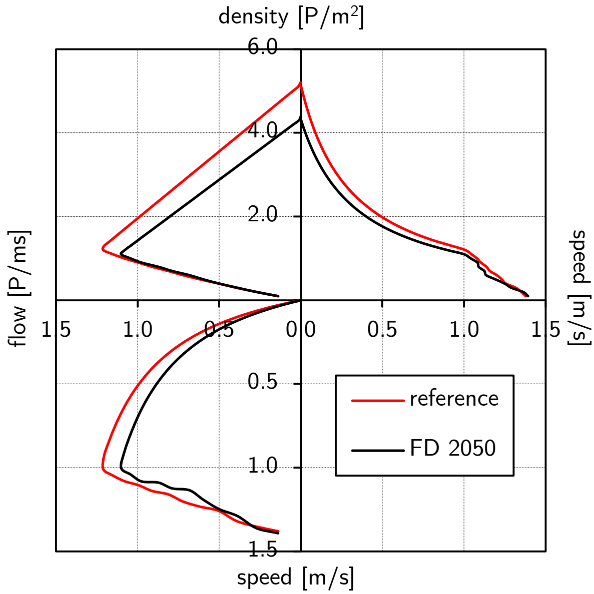

FIGURE 9.9: Estimated fundamental diagram for the year 2050.

10

DISCUSSION AND SYNTHESIS

In every walk with nature one receives far more than he seeks.

— John Muir, Mormon Lilies

10.1 OVERVIEW

In this chapter, the results of this work as well as the contributions to the research question are summarized. The method used is critically analysed by discussing the strength and weaknesses of the research approach and the model created. Further, the implication of the findings on the design of pedestrian facilities and the Level of Service concept will be evaluated. In addition, the potentials as well as the limitations will be discussed. Last but not least, recommendations about areas showing a need for further research will be made.

10.2 SYNOPSIS

The main idea behind this work is that a generic description of human walking could be used to create a pedestrian fundamental diagram. Such a model would be able to describe the basic walking principles and the interactions of humans while walking and thus provide more information than existing models using analogies. This idea was tested by developing a generic model for the generation of situation specific fundamental diagrams. These fundamental diagrams are expected to be useful for a more precise design of pedestrian facilities. This led to the research question:

Is it possible to derive a generic model for the pedestrian fundamental diagram based on the principles of human walking and its relevant influences, so that it can be adapted to every specific situation?

The research question was answered by creating a generic fundamental diagram model whose input parameters can be adapted according to the estimated pedestrian composition. For the fundamental diagram model a pedestrian walking model was used as a basis, which describes the main walking principles focussing on an individual pedestrian. For this, the most important aspects of human walking were extracted from literature and combined to a generic walking model. Apart from building the foundation for the fundamental diagram model it will be useful to study the main principles of walking and the effect of different influences on the walking behaviour. Here, also the proposed hypotheses about the human walking model have been accepted.

Given the limitations set in this work, the research question can be answered in the affirmative. The model provides a generic fundamental diagram model for unidirectional flow. It was validated using empirical data and found to describe the speed-density relation adequately enough to be useful for the design of pedestrian facilities and other applications. For example, the model results can be compared to empirical data to obtain further insights about relevant influences. The results can also be used for the the validation and calibration of other pedestrian model, if no empirical data is available.

Compared to other widely used models, namely the fundamental diagram proposed by Weidmann (1993), a good fit to the empirical data was found. It can be recommended to use the model for situations, where no empirical data is available. If the input parameter values cannot be estimated well enough, it is suggested to use an adapted Kladek curve with a situation specific free-flow speed.

Apart from answering the research question and hypotheses, several other contributions were made in this work. A review of the literature on walking speed measurements were made. This allowed to estimate the effect of different influences on the pedestrian walking speed. It was found that no clear definition of the fundamental diagram exists which is suitable for the purpose of this work and hence make it easier to find right measurement procedures. Here, a new definition of the fundamental diagram was proposed.

For design purposes, the fundamental diagram is closely linked to the Level of Service concept. Therefore, the existing literature on this topic was studied. It was concluded that, similar to the fundamental diagram, the time aspect is not very well considered. Thus, this issue was also addressed.

Besides the field of facility design, the generic pedestrian walking model and the fundamental diagram model can be useful for many purposes. For example, as they are based on a thoroughly literature review, they can be used to detect existing research gaps. As a generic framework, they also allow to be extended and refined further.

10.3 STRENGTHS AND WEAKNESSES

The main strength of the applied concept, a generic approach to the pedestrian fundamental diagram, is clearly the close link to the real walking behaviour. It was possible to model a fundamental diagram without the need of using analogies as it is done in other microsimulation models such as the social force model. The resulting model is capable of simulating synthetic pedestrian compositions, hence making it possible to generate specific fundamental diagrams even for situations where no measurement data exist. The validation also showed that the results do correspond well to the empirical values for the situations considered. Based on this, the model can be recommended for use if no empirical data is available.

The model creation was heavily based on existing knowledge extracted from literature in the relevant fields. Most aspects of human walking are already described in detail there. Hence, by using this information an efficient progress on this work was possible. In addition, no similar studies were found aiming at integrating all aspects of walking into a single model, which provides some novelty to the approach in this field. In this work, it was also decided to rely on available empirical data for the model calibration and verification rather than performing own measurements. This allowed to have measurement data available for a variety of settings which would not have been possible to cover by own measurements. Therefore, the validation and calibration was based on a broader range of parameter values.

A drawback of this method is obviously the fact that literature sources are usually made with a certain background; hence focussing on specific aspects from a distinct point of view. The combination of these aspects can be challenging, and it is difficult to judge if all relevant aspects are covered by the existing literature. Specifically, the focus on this thesis is clearly on the design of pedestrian facilities. However, studies about physical walking principles are mainly done by researchers with a medical or biomechanical background. Distance behaviour is researched by social scientists and psychologists. Mainly the work on pedestrian flows can be related to the field of civil engineering. These differences in the background do result in different research focuses. When creating a coherent model this can result in difficulties.

The model is based on a strict definition of the fundamental diagram. It is valid only for unidirectional steady state flow, which in reality will never be reached. Nevertheless, using real-life data from SBB showed that even though these conditions might not be met in reality, reasonably similar conditions could also be assumed in these settings. Here, further calculation steps are needed to transform the results of the fundamental diagram models to applicable design values.

Although the model parameters are derived from physical, psychological or similar quantities, their estimates were often found to be challenging. Here, useful literature values were often scarce, in particular as these properties were often determined for a different purpose, if measured at all. This then also limits the usability of the model, as experience is needed to estimate adequate parameter values for a specific setting. Nevertheless, the situations presented in the calibration and validation provide some insights about appropriate input parameter values, which can be used as orientation for other setting. New model applications for known situations will then provide further information.

During model creation it was found to be difficult to establish a fully two-dimensional model which produces reasonable results. Therefore, the final model still consists of lane movement with the implementation of lane-changing behaviour. In this aspect it is assumed that some knowledge about the influence of lateral distances on the fundamental diagram is missing. It seems that the interaction and distances kept to others while walking in a unidirectional flow are not yet well researched. Closely coupled to this is the overtaking behaviour. Depending on the distances kept between pedestrians, overtaking is possible or severely restricted. Lane changing behaviour, which is needed for overtaking, was mainly experienced at lower densities in the model. Still, it is unclear if this behaviour corresponds to the real-life situation. Empirical observations are needed to get more insights in this topic.

Although the model did produce good estimates for the average walking speeds expressed in the fundamental diagram, the range of walking speeds did differ considerably from the empirical results for some situations. Here, two explanations are possible. Either the model underestimates the variations in walking speeds or the differences exist due to the steady state, which is very well reached in the model but almost never reached in reality. In addition, the model did show less stop-and-go waves compared to experimental data. Although the main results are not affected by this, it can be considered as a weakness of the model.

The maximum density is a property, for which a wide range of values can be found in literature. Roughly, a range between 4 and 11 $^{P}/_{m^2}$ can be found in literature. Compared to this range, in the model application some unexpected low maximum densities were computed, for example for festivals. Still, it is unclear, how these densities are generated in real life. If pedestrians are pushed from one direction, force might be applied from outside the area and higher density are reached. These densities, as well as the generated movement, are not obtained from the flow itself, but from an external source which is not included in the fundamental diagram.

10.4 FACILITY DESIGN AND LEVEL OF SERVICE

The main purpose of the created fundamental diagram model is to serve as a tool for the quantitative design of pedestrian facilities. Here, the fundamental diagram is used to determine the capacity of a facility as well as, in conjunction with the Level of Service concept, to ensure a certain quality of the flow.

The created model provides situation specific fundamental diagrams for the planner; hence a better estimation of the capacity is reached. In addition, as the Level of Service is usually expressed by a certain density, different flow and speed values are derived for the same density limits, depending on the expected situation. Potentially, this can also lead to different service levels for the same flow values.

Usually, the different quality levels are distinguished based on specific flow characteristics, such as the ability to freely select the walking speed or to bypass other pedestrians (Fruin, 1971a; Oeding, 1963; Weidmann, 1993). But up to now, the assignment of these properties to specific densities is only based on very little available data. As the generic model aims at replicating the main walking principles it can also be used to estimate these abilities. For example, the amount of overtaking at each density can be estimated for different pedestrian compositions. This can lead to a situation specific determination of the density limits within the Level of Service concept. Hence a more precise definition of the Level of Service can be made, resulting in a better facility design.

Nevertheless, the model was not validated in respect to these properties, as the Level of Service was not the main focus of this work. Especially it is unclear, if the existence of overtaking is done precise enough for this purpose. In addition, as the model only considers unidirectional flow, some of the parameters used to distinguish the levels cannot be estimated using the model. Obviously, more research is needed on this topic. The generated model can serve here as a starting point.

10.5 ADAPTABILITY, EXTENDIBILITY AND LIMITATIONS

One advantage of a generic approach is its flexibility. As the model aims at being as close as possible to the real walking behaviour, as it is known today, refinements of parts of the models are usually possible without the need for fundamental changes. Obviously, due to the complexity of the topic and some knowledge gaps, some parts of the model only estimate roughly the behaviour based on the current knowledge. Here, it is possible to improve the model, if new results are available.

It is also possible to extend the fundamental diagram model to also include fully two-dimensional behaviour or other walking behaviour like bidirectional or crossing flows. However, during the model creation it was observed that it was not possible to extend the model for unlimited lateral movement. Here, it seemed that some interaction principles are not yet described well enough to be able to produce a valid generic model. It is unclear, whether some model assumptions did not represent the real behaviour well enough or relevant processes are missing in the model. Still, the aim of this model is to generate generic fundamental diagrams and not to model complex pedestrian facilities, for which other models exist.

Naturally, a modelling approach always has certain limitations. Relying on literature and literature data does not ensure that the information is coherent and aligned with the specific task. Thus, some assumptions have to be made in order to make different sources comparable and suitable for this work. This obviously also produces some uncertainties in the data. Still, the model validation did not reveal any severe shortcomings.

The model itself is limited to unidirectional flow and focuses on the design purpose. Therefore, the model cannot be used to explain certain microscopic phenomena. The accuracy of the model can be estimated to be in the range of $\pm 10\,\%$, which might be too large for some applications. Here, the quality of the model results also strongly relies on the quality of the input parameter estimation. Although they are based on theoretically measurable quantities, they are often unknown. Still, the parameter values for the calibration, validation and application scenarios can be used as reference for future uses.

10.6 PERSPECTIVES FOR FURTHER RESEARCH

Throughout this work, several research gaps and needs were identified. Clearly, as literature from a variety of fields was combined, comparability and coordination was always an issue. Also within some fields, an agreement on basic techniques and definitions seems to be missing, for example when measuring walking speed or calculating a fundamental diagram. Although the application of different techniques and approaches is essential to gather new knowledge, without certain agreements the use of the research for similar work is reduced. Walking speed is measured since decades, however the comparability between different measurements is still challenging. Different measurement and evaluation techniques were applied, but often basic information about the measurements are missing. Describing the main influence parameters on the walking speed would already improve the comparability for future research. Other examples where consensus is appreciated are the definition of the fundamental diagram or the measurement of pedestrian density.

Different research communities concentrate of different aspects of walking. This leaves gaps in between, which hinder the generation of a complete and coherent model of human walking. Especially the microscopic interaction of pedestrians and the distances kept to each other in certain scenarios is only little researched. Further knowledge in this area can help to understand how exactly pedestrians are reacting to others in their vicinity and thus improve the interaction models. In particular the overtaking behaviour seems to be underrepresented in the literature. Although it is commonly accepted that pedestrians are overtaking, little literature is available on the space demand as well as the density regions, where overtaking is relevant. The ongoing improvements in the field of pedestrian detection and tracking will enable to collect better data and to intensify the research in this field.

The biomechanical processes of walking and the transport related quantities of walking are well discussed in literature. Still, widely missing are the psychological aspects of walking. Research is encouraged to better understand the behavioural aspects of pedestrian navigation around other pedestrians. Especially related to the Level of Service concept also aspects on the perceived quality and the emotions while walking can be used to design facilities closer to the needs and desires of pedestrian. When a broader view on the topic of pedestrian flows is made also the macroscopic flow behaviour is relevant and needs further attention. For example, a wide range of maximum density values is documented. Here, further research is needed to understand the creation of these densities. The questions, whether these densities occur from within a uniform flow or are due to external influences and the relation between the area and the density are still not answered satisfactorily.

Another promising research idea in this field is the data driven approach, like it was done by Duives et al. (2017) for a similar topic. More and better detection and tracking technologies are being developed, also allowing long term measurements in real-life situations. Here, the amount and resolution of the measurement data allows to study the distribution of microscopic characteristics. For example, it might be possible to quantify the input parameters of the fundamental diagram model or to improve the model based on insights gained from observing real-life behaviour.

Apart from these suggested topics there are obviously many more open questions in the related fields. As this work shows, closing these research gaps can also help fostering research in fields not considered. In the end, the greatest help for future research is to make results and especially data publicly available.

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APPENDIX

A.1 WALKING SPEED LITERATURE

Estimating pedestrian speed using aggregated literature data (Chapter 2.3 and Bosina and Weidmann (2017c)) – used data:

Akcelik & Associates Pty Ltd (2001). An Investigation of Pedestrian Movement Characteristics at Mid-Block Signalized Crossings. Victoria: Akcelik & Associates Pty Ltd.

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A.2 FUNDAMENTAL DIAGRAM MODEL – PYTHON CODE

A.2.1 *Model structure*

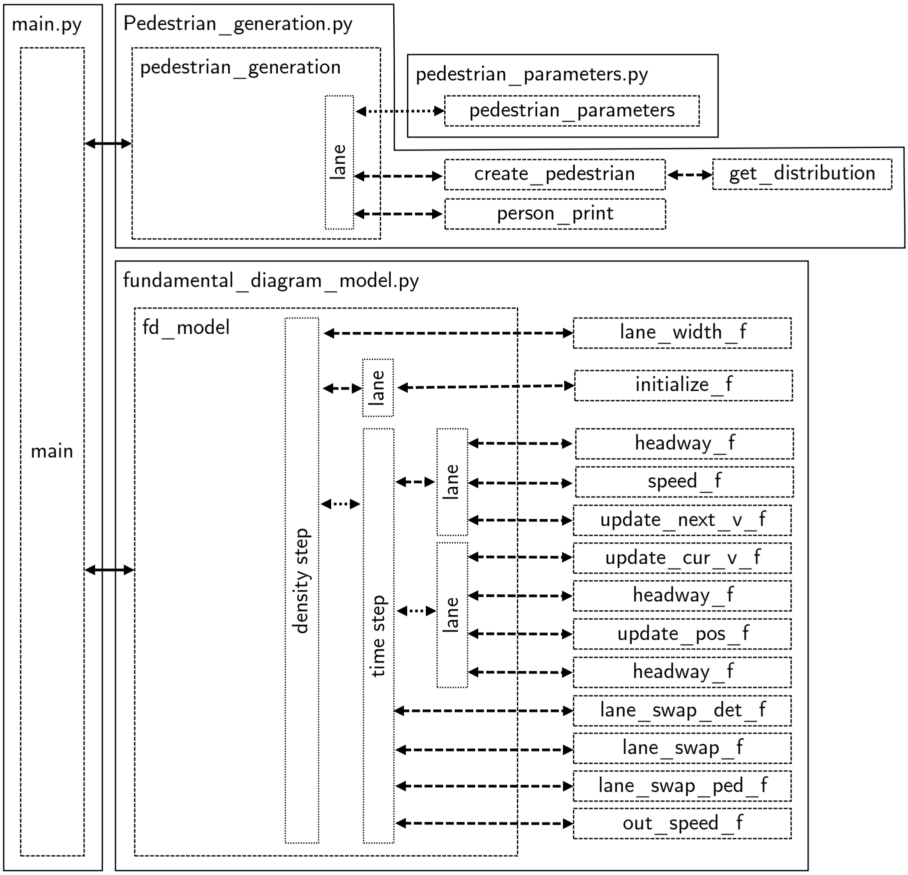

FIGURE A.1: Model structure of final model (Model E)

The python files are reduced to minimize the space demand. The complete files are available at:

http://dx.doi.org/10.3929/ethz-b-000290796

A.2.2 *main.py*

```
from class_sim_param import SimulationParameter
from class_glob_ped_char import GlobalPedestrianCharacteristics
from fundamental_diagram_model import fd_model
from pedestrian_generation import pedestrian_generation
```

```
def main():
    """
    Definition of the simulation parameters and simulation inputs
    Please specify the limits and distributions of the input parameters in the
    file pedestrian_generation.py
    """

    simulation = SimulationParameter()
    input_values = GlobalPedestrianCharacteristics()

    simulation.density_max = 5.4
    simulation.no_ped = 100
    simulation.duration = 1000
    simulation.resolution = 0.1
    simulation.interval = 0.10
    simulation.last_x = 1000
    simulation.lanes = 10
    input_values.ts_skip = 100

    input_values.random_noise = 0.07
    input_values.step_duration = 1
    input_values.max_react = 0.6
    input_values.speed_thresh = 0.00
    input_values.reaction_delay_min = 0.300
    input_values.reaction_delay_max = 0.300
    input_values.lane_back = 3.5
    input_values.reaction_headway = 4

    person = pedestrian_generation(simulation.lanes, simulation.no_ped)

    (d, v_mean, v_indiv, v_total) = fd_model(simulation, input_values, person)
```

A.2.3 *pedestrian_generation.py*

```
import numpy as np
from scipy.stats import truncnorm
from class_pedestrian import Pedestrian
from pedestrian_parameters import pedestrian_parameters


def pedestrian_generation(lanes, no_ped):
    ''' set pedestrians for each lane '''

    p_lanes = [0 for x in range(lanes)]

    for k in range(lanes):
        p_min, p_max, p_mu, p_sigma, dist = pedestrian_parameters()
        p_lanes[k] = create_ped(p_min, p_max, p_mu, p_sigma, dist, no_ped)
        p_lanes[k].p_id = p_lanes[k].p_id + 10000 * k

    return p_lanes


def create_ped(p_min, p_max, p_mu, p_sigma, distribution, no_ped):
    ''' return set of pedestrians in one pedestrian object '''

    attr_all = dir(p_min)
    attributes = list()
    for i in attr_all:
        if not i.startswith('_') and i != 'p_id':
            attributes.append(i)
```

```
    person = Pedestrian()
    person.p_id = np.arange(1, no_ped+1)

    for i in attributes:
        minimum = getattr(p_min, i)
        maximum = getattr(p_max, i)
        m_u = getattr(p_mu, i)
        sigma = getattr(p_sigma, i)
        dist = getattr(distribution, i)
        values = get_distribution(no_ped, dist, minimum, maximum, m_u, sigma)
        setattr(person, i, values)

    return person


def get_distribution(number, distribution, mini, maxi, m_u, sigma):
    ''' create distributed values '''

    if distribution == 0:
        return truncnorm.rvs((mini - m_u) / sigma, (maxi - m_u) / sigma,
                             loc=m_u, scale=sigma, size=number)
    elif distribution == 1:
        return (maxi + mini)/2 * np.ones(number)
    elif distribution == 2:
        return np.random.uniform(mini, maxi, (number,))
    elif distribution == 3:
        return np.ones(number) * maxi
    elif distribution == 4:
        return np.ones(number) * mini
    else:
        print('Distribution not set')
        return 0
```

A.2.4 *pedestrian_parameters.py*

```
from class_pedestrian import Pedestrian


def pedestrian_parameters():
    ''' creates characteristics for given number of pedestrians '''

    p_min = Pedestrian()
    p_max = Pedestrian()
    p_mu = Pedestrian()
    p_sigma = Pedestrian()
    distribution = Pedestrian()

    p_min.desired_v = 1.00
    p_max.desired_v = 1.90
    p_mu.desired_v = 1.45
    p_sigma.desired_v = 0.20
    distribution.desired_v = 0

    p_min.b_width = 0.30
    p_max.b_width = 0.50
    p_mu.b_width = 0.40
    p_sigma.b_width = 0.05
    distribution.b_width = 0

    p_min.sway_width = 0.04
    p_max.sway_width = 0.06
    p_mu.sway_width = 0.05
    p_sigma.sway_width = 0.01
    distribution.sway_width = 0
```

```
    p_min.b_depth = 0.15
    p_max.b_depth = 0.35
    p_mu.b_depth = 0.25
    p_sigma.b_depth = 0.05
    distribution.b_depth = 0

    p_min.d_intimate = 0.15
    p_max.d_intimate = 0.20
    p_mu.d_intimate = 0.17
    p_sigma.d_intimate = 0.01
    distribution.d_intimate = 0

    p_min.t_react = 0.30
    p_max.t_react = 0.80
    p_mu.t_react = 0.55
    p_sigma.t_react = 0.13
    distribution.t_react = 0

    p_min.t_decel = 0.30
    p_max.t_decel = 1.10
    p_mu.t_decel = 0.70
    p_sigma.t_decel = 0.20
    distribution.t_decel = 0

    p_min.max_acc = 0.20
    p_max.max_acc = 0.80
    p_mu.max_acc = 0.50
    p_sigma.max_acc = 0.15
    distribution.max_acc = 0

    return p_min, p_max, p_mu, p_sigma, distribution
```

A.2.5 *Fundamental_diagram_model.py*

```
import numpy as np

from class_model_state import ModelState
from copy import deepcopy


def fd_model(sim_param, glob_ped_char, person_original):
    """
    runs the model
     - initialize variables
     - loop over all densities
     - loop over all timesteps for each density
     - generate the model output
    """

    peds = sim_param.no_ped
    sim_param.calc_steps()
    sim_param.calc_density()
    speed_mean = np.zeros((sim_param.lanes + 1, sim_param.steps))
    speed_dist = np.zeros((sim_param.steps, 22))
    speed_last = np.zeros((sim_param.steps, 22))

    t_max = int(sim_param.duration / sim_param.interval)

    for i in range(sim_param.steps):
        person = deepcopy(person_original)
        model_state = [0 for x in range(sim_param.lanes)]
        model_out = [0 for x in range(sim_param.lanes)]
        ped_lanes = np.zeros([sim_param.lanes, t_max])
```

```
    sim_param.length_x = lane_width_f(person, sim_param.lanes,
                                      sim_param.density[i])

    for k in range(sim_param.lanes):
        model_state[k] = ModelState(ts_v=np.ones(peds),
                                    ts_next_v=np.ones(peds),
                                    max_a=person[k].max_acc,
                                    next_dir=np.zeros(peds),
                                    cur_dir=np.zeros(peds))
        (model_state[k].x, model_state[k].cur_v) = (
            initialize_f(sim_param.density[i], peds,
                         person[k], sim_param.length_x))
        model_out[k] = ModelState(x=np.zeros([peds * 3, t_max + 1]),
                                  cur_v=np.zeros([peds * 3, t_max + 1]),
                                  ts_next_v=[model_state[k].ts_next_v])
        model_out[k].x[0:peds, 0] = model_state[k].x
        model_out[k].cur_v[0:peds, 0] = model_state[k].cur_v

    for j in range(t_max):

        for k in range(sim_param.lanes):
            model_state[k].timestep()

            model_state[k].pos_front = headway_f(sim_param, person[k],
                                                 sim_param.interval,
                                                 model_state[k])
            chosen_v = speed_f(model_state[k].pos_front, person[k],
                               glob_ped_char, model_state[k])
            model_state[k] = update_next_v_f(model_state[k], chosen_v)

        for k in range(sim_param.lanes):
            model_state[k] = update_cur_v_f(sim_param, model_state[k],
                                            glob_ped_char, person[k])

            model_state[k].pos_front = headway_f(sim_param, person[k], 0,
                                                 model_state[k])
            headway = model_state[k].pos_front - person[k].b_depth / 2
            model_state[k] = update_pos_f(sim_param, model_state[k],
                                          headway)
            model_state[k].pos_front = headway_f(sim_param, person[k], 0,
                                                 model_state[k])

        if j > glob_ped_char.ts_skip:
            model_state = lane_swap_det_f(model_state, sim_param, person,
                                          glob_ped_char)
            (model_state, sort) = lane_swap_f(model_state, sim_param)
            person = lane_swap_ped_f(model_state, sim_param, person, sort)

        for k in range(sim_param.lanes):
            lane = len(model_state[k].x)
            ped_lanes[k, j] = lane
            model_out[k].x[:lane, j+1] = model_state[k].x
            model_out[k].cur_v[:lane, j+1] = model_state[k].cur_v
            model_out[k].x[lane:, j+1] = np.nan
            model_out[k].cur_v[lane:, j+1] = np.nan

    speed_out = np.zeros((sim_param.lanes * peds * 3, sim_param.last_x))
    s_n = 0
    e_n = 0

    for k in range(sim_param.lanes):
        model_out[k].x = np.transpose(model_out[k].x)
        speed_mean[k+1, i] = np.nanmean(
            model_out[k].cur_v[:, -sim_param.last_x:])
        e_n = s_n + len(model_out[k].cur_v)
```

```
            speed_out[s_n:e_n, :] = model_out[k].cur_v[:, -sim_param.last_x:]
            s_n = e_n
        (speed_mean[0, i], speed_dist[i, :], speed_last[i, :]) = (
                out_speed_f(sim_param.density[i], model_out, sim_param.last_x,
                            ped_lanes, speed_out))

    return(sim_param.density, speed_mean, speed_dist, speed_last)


def out_speed_f(density, model_out, last_x, ped_lanes, speed_out):
    """ Generate output matrices """

    speed_dist = np.zeros((1, 22))
    speed_last = np.zeros((1, 22))
    speed_mean = np.nanmean(speed_out)

    speed_last[:, 0] = np.nanstd(speed_out)
    for i in range(1, 22):
        speed_last[:, i] = np.nanpercentile(speed_out, (i-1) * 5)

    speed_out = np.nanmean(speed_out, axis=1)
    speed_dist[:, 0] = np.nanstd(speed_out)
    for i in range(1, 22):
        speed_dist[:, i] = np.nanpercentile(speed_out, (i-1) * 5)

    print('Density:', round(density, 2), 'Speed:', round(speed_last[0, 1], 2),
          round(speed_mean, 2), round(speed_last[0, -1], 2))

    return (speed_mean, speed_dist, speed_last)


def lane_width_f(person, lanes, density):
    """ determine track length """

    lane_width = [0 for x in range(lanes)]
    for k in range(lanes):
        lane_width = np.mean(person[k].b_width + person[k].sway_width)
    headway = 1/(density * np.mean(lane_width))
    tracklength = len(person[0].b_width) * headway

    return tracklength


def initialize_f(density, number_pedestrian, person, length_x):
    """ define initial position and speed """

    pos_x = np.random.uniform(0.01, 1.99, (number_pedestrian,))
    pos_x = np.cumsum(pos_x)
    pos_x = pos_x * length_x / pos_x[-1]

    speed = person.desired_v * np.random.uniform(0, 1, (number_pedestrian,))

    return (pos_x, speed)


def update_next_v_f(model_state, chosen_v):
    """  Step 1: update value of next speed """

    switch_v = model_state.ts_next_v * 1
    switch_v[switch_v != 0] = 1
    switch_i = abs(switch_v-1)
    model_state.next_v = model_state.next_v * switch_v + chosen_v * switch_i
    model_state.ts_next_v = model_state.ts_next_v * switch_v + 99 * switch_i

    return model_state
```

```
def update_cur_v_f(sim_param, m_state, glob_ped_char, person):
    """ Step 2: Update speed """

    switch_v = m_state.ts_v * 1
    switch_v[switch_v != 0] = 1
    switch_i = abs(switch_v -1)
    m_state.cur_v = m_state.cur_v * switch_v + m_state.next_v * switch_i

    step_speed = m_state.cur_v * 1
    step_speed[step_speed == 0] = 0.1

    if glob_ped_char.step_duration == 1:  # Cavagna and Margaria (1966)
        next_step = 0.362 / step_speed + 0.257
        next_v = np.minimum(next_step, glob_ped_char.max_react)
    elif glob_ped_char.step_duration == 2:  # Margaria (1976) [Weidmann (1993)]
        next_step = 0.235 / step_speed + 0.302
        next_v = np.minimum(next_step, glob_ped_char.max_react)
    elif glob_ped_char.step_duration == 3:  # Jelic, 2012
        next_step = 0.065 / step_speed + 0.720
        next_v = np.minimum(next_step, glob_ped_char.max_react)

    next_v[m_state.cur_v == 0] = 0.1
    next_v = np.round(next_v / sim_param.interval, decimals=0)
    m_state.ts_v = m_state.ts_v * switch_v + next_v * switch_i

    m_state.max_a = m_state.max_a * switch_v + (
        m_state.ts_v * sim_param.interval * person.max_acc * switch_i)
    reaction_delay = np.random.uniform(glob_ped_char.reaction_delay_min,
                                       glob_ped_char.reaction_delay_max,
                                       len(m_state.x))
    next_v = np.maximum(next_v - np.round(reaction_delay / sim_param.interval,
                                          decimals=0), 1)
    m_state.ts_next_v = m_state.ts_next_v * switch_v + next_v * switch_i

    return m_state


def update_pos_f(sim_param, model_state, headway):
    """ Step 3: Update position """

    walking_distance = model_state.cur_v * sim_param.interval
    walking_distance = np.minimum(walking_distance, headway - 0.01)
    walking_distance = np.maximum(walking_distance, 0)
    model_state.cur_v = walking_distance / sim_param.interval
    model_state.x = model_state.x + walking_distance
    model_state.x = np.mod(model_state.x, sim_param.length_x)
    model_state.cur_dir[np.isnan(model_state.cur_dir)] = 0

    return model_state


def headway_f(sim_param, person, interval, m_state):
    """ Determines the distances to the pedestrian in front """

    p_front = ModelState()
    p_front.x = np.concatenate((m_state.x[1:], [m_state.x[0]]))
    p_front.cur_v = np.concatenate((m_state.cur_v[1:], [m_state.cur_v[0]]))
    p_next = ModelState()
    p_next.x = m_state.x + m_state.cur_v * interval * (m_state.ts_v + 1)
    p_front.x = p_front.x + p_front.cur_v * interval * (m_state.ts_v + 1)
    b_depth = np.concatenate((person.b_depth[1:], [person.b_depth[0]]))
    dist = p_front.x - p_next.x
    dist = np.mod(dist, sim_param.length_x)
```

```
    dist = dist - b_depth / 2
    dist[dist < 0] = 0

    return dist


def speed_f(distance, person, glob_ped_char, model_state):
    """
    Calculates the current walking speed for each person based on the persons
    characteristics and the headway
    """

    speed = (distance - (person.b_depth / 2 + person.d_intimate)) / (
        person.t_react + person.t_decel)
    speed[speed < glob_ped_char.speed_thresh] = 0
    speed = np.minimum(person.desired_v, speed)
    speed = np.maximum(person.desired_v * 0, speed)
    speed = speed * np.random.normal(1, glob_ped_char.random_noise,
                                     (len(speed),))
    speed = np.minimum(model_state.cur_v + model_state.max_a, speed)
    speed = np.maximum(model_state.cur_v - model_state.max_a, speed)

    return speed


def lane_swap_det_f(model_state, sim_param, person, glob_ped_char):
    """ Determines, if a pedestrian is planning a lane swap """

    for k in range(sim_param.lanes):
        l_n = (k + 1) % sim_param.lanes
        positions = model_state[l_n].x
        body = person[l_n].b_depth
        positions = np.mod(positions, sim_param.length_x)
        sort = np.argsort(positions)
        positions = positions[sort]
        body = body[sort]
        positions = np.concatenate([[positions[-1] - sim_param.length_x],
                                    positions,
                                    [positions[0] + sim_param.length_x]])
        body = np.concatenate([[body[-1]], body, [body[0]]])
        n_id = np.searchsorted(positions, model_state[k].x)
        neighbour_p_f = positions[n_id] - (body[n_id] / 2) - model_state[k].x
        neighbour_p_f[neighbour_p_f <= (person[k].b_depth / 2)] = 0

        n_id = (n_id - 1) % len(positions)
        neighbour_p_b = positions[n_id] + (body[n_id] / 2) - model_state[k].x
        neighbour_p_f[-neighbour_p_b <= (person[k].b_depth / 2)] = 0

        l_n = (k - 1) % sim_param.lanes
        positions = model_state[l_n].x
        body = person[l_n].b_depth
        positions = np.mod(positions, sim_param.length_x)
        sort = np.argsort(positions)
        positions = positions[sort]
        body = body[sort]
        positions = np.concatenate([[positions[-1] - sim_param.length_x],
                                    positions,
                                    [positions[0] + sim_param.length_x]])
        body = np.concatenate([[body[-1]], body, [body[0]]])
        n_id = np.searchsorted(positions, model_state[k].x)
        neighbour_m_f = positions[n_id] - (body[n_id] / 2) - model_state[k].x
        neighbour_m_f[neighbour_m_f <= (person[k].b_depth / 2)] = 0

        n_id = (n_id - 1) % len(positions)
        neighbour_m_b = positions[n_id] + (body[n_id] / 2) - model_state[k].x
```

```
        neighbour_m_f[-neighbour_m_b <= (person[k].b_depth / 2)] = 0

        speed_red = model_state[k].cur_v < person[k].desired_v
        neighbour_p_f[-neighbour_p_b < glob_ped_char.lane_back] = 0
        neighbour_m_f[-neighbour_m_b < glob_ped_char.lane_back] = 0
        lane_change = np.maximum(neighbour_p_f > model_state[k].pos_front,
                                 neighbour_m_f > model_state[k].pos_front)
        lane_change[model_state[k].pos_front >
                    glob_ped_char.reaction_headway] = 0
        lane_direction = neighbour_p_f > neighbour_m_f
        lane_direction = lane_direction * 2 - 1
        update_now = model_state[k].ts_v == 1
        model_state[k].lane_ch = lane_change * speed_red * lane_direction * (
            update_now)

    return model_state


def lane_swap_f(model_state, sim_param):
    """ performs a lane swap """

    for k in range(sim_param.lanes):
        l_n = (k + 1) % sim_param.lanes
        lanes_a = model_state[k].lane_ch
        missing = len(model_state[k].x) - len(lanes_a)

        if missing > 0:
            lanes_a = np.concatenate([lanes_a, [0 for x in range(missing)]])

        lanes = lanes_a == 1
        stay = lanes != 1

        if max(lanes) == 1:
            out = np.extract(lanes, model_state[k].x)
            model_state[l_n].x = np.concatenate([model_state[l_n].x, out])
            model_state[k].x = model_state[k].x[stay, ...]

            out = np.extract(lanes, model_state[k].ts_v)
            model_state[l_n].ts_v = np.concatenate([model_state[l_n].ts_v,
                                                    out])
            model_state[k].ts_v = model_state[k].ts_v[stay, ...]

            out = np.extract(lanes, model_state[k].ts_next_v)
            model_state[l_n].ts_next_v = np.concatenate(
                [model_state[l_n].ts_next_v, out])
            model_state[k].ts_next_v = model_state[k].ts_next_v[stay, ...]

            out = np.extract(lanes, model_state[k].next_v)
            model_state[l_n].next_v = np.concatenate([model_state[l_n].next_v,
                                                      out])
            model_state[k].next_v = model_state[k].next_v[stay, ...]

            out = np.extract(lanes, model_state[k].cur_v)
            model_state[l_n].cur_v = np.concatenate([model_state[l_n].cur_v,
                                                     out])
            model_state[k].cur_v = model_state[k].cur_v[stay, ...]

            out = np.extract(lanes, model_state[k].max_a)
            model_state[l_n].max_a = np.concatenate([model_state[l_n].max_a,
                                                     out])
            model_state[k].max_a = model_state[k].max_a[stay, ...]

        lanes = lanes_a[stay, ...]
        l_n = (k - 1) % sim_param.lanes
        lanes = (lanes == -1) * 1
```

```
    stay = lanes != 1

    if max(lanes) == 1:
        out = np.extract(lanes, model_state[k].x)
        model_state[l_n].x = np.concatenate([model_state[l_n].x, out])
        model_state[k].x = model_state[k].x[stay, ...]

        out = np.extract(lanes, model_state[k].ts_v)
        model_state[l_n].ts_v = np.concatenate([model_state[l_n].ts_v,
                                                out])
        model_state[k].ts_v = model_state[k].ts_v[stay, ...]

        out = np.extract(lanes, model_state[k].ts_next_v)
        model_state[l_n].ts_next_v = np.concatenate(
            [model_state[l_n].ts_next_v, out])
        model_state[k].ts_next_v = model_state[k].ts_next_v[stay, ...]

        out = np.extract(lanes, model_state[k].next_v)
        model_state[l_n].next_v = np.concatenate([model_state[l_n].next_v,
                                                  out])
        model_state[k].next_v = model_state[k].next_v[stay, ...]

        out = np.extract(lanes, model_state[k].cur_v)
        model_state[l_n].cur_v = np.concatenate([model_state[l_n].cur_v,
                                                 out])
        model_state[k].cur_v = model_state[k].cur_v[stay, ...]

        out = np.extract(lanes, model_state[k].max_a)
        model_state[l_n].max_a = np.concatenate([model_state[l_n].max_a,
                                                 out])
        model_state[k].max_a = model_state[k].max_a[stay, ...]

    sort = [0 for x in range(sim_param.lanes)]

    for k in range(sim_param.lanes):
        sort[k] = np.argsort(model_state[k].x)
        model_state[k].x = model_state[k].x[sort[k]]
        model_state[k].ts_v = model_state[k].ts_v[sort[k]]
        model_state[k].ts_next_v = model_state[k].ts_next_v[sort[k]]
        model_state[k].next_v = model_state[k].next_v[sort[k]]
        model_state[k].cur_v = model_state[k].cur_v[sort[k]]
        model_state[k].max_a = model_state[k].max_a[sort[k]]

    return (model_state, sort)


def lane_swap_ped_f(model_state, sim_param, person, sort):
    """ Updates the pedestrian matrix based on the lane changes """

    for k in range(sim_param.lanes):
        l_n = (k + 1) % sim_param.lanes
        lanes_a = model_state[k].lane_ch
        missing = len(person[k].p_id) - len(lanes_a)

        if missing > 0:
            lanes_a = np.concatenate([lanes_a, [0 for x in range(missing)]])

        lanes = lanes_a == 1
        stay = lanes != 1

        if max(lanes) == 1:
            out = np.extract(lanes, person[k].p_id)
            person[l_n].p_id = np.concatenate([person[l_n].p_id, out])
            person[k].p_id = person[k].p_id[stay, ...]
```

```
        out = np.extract(lanes, person[k].desired_v)
        person[l_n].desired_v = np.concatenate([person[l_n].desired_v,
                                               out])
        person[k].desired_v = person[k].desired_v[stay, ...]

        out = np.extract(lanes, person[k].b_width)
        person[l_n].b_width = np.concatenate([person[l_n].b_width, out])
        person[k].b_width = person[k].b_width[stay, ...]

        out = np.extract(lanes, person[k].sway_width)
        person[l_n].sway_width = np.concatenate([person[l_n].sway_width,
                                                out])
        person[k].sway_width = person[k].sway_width[stay, ...]

        out = np.extract(lanes, person[k].b_depth)
        person[l_n].b_depth = np.concatenate([person[l_n].b_depth, out])
        person[k].b_depth = person[k].b_depth[stay, ...]

        out = np.extract(lanes, person[k].d_intimate)
        person[l_n].d_intimate = np.concatenate([person[l_n].d_intimate,
                                                out])
        person[k].d_intimate = person[k].d_intimate[stay, ...]

        out = np.extract(lanes, person[k].t_react)
        person[l_n].t_react = np.concatenate([person[l_n].t_react, out])
        person[k].t_react = person[k].t_react[stay, ...]

        out = np.extract(lanes, person[k].t_decel)
        person[l_n].t_decel = np.concatenate([person[l_n].t_decel, out])
        person[k].t_decel = person[k].t_decel[stay, ...]

        out = np.extract(lanes, person[k].max_acc)
        person[l_n].max_acc = np.concatenate([person[l_n].max_acc, out])
        person[k].max_acc = person[k].max_acc[stay, ...]

    lanes = lanes_a[stay, ...]
    l_n = (k - 1) % sim_param.lanes
    lanes = (lanes == -1) * 1
    stay = lanes != 1

    if max(lanes) == 1:
        out = np.extract(lanes, person[k].p_id)
        person[l_n].p_id = np.concatenate([person[l_n].p_id, out])
        person[k].p_id = person[k].p_id[stay, ...]

        out = np.extract(lanes, person[k].desired_v)
        person[l_n].desired_v = np.concatenate([person[l_n].desired_v,
                                               out])
        person[k].desired_v = person[k].desired_v[stay, ...]

        out = np.extract(lanes, person[k].b_width)
        person[l_n].b_width = np.concatenate([person[l_n].b_width, out])
        person[k].b_width = person[k].b_width[stay, ...]

        out = np.extract(lanes, person[k].sway_width)
        person[l_n].sway_width = np.concatenate([person[l_n].sway_width,
                                                out])
        person[k].sway_width = person[k].sway_width[stay, ...]

        out = np.extract(lanes, person[k].b_depth)
        person[l_n].b_depth = np.concatenate([person[l_n].b_depth, out])
        person[k].b_depth = person[k].b_depth[stay, ...]

        out = np.extract(lanes, person[k].d_intimate)
        person[l_n].d_intimate = np.concatenate([person[l_n].d_intimate,
```

```
                                            out])
            person[k].d_intimate = person[k].d_intimate[stay, ...]

            out = np.extract(lanes, person[k].t_react)
            person[l_n].t_react = np.concatenate([person[l_n].t_react, out])
            person[k].t_react = person[k].t_react[stay, ...]

            out = np.extract(lanes, person[k].t_decel)
            person[l_n].t_decel = np.concatenate([person[l_n].t_decel, out])
            person[k].t_decel = person[k].t_decel[stay, ...]

            out = np.extract(lanes, person[k].max_acc)
            person[l_n].max_acc = np.concatenate([person[l_n].max_acc, out])
            person[k].max_acc = person[k].max_acc[stay, ...]

    for k in range(sim_param.lanes):
        person[k].p_id = person[k].p_id[sort[k]]
        person[k].desired_v = person[k].desired_v[sort[k]]
        person[k].b_width = person[k].b_width[sort[k]]
        person[k].sway_width = person[k].sway_width[sort[k]]
        person[k].b_depth = person[k].b_depth[sort[k]]
        person[k].d_intimate = person[k].d_intimate[sort[k]]
        person[k].t_react = person[k].t_react[sort[k]]
        person[k].t_decel = person[k].t_decel[sort[k]]
        person[k].max_acc = person[k].max_acc[sort[k]]

    return person
```

A.3 DATA COLLECTION - RESULTS

A.3.1 *Bosina and Weidmann (2017c)*

Table A.1: Speed-density data (mean, standard deviation, 5 % and 95 % percentile) calculated from Bosina and Weidmann (2017c).

D [P/m²]	v_{mean} [m/s]	v_{SD} [m/s]	$v_{5\,\%}$ [m/s]	$v_{95\,\%}$ [m/s]	D [P/m²]	v_{mean} [m/s]	v_{SD} [m/s]	$v_{5\,\%}$ [m/s]	$v_{95\,\%}$ [m/s]
0.0	1.35	0.22	1.02	1.65	4.6	0.31	0.10	0.19	0.39
0.1	1.32	0.33	0.58	1.70	4.7	0.29	0.10	0.20	0.37
0.2	1.26	0.23	0.92	1.59	4.8	0.29	0.10	0.18	0.36
0.3	1.20	0.24	0.81	1.55	4.9	0.30	0.09	0.20	0.37
0.4	1.20	0.20	0.94	1.46	5.0	0.24	0.08	0.16	0.33
0.5	1.20	0.21	0.92	1.51	5.1	0.29	0.11	0.16	0.39
0.6	1.17	0.20	0.84	1.44	5.2	0.27	0.05	0.22	0.31
0.7	1.10	0.22	0.69	1.42	5.3	0.27	0.07	0.20	0.33
0.8	1.07	0.22	0.67	1.35	5.4	0.23	0.08	0.16	0.31
0.9	1.03	0.21	0.73	1.37	5.5	0.24	0.07	0.17	0.31
1.0	1.01	0.35	0.61	1.31	5.6	0.22	0.04	0.18	0.25
1.1	0.88	0.25	0.55	1.30	5.7	0.20	0.04	0.16	0.23

Table A.1: Speed-density data (mean, standard deviation, 5 % and 95 % percentile) calculated from Bosina and Weidmann (2017c).

D [P/m²]	v_{mean} [m/s]	v_{SD} [m/s]	$v_{5\,\%}$ [m/s]	$v_{95\,\%}$ [m/s]	D [P/m²]	v_{mean} [m/s]	v_{SD} [m/s]	$v_{5\,\%}$ [m/s]	$v_{95\,\%}$ [m/s]
1.2	0.88	0.25	0.48	1.23	5.8	0.18	0.03	0.16	0.21
1.3	0.80	0.23	0.42	1.14	5.9	0.17	0.01	0.16	0.19
1.4	0.76	0.25	0.29	1.11	6.0	0.20	0.05	0.16	0.25
1.5	0.75	0.23	0.35	1.11	6.1	0.15	0.01	0.14	0.15
1.6	0.72	0.22	0.35	1.04	6.2	0.15	0.02	0.13	0.17
1.7	0.66	0.23	0.27	0.98	6.3	0.14	0.02	0.13	0.16
1.8	0.64	0.23	0.24	0.88	6.4	0.13	0.02	0.11	0.15
1.9	0.61	0.22	0.22	0.90	6.5	0.12	0.02	0.10	0.13
2.0	0.63	0.27	0.24	0.99	6.6	0.12	0.03	0.10	0.15
2.1	0.56	0.21	0.30	0.86	6.7	0.12	0.04	0.08	0.15
2.2	0.53	0.21	0.23	0.89	6.8	0.11	0.03	0.09	0.14
2.3	0.54	0.22	0.23	0.93	6.9	0.11	0.04	0.08	0.15
2.4	0.52	0.22	0.21	0.91	7.0	0.11	0.03	0.08	0.13
2.5	0.48	0.20	0.22	0.75	7.1	0.11	0.04	0.08	0.14
2.6	0.46	0.20	0.19	0.66	7.2	0.09	0.03	0.07	0.11
2.7	0.44	0.21	0.14	0.77	7.3	0.09	0.03	0.07	0.12
2.8	0.41	0.20	0.14	0.75	7.4	0.11	0.05	0.06	0.15
2.9	0.46	0.26	0.23	0.96	7.5	0.10	0.05	0.06	0.15
3.0	0.43	0.24	0.22	0.83	7.6	0.10	0.04	0.07	0.13
3.1	0.43	0.23	0.22	0.86	7.7	0.09	0.03	0.07	0.12
3.2	0.43	0.21	0.22	0.79	7.8	0.08	0.03	0.06	0.11
3.3	0.46	0.29	0.19	1.00	7.9	0.10	0.04	0.06	0.14
3.4	0.45	0.31	0.14	1.00	8.0	0.06	0.00	0.06	0.06
3.5	0.40	0.19	0.20	0.69	8.1	0.09	0.04	0.05	0.12
3.6	0.41	0.16	0.20	0.62	8.2	0.09	0.03	0.06	0.12
3.7	0.32	0.19	0.15	0.64	8.3	0.06	0.00	0.06	0.06
3.8	0.28	0.12	0.16	0.45	8.4	0.05	0.00	0.05	0.05
3.9	0.27	0.10	0.17	0.43	8.5	0.04	0.00	0.04	0.04
4.0	0.30	0.13	0.16	0.45	8.6	0.06	0.00	0.06	0.06
4.1	0.28	0.14	0.15	0.46	8.7	0.06	0.00	0.06	0.06
4.2	0.28	0.13	0.13	0.43	8.8	0.05	0.00	0.05	0.05
4.3	0.29	0.12	0.18	0.39	8.9	0.06	0.00	0.06	0.06

TABLE A.1: Speed-density data (mean, standard deviation, 5 % and 95 % percentile) calculated from Bosina and Weidmann (2017c).

D [P/m²]	v_{mean} [m/s]	v_{SD} [m/s]	$v_{5\,\%}$ [m/s]	$v_{95\,\%}$ [m/s]	D [P/m²]	v_{mean} [m/s]	v_{SD} [m/s]	$v_{5\,\%}$ [m/s]	$v_{95\,\%}$ [m/s]
4.4	0.24	0.10	0.16	0.38	9.0	0.05	0.00	0.05	0.05
4.5	0.30	0.09	0.22	0.39					

A.3.2 *Single-file movement, Rotunde (FZ Jülich)*

TABLE A.2: Speed-density data (mean, standard deviation, 5 % and 95 % percentile) calculated from dataset "Single-file movement, Rotunde (FZ Jülich)".

D [P/m²]	v_{mean} [m/s]	v_{SD} [m/s]	$v_{5\,\%}$ [m/s]	$v_{95\,\%}$ [m/s]
0.867	0.899	0.045	0.824	0.962
1.156	0.557	0.050	0.468	0.624
1.445	0.345	0.039	0.277	0.397
1.734	0.229	0.027	0.193	0.278
1.965	0.168	0.030	0.136	0.227

A.3.3 *Single-file movement, Casern (FZ Jülich)*

TABLE A.3: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from dataset "Single-file movement, Casern (FZ Jülich)".

EXP.	D [P/m²]	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
n14	0.54	1.20	0.06	1.11	1.30	1.19	0.08	1.06	1.34
n17	0.65	1.06	0.07	0.94	1.18	1.06	0.09	0.91	1.19
n20	0.77	0.95	0.05	0.86	1.04	0.95	0.08	0.81	1.08
n22	0.85	0.82	0.06	0.72	0.90	0.81	0.08	0.68	0.95
n25	0.96	0.85	0.05	0.76	0.93	0.85	0.08	0.70	0.96
n28	1.08	0.57	0.04	0.50	0.64	0.57	0.08	0.45	0.69
n34	1.31	0.47	0.05	0.39	0.54	0.47	0.09	0.32	0.60
n39	1.50	0.37	0.05	0.30	0.46	0.37	0.09	0.23	0.52
n45	1.73	0.23	0.03	0.18	0.27	0.22	0.07	0.11	0.34
n56	2.15	0.15	0.05	0.10	0.22	0.15	0.07	0.02	0.27
n62	2.38	0.11	0.04	0.07	0.18	0.10	0.07	−0.01	0.22
n70	2.69	0.03	0.01	0.01	0.05	0.03	0.06	−0.03	0.15

A.3.4 *Single-file motion of pupils (FZ Jülich)*

TABLE A.4: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from dataset "School GymBay, main circle" (FZ Jülich).

FILE	P	L_0 [m]	D [P/m²]	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
1_1_00.txt	0	16.19	0.00	1.17	0.20	0.84	1.43	1.12	0.25	0.60	1.47
1_1_01.txt	17	16.11	1.06	0.89	0.02	0.86	0.93	0.89	0.08	0.76	1.03
1_1_02.txt	51	16.76	3.04	0.07	0.04	0.04	0.17	0.06	0.06	−0.04	0.17
1_1_03.txt	41	16.41	2.50	0.07	0.03	0.05	0.12	0.07	0.11	−0.04	0.29
1_1_04.txt	33	16.51	2.00	0.29	0.02	0.26	0.32	0.29	0.15	0.05	0.53
1_1_05.txt	11	15.58	0.71	1.27	0.03	1.23	1.31	1.27	0.14	1.07	1.49
1_1_06.txt	25	16.32	1.53	0.52	0.09	0.36	0.61	0.50	0.17	0.22	0.78
1_1_07.txt	28	16.19	1.73	0.47	0.12	0.31	0.68	0.44	0.18	0.21	0.76
1_1_08.txt	29	15.86	1.83	0.57	0.03	0.52	0.63	0.56	0.08	0.44	0.70
1_1_09.txt	0	15.54	0.00	1.30	0.28	1.02	1.84	1.15	0.28	0.80	1.70
1_2_00.txt	0	16.47	0.00	1.30	0.13	1.16	1.48	1.28	0.17	1.11	1.55
1_2_01.txt	15	16.13	0.93	0.84	0.02	0.82	0.87	0.84	0.06	0.75	0.94
1_2_02.txt	40	16.38	2.44	0.08	0.04	0.05	0.13	0.07	0.06	−0.02	0.19
1_2_03.txt	6	15.24	0.39	1.28	0.04	1.24	1.33	1.27	0.08	1.13	1.39
1_2_04.txt	34	16.43	2.07	0.16	0.01	0.15	0.18	0.16	0.06	0.07	0.26
1_2_05.txt	13	15.93	0.82	0.98	0.02	0.95	1.01	0.98	0.06	0.87	1.07
1_2_06.txt	24	16.31	1.47	0.39	0.02	0.37	0.42	0.39	0.07	0.28	0.51
1_2_07.txt	16	16.08	1.00	0.78	0.02	0.76	0.83	0.78	0.09	0.64	0.94
1_2_08.txt	25	15.76	1.59	0.62	0.05	0.56	0.69	0.62	0.07	0.49	0.74
1_3_01.txt	16	15.98	1.00	0.79	0.02	0.77	0.82	0.79	0.07	0.67	0.90
1_3_02.txt	43	16.30	2.64	0.05	0.03	0.02	0.12	0.05	0.05	−0.02	0.14
1_3_03.txt	47	16.13	2.91	0.03	0.02	0.01	0.08	0.03	0.06	−0.05	0.14
1_3_04.txt	6	15.19	0.39	1.36	0.04	1.31	1.41	1.36	0.09	1.20	1.51
1_3_05.txt	34	16.41	2.07	0.19	0.02	0.17	0.22	0.18	0.08	0.05	0.32
1_3_06.txt	12	15.62	0.77	1.09	0.02	1.06	1.12	1.09	0.08	0.96	1.21
1_3_07.txt	25	16.39	1.53	0.37	0.04	0.32	0.44	0.36	0.09	0.21	0.50
1_3_08.txt	0	15.89	0.00	1.38	0.11	1.20	1.54	1.37	0.13	1.17	1.60

Table A.5: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from dataset "School GymBay, ancillary circle" (FZ Jülich).

FILE	P	L_0 [m]	D [P/m²]	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
2_1_01.txt	25	16.23	1.54	0.53	0.05	0.46	0.59	0.52	0.09	0.38	0.67
2_1_02.txt	6	15.35	0.39	1.26	0.05	1.18	1.30	1.26	0.12	1.09	1.43
2_1_04.txt	12	15.45	0.78	1.24	0.02	1.22	1.27	1.24	0.09	1.11	1.38
2_1_05.txt	36	16.36	2.20	0.13	0.03	0.10	0.18	0.13	0.13	−0.02	0.37
2_1_06.txt	17	15.88	1.07	0.74	0.02	0.71	0.78	0.74	0.10	0.57	0.90
2_1_07.txt	29	16.13	1.80	0.29	0.04	0.22	0.38	0.29	0.09	0.14	0.45
2_1_08.txt	28	16.01	1.75	0.44	0.09	0.32	0.59	0.42	0.11	0.27	0.61
2_1_09.txt	0	15.36	0.00	1.42	0.13	1.19	1.60	1.41	0.16	1.14	1.68
2_2_01.txt	22	15.93	1.38	0.42	0.02	0.39	0.46	0.42	0.07	0.31	0.53
2_2_02.txt	6	15.62	0.38	1.14	0.03	1.09	1.17	1.14	0.06	1.02	1.23
2_2_03.txt	40	16.12	2.48	0.07	0.02	0.03	0.10	0.07	0.06	−0.01	0.17
2_2_04.txt	10	15.46	0.65	1.01	0.03	0.98	1.05	1.01	0.06	0.91	1.11
2_2_05.txt	30	16.23	1.85	0.17	0.01	0.14	0.19	0.17	0.06	0.07	0.26
2_3_01.txt	34	16.10	2.11	0.16	0.02	0.13	0.19	0.16	0.06	0.07	0.26
2_3_02.txt	12	15.47	0.78	1.03	0.02	1.00	1.06	1.03	0.07	0.92	1.13
2_3_03.txt	6	14.83	0.40	1.37	0.03	1.34	1.40	1.37	0.09	1.22	1.52
2_3_04.txt	48	16.27	2.95	0.02	0.01	0.00	0.04	0.02	0.05	−0.04	0.11
2_3_05.txt	16	15.88	1.01	0.92	0.03	0.87	0.96	0.92	0.10	0.77	1.10
2_3_06.txt	34	16.46	2.07	0.16	0.03	0.11	0.21	0.15	0.08	0.02	0.30
2_3_07.txt	24	16.15	1.49	0.49	0.03	0.44	0.54	0.49	0.09	0.36	0.64
2_3_08.txt	0	15.23	0.00	1.47	0.21	1.16	1.82	1.44	0.23	1.02	1.85

TABLE A.6: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from dataset "School WGD, main circle" (FZ Jülich).

FILE	P	L_0 [m]	D [P/m²]	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
3_1_00.txt	0	15.84	0.00	1.45	0.14	1.24	1.65	1.44	0.15	1.21	1.66
3_1_01.txt	16	15.74	1.02	0.82	0.03	0.78	0.87	0.82	0.08	0.68	0.94
3_1_02.txt	39	15.98	2.44	0.14	0.02	0.10	0.18	0.13	0.06	0.04	0.23
3_1_03.txt	29	16.08	1.80	0.36	0.04	0.31	0.42	0.35	0.09	0.21	0.51
3_1_04.txt	6	15.02	0.40	1.31	0.03	1.27	1.35	1.31	0.08	1.17	1.43
3_1_05.txt	25	15.90	1.57	0.46	0.05	0.37	0.54	0.45	0.10	0.27	0.60
3_1_06.txt	11	15.22	0.72	1.08	0.02	1.05	1.12	1.08	0.06	0.98	1.17
3_1_07.txt	39	16.16	2.41	0.22	0.03	0.17	0.27	0.22	0.05	0.14	0.31
3_1_08.txt	39	16.43	2.37	0.38	0.05	0.28	0.45	0.38	0.07	0.24	0.49
3_1_09.txt	32	15.98	2.00	0.29	0.08	0.20	0.41	0.27	0.11	0.13	0.46
3_1_10.txt	16	15.82	1.01	0.87	0.02	0.84	0.91	0.87	0.08	0.75	1.03
3_1_11.txt	0	15.49	0.00	1.44	0.12	1.24	1.58	1.43	0.14	1.19	1.64
3_2_00.txt	0	15.36	0.00	1.46	0.13	1.27	1.63	1.44	0.13	1.24	1.63
3_2_01.txt	17	15.69	1.08	0.77	0.03	0.72	0.82	0.77	0.06	0.65	0.87
3_2_02.txt	43	16.03	2.68	0.08	0.04	0.03	0.12	0.07	0.06	−0.01	0.17
3_2_03.txt	15	15.79	0.95	0.87	0.02	0.83	0.90	0.86	0.07	0.76	0.98
3_2_04.txt	6	15.37	0.39	1.20	0.01	1.18	1.21	1.20	0.06	1.10	1.29
3_2_05.txt	36	16.05	2.24	0.11	0.01	0.10	0.13	0.11	0.04	0.05	0.18
3_2_06.txt	12	15.28	0.79	1.17	0.03	1.14	1.22	1.17	0.06	1.07	1.26
3_2_07.txt	25	16.15	1.55	0.34	0.02	0.31	0.38	0.34	0.07	0.23	0.47
3_2_08.txt	39	15.91	2.45	0.23	0.02	0.20	0.27	0.22	0.05	0.14	0.29
3_2_09.txt	39	16.07	2.43	0.23	0.03	0.17	0.27	0.23	0.07	0.14	0.35
3_2_09_2.txt	38	16.17	2.35	0.54	0.04	0.49	0.60	0.54	0.06	0.46	0.63
3_2_10.txt	16	15.75	1.02	0.87	0.02	0.84	0.91	0.87	0.06	0.78	0.97
3_2_11.txt	0	15.83	0.00	1.39	0.13	1.17	1.56	1.38	0.15	1.16	1.55
3_3_01.txt	15	15.39	0.97	1.02	0.03	0.99	1.07	1.02	0.06	0.92	1.13
3_3_02.txt	37	16.05	2.30	0.12	0.01	0.10	0.14	0.11	0.06	0.03	0.21
3_3_03.txt	44	15.83	2.78	0.05	0.01	0.03	0.07	0.04	0.04	−0.02	0.11
3_3_04.txt	6	14.83	0.40	1.33	0.03	1.30	1.37	1.33	0.09	1.16	1.46
3_3_05.txt	33	15.94	2.07	0.14	0.01	0.13	0.17	0.14	0.05	0.07	0.22
3_3_06.txt	15	15.59	0.96	0.98	0.03	0.93	1.02	0.98	0.07	0.88	1.08
3_3_07.txt	23	16.08	1.43	0.47	0.03	0.43	0.51	0.47	0.07	0.34	0.59

TABLE A.7: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from dataset "School WGD, ancillary circle" (FZ Jülich).

FILE	P	L_0 [m]	D [P/m²]	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
2_1_01.txt	25	16.23	1.54	0.53	0.05	0.47	0.59	0.52	0.09	0.39	0.68
2_1_02.txt	6	15.33	0.39	1.26	0.05	1.19	1.30	1.26	0.12	1.10	1.43
2_1_04.txt	12	15.45	0.78	1.24	0.02	1.22	1.26	1.24	0.09	1.11	1.38
2_1_05.txt	36	16.35	2.20	0.13	0.03	0.10	0.18	0.13	0.12	−0.02	0.37
2_1_06.txt	17	15.87	1.07	0.73	0.03	0.70	0.77	0.73	0.10	0.57	0.90
2_1_07.txt	29	16.13	1.80	0.30	0.03	0.26	0.37	0.30	0.09	0.14	0.46
2_1_08.txt	28	16.01	1.75	0.44	0.09	0.32	0.59	0.42	0.11	0.27	0.61
2_1_09.txt	0	15.36	0.00	1.42	0.14	1.19	1.60	1.41	0.16	1.13	1.68
2_2_01.txt	22	15.92	1.38	0.42	0.02	0.39	0.46	0.42	0.07	0.31	0.53
2_2_02.txt	6	15.62	0.38	1.13	0.03	1.09	1.17	1.14	0.06	1.02	1.23
2_2_03.txt	40	16.12	2.48	0.07	0.02	0.03	0.10	0.07	0.06	−0.01	0.17
2_2_04.txt	10	15.48	0.65	1.01	0.03	0.98	1.05	1.01	0.06	0.91	1.12
2_2_05.txt	30	16.23	1.85	0.17	0.02	0.14	0.19	0.17	0.06	0.07	0.27
2_3_01.txt	34	15.94	2.13	0.16	0.02	0.13	0.18	0.15	0.06	0.05	0.24
2_3_02.txt	12	15.31	0.78	0.98	0.02	0.95	1.01	0.98	0.07	0.87	1.08
2_3_03.txt	6	14.57	0.41	1.30	0.03	1.27	1.33	1.30	0.08	1.17	1.43
2_3_04.txt	48	16.04	2.99	0.02	0.01	0.00	0.04	0.02	0.05	−0.03	0.11
2_3_05.txt	16	15.62	1.02	0.87	0.03	0.82	0.90	0.87	0.10	0.71	1.04
2_3_06.txt	34	16.24	2.09	0.15	0.03	0.11	0.20	0.14	0.08	0.02	0.27
2_3_07.txt	24	15.85	1.51	0.46	0.02	0.43	0.50	0.46	0.08	0.33	0.60
2_3_08.txt	0	15.06	0.00	1.37	0.19	1.07	1.71	1.34	0.21	1.05	1.69

A.3.5 *HERMES: corridor experiment UG*

TABLE A.8: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from HERMES experiment: Corridor UG.

FILE *.TXT	P	A_0 $[m^2]$	D $[P/m^2]$	$v_{i,mean}$ $[m/s]$	$v_{i,SD}$ $[m/s]$	$v_{i,5\%}$ $[m/s]$	$v_{i,95\%}$ $[m/s]$	$v_{t,mean}$ $[m/s]$	$v_{t,SD}$ $[m/s]$	$v_{t,5\%}$ $[m/s]$	$v_{t,95\%}$ $[m/s]$
ug-100-007	0.95	4.0	0.24	1.45	0.06	1.36	1.54	1.45	0.07	1.34	1.57
ug-100-015	2.36	4.0	0.59	1.39	0.10	1.28	1.56	1.39	0.11	1.24	1.57
ug-100-030	4.42	4.0	1.11	0.93	0.07	0.83	1.07	0.92	0.10	0.72	1.05
ug-100-045	6.43	4.0	1.61	0.79	0.05	0.72	0.88	0.79	0.13	0.60	0.99
ug-100-060	7.88	4.0	1.97	0.45	0.13	0.28	0.68	0.45	0.15	0.22	0.71
ug-100-075	10.19	4.0	2.55	0.34	0.09	0.23	0.53	0.31	0.12	0.13	0.55
ug-100-090	12.19	4.0	3.05	0.23	0.12	0.04	0.45	0.19	0.17	−0.02	0.50
ug-100-120	14.57	4.0	3.64	0.08	0.05	0.04	0.19	0.06	0.08	−0.03	0.21
ug-140-010	1.39	5.6	0.25	1.35	0.06	1.27	1.46	1.34	0.07	1.23	1.47
ug-140-020	2.91	5.6	0.52	1.37	0.09	1.25	1.54	1.36	0.11	1.20	1.52
ug-140-045	6.26	5.6	1.12	1.32	0.07	1.22	1.46	1.32	0.09	1.18	1.48
ug-140-065	8.50	5.6	1.52	0.87	0.08	0.74	0.98	0.86	0.11	0.70	1.07
ug-140-085	11.90	5.6	2.13	0.51	0.27	0.06	0.91	0.39	0.33	−0.02	0.93
ug-140-110	15.64	5.6	2.79	0.27	0.04	0.21	0.35	0.27	0.09	0.14	0.42
ug-140-130	22.80	5.6	4.07	0.11	0.04	0.06	0.19	0.10	0.09	−0.03	0.24
ug-180-015	1.99	7.2	0.28	1.14	0.08	1.01	1.23	1.14	0.09	1.00	1.26
ug-180-030	4.22	7.2	0.59	1.01	0.05	0.94	1.08	1.00	0.06	0.90	1.09
ug-180-060	8.63	7.2	1.20	0.78	0.06	0.70	0.87	0.78	0.08	0.65	0.92
ug-180-085	10.69	7.2	1.49	0.52	0.04	0.46	0.61	0.51	0.06	0.40	0.62
ug-180-095	17.97	7.2	2.50	0.27	0.05	0.17	0.34	0.26	0.12	0.00	0.45
ug-180-110	14.25	7.2	1.98	0.32	0.16	0.14	0.53	0.23	0.21	−0.03	0.55
ug-180-110_2	13.56	7.2	1.88	0.47	0.08	0.27	0.56	0.45	0.14	0.04	0.62
ug-180-140	20.05	7.2	2.79	0.22	0.13	0.09	0.43	0.17	0.13	−0.01	0.43
ug-180-230	28.85	7.2	4.01	0.07	0.02	0.04	0.10	0.06	0.07	−0.03	0.20

A.3.6 *HERMES: corridor experiment UO*

TABLE A.9: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from HERMES experiment: Corridor UO.

FILE *_combined_MB.txt	P	A_0 [m²]	D [P/m²]	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
uo-050-180-180	3.33	7.2	0.46	1.37	0.18	1.14	1.66	1.34	0.18	1.34	1.72
uo-060-180-180	3.79	7.2	0.53	1.46	0.19	1.17	1.74	1.45	0.19	1.23	1.82
uo-065-240-240	3.97	9.6	0.41	1.51	0.13	1.35	1.70	1.51	0.14	1.05	1.65
uo-070-180-180	4.41	7.2	0.61	1.35	0.15	1.13	1.57	1.33	0.16	1.24	1.69
uo-080-240-240	5.53	9.6	0.58	1.44	0.17	1.23	1.71	1.42	0.19	1.12	1.72
uo-080-300-300v2	5.21	12.0	0.43	1.53	0.18	1.25	1.83	1.52	0.19	1.20	1.72
uo-095-240-240	6.28	9.6	0.65	1.43	0.17	1.11	1.69	1.41	0.18	1.07	1.57
uo-100-180-180	8.13	7.2	1.13	1.22	0.15	1.00	1.44	1.19	0.15	1.10	1.68
uo-100-300-300	6.18	12.0	0.52	1.45	0.12	1.26	1.72	1.44	0.13	1.21	1.72
uo-120-300-300	7.92	12.0	0.66	1.45	0.15	1.24	1.75	1.43	0.15	1.12	1.50
uo-145-180-180	11.69	7.2	1.62	0.99	0.15	0.80	1.22	0.98	0.15	0.97	1.44
uo-145-240-240	9.73	9.6	1.01	1.32	0.13	1.13	1.51	1.31	0.13	1.05	1.38
uo-180-180-070	21.88	7.2	3.04	0.30	0.03	0.27	0.34	0.30	0.07	0.95	1.32
uo-180-180-095	18.24	7.2	2.53	0.41	0.03	0.38	0.45	0.41	0.07	0.77	1.24
uo-180-180-120	15.46	7.2	2.15	0.60	0.05	0.51	0.67	0.59	0.08	0.79	1.17
uo-180-180-180	12.16	7.2	1.69	0.95	0.08	0.83	1.06	0.95	0.09	0.81	1.10
uo-180-300-300	13.76	12.0	1.15	1.20	0.09	1.08	1.38	1.20	0.10	0.73	1.14
uo-190-240-240	15.63	9.6	1.63	0.98	0.11	0.83	1.16	0.96	0.12	0.68	1.10
uo-240-240-100	26.53	9.6	2.76	0.34	0.03	0.30	0.39	0.34	0.07	0.48	0.72
uo-240-240-130	23.62	9.6	2.46	0.45	0.05	0.38	0.53	0.46	0.08	0.45	0.72
uo-240-240-160	21.60	9.6	2.25	0.59	0.05	0.52	0.66	0.59	0.08	0.44	0.67
uo-240-240-240	18.18	9.6	1.89	0.88	0.13	0.71	1.13	0.87	0.13	0.31	0.54
uo-240-300-300	17.92	12.0	1.49	1.13	0.10	0.99	1.32	1.12	0.11	0.33	0.60
uo-300-300-080	40.06	12.0	3.34	0.18	0.02	0.15	0.21	0.18	0.06	0.30	0.52
uo-300-300-120	33.29	12.0	2.77	0.33	0.03	0.28	0.38	0.33	0.07	0.22	0.46
uo-300-300-160	29.08	12.0	2.42	0.42	0.04	0.36	0.47	0.43	0.07	0.22	0.44
uo-300-300-200	28.00	12.0	2.33	0.56	0.04	0.51	0.62	0.55	0.07	0.20	0.41
uo-300-300-300	22.16	12.0	1.85	0.94	0.13	0.76	1.14	0.92	0.14	0.08	0.28

A.3.7 *BaSiGo: corridor experiment UNI_CORR_500*

TABLE A.10: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from BaSiGo experiment: Corridor UNI_CORR_500.

FILE *.TXT	P	A_0 [m²]	D [P/m²]	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
UNI_CORR_500_1	10.36	35.0	0.30	1.18	0.16	0.90	1.39	1.15	0.23	0.78	1.49
UNI_CORR_500_3	49.66	35.0	1.42	0.77	0.08	0.68	0.89	0.75	0.22	0.50	1.22
UNI_CORR_500_6	47.77	27.5	1.74	0.56	0.07	0.46	0.67	0.55	0.23	0.27	1.02
UNI_CORR_500_4	80.10	40.0	2.00	0.58	0.07	0.47	0.70	0.57	0.23	0.30	1.06
UNI_CORR_500_5	73.38	35.0	2.10	0.57	0.08	0.47	0.71	0.56	0.23	0.30	1.04
UNI_CORR_500_7	35.22	15.0	2.35	0.40	0.05	0.32	0.48	0.39	0.18	0.18	0.77
UNI_CORR_500_8	58.57	20.0	2.93	0.26	0.06	0.20	0.37	0.25	0.15	0.06	0.54
UNI_CORR_500_9	30.87	10.0	3.09	0.10	0.10	0.01	0.24	0.04	0.10	−0.08	0.22

A.4 DATA PROCESSING SBB DATASET

A.4.1 *Start and end of tracks*

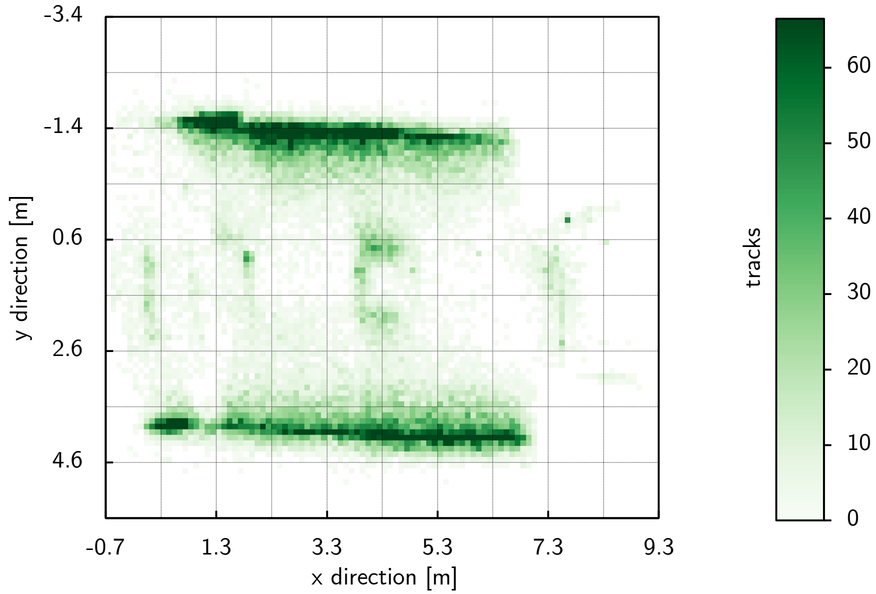

FIGURE A.2: Day: 12.05.2016; Area 2; Start points of pedestrian trajectories.

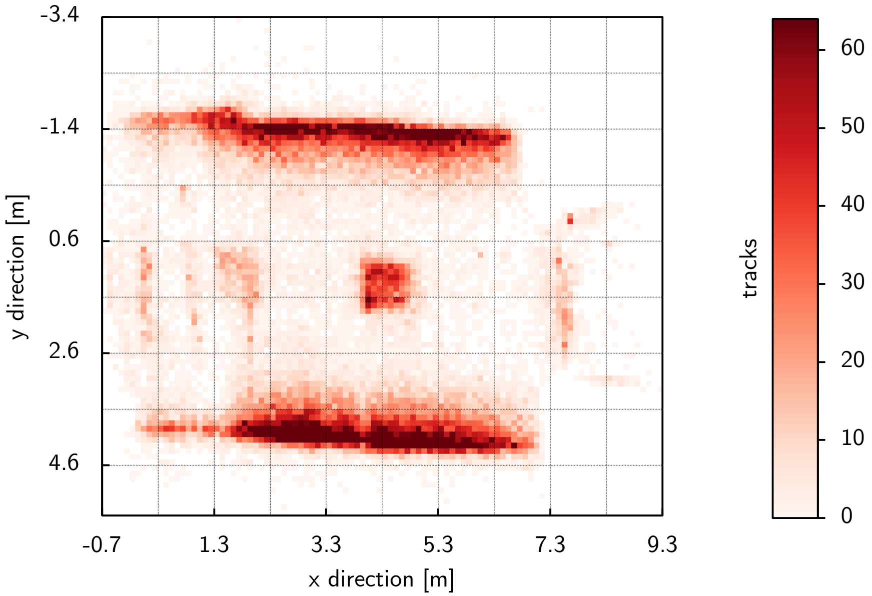

FIGURE A.3: Day: 12.05.2016; Area 2; Endpoints of pedestrian trajectories.

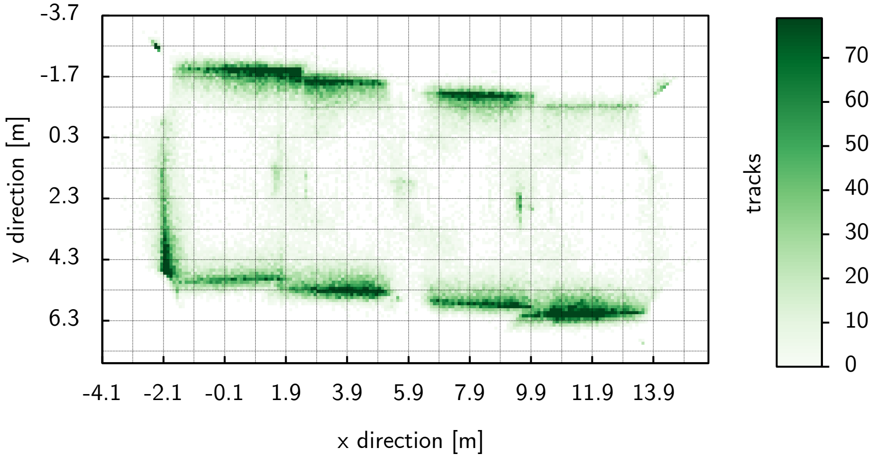

FIGURE A.4: Day: 12.05.2016; Area 3; Start points of pedestrian trajectories.

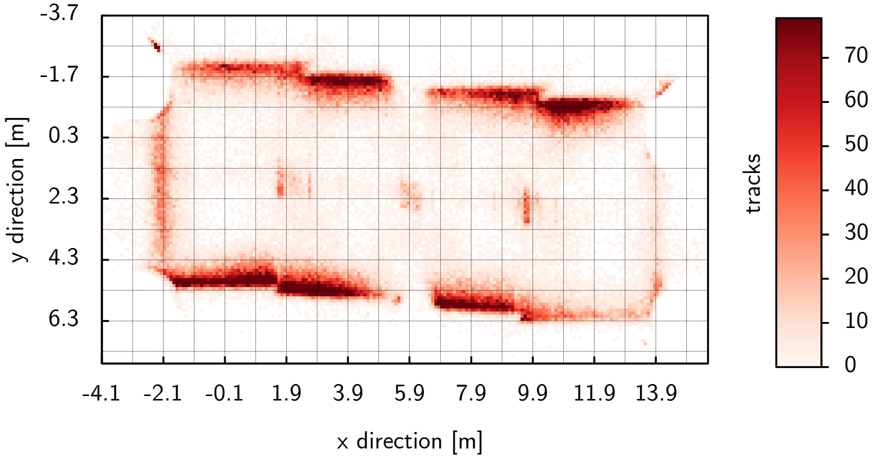

FIGURE A.5: Day: 12.05.2016; Area 3; Endpoints of pedestrian trajectories.

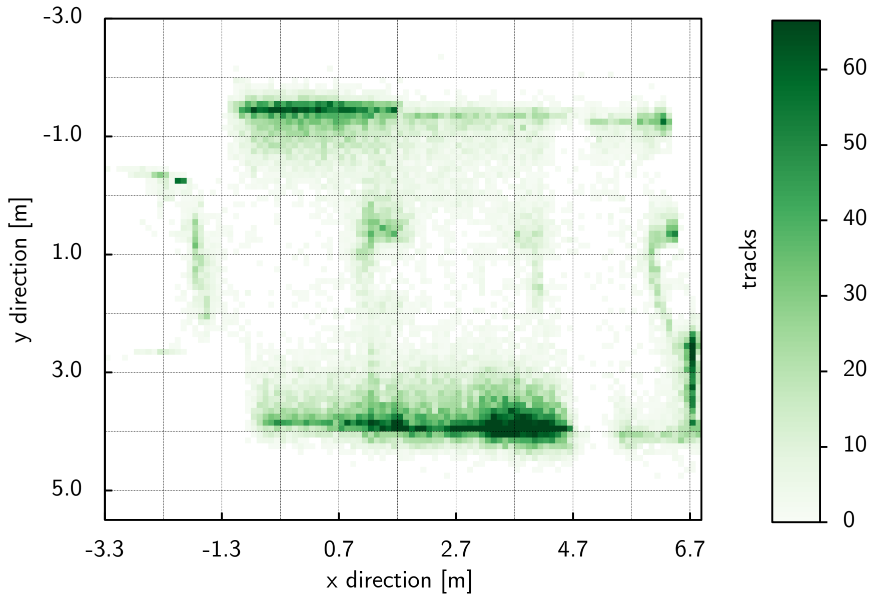

FIGURE A.6: Day: 12.05.2016; Area 4; Start points of pedestrian trajectories.

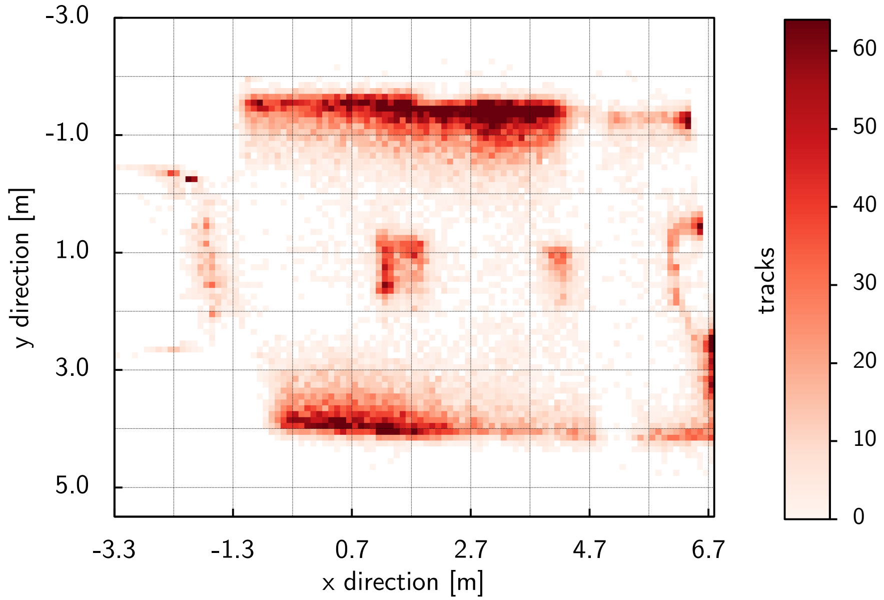

FIGURE A.7: Day: 12.05.2016; Area 4; Endpoints of pedestrian trajectories.

A.4.2 *Average walking speed*

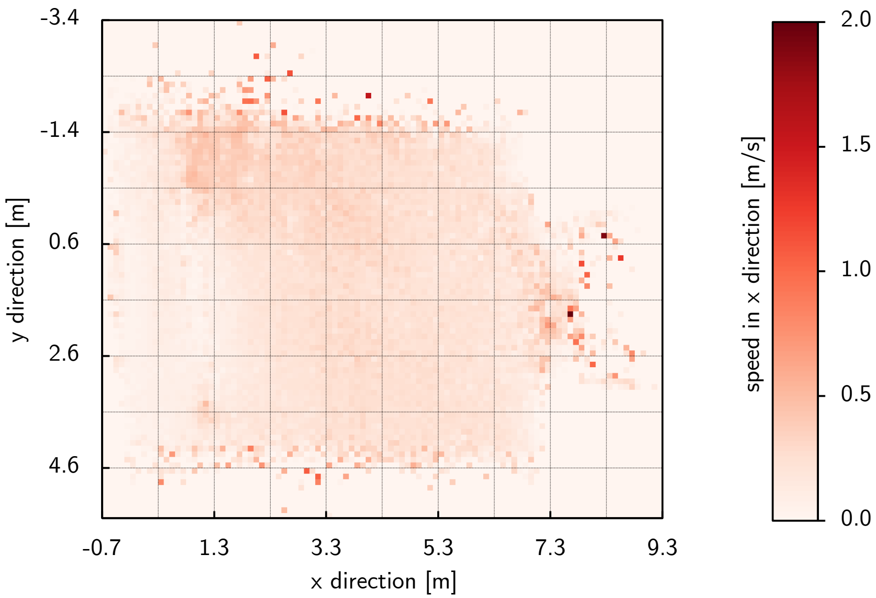

FIGURE A.8: Day: 12.05.2016; Area 2; mean speed in x direction.

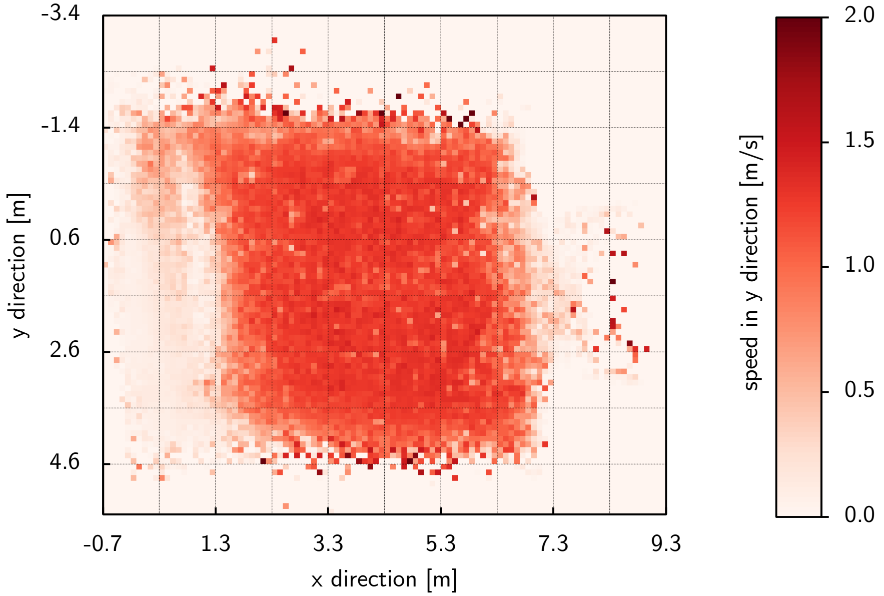

FIGURE A.9: Day: 12.05.2016; Area 2; mean speed in y (main walking) direction.

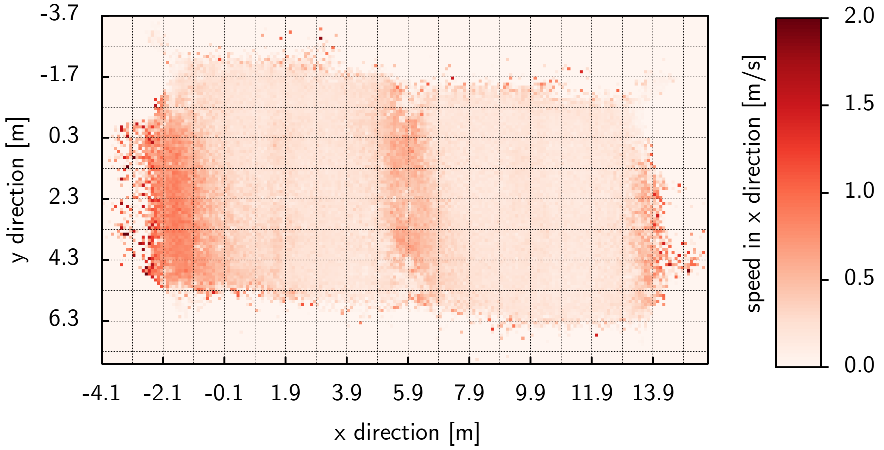

FIGURE A.10: Day: 12.05.2016; Area 3; mean speed in x direction.

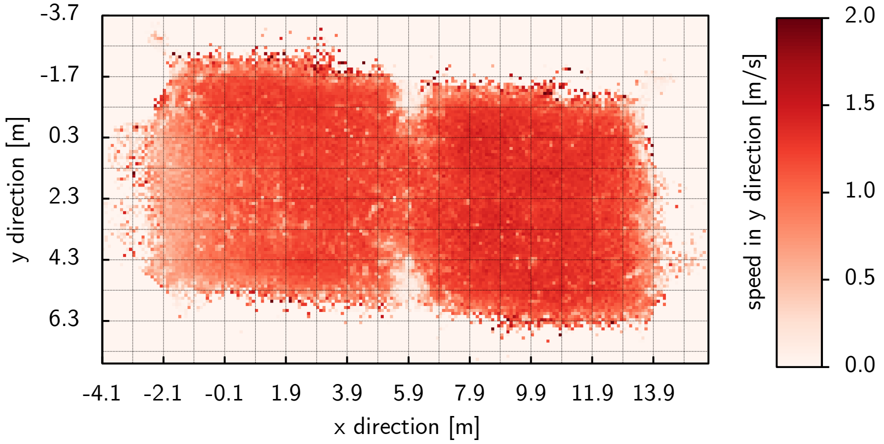

Figure A.11: Day: 12.05.2016; Area 3; mean speed in y (main walking) direction.

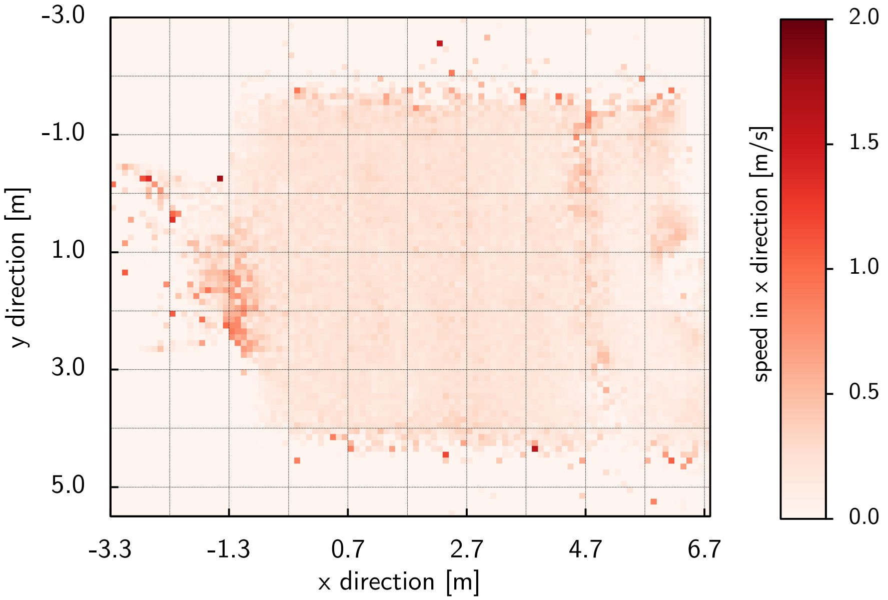

Figure A.12: Day: 12.05.2016; Area 4; mean speed in x direction.

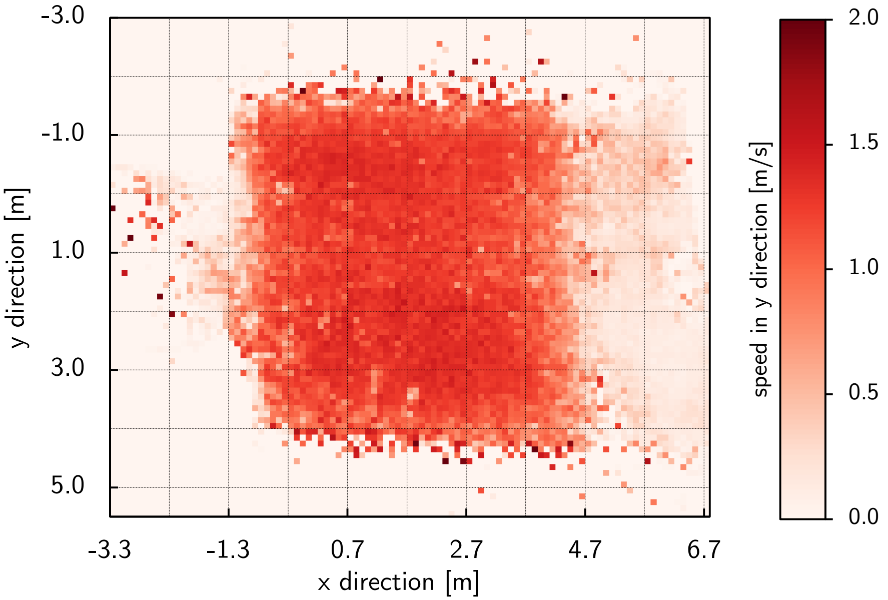

FIGURE A.13: Day: 12.05.2016; Area 4; average walking speed in y (main walking) direction.

A.4.3 *Pedestrian Counts*

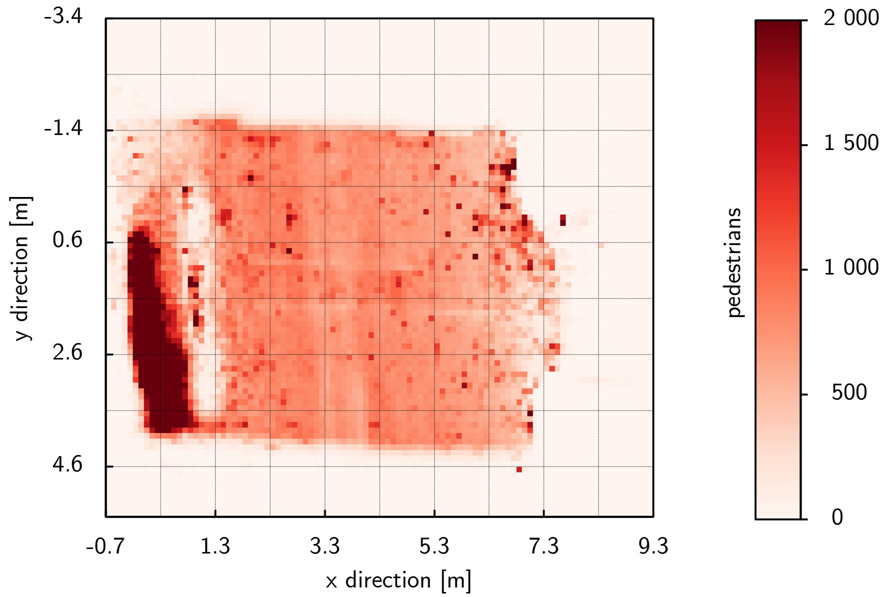

FIGURE A.14: Day: 12.05.2016; Area 2; number of pedestrians per grid cell.

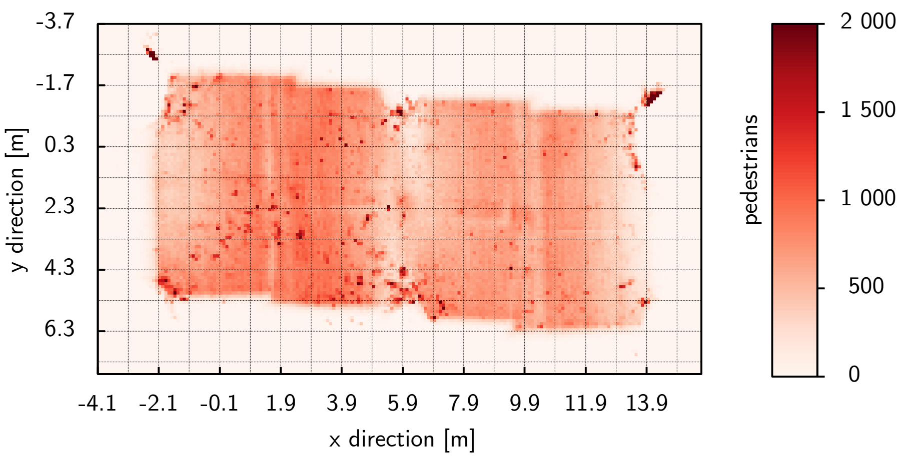

FIGURE A.15: Day: 12.05.2016; Area 3; number of pedestrians per grid cell.

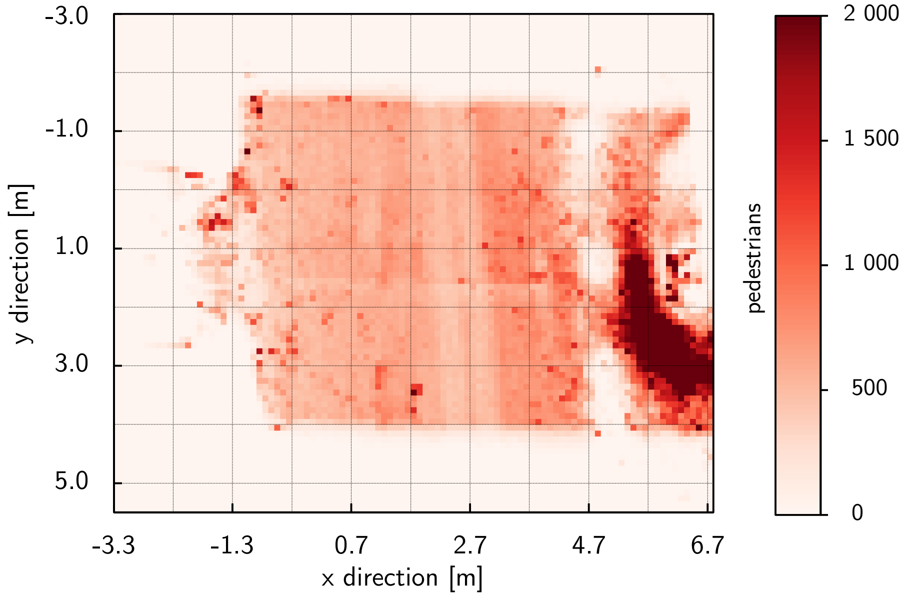

FIGURE A.16: Day: 12.05.2016; Area 4; number of pedestrians per grid cell.

A.4.4 *Area 2: analysis region – individual data point*

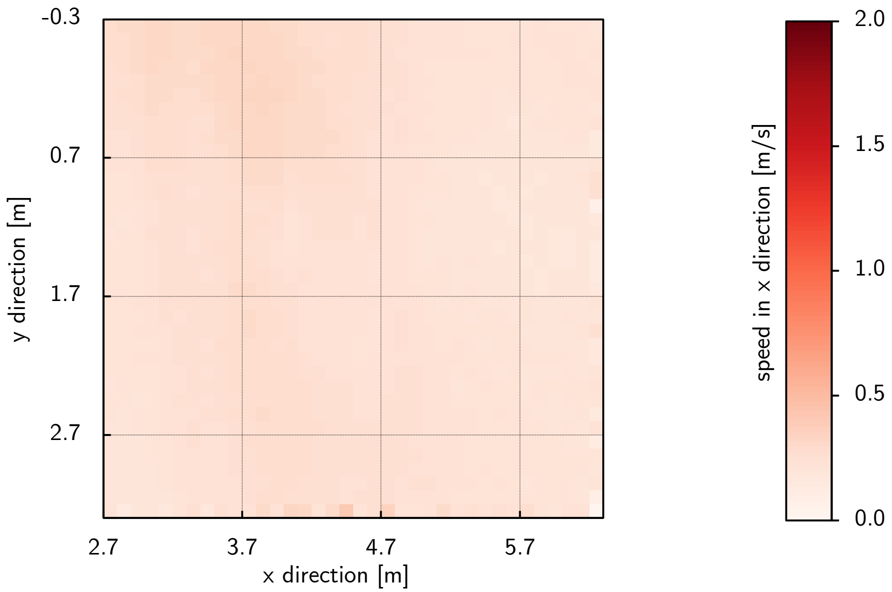

FIGURE A.17: 09.05.2016 – 24.07.2016; Area 2, analysis region; average walking speed in x direction.

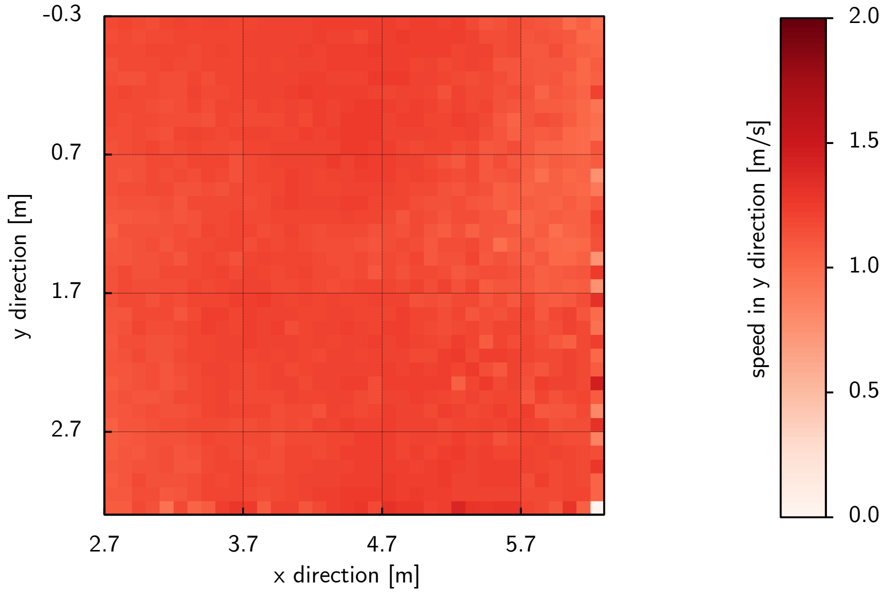

FIGURE A.18: 09.05.2016 – 24.07.2016; Area 2, average walking speed in y (main walking) direction.

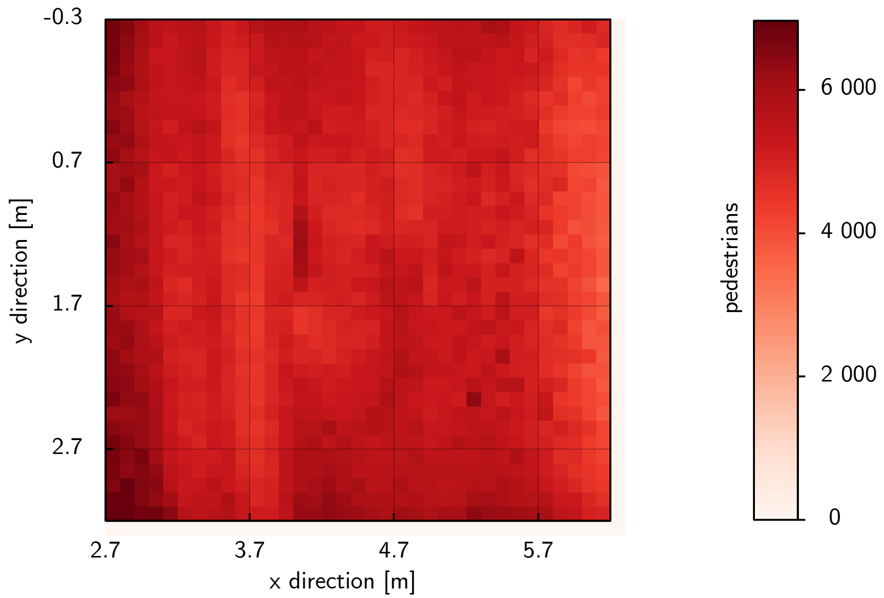

FIGURE A.19: 09.05.2016 – 24.07.2016; Area 2, analysis region; number of pedestrians per grid cell

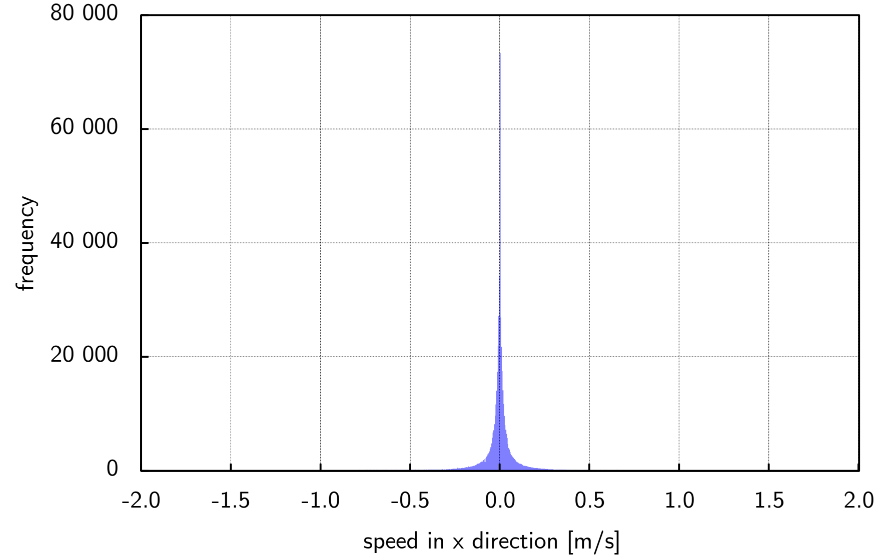

FIGURE A.20: 09.05.2016 – 24.07.2016; Area 2, analysis region; histogram of walking speeds in x direction for $v_y \leq 0.25\,\mathrm{m/s}$ (absolute values).

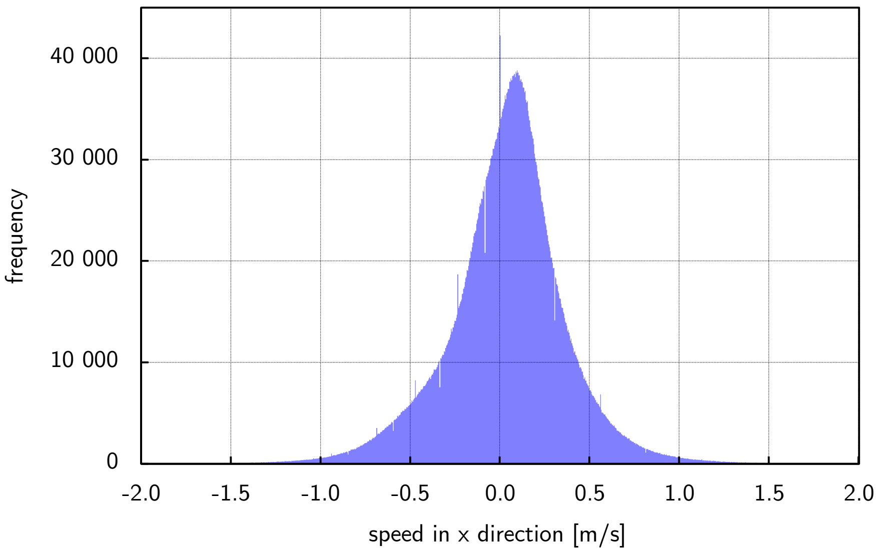

FIGURE A.21: 09.05.2016 – 24.07.2016; Area 2, analysis region; histogram of walking speeds in x direction for $v_y > 0.25\,\mathrm{m/s}$ (absolute values).

A.4.5 *Area 2: analysis region – trajectories aggregated*

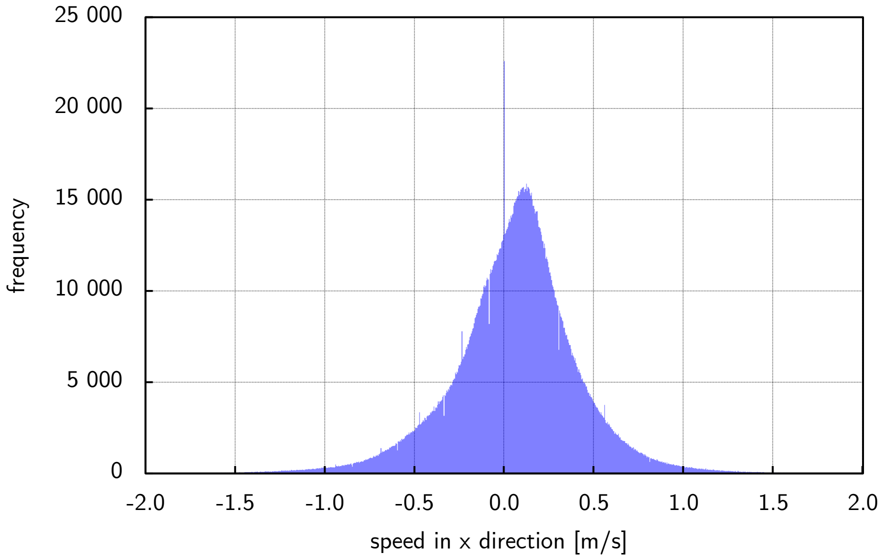

FIGURE A.22: 09.05.2016 – 24.07.2016; Area 2, analysis region; histogram of walking speeds in x direction, trajectory average.

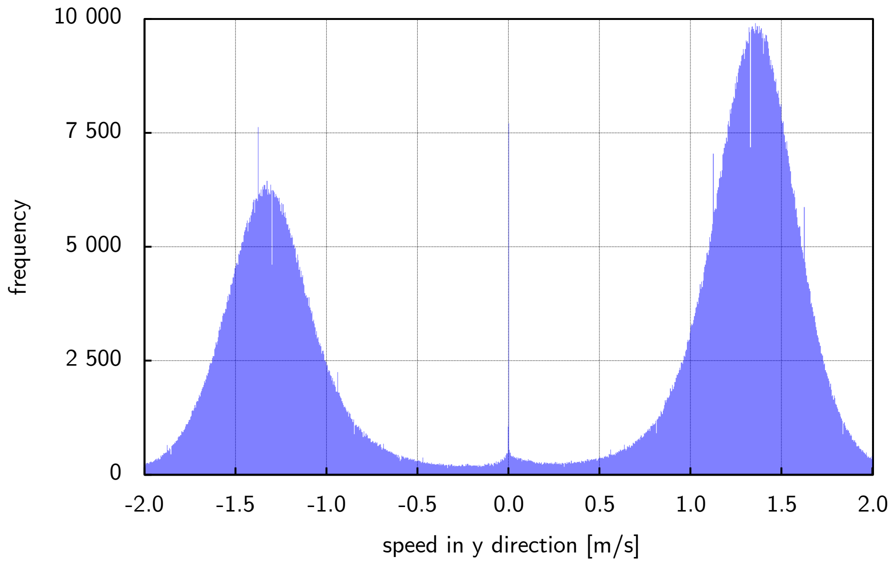

FIGURE A.23: 09.05.2016 – 24.07.2016; Area 2, analysis region; histogram of walking speeds in y direction, trajectory average.

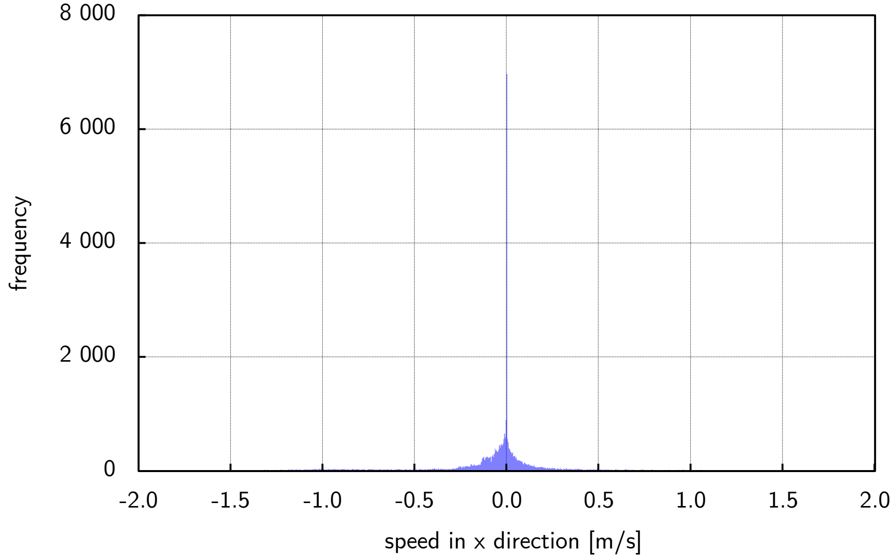

FIGURE A.24: 09.05.2016 – 24.07.2016; Area 2, analysis region; histogram of walking speeds in x direction for $v_y \leq 0.25\,\mathrm{m/s}$ (absolute values), trajectory average.

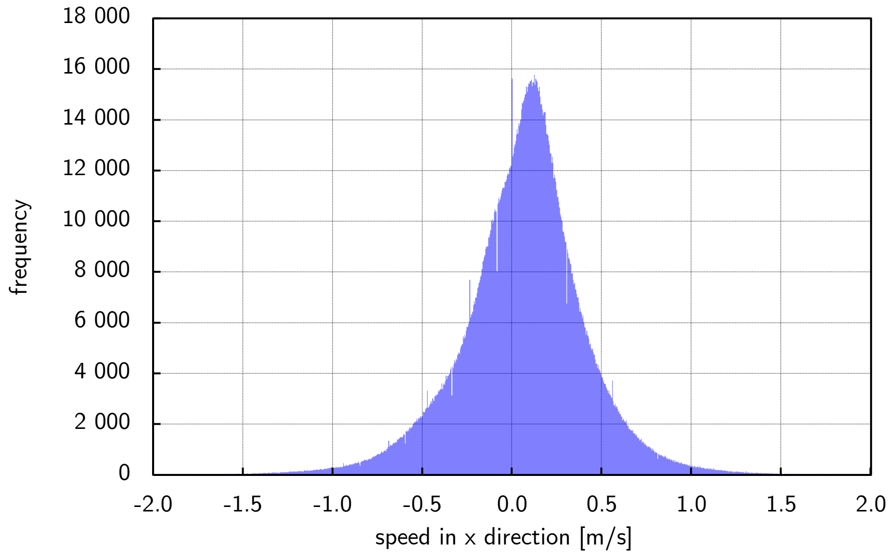

FIGURE A.25: 09.05.2016 – 24.07.2016; Area 2, analysis region; histogram of walking speeds in x direction for $v_y > 0.25\,\mathrm{m/s}$ (absolute values), trajectory average.

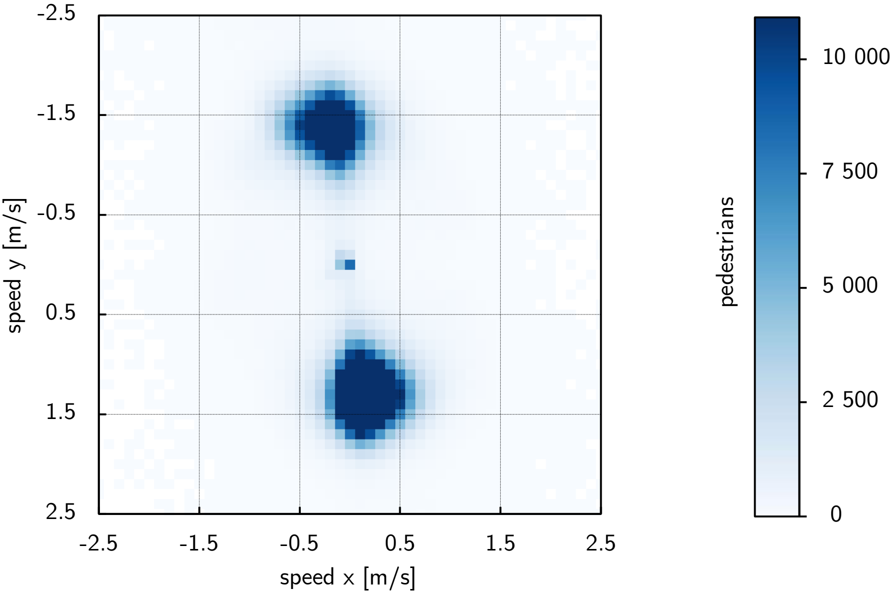

FIGURE A.26: 09.05.2016 – 24.07.2016; Area 2, analysis region; number of data points for each v_x - v_y combination, colour map cut at 20 % of the maximum value, trajectory average.

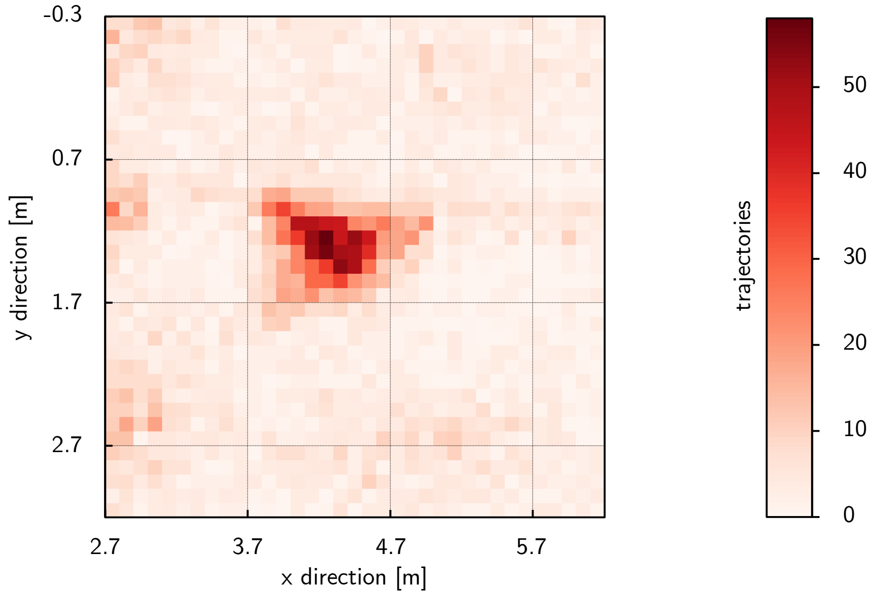

FIGURE A.27: 09.05.2016 – 24.07.2016; Area 2, analysis region; distribution of trajectories with an average speed of $v = 0$.

A.4.6 *Speed-density data*

Table A.11: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from SBB Data Bern railway station.

D [P/m²]	N	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	N	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
0.1	1 055 170	1.24	0.48	0.10	1.77	492 120	1.37	0.44	0.74	1.85
0.2	2 490 960	1.19	0.48	0.04	1.74	844 425	1.33	0.42	0.67	1.81
0.3	898 988	1.16	0.48	0.02	1.71	416 409	1.27	0.38	0.59	1.74
0.4	648 820	1.14	0.48	0.02	1.69	342 632	1.27	0.35	0.66	1.71
0.5	455 634	1.12	0.47	0.02	1.67	184 982	1.24	0.35	0.60	1.68
0.6	302 694	1.10	0.46	0.02	1.65	101 960	1.21	0.36	0.55	1.67
0.7	321 633	1.07	0.45	0.02	1.61	81 366	1.19	0.36	0.50	1.66
0.8	77 180	1.03	0.45	0.02	1.57	28 500	1.14	0.33	0.55	1.58
0.9	45 793	1.01	0.45	0.02	1.55	14 183	1.12	0.34	0.49	1.57
1.0	28 476	0.97	0.44	0.02	1.51	7 477	1.07	0.34	0.41	1.53
1.1	27 250	0.92	0.44	0.02	1.47	4 494	1.04	0.36	0.27	1.54
1.2	5 100	0.86	0.44	0.01	1.42	1 235	0.96	0.33	0.25	1.42
1.3	4 048	0.81	0.44	0.01	1.38	784	0.96	0.36	0.13	1.41
1.4	1 819	0.76	0.44	0.01	1.34	297	0.89	0.36	0.03	1.38
1.5	1 206	0.68	0.46	0.00	1.32	121	0.85	0.34	0.24	1.34
1.6	1 164	0.65	0.49	0.00	1.33	98	0.89	0.44	0.03	1.54
1.7	189	0.33	0.41	0.00	1.17	9	0.92	0.34	0.54	1.42
1.8	154	0.44	0.46	0.00	1.19	9	1.03	0.22	0.65	1.26
1.9	46	0.38	0.35	0.00	0.92	1	0.74	0.00	0.74	0.74
2.0	24	0.76	0.53	0.00	1.35	3	0.96	0.58	0.47	1.66
2.1	26	0.60	0.30	0.07	1.03	1	1.40	0.00	1.40	1.40

TABLE A.12: Speed-density data (mean, standard deviation, 5 % and 95 % percentile for individual mean and instantaneous walking speed) calculated from SBB Data Bern railway station, speed threshold 0.25 m/s.

D [P/m²]	N	$v_{i,mean}$ [m/s]	$v_{i,SD}$ [m/s]	$v_{i,5\%}$ [m/s]	$v_{i,95\%}$ [m/s]	N	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
0.1	986 040	1.32	0.38	0.70	1.79	484 641	1.39	0.41	0.83	1.85
0.2	2 288 350	1.30	0.35	0.70	1.76	826 347	1.36	0.38	0.81	1.81
0.3	812 740	1.27	0.33	0.70	1.73	405 320	1.31	0.33	0.78	1.74
0.4	582 993	1.26	0.32	0.69	1.70	334 758	1.30	0.30	0.80	1.71
0.5	409 252	1.24	0.31	0.68	1.68	179 973	1.27	0.30	0.78	1.68
0.6	271 277	1.22	0.31	0.66	1.66	98 956	1.24	0.31	0.74	1.68
0.7	288 672	1.19	0.31	0.64	1.63	78 804	1.23	0.30	0.72	1.66
0.8	68 623	1.15	0.30	0.61	1.59	27 719	1.17	0.28	0.70	1.58
0.9	40 497	1.13	0.30	0.59	1.57	13 743	1.15	0.29	0.66	1.57
1.0	25 156	1.10	0.30	0.54	1.53	7 218	1.11	0.29	0.62	1.53
1.1	23 620	1.05	0.29	0.52	1.49	4 276	1.09	0.29	0.61	1.55
1.2	4 249	1.02	0.28	0.50	1.44	1 172	1.00	0.27	0.55	1.43
1.3	3 348	0.97	0.30	0.44	1.41	735	1.02	0.29	0.54	1.43
1.4	1 432	0.95	0.29	0.43	1.36	275	0.96	0.27	0.51	1.39
1.5	889	0.90	0.29	0.42	1.35	113	0.91	0.28	0.48	1.34
1.6	789	0.94	0.30	0.44	1.40	88	0.99	0.35	0.48	1.55
1.7	73	0.79	0.32	0.31	1.30	9	0.92	0.34	0.54	1.42
1.8	75	0.87	0.27	0.40	1.37	9	1.03	0.22	0.65	1.26
1.9	28	0.60	0.28	0.33	1.16	1	0.74	0.00	0.74	0.74
2.0	17	1.06	0.30	0.61	1.44	3	0.96	0.58	0.47	1.66
2.1	22	0.69	0.22	0.48	1.07	1	1.40	0.00	1.40	1.40

A.5 MODEL CALIBRATION

A.5.1 *Calibration data HERMES UO* ($b = 2.4\,\mathrm{m}$)

TABLE A.13: Speed-density data used for calibration (mean, standard deviation, 5 % and 95 % percentile for instantaneous walking speed) calculated from HERMES experiment: Corridor UO.

D [P/m²]	$v_{t,mean}$ [m/s]	$v_{t,SD}$ [m/s]	$v_{t,5\%}$ [m/s]	$v_{t,95\%}$ [m/s]
0.1	1.54	0.17	1.27	1.81
0.2	1.53	0.16	1.29	1.78
0.3	1.52	0.15	1.31	1.75
0.4	1.51	0.14	1.33	1.72
0.5	1.46	0.16	1.26	1.72
0.6	1.41	0.19	1.17	1.71
0.7	1.39	0.17	1.10	1.65
0.8	1.37	0.16	1.11	1.60
0.9	1.34	0.15	1.11	1.55
1.0	1.31	0.13	1.12	1.51
1.1	1.26	0.13	1.07	1.45
1.2	1.20	0.13	1.02	1.40
1.3	1.15	0.12	0.96	1.35
1.4	1.09	0.12	0.91	1.29
1.5	1.04	0.12	0.86	1.24
1.6	0.98	0.12	0.80	1.19
1.7	0.94	0.12	0.76	1.15
1.8	0.90	0.13	0.71	1.12
1.9	0.86	0.13	0.67	1.09
2.0	0.78	0.12	0.61	0.98
2.1	0.70	0.10	0.54	0.88
2.2	0.62	0.09	0.48	0.78
2.3	0.55	0.08	0.42	0.69
2.4	0.49	0.08	0.37	0.64
2.5	0.44	0.08	0.32	0.58
2.6	0.40	0.08	0.28	0.54
2.7	0.36	0.07	0.25	0.49
2.8	0.34	0.07	0.22	0.46

A.5.2 *Calibration runs*

TABLE A.14: Parameter values and RMSE for the calibration runs performed. Calibration set 1, only parameter values different from model run 1 are shown.

RUN	d_{back} [m]	$h_{r,max}$ [m]	$t_{r,max}$ [s]	v_{min} [m/s]	r_n [%]	t_{rd} STEP [s]	FORMULA	RMSE [m/s] v_{mean}	v_{SD}	$v_{5\%}$	$v_{95\%}$
1	3.0	4.00	1.00	0.00	10	$0.2 - 0.4$	Cavagna	0.080	0.070	0.181	0.097
1a								0.081	0.065	0.175	0.092
1b								0.085	0.066	0.181	0.090
1c								0.077	0.066	0.169	0.100
2						0.20		0.078	0.042	0.133	0.078
3						0.40		0.080	0.263	0.440	0.431
4						0.30		0.080	0.061	0.167	0.088
5					0			0.074	0.060	0.114	0.139
6					20			0.094	0.354	0.492	0.533
7					30			0.464	0.367	0.680	0.361
8				0.10				0.083	0.244	0.370	0.421
9				0.30				0.178	0.412	0.549	0.560
10				0.50				0.265	0.432	0.588	0.567
11			0.50					0.080	0.025	0.087	0.107
12			0.80					0.076	0.045	0.135	0.081
13			1.20					0.097	0.320	0.451	0.505
14			1.50					0.181	0.414	0.549	0.561
15		2.00						0.084	0.065	0.181	0.085
16		3.00						0.079	0.068	0.179	0.091
17		5.00						0.081	0.066	0.176	0.093
18		6.00						0.075	0.068	0.170	0.097
19	1.0							0.087	0.069	0.171	0.118
20	2.0							0.081	0.068	0.173	0.107
21	4.0							0.079	0.068	0.178	0.090
22	5.0							0.082	0.068	0.182	0.086
23							Jelic	0.083	0.159	0.360	0.209

Table A.15: Parameter values and RMSE for the calibration runs performed. Calibration set 2, only parameter values different from model run 1 are shown.

RUN	d_{back} [m]	$h_{r,max}$ [m]	$t_{r,max}$ [s]	v_{min} [m/s]	r_n [%]	t_{rd} [s]	STEP FORMULA	RMSE [m/s] v_{mean}	v_{SD}	$v_{5\%}$	$v_{95\%}$
1	4.0	6.00	0.80	0.00	0	0.20	Cavagna	0.075	0.067	0.098	0.161
1a								0.073	0.067	0.098	0.160
1b								0.078	0.066	0.097	0.165
1c								0.070	0.065	0.098	0.152
1d								0.076	0.065	0.097	0.160
2						0.10		0.073	0.070	0.101	0.162
3						0.15		0.077	0.072	0.100	0.173
4						0.25		0.069	0.065	0.103	0.150
5						0.30		0.076	0.055	0.106	0.124
6					5			0.079	0.026	0.066	0.114
7					10			0.080	0.030	0.116	0.082
8				0.05				0.072	0.067	0.101	0.157
9				0.10				0.077	0.066	0.096	0.163
10			0.60					0.074	0.069	0.098	0.166
11			0.70					0.076	0.069	0.099	0.166
12			0.90					0.076	0.066	0.096	0.161
13			1.00					0.076	0.063	0.099	0.156
14		5.00						0.072	0.068	0.104	0.156
15		5.50						0.076	0.066	0.097	0.161
16		6.50						0.082	0.069	0.094	0.172
17		7.00						0.078	0.067	0.096	0.168
18	3.0							0.078	0.067	0.100	0.163
19	3.5							0.076	0.067	0.099	0.163
20	4.5							0.076	0.069	0.096	0.166
21	5.0							0.076	0.068	0.098	0.163
23							Jelic	0.079	0.054	0.093	0.147

Table A.16: Parameter values and RMSE for the calibration runs performed. Calibration set 3, only parameter values different from model run 1 are shown.

RUN	d_{back} [m]	$h_{r,max}$ [m]	$t_{r,max}$ [s]	v_{min} [m/s]	r_n [%]	t_{rd} [s]	STEP FORMULA	RMSE [m/s] v_{mean}	v_{SD}	$v_{5\%}$	$v_{95\%}$
1	4.0	5.00	0.80	0.00	5	0.25	Cavagna	0.077	0.026	0.064	0.110
1a								0.080	0.026	0.066	0.114
1b								0.074	0.027	0.063	0.108
1c								0.075	0.027	0.064	0.108
1d								0.080	0.027	0.066	0.115
2						0.20		0.078	0.026	0.065	0.113
3						0.23		0.079	0.026	0.065	0.114
4						0.27		0.076	0.018	0.075	0.091
5						0.30		0.076	0.019	0.079	0.088
6					0			0.078	0.067	0.097	0.165
7					3			0.075	0.048	0.069	0.137
8					7			0.076	0.014	0.079	0.091
9					10			0.078	0.031	0.115	0.080
10				0.05				0.074	0.027	0.065	0.106
11				0.10				0.080	0.027	0.064	0.115
12			0.50					0.075	0.041	0.058	0.132
13			0.60					0.074	0.035	0.059	0.120
14			0.70					0.076	0.031	0.061	0.117
15		4.00						0.074	0.026	0.064	0.106
16		4.50						0.077	0.026	0.065	0.109
17		5.50						0.079	0.026	0.066	0.113
18		6.00						0.076	0.027	0.065	0.111

Table A.17: Parameter values and RMSE for the calibration runs performed. Calibration set 4, only parameter values different from model run 1 are shown.

RUN	d_{back} [m]	$h_{r,max}$ [m]	$t_{r,max}$ [s]	v_{min} [m/s]	r_n [%]	t_{rd} [s]	STEP FORMULA	RMSE [m/s] v_{mean}	v_{SD}	$v_{5\%}$	$v_{95\%}$
1	4.0	4.00	0.60	0.00	5	0.30	Cavagna	0.074	0.030	0.059	0.114
1a								0.078	0.031	0.060	0.121
1b								0.073	0.030	0.059	0.114
1c								0.075	0.030	0.059	0.117
2a						0.20		0.077	0.034	0.058	0.125
2b						0.20		0.078	0.035	0.058	0.129
2c						0.20		0.078	0.035	0.058	0.127

Table A.17: Parameter values and RMSE for the calibration runs performed. Calibration set 4, only parameter values different from model run 1 are shown.

RUN	d_{back} [m]	$h_{r,max}$ [m]	$t_{r,max}$ [s]	v_{min} [m/s]	r_n [%]	t_{rd} [s]	STEP FORMULA	RMSE [m/s] v_{mean}	v_{SD}	$v_{5\%}$	$v_{95\%}$
3a						0.23		0.076	0.033	0.057	0.123
3b						0.23		0.073	0.034	0.058	0.120
3c						0.23		0.076	0.034	0.058	0.125
4a						0.27		0.079	0.030	0.061	0.122
4b						0.27		0.076	0.030	0.059	0.117
4c						0.27		0.078	0.030	0.059	0.120
5a						0.32		0.072	0.030	0.058	0.114
5b						0.32		0.077	0.030	0.060	0.119
5c						0.32		0.078	0.031	0.057	0.123
5d						0.32		0.072	0.030	0.058	0.113
5e						0.32		0.075	0.030	0.058	0.116
6a						0.34		0.075	0.031	0.059	0.119
6b						0.34		0.080	0.030	0.060	0.123
6c						0.34		0.076	0.030	0.060	0.118
7a						0.36		0.073	0.023	0.064	0.103
7b						0.36		0.078	0.024	0.067	0.108
7c						0.36		0.074	0.022	0.063	0.104
8a					0			0.077	0.069	0.097	0.166
8b					0			0.074	0.069	0.098	0.165
8c					0			0.075	0.070	0.096	0.169
9a					3			0.077	0.051	0.068	0.145
9b					3			0.074	0.050	0.064	0.141
9c					3			0.078	0.050	0.065	0.147
10a					7			0.075	0.018	0.072	0.098
10b					7			0.072	0.017	0.070	0.094
10c					7			0.073	0.018	0.068	0.098
11a					10			0.071	0.031	0.104	0.085
11b					10			0.078	0.030	0.110	0.088
11c					10			0.076	0.031	0.111	0.083
12a			0.00	0.05	7			0.076	0.018	0.073	0.099
12b				0.05	7			0.077	0.018	0.073	0.101
12c				0.05	7			0.081	0.019	0.076	0.104

TABLE A.17: Parameter values and RMSE for the calibration runs performed. Calibration set 4, only parameter values different from model run 1 are shown.

RUN	d_{back} [m]	$h_{r,max}$ [m]	$t_{r,max}$ [s]	v_{min} [m/s]	r_n [%]	t_{rd} [s]	STEP FORMULA	RMSE [m/s] v_{mean}	v_{SD}	$v_{5\%}$	$v_{95\%}$
13a				0.10	7			0.075	0.017	0.073	0.097
13b				0.10	7			0.074	0.017	0.070	0.097
13c				0.10	7			0.073	0.018	0.070	0.098
14a			0.55		7			0.082	0.019	0.079	0.106
14b			0.55		7			0.075	0.018	0.071	0.098
14c			0.55		7			0.074	0.018	0.073	0.095
15a			0.65		7			0.077	0.018	0.071	0.102
15b			0.65		7			0.077	0.019	0.075	0.101
15c			0.65		7			0.073	0.017	0.069	0.096
16a					7			0.077	0.018	0.072	0.101
16b		3.50			7			0.070	0.017	0.070	0.092
16c		3.50			7			0.078	0.018	0.073	0.102
17a		4.50			7			0.077	0.018	0.072	0.101
17b		4.50			7			0.074	0.017	0.072	0.095
17c		4.50			7			0.077	0.018	0.074	0.098
18a	3.5				7			0.070	0.017	0.068	0.094
18b	3.5				7			0.071	0.017	0.068	0.095
18c	3.5				7			0.074	0.018	0.072	0.097
19a	4.5				7			0.080	0.018	0.077	0.102
19b	4.5				7			0.077	0.017	0.073	0.099
19c	4.5				7			0.075	0.017	0.073	0.097
20a	3.0				7			0.078	0.018	0.073	0.103
20b	3.0				7			0.078	0.019	0.073	0.106
20c	3.0				7			0.072	0.017	0.067	0.097

TABLE A.18: Parameter values and RMSE for the calibration runs performed. Calibration set 5, only parameter values different from model run 1 are shown.

RUN	d_{back} [m]	$h_{r,max}$ [m]	$t_{r,max}$ [s]	v_{min} [m/s]	r_n [%]	t_{rd} [s]	STEP FORMULA	RMSE [m/s] v_{mean}	v_{SD}	$v_{5\%}$	$v_{95\%}$
1	3.5	4.00	0.60	0.00	7	0.30	Cavagna	0.072	0.017	0.069	0.095
2a						0.28		0.078	0.017	0.073	0.102
2b						0.28		0.076	0.018	0.071	0.101
2c						0.28		0.074	0.017	0.070	0.098
3a						0.32		0.076	0.018	0.073	0.099
3b						0.32		0.074	0.017	0.072	0.096
3c						0.32		0.075	0.018	0.070	0.099
4a					5			0.076	0.031	0.059	0.118
4b					5			0.073	0.029	0.058	0.114
4c					5			0.073	0.029	0.059	0.112
5a					9			0.074	0.024	0.092	0.091
5b					9			0.069	0.025	0.089	0.089
5c					9			0.073	0.024	0.093	0.088
6a			0.55					0.075	0.017	0.071	0.098
6b			0.55					0.074	0.018	0.072	0.099
6c			0.55					0.077	0.017	0.072	0.101
7a			0.65					0.077	0.019	0.074	0.101
7b			0.65					0.075	0.018	0.071	0.099
7c			0.65					0.078	0.018	0.073	0.102
8a		3.50						0.076	0.018	0.073	0.099
8b		3.50						0.076	0.018	0.074	0.099
8c		3.50						0.074	0.018	0.071	0.099
9a		4.50						0.074	0.018	0.070	0.099
9b		4.50						0.075	0.018	0.073	0.099
9c		4.50						0.075	0.017	0.071	0.099

A.6 MODEL VALIDATION: PARAMETER RANGE

TABLE A.19: Parameter values (μ/σ) for the simulations done to study the parameter range.

RUN	v_d [m/s]	w_B [m]	w_S [m]	d_B [m]	d_i [m]	t_r [s]	t_d [s]	a_{max} [m/s²]
1				Uniform				
2				Maximum				
3				Minimum				
4				Average				
5	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
6	1.45/0.10	0.40/0.02	0.05/0.01	0.25/0.02	0.17/0.01	0.55/0.06	0.70/0.10	0.50/0.07
7	1.10/0.10	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
8	1.80/0.10	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
9	1.45/0.20	0.35/0.02	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
10	1.45/0.20	0.45/0.02	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
11	1.45/0.20	0.40/0.05	0.04/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
12	1.45/0.20	0.40/0.05	0.06/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
13	1.45/0.20	0.40/0.05	0.05/0.01	0.20/0.02	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
14	1.45/0.20	0.40/0.05	0.05/0.01	0.30/0.02	0.17/0.01	0.55/0.13	0.70/0.20	0.50/0.15
15	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.16/0.01	0.55/0.13	0.70/0.20	0.50/0.15
16	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.19/0.01	0.55/0.13	0.70/0.20	0.50/0.15
17	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.40/0.06	0.70/0.20	0.50/0.15
18	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.70/0.06	0.70/0.20	0.50/0.15
19	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.40/0.10	0.50/0.15
20	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	1.00/0.10	0.50/0.15
21	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.30/0.07
22	1.45/0.20	0.40/0.05	0.05/0.01	0.25/0.05	0.17/0.01	0.55/0.13	0.70/0.20	0.70/0.07
23	1.58/0.27	0.42/0.08	0.05/0.00	0.16/0.02	0.18/0.02	0.64/0.03	1.02/0.18	0.77/0.28
24	1.05/0.28	0.37/0.01	0.06/0.00	0.32/0.08	0.15/0.02	0.61/0.10	0.86/0.37	0.49/0.15

A.7 MODEL APPLICATION

TABLE A.20: Parameter values (μ/σ) for the model applications.

RUN	v_d [m/s]	w_B [m]	w_S [m]	d_B [m]	d_i [m]	t_r [s]	t_d [s]	a_{max} [m/s²]
Standard	1.34/0.26	0.41/0.04	0.05/0.01	0.25/0.03	0.17/0.01	0.60/0.10	0.75/0.12	0.50/0.15
Young	1.50/0.20	0.41/0.04	0.05/0.01	0.26/0.02	0.16/0.01	0.45/0.10	0.50/0.20	0.70/0.10
Old	1.00/0.20	0.41/0.04	0.06/0.01	0.30/0.04	0.19/0.01	0.75/0.15	1.00/0.20	0.30/0.10
Asian	1.25/0.20	0.42/0.03	0.04/0.01	0.23/0.03	0.15/0.01	0.65/0.10	0.65/0.12	0.50/0.10
European	1.34/0.20	0.46/0.02	0.05/0.01	0.29/0.03	0.19/0.01	0.55/0.10	0.85/0.12	0.50/0.10
Men	1.39/0.20	0.44/0.02	0.05/0.01	0.28/0.03	0.16/0.01	0.60/0.10	0.75/0.12	0.55/0.10
Women	1.29/0.20	0.38/0.02	0.05/0.01	0.29/0.02	0.18/0.01	0.60/0.10	0.75/0.12	0.45/0.10
High temp.	1.45/0.26	0.41/0.04	0.05/0.01	0.25/0.03	0.17/0.01	0.65/0.10	0.75/0.12	0.40/0.10
Low temp.	1.28/0.26	0.41/0.04	0.05/0.01	0.27/0.03	0.17/0.01	0.60/0.10	0.75/0.12	0.60/0.10
Business	1.34/0.20	0.40/0.04	0.05/0.01	0.23/0.03	0.16/0.01	0.50/0.10	0.50/0.15	0.70/0.10
Leisure	1.28/0.20	0.41/0.04	0.06/0.01	0.25/0.03	0.18/0.01	0.70/0.10	0.90/0.15	0.40/0.15
Commuters	1.34/0.20	0.40/0.04	0.05/0.01	0.23/0.03	0.16/0.01	0.50/0.10	0.50/0.15	0.70/0.10
Shop./leis.	1.15/0.20	0.41/0.04	0.06/0.01	0.25/0.03	0.18/0.01	0.70/0.10	0.90/0.15	0.30/0.15
Mixed	random mixture between commuters and shopping/leisure							
FD 2050	1.30/0.40	0.44/0.04	0.06/0.01	0.29/0.04	0.19/0.01	0.65/0.15	0.80/0.25	0.45/0.25
Festival	1.11/0.10	0.41/0.04	0.05/0.01	0.28/0.03	0.15/0.02	0.75/0.10	1.00/0.20	0.30/0.10

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