The Influence of Individual Characteristics on Crowd Dynamics

Paul Geoerg

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Abstract

Adequately dimensioned egress routes are important for designing safe buildings. However, their capacity analysis is usually based on studies under controlled conditions with populations defined by homogeneous movement characteristics. As a consequence, the nowadays increasing proportions of older people or persons with disabilities are not taken into account in these studies. As a result, these groups are not considered in functional relationships of pedestrian movement and therefore an issue for crowd dynamics analysis. Thus, there is a need to provide valid engineering egress data considering heterogeneous crowds, i.e. with older people and persons with disabilities. In this sense, this doctoral thesis introduces empirical insights into movement characteristics of crowds with different conditions of heterogeneity to estimate the influence of individual movement characteristics on key performance values, e.g. like speeds or flow rates.

Therefore a series of studies were conducted in corridor and bottleneck situations with about 10 % of participants with various disabilities and different assistive devices. These studies comprised ten to 80 participants and focused on the analysis of unimpeded speed, the individual time gap and the specific flow concept as well as the speed-density-relations and flow-density-relations. First, the unimpeded speed in the horizontal motion and its dependency on individual characteristics was determined. Second, an influence on gaps between participants and effects on the specific flow in different conditions of crowd heterogeneity was assessed. Third, empirical speed-density- and flow-density-relations were analysed to perform a capacity analysis.

As a result, the diversity of individual characteristics strongly affected the local stationarity of the measures of individual velocity, density and flow rate, the dependency between density and movement speed or flow as well as increased the rate of interpersonal interactions. To integrate these results into egress calculation methods, a new analysis concept was established. Its four steps are: first, the consideration of an extended range of individual preparation times to start egress activities; second, an extended variation in distributed individual speeds; third, an adoption of empirical relations and fourth, an estimation of the flow rate based on scattered individual time gaps. Thus, this proposed concept allows the consideration of individual, heterogeneous abilities for participation in egress calculation methods.

Kurzfassung

Die sichere Bewegung in Fußgängergruppen wird durch ausreichend dimensionierte Flucht- und Rettungswege garantiert. Deren geplante Kapazitäten beruhen in der Regel auf wissenschaftlichen Studien, die mit Gruppen junger Personen mit vergleichbarer körperlicher oder geistiger Leistungsfähigkeit durchgeführt wurden. Dadurch wird der zunehmende Anteil von älteren Menschen oder Menschen mit körperlichen, geistigen oder altersbedingten Beeinträchtigungen nicht in den funktionalen Beziehungen der Fußgängerbewegung berücksichtigt. Die vorliegende Dissertation untersucht daher den Einfluss individueller Personeneigenschaften auf Kennwerte der Bewegung in heterogenen Personengruppen wie beispielsweise die Bewegungsgeschwindigkeit oder Flussraten.

Dazu wurden in einem interdisziplinären Forschungsprojekt klein- und großskalige Bewegungsstudien unter Laborbedingungen durchgeführt. Die Gesamtpopulation betrug zehn bzw. etwa 80 Teilnehmende je Studie, von denen etwa 10 % unterschiedliche körperliche, geistige oder altersbedingte Beeinträchtigung aufwiesen oder auf die Nutzung unterschiedlicher Assistenzmittel angewiesen waren. Es wurden insbesondere die freie horizontale Bewegungsgeschwindigkeit, die Dichteabhängigkeit der Bewegungsgeschwindigkeit sowie des Personenflusses analysiert. Die Gültigkeit des spezifischen Flusskonzeptes wurde überprüft.

Es zeigt sich ein sensitiver Zusammenhang zwischen der Heterogenität individueller Bewegungseigenschaften und den zentralen Kennwerten der Fußgängerbewegung. Die Berücksichtigung dieser Erkenntnisse in Bewertungsmethoden der Fußgängerbewegung wird in einem vierstufigen Konzept realisiert: erstens, sind eine erhöhte Streuung der Vorbereitungszeiten sowie, zweitens, breite Verteilungen individueller Bewegungsgeschwindigkeiten zu berücksichtigen. Die Präsenz von Menschen mit Beeinträchtigungen in einer Gruppe kann, drittens, zu einer Anpassung der Dichteabhängigkeit von Bewegungsgeschwindigkeit und Personenfluss führen und ist zu berücksichtigen. Der Personenfluss durch den Querschnitt eines Rettungsweges lässt sich, basierend auf individuellen Durchgangszeiten, abschätzen und für Ingenieurmethoden nutzen. Anhand der des vorgeschlagenen Konzepts wird die Berücksichtigung individueller, heterogener Mobilitätseigenschaften in Methoden der Evakuierungsberechnung ermöglicht.

Acknowledgements

This dissertation summarises my research during the last seven years. The work has accompanied me at two institutes and through various research projects. I started with specific questions that I wanted to answer. And now, at the end of my PhD studies, I seem to have more unanswered questions than answers. But many people accompanied me through this multifaceted journey of ups and downs. These people I want to mention here.

First, I want to express my sincere thanks to my supervisor and doctoral advisor, Prof. Armin Seyfried, who believed, supported, advised and guided me along the way. Thank you for all the patient, constructive discussions, lively debates, trust and support during this time. I would thank Prof. Ulrich Krause who believed in me and gave me his trust over this period. Thanks to Prof. Frank Fiedrich for his valuable comments and advice in the third party review and Prof. Jürgen Gerlach for chairing the defence of this dissertation.

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Chapter 1

Introduction

1.1 Motivation and Scope

The adequate dimensioning of egress routes and evaluation of evacuation processes is an important component in the functional consideration of safety in built environments. Great efforts have been made to understand and calculate the movement of pedestrians in crowds [1–5] in the recent decades. For pragmatic reasons, these studies were often conducted with participants who had similar age or mobility profiles (homogeneous crowd conditions) [6, 7]. The assessment of the influence of individual characteristics (e.g. physiological characteristics, functional consequences) is therefore based on the studies of homogeneous groups.

The probability of dying in a disaster event is particularly high for people with disabilities (e.g. [9–15], [16, pp. 74-76)] and older people [17, 18]. This is becoming increasingly important as life expectancy increases in industrialised countries. For example, the median age of societies in Canada, the UK, Japan, the USA, France and Germany has risen from 35-40 years in 2000 to 40-45 years in 2017 [19]. This trend is also illustrated by the transformation of the population pyramids into population barrels, as exemplified in Fig. 1.1 for the years 1995 and 2015 in Germany and Great Britain.

In combination with low birth rates, rising life expectancy leads to the average ageing of society. Despite a process of adjustment, the life expectancy of people with disabilities remains well below the average life expectancy of society as a whole. It is largely dependent on the type of impairment [20, pp. 27 sqq]. Due to the increasing concentration in cities and rapidly rising mobility needs, the consideration of individual characteristics in standards and engineering methods is becoming all the more important.

The thesis investigates whether the parameters currently used to describe movement are also suitable for heterogeneous crowds. In this dissertation, heterogeneity refers to the varying degrees of a person's ability to move independently or assisted, alone or in a group. Physical, mental or age-related impairments are used as indicators of this heterogeneity

Figure 1.1: *Ageing barrels depending on gender for Germany and the United Kingdom. In general, current demographic trends mean that societies in developed countries are growing older. An increased ratio between inhabitants older than 65 years and in age between 15 and 65 years (ageing quotient) is observed in these countries.*
Source: [8].

and operationalised through individual forms of characteristics. The focus is not on the cause of impairment, but on its consequences for the movement of a pedestrian (e.g. being able to move exclusively with the help of a technical means of assistance). This results in different characteristics of the need for assistance, changed demands on individual and social space requirements or the influence on characteristics of the movement sequence such as acceleration or compensatory movements.

Disabilities are divided into four categories, which are related to important sub-processes of movement:

– Impairments in perception,

– Impairment of information processing and decision making,

– Impairments in the realisation of the movement,

– Impairments, which may affect two or all three categories.

This dissertation deals with the issue of how individual characteristics of individuals in a crowd determine the engineering parameters of pedestrian safety (Objective 1). The focus is on the influence of physical, mental or age-related disabilities on parameters of movement in the pre-movement (pre-movement time) and movement phase (fundamental diagram, analysis of time gaps and specific flow). A concept is presented how the movement of heterogeneous crowds can be described and used in engineering procedures (Objective 2).

To quantify the time required by people with disabilities in the pre-movement phase of an evacuation, the time required for the preparation of an assistive device by two assistants and the time required for the change of position of individuals was determined depending on the assistive device used. For the description of the movement phase, the unidirectional movement in a crowd on flat surfaces in corridors and bottlenecks was investigated. The analyses are based on empirical studies under controlled conditions. The focus of the investigations is on density ranges up to about $2.5\,\mathrm{m}^{-2}$. The participants in the studies were self-reported. Distribution of socio-demographic characteristics in the sample as in a full survey cannot, therefore, be assumed (selection bias). It provides an insight into the complex, linked and dynamic process of movement in heterogeneously composed crowds. Parameters of the performance of pedestrian traffic systems can be improved on this basis and standards and legislation determining the safety of pedestrian traffic can be extended. With the presented results, models for calculating the movement of heterogeneously composed groups of people can be developed, validated and verified. For this purpose, the description of a crowds' motion from an engineering perspective is focused and follows a scientific description.

1.2 Outline of the Thesis

The structure of the work is organised in seven chapters (Fig. 1.2). Ch. 2 summarises the state of the art of empirical research on the pre-movement and movement phase of an evacuation, taking people with disabilities into account. For this purpose, findings from studies at both lower and higher density conditions are considered and the concept of the fundamental diagram is introduced. In Ch. 3 all relevant information on the study design, study plan, participants, boundary conditions, and the collection of raw data in the conducted empirical studies are presented. A method to classify and operationalise types of impairments is introduced. The Ch. 4 describes methods for calculating the key performance values which are used for analysis. The results for the pre-movement and movement phase are analysed in Ch. 5. First, the preparation of movement depending on starting location and assistive device used are analysed. Then, performance values to quantify the movement phase are presented: unimpeded speeds, capacity analysis, time gaps and specific flow analysis are provided for different crowd heterogeneity conditions. Subsequently, a concept is presented to estimate the influence of heterogeneous characteristics on parameters of crowd motion in an engineering procedure (Ch. 6). Finally, Ch. 7 summarises the findings and gives an outlook on still open research questions for future work.

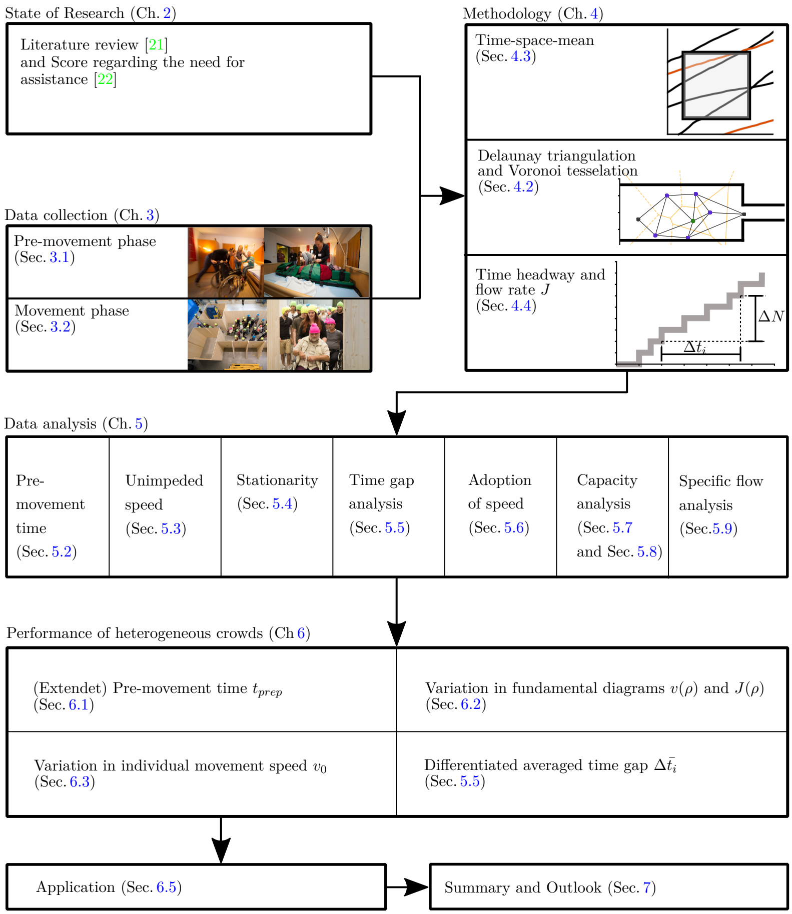


Figure 1.2: *Schematic structure of the work.*

Chapter 2

State of Research

Notice: Major parts of this section have already been published directly or with similar content [21, 23].

The process of egress is not only characterised by the phase of individual movement and crowd motion dynamics phenomena but it consists of many partial phases before the beginning of movement activities. It extends from the start of an egress scenario to when untenable conditions of a facility are reached in a specific scenario [1]. The evacuation process can be represented in a timeline model as shown in Fig. 2.1 [24–27] and is already implemented by standards BS PD 7974-6 [28] and ISO TS 29761:2015 [29]. The evacuation timeline represents egress as a result of several distinct phases [1] and results in a time requirement for an evacuation. The required safe egress time (RSET) is supplemented by a certain margin of safety and opposed to the available time for safe egress (ASET). ASET defines the resistance of a facility against consequences of an event or damage scenario before conditions become untenable [30, p. 27]. On the other hand, RSET defines the egress process itself as the sum of various (time-based) components. It is separated into two main components: the pre-movement and the movement phase. The pre-movement time t_{pre} relates to the interval between the time at which a general alarm signal or warning is given and the time at which the first movement activity is made. This phase is distinguished in the time required to percept and process the warning information (perception time) followed by an interval required to make a decision (decision time). Finally, additional time is supplemented to prepare the realisation of the movement decision (preparation time t_{prep}). The movement phase – or in terms of times: the movement time t_{move} – is the time between the beginning and the end of motion.

Each part of the timeline model influences the main results, namely, the predicted required safe egress time, also called evacuation time. This time depends on the scenario, e.g., usage and spatial structure of the building, characteristics of evacuees, and technical building services.

This chapter summarises the state of research with a focus on empirical data regarding

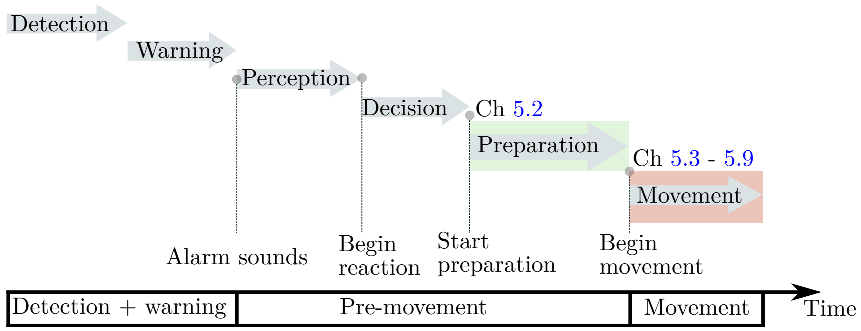


Figure 2.1: *Engineering timeline model of an egress process. It is focused here on two main phases: the pre-movement (green) and the movement (red) phase. The influence of each component on the predicted RSET depends on the scenario (e.g. usage and spatial surroundings of the built environment, characteristics of evacuees and technical building services).*

the egress process considering populations with (potentially) limited abilities in the pre-movement and the movement phase. It adopts contents of a recently published extended review of engineering egress data [21] and further updates it. First, Sec. 2.1 presents data to quantify the pre-movement phase. Then, data-sets for characterisation of the movement phase are provided in Sec. 2.2. The importance of the empirical relations (fundamental diagrams [31]) for assessment of the movement phase and to estimate the capacity of facilities is highlighted in Sec. 2.3.

2.1 Engineering Data for the Pre-movement Phase

Although the pre-movement phase significantly influences the evacuation performance, research on this part of the engineering timeline is rarely available for occupants with disabilities or other individuals with reduced mobility. Gwynne and Boyce [1] have published a comprehensive review study of engineering egress data sets and presented the results with statistical analysis. Data are published in the Ch. „Engineering data“ as part of the 'SFPE Handbook of Fire Protection Engineering' [32]. In general, it is stated that the phase to initiate the movement is difficult to estimate. It is summarised, that the pre-movement phase is influenced by '[...] situational, structural, procedural, organizational, behavioral, procedural and environmental [...]' ([1, p 2461]) components.

To consider differences in population characteristics, data is presented by building type and layout. Only two data sets were presented that directly compare the time that participants with disabilities spent in various activities before the beginning of the movement ([33, 34]). Both studies indicate an increase in the pre-movement time if pedestrians with disabilities are present. Even in homogeneously composed populations without consideration of people with impairments, the data usually show highly dispersed distributions. This is primarily due to most occupants initiating movement within a short pre-movement time and a few occupants initiating movement after a very long pre-movement time [26, 35]. Thus, the pre-movement time is rarely normally distributed. It should be noted that supplementary assistance for occupants with disabilities may mitigate the impact of the disability and reduce the pre-movement time, while occupants with temporary or recent movement issues, who have no aid, will not have such assistance as e.g. in [1, Tab. 64.6].

Lovreglio et al. [36] presented a systematic review on available data sets to quantify the pre-movement phase. Overall 103 evacuation drills and training were included in the analysis. Distributions of pre-movement times according to sub-groups, occupancy types and results of clustering analyses were presented. Additionally, calibrated distributions of pre-evacuation times were presented.

Although many studies determined the pre-movement time for different populations, few have specifically addressed aspects of the pre-movement time for people with disabilities. Analysis of the available research considering occupants with disabilities is summarised in Fig. 2.2 and suggests a wide variation in pre-movement times with periods from seconds up to half an hour. The pre-movement time depends on attributes of the population which is influenced by the building type. While, for instance, and in contrast to residential buildings, many occupants in high-rise office buildings may be characterised by a high variance of individual characteristics and an alarm is conceptually organized in case of an emergency.

Geoerg et al. [22, 47] present results from unannounced evacuations in a sheltered workshop and an assisted living accommodation which are documented by video footage. Pre-movement times t_{pre} of occupants with different kinds of individual or multiple disabilities and assistive devices were analysed and characterised by interquartile range, median and range.

Hall [46] carried out evacuation studies using different kinds of assistive devices to assist transportation, e.g. blanket, picky-back, bed, etc. in a hospital with trained and untrained staff. The average of the preparation time t_{prep} is presented for each transportation method.

Hunt et al. [41, 48] shows results from evacuation exercises in a hospital with trained staff assisting occupants with disabilities. The pre-movement time and the horizontal and vertical speed were determined in 32 trials with different technical assistance devices (stretcher, carry chair, evacuation chair, rescue sheet) being used by different teams. Preparation time t_{prep} is given by the mean and standard deviation depending on technical device and gender.

MacCallum et al. [44] published data from six video-captured announced and one unannounced evacuation in different types of facilities and present preparation times t_{prep} (average, standard deviation, minimum, maximum) for the change from one technical device to another (e.g. from a comfortable chair to a wheelchair, a toilet to a wheelchair, etc.).

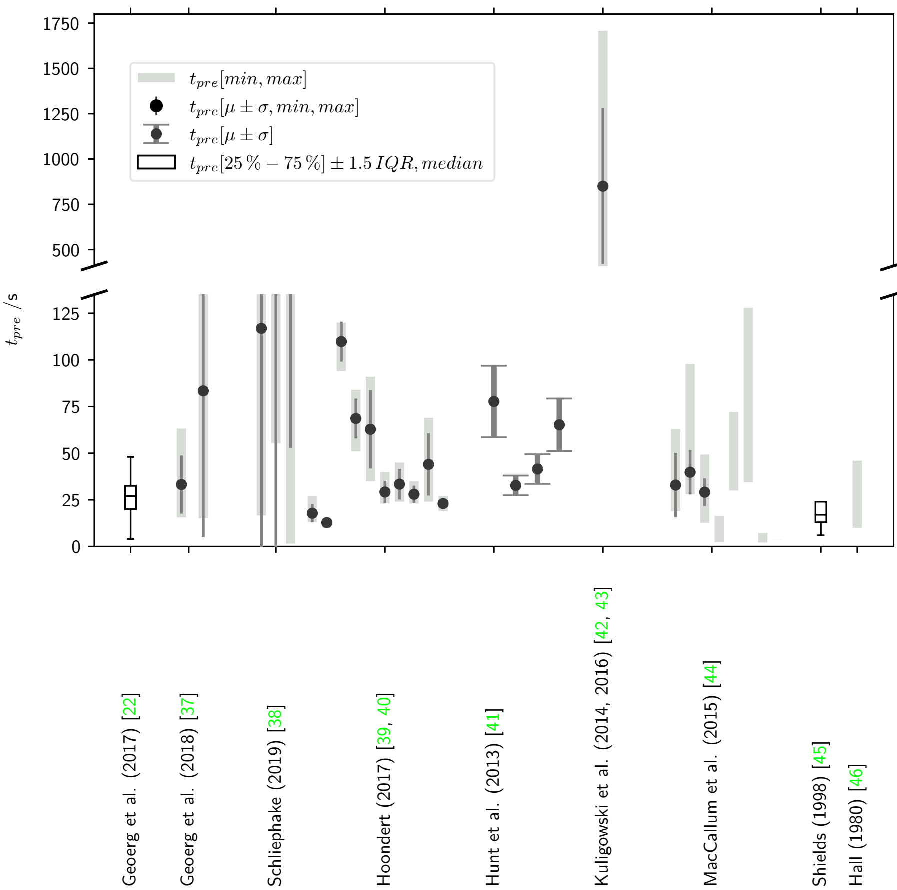


Figure 2.2: *Pre-movement times t_{pre} regarding occupants with disabilities. The following convention is used to visualise different data types: data published by [22, 45] enables a box-and-whisker-plot with mean, interquartile range and range between minimum and maximum; the data by [41] gives mean and standard deviation represented by the grey point plot with error bars. Data only given by the range of minimum and maximum is represented by grey boxes, e.g. [46]. Data by [37, 39, 40, 42–44, 47] gives mean, standard deviation (point plot with black error bars) and range between minimum and maximum with light grey coloured error bars. Please note the discontinuous y-axis for better visualisation of the data published by [42, 43, 47].*

Shields et al. [45] presented the results of two unannounced evacuations in two residential homes involving twelve participants with learning disabilities. In this case, pre-movement was defined as the time from alarm to the time leaving the bedroom and was provided by the interquartile range, the median and the range.

Kuligowski et al. [42, 43, 49] collected data during five announced evacuations in office and residential buildings. These activities contained 160 data points from a population without disabilities (NDP) and 170 data points from participants with disabilities (PWD). Data was presented by average and standard deviation.

Hoondert [39, 40] deals with evacuation studies under laboratory conditions in a hospital. Pre-movement times, especially uncoupling times of medical devices and times to leave room for different types of patients, e.g. dialysis, intensive care, neonatal incubator, were presented. The influence of experience/lack of experience of the staff was displayed.

Hamilton et al. [50] present findings of twelve unannounced evacuations in primary schools in Ireland with participants in an age range from four to twelve years. The numbers of participants varied between each exercise between 124 to 249. The pre-movement time in this publication is defined as the time from the first activation to the time the first person exits the room.

In general, the research on characteristics of the pre-movement phase presented here was carried out in controlled settings with predominantly trained or instructed staff and in familiar surroundings. Despite this, the methodological design of the presented studies differs in the selection, number and participatory abilities of the participants, the general character of the study (laboratory study with controlled boundary conditions, evacuation exercise) and the definition of sub-processes of the pre-movement phase. Differences in the data collection techniques (CCTV, questionnaires and interview analysis), evacuation procedure or daytime lead to a limited comparability [36]. Even if a quantitative evaluation of the studies indicates comparable results, the pre-movement time to be taken into account under real-scale conditions is decisively dependent on the nature of the event (exercise vs real event), initial conditions and can practically not be reproduced. The presence of a well-developed organisational setting (like a sheltered workshop or health-care facility), the availability of professional staff and additional assistance may reduce times in the pre-movement phase [35]. Furthermore, occupants with disabilities may be aware of their abilities and limitations and may profit from self-taught workarounds in daily life [51, Participant E]. However, systematic research on the effect of certain disabilities on the quantification of the pre-movement phase is rarely available. Beyond well-controlled organisational settings, individual pre-movement times of occupants with disabilities may also be increased by potential difficulties in reception, perception, response, and preparation, due to the specific nature of their disabilities [52, pp. 657 sqq].

2.2 Engineering Data for the Movement Phase

Research under controlled laboratory conditions on the movement phase and pedestrian dynamics has been widely improved during the last decades. Many studies under laboratory or field conditions have been performed to address movement characteristics, improve tracking methods, or investigate behavioural insights. Usually, the analysis is addressing the geometrical type, e.g. corridors, rooms or junctions; the kind of movement, e.g. uni-, bi- or multi-directional movement; or boundary conditions as a field- or laboratory study settings. It is well acknowledged, that individual characteristic, measurement methods and environmental conditions influence the desired speed [7, 53]. For this reason, the individual speed of pedestrians on the horizontal vary widely ranging from $0.3\,\mathrm{m\,s^{-1}}$ to $2.5\,\mathrm{m\,s^{-1}}$ [1, 7]. Based on the original work by Fruin ([54]), Predtechenskii and Milinski [55], Weidmann [53], and Pauls [56], international design codes and recommendations either suggest an speed v_0 of around $1.2\,\mathrm{m\,s^{-1}}$ [57, 58] or do not provide specific values [59, 60]. The common feature of all recommendations is that they do not take the movement characteristics of occupants with disabilities or assisted movement into account. To fill this gap, the body of research describing the unimpeded speed of people with disabilities is presented in the following and the data available is summarised in Fig. 2.3.

Gwynne and Boyce have summarised data for individual horizontal movement depending on nature of the movement, spatial configuration and type of participants in the „Engineering data“ publication [1]. They identified a few studies that present some data on the movement of participants with disabilities that can indicate a difference in the speed and the impact of supportive actions or usage of assistive devices. A possible impact of fatigue and a cross-sectional influence of multiple disabilities and differences in orientation are discussed. Haghani recently compiled an extended review and presented a large data collection on crowd dynamics [4, 5]. The consideration of heterogeneous crowd conditions and the influence of disabilities on crowd motion are highlighted in the identified emerging topics, methodological developments and controversial topics.

Cabrera et al. [61] present the individual speed for three groups of older participants characterised by different ages. Speed was measured in a field study located in a public park. The impact of assistive devices and grouping behaviour (group size and spatial orientation) was analysed and compared with unimpeded movement. Hamilton et al. [50] present horizontal speed collected at twelve unannounced evacuation training in primary schools in Ireland with participants in an age ranging from four to twelve years. The numbers of participants varied in each exercise from 124 to 249. Fritz et al. [64] published an analysis of age-related changes in mobility and balance by backwards walking measures. For comparison, they also provided gait characteristics of forwarding walking speed, gait length, swing percent, etc.) for different groups of age. The increased variability across older groups is discussed. Research presented by Kang et al. [66] compared the effect of

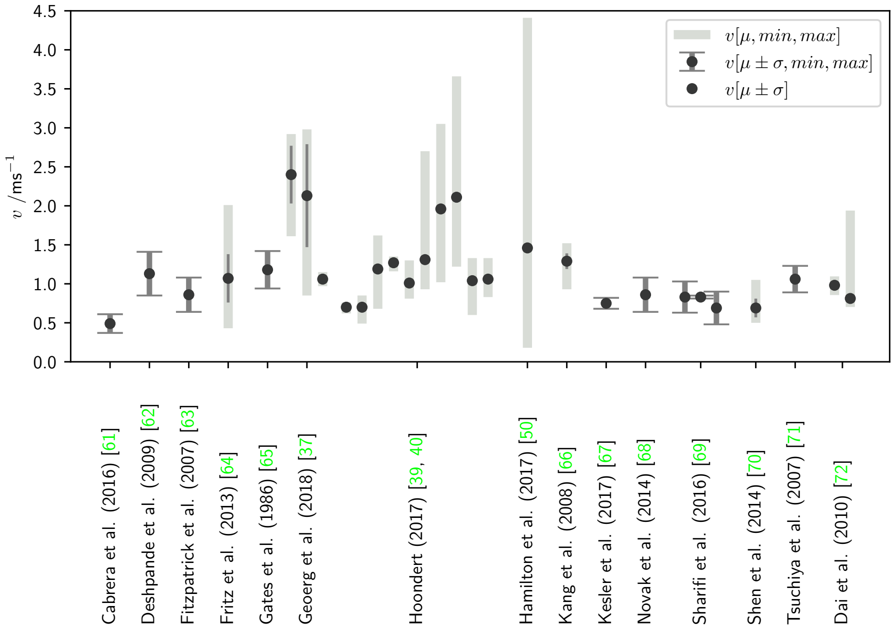


Figure 2.3: *Unimpeded speed regarding participants with disabilities. The following conventions are used to visualise different data types: data published by [61–63, 65, 67–69, 71, 73] give mean and standard deviation represented by the grey point plot with error bars. Data by [37, 39, 40, 50, 64, 66, 70] gives mean, standard deviation (point plot with black error bars) and range between minimum and maximum with light grey coloured error bars. The publication by [72] contains mean and range between minimum and maximum (black dot with grey coloured bar).*

speed, strength and range of motion on gait measures for younger and older participants under controlled conditions. Gates et al. [65] presented a data set of speed resulting from a field study involving persons of different ages and gender. In addition, the effect of the group size was investigated. Novak et al. [68] presents the impact of ageing on the body and segmental control of functional body parts. Kinematic data was collected from participants walking along a pathway and passing an obstacle. Speed, gait length and stepping frequency are compared for young and old participants. A publication by Dai et al. [72] deals with the findings of a field study comparing speeds depending on age groups in public spaces of a shopping centre. A reduction of individual speed in crowd motion depending on reduced visibility was reported by Xie et al. [74]. A decreased probability to overtake slower participants was reported and they observed an increase of helping behavioural actions in groups with the participation of persons with reduced vision. Helping behavioural actions as physical interaction or verbal instructions were frequently observed in trials with participants with low visibility.

The impact of mental disabilities on movement characteristics was investigated by Deshpande et al. [62]. They present results on walking performance by mental and physical status of older participants. They concluded that uniform movement is challenging in a neuromuscular manner while accelerated movement with simultaneous talking may be more challenging with cognitive decline. Further on, Fitzpatrick et al. [63] reported gait speeds according to cognitive function measured in a laboratory setting. They focus on the prediction of early cognitive decline indicated by individual speed, but also provide a comprehensive data set of speeds depending on different variables (e.g. age, gender, education, body mass index, etc.).

The impact of vision loss and gender on speed was investigated in a controlled study in a classroom presented by Shen et al. [70]. Reduced vision (zero or full vision) was simulated by an eye mask and the impact on the speed of young participants was compared to similar studies. Results depending on different visibility scenarios were presented. Samoshin et al. [75] has presented empirical relationships between flow and density as well as speed and density depending on familiarity with the route and the influence of the facility. They considered blind and visually impaired participants in field observations. A comparison of movement characteristics and evacuation times under different vision conditions was published by Cao et al. [76]. Movement and speeds under good and limited visibility were analysed and observed behavioural characteristics like exit choice, the following behaviour or helping actions were studied. Normal distributed speed were reported where the mean for the participants without disabilities (NDP) was slightly higher than for the participants with disabilities (PWD), while the standard deviation was smaller for PWD ($v_0(NDP) = 1.2 \pm 0.19\,\mathrm{m\,s^{-1}}$, $v_0(PWD) = 0.9 \pm 0.14\,\mathrm{m\,s^{-1}}$). Increased behavioural actions were reported as a consequence of social identification in the entire group.

Movement in a crowd with consideration of wheelchair users was investigated by Tsuchiya et al. [71]. A comparison of individual unimpeded speed, speeds in homogeneous groups and speeds of wheelchair users in heterogeneous groups are presented. Additionally, behavioural observations such as spatio-temporal requirements of participants and overtaking procedures were analysed. An averaged unimpeded speed of $1.06 \pm 0.17\,\mathrm{m\,s^{-1}}$ for 267 wheelchair users were reported.

Concerning different disabilities and heterogeneous crowd conditions, the influences on flow characteristics in heterogeneous pedestrian crowds were published by Sharifi et al. [69, 73, 77]. Density and speed of participants characterised by different disabilities in a circuit of right-angles, oblique-angles, passageways and bottlenecks were collected and empirical relation was presented.

The impact of multiple sclerosis on straight movement was investigated by Kesler et al. [67]. The ability to walk a horizontal distance of 48 m before and after performing a six-minute walk was tested. Passive motion capture markers were placed on each participant to collect gait parameters like step width and length. Speed, oxygen consumption and gait width and length were compared. Jiang et al. [78] present a comparative analysis of speeds collected at typical observation points in hospitals and other public buildings. The impact of age and gender was investigated and the influence of the health status was compared. Hoondert [39, 40] carried out studies under laboratory conditions in a hospital concerning the influence of assistive devices. Speeds considering different types of patients (e.g. dialysis, intensive care, neonatal incubator) were presented.

Summing up, published data for unimpeded speed considering the influence of individual abilities results in a range of $\approx 0.23 - 1.95\,\mathrm{m\,s^{-1}}$. They are significantly influenced by the individual physical possibilities to move forward. Since participants with disabilities often use technical assistive devices (wheelchairs, canes, sticks, and crutches) or require personnel assistance, the differences may partly be explained by increased coordination and concentration regarding the use of assistive devices and the concentration on communicating with the assister. The unimpeded, free speed of people with disabilities can be summarised for certain groups and can be attributed to the type of impairment or the use of the assistance device. While the influence of slowly moving objects or obstacles on movement parameters has been investigated to some extent in the past [79–81], the consideration and effects of motion assistants on motion performance has not yet been taken into account. In particular, the uniformity of the movement (e.g. impulse-like movement in front of walking frames or pedestals) may influence distances to neighbours or walls and requires a more detailed analysis about artificial distances. A recently published study indicates a positive effect of routing information for wheelchair users on the total evacuation time of a population under laboratory conditions [82]. The authors conclude that routing information for the most vulnerable population of a scenario is sufficient to observe an effect on the evacuation time. It is not known whether these findings are transferable to people with disabilities without assistive devices.

By contrast, individual requirements such as response capacity, familiarity, and social norms affect the speed of individuals in heterogeneous groups [83, 84]. Since the primary source of information in crowds is visual, a study showed that pedestrians in a crowd who are within a 2 m radius from each other exchange and sometimes copy gazes [85]. The dynamics in a crowd are governed by the information processed by individual pedestrians, as the interactions between pedestrians shape global patterns of crowd motion [86]. Complex interpersonal interactions as assistive behaviour or the formation of social roles influence the individual speed in the immediate area of a person with disabilities. A generalisation of a value range is then no longer meaningful. To take diversity into account, it must be defined for the concrete application case how the influence of individual properties on patterns of movement can be quantified.

2.3 Importance of Empirical Relations

In accordance to Treiber and Kersting [87], it is distinguished between empirical aggregated data and the theoretical relation between speed v or density ρ and flow rate J called fundamental diagram [31]. The speed v is the quotient of the covered distance in a defined time interval. The (traffic) density ρ describes the number of individuals per unit area. And the flow rate J is used to describe the number of persons that pass through a cross-section within a time step. Given the passage width w of a facility, the flow is calculated according to Eq 2.1.

$$J = \rho \cdot v \cdot w \tag{Eq 2.1}$$

The specific flow $J_s = \rho \cdot v$ defines the flow rate J per unit-width.

$$J_s = \frac{J}{w} \tag{Eq 2.2}$$

$$= \frac{\rho \cdot v \cdot \not{w}}{\not{w}} \tag{Eq 2.3}$$

Assuming that Eq 2.2 is valid for different types of geometries, the fundamental diagrams for different passage width w '[...] merge into one universal fundamental diagram for the specific flow rate $J_s(\rho)$.' ([88, p 396]) The passage width w can be used as a scaling factor for the given geometries. The performance of a facility (specific capacity $J_{s,c}$) increases proportionally with the passage width [89].

Empirical data for fundamental diagrams are derived from stationary, homogeneous traffic situations and they are important models to quantify traffic systems [3, 31]. But empirical relations also allow the description of non-stationary pedestrian traffic situations.

Important quantities and characterising points of these relationships (Fig. 2.4) according to [87, p. 27 sqq.] are:

– unimpeded (free) speed v_0, where pedestrians move with their desired speed and are not influenced or restricted by others or boundaries;

– specific capacity $J_{s,c}$; where the flow rate is maximal;

– capacity density ρ_c: the density where the flow rate J is maximal;

– jam density ρ_{max} where overcrowding results in impossibility of movement.

Empirical relations (fundamental diagrams respectively) for movement in the horizontal consists of different branches [90]:

– a free-flow branch at low-density regions, where the specific flow rate J_s increases with increasing density ρ and the speed v is similar to the unimpeded (free) speed v_0;

– a branch where interactions between pedestrians occur with needs for changes of speed and directions but still resulting in stable flow conditions;

– a congested branch at higher densities where the flow rate decreases with increasing density due to the decreasing distance between neighbours which consequently leads to the formation of jams.

Examples of the two fundamental diagrams are presented in Fig. 2.4. The region of interest for capacity analysis according to this work is plotted in blue.

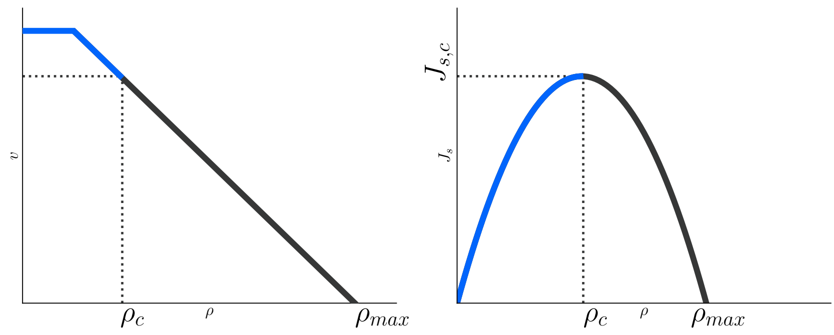


Figure 2.4: *Principle of the fundamental diagram v and J_s (visualisation according to [91]). The region of interest for capacity analysis according to this work is coloured in blue.*

Research addressed to different types of movement with homogeneous crowd conditions without consideration of disabled participants has been published for single-file movement [90, 92–100], bidirectional movement [89, 101–105], movement through corridor [94, 106–

110], considering a bottleneck situation [88, 94, 107, 108, 111–130] or multi directional movement [89, 94, 131–142].

The results of this research activities were recently collected, comparatively prepared and discussed by extended reviews focusing on different flow types and geometries [143], empirical data collection about the complexity of movement ([2, 144]) and movement dynamics [3]. Haghani and Sarvi [145] have compiled a detailed discussion of empirical methods on studies of crowd behaviour and motion. Different study designs result in significant differences in scope, pattern and characteristics. Possible consequences of the demographic transformation process on the validity of assessment methods for movement characteristics and functional relationships are discussed by [6, 7, 19, 146, 147]. It is debatable whether those data are still representative in terms of transferability to diverse, inhomogeneous and more realistic populations.

A comparison between frequently referenced fundamental diagrams by [53–55, 148] and empirical relations $v(\rho)$ and $J_s(\rho)$ considering participants with disabilities are presented in Fig. 2.5. Only a few studies considered participants with more heterogeneous characteristics or heterogeneous crowd conditions. Daamen et al. [113, 114] have performed movement studies using a bottleneck configuration considering participants with disabilities. A significant decrease in the bottleneck capacity for disabled participants is reported.

The influence of age (older or younger populations) on empirical relations was investigated by [113, 114, 149, 155–163]. A difference in characteristics of the relationships was observed and stop-and-go-waves are more probably to occur for populations consisting of a broader age range [158]. Contrary to this, Kolshevnikov et al. [155] found, that general characteristics of empirical relations considering older participants are comparable to younger populations. An overall reduction of speed and flow rate for the older population compared to younger adults under similar density conditions is reported. The distance headways tend to increase with increasing age [162]. Normally distributed headway and speed distributions for older participants under different global density conditions in a single-file movement study were reported by [164]. Three linear regimes (free, weakly constrained and strongly constrained) were observed in the fundamental diagram: for lower distance headway regimes of $\leq 2.6\,\mathrm{m}$, the speed of older participants is lower than for young populations. Since the studies were conducted in weakly constrained conditions, the speed of both populations is similar and the adaptation time of older participants increases with an increased distance headway greater than $1.1\,\mathrm{m}$ (strongly constrained regime). Findings presented by [163] suggest that the speed of older participants is reduced in crowd motion and affected by socio-cultural influences.

The impact of vision loss, reduced visibility or blindness on movement characteristics was analysed by [69, 75, 76, 151, 152, 165, 166]. A slightly higher tendency to walk in groups or close to boundaries is reported by [75]. Another study by Cao et al. [165, 166] has published an in-depth analysis of the impact of reduced vision on empirical relations.

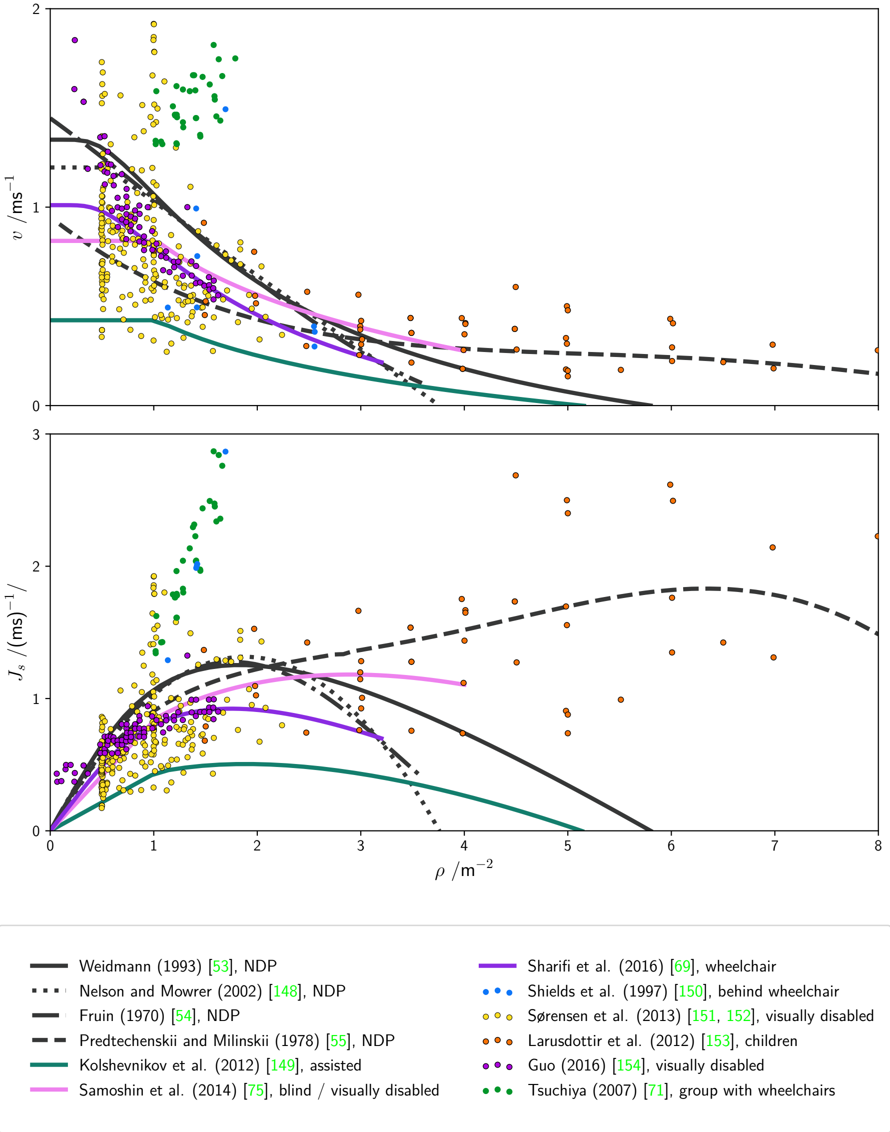


Figure 2.5: *Fundamental diagrams and empirical relations $\bar{v}(\bar{\rho})$ and $\bar{J}_s(\bar{\rho})$ for a crowds movement through a bottleneck considering pedestrians with disabilities compared to frequently referenced fundamental diagrams by [53–55, 148] (with $f = 0.113\,\mathrm{m}^2$).*
Data picked up with Web plot digitizer by the author from the referenced publication.

The conditions of visibility were realised by glasses with different light transmission and fundamental diagrams, time-space diagrams and headway-movement-speed relations are presented. They found that participants with limited light transmission glasses tend to use their hands to perceive the distance to predecessors. Declined distance headways and speeds corresponding to a decrease of light transmission are reported. Improved orientation and thus increased speed by touching walls were observed by Cao et al. [166, 167]. A preference to keep a distance to walls between 0.28 m to 0.53 m was reported by Cao et al. [165, 166]. Furthermore, a reduction of flow rate and significantly more unstable flow rate conditions were reported by [165].

Guo et al. [154] published findings from laboratory studies in China. The limitation of vision was simulated by blindfolds. A remarkable reduction of the flow rate was observed in the case of blindfolded participants. Due to the limited number of participants, the congested branch of the fundamental diagram was not observed. Soong et al. [168] investigated the preferred speed for assessment of mobility performance of those with visual impairments. Speed of visually impaired participants depending on guidance by blind or non-blind participants was compared.

The importance of individual space requirements on speed, flow rate and crowd density was investigated by [69] (participants with heterogeneous, different disabilities), [71] (presence of wheelchair users), and [169] (impact of luggage). An important influence by the presence of wheelchair users on speed and spatial distance headway characteristics were reported. While carrying luggage had a minor effect on the mean speed [169], the presence of wheelchair users in a crowd reduces the mean speed of the participants up to 20 % [69, 71]. People with increased personal space requirements inside a crowd, e.g. for luggage, maintain greater spatial distances and tend to move slower at higher densities [170]. The influence of the mixing rate of wheelchair users on the flow rate was investigated by [171]. A reduction in the flow rate of crowds with the participation of wheelchair users and a small impact of increased passage width is reported. The article presents a method to estimate the flow rate based on ergonomic elements, personal occupation area, crowd speed and the wheelchair users mixing rate. A recently published study presents findings from movement studies under laboratory conditions with a focus on the impact of the bottleneck shape and the ratio of wheelchair users on the crowd dynamics [172]. They found a relation between the mixing ratio of wheelchair users in the crowd and '[. . .] efficiency of traffic and congestion in the bottleneck [. . .]' ([172, p 17]), an increase of the egress time and time headway Δt_i. A reduced speed of wheelchair users with an increased share of wheelchair users in the crowd is reported. Additionally, research on several impacts like fatigue (decrease of speed with longer walking distance [173]), stress (higher urgency leads to a higher capacity [174]) or distraction (higher stopping duration with background music [175]) was published.

Chapter 3

Data Collection

Empirical studies to investigate the impact of heterogeneous individual characteristics on key performance measures of pedestrian dynamics were performed within the joint research project ”Safety for people with physical, mental or age-related disabilities (SiME)”. SiME was funded by the German Ministry of Education and Research in the Federal Government ”Research for civil security 2012-2017” framework programme between February 2016 until May 2019 under grant number 13N13946 sqq. Empirical studies were conducted at various detailed levels to provide characteristic indicators for the pre-movement phase and the movement phase of an evacuation for heterogeneously composed crowds. Tab. 3.1 compares the empirical studies conducted on different phases of the timeline and presents the most important findings.

The data analysed in this dissertation refers to empirical studies on preparation, movement in low-density situations and motion towards dense crowds. They were conducted in June and December 2017 in a sheltered workshop in Wermelskirchen and an assisted living located in Dabringhausen, Germany. The studies were realised within the sub-projects ”Influence of heterogeneity on the movement of pedestrians in crowds” (grant number: 13N13946) under the responsibility of Bundesanstalt für Materialforschung und -prüfung), ”Practice-oriented integration and concept testing” (grant number: 13N13949) under the responsibility of stakeholder Lebenshilfe Bergisches Land and ”Parameter studies for the safe evacuation of heterogeneous crowd” (grant number: 13N13950) under the responsibility of the stakeholder Jülich Research Center.

Table 3.1: *Empirical studies with focus on different phases in the engineering timeline. QVA: Qualitative video analysis; QuanVA: Quantitative video analysis; QSS: Qualitative standardised survey; PTA: Trajectory analysis; PWD: participants with disabilities; NDP: participants without disabilities.*

Method	Analysis	Dependent variable	N PWD	N NDP	Main findings	Main reference
Studies in real-scale evacuation						
Field study[a]	QVA	t_{pre}, t_{evac}	66	11	high level of self-organisation, trained procedures, short t_{evac}	[176]
Field study[b]	QuanVA	t_{pre}, t_{evac}, v_0	34	6	high level of individual assistive activities, large t_{pre}, long t_{evac}	[38, 177]
Survey[a]	QSS	-	35	12	high level of individual compensation strategies; distinct self-assessment of own possibilities	[178]
Studies on Preparation and Low Density Movement						
Laboratory conditions	QuanVA	$t_{prep}(ass)$, v_0, (v_v)	10	6	dependency of t_{prep} and $\bar{v}_h$ on assistive devices	Sec. 5.2, Sec. 5.3, [37]
Laboratory conditions	PTA	v_0	46	≈ 130	Dependency of individual disability and physical dimension of assistive device	Sec. 5.3, [37, 176, 179]
Studies on Movement in Groups and Toward Dense Crowds						
Laboratory conditions	PTA, QSS	$\bar{v}(\bar{\rho})$, $\bar{J}(\bar{\rho})$, Δt_i	46	≈ 130	high influence of social behaviour between subpopulations on movement characteristics, increased Δt_i for studies with wheelchair users and mixed populations	Ch. 5 - Ch. 6, [23, 179–182]

[a] Sheltered workshop
[b] Assisted living

3.1 Studies on Preparation and Low Density Movement

First, the analysis was focused on the quantification of the pre-movement phase t_{pre} and in particular, the time to prepare movement activities t_{prep} of participants with disabilities (PWD). Second, assisted movement of PWD in the horizontal plane was quantified by the unimpeded (assisted) speed v_0.

3.1.1 Participants

The studies on preparation (phase) and low density movement were conducted with ten participants characterised by different kind of disabilities in a mean age of 49.1 ± 14.8 years (Fig. 3.1). They were assisted by six professional caregivers. The cooperating association Lebenshilfe Bergisches Land supports the participation of people with disabilities in working life including accommodation and has proposed suitable participants with disabilities for the studies on evacuation behaviour. The studies were conducted in a residential home where the participants were accommodated. Thus all participants were familiar with the surrounding and the assistant staff was formally instructed in the usage of the assistive devices (cf. Appendix A.2.1 for details).

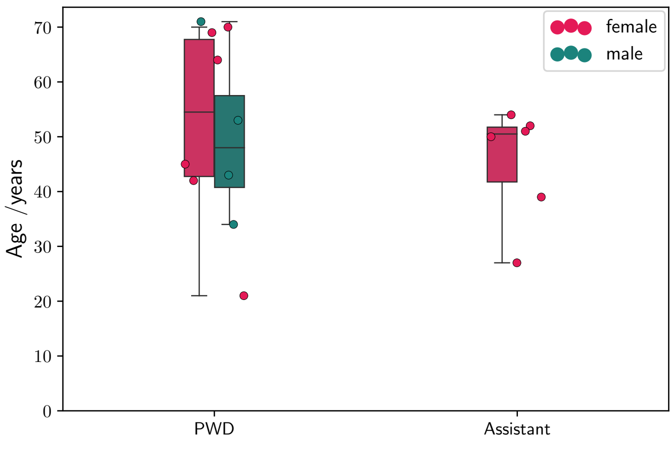


Figure 3.1: *Ageing distribution of the participants in each study.*

An essential characteristic of the studies presented is the individuality of the participants. At the same time, assumptions were made to cluster the individual characteristics and to assign generic terms. For a deeper understanding of the far-reaching individual characteristics of each participant and the resulting consequences on the reproducibility of measurements, participants were characterised by the following features:

PWD_90: Female participant, limited cognition, use of a wheelchair.

PWD_91: Female lightweight participant, assisted by wheelchair.

PWD_92: Small, older female participant with walking impairments; assisted by walking frames.

PWD_93: Visibly cognitively impaired, communicative female lightweight participant.

PWD_94: Older male participant with age-related disabilities and walking frames.

PWD_95: Heavy weight female participant with limited mobility and cognitive abilities, no assistive devices.

PWD_96: Male participant, average weight, limited physical and cognitive abilities, no assistive devices.

PWD_97: Older, averaged weighted female participant with walking disabilities, assisted by walking frames.

NDP_98: Participant without disabilities, male team member.

NDP_99: Participant without disabilities, male team member.

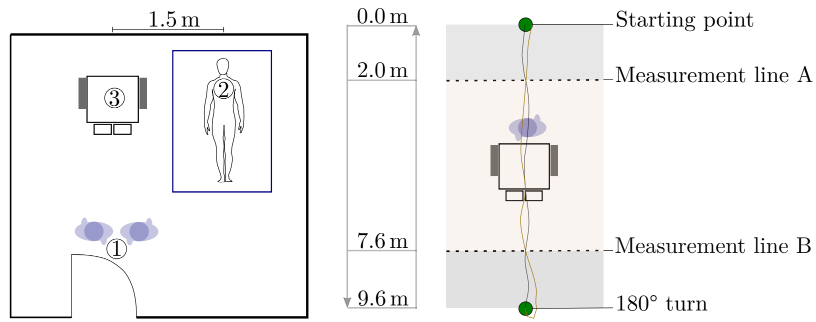
3.1.2 Study Setup

Overall 56 single trials were conducted in the Residential home for people with disabilities and were captured by cameras with high resolution. Each trial has been performed by a participant with a disability supported by an assistant or an assistive team of two caregivers. The collected footage was synchronised by time and used to extract the preparation time t_{prep} and movement times t_{move} of participants or assistive teams.

Studies on the preparation time depending on starting position and assistive device were conducted by fixed assistive teams. Assistants and target assistive device were located at a fixed position inside the room. (Fig. 3.2a). The starting position of the participants was horizontally (study A) or sitting (study B) in bed (position of the bed was fixed over all trials). The assistive devices were set up in each trial by the assistants and prepared ready for operation (for a detailed list of the necessary sub-processes see Tab. A.1 in Appendix A.2.1). The time needed to prepare and set up the assistance equipment was determined by individual factors (team composition, familiarity, time of the last exercise, number of repetitions). It is included in the presented pre-movement time. After the assistance device had been prepared for operation, the team placed itself on markers in the room (Fig. 3.2a) and the study was authorised by the study coordinator.

The study procedure is described as: the assistive team moves from starting point (1) towards the bed location (2) and transfers the participant from bed to target seating position (3). Afterwards, the participant is moved assisted by a wheelchair outside of the room. Based on the video recordings, the times of (a) start of the trial, (b) arrival at the bed and start preparation of the assistive device, (c) start manoeuvring the transfer and, (d) arrival at reference point were extracted. Performed actions of the assistants were spoken aloud by the assistants, recorded and documented. The preparation time t_{prep} ranges from reference point (a) to (d).

Studying the dependence of the unimpeded speed v_0 on the assistive device used was realised by a slightly modified ten-meter walking test (10MWT) [183–185]. It is a clinical test assessing the speed over a short distance of 6 m by considering a distance of 2 m for acceleration and deceleration respectively (Fig. 3.2b). The test has been performed and analysed for individuals with a multitude of physical, mental or age-related disabilities (cf. [183] for details). Due to a technical camera shift, the length of the measurement area in the 10MWT has been modified to 5.6 m for analysis in this study.



(a) *Measuring the preparation times.* **(b)** *Measuring the unimpeded speed.*

Figure 3.2: *Principle of studies on (a) preparation phase and (b) unimpeded speed v_0 by using a modified 10MWT.*
1: start and end position assistive team; 2: start position PWD; 3: target position wheelchair.

3.2 Studies on Movement in Groups and Toward Dense Crowds

The movement of individuals in denser situations has been investigated by large-scaled movement studies with a focus on measuring pedestrian dynamics to provide new empirical data and concerning objective 2 of this doctoral thesis.

3.2.1 Participants

Considering vulnerability as a function of the available physical and psychological resources as well as spatial and temporal boundary conditions of a specific egress scenario, the resilience of an individual is sensitive to individual abilities. The vulnerability to a disaster is socially constructed [186] and derives from physical or mental domains [187] . This approach is called ‘Hazard-of-place(H-O-P)’ [188–190] and is frequently discussed in several disciplines of civil safety research; cf. e.g. [187]. The selection of the participants for this studies reflects the importance of the mean age of the population and differences in physical and mental abilities on performance criteria (crowd heterogeneity) .

The methods to recruit a sufficient number of PWD and NDP differ. To attract participation for sufficient volunteers without disabilities, a call for participation was published in local media, on the website of Forschungszentrum Jülich and through announcements in the University of Wuppertal, the Niederrhein University of Applied Sciences and the University of Aachen. In addition, unaddressed mail was distributed in the local area of the city of Wermelskirchen, Dabringhausen and the neighbouring municipalities with a call for participation. The registration of the participants without disabilities was realised by a specially set up website for this purpose.

Participants with disabilities were recruited by the project partner Lebenshilfe Bergisches Land. The acquisition, clarification and recording of personal data relevant to invoicing etc. were carried out exclusively by the project partner due to data protection requirements (cf. Appendix A.1). Educational and consent materials were prepared in simple language to support the consent process in cooperation with experienced employees of Lebenshilfe Bergisches Land. These employees know the involved PWD and the legal guardians personally and are in a position to guarantee explicit consent and the preservation of subject orientation.

Additionally, the consent of a legal guardian was possible. If the legal guardian has given consent on a representative basis, the employees of the Lebenshilfe Bergisches Land checked whether the consent was following the actual will of the PWD concerned. The resulting anonymous data were made available for scientific analysis: consecutive number, score regarding the need for assistance (Score RNA) value (which scores the participation of a person on evacuation process activities and is introduced in the following), gender, age, body height and confirmation of the consent of the PWD.

Participation was voluntary for everybody and cancellation of participation without any negative consequences was possible at any time. All participants have been paid 25 € per half a day of participation. Only generalised attributes (quasi-identifiers as age, gender and membership of a subpopulation) was used for the studies and the methodological design. The data storage process and the access authorisation for data were approved by the ethics committee of the Bergische University of Wuppertal (for a more detailed ethical reflection see Appendix A.1). No ethical concerns were mentioned.

A scoring approach was designed to assess the individual ability to participate in egress activities and to describe the recruiting process in a transparent and reproducible way [22]. It follows the engineering timeline of egress (cf. Fig. 2.1) and indicates relevant abilities (indicators) for egress in three dimensions (Fig. 3.3): (1) reception and perception (operationalised by blindness and deafness), (2) information processing (operationalised by MELBA-SL-Score threshold) and (3) action (realisation of movement indicated by walking impairment and wheelchair usage), which is in case of evacuation usually the movement to a safe place. Movement is affected by walking disabilities and the requirement for assistance devices. Last, a cross-section variable[1] (age) is assigned which influences the other dimensions at once (e.g. the process of ageing could influence seeing/hearing, mental status (dementia) and body strength at the same time). The ability of a PWD to participate in egress is not a fixed, individual characteristic. Rather, they are the result of a combination of individual characteristics and environmental boundary conditions.

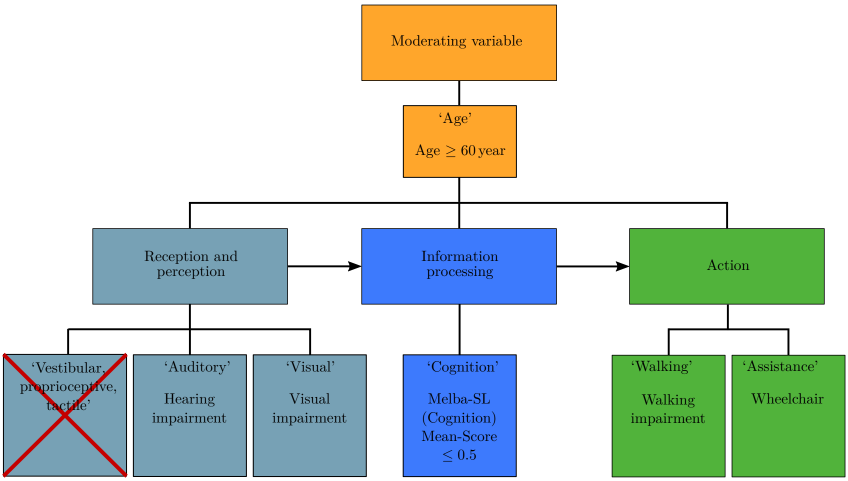


Figure 3.3: *Relationship of relevant processes in egress tasks: reception and perception, information processing and action (according to [191, 192]).*

As the first dimension, reception and perception is an active process of signal detection and self-positioning in time, space and social environment. It is related to the pre-movement and the movement phase and a base for further processes and necessary for spatial classification. It depends primarily on the individual abilities to see, hear, smell and feel. Visual or auditive information is sensed and transformed into processable signals. Vestibular, proprioceptive and tactile senses were considered in the concept of sensory integration by Ayres and Soechting [191], but regarding the impact on egress tasks and concerning the engineering timeline model, the Score RNA focusses on the auditory and visual reception for evaluation. The marking 'bl' for blindness and 'gl' for deafness in the Disability ID Card

[1]Colloquially, the term 'moderating variable' is used to describe an influence of another variable, e.g. the effect of ageing on vision or the handling of a wheelchair. From a statistical point of view, a moderator influences the interaction of two other variables - for instance, the influence of the age of participants in parameter studies on the movement times of wheelchair users. The term "moderating variable" is – depending on the context – used in both meanings.

[193] are used for operationalisation. These markings indicate the type of disability in the context of possible associated benefits and privileges granted by the pension office. They are based on individual medical diagnosis routines.

A second dimension to be parameterised is that of information processing. All procedures of cognitive performance, especially interpretation and focusing attention are addressed. It is an area of conscious and subconscious experiences. Depending on the degree of transformation, different abilities are required for this process step. An exemplary discussion of a possible spectrum range is proposed by Rasmussen [194]. It ranges from automatic, intuitive actions up to an application of knowledge, extrapolation or estimation for a sequence of actions from experience. Capturing detected information concerns characteristics, intensity and consistency of the situation. The meaning and bearing of the process are associated with everyday experience and existing patterns of action. It requires a mental condition of receptivity that focuses consciously or unconsciously knowledge on procedures, objects and situations. Information is selected by orientation and screening.

The profiling concept ‘MELBA-SL’ is used to assess the participation of people with disabilities in working spaces. Here it is used to operationalise the information processing dimension [195] (available only in German; cf. Achterberg et al. 2013 [196] for an English summary). Overall, 29 different characteristics related to different clusters are included in MELBA SL to evaluate the participation of an individual. The assessment of the cognition cluster contains eight items of cognitive abilities: work planning, conception, attention, concentration, learning and remembering, problem-solving, conversion, and presentation.

All 320 employees of the workshop were interviewed according to the cognition items by two specially trained staff members. The coding allows values in the range from zero to five. The cognitive levels A and B resulting from the MELBA-SL evaluation of all cognition items were defined as the threshold value. As example, the item ’information processing’ is explained in detail in Tab. 3.2. Participants with a scoring value less than 0.5 do not seem to possess the cognitive abilities, to perceive a change of the situation on their own, to interpret it accordingly and to initialise appropriate actions.

Table 3.2: *Coding description and threshold value criterion based on the MELBA-SL-Cognition Mean Score. Reproduced, adopted and extended from [195, 197].*

Score RNA Coding	Original MELBA-SL coding	Original remarks for the evaluation of MELBA-SL	Example
0.0	A	Participant does not show the ability to be evaluated in any situation. The participant does not perceive even a very clear change in a situation or a condition. The meaning of a situation is not grasped. The person acts disorderly or not purposefully.	Participant did not understand or respond to short and simple instructions, e.g. 'Stop!'.
0.5	B	The participant shows the ability to be assessed in very simple and strongly pre-structured situations. The participant is able to perceives occasionally sufficient changes in a determined situation. The participant occasionally grasps the meaning of a clear, not complex situation and acts with easily manageable tasks and in an orderly manner or target-oriented.	The participant can understand simple, very short instructions (e.g. one-word prompts) and can understand the simplest, clearest signals (e.g. pipe tones) without assessment of their meaning for own activities.
1.0	C	The participant shows the ability conditionally in simple, pre-structured situations. Mostly captures the meaning of a clear, not complex situation. Acts now and then in an orderly or target-oriented manner with manageable tasks.	Can understand very simple instructions. Recognises simple signals at work and understands their meaning for one's own work.
...			

The third dimension, the realisation of a movement decision, the action was defined as the point in time about the beginning of a straightened movement. This process step is dominated by motor skills, which are operationalised by the individual ability to move and the individual requirement on an assistive device. Here, the usage of a wheelchair in everyday life was considered as well as the marking ‘aG’ (severe walking disability) in the Disability ID Card.

Last, the moderating, cross-sectional variable was defined as an age ≥ 60 years. Even if the life expectancy of physically disabled individuals approximates on the entire population, the life expectancy of individuals with reduced mental abilities today is up to twelve years lower in Germany [20]. An international review presents a particularly low life expectancy for individuals with Down syndrome, even if the scaling has been approached from nine years in 1929 up to approximately 60 years in 2002 [198]. But today the life expectancy of this specific population is still even lower than others. Although an age over 65 years (sometimes equal to the retirement age) is often used to define older persons, a lower age limit of equal to 60 years is used in this studies (similarly in [199]). Participants assigned to this category did not have any other reported disabilities in terms of the Score RNA.

A set of twelve combinations of disabilities is identified in the sheltered workshop population and used to distinguish between the subpopulations (Tab. A.3 in Appendix A.3.1). The determined characteristics (indicators) are defined as binary coded attributes with ‘1’ representing ‘true’ and ‘0’ representing ‘false’ (cf. Tab. 3.3). They are in general in line with the definition of the populations with special needs determined by the German standard „General requirements and planning principles on barrier-free buildings“[200].

Table 3.3: *Operationalisation of the impact of disabilities on tasks according to the engineering timeline model using the Score RNA approach. Each dimension is associated with potentially relevant disabilities (indicators). The parametrisation is based on different sources.*

Dimension and indicator	Characteristic
Reception and perception	
Blind	Marking in Disability ID card
Deaf	Marking in Disability ID card
Information processing	
Cognition	MELBA-SL Mean-score ≤ 0.5
Action	
Walking impaired	Marking in Disability ID card
Wheelchair	Document
Moderating variable	
Age	Age ≥ 60

A small and reproducible number of participants with well-defined disabilities from a basic population of 320 employees of a sheltered workshop was recruited by application of the Score RNA method (Fig. 3.4). In accordance to the reported ≈ 10 % of inhabitants with disabilities in Germany [201], 15 % for EU-27 [202], 19 % for the USA [203], and an estimated prevalence of high and medium disabilities world wide of approximately 15 % [204], a comparable configuration of the populations was attempted. This results in a share of PWD between approximately 5 - 10 % for studies with participants with single disabilities and of approximately 15 % for studies considering PWD with multiple severe disabilities.

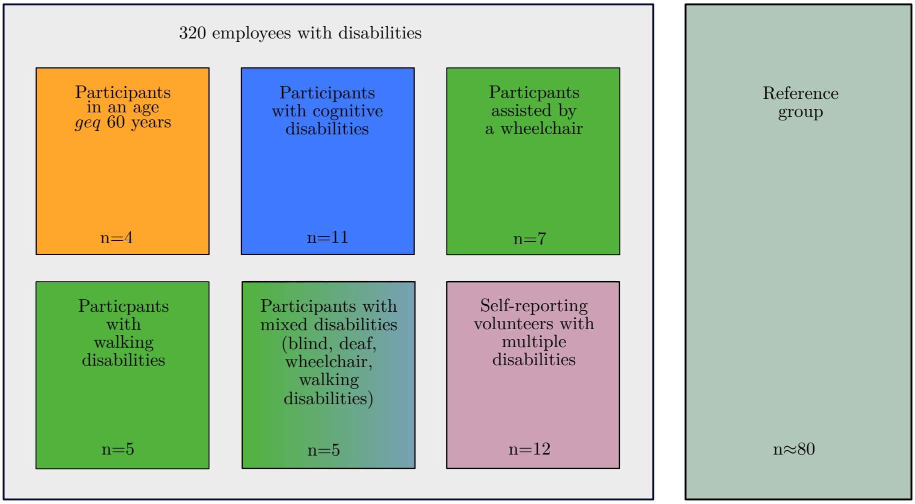


Figure 3.4: *Selection of participants and configuration of study groups. Using the Score RNA approach, participants with defined impairments were selected from the population of 320 employees with disabilities. This resulted in six variations of heterogeneity, whose parameters of the movement were compared in the studies.*

A total of 130 NDP, 46 PWD and 38 volunteer helpers have participated in the studies. The minimum number of participants at which the studies could have been carried out was set to 40 NDP supplemented by 5 PWD. Volunteers have supported the organisers of the studies, by distributing the participants, assist the movement and they have participated as pedestrians during the studies.

Overall, the averaged age was 34.2 ± 15.8 years in a range between 16 and 80 years (Fig. 3.5). Both genders, male and female, were almost equally represented (male: 48.5 %, female: 51.5 %). Due to different organisational boundaries, slight differences in ageing characteristics were observed. Participants on the first day of studies (Saturday) had an mean age of 36.4 ± 16.1 years, and a total range of 16 - 80 years. On the second day of study (Sunday), a mean age of 32.2 (± 15.1, (16 - 80 years) was determined. Concerning the populations, the overall mean age of PWD was 47.6 ± 7.0 years and the mean age of

NDP was 35.9 ± 16.3 years.

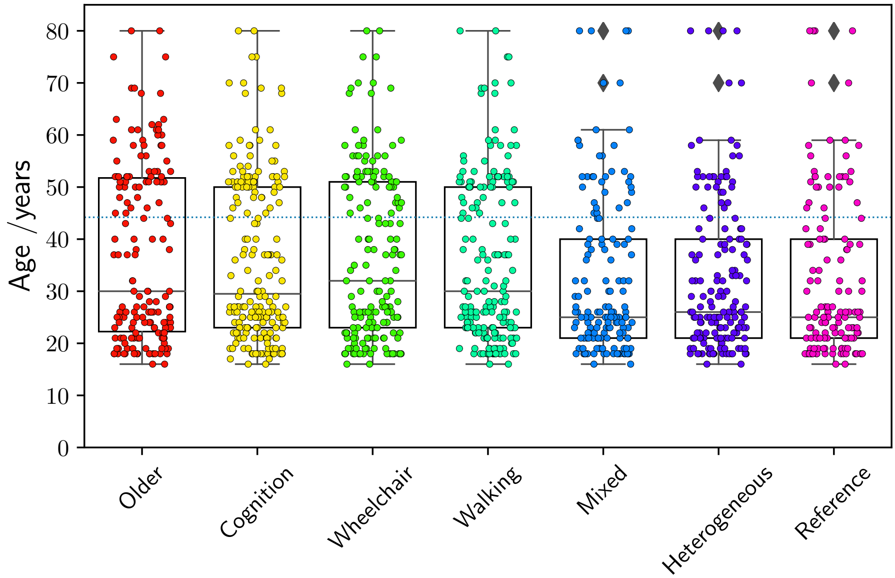


Figure 3.5: *Age distribution of the participants for each condition of crowd heterogeneity. Participants were in a mean age of* 34.2 ± 15.8 *years in a range between* 16 *and* 80 *years. For comparison, the median age of* 44.4 *years for Germany in 2015 is shown by the blue dotted line for orientation [205].*

Seven different subpopulations were considered for these studies:

Older population (old): participants with an age ≥ 60 years (Score RNA: 0.059) without any further disability. The total population consists of 4 PWD and 81 NDP.

Cognition disabled population (cog): participants with a cognition related disability scored by the Melba-SL-Mean-criterion in Tab. 3.3 (Score RNA: 0.235). The total population consists of 11 PWD and 88 NDP.

Population using a wheelchair (whe): participants using a wheelchair (Score RNA: 0.235). The total population consists of 7 PWD and 82 NDP.

Population with walking disabilities (wal): Participants with walking disabilities (Score RNA: 0.118). The total population consists of 5 PWD and 81 NDP.

Population with mixed disabilities (mix): Since the availability of participants who met the requirements regarding blindness or deafness (Score RNA: 0.235) was too low, these populations were joined in one group for pragmatic reasons. To increase the number of possible participants, participants with more than one single disability (e.g. persons who are blind and walking disabled or persons who are blind, aged over 60 years and cognitive disabled) were aggregated in the mixed subpopulation. The total population consists of 5 PWD and 75 NDP.

Population with heterogeneous disabilities (het): Some employees of the sheltered workshop wanted to participate in the studies even if they did not meet the Score RNA conditions for participation. Therefore an additional subpopulation was conducted to merge all self-reporters with heterogeneous single- or multiple severe disabilities. The total population consists of 12 PWD and 72 NDP.

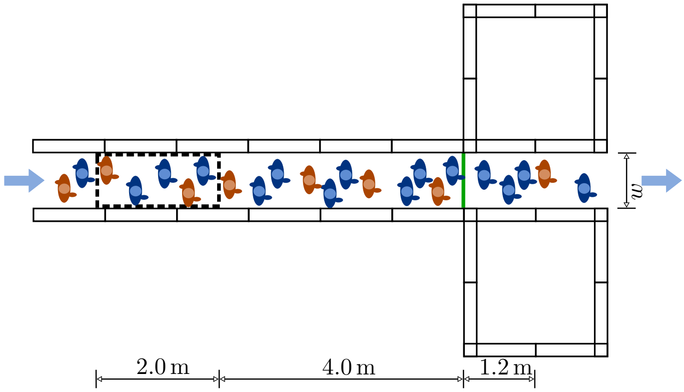
Population without disabilities (ref): 68 control group consisting of participants without any disability, recruited by public call.

A random sample of PWD was invited to participate in an accompanying psychological survey. In semi-standardised interviews, the influence of restrictions on individual movement was assessed. This survey focussed on supplementing the user's view and the empirical knowledge in the research context. In terms of content, methodology and organisation, the accompanying study was carried out with the external support of consulting psychologists (Team HF). The results have been incorporated into the BMBF-funded research project ORPHEUS (BMBF grant number 13N13266) and published as a report [180].

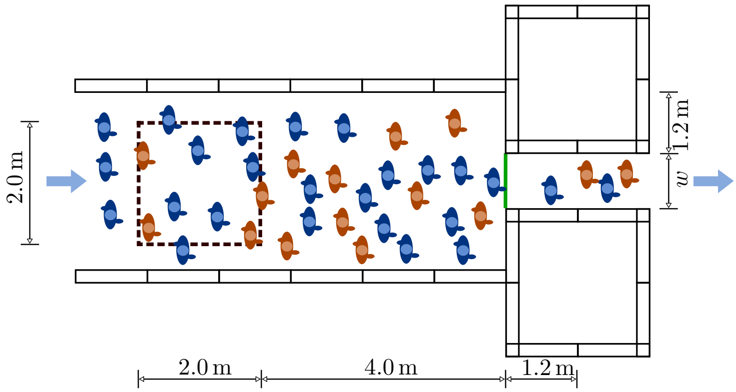
3.2.2 Study Setup

To follow the classification of complex movements by Shi et al. [2], investigations of internally driven movements in multi-lane pedestrian traffic were focused on in this study. Self-slowing, grouping, queuing are considered effects usually observed in egress situations. Since the goal of this dissertation was to quantify the impact of heterogeneous characteristics on crowd movement, on the one hand, the complexity of the geometry has been increased starting with a straight corridor (Fig. 3.6a) to a narrowing corridor (bottleneck, cf. Fig. 3.6b) and, second, the passage width w has been varied to control the outflow of the geometry and in consequence the participants' density in front of the bottleneck entrance. The minimum passage width was set to 0.9 m and was increased in increments of 0.1 m up to 1.2 m (which is in line with [88]). The minimum passage width has been set regarding the minimum width for doors in publicly accessible buildings in Germany [206]. In the case of the bottleneck situation, the length l of the bottleneck was set to 2.4 m. The controlled study area had a total length of 9.6 m. The boundaries were built from wooden three-layer panels with a height of 2.0 m.

A waiting area of $\approx 30\,\text{m}^2$ was located 12 m in front of the bottleneck entrance (cf. Fig. 3.6). An initial density of $3.0\,\text{m}^{-2}$ was aimed for each trial. Participants with disabilities were placed randomly over the entire space. The distance between the waiting area and the measurement area was meant to buffer starting conditions and minimize the effects of entering the geometry.



(a) *Principle of the corridor study.*



(b) *Principle of the bottleneck study.*

Figure 3.6: *Study configuration for (a) corridor and (b) bottleneck situations. The passage width w has been varied starting from* 0.9 m *in increments of* 0.1 m *up to* 1.2 m*. The measurement area is presented by the dotted rectangle. The measurement line for the time gap analysis is located at the bottleneck entrance (green coloured line).*

Participants were advised by oral instructions to move through the bottleneck without haste. The instructions were standardised and given in German. To make the content understandable for people with mental disabilities, it was prepared in simple language. It was emphasized not to push, and to move by the preferred velocity. A trial was started on the instruction of the experiment leader. When participants left the geometry, they returned to the waiting area for the next trial. All trials were repeated two times.

Since the empirical characteristics density ρ, speed v and flow rate J were measured in a quadratic measurement area of $4\,\mathrm{m}^2$ located four meters in front of the bottleneck entrance (see Fig. 3.6 and Fig. 3.8), the individual time gap Δt_i, which is defined as the approximate time gap between the crossing of a line between two following pedestrians, has been quantified at the bottleneck entrance ($x = 0\,\mathrm{m}$).

3.2.3 Data Capture

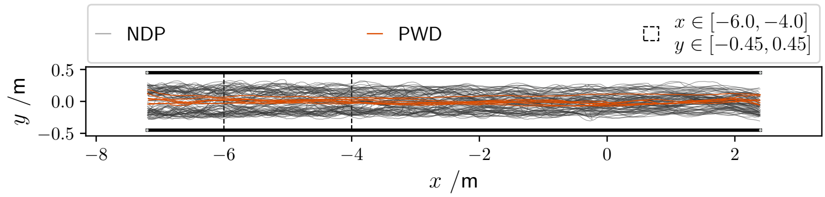
Each trial was captured by nine high-definition cameras attached to the ceiling of the assembly hall in a height of 6.34 m (cf. Tab. A.6 in Appendix A.3.3). The footage was captured with 25 frames per second. All participants wore a coloured cap according to their body height (Fig. 3.7a). The Petrack framework was used to detect and track the individual positions and to combine the trajectories over each time step [207]. Assuming a participants head as a circle, the centre of a precise coloured area is detected. For each consecutive time step, the projection of the detected centre of a head represents the position of a participant on the ground floor.

(a) *Colour coding.* **(b)** *Coloured caps as coded body heights. Source: Ralf Eisenbach.*

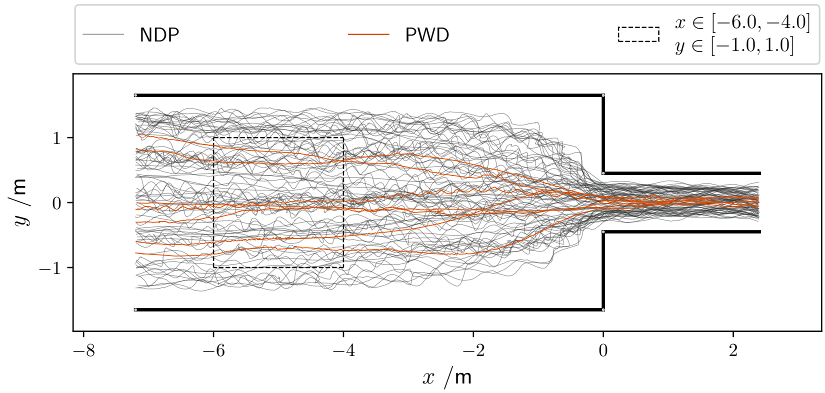
Figure 3.7: *Colour coding according to the participants body heights:* $h \leq 1.49\,\mathrm{m}$ = *pink,* $1.50\,\mathrm{m} \leq h \leq 1.61\,\mathrm{m}$ = *orange;* $162\,\mathrm{m} \leq h \leq 1.73\,\mathrm{m}$ = *yellow,* $1.74\,\mathrm{m} \leq h \leq 1.85\,\mathrm{m}$ = *green and* $h \leq 1.86\,\mathrm{m}$ = *blue.*

The extraction process was carried out by colleagues of the Juelich Research Center. All resulting trajectories were checked and corrected manually and characterised by a precision of approximately 0.092 m in the perspective of the centred camera (for details of the error calculation cf. Appendix A.3.3 and [208]). It was manually annotated which trajectories belong to participants with disabilities. The trajectories of all participants were combined from three different camera perspectives. The combination of trajectories resulting from different camera perspectives was realised by finding similar positions in overlapping areas. Couples of similar positions were tracked in space and time and combined over a weighting function (considering the more precise trajectories of the 4k-perspective). Starting with the 4k-perspective directly above the bottleneck entrance the combination was performed flow-upwards: 4k → X3000 → GoPro3. This feature was developed by Juliane Adrian [209].

The combined positions of all participants at each time step (trajectory) is exemplarily presented in Fig. 3.8 for a corridor- and a bottleneck trial with participation of wheelchair users. Individual trajectories of PWD are coloured in orange, trajectories of NDP are coloured in grey.



(a) *Participants trajectories for Cor_whe_01.*



(b) *Participants trajectories for Bot_whe_01.*

Figure 3.8: *Participants trajectories for (a) corridor and (b) bottleneck situation with participation of wheelchair users (coloured in orange). The measurement area for the empirical relations is given by the black dotted area.*

3.2.4 Data Availability

Trajectory data and video recordings have been published in the „Pedestrian Dynamics Data Archive“ powered by the Institute of Civil Safety Research. It can be open and long-term accessed by:

– http://ped.fz-juelich.de/da/2017sime

– https://doi.org/10.34735/PED.2017.1

An extended data documentation is available at Link to documentation

Chapter 4

Methodology

The following chapter outlines the methods used to compare the motion of pedestrian crowds in homogeneous and heterogeneous conditions. Since the stationarity of the measured values depends on the space and time scale of the measurement area, the influence of its location and the starting position of PWD was firstly determined (Sec. 4.1). Thus, the methodology used is separated into three approaches: first, the Voronoi method was used to calculate instantaneous characteristics as individual speeds v_i along a trajectory (Sec. 4.2). Second, the time-space-mean characteristics (Sec. 4.3), described in [210] and generalised by [89], were used to determine the empirical relations $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$. For this purpose, the distance covered at a fixed location in a small time interval (space-mean) is used. This approach was used because the global mean of a characteristic is of great interest to assess the capacity of a facility. Consequently, space-mean characteristics are arithmetic means of the single characteristic (e.g. speed) at a fixed time. Third, the flow rate J of participants at a fixed location was measured by using the individual time gap Δt_i between two consecutive participants (time-mean) at a measurement line (Sec. 4.4). It was used to check whether the hypothesis of a proportional relationship between flow rate J and passage width w can be confirmed for heterogeneous crowd conditions.

4.1 Starting Position and Measurement Area

Since empirical studies on the movement in crowds are characterised by short duration (see Tab. A.7) and the individual arrival of a PWD at the measurement area, the participants were distributed randomly in the waiting area. If agglomeration, in particular of PWD, were observed, the starting position was changed by the instructors. Cumulative starting positions for all trials of studies with wheelchair users and heterogeneous disabled participants are presented in Fig. 4.2 (see App. A.3.4 for the cumulative starting positions of all studies). In summary, individual starting positions of PWD inside the waiting area was assigned to realise a homogeneous distribution with an averaged starting density of approximately $3\,\mathrm{m}^{-2}$.

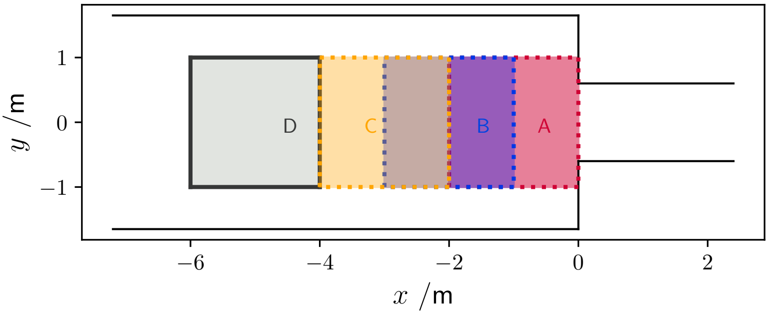
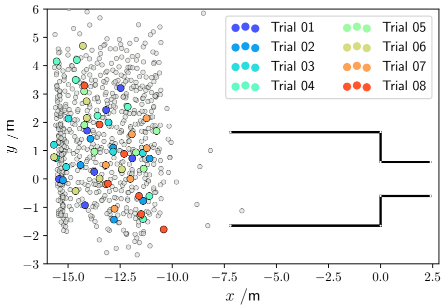
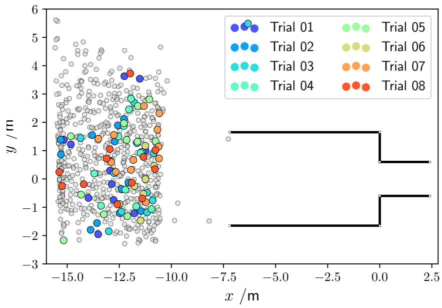


Figure 4.1: *Different positions of the measurement area in the bottleneck configuration.*



(a) *Population with wheelchair users.*



(b) *Population with multiple impaired (mixed) participants.*

Figure 4.2: *Position of participants in all bottleneck studies with participation of (a) wheelchair users and (b) heterogeneous disabled participants before starting the experimental trials. Positions of PWD are coloured according to the number of the trial.*

The spatial position of the measurement area is determined by an iterative process: Four positions of the measurement area, as shown in Fig. 4.1, were tested for reproducibility of the measures (cf. Sec. 5.4 for a detailed description of the procedure). Finally, a measurement area of $4\,\mathrm{m}^2$ located four meters in front of the bottleneck entrance was selected (measurement area D in Fig. 4.1).

4.2 Delaunay Triangulation and Voronoi Tessellation

A participant's position in space and time $P((x,y)(t))$ can be represented as a set of points in a two dimensional metric space (Fig. 4.3a). First, a Delaunay triangulation is generated. For this purpose, three points are defined as connected to a triangle, if and only if the interior of a uniquely defined circumcircle does not contain another point from the set of points (empty circle property), Fig. 4.3b [211] (summarised and discussed in detail by

[212]). The result is that for each edge in a Delaunay triangulation there is an empty circle property through the endpoints of the edge (Fig. 4.3c). The points on the circumcircle are called *natural neighbours* [212, p. 74]. The smallest interior angle for all triangles inside this mesh is maximised.

Participants' position can be used to transfer individual space for movement into a Voronoi diagram [110, 213]. The Voronoi tessellation – exemplary presented in Fig. 4.3e – assigns an individual required space to each person, called Voronoi cell $A_i(t)$, which includes all points of the Euclidean plane that are closer to a participant i than to all other participants [97, 213, 214]. In addition, the Voronoi cell is restricted by walls, obstacles, and generally also by a cutoff radius r_c (here set to 2.0 m) that represents the participant's maximum range of influence. The Voronoi diagram is dual to the Delaunay triangulation: the edges of the Delaunay triangulation are perpendicular to those of the Voronoi diagram.

The relation between Delaunay triangulation and Voronoi tessellation is exemplified presented in Fig. 4.3. Since neighbours of a given participant with the identification number (persID) 3 (orange) – here defined as points with shared edges of triangles (natural neighbours) – are coloured in green, the participants coloured in black with persID $\in [1, 5, 9, 10]$ are not neighbours (Fig. 4.3d). Circumcircles and circumcenters of the resulting triangles are indicated in light grey.

Concerning interactions between participants and boundaries of the built environment, artificial geometry points are additionally defined. They are placed in the corners of the geometry and are interpreted as 'virtual neighbours' and are included in the calculation of the Voronoi cells. Therefore, an artificial distance between a participant's Voronoi cell and the edge of the wall is maintained. The arrangement of the points enables unused space to be represented in the bottleneck entrance area of the Voronoi cell model without over-representing the influence of the structural edges.

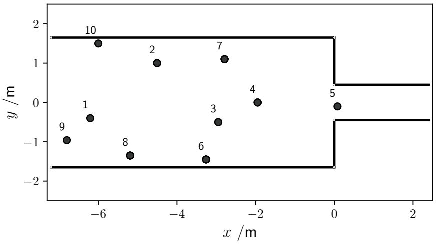
Thus, the individual density ρ_i and speed v_i of a participant's i position (x, y) and his Voronoi cell A_i at time t is defined as:

$$\rho_i(x, y, t) = \begin{cases} \frac{1}{A_i(t)} & , \forall (x, y) \in A_i(t) \\ 0 & , \text{other} \end{cases} \qquad \text{(Eq 4.1)}$$

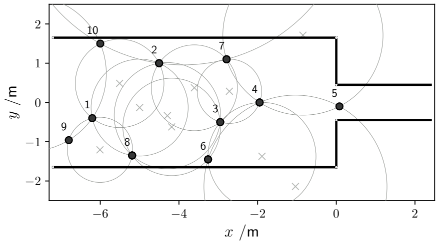
and

$$v_i(x, y, t) = \begin{cases} v_i(t) & , \forall (x, y) \in A_i(t) \\ 0 & , \text{other} \end{cases} \qquad \text{(Eq 4.2)}$$

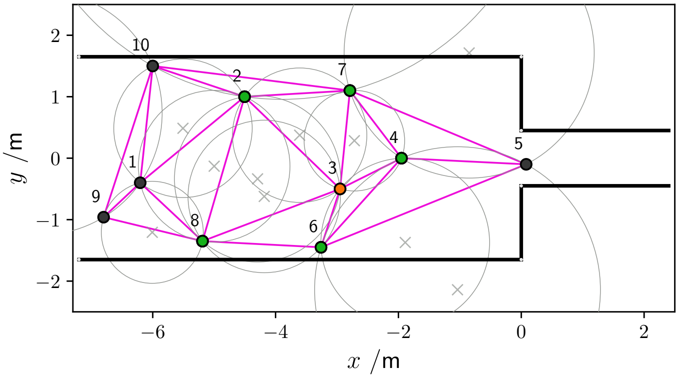
The density distribution ρ and the velocity distribution v of the positions x, y inside the



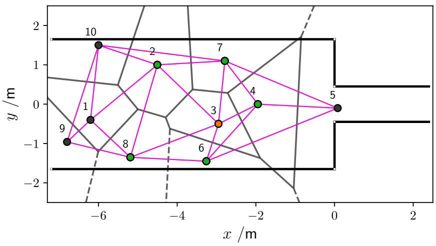
(a) *Position of participants.*



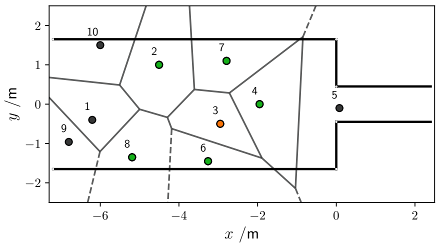
(b) *Optimised circumcircles.*



(c) *Natural neighbours based on empty circle property (Delaunay neighbours).*



(d) *Delaunay triangulation and Voronoi tessellation.*



(e) *Voronoi tesselation.*

Figure 4.3: *Relationship between Delaunay triangulation and Voronoi tessellation presented for a set of ten trajectory points. (a) Ten trajectory points in a bottleneck geometry; (b) calculation of unique circles that passes through each trajectory point and has no other point in his interior; (c) triangulation of the point set satisfying the empty circle property (Delaunay triangulation); (d) relationship to Voronoi tessellation defined as the perpendicular to the connecting lines between two points, and (e) resulting Voronoi cells.*
Neighbours (green) of a participant of interest (orange) are defined as trajectory points connected by Delaunay edges (pink).

measuring area $\Delta x \cdot \Delta y$ result at time t according to [89, 214, 215] from:

$$\rho(x,y,t) = \sum_i \rho_i(x,y,t) \qquad \text{(Eq 4.3)}$$

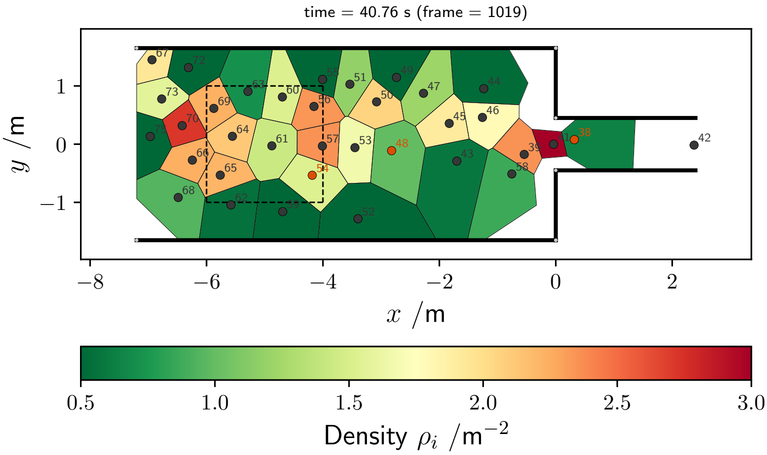
$$v(x,y,t) = \sum_i v_i(x,y,t) \qquad \text{(Eq 4.4)}$$

The density within the Voronoi cell $A_i(t)$ is calculated as the reciprocal of the area of the cell. This makes it possible to weigh the influence of individual parts of neighbouring participants inside the measuring area. With densities (Eq 4.1) and speeds (Eq 4.1) related to individual positions, the Voronoi density ρ_v (Eq 4.5) and Voronoi speed v_v (Eq 4.6) are obtained at time step t inside the measuring area $\Delta x \cdot \Delta y$:

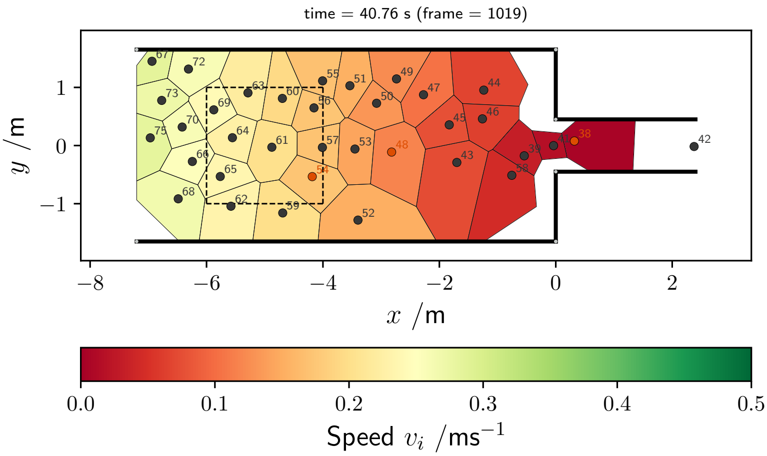
$$\rho_v(t,\Delta x,\Delta y) = \frac{1}{\Delta x \cdot \Delta y} \iint \rho_i(x,y,t)\mathrm{d}x\mathrm{d}y \qquad \text{(Eq 4.5)}$$

$$v_v(t,\Delta x,\Delta y) = \frac{1}{\Delta x \cdot \Delta y} \iint v_i(x,y,t)\mathrm{d}x\mathrm{d}y \qquad \text{(Eq 4.6)}$$

An example for the spatial distribution of the individual density ρ_i and speed v_i in a bottleneck (at time step 40.08 s) in heterogeneous crowd conditions (Bot_whe_01) is presented in Fig. 4.4.



(a) *Voronoi cells coloured by individual density ρ_i.*



(b) *Voronoi cells coloured by individual speed v_i.*

Figure 4.4: *Visualisation of individual (a) density ρ_i and (b) speed v_i in a bottleneck. Colouring of tracked trajectory points and annotation of persIDs are according to their population: grey for NDP and orange for PWD. The participants with disabilities were using electric (persID 48, 54) and manually (persID 38) operated wheelchairs.*

4.3 Space-time-mean

After analysing individual characteristics with the Voronoi- and Delaunay-method, the space-time-mean method was used to calculate averaged values for density ρ and speed v over space and time. The method was introduced by Edie [210] and generalised by Holl [89]. Characteristics were measured in a consecutive time interval of a length of $\Delta t = 2\,\mathrm{s}$. The Fig. 4.5 uses the following notation to introduce the method.

A : Measurement area for space-time-mean calculation of density $\bar{\rho}$, speed $\bar{v}$ and flow $\bar{J}$. The measurement area is constraint to convex forms.

$\vec{a_i}, a_i$: A vector between points of entrance $P_{i,in}$ and exit $P_{i,out}$ of a participant i. $\vec{a_i} = \vec{x_i}(t_{i,out}) - \vec{x_i}(t_{i,in})$. The magnitude $a_i = |\vec{a_i}|$ is the distance necessary to cover the measurement area.

b_i : Length of straight line approximating the path covered by participant i inside the measurement area during the measurement interval. Five cases are distinguished:

$$b_i = \begin{cases} |\vec{x_i}(t_{i,in}) - \vec{x_i}(t_1)| & \text{Case 1:} \quad (t_0 \leq t_{i,in}) \wedge (t_1 > t_{i,in}) \wedge (t_1 < t_{i,out}) \\ |\vec{x_i}(t_0) - \vec{x_i}(t_1)| & \text{Case 2:} \quad (t_0 > t_{i,in}) \wedge) t_1 < t_{i,out}) \\ |\vec{x_i}(t_0) - \vec{x_i}(t_{i,out})| & \text{Case 3:} \quad (t_0 > t_{i,in}) \wedge (t_0 < t_{i,out}) \wedge (t_1 \geq t_{i,out}) \\ |\vec{x_i}(t_{i,in}) - \vec{x_i}(t_{i,out})| & \text{Case 4:} \quad (t_0 \leq t_{i,in}) \wedge (t_1 \geq t_{i,out}) \\ 0 & \text{Case 5:} \quad (t_1 \leq t_{i,in}) \vee (t_0 \geq t_{i,out} = \end{cases}$$

c_i : Length of straight line approximating the path covered by participant i inside the measurement area, but not during the measurement interval. Five cases are distinguished:

$$c_i = \begin{cases} |\vec{x_i}(t_1) - \vec{x_i}(t_{i,out})| & \text{Case 1} \\ |\vec{x_i}(t_{i,in}) - \vec{x_i}(t_0)| + |\vec{x_i}(t_1) - \vec{x_i}(t_{i,out})| & \text{Case 2} \\ |\vec{x_i}(t_{i,in}) - \vec{x_i}(t_0)| & \text{Case 3} \\ 0 & \text{Case 4} \\ |\vec{x_i}(t_{i,in}) - \vec{x_i}(t_{i,out})| & \text{Case 5} \end{cases}$$

d_i : Dimensionless relationship between the path lengths covered inside the measurement area and outside of the measurement interval.

$$d_i = \frac{b_i}{b_i + c_i} \in [0, 1] \tag{Eq 4.7}$$

e_i : As main result of the calculation, the distance covered by participant i along the main movement direction during the measurement interval.

$$e_i = d_i \cdot a_i \tag{Eq 4.8}$$

t_0, t_1	:	Lower and upper limits of the measurement interval. Default: $\Delta t = t_1 - t_0 = 2\,\mathrm{s}$ which corresponds to 50 frames (for recordings with $25\,\mathrm{s}^{-1}$)
$t_{i,in}, t_{i,out}$	:	Points in time at which participant i enters and exits the measurement area. The first point is considered here, which is completely within ($t_{i,in}$) or outside ($t_{i,out}$) the measurement area.
$\vec{x_i}(t)$	:	Position vector of participant i at time t. $\vec{x_i}(t) = \begin{pmatrix} x_i(t) \\ y_i(t) \end{pmatrix}$.
$\vec{x_i}(t_0), \vec{x_i}(t_1)$	:	Location of participant i at beginning and end of measured interval.

Using this method, it is crucial to calculate the averages of density, speed and flow rate at the same space and time. The movement direction of each participant corresponds to the real, unbounded movement direction inside the geometry.

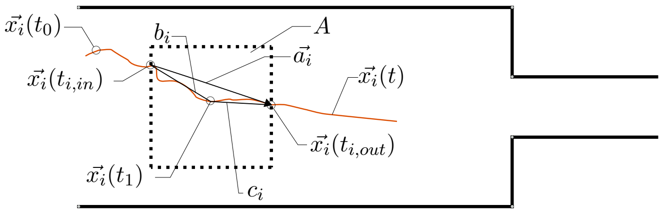


Figure 4.5: *Schematic representation of space-time-mean method. The motion of a participant i is represented by the orange trajectory. It is located inside the measuring area A during the time interval $\Delta t = [t_0, t_1]$ and – in this example – did not pass the measurement area completely.*

The mean density $\bar{\rho}(A, \Delta t)$ of n persons is defined as individual ratio of a participant i on the overall density in context to their effective time interval $[t_0, t_1]$ inside the measurement area A during the sampling interval $\Delta t_i(A) = t_{i,1} - t_{i,in}$ (Eq 4.9). A density $\bar{\rho}(A, \Delta t)$ within the measurement area A is defined as the sum of the individual ratios of the density [89].

$$\bar{\rho}(A, \Delta t) = \frac{1}{A \cdot \Delta t} \sum_{i=1}^{n} \Delta t_i(A) \tag{Eq 4.9}$$

The mean speed $\bar{v}(A, \Delta t)$ along the main movement direction (x-direction) is defined as the ratio of the sum of all covered distances $e_i(\Delta t)$ during the sampling interval $[t_0, t_1]$ to the sum of the time $\Delta t_i(A)$ spent inside the measurement area A (Eq 4.10).

$$\bar{v}(A, \Delta t) = \frac{\sum_{i=1}^{n} e_i(\Delta t)}{\sum_{i=1}^{n} \Delta t_i(A)} \tag{Eq 4.10}$$

Assuming the hydrodynamic relationship and a strictly one-directional movement, the average specific flow $\bar{J}_s$ is defined as a product of density $\bar{\rho}$ and speed $\bar{v}$. Using Eq 4.9 and Eq 4.10 results in:

$$\bar{J}_s(A, \Delta t) = \bar{\rho}(A, \Delta t) \cdot \bar{v}(A, \Delta t) \tag{Eq 4.11}$$

$$= \sum_{i=1}^{n} \frac{\Delta t_i(A)}{\Delta t} \cdot \frac{1}{A} \cdot \frac{\sum_{i=1}^{n} e_i(\Delta t)}{\sum_{i=1}^{n} \Delta t_i(A)} \tag{Eq 4.12}$$

$$= \frac{1}{A \cdot \Delta t} \sum_{i=1}^{n} e_i(\Delta t) \tag{Eq 4.13}$$

The overall flow rate $\bar{J}$ of all participants is calculated as the summed individual ratio of each participant in the measurement interval and measurement area.

4.4 Specific Flow Concept

One of the most important questions while assessing the performance of a facility is to quantify the capacity of a bottleneck and the relation between capacity and passage width [88, 216]. Especially against the backdrop of the minimal time needed to evacuate a given built environment, the flow rate depends on the individual time interval (or spatial distance) between any two consecutively passing participants (Fig. 4.6).

The flow rate J based on individual time gaps Δt_i between N participants is similar to the number of participants crossing the fixed location at $x = 0$ [3]. Therefore, the time gaps $\Delta t_i = t_{i+1} - t_i$ are calculated between the consecutive participants i and $i + 1$ (Fig. 4.6). The sum of individual time gaps is directly related to the flow rate J (Eq 4.14 et seq.).

$$J = \frac{1}{\Delta t_i} \quad \text{with} \quad \Delta t_i = \frac{1}{N} \sum_{i=1}^{N} (t_{i+1} - t_i) \tag{Eq 4.14}$$

$$= \frac{N}{\sum_{i=1}^{N} (t_{i+1} - t_i)} \tag{Eq 4.15}$$

The specific flow J_s giving the flow per unit width is defined as the normalised flow rate J related to the passage width w (Eq 4.16).

$$J_s = \frac{J}{w} \tag{Eq 4.16}$$

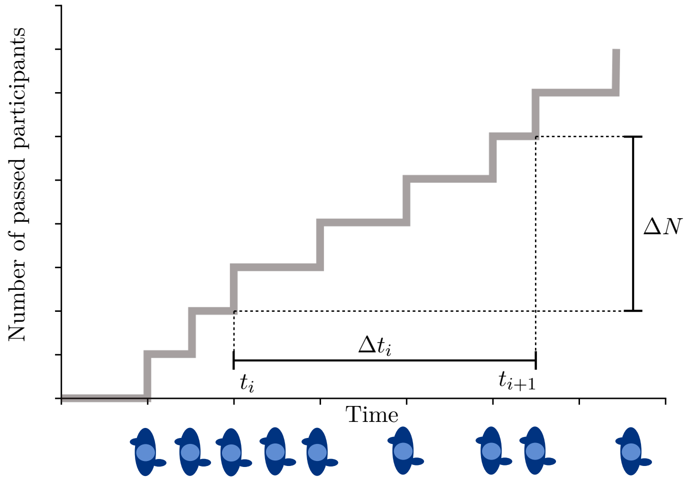


Figure 4.6: *Derivation of the cumulative flow rate J on a time interval $[t_i, t_{i+1}]$ based on individual time gap. The share of individual time gaps Δt_i is similar to the flow rate of N participants.*

4.5 Description of visible disabilities

The configuration of the crowd heterogeneity (operationalised as differences in the study population) was specifically varied in the presented studies. With the use of the Score RNA approach, both the type and the characteristics of impairments were objectively described and clustered (Sec. 3.2.1). In the realisation of the study, the atmosphere was characterised by an artificial impression: all participants were very conscious about the laboratory character of the situation which means being in an observed situation. It cannot, therefore, be ruled out that participants have adapted their natural behaviour because they know that they are participating in an artificial situation and are under observation. It is also not known what level of experience and familiarity participants from the NDP group had in dealing with people with disabilities. Nevertheless, the presence of persons with overtly visible disabilities (i.e., a person who lives with an overtly visible disability such as a wheelchair user) is recognisable to an observer and can influence the movement of the group and behaviour. Additionally, the participants with disabilities were recruited from the same basic population (workshop) and were in consequence known to each other.

To make the influence of the presence of PWD on the behaviour of all participants in an observed study situation interpretable, a standardised narrative description of participants with disabilities based on a phrasing template was developed. The result is a description of persons who, when viewed from an observation view, are visible (and recognisable) and objectifiable as having a disability. The description is based on a five-step process:

1. Identifying behavioural phenomena,
2. Coded description of the observation,
3. Revision of the descriptions and clustering (coding manual),
4. Encoding footage by using the coding manual,
5. Supplement and review coded keywords by a second rater.

First, observed behaviours were determined from three video compilations in a standardised interview with a free answer format. This survey involved 33 people (age: 34 ± 7.2 (23 - 57) years) with professional background in engineering, psychology, human factors, social sciences, geography, physics and, computer science. The aim was to provide the assumed phenomena with a name that is comprehensible from an interdisciplinary perspective. Among the most frequently mentioned presumed reasons for the phenomena observed in the footage were: 'considerate behaviour', 'norm', 'politeness' and, 'responsiveness', which suggests the presence of a person with disabilities.

In the next step, secondly, an objectified description of the observation was carried out by inductive-deductive coding with recourse to defined terms (see coding manual in Tab. A.4 in App. A.3.2). This step aimed to identify how impairments or disabilities can be perceived by other participants. In Fig 4.7 an example of a scene is presented, where a participant uses a white stick to navigate his way into the entrance of the narrow passage. The coding was event-based, which means that no temporal definition of the coding units was given, but individual definitions in the form of start- and endpoints were possible. A collection of generic categories such as 'gait striking' or 'assisted by a wheelchair or white stick' was created during an iterative process. To make the specifications more precise, adjectives or attributes were assigned, e.g. 'strong/weak' or 'fast/slow'. Subsequently, these specifications were determined by assigning inter-rater identifiable indicators to the appropriate category (operationalisation). The result is a narrative description of the motion style of a participant, as it can be perceived from a bird's-eye view without specific individual diagnostic knowledge. In the case of the specific example of a participant manoeuvring with a white stick, the identified category 'use of an assistive device' with the characteristic 'permanent' is operationalised by the 'scanning movement of the environment by the white stick'.

Thirdly, this collection was revised to provide an uniform, well applicable clustered description. Fourthly, the video sequences, were encoded by using the coding manual (Tab. A.4 in App. A.3.2). During the last step, fifthly, the coding was checked and completed by a second person who knows the identity of the individuals with disabilities and is familiar

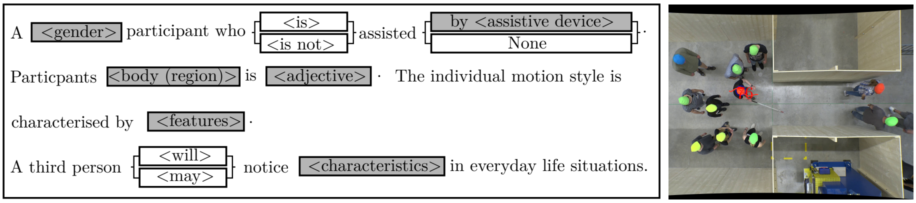


Figure 4.7: *Phrasing template to describe disabilities based on the visibility of the disability to a third person (left). An example of a scene where a participant uses a white stick (highlighted by the trajectory points) to navigate his way into the entrance of the narrow passage (right).*

with these people from daily work. Thus, it was possible to supplement characteristics that are not visible through video observation, for example, strong salivation. The narrative description of each PWD (phrasing) was created (cf. App. A.3.2) with the use of these coded keyword according to the scheme presented in Fig 4.7. Exemplary, the narrative description of PWD_54 is:

PWD_54: A *female* participant who *is* assisted by a *white stick and personnel assistant*. Participants *body* is *characterised by no characteristic features*. The individual motion style is characterised by *orientation by hand and usage of arms for orientation*. A third person *may* notice *no characteristic features* in everyday life situations.

4.6 Indicating the Impact of Heterogeneity

Based on the findings in Sec. 2, three methods to generate the performance characteristics for pedestrians in heterogeneous crowds were introduced, see Sec. 4.2 - Sec. 4.4. Studies under controlled boundary conditions (Sec. 3) serve as empirical input to provide density, speed and flow rate for capacity analysis. In the following, methods to quantify the influence of crowd heterogeneity on performance criteria of crowd motion are introduced in five steps.

First, the time requirements to start an individuals movement depending on the usage of common assistive devices (Sec. 5.2) and the unimpeded (unrestricted) speed (Sec. 5.3) are analysed. Second, the interpersonal time gap is used to describe the distance between the centre of a participants head and the preceding person to derive the specific flow rate J_s (Sec. 5.5).

Third, the Voronoi approach is used to analyse key performance values such as individual speed, acceleration (Sec. 5.6) or variations in empiric relations (Sec. 6.3). It is assumed that the standard deviation of the mean speed σ_v provides a suitable criterion to describe differences in traffic conditions. This approach is used to describe differences between conditions of crowd heterogeneity (operationalised by different populations, cf. Sec. 6.4).

Then, fourth, a space-time-mean approach is used to determine empiric relations of $v(\rho)$ or $J(\rho)$ and provide a capacity analysis for corridors (Sec. 5.7) and bottlenecks (Sec. 5.8) for different conditions of crowd heterogenity. Due to the practical relevance, the focus here was on the free flow branch of the empirical relation, which reaches up to the maximum flow rate. The characteristics J_c, ρ_c and σ_{Jc} were used as key performance parameters to assess the efficiency of a crowds motions in built environments.

Fifth, the well-established concept of specific flow rate J_s is used to estimate the proportional relationship between the capacity and the passage width of a geometry (Sec. 5.9). It will be verified whether the linear relationship between passage width and capacity also applies to heterogeneous crowds. It is assumed, that the individual speed depends on the spatial headway (e.g. [90, 95, 158]) and describes the microscopic density of a participant.

Afterwards, the findings of a capacity analysis are summarised (Sec. 6.4) and, last, an application in engineering egress calculation is proposed to estimate the flow rate of a heterogeneous crowd based on individual time gap.

Chapter 5

Data Analysis

5.1 Objectives

The parametrisation of egress performance of heterogeneous crowds is based on findings from studies under laboratory conditions. In particular, the focus was on two important time ranges of the engineering timeline, influenced by individual characteristics (Fig. 2.1): the pre-movement and movement phase. The analysis is oriented towards answering the following research questions with high relevance for the design of safe pedestrian traffic facilities:

1. How much time is required to prepare an individual by themselves or by an assistant to realise movement by using technical assistive devices?

2. What is the maximum performance (capacity) of traffic facilities used by heterogeneous crowds? Is the capacity depending on population characteristics and which density can be achieved under safe conditions?

The study design follows the concept of the increasing complexity of individual characteristics: first, a population without disabled participants represents the simplest case of complexity (homogeneous condition). A more complex situation (heterogeneous condition) follows which is characterised by static space requirements of assistive devices (wheelchairs) and differences in characteristics of the step-cycle (mixed and heterogeneous disabled population). In each scenario, the time required to prepare movement realisation (preparation time t_{prep}) depending on frequently used assistive devices is analysed. Second, unimpeded (free) speeds v_0 for a) the entire population, b) participants with disabilities and, c) depending on assistive devices were analysed to characterise the free movement as a parameter and a reference to the movement in heterogeneous crowds in more dense situations (Sec. 5.3). Third, the adaptation of individual speed is analysed to investigate the influence of geometric boundary conditions and maintained interpersonal interactions (Sec. 5.6). Due to the high practical relevance, the presented studies were designed to enable a capacity analysis

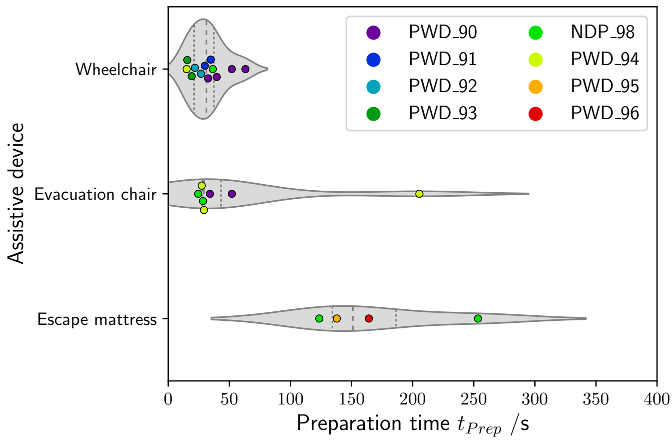
($v(\rho)$ or $J(\rho)$) in Sec. 5.7 and Sec. 5.8. Here, the free flow branch up to the maximum capacity was considered (cf. Fig. 2.4 on p. 15). Lastly, the individual passage time gap Δt_i is analysed in Sec. 5.5 to indicate the influence of individual characteristics on crowd motion and, in consequence, on macroscopic criteria like the specific flow concept (Sec. 5.9).

5.2 Pre-movement Phase

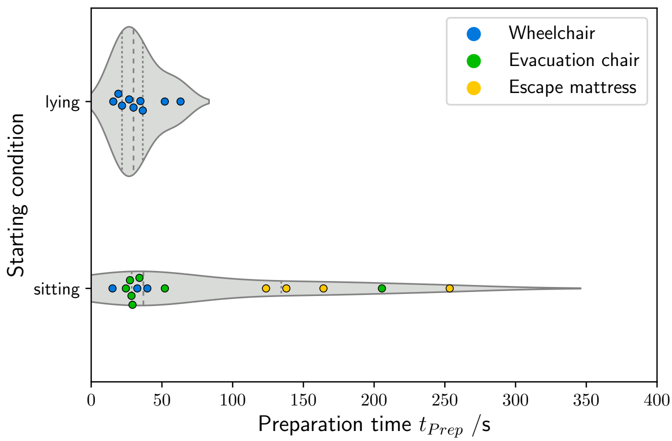
If a person's ability to move independently depends on an assistive device, the set-up time (preparation) of the device becomes important in the pre-movement phase of an egress. Since both the construction procedure and the handling can depend on own experience of use, this applies to the use by oneself and the use by assistants [41]. Required times to prepare an assistive device t_{prep} resulting from studies on preparation of a wheelchair, an evacuation chair and an escape mattress under laboratory conditions are presented in Fig. 5.1 (cf. App. A.2 for details on study implementation). As reported in previous publications on the pre-movement phase (cf. Fig. 2.2), the results are characterised by a wide distribution of required times. In addition, both, the mean preparation time and the standard deviation, differ depending on the assistive device used (Fig. 5.1a). While the preparation time for a wheelchair takes (32 ± 15) s, the time requirements increase for the usage of an evacuation chair (57 ± 66) s and for the escape mattress (170 ± 58) s.

The starting condition of PWD (lying, sitting) does not seem to influence the level of required preparation time. Except for an outlier regarding the preparation of an evacuation chair, all high time requirements belong to the preparation of the escape mattress device, cf. Fig. 5.1b. Here, it is not the positioning of the body that is decisive, but the time required for the preparation of the assistive device. Especially in the first part of the study period, it was shown that the use of wheelchairs and evacuation chairs was smooth and intuitive, while the use of an escape mattress was uncommon and unintuitive for all assistants despite training. Transferring the participant horizontally from the bed to the escape mattress requires physical strength, technique and experience. Uncertainty about the way the escape mattress works (cf. App. A.2.1), coordination and an iterative process regarding the procedure for lifting the PWD make up a high proportion of the total time required for this assistant device.

For characterisation of the pre-movement phase, especially concerning the process optimisation and the strengthening of the self-rescue capability, the mere analysis of the time required is not sufficient. On the one hand, a decreased familiarity of a wheelchair user's assistant for handling procedures of an escape mattress results in increased preparation times (Fig. 5.1a). On the other hand, the courses of action and interaction between human and technology are too complex to derive threshold values only from the preparation times. in line with previous research findings (cf. Sec. 2.1), an increased preparation time with increasing variance can be observed if the complexity of the assistance increases.



(a) *Preparation times depending on the assistive device.*



(b) *Preparation times depending on the starting position.*

Figure 5.1: *Preparation times depending on (a) assistive device and (b) starting condition. Dashed lines represent the median and the interquartile range between 25th and the 75th percentile. The estimated distribution is represented by the grey area.*

5.3 Unimpeded Speed

First, the unimpeded speed v_0 of PWD depending on the assistive device used was determined (Tab. 5.1; see Sec. A.2.3 for the description of the method and more details). While comparable unimpeded speeds were observed for participants without disabilities, increased unimpeded speeds in the plane were measured for participants using wheelchairs and evacuation chairs. If an escape mattress was used as an assistive device, the unimpeded speed was massively reduced in trials. Efforts in pulling the escape mattress over the ground depend on friction and require a high physical strength of the assistant. While the assisted unimpeded speed using a wheelchair or an evacuation chair depends on the person moving the assistive device, in case of an escape mattress being used the measured speed is affected by an individuals possibility to overcome the friction [37]. The floor covering on which the 10MWT was carried out was made of linoleum. The surface was studded to increase the slip resistance which seriously complicates pulling the mattress, especially when pulling heavy persons. This has resulted in the escape mattress often pulled backwards so that less effort is required (cf. Fig 5.2).

(a) *Evacuation chair.* **(b)** *Escape mattress.*

Figure 5.2: *Use of the (a) evacuation chair and the (b) escape mattress as assistive devices in the 10MWT. While the wheelchair was always pushed by the assistant, the escape mattress was often pulled backwards to overcome the frictional force more easily.*
Source: Ralf Eisenbach.

Table 5.1: *Unimpeded assisted speed in dependence of the assistive device used. Data is obtained by the 10MWT [183] and presented as: mean [standard deviation, minimum - maximum]. Please note, that trials using an escape mattress were carried out with NDP because of ethical concerns.*

Study	PWD		NDP		Reference literature
	N	v_0 /m s^{-1}	N	v_0 /m s^{-1}	v_0 /m s^{-1}
Wheelchair	22	2.13 [0.34, 1.44 - 2.60]	–	–	0.89±0.25 [61][a] 1.30 [217][b]
Evacuation chair	10	1.97 [0.56, 0.76 - 2.66]	–	–	1.46±0.09 [48, 218][c]
Escape mattress	–	–	2	0.95 [0.11, 0.87 - 1.02]	0.89±0.24 [48, 218][c,d]

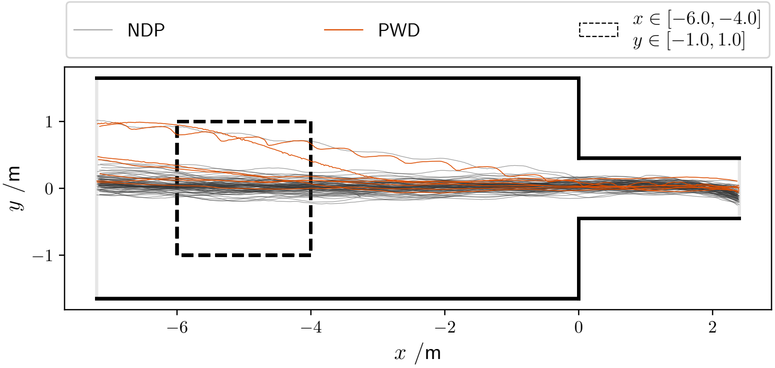
[a] Older participants using a wheelchair outdoor.
[b] Manual operated and assisted wheelchair.
[c] Horizontal travel speed over a distance of 60 m.
[d] Data were generated with a rescue sheet and not with an escape mattress.

Second, the unimpeded speed of each participant was measured at the beginning of each study on the movement of groups towards dense crowds. Participants were instructed to move alone through the bottleneck setup with a passage width of 0.9 m. A measurement area of 2×2 m was located 4 m in front of a bottleneck entrance (see black rectangle in Fig. 5.3a).

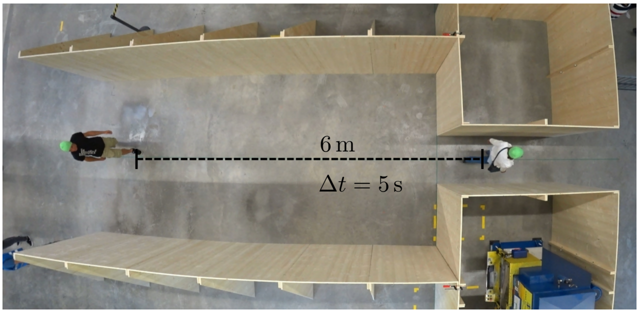
The start of an individual's movement was controlled by the distance to the predecessor. An approximate time offset of 5 s between each start has been maintained which leads – if a free speed of $\approx 1.2\,\mathrm{m\,s^{-1}}$ is supposed – to an interpersonal distance of ≈ 6 m (Fig. 5.3b). It can therefore be concluded that the movement of a participant was not influenced by their predecessor.

The measured averaged unimpeded speeds inside the measurement area for all NDP is $1.48 \pm 0.20\,\mathrm{m\,s^{-1}}$ and is in accordance with literature findings [1, 21] (cf. Fig. 2.3 on p. 11). The unimpeded speed of PWD depends decisively on individual characteristics such as the kind of movement ability and can therefore lead to a broad distribution of the results (Fig. 5.4). This is particularly evident for the populations of wheelchair users ($v_0 = 0.85 \pm 0.37\,\mathrm{m\,s^{-1}}$), mixed ($v_0 = 0.75 \pm 0.22\,\mathrm{m\,s^{-1}}$) or heterogeneous disabled participants ($v_0 = 1.32 \pm 0.29\,\mathrm{m\,s^{-1}}$).

Whereas for the consideration of wheelchair users the possibility is conceivable that wheelchair users already slow down movement for manoeuvring into the bottleneck, the study considering participants with mixed disabilities involving two blind persons assisted by a white stick and guided by a personal assistant. Orientation by tactile sensing of the



(a) *Trajectories.*



(b) *Overview of the scene.*

Figure 5.3: *Trajectories for each participant (Fig. 5.3a) and an exemplary image of measuring the unimpeded speed (Fig. 5.3b). To guarantee an individual movement independent of predecessors, the beginning of the movement was controlled (see text).*

surroundings and careful movement reduces the desired speed noticeably. Note that the wheelchairs used in this study had a mean width of 0.60 ± 0.08 m which leads to navigation difficulties at the entrance to the bottleneck (see App. A.3.2 for more details on the characteristics of the PWD). Participants with multiple severe disabilities participated in the study with a heterogeneous subpopulation. A mono-causal reason for the reduction of the unimpeded speed is not apparent here.

Even if the observed unimpeded speeds are slightly higher, data presented here confirm in general an unimpeded speed for NDPs that meets and validates the expectations of published values (Sec. 2.2). Considering the subpopulation of PWD, a dependence of speed on individual possibilities and abilities is apparent. While for some (sub-)populations a significant reduction in desired speed was measurable (wheelchair users, walking disabled participants, participants with mixed disabilities, and participants of the heterogeneous group), the unimpeded speed of other populations was not influenced at all by the type of disability (older and cognition disabled participants).

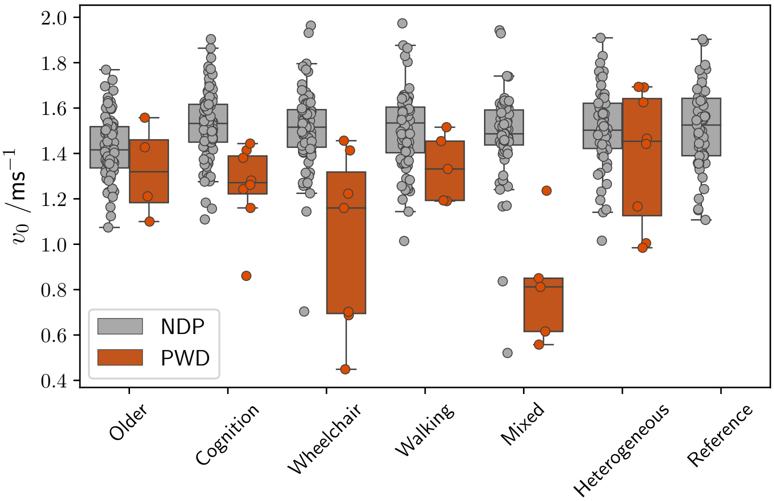


Figure 5.4: *Unimpeded speeds v_0 depending on population.*

5.4 Stationarity

Empirical relations of pedestrian's movement are statistical relations under similar (average) conditions [219]. It is ensured that the conditions in the participants' waiting area (Fig. A.5 and Fig. A.6 on p. 150) have no significance for the measurement. This means in particular that statistical properties such as mean, variance and covariance remain constant over a stable period (stationarity). Statistical properties in stationary states are '[. . .] similar to those of the time-shifted series [. . .] for each integer [. . .].' ([220, p 13])

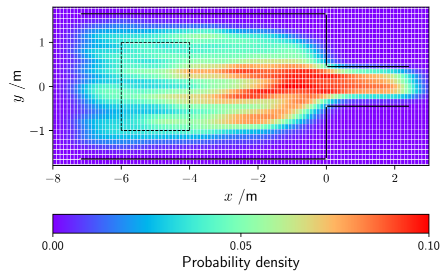
Traffic processes are – even in classical transportation science – generally not stationary since vehicle and group compositions and the type and intensity of interactions between traffic participants are heterogeneous [221]. In practice, long measurement intervals may reduce fluctuations and short measurement intervals may reduce the statistical meaning of the observed phenomena [221–223]. While in field studies of car traffic observational periods of three to five minutes are common for the determination of moving averages [221], controlled studies of pedestrian dynamics usually have qualitatively shorter running times. This is due to limited personnel and financial factors which is unlike in field studies of vehicle traffic. Thus, a significant part of the period depends on the (random distributed) start and end conditions (e.g. low densities at the beginning and the end of a trial). These considerations are particularly important if the study population consists of participants with different unimpeded speeds (cf. Sec. 5.3). The distance between the waiting area and the entrance of the bottleneck leads to the separation of the groups. Faster moving participants overtake the slower participants (e.g. wheelchair users). A segregation process happens. The concept of stationarity is therefore only of limited application for the data presented. Therefore, the following analysis steps were carried out to determine a location for the measurement area and a time interval yielding stable conditions for each trial:

1. Identification of frequently occupied positions inside the geometry;
2. Time-space-analysis of any discontinuity by qualitative trajectory analysis;
3. Stationarity analysis of measured mean density $\bar{\rho}$, mean speed $\bar{v}$ and mean flow rate $\bar{J}$ in time series to define the start-, stationary- and end phase.
4. Analysis of averaged flow rates (simple moving average) during the stationary period detected in the previous step. Ensuring that no significant changes in standard deviations, or systematic components that changes over time and does repeat (trend) or not (short-term fluctuations) are recognisable (cf. e.g. Fig. A.7 and Fig. A.9 in App. A.3.5).
5. Qualitative analysis and proof of the video recordings.

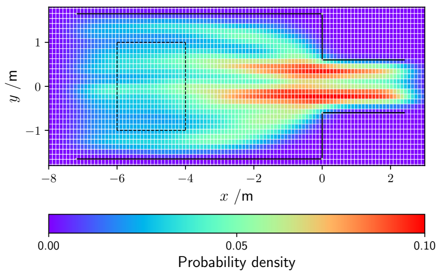
Initially, and to identify particularly attractive (often frequented) areas in the geometry, the averaged x- and y-position of all participants were analysed. The density distribution of the occupancy of a cell was estimated on a grid with a width of 0.1 m. If a part of the trajectory matches the particular bin, a weight is added to the surrounding bins following the Gaussian characteristic (contoured kernel-density-estimate). Figure 5.5 provides insights into the spatial characteristics of crowd motion considering a population without any disability (top row) and with participating wheelchair users (bottom row). As natural, the space directly in front of the bottleneck entrance is quite frequently occupied, whereas the occupancy decreases with increasing distance to the bottleneck entrance and is lowest to the edges of the boundaries. Analysing the study without disabled participants, a single lane is formed at smaller passage widths ($w = 0.9$ m, Fig. 5.5a) and the probability to form a second lane increases by a width of $w \geq 1.0$ m. However, this second lane does not have to be synchronised with the first. It rather means that the lanes are not formed at the same time, but that shifted movement is also possible. If wheelchair users participate, lower densities were observed in front of the bottleneck entrance independently of the passage width (Fig. 5.5c and Fig. 5.5d). Increasing the passage width ($w \geq 1.1$ m), the development of a second lane characterised by a noticeable lower intensity can be observed. It is conspicuous that the spatial spread of higher frequented areas in front of the bottleneck entrance is much more closely related to the boundary areas of the geometry. It suggests that the concentration of frequently occupied areas in case of participation of wheelchair users extends much further away from the bottleneck entrance and is distributed over a wider area (Fig. 5.5d). The lanes formed at the upper and lower borders of the geometry result from anticipated movement close to wheelchair users and leads to initialisation of an ordering process (Zipper-effect) directly in front of the bottleneck entrance (cf. Sec. 5.8 and in particular Fig. 5.18 on p. 80 for a deeper analysis of the occurrence of behavioural actions).

Second, the obtained trajectory data enable the analysis of individual movement in space and time (Fig. 5.6). Sequences of the trajectories with a slow instantaneous speeds ($v_i \leq 0.1\,\mathrm{m\,s^{-1}}$) as calculated by the Voronoi method (described in Sec. 4.2) are coloured in red. Data for the NDP population (top row), a subpopulation with wheelchair users (middle row) and a mixed, heterogeneous population (bottom row) are shown.

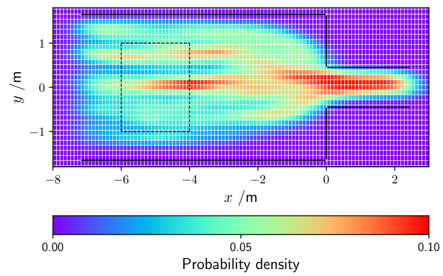
Movement characteristics of the NDP population are uniform and homogeneous for all analysed geometrical settings. All participants overcame the same distances at a similar time and without noticeable overtaking or clogging effects (Fig. 5.6, top row). Significant changes of uniformity in the movement were observed in front of the bottleneck for populations with wheelchair users and participants with mixed disabilities (Fig. 5.6, bottom row). Phases of reduced speeds occur more likely in cases where wheelchair users or mixed disabled participants are present. These phases propagate with a certain speed upwards the flow and are certainly related to the entrance of a participant with a disability at the bottleneck. Further on, phases of waiting and overtaking manoeuvres (crossing of trajectories) result in an inhomogeneous movement characteristic and, in consequence, in a situational change



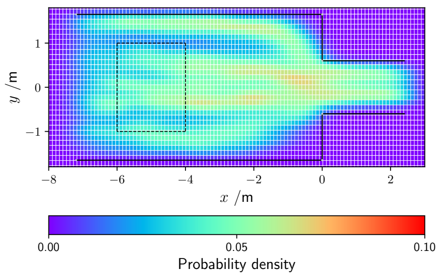
(a) *Bot_ref_01.*



(b) *Bot_ref_08.*



(c) *Bot_whe_01.*



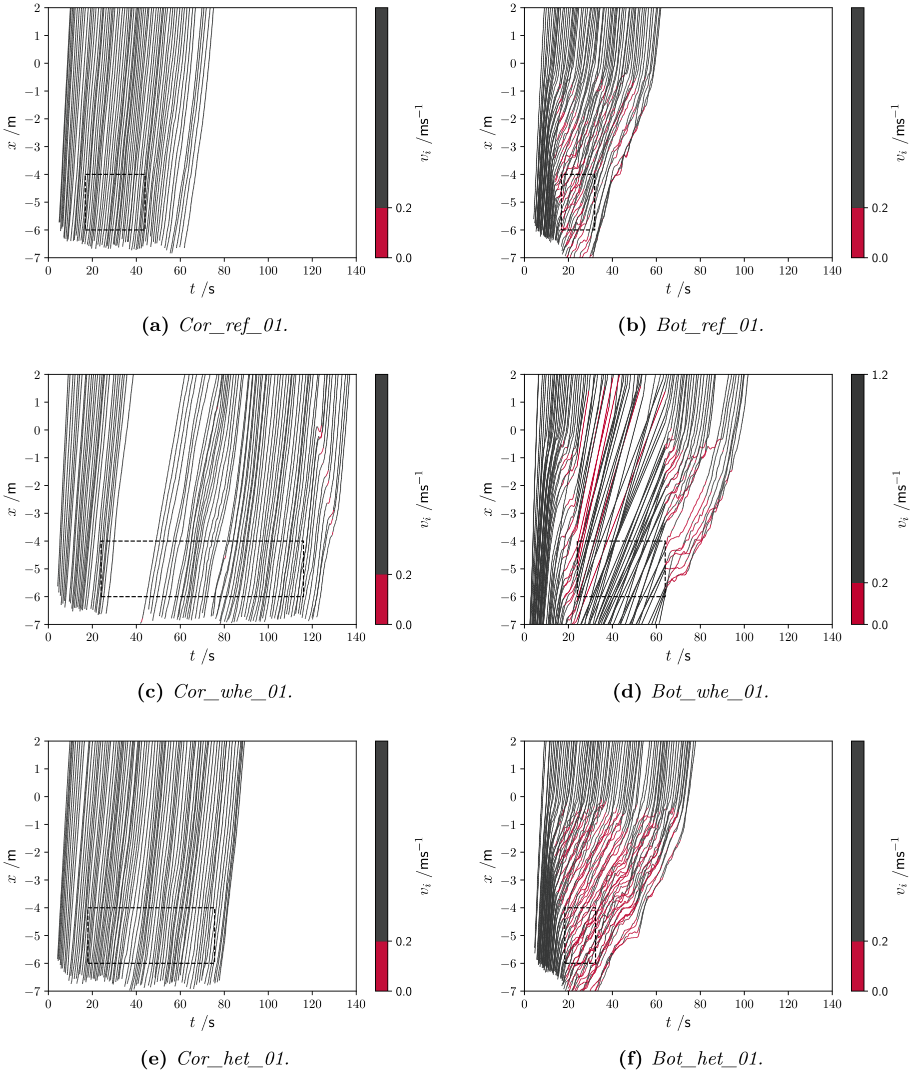
(d) *Bot_whe_08.*

Figure 5.5: *Smoothed distribution (grid size:* $0.1\,\mathrm{m}$*) of occupied areas in bottleneck situations with a width of* $w = 0.9\,\mathrm{m}$ *(left) and* $w = 1.2\,\mathrm{m}$ *(right) respectively. The density distribution (KDE) is presented for a population without any participants with disabilities (top row) and considering wheelchair users (bottom row). The measurement area is presented by the dashed black rectangle.*

of instantaneous speed dependent on the individual desired speed. This observation is in line with findings from a recently published study by Fujita et al. [224]. An increasing tendency to form clusters in heterogeneous crowds which is triggered by the slower moving participant is reported there and results in a relationship between heterogeneity and speed.

Third, such fluctuations become particularly visible by performing time series analysis on speed, density and flow rate (Fig. 5.7). Fluctuations are caused by the entrance situation of participants with disabilities, especially those who rely on an assistive device like a white cane or wheelchair and whose disability is overtly visible for others. In consequence, summary statistics of the time-dependent flow rate are characterised by significant changes (cf. Tab. A.8 in App. A.3.5).

While the data analysis conflicts with the demand for steady-state condition, a central aim of this dissertation is to compare the influences on movement characteristics by different types of population heterogeneities. Time series of heterogeneous populations are characterised by fluctuations, which are interpreted as a characteristic feature of the system and



(a) *Cor_ref_01.* **(b)** *Bot_ref_01.*

(c) *Cor_whe_01.* **(d)** *Bot_whe_01.*

(e) *Cor_het_01.* **(f)** *Bot_het_01.*

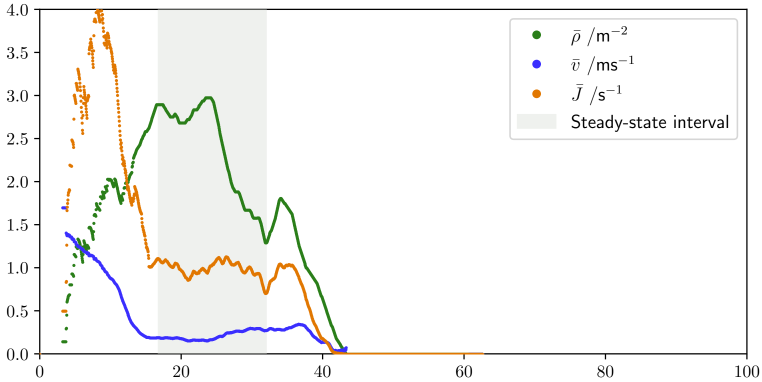
Figure 5.6: *Time-space plots for corridor (left) and bottleneck (right) situations ($w = 0.9\,\mathrm{m}$). Individual trajectories (movement in x-direction) are coloured by instantaneous speed v_i. Studies with the reference population (top line) and considering participants with disabilities (wheelchair users in the middle row or mixed and heterogeneous in the bottom line) are presented. The measurement area in space and time (stable time interval inside spatial measurement area) is presented by the black rectangle.*

therefore important for consideration in the analysis. This results in the analysis balancing considerations of data by disabled participants (fluctuating characteristic) and the need for stable conditions (steady-state condition).

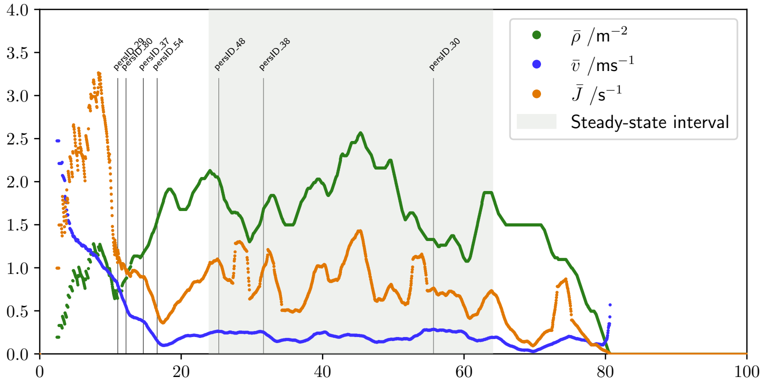
For this reason and following the methods used by [89, 99, 118, 139, 214, 225], intervals of relatively stable conditions were set manually for this analysis. It was realised by a qualitative time series analysis for density $\bar{\rho}$, speed $\bar{v}$ and flow rate $\bar{J}$ and results in different measuring intervals in time (cf. differences in the grey-coloured area in Fig. 5.7). In constant space-dimension the measurement area was set at a distance of 4.0 m to the bottleneck entrance (Fig. 3.6b and Fig. 3.8).

Overall, crowd densities $\bar{\rho}$ in a range between $2\,\mathrm{m}^{-2}$ and $3\,\mathrm{m}^{-2}$ were observed in all configurations (varied passage width and subpopulations) with slow average speeds and moderate flow rates. The latter can be justified by a manageable number of participants and as a result of the polite and considerate behaviour between participants. Since the participants were instructed to move straight but without rushing, it can be reasonably assumed that they were not motivated to quickly complete the study setup. Focussing on the development of a study without the participation of PWD over time, the measured performance criterion does not show remarkable fluctuations: the flow rate inside the measurement area increases after the start, then continues to a small steady-state condition plateau of approximately 10 s and decreases afterwards. The appearance of averaged values is harmonious without noticeable fluctuations (Fig. 5.7a). If subpopulations of PWD were considered, density increases within 25 s from initial density up to a local maximum and remains stable but fluctuating for approximately 40 s (Fig. 5.7b). A comparison of the flow rate and the related rolling standard deviation σ_{SMA} over a window of 2 s was used to define intervals of steady state conditions (cf. Tab. A.8 in App. A.3.5). While the temporal progress of the speed is stable even if PWD participate, the appearance of the time-dependent fluctuations is remarkable for the results in average density and flow rate (cf. for instance at time 30 s or 55 s in Fig. 5.7b). Such fluctuations are caused by the entrance manoeuvring actions of wheelchair users into the bottleneck. Hardly any changes are observable across the entire study regime.

In consequence, the process to obtain the empirical relations $v(\rho)$ and $J(\rho)$ for heterogeneous crowds must consider the data of PWD (which are characterised by fluctuations) and results in, fourth, significant changes of the statistics, in particular the covariance. Lastly, the resulting intervals of stationary conditions were proved by qualitative analysis for special features in the video recordings. The final resulting steady-state intervals used for further analysis are presented in Tab. A.7 in App. A.3.5.



(a) *Bot_ref_01.*

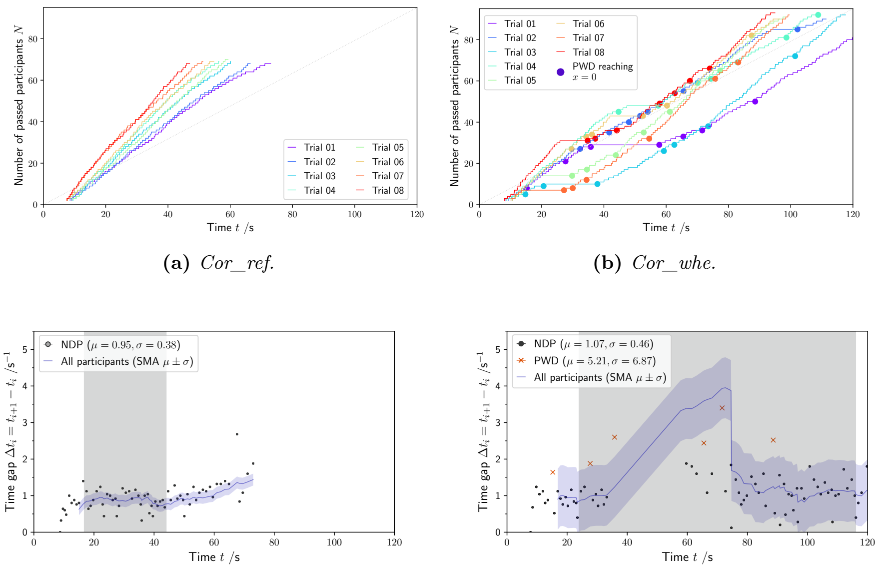


(b) *Bot_whe_01.*

Figure 5.7: *Time series of $\bar{\rho}(t)$, $\bar{v}(t)$, and $\bar{J}(t)$ as moving averaged over a time interval of 2 s for bottleneck configurations with a passage width of 0.9 m. A reference population (a) and a subpopulation of wheelchair users (b) is considered. The time of entry into the measurement area of a PWD is emphasised by the vertical lines and the related persID is presented. The period of assumed stationary flow conditions is presented by the grey-coloured area. For a more detailed description of the characteristics of the persID see App. A.3.2.*

5.5 Individual Time Gap

The interpersonal time gap Δt_i between the passage of a measurement line by a participant and his predecessor is analysed to describe the macroscopic flow rate according to Sec. 4.4. The number of participants passing a line as a function of time is displayed for a corridor situation with and without the presence of a population of wheelchair users in Fig. 5.8a and Fig. 5.8b. Horizontal time gaps display the time interval without passage of the measurement line at $x = 0$. A salient feature is the increased variation between the different population settings: It is visible, that participants using wheelchairs have a higher time distance to the predecessor than participants without impairments (cf. the coloured dots for passage time of PWDs in Fig. 5.8b and Fig. C.1 - Fig. C.2 in App. C.1 for additional subpopulations).



(a) *Cor_ref.* **(b)** *Cor_whe.*

(c) *Cor_ref_01.* **(d)** *Cor_whe_01.*

Figure 5.8: *The number of participants N passing a measurement line ($x = 0$) at time t in all corridor studies (top row) with wheelchair users (right column) and without any participants with impairments (left column). The time when a PWD has reached the bottleneck entrance in (b) is depicted by the scatter points.*
A comparison of individual passage time gaps Δt_i for a specific trial with a passage width of $0.9\,\mathrm{m}$ considering participants in wheelchairs (right) and without any disabilities (left) is presented at the bottom row. Individual time gaps of participants with disabilities are highlighted in orange markers, the interval used for capacity analysis is coloured in light grey. The 2σ-interval of the overall average time gap is blue coloured.

Figure 5.8c and Fig. 5.8d present a comparison of time gap analyses for a corridor geometry with regard to participation of wheelchair users and a corresponding passage width of

0.9 m. The complete results of the individual time gap analysis for bottleneck and corridor settings are presented in Tab. C.1 in App. C.1. It is shown (cf. differences in the vertical position between black and orange markers), that using a wheelchair increases the individual distance headway.

While it is understandable that a participant using an assistive device requires an increased time to navigate through a bottleneck, reasons for differences in individual time gaps Δt_i for other PWDs are as diverse as the individual characteristics (cf. App. A.3.2 for a detailed description of all participants with disabilities).

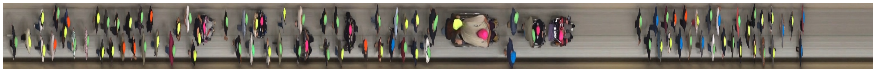
First, wheelchair users tend to reduce their speed during movement in crowded situations because of their spatial boundaries, required static space, longer stopping time, slower response time and, risk of injury in collisions. They increase the distance to the predecessors over time which results naturally in increased time gaps over long distances.

The passage width was expanded during the study from 0.9 m up to 1.2 m in increments of 0.1 m. Assuming a minimum width of 0.8 m for a wheelchair and in accordance to the German standard DIN 18040, which requires a minimum width of 0.9 m for movement without change in direction in publicly accessible buildings [206, Fig. 1], the additional cross-sectional area generated by the increments used are too small to increase the speed and decrease the passage time.

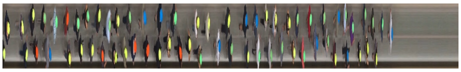
Second, orientation, manoeuvring and navigation through narrow geometries are challenging for PWD. Using assistive devices like white canes, tactile sticks or being assisted by a caregiver leads to slower speeds and increased distances to predecessors (see the increased lateral distance between PWD and NDP in Fig. 5.9a and Fig. 5.9c). This is supported by the observation that NDP actively ensures that the movement area around the person with the assistive device remains free. Especially in case of bottleneck situations, increased interaction and communication between participants with visible disabilities and using assistive devices and non-disabled-participants was noticed (cf. discussion in Sec. 5.8).

Third, the movement for participants with walking disabilities depends on the individual ability to move and less on geometrical boundary conditions. A slightly increased distance to a predecessor over movement time is observable which leads to slightly longer averaged time gaps at the measurement line, as a result of their individual characteristic and their slower possible speeds (cf. Fig. 6.5 in Sec. 6.3).

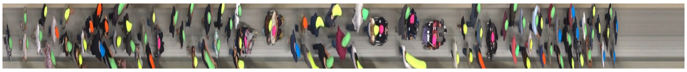
A comparison of individual passage time gaps Δt_i is presented in Fig. 5.10. In general, smaller averaged time gaps $\bar{\Delta t_i}$ were observed in bottleneck situations for populations considering wheelchair users and participants with mixed disabilities, while for other populations $\bar{\Delta t_i}$ is comparable. Increased $\bar{\Delta t_i}$ in corridor situations are accompanied by noticeable higher variances (Fig. 5.10a). As the passage width increases from left to right in each crowd heterogeneity condition, a slight relation between passage width and mean time gap is recognizable for all populations. Analysing the bottleneck situation, the scatter



(a) *Corridor situation ($w = 1.2\,\mathrm{m}$) considering $\approx 10\,\%$ participants using wheelchairs.*



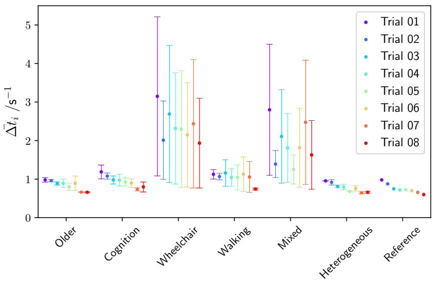
(b) *Corridor situation ($w = 1.2\,\mathrm{m}$) without participation of PWD.*



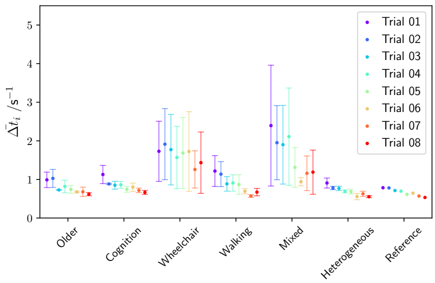
(c) *Bottleneck situation ($w = 1.2\,\mathrm{m}$) considering $\approx 10\,\%$ participants using wheelchairs.*

(d) *Bottleneck situation ($w = 1.2\,\mathrm{m}$) without participation of PWD.*

Figure 5.9: *Spatio-temporal relation for corridor and bottleneck situations with and without the participation of wheelchair users. A sequence of sample images is presented which were extracted at $x = 0.0$ with a frequency of $25\,\mathrm{s}^{-1}$. Each sample image has a length of 1 px. Movement direction is from left to right and all pictures are from the same time scale. The visualisation method is based on an idea of [226, 227].*



(a) Δt_i *for corridor studies.*

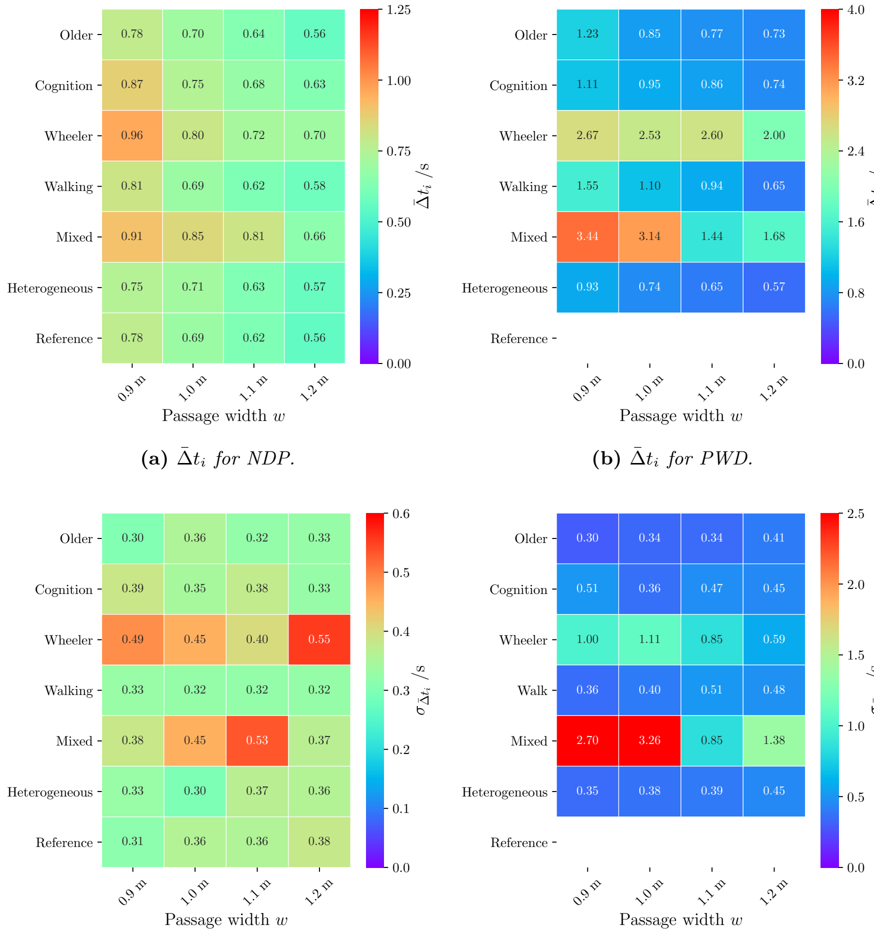


(b) Δt_i *for bottleneck studies.*

Figure 5.10: *Comparison of mean individual passage time gaps Δt_i and standard deviation depending on geometry, passage width and population. Increased variances are noticeable for all passage widths if participants in wheelchairs, walking disabled or heterogeneous disabled participants were part of the crowd.*

for wheelchair users, walking and mixed disabled participants is still noticeably higher than in other populations; however, the tendency of reduced averaged time gaps decreases with increasing width. An increase of passage width may increase the standard deviation of the averaged time gap for the NDP (Fig. 5.11c), which may indicate an intensified ordering process between the subpopulations. It turns out, that the averaged time gaps of participants belonging to populations with disabilities are up to four times as high (Fig. 5.11a and Fig. 5.11b). Noticeable differences in the standard deviations of the mean time gaps $\sigma_{\bar{\Delta t_i}}$ of the disabled and the non-disabled populations in both geometrical settings are remarkable for the studies consisting of wheelchair users and mixed populations. This leads to an increased range of the averaged distance headway (see for instance the blue coloured range in Fig. 5.8d) for heterogeneous populations.

In summary, the interpersonal time gap Δt_i between non-disabled-participants and participants with disabilities increases if the disability of a participant leads to significantly reduced speeds (and in consequence to an increased distance to predecessors). On the other hand, the visibility of a disability may support larger distances of NDP to PWD. Therefore, time gaps are an important indicator to describe the interactions between participants of different subpopulations and it is furthermore the basis to quantify the specific flow (cf. Sec. 4.4). The increased averaged time gaps $\bar{\Delta t_i}$ for some subpopulations are a consequence of the (social) behaviour and speed adjustments described in Sec. 5.6 and Sec. 5.8. Participants with overtly visible disabilities (in this case wheelchair users and people with tactile sticks in the mixed population) arrange the priority of entry into the bottleneck with other NDP. The coordination process between the two subpopulations starts further away from the bottleneck entrance and requires more time. This communication and coordination process leads to an increased required passage time and higher interpersonal distances through deceleration during braking and acceleration. In result, the mean passage time gap $\bar{\Delta t_i}$ of populations with disabilities is up to four times as high (Tab. 6.2) and should be considered separately in flow rate calculation methods.



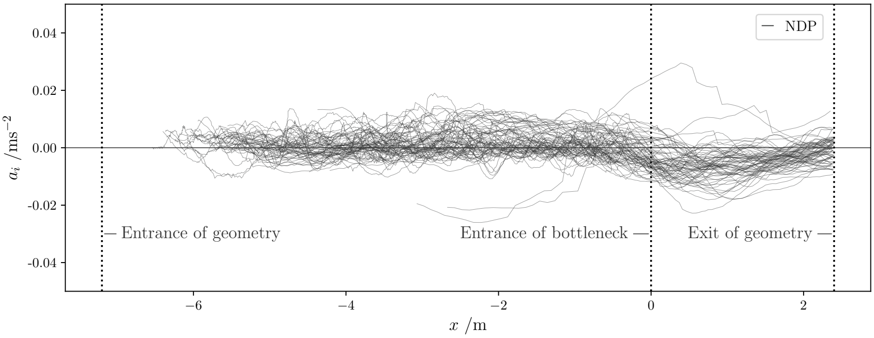
(a) $\bar{\Delta}t_i$ *for NDP.* **(b)** $\bar{\Delta}t_i$ *for PWD.*

(c) $\sigma_{\bar{\Delta}t_i}$ *for NDP.* **(d)** $\sigma_{\bar{\Delta}t_i}$ *for PWD.*

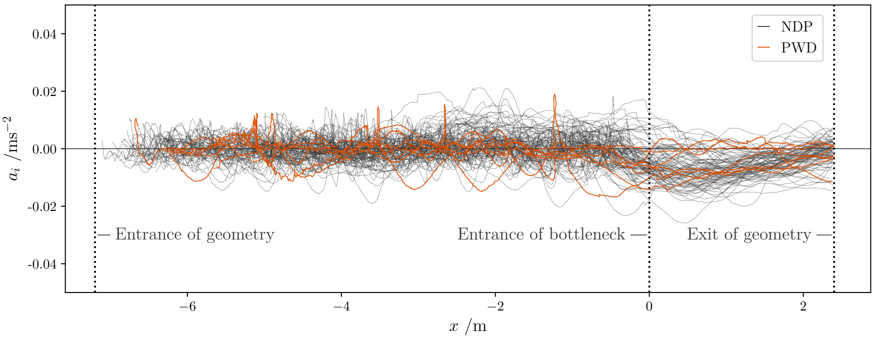
Figure 5.11: *Mean time gap* $\bar{\Delta}t_i$ *(top) and standard deviation of mean time gap* $\sigma_{\bar{\Delta}t_i}$ *(bottom) for NDP (left) and PWD (right) subpopulations according to their disability and depending on the passage width for a bottleneck. Please note the different scaling of the colorbar for the PWD and NDP population.*

5.6 Adaptation of Speed

The pattern of pedestrians' movement through (artificial) geometries is not constant for the conducted studies but characterised by fluctuations. The individual movement contains phases of acceleration and deceleration. Figure 5.12 shows an example for a bottleneck trial with (Fig. 5.12b) and without participation (Fig. 5.12a), where the averaged difference in individual acceleration a_i according to a time interval of 1 s is presented. Individual adjustments in speed were maintained to avoid collisions with walls, to maintain preferred distances to neighbours or to reduce gaps in space or time.



(a) *a_i for Bot_ref_08.*



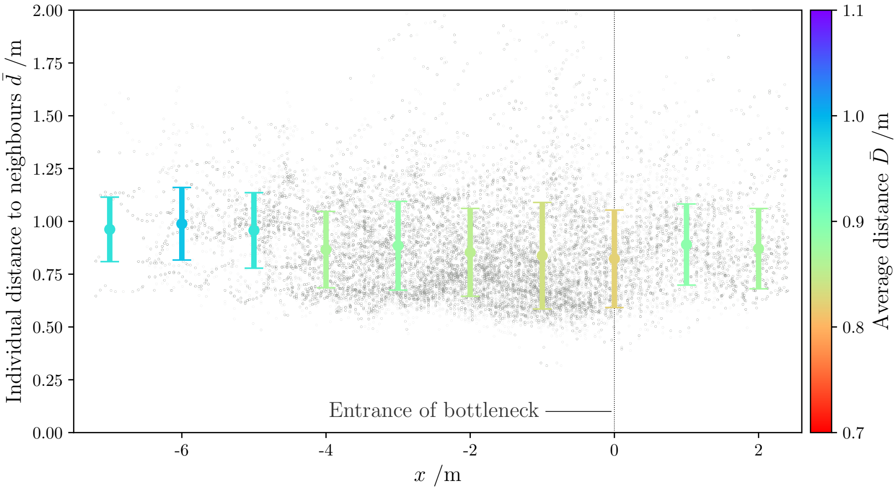
(b) *a_i for Bot_whe_08.*

Figure 5.12: *Individual acceleration a_i depending on x-position in a bottleneck situation ($w = 1.2$ m) without participation of PWD (top) and with participation of wheelchair users (bottom). The acceleration is calculated as average for an interval of 1 s.*
$\bar{a}_i > 0$: acceleration, $\bar{a}_i < 0$: deceleration.

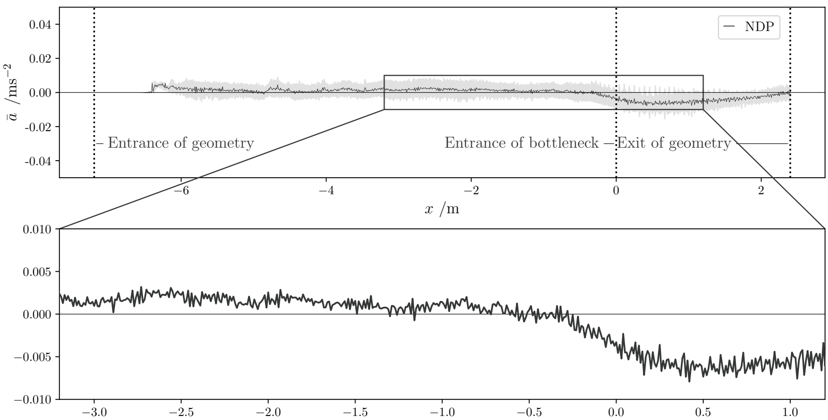
Stationary states in the time series were hard to identify because the individuals move at different speeds, especially depending on their need for assistance and depending on the location in the experimental setting. Qualitatively, three distinct regions were identified. Participants with disabilities were overtaken by faster participants without disabilities between the waiting area and the entrance to the geometry. Then, within the geometry at approximately $x = [-6.0, -3.0]$m, the speed of PWD and NDP was uniform. About 2 m in front of the bottleneck entrance the cooperative process of arranging occurred. From this point, the acceleration behaviour differs again. Therefore and to identify a proper measurement area, the accelerations were analysed concerning the individual x-position to identify areas of speed adaptation and to ensure that the selected measurement areas are not disproportionately influenced by the dynamic ranges.

In the case of reducing the passage width in the bottleneck situation, a global reduction of the speeds by approximately 1.0 m in front of the bottleneck entrance was observed for the overall population to support the entrance manoeuvring (Fig. 5.13b). Analysing the same configuration with the participation of wheelchair users, the location of speed reduction differs regarding to the population characteristics (Fig. 5.14b). While the location of speed reduction is constant for the overall NDP-population, an additional local minimum of the average acceleration was observed for wheelchair users at approximately 3.0 m, 2.2 m and 1.0 m in front of the bottleneck. It is related to the area where the interaction between PWD and NDP most frequently occur (cf. Fig. 5.18 on p. 80 as an example) and where distances between Delaunay neighbours D are maintained (c.f. description in App. C.2 to identify Delaunay neighbours). While distances between neighbours for NDPs decrease towards the bottleneck entrance (Fig. 5.13a), slightly increasing Delaunay distances between neighbours were observed in heterogeneous populations (Fig. 5.14a). From an in-depth analysis of each trial, wheelchair users tend to slow down at a larger distance before the entrance manoeuvre into the bottleneck than NDPs. In general, participants with disabilities reduce the distances to their neighbours up to about 3 m m before the bottleneck. In this area, interactions and gestures between the participants can be observed. As the proximity to the bottleneck increases, the distance increases again. The share of people without disabilities in this group keeps their distances to neighbours constant: The participants without disabilities align their speed with the PWD in front. They move closer to the bottleneck entrance and reduce their speed more slowly before the entrance is communicatively arranged (Fig. 5.14b). The differences in speed adoption between the groups result from polite behaviour and priority gestures. In consequence, the location where speed changes were detected, depends rather on interpersonal situation and interaction than on x-position (see a detailed comparison of averaged interpersonal distances between neighbours depending on the population in App. C.2).

The averaged acceleration $\bar{a}$ for the NDP population is comparable over all conducted studies and variations of passage widths. In general, the scatter of the averaged acceleration and the standard deviation is larger for PWD than for NDP. In particular, the older, cognition disabled and heterogeneous populations are characterised by large standard deviations in the change of speed, while the standard deviation of the acceleration of wheelchair users



(a) *Distance to neighbours Bot_ref_08.*

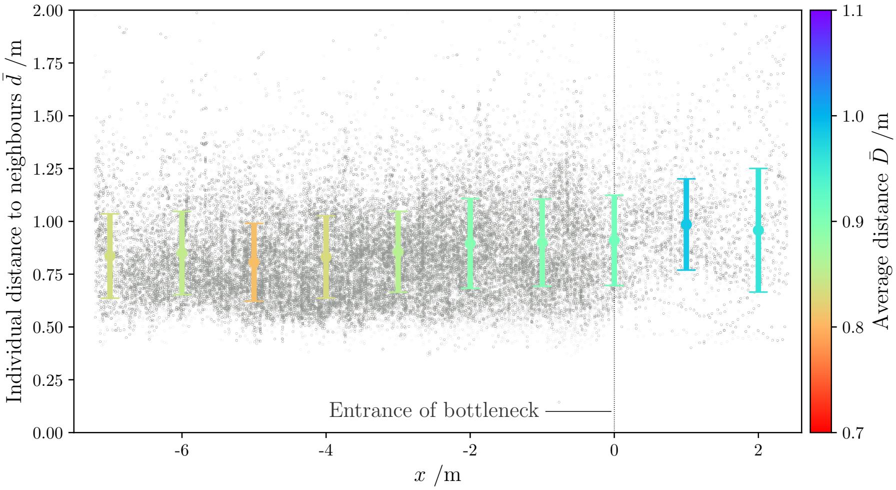


(b) $\Delta\bar{v}_i$ *for Bot_ref_08.*

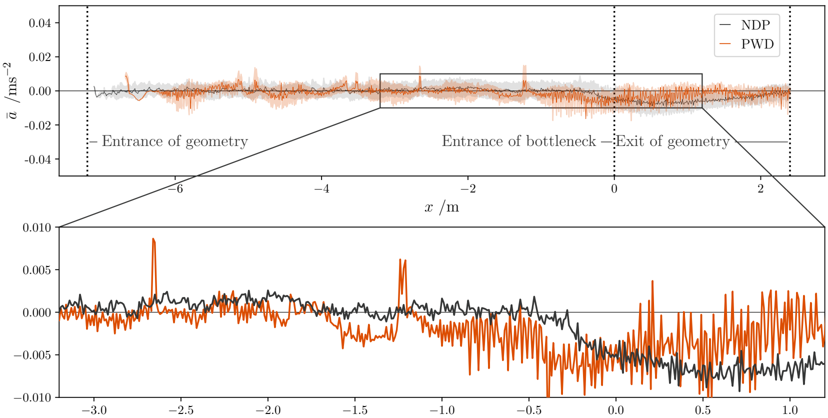
Figure 5.13: *Distance to neighbours and average acceleration in a study without the participation of participants with disabilities depending on x-position in a bottleneck with a passage width of* 1.2 m*. The averaged acceleration* $\bar{a}_i$ *and the associated standard deviation is calculated as rolling mean of* a_i *over* 1 s*. Please note that only* a_i *is presented in the zoomed plot.*

in the bottleneck configuration tends to be lower than other PWD populations. This indicates that the influence of the type of wheelchairs on the speed decreases with increasing passage width compared to other studies.

Analysing the individual characteristics of PWD, different movement patterns concern-



(a) *Distance to neighbours for Bot_whe_08.*



(b) $\Delta\bar{v}_i$ *for Bot_whe_08.*

Figure 5.14: *Distance to neighbours and average acceleration with PWD depending on x-position in a bottleneck with a passage width of* 1.2 m*. The averaged acceleration* $\bar{a}_i$ *and the associated standard deviation is calculated as a rolling mean of* a_i *over* 1 s *for the population of PWD or NDP respectively. Data for PWD is coloured in orange, data for NDP is coloured in black. Please note that only* a_i *is presented in the zoomed plot.*

ing the assistive device used were observed, e.g. difference in acceleration of wheelchair users was in some cases approximately constant, in other cases, they were characterised by high fluctuations. These differences result from different modes of movement: first, some wheelchair users push and control wheelchairs on their own, others were operated by pushers. The uniformity of the movement, especially with the position of the head, influences the noise of the tracking position and in consequence the derived acceleration a_i of an individual. In particular, if wheelchairs were self-operated, the position of the head frequently changed due to compensatory movement of the body. And, second, electrically operated wheelchairs are characterised by inertia due to the delay in the control which may result in a smoothed signal.

5.7 Capacity Analysis for Corridors Depending on Population

A capacity analysis for corridors is presented to investigate the impact of heterogeneous crowd conditions (combination of non-disabled and disabled participants) on performance criteria for movement in built environments. The analysis of the fundamental relationship of $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$ derived from the steady-state intervalls described in Sec. 5.4 for unidirectional movement is examined in this section. Measures depending on the passage width and population are presented as simple moving averages (SMA) for a period of 2 s (which corresponds to 50 frames) and standard deviations. The resulting empirical relations $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$ of heterogeneous crowds are based on the space-time-mean method (Sec. 4.3) and are presented in Fig. 5.15 and Fig. 5.16. For the sake of clarity and to emphasise the principles, this section presents only empirical relations for populations with wheelchair users (Cor_whe) compared to the reference population without PWD (Cor_ref). The overall data for each experimental trial is presented by the scatter, supplemented by the coloured two dimensional (Gaussian) density contours of the data. The one-dimensional distribution of speed and density or, respectively, the flow rate and density are presented at the margins. As a result of polynomial regression, two fits are provided:

1. the most commonly used Kladek-relation [228] which describes the speed v related to the density ρ and the constants v_0, γ and ρ_{max} is used to fit data of the empirical studies (Eq 5.1). A similar procedure has been used by the research of [94, 229].

$$v(\rho) = v_0 \cdot \left(1 - \exp\left(\gamma \cdot \left(\frac{1}{\rho} - \frac{1}{\rho_{max}}\right)\right)\right) \qquad \text{(Eq 5.1)}$$

with

v_0 = unimpeded (free) speed (obtained from Tab. 5.1 on p. 53)

γ = calibration constant (obtained from regression analysis in Sec. 5.7 and Sec. 5.8)

ρ_{max} = jam density (set as constant to $\rho_0 = 5.4\,\text{m}^{-2}$)

2. Speed v as a weighted polynomial function of ρ with four degrees of freedom, described by the parameters a, b, c and d (Eq 5.2).

$$v(\rho) = a \cdot \rho^3 + b \cdot \rho^2 + c \cdot \rho + d \qquad \text{(Eq 5.2)}$$

The empirical relations for the other conditions of heterogeneity can be found in the App. B.1.

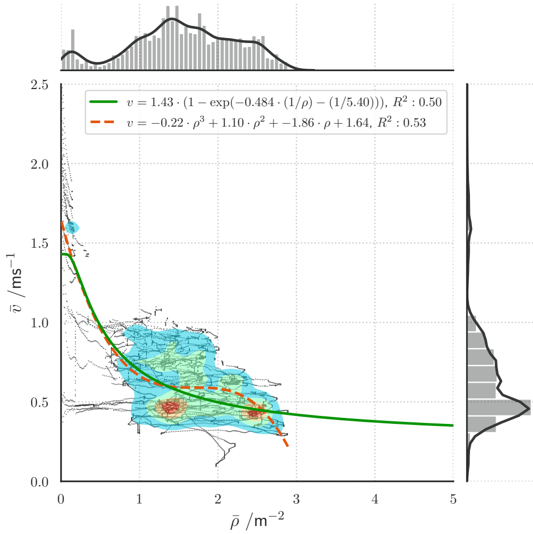
A dependency between density and speed is confirmed for all corridor studies. It is standing out, that a predominant density interval is increased for the participation of disabled subpopulations. It is $1.2\,\mathrm{m}^{-2} \leq \bar{\rho} \leq 2.3\,\mathrm{m}^{-2}$ for corridor studies with NDP and $0.7\,\mathrm{m}^{-2} \leq \bar{\rho} \leq 3.0\,\mathrm{m}^{-2}$ for corridor studies with wheelchair users. This is accompanied by a predominant interval of speed of $0.5\,\mathrm{m\,s}^{-1} \leq \bar{v} \leq 0.9\,\mathrm{m\,s}^{-1}$ for a population of NDP (Fig. 5.15b) and of $0.3\,\mathrm{m\,s}^{-1} \leq \bar{v} \leq 0.9\,\mathrm{m\,s}^{-1}$ for a population considering wheelchair users (Fig. 5.15a).

Since the averaged speed during the steady-state intervall for participants in the reference study is $0.78 \pm 0.09\,\mathrm{m\,s}^{-1}$, the averaged speed for the NDP with presence of wheelchair users is decreased to $(0.58 \pm 0.11\,\mathrm{m\,s}^{-1})$. The averaged speed for the participants using wheelchairs is reduced to $0.62 \pm 0.22\,\mathrm{m\,s}^{-1}$ compared to the unimpeded speed (for findings on other subpopulations cf. the summary in Fig. 6.5 in Sec. 6.3). It is quite obvious that variances in speed increase with increasing heterogeneity, especially for participation of wheelchair users, mixed population and multiple disabled (heterogeneous) populations, while the median of speeds between populations across the studies are similar. This observation is reasonable against the background that the corridor had a maximum width of 1.2 m. While overtaking is not possible in the corridor geometry, the individual speed is determined by preceding participants and with high impact on the individual characteristic of a specific PWD (cf. Ta. A.5 in App. A.3.2 for an extended narrative description of the participants' characteristics).

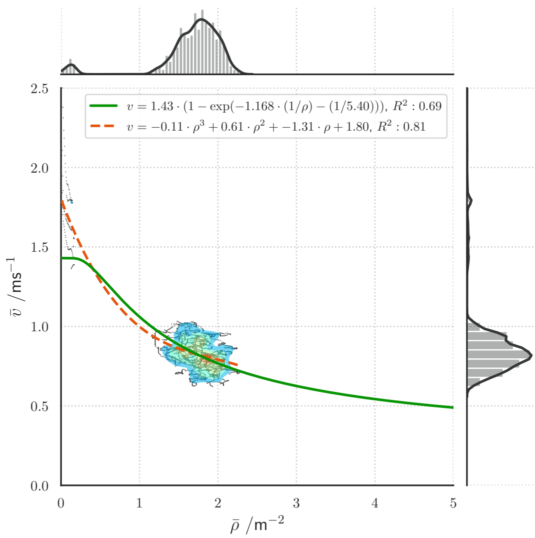
The comparison of the empirical relation $\bar{J}(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ using the space-time-mean method for a heterogeneous population considering wheelchair users and a homogeneous population without any disabled participants is presented in Fig. 5.16. In general, the form of $\bar{J}(\bar{\rho})$ is similar to previously published studies and characterised by a branch of an increasing flow rate with increasing density. The maximum flow rate (specific capacity J_c) and a decrease of flow rate follows (cf. Fig. 2.4 in Sec. 2.3).

The characteristic point of specific capacity J_c was reached for each population in the corridor studes. It ranges from $1.40\,\mathrm{m}^{-1}\,\mathrm{s}^{-1} \leq J_c \leq 1.73\,\mathrm{m}^{-1}\,\mathrm{s}^{-1}$ in a density range of $1.84\,\mathrm{m}^{-2} \leq \rho_c \leq 2.21\,\mathrm{m}^{-2}$. Even more, the corresponding specific densities ρ_c depend on the population in corridor trials. While $J_c = 1.46\,\mathrm{m}^{-1}\,\mathrm{s}^{-1}$ for a heterogeneous crowd condition (population with wheelchair users) is reached at a density of $\rho_c = 1.81\,\mathrm{m}^{-2}$, the maximum capacity for a homogeneous crowd condition (population without any disabled participant) is $J_c = 1.73\,\mathrm{m}^{-1}\,\mathrm{s}^{-1}$ at a density of $\rho_c = 2.10\,\mathrm{m}^{-2}$.

To sum up, a qualitatively comparable relationship between speed and density was observed, also taking heterogeneity of the population characteristics into account. However, the characterising points relevant for the assessment of facilities performance shifted significantly. In some cases capacity was not reached due to limited population size. A summary of the thresholds for all population configurations is presented in Tab. 6.2 on p. 94.

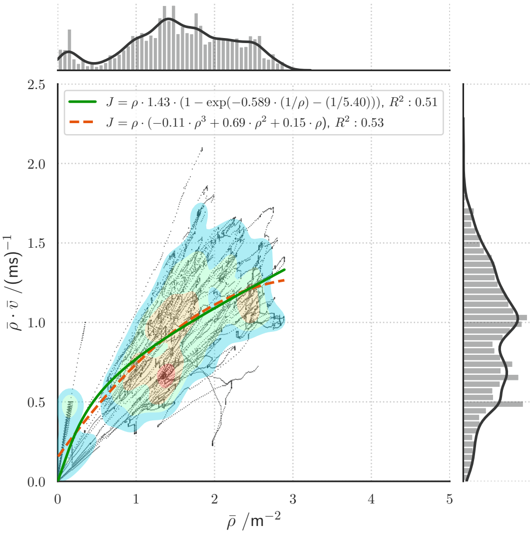


(a) $\bar{v}(\bar{\rho})$ *considering wheelchair users in a corridor.*

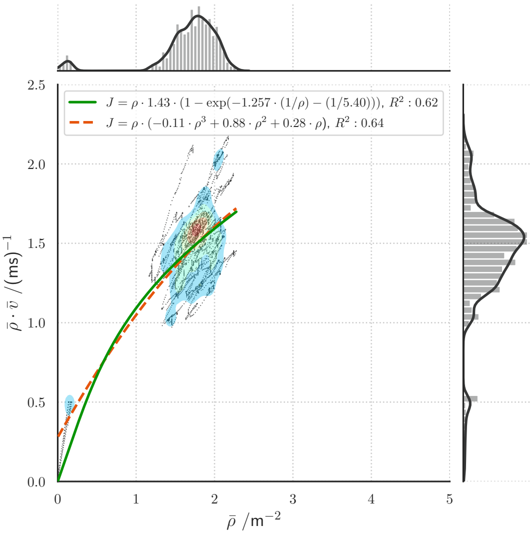


(b) $\bar{v}(\bar{\rho})$ *without PWD in a corridor.*

Figure 5.15: *Empirical relation $\bar{v}(\bar{\rho})$ for corridors in heterogeneous crowd conditions with participants using wheelchairs (a) and homogeneous crowd conditions (b) with a population consisting of participants without disabilities. Data is presented as Gaussian Kernel Density Estimation using five gradients. Additionally, the distribution of speed and density is shown at the grid's margins. Fitted results according to the Kladek-relation and as a weighted polynomial function are presented.*



(a) *$\bar{J}(\bar{\rho})$ considering wheelchair users in a corridor.*



(b) *$\bar{J}(\bar{\rho})$ without PWD in a corridor.*

Figure 5.16: *Empirical relation $\bar{J}(\bar{\rho})$ for corridors in heterogeneous crowd conditions with participants using wheelchairs (a) and homogeneous crowd conditions (b) with a population consisting of participants without disabilities. Data is presented as Gaussian Kernel Density Estimation using five gradients. Additionally, the distribution of speed and density is shown at the grid's margins. Fitted results according to the Kladek-relation and as a weighted polynomial function are presented.*

5.8 Capacity Analysis for Bottlenecks Depending on Population

Following the classification of complexity of movements by Shi et al. [2], an increased level of complexity that includes phenomena like internally driven movements in multi-lane pedestrian traffic, self-slowing and group queueing is reached in egress situations (bottlenecks). In analogy to the procedure in Sec. 5.7, a capacity analysis is provided for the movement of crowds in heterogeneous conditions through bottlenecks.

The analysis of fundamental relationship between $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$ derived from the steady-state intervalls described in Sec. 5.4. Measures are presented as simple moving averages (SMA) for a period of 2 s and standard deviations. The resulting empirical relations $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$ of heterogeneous crowds through bottlenecks based on the space-time-mean-method (Sec. 4.3) are presented in Fig. 5.17 and Fig. 5.19. Only empirical relations for populations with wheelchair users (Bot_whe) compared to the reference population without PWD (Bot_ref) are presented. Empirical relations for the other population combinations can be found in App. B.2.

Analysing the empirical relation $\bar{v}(\bar{\rho})$ for the bottleneck situation regarding homogeneous crowd conditions (population without participants with disabilities) shows a predominant interval of slowed speeds in a range of $0.1\,\mathrm{m\,s^{-1}} \leq \bar{v} \leq 0.2\,\mathrm{m\,s^{-1}}$ with an averaged individual speed of $0.22 \pm 0.05\,\mathrm{m\,s^{-1}}$ and a corresponding density interval of $1.0\,\mathrm{m^{-2}} \leq \bar{\rho} \leq 2.9\,\mathrm{m^{-2}}$ (Fig. 5.17b). Comparing the heterogeneous crowd condition, the individual speed is independent of the density if wheelchair users are part of the crowd (Fig. 5.17a). An averaged speed of $0.21 \pm 0.03\,\mathrm{m\,s^{-1}}$ was measured for NDP and $0.18 \pm 0.05\,\mathrm{m\,s^{-1}}$ for participants using a wheelchair. The independence of speed from density occurs in crowd conditions in which people participate, whose impairments are overtly visible to other participants. In particular, if wheelchair users and participants with multiple disabilities become part of the crowd (see a narrative description of participants of these experimental trials in App. A.3.2). A combination of a participant's familiarity and the visibility of the need for assistance to others leads to communicative, considerate behaviour between participants in wheelchairs and participants without disabilities. This may indicate an increased solidarity, caused by a '[. . .] strong feeling of social identification [. . .]' ([230, p. 2]).

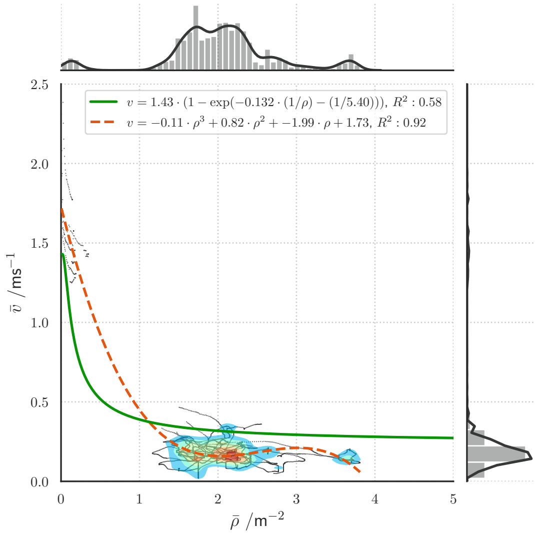
Against the background of a shared identification belonging to a population and, assuming that participants are influenced by neighbours, an area of interaction is observed [86]. Co-operative behaviour has a price (e.g. a reduced speed and, in consequence, a delayed passage of the bottleneck), but may also lead to positive feedback from the group and increases the chance of receiving help from others [231, 232, p. 495]. It is reasonable, that participants with disabilities and their neighbours may be part of a psychological crowd in a bottleneck situation, which shares some additional characteristics like slower speeds and considerate behaviour [233]. Such effects may explain the results and keep them in line with findings of empirical studies, where increased solidarity was reported if a strong social identity was observed [230]. Please note, that the studies were designed due to a comparison of empirical relations and therefore measurement of social interaction was not methodically considered in the study design. Besides that, additional measurement tools are available, which measure the tendency of an individual to behave in a social or altruistic manner, e.g. the Social Value Orientation [234] as used in [230, 235].

Subgroups of PWD and NDP interact and solve priority of movement by communication actions as illustrated by Fig. 5.18. As a result, the speed of NDP is locally and temporally adjusted to the speed of the slower moving wheelchair users [23, 236]. This impacts both, the number of neighbours and the interpersonal distance between neighbours (cf. App. C.2).

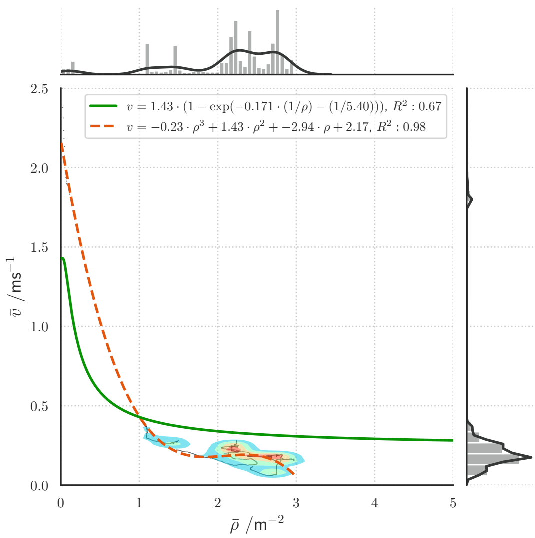
PWD may classify here as slow-moving obstacles. The slower speed of the individual results in a qualitative modification of the trajectory. Such behaviour-dependent interactions increase the complexity of the scenario. The system of movement thus becomes more heterogeneous (cf. Fig. 5.6). While the capacity analysis of a bottleneck situation with homogeneous crowd conditions (participants without disabilities) does not reach the capacity point (similar results were observed for studies with older and heterogeneous disabled populations), in contrast, a J_c of $1.16\,\mathrm{m}^{-1}\,\mathrm{s}^{-1}$ is observed at a density of $\rho_c = 2.57\,\mathrm{m}^{-2}$ if wheelchair users are considered.

If participants with increased space requirements, e.g. participants assisted by wheelchairs, are inside the measuring area, higher densities occur upstream, since overtaking manoeuvres are avoided, while low densities are measured in front of PWD due to their slower speed and the resulting increased distance to predecessors (cf. comparison of individual time gaps in Fig. C.2). The social behaviour described above not only leads to an adaptation of the speed but also yields areas characterised by higher densities and fluctuations in the flow rate. These fluctuations lead to high, short-term variations in the speed of individual participants.

An estimation of the influence of heterogeneity on empiric relations is not easily feasible. The well-controlled system of variables in unidirectional movement is altered here by additional degrees of freedom because of different individual space requirements, variable (social) distances and interactions. This results in a complex dynamic system where the influence of a (controlled) variable (e.g. density) on speed or flow rate is no longer affected by itself. The influence of individual behaviour in dealing with neighbours is becoming more significant. This is because the individual perception about the participation of PWD supports local accelerations and influences distances to neighbours. As a result, the available space is used less evenly and the density is distributed more heterogeneously. Particularly in the case of bottlenecks, the time, required for cooperation to manage the entrance to the bottleneck entrance, increases. As a result, the speed, especially in low-density situations, is even less determined by physical forces alone [237].



(a) $\bar{v}(\bar{\rho})$ *considering wheelchair users in a bottleneck.*

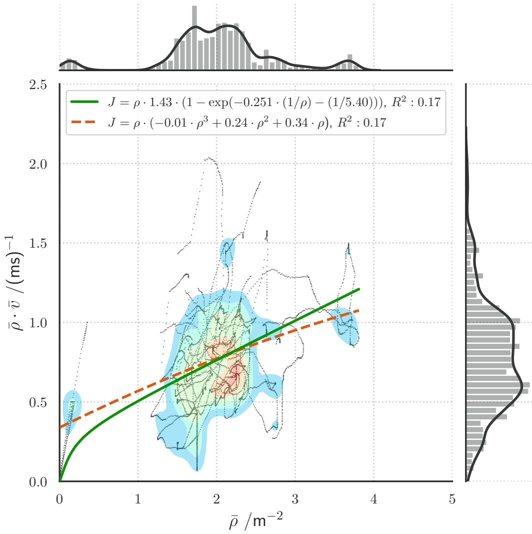


(b) $\bar{v}(\bar{\rho})$ *without PWD in a bottleneck.*

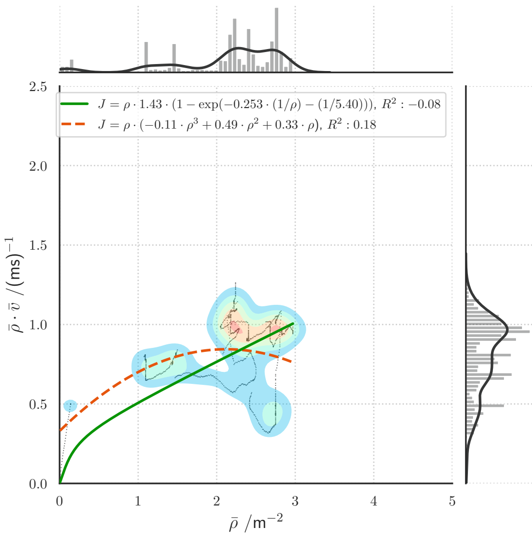
Figure 5.17: *Empirical relation $\bar{v}(\bar{\rho})$ for bottlenecks in heterogeneous crowd conditions with participants using wheelchairs (a) and homogeneous crowd conditions (b) with a population consisting of participants without disabilities. Data is presented as Gaussian Kernel Density Estimation using five gradients. Additionally, the distribution of speed and density is shown at the grid's margins. Fitted results according to the Kladek-relation and as a weighted polynomial function are presented.*

(a) $t = 15\,\mathrm{s}, x = -3.6\,\mathrm{m}$. **(b)** $t = 21\,\mathrm{s}, x = -1.2\,\mathrm{m}$. **(c)** $t = 25\,\mathrm{s}, x = 0.0\,\mathrm{m}$.

Figure 5.18: *Exemplary considerate behaviour in a bottleneck situation with heterogeneous crowd conditions (participation of wheelchair users). Sample images were taken at* $t = [15, 21, 25]\,\mathrm{s}$ *at different x-positions (black dotted line for* $x = [-3.6, -1.2, 0.0]\,\mathrm{m}$*). The upper participant (grey coloured) reduces speed and signals priority by turning the head towards the wheelchair user (orange) and giving a one-handed gesture.*



(a) *$\bar{J}(\bar{\rho})$ considering wheelchair users in a bottleneck.*

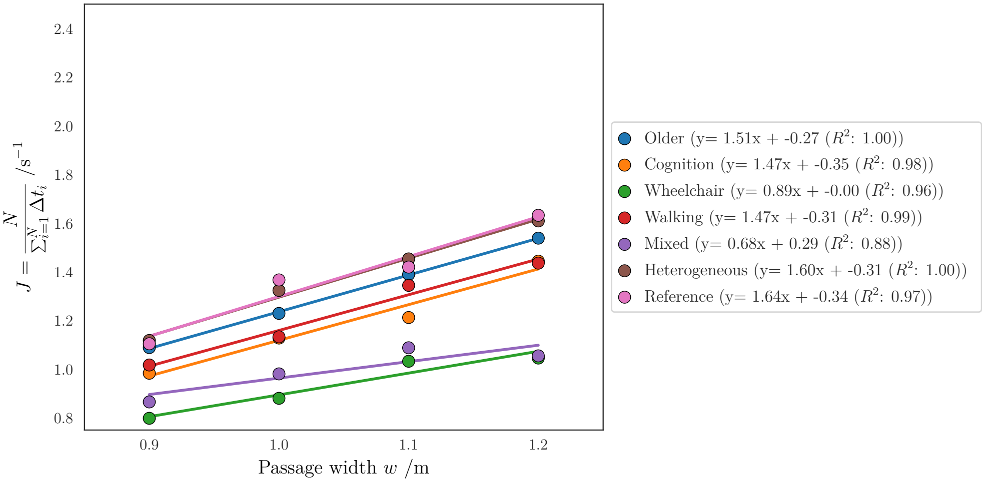


(b) *$\bar{J}(\bar{\rho})$ without PWD in a bottleneck.*

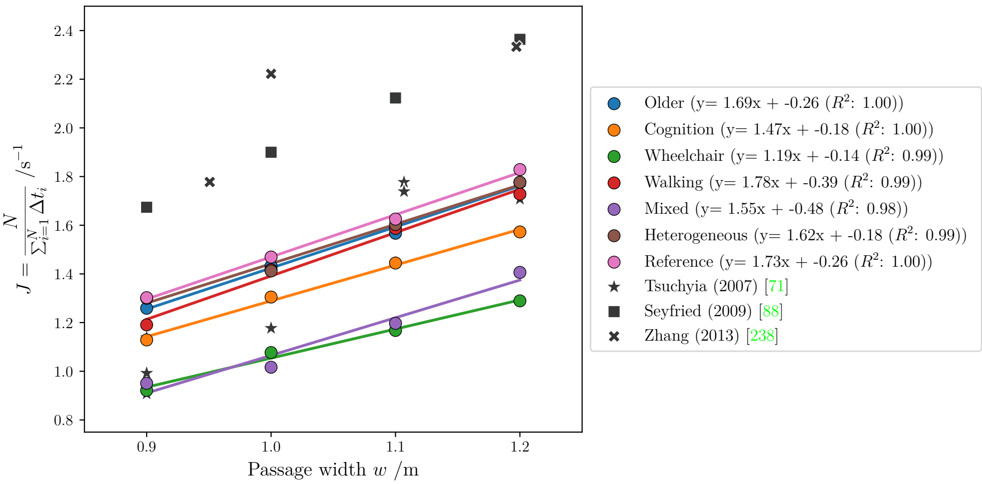
Figure 5.19: *Empirical relation $\bar{J}(\bar{\rho})$ for bottlenecks in heterogeneous crowd conditions with participants using wheelchairs (a) and homogeneous crowd conditions (b) with a population consisting of participants without disabilities. Data is presented as Gaussian Kernel Density Estimation using five gradients. Additionally, the distribution of speed and density is shown at the grid's margins. Fitted results according to the Kladek-relation and as a weighted polynomial function are presented.*

5.9 Validity of Specific Flow Concept

To quantify the flow rate J of a crowd through a facility, commonly the cumulative number of N participants passing the passage line is counted (Sec. 4.4). It is then the derivative in time of the cumulative flow [3, p. 4] and the specific flow rate J_s defined as flow per unit width. The flow rate J as a function of passage width and population configuration is presented in Fig. 5.20. While earlier studies concluded that flow increases step-wise with width (e.g. [116]), the correlation has been refuted and a linear relationship between flow rate and passage width is assumed (e.g. [88, 117, 125]. Using this assumption, the specific flow rate is commonly used for scaling, to estimate the performance of a facility [89, p. 42].



(a) *Flow rate J for a corridor setup.*



(b) *Flow rate J for a bottleneck setup.*

Figure 5.20: *Relation between flow rate J, passage width w and crowd heterogeneity for (a) corridors and (b) bottlenecks. The flow rate is determined by the overall population of NDP and PWD.*

Taking different conditions on crowd heterogeneity into account, a linear relationship between flow rate and passage width is observed for all configurations. The data shows that with an increase of passage width, the efficiency of the geometry increases proportionally. The relationship is valid for all observed populations in both geometries, whereby the flow rate in corridors is somewhat lower than in bottlenecks. This may be due to the comparatively large length of the corridor ($l_{cor} = 9.6$ m). While the flow rate is highest for the crowd with homogeneous conditions (reference population) in both geometries, the presence of wheelchair users and the mixed disabled populations reduces the flow rate in the bottleneck as well as in the corridor across all passage widths (which is in line with the findings of [114]). The effect is stronger in the bottleneck situation than in the corridor. The static space requirement of participants are of significant influence here (see a description of the assistive devices in App. A.3.2): the comparatively large width of the assistive devices (wheelchairs, tactile sticks) resulted in small individual distances to walls. And, in consequence, to a reduced global flow rate (cf. Fig. 5.9 for increased distances between PWD and NDP on the entrance line; and Fig. 5.11 for the high dependence on population). An increase of the passage width by 0.1 m to 0.3 m is only usable for agile, flexible participants without using assistive devices with increased requirements in space.

5.10 Summary

The influence of crowd heterogeneity on key performance values for egress analysis was analysed in this section. First, the time required to prepare assistive devices for the movement in case of egress was investigated (Sec. 5.2). Then, the unimpeded (free) speed of individuals with different movement abilities (PWD, NDP) was measured and compared (Sec. 5.3). Third, the movement of individuals towards dense crowds (simultaneous movement of PWD and NDP) in different conditions of crowd heterogeneity was analysed by benchmarking the speed v, density ρ and flow rate J. A capacity analysis for different geometries and different passage widths concerning different conditions of heterogeneity was provided in Sec. 5.7 and Sec. 5.8. Fourth, an analysis of passage time gap characteristics Δt_i was presented (Sec. 5.5). Then, the validity of the specific flow concept Js has been confirmed (Sec. 5.9). Lastly and across all sections, the influence of individual behavioural characteristics on key performance values was analysed. The presented findings are intended to supplement the knowledge gained in recent decades in the field of pedestrian dynamics and extend it by the evaluation of movement in heterogeneous crowds within the framework of engineering egress.

Chapter 6

Performance of Heterogeneous Crowds

This chapter proposes an approach to consider heterogeneous characteristics of individuals in the evaluate trial design-step of performance-based design processes [239, p. 1237]. A suitable adaptation for parameters of sub-processes in evacuation is presented, allowing the evacuation performance of heterogeneous crowds to be estimated. The procedure is in five steps: first, consideration of extended individual preparation times (Sec. 6.1); second, an extended variation in distributed individual speed (Sec. 6.3); third, adoption of empirical relations (Sec. 6.2) and; fourth, estimation of flow rate by using the individual time gap method (Sec. 4.4). Suggestions for application in engineering egress calculation methods are presented in Sec. 6.4 and Sec. 6.5.

6.1 Extended Pre-movement Phase

The pre-movement phase of an evacuation is in general characterised by a lack of information, in which an individual tries to achieve short, medium or long-term goals through a sequence of decisions. Information is compared with highly individualised empirical knowledge and integrated into action strategies. A large body of research has outlined this imperfect and multi-influenced character of the pre-movement and evacuation decision making process [240]. Additionally, parameter studies using agent-based computer simulation have shown that an increased degree of heterogeneity in pre-movement increases the total evacuation times [241–243]. The time required for decision and preparation increases, if – by oneself or with the help of third parties – assistive devices such as wheelchairs, evacuation chairs or escape mattress' have to be prepared for usage. To estimate the time required to begin individual movement activities, it is recommended to take extended time requirements into account. The data in Tab. 6.1 is based on the evaluation of the laboratory studies discussed in Ch. 5 compared to literature findings.

Table 6.1: *Time required to begin movement t_{prep}.*

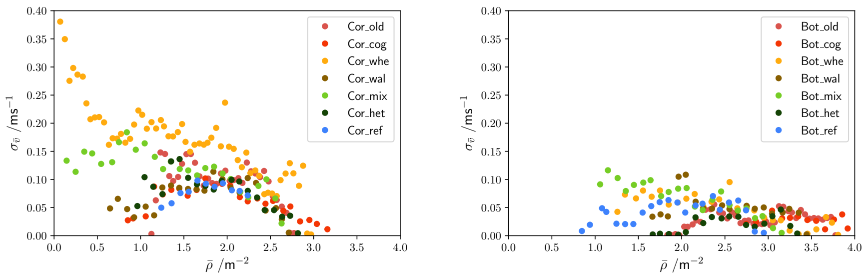
Assistive device	Preparation time t_{prep} /s	
	This study	Reference literature
Wheelchair	31.26 ± 14.50	–
Evacuation chair	29.20 ± 65.92	32.7 ± 5.3 [48]
Escape mattress	151.08 ± 58.24	62.2 ± 14.1 [48][a]

[a] Data were generated with a rescue sheet and not with an escape mattress.

6.2 Variation of the Empirical Relations

Crowd motion is a multi-factorially influenced, complex process. Especially when behaviour-driven factors are taken into account. It is questionable whether a change of regions and points of interest in the empiric relations as $J_{s,c}$, or ρ_{max} is significant or not, as individual characteristics differ and individuals interact with each other. For this purpose, the empirical relations are analysed in three steps: first, the standard deviation of speed $\sigma_{\bar{v}}$ is interpreted as an indicator to describe the transformation from free to congested states of movement (secondary quotation after [89, p. 21]). Second, the differences in empirical relations $\bar{v}(\bar{\rho})$ caused by the presence of participants with disabilities were tested on statistical significance. Third, the results of curve fit by non-linear least squares are presented for the Kladek-formula (Eq 5.1) as a first approximation for use in calculations.

Standard deviation of averaged speed as threshold: A threshold of the standard deviation of the mean speed of $\sigma_{\bar{v}} = 0.40\,\mathrm{m\,s^{-1}}$ is proposed as an indicator for the transition between the free and congested branch of a fundamental diagram in accordance to Alrutz et al. [244]. Following this concept, the standard deviation of speeds decreases with increasing density. The ability of the individual to choose the desired speed freely decreases with increasing density. A standard deviation greater than $0.40\,\mathrm{m\,s^{-1}}$, on the other hand, indicates that participants are free to choose their speed and can move at their desired speed. This threshold is not reached in the studies presented, except at very low densities in the population with wheelchair users in the corridor. In the studies presented here, the standard deviation of speed is about $0.10\,\mathrm{m\,s^{-1}}$ in the corridor (Fig 6.1a) and less than $0.10\,\mathrm{m\,s^{-1}}$ in the bottleneck configuration (Fig 6.1b). The reasons for this can be found, similar to those discussed in [89, Fig. 5.26], in the controlled boundary conditions and the already discussed considerate behaviour of participants in the studies shown here. However, it can be observed that the capacity is reached between a density of $1.81\,\mathrm{m^{-2}}$ (Cor_whe) and $2.21\,\mathrm{m^{-2}}$ (Cor_wal) in the corridor setting. At higher densities, the standard deviation of speed decreases in all populations. Pedestrians' movement is, following the conclusions in Ch. 5.7 et seq., restricted and the participants move below their free speed. Populations including wheelchair users and mixed populations lead to a generally higher standard deviation ($\sigma_{\bar{v}}(whe) \approx 0.16\,\mathrm{m\,s^{-1}}$, $\sigma_{\bar{v}}(mix) \approx 0.12\,\mathrm{m\,s^{-1}}$), decreasing with increasing density. For the other heterogeneity conditions, the standard deviation in speed was measured for both structural types by about $\sigma_{\bar{v}}(ref) \approx 0.10\,\mathrm{m\,s^{-1}}$ in the corridor and $\sigma_{\bar{v}}(ref) \approx 0.05\,\mathrm{m\,s^{-1}}$ in the bottleneck setting.



(a) *$\sigma_{\bar{v}}(\rho)$ for corridor studies.* **(b)** *$\sigma_{\bar{v}}(\rho)$ for bottleneck studies.*

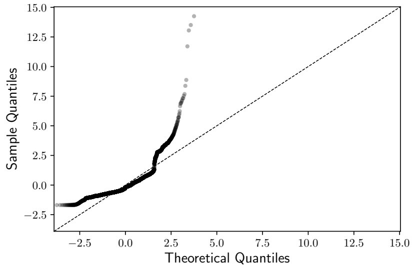
Figure 6.1: *Comparison of standard deviations $\sigma_{\bar{v}}$ for different conditions of heterogeneity.*

Similar standard deviations of the mean speed between populations were observed in the bottleneck configuration (Fig. 6.1b). Although they are of lower magnitude in general, mixed populations and populations including wheelchair users represent the upper level. Even if the capacity in the bottleneck studies is reached at higher densities, a reduction of the standard deviation with increasing density can be observed for this structure. Here, just a slight dependency between density and standard deviation of speed is observed and in most cases $\sigma_{\bar{v}} \leq 0.05\,\mathrm{m\,s^{-1}}$.

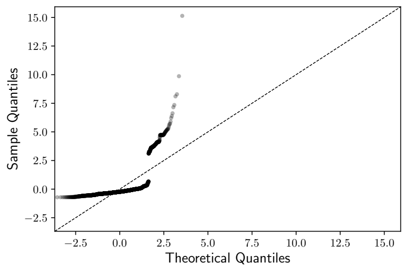
To summarise, the presence of wheelchair users and participants of the mixed population leads to differences in the mean speeds (cf. Fig 6.3). Heterogeneous crowds can therefore be characterised by standard deviations in the averaged speed, which are increased at low densities.

Distribution of $\bar{v}(\bar{\rho})$: Furthermore, samples of mean speeds $\bar{v}$ were tested for normal distribution in $\bar{v}(\bar{\rho})$ by analysing the quantile-quantile-plots (cf. for instance Fig. 6.2). Quantile-quantile analysis indicates the conformity of distribution of residuals and their deviations from a theoretical normal distribution [245]. Anything quite off the dashed diagonal lines may be a concern for further investigation. The deviation to the normally distributed values in Fig. 6.2 reveals that the errors are not normally distributed because data of all population settings shows several points that are far from the dashed line.

To deal with the location-shift of different $\bar{v}(\bar{\rho})$-distributions, a Mann-Whitney-U-test [246] is used. It tests whether the means of an empirical distribution are from the same dis-



(a) *Cor_whe:* $\bar{v}(\bar{\rho})$.



(b) *Bot_whe:* $\bar{v}(\bar{\rho})$.

Figure 6.2: *Quantile-quantile-plot of $\bar{v}(\bar{\rho})$ for (a) a corridor and (b) a bottleneck situation considering participants using wheelchairs. The dotted line represents the standard normal distribution.*

tribution or not. The Mann-Whitney-U-test can only be interpreted as a median comparison if the samples come from distributions of the same shape (alpha-shift). This inevitably leads to the rejection of the null hypothesis, if the empirical values do not derive from the same distribution. As argued by [247], a Mann-Whitney-U-test is suitable to analyse differences in skewed data, but in generally not '[...] capable of complex analyses, in particular those with multiple explanatory (predictor) variables.' ([247, p 689]) Statistically significance in the central tendency of the distribution is of particular interest:

– $H_0 : \bar{v}(\bar{\rho})_{het} = \bar{v}(\bar{\rho})_{ref}$

– $H_1 : \bar{v}(\bar{\rho})_{het} \neq \bar{v}(\bar{\rho})_{ref}$

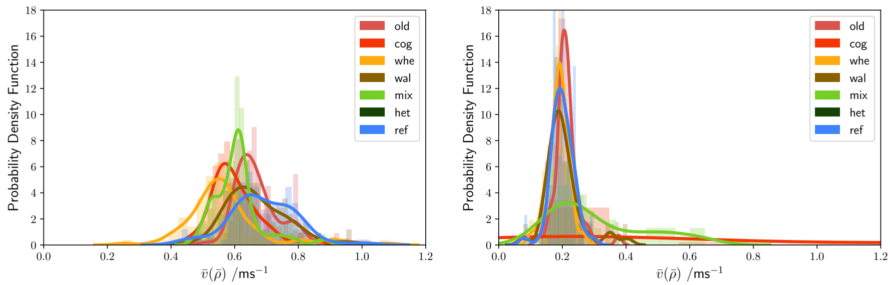
The null hypothesis was rejected for each population shown in Fig. 6.3, which strongly suggests that the distributions are different.

Calibration of Kladek-model: As a first approximation the Kladek-model (Eq 5.1 on p. 72 was calibrated).

Using the Kladek-model allows the qualitative description of the mean speed in both conditions of crowd heterogeneity. As a mathematical context, it is a good approximation, but not applicable in general. The physical significance is controversially discussed [94][2] as well as the complexity of the transformation from one-dimensional- to two-dimensional movement since the importance of longitudinal and lateral motion in two-dimensional systems [248].

The dependence of speed in heterogeneous groups was confirmed in the conducted studies (cf. App. B). Data of PWD is observed more frequently in certain density intervals.

[2]Similar to the study presented by Feliciani et al. 2018, fitting values of ρ_{max}-parameter in the Kladek-model is being almost far beyond the physical limit of humans.



(a) *$\bar{v}(\bar{\rho})$ for corridor studies.* **(b)** *$\bar{v}(\bar{\rho})$ for bottleneck studies.*

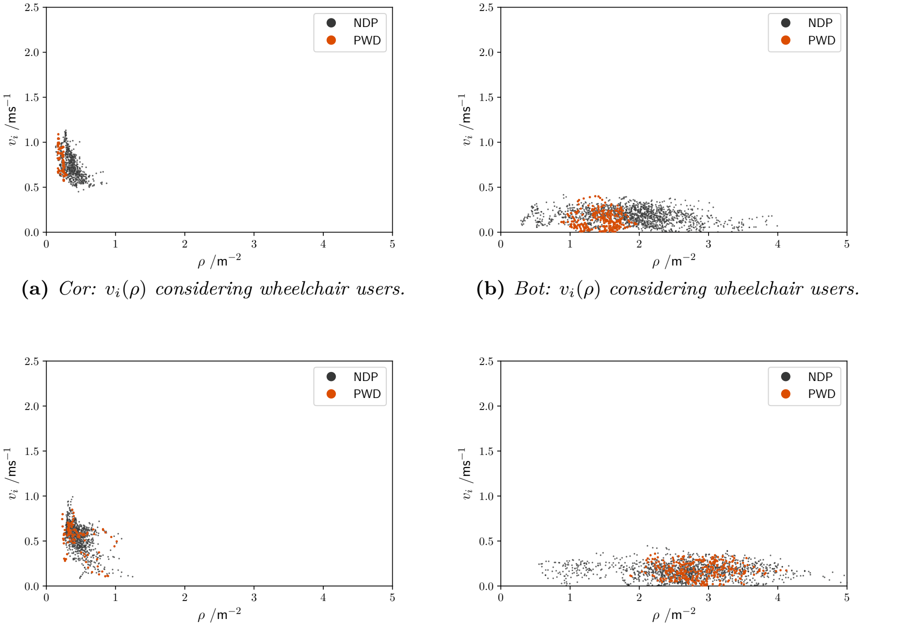
Figure 6.3: *Distribution of observations of $\bar{v}(\bar{\rho})$ as a histogram depending on population configuration for corridor and bottleneck setup. Note: the bin height shows a probability density function (where the integral over the function is equal to one) rather than a count and is related to the estimated density fit (KDE method).*

Participants using assistive devices are represented at certain, especially lower density domains in corridor situations as well as in bottlenecks (Fig. 6.4). On the one hand, this is a result of slower unimpeded speeds for PWD (Sec. 5.3), and on the other hand, it is due to the maintenance of higher distances to enhance navigation options. In addition, this observation is plausible because PWD kept a greater distance from predecessors. Distances to neighbours at the sides and the rear are also increased concerning participants without using assistive devices. This leads to larger Voronoi regions for PWD and therefore to smaller individual densities inside the measuring areas.

In consequence, the use of empirical relations to analyse the performance of pedestrian traffic systems should therefore be carried out with the utmost care. It should be noted that the presented studies only provide data for a small section of the density range. Rather, local fluctuations and the preference for certain dense regions will gain importance by taking into account people of different mobility abilities (cf. for example differences for orange scatter in Fig. 6.4). The crucial factor in this observation is not the individual mobility characteristic, but rather the interaction of the assistance means used with neighbours and the geometric boundary conditions (navigation, distances to walls, etc.).

6.3 Variation of Individual Speed in a Crowd

The speed of individuals in crowd motion depends on population characteristics (cf. Sec. 5.7 and Sec. 5.8). It shows that the standard deviation σ of an average individual speed $\bar{v}_i$ can be a suitable indicator to estimate the impact of individual differences in ability on motion of heterogeneous crowds. The average individual speed $\bar{v}_i(\rho)$ of all participants is considered here over density increments of 0.2 m^{-2} and a rolling window of 1 s. An overall summary of



(a) *Cor: $v_i(\rho)$ considering wheelchair users.*

(b) *Bot: $v_i(\rho)$ considering wheelchair users.*

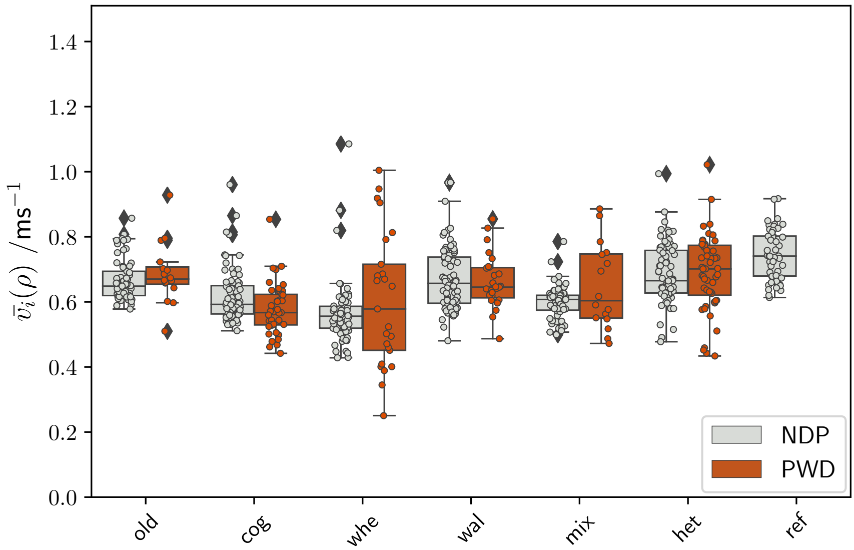
(c) *Cor: $v_i(\rho)$ considering cognition disabled . participants*

(d) *Bot: $v_i(\rho)$ considering cognition disabled participants.*

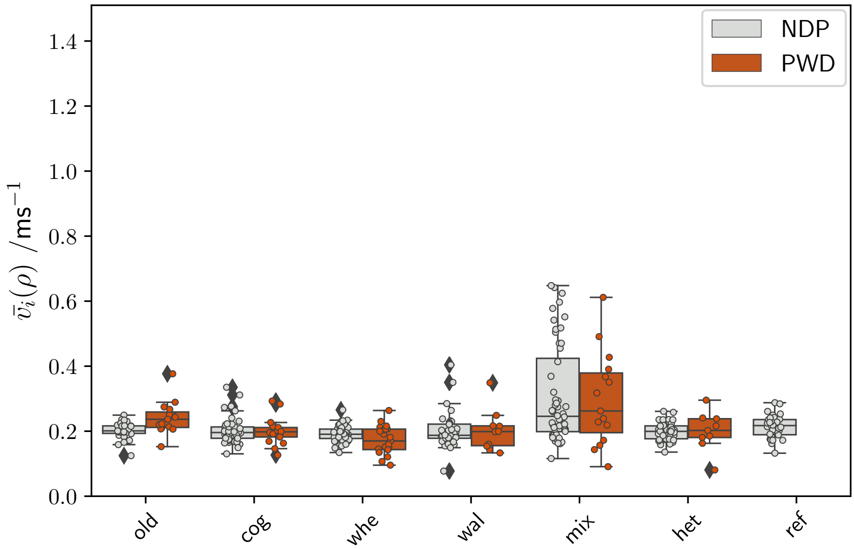
Figure 6.4: *Preferred domains in empirical relations $v_i(\rho)$ of participants using wheelchairs (top line) and participants with cognitive disabilities (bottom line). Results are presented for a corridor (left column) and a bottleneck (right column) with a passage width of* 0.9 m. *Data is calculated by using the Voronoi method and scatter for PWD are coloured in orange.*

$\bar{v}_i(\rho)$ considering all conditions of crowd heterogeneity for both geometries (corridors and bottlenecks) and across all passage widths (0.9 m to 1.2 m) is presented in Fig. 6.5.

It shows a higher variation of $\bar{v}_i(\rho)$ in corridors (Fig. 6.5a) for participants with disabilities than for participants without disabilities. In particular, populations with wheelchair users (Cor_whe), mixed populations (Cor_mix) and populations with multiple severe disabilities (heterogeneous population in Cor_het) are characterised by a wider interquartile range and enlarged ranges between the minimum and maximum values. Members of these populations predominantly use recognisable assistive devices to assist their movement by themselves or by assistants. Narrow dimensions of the corridors resulted in increased attention when navigating through the long corridor. The speed is therefore determined by the available passage width and the dimensions of the assistive device. The devices have different widths (cf. App. A.3.2) and consequently the influence on the individual speed is different. In contrast, distributions of $\bar{v}_i(\rho)$ for the remaining crowd heterogeneity conditions are similar to the share of NDP (Fig. 6.5a), except Cor_whe and Cor mix. These results were due because overtaking manoeuvres were not possible due to small passage widths and the speed of a few NDP was controlled by a predecessor using assistive devices. The variation of $\bar{v}_i(\rho)$ for NDP in the reference population is larger in corridor settings than in bottleneck situations. Summarising the differences of $\bar{v}_i(\rho)$ for bottleneck configurations (Fig. 6.5b), a smaller spread for NDP than for PWD is observed. In contrast, an increased variation is observed in studies considering wheelchair users (Bot_whe), mixed populations (Bot_mix) and multiple severed disabled population (Bot_het). Here, the averaged speed $\bar{v}_i(\rho)$ of neighbours with disabilities is influenced by social interactions such as NDPs gesturing to indicate that they would let a PWD pass before them. Negotiating and communicating priority rules between NDPs and PWDs take time and therefore reduce speed. In some cases, it could be observed that PWDs were given priority when manoeuvring into the bottleneck (cf. [23]). As in these studies overtaking actions of PWD were avoided by NDP, individual speed was adapted and thus the range of averaged individual speeds for the entire population increases.



(a) *$\bar{v}_i(\rho)$ for corridor studies.*



(b) *$\bar{v}_i(\rho)$ for bottleneck studies.*

Figure 6.5: *Comparison of averaged individual speeds $\bar{v}_i(\rho)$ for different populations and geometries. Speed is calculated by the Voronoi method as moving averaged (window size: 1 s) during the steady-state intervals and inside the measurement area.*

6.4 Parametrisation of Movement in Heterogeneous Crowds

The final evaluation of performance criteria for crowd movement by heterogeneous populations mostly considers the following quantities:

- Regions relevant for consideration in capacity analysis of $v(\rho)$ and $J(\rho)$,
- Averaged time gaps $\bar{\Delta t_i}$, and
- Validity of the empirical relations for prediction in calculation methods.

Up to now, only results from parameter studies conducted with homogeneous populations were available for this purpose. In the lack of appropriate values, the consideration of individual characteristics in engineering applications is often realised by a suitable reduction factor. Additional empirical safety coefficients were used to take heterogeneous characteristics into account.

For example, in [28, Tab. G.2], the influence of density on speed in vertical movement is taken into account by different constants. In Italian standardisation, speed is clustered in 'slow', 'medium' or 'fast' [249, Tab. 2]. And finally, Hunt et al. proposed rated factors based on empirical findings for the consideration of assistive devices in the evacuation calculation [48, Tab. XI].

To fill this gap, findings based on empirical studies under controlled conditions (Tab. 3.1) were presented. Against the backdrop of the high user acceptance, fitting parameters of the Kladek-equation for different population settings in corridor and bottleneck situations are presented. With all the weaknesses of this fitting method discussed in Sec. 6.2, it becomes clear that in particular, the consideration of people with recognisable disabilities induces a reduction in the speed of the entire crowd. This is underlined by the results of the polynomial fitting method (cf. curves of Cor_mix, Cor_wal and Cor_whe in Fig. B.29). This observation has consequences for the basic shape of the curves in the bottleneck geometry, where noticeably higher maximum densities can be achieved for populations with older or cognitive disabled participants. Both settings are characterised by the participation of PWD with an overtly visible disability such as a wheelchair user and an observed high degree of cooperation and mutual consideration. Tab. 6.2 summarises the key performance values of the empirical relations required for a capacity analysis supplemented by the fitted coefficients for the Kladek-equation (Eq 5.1 on p. 72).

Table 6.2: *Summary of key performance values regarding the empirical relation $\bar{v}(\bar{\rho})$ with heterogeneous populations. Here the threshold J_c is defined as the maximum mean value of $\bar{J} = \bar{\rho} \cdot \bar{v}$. The maximum density ρ_{max} for the Kladek-fit was assumed to be $5.4\,\mathrm{m}^{-2}$.*

Study	Figures	Empirical characteristics			Kladek coefficients for $v(\rho)$	
		J_c $/\mathrm{m}^{-1}\,\mathrm{s}^{-1}$	ρ_C $/\mathrm{m}^{-2}$	σ_{Jc} $/\mathrm{m}^{-1}\,\mathrm{s}^{-1}$	v_0 $/\mathrm{m}\,\mathrm{s}^{-1}$	γ –
Cor_eld	Fig. B.1	1.54	1.84	0.27	1.41	0.918
Cor_cog	Fig. B.3	1.48	2.01	0.28	1.43	0.695
Cor_whe	Fig. B.5	1.46	1.81	0.35	1.43	0.468
Cor_wal	Fig. B.7	1.56	2.21	0.18	1.43	0.914
Cor_mix[a]	Fig. B.9	1.40	1.92	0.15	1.42	0.621
Cor_het	Fig. B.11	1.73	2.10	0.33	1.42	1.002
Cor_ref	Fig. B.13	1.56	2.12	0.19	1.43	1.185
Bot_eld[b]	Fig. B.15	–	–	–	1.41	0.423
Bot_cog	Fig. B.17	1.21	3.75	0.23	1.43	0.336
Bot_whe	Fig. B.19	1.16	2.57	0.31	1.43	0.132
Bot_wal	Fig. B.21	1.04	3.32	0.25	1.43	0.174
Bot_mix	Fig. B.23	1.26	1.46	1.61	0.28	0.160
Bot_het[b]	Fig. B.25	–	–	–	1.42	0.154
Bot_ref[b]	Fig. B.27	–	–	–	1.43	0.156

[a] Noticeable high fluctuations for $\bar{\rho} \geq 2.5\,\mathrm{m}^{-2}$.
[b] Capacity not reached.

6.5 Application in Engineering Egress Calculation

Once the flow rate based on averaged individual time gaps Δt_i (cf. Eq 4.14 on p. 44) for a specific population is known, it is possible to use it according to Eq 6.1 for engineering egress calculations considering different demographic scenarios.

$$J = \frac{N_{all}}{\sum_{k=A}^{N} N_{pop,k} \cdot \Delta\bar{t}_{i,k}} \tag{Eq 6.1}$$

For comparison, a population is initialised to illustrate the methodological approach. It consists of 100 NDPs and a variable number of PWDs. Time gaps for PWDs were assigned as averaged time gaps drawn from the trials for the corresponding passage width of the geometry. Time gaps for NDPs were assigned by the same method. The time gap data used are tabulated in App. C.1. Then, the share of PWD in a population was varied and the effect on the resulting flow rate was compared with the flow rate measured in the reference study. It is undoubtedly part of a diligent analysis that the extremes (minimum and maximum) are also considered and included in the calculation. The use of the average flow rate is an optimistic estimate here to demonstrate the principle.

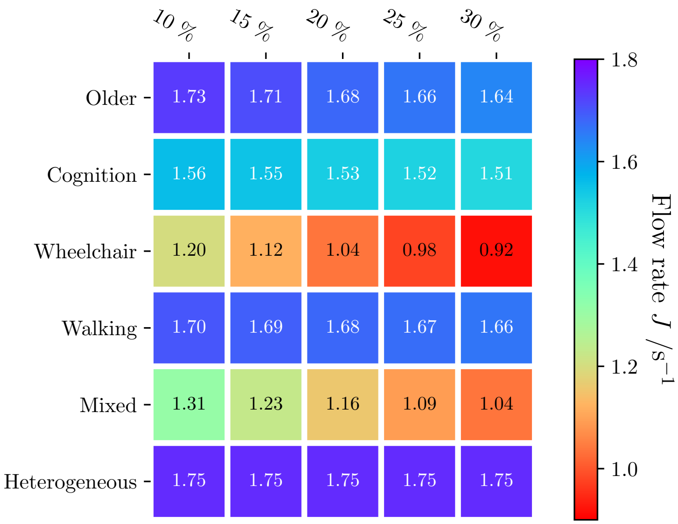


Figure 6.6: *Changes in population-adjusted flow rate for artificial populations with a size of* $N = 100$ *through a bottleneck and a passage width of* 1.2 m*. The difference refers to the empirical flow rate of a population without people with disabilities* $J_{ref} = 1.78\,\mathrm{s}^{-1}$*. Absolute flow values according to each modified population are given as values.*

Given an overall population size of 100 participants with different ratios of PWDs, the difference in flow rate through a bottleneck with a width of 1.2 m is compared to the flow rate of a reference population ($J_{ref} = 1.78\,\mathrm{s}^{-1}$) in Fig. 6.6. Assuming time gaps of NDPs as constant, the decrease of flow rate is strongly influenced by the kind of population and the ratio of participants with disabilities. Since the flow rate in a scenario with 30 % of participants aged ≥ 60 years is reduced by approximately 10 % ($1.64\,\mathrm{s}^{-1}$), a similar share of wheelchair users in the scenario reduces the flow rate by half ($0.92\,\mathrm{s}^{-1}$). The group of people with mixed disabilities two blind participants assisted by a white stick and a personal assistant with a very high individual time gap (cf. Fig. 5.10 on p. 64). With PWD accounting for 30 % of the total population, about 2 % of people are dependent on personal assistance or a white stick. In this crowd heterogeneity, it is clearly shown how a small proportion of people with an increased time gap can reduce the overall flow ($1.04\,\mathrm{s}^{-1}$). The results presented in this dissertation indicate that the individual time gaps of NDP, in reality, are also increased by the presence of PWD. It should be noted that this kind of applications tends to slightly underestimate the flow reduction.

Chapter 7

Summary and Conclusions

7.1 Summary

Empirical data on movement characteristics for different populations with physical-, mental- or age-related disabilities and reduced movement abilities are presented in this dissertation to better understand the movement of heterogeneous crowds. The presented studies are a first step towards understanding the movement of heterogeneous groups of people, quantifying the influence of assistive devices on parameters of pedestrian dynamics, and determining the performance of pedestrian traffic systems based on empirical data.

This work identifies differences in the prediction of key performance values of egress and takes individual characteristics in heterogeneous crowds into account. Parameters for the description of the pre-movement phase and movement phase of an evacuation were obtained in studies under controlled boundary conditions. The pre-movement phase studies were conducted with ten people with disabilities and six assistants. The studies on movement in higher densities involved a population of about 80 participants without disabilities. In addition, depending on the configuration of the study, between 4 and 12 participants with disabilities participated, so that a proportion of people with disabilities of about 10 % could be realised. The main contribution of this work is the consideration of participants with disabilities in movement studies under laboratory conditions and the assessment of the impact on characteristics of crowd dynamics. The well-controlled studies aimed to quantify the preparation of movement concerning the use of assistive devices and to describe crowd dynamics during the movement phase.

Enlarged preparation times: Pre-Movement times for people without disabilities are widely published. They are strongly dependent on the type of use and the context of the alarm (e.g. at night time, in a foreign environment). Little is known about the influence of assistive devices on pre-movement time. At a first step, preparation times (objective 1, p. 49) of participants using wheelchairs, evacuation chairs and escape mattresses are provided from studies under controlled conditions (Sec. 5.2). An extended preparation time for occupants with the usage of assistive devices was observed (wheelchair: $t_{prep} = 21.26 \pm 14.50\,\mathrm{s}$, evacuation chair: $t_{prep} = 29.20 \pm 65.92\,\mathrm{s}$ and escape mattress: $t_{prep} = 151.08 \pm 58.24\,\mathrm{s}$). It was also observed that the additional time for preparation depends on the kind of assistive device and the operators' familiarity with the standard handling procedure.

Variability of unimpeded speed: Next, the unimpeded speed was measured and analysed concerning to individual abilities (Sec. 5.3). The expected unimpeded speeds of $1.47 \pm 0.17\,\mathrm{m\,s^{-1}}$ were observed with the reference population without attending participants with disabilities. This result is consistent with literature findings [21]. Focusing on the unimpeded speed of populations concerning participants with different disabilities, either slower or a comparable speed was measured for wheelchair users ($0.96 \pm 0.35\,\mathrm{m\,s^{-1}}$) and walking disabled ($1.28 \pm 0.12\,\mathrm{m\,s^{-1}}$) or participants with multiple disabilities ($1.33 \pm 0.29\,\mathrm{m\,s^{-1}}$), respectively.

Cyclic components in time series: Time series density, speed, and flow rate were analysed for heterogeneous crowd conditions in Sec. 5.4. The magnitude and length of the fluctuations in the crowd density, speed, and flow rate caused by interpersonal communication and interaction varied. They are linked to the type of disability and the assistive device used. The pattern of the fluctuation is not characterised as periodically recurring short-term fluctuations, but depend on the individual starting position (and may appear cyclic, cf. Fig. A.9a and Fig. A.9d in App. A.3.5). Furthermore, one or multiple participants with disabilities in a crowd do not necessarily lead to an observable fluctuation in each trial. It is rather the combination of the crowd density, the presence of a single person or multiple persons with recognisable disabilities (e.g. wheelchair users, participants using a white stick, etc.). And in addition that the immediate neighbours are known to each other which leads to different intensities of fluctuations due to interaction, e.g. reduction of speed, implied behavioural activities, or gestures. This behaviour causes fluctuations in intensity and duration.

Capacity reduction: A series of well-controlled studies on movement characteristics in corridor and bottleneck situations were conducted to perform a capacity analysis with a focus on heterogeneous crowds. The passage width of the corridor and the bottleneck was varied to analyse situations of different density (Sec. 5.7 and Sec. 5.8). As a result of these studies, this doctoral thesis provides a capacity analysis for corridors and bottlenecks, individual speeds, time gaps and specific flow rates for populations which are characterised by different individual abilities.

The focus in these studies lies on the free flow branch of the fundamental diagram up to the capacity. The results are, especially if wheelchair users and mixed disabled participants are taking part, different fundamental diagrams than those to be expected from homogeneous crowds. They are the result of, among other things, slow speeds of people with certain impairments, different space requirements, adjustments of speeds for navigating with assistive devices and cooperative and polite behaviour between populations. Additional available space in case of larger passage widths has no effects on the performance criteria of wheelchair users because the additional space is not used for overtaking or forming a second lane. Flow rate and density show an approximately linear relationship for these populations in the free flow regime of the fundamental diagram. This observation is valid across all populations, including the participation of wheelchair users. The measurements show no or only a very small change in speed in the density interval between approximately $1\,\mathrm{m}^{-2}$ and $2\,\mathrm{m}^{-2}$ (speed is independent of density). In addition, for density ranges between $0.5\,\mathrm{m}^{-2}$ and $1.0\,\mathrm{m}^{-2}$, in which a reduction in desired speed is expected, only a few data are available.

Large differences and scatter in the descriptive variables suggest that averaged variables are not sufficient as input variables in evacuation calculations. Rather, it is important to use the scatter as a basis for sensitivity analyses to be able to estimate the influence of heterogeneous characteristics of persons on parameters of movement. An estimation of the influence of heterogeneity on empiric relations is not easily feasible. The studies were conducted under laboratory conditions. This implies that the independent variables population configuration, type of geometry and, passage width were controlled and varied. It was observed that the dependent variables speed, density and flow rate were influenced by other factors, like cooperative and polite behaviour or diverging interpersonal distances. Thus, empirical relations depend on the presence of participants with disabilities. In particular, the presence of participants with recognisable disabilities leads to slow and density-independent movement of the overall crowd in the measured density interval. However, it is to be expected that the dependency of speed will increase at densities higher than the critical density. Slower speed, mutual consideration and cooperation at bottleneck entrances leads to higher individual distance headways and reduced flow rates.

Dynamic individual distances: Lastly, the individual time gap is introduced and the validity of the specific flow rate has been reviewed (Sec. 5.9). It was found that participants using wheelchairs keep larger distances to their predecessors, which is caused by the maintenance of stopping distances, slower speeds in corridors, and as a consequence of cooperation in front of the bottleneck. The distances vary according to the individual position in the geometry and the population setting. The smallest distance in all directions between neighbours (head positions) was located at a distance of 2 - 4 m in front of the bottleneck entrance (App. C.2).

In summary, the following adaptations are proposed for consideration of heterogeneous crowds in engineering egress calculations (objective 2, p. 49): (a) attention to an extended pre-movement phase (Sec. 6.1); (b) variation of unimpeded speed (Sec. 6.3); (c) consideration of variation in fundamental diagrams (Sec. 6.2); and (d) varying time gaps for flow rate estimation (Sec. 6.5).

7.2 Outlook

To gain a complete understanding and description of the influences of individual characteristics on the performance of crowd motion, the following topics need to be addressed in the coming years.

First, it was shown in this doctoral thesis that social interactions as a consequence of the heterogeneity in crowds can influence the individual movement pattern as well as crowd motion characteristics. However, existing methods to quantify these influences are insufficient. Methods of qualitative video analysis [250] and graphical mapping approaches (e.g. [251, 252]) could be a next step to quantify the time-dependent spatial-social relationship between type and meaning of interaction and movement characteristic. In a further step, it would be conceivable to transfer the findings into existing protective action decision models (PADM, [253]) which was already adapted for use in building fires [254, 255].

Even for homogeneously composed crowds data on the biomechanical parameters for the movement sequence are insufficient. Further, additional influencing factors are taken into account when considering people with disabilities and the use of assistive devices: assisting others, accelerating, decelerating, adapting gait, preserving individual space or respecting the space to others and, transitions between walking and running [237, p. 205]. In particular, the impact of (different) disabilities on spatial requirements, like postural stability and lateral sway – especially related to movement in natural environments [256] – is not known. Such parameters must be used to describe the differences in movement characteristic.

The impact of disabilities is not confined to the movement process; some types of disabilities may have a more complex influence. For instance, obesity may reduce postural stability which can make it more difficult to adapt the movement pattern when the terrain changes [147], increase the individual space requirement [6] and may decrease the individual speed [257]. Cognitive impairment may reduce memory and can result in an altered capacity for spatial and situational orientation, while at the same time, difficulties in concentration can distract from the original goal of movement (reduces speed) [258].

Multiple factors influence movement performance and little is known about the interaction in between, e.g. assistive device, weight, age, terrain, etc. In addition, the presence of persons with impairments may have a physical and social impact on others around them.

Besides, the influence on individual movement characteristics, the presence of people with disabilities may change the temporal development of key performance values of crowd motion like the flow rate. The studies presented are influenced by the starting conditions like most experimental studies. Due to the large distance between the waiting area and the measurement area, a separation of the populations occurred. An investigation of this process could be a practical issue for further studies. In particular, if the segregation process is completed across larger distances, the significance of heterogeneous crowds in the context of evacuations would be much less significant. It is worth focusing on this detail in future laboratory investigations and with a more controlled initial position of each participant. The influence of persons with disabilities on flow rate fluctuations should be interpreted and adjusted like recurring events (cf. for instance trend- and short-term fluctuation-dependent flow rates in Fig. A.9 on p. 162). Such temporary changes of a parameter are well known from other disciplines, e.g. in the time-dependent analysis of the unemployment rate, sales during the Christmas season or flight route utilisation during holidays. To analyse a long-term trend, the time series of a parameter must be adjusted for cyclic trends [220, p 5]. Fluctuation- and trend-adjusted time series would then be tested for stationarity using statistical test procedures or divided into stationary and transient intervals. The Augmented-Dickey-Fuller (ADF, [259])- or Kwiatkowski-Phillips-Schmidt-Shin (KPSS, [260]) test would be particularly suitable for this purpose.

It is worth mentioning that the number of data for participants with disabilities was limited and similar sized wheelchairs were considered in this doctoral thesis. The usage of larger increments of additional passage widths (e.g. a multiple of a wheelchair width) may have an impact on the flow rate and may change the outcome. The presented dissertation is based on studies under laboratory conditions, which allows high precision and control of the initial conditions. The control of the initial conditions implies a limited transferability to real situations. Accepting less controlled conditions, e.g. in trajectory precision, for instance, field studies could be used to verify whether the observed politeness bias can be identified even in situations where the subjects are not aware of the observation.

Using the Voronoi method for calculating individual movement parameters results – depending on the number of neighbours – in polygons with n corners. In particular, if virtual wall cells on the boundary layers were used to take the distance between participant and walls into account, the individual density may be overestimated. The Voronoi decomposition ignores the real physical boundaries of individuals. This becomes important when considering the use of assistive devices in high-density situations. In particular, it is not possible for participants using assistive devices with static space requirements (e.g. canes, wheelchairs, walking frames) to adjust the space requirements. A promising approach to consider assistive devices in Voronoi calculations is to implement an elliptical representation of the device in the Voronoi cells for future analysis. Such an assumption has been discussed for many years (e.g. [261, p. 79]) and could also be implemented.

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Appendix A

Study Documentation

A.1 Research involving human participants

This study was performed with human participants. Thus, much of the experimental planning was devoted to participants safety and ethical considerations. People with and without physical, mental or age-related disabilities participated in experimental setup and study design. The development and dissemination of the findings took not only the aspects of data protection law and the comprehensive consultation and approval by the ethics committee of the University of Wuppertal into account. But also the guiding principles of involving human participants into research [262]. This means in particular strictly voluntariness and the possibility of withdrawal without consequences. In addition to respectful treatment and carry on dialogues on equal terms, this was ensured in particular by the following arrangements:

– Participants have not experienced any research-induced disadvantages and have not been exposed to any extraordinary conditions such as high motivation of participants, focussed high densities or unexpected variations of the study setting (closed doors, smoke, etc). The disadvantages to being avoided include unrealistic expectations, manipulation, exploitation and stigmatisation [263]. But it is noted that special treatments for a subpopulation always lead to a reproduction of the diversity (see [264] and most of all [182] for a detailed discussion on the conceptualisation of vulnerability in case of disaster. Possible risks that extend beyond the generally accepted life risk were analysed and explicitly explained.

– Participation is by consent based on written and oral information. A signed and informed consent permitting video recordings, photographs and usage of the results has been obtained. Alternatively, consent was obtained from the legal guardian. To the extent that the legal guardian gave this consent on behalf of the person concerned, additional discussions were held with the affected participant to conclude that the consent was following the actual will of the person with disabilities concerned.

- The anonymity of the participants was guaranteed by the strict separation of personal data and data collected for research purposes. At no time did the study organisers have access to personal data.
- Confidential information obtained from participants was treated accordingly. This commitment was and is valid for all members of the consortium (including research assistants, interviewers, coders, etc.).
- Carrying out a movement study and the associated observations, surveys and measurements involves an effort that is reflected both in the research costs and in the strain on the disabled and non-disabled participants. On the other hand, there has to be an expected benefit. In the presented work, fundamental relationships of the movement of heterogeneously composed groups of people in a built environment have been worked out, which is in further use suitable for the development of safety strategies adapted to the target group. A useful property is obvious. Ethically critical questions such as blind tests or double-blind tests or indications of instrumentalisation of the participating persons for the benefit of others or questionable benefit calculations are not present in this studies.

Methodological design, the data storage process, and the access authorisation for (personal) data were approved by the ethics committee of the Bergische Universität Wuppertal. No ethical concerns were mentioned.

A.2 Studies on Preparation and Low Density Movement

A.2.1 Assistive devices

Three different assistive devices to support the motion of participants with disabilities were used in the studies: a standard foldable wheelchair (Bischoff & Bischoff type S-Top, cf. Fig. A.1a), an evacuation chair (Escape-Mobility Escape Chair type CF, cf. Fig. A.1b), and an escape mattress (Escape-Mobility Escape Mattress type Fold 55, cf. Fig. A.1c). The selection took into account that the assistive device could be used by all participants and that assistants had the utmost everyday experience in its use. All assistants were instructed and trained in the use of the assistance equipment.

(a) *Foldable wheelchair.* **(b)** *Evacuation chair.* **(c)** *Escape mattress.*

Figure A.1: *Studies on preparation and low-density movement: assisted devices.*

Table A.1: *Studies on preparation and low density movement: Procedure for the use of assistive devices to measure the preparation time t_{prpe}.*

Subprocess	#	Asssistive device		
		Wheelchair	Evacuation chair	Escape mattress
Preparation of assistive device	1	Assistants move from the starting position[a] to the assistant device	Assistants move from the starting position[b] to the assistant device	Assistants move from the starting position[b] to the assistant device
	2	–	Remove cover	Remove cover
	3	–	Lifting the escape chair from the mounting to the floor	–
	4	–	Fold out assistive device	–
	5	–	Tilting the assistive device	–
	6	Push the assistive device to the participant	Push the assistive device to the participant	Carry assistive device to the participant
	7	Turn assistive device	Turn assistive device	–
	8	Fasten brakes	–	Fold out assistive device

Continued on the next page

Table A.1 – Continued from previous page

Subprocess	#	Asssistive device Wheelchair	Evacuation chair	Escape mattress
	9	Raising footrests	–	Position belts laterally
Transferring and making it transportable	10	–	–	Push patient to the side
	11	–	–	Lift escape mattress onto the bed
	12	Set up participant	Set up participant	–
	13	Preparing to grasp and lift	Preparing to grasp and lift	–
	14	Straightening participant up	Straightening participant up	–
	15	Transferring participant	Transferring participant	Transferring participant
	16	Putting participant on the assistive device	Putting participant on the assistive device	Putting participant on the assistive device
	17	Fold down footrests	–	–
	18	Fixing the feet	–	Fixing the feet
	19	–	–	Fixing the torso
	20	–	–	Fixing the legs
	21	–	–	Fixing the head
Transport	22	Tilting the assistive device	Lift the assistive device onto the floor	
	23	Push the assistive device over the measuring line	Push the assistive device over the measuring line	Pull the escape mattress over the measuring line

[a] Room
[b] Floor

A.2.2 Trial Sequence

Table A.2: *Experimental trial sequence.*

Trial_ID	PWD_ID	# assistants	Start device	Target device
Study A:				
A_01	PWD_90	2	Bed	Wheelchair
A_02	PWD_90	2	Bed	Wheelchair
A_03	PWD_91	2	Bed	Wheelchair
A_04	PWD_91	2	Bed	Wheelchair
A_05	PWD_92	2	Bed	Wheelchair
A_06	PWD_92	2	Bed	Wheelchair
A_07	PWD_93	2	Bed	Wheelchair
A_08	PWD_93	2	Bed	Wheelchair
A_09	NDP_98	2	Bed	Wheelchair
Study B:				
B_01	PWD_90	2	Bed	Wheelchair
B_02	PWD_90	2	Bed	Wheelchair
B_03	PWD_90	2	Bed	Wheelchair
B_04	PWD_90	2	Bed	Wheelchair
B_05	PWD_94	2	Bed	Wheelchair
B_06	PWD_94	2	Bed	Wheelchair
B_07	PWD_94	2	Bed	Wheelchair
B_08	PWD_94	2	Bed	Wheelchair
B_09	NDP_98	2	Bed	Wheelchair
B_20	NDP_98	2	Bed	Wheelchair
B_11	NDP_98	2	Bed	Wheelchair
B_12	PWD_95	2	Bed	Wheelchair
B_13	PWD_96	2	Bed	Wheelchair
B_14	NDP_98	2	Bed	Wheelchair
Study C:				
C_01	PWD_90	1	Wheelchair	–
C_02	PWD_90	1	Wheelchair	–
C_03	PWD_91	1	Wheelchair	–
C_04	PWD_91	1	Wheelchair	–
C_05	PWD_92	1	Wheelchair	–

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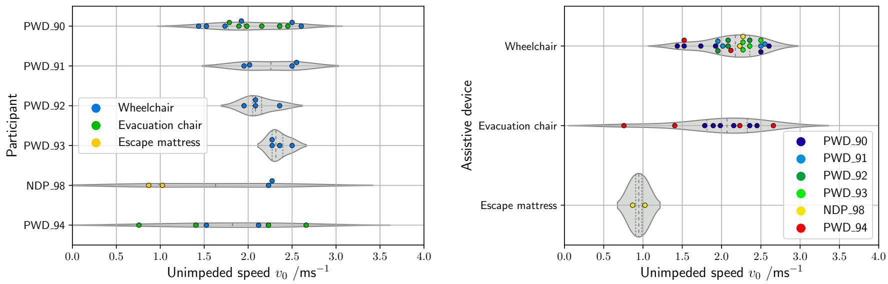
Table A.2 – continued from the previous page

Trial_ID	PWD_ID	# assistants	Start device	Target device
C_06	PWD_92	1	Wheelchair	–
C_07	PWD_93	1	Wheelchair	–
C_08	PWD_93	1	Wheelchair	–
C_09	NDP_98	1	Wheelchair	–
C_10	PWD_90	1	Wheelchair	–
C_11	PWD_90	1	Evacuation chair	–
C_12	PWD_90	1	Evacuation chair	–
C_13	PWD_90	1	Wheelchair	–
C_14	PWD_94	1	Wheelchair	–
C_15	PWD_94	1	Evacuation chair	–
C_16	PWD_94	1	Evacuation chair	–
C_17 - C_21 [a]				
C_22	NDP_98	1	Escape mattress	–
Study D:				
D_01	PWD_93	2	Evacuation chair	–
D_02	PWD_93	2	Evacuation chair	–
D_03	PWD_97	2	Evacuation chair	–
D_04	PWD_97	2	Evacuation chair	–
D_05	PWD_95	2	Evacuation chair	–
D_06	PWD_95	2	Evacuation chair	–
D_07	NDP_98	2	Evacuation chair	–
D_08	NDP_98	2	Evacuation chair	–
D_09	NDP_98	2	Escape mattress	–
D_10	NDP_98	2	Escape mattress	–
D_11	NDP_99	2	Escape mattress	–

[a] No video data is available for this trial because of a technical issue with the camera system.

A.2.3 Unimpeded Assisted Speed on the Horizontal

The unimpeded speed v_0 depending on the assistive device used was measured by a modified 10MWT. An overall mean unimpeded speed of $2.01 \pm 0.49\,\mathrm{m\,s^{-1}}$ ($0.76\,\mathrm{m\,s^{-1}}$ up to $2.69\,\mathrm{m\,s^{-1}}$) was observed. These comparatively high values result in the highly motivated assistance staff: while the time required in the preparation studies was quite high, the assistants tried to compensate for this disadvantage during the movement study. Even if the participants were instructed not to hurry and move normally, qualitative observation of hurrying was documented. In general, wide variations of unimpeded speeds between between $0.3\,\mathrm{m\,s^{-1}}$ up to $2.5\,\mathrm{m\,s^{-1}}$ are well documented for non-disabled populations (e.g. [1], [7], [89]). Take participants with disabilities and assisted movement into account leads to comparable ranges and variations of unimpeded speeds ($0.23\,\mathrm{m\,s^{-1}}$ up to $1.95\,\mathrm{m\,s^{-1}}$ [37]). The unimpeded peed is influenced by the choice of the assistance device and independent of individual characteristics of the PWD (Fig. A.2) in case of an assisted movement.



(a) *v_0 depending on the participant.* **(b)** *v_0 depending on the assistive device.*

Figure A.2: *Unimpeded speeds v_0 measured by the 10 m-walking-test depending on individual characteristics of the participants (left) and on the assistive device (right).*

A.3 Studies on Movement in Groups and Toward Dense Crowds

A.3.1 Scoring the Basic Population Towards Participation

Twelve configurations of a single or multiple disabilities were identified among the total population of the sample of potential participants with disabilities (n=320) by using the presented score regarding the need for assistance, (Tab. A.3). First, representatives of a single indicator for each dimension were identified (shown in the configuration 2-5, 9, and 10). The only exception is the combination of wheelchair assistance and walking disability. This is because every wheelchair user had a recognised severe disability (which leads to a positive indication in the Score RNA concept). Second, further combinations of disabilities were identified which may be interesting for safety research.

Table A.3: *Configurations using the Score RNA – a single indicator of a disability (configuration 2 - 5, 9, 10) and representatives with more than one indicator (configurations 6, - 8, 11 and 12).*

	Indicator						Score RNA	N_{all}[a]
	Reception and perception		Action		Information processing	Moderator		
#	blind	deaf	walking	wheelchair	MELBA-SL-Mean $\leq$ 0.5	age $\geq$ 60		
1	-	-	-	-	-	-	0.000	220
2	-	-	-	-	✓	-	0.235	27
3	-	-	-	-	-	✓	0.059	17
4	-	-	✓	-	-	-	0.118	16
5	-	-	(✓)	✓	-	-	0.235	13
9	-	✓	-	-	-	-	0.235	2
10	✓	-	-	-	-	-	0.235	2
6	-	-	✓	-	✓	-	0.353	8
7	-	-	-	-	✓	✓	0.294	4
8	-	-	✓	✓	✓	-	0.471	4
11	-	-	✓	-	-	✓	0.176	2
12	✓	-	✓	-	-	-	0.353	2

[a] Includes only persons with a complete data-set (information on all indicators).

A.3.2 Population Characteristics

The individual body height was measured for each participant since it influences the precision of the tracking of the positions (App. A.3.3). Body heights of all participants range from 1.45 m to 2.04 with a mean of 1.74 m ± 0.1 m for both study days (Fig. A.3). The mean and standard deviation is comparable for both study days with a body height on Saturday of 1.74 m ± 0.10 m and on Sunday of 1.74 m ± 0.11 m

The identification numbers of the participants (persID) are not preserved across trials. The persID related to a participants with disabilities (PWD_ID) are documented in the header of the trajectory-files and described in Tab. A.5. An important feature of these studies is the consideration of individual mobility characteristics (disabilities) as an operationalisation of crowd heterogeneity. At the same time, assumptions were made to cluster the individual characteristics and to assign generic terms. For a deeper understanding of

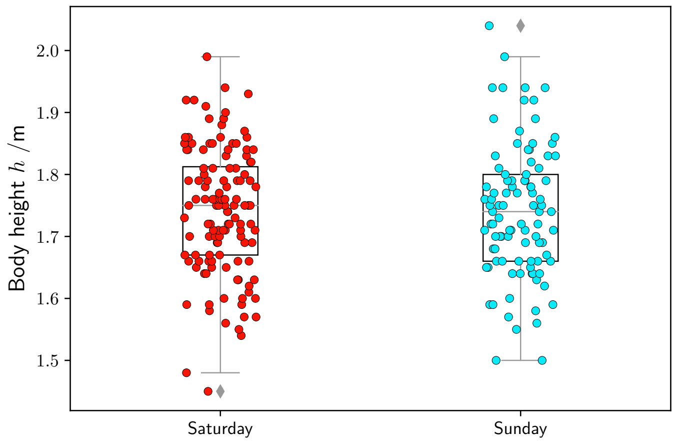


Figure A.3: *Distribution of participants body heights h for the studies towards dense crowds.*

the far-reaching individual characteristics of each participant and the resulting consequences on the reproducibility of the measurements, in the following a narrative description of the participants based on the coding manual (Tab A.4) generated with the methods described in Sec. 4.5 is presented.

Table A.4: *Coding manual for the narrative description of PWD.*

Main category	Attribution	Categorisation	Specification
Gender	male ∨ female ∨ not specified	–	–
Assistive device	Personal ∨ Walking frame ∨ Walking stick ∨ White cane ∨ White stick ∨ Wheelchair	electrically operated ∨ manually operated	by hand ∨ by chin
Body region	arm ∨ body ∨ brain ∨ hands ∨ head ∨ foot ∨ knee ∨ leg ∨ palms ∨ shoulder	–	–
Adjective	hang down ∨ gesticulation ∨ knock-knees ∨ obese ∨ often stretched out ∨ playing ∨ saliva flow ∨ spasticity ∨ sporty ∨ is swinging forth and back ∨ talkative ∨ tilts	wildly ∨ strong ∨ unilateral ∨ bilateral ∨ to the side	–

Continued on the next page

Table A.4 – continued from the previous page

Main category	Attribution	Categorisation	Specification
Features	assistance ∨ distanced to ∨ disturbed balance ∨ following ∨ gait posture ∨ gait style ∨ hands ∨ look around ∨ nervous ∨ operating ∨ orientation difficulties ∨ oriented to ∨ holding the shoulder of a predecessor ∨ outgoing ∨ reaction ∨ seeking for information ∨ self-confident ∨ step frequency ∨ step size ∨ strained ∨ turned to the outside (hands)	personal ∨ others ∨ environment ∨ neighbours ∨ person of trust ∨ cool ∨ upright ∨ respectfully ∨ distanced ∨ angled ∨ springing ∨ agile ∨ jerky ∨ manoeuvrable ∨ swaying ∨ bent / bended ∨ uses foot to push off ∨ limps ∨ wiggles ∨ see sawing ∨ on body ∨ spread out ∨ frequently ∨ once in a while ∨ single-handed ∨ two-handed ∨ neighbours ∨ person of trust ∨ environment ∨ all directions ∨ delayed ∨ fast ∨ fast ∨ slow ∨ influenced by shortened legs ∨ small ∨ large	wildly ∨ fixed ∨ various ∨

Continued on the next page

Table A.4 – continued from the previous page

Main category	Attribution	Categorisation	Specification
Characteristics	activity ∨ appearance ∨ articulation ∨ communication style is ∨ curious ∨ deflect ∨ distancing ∨ impairment ∨ interested in ∨ may stand for a short time ∨ no characteristic features ∨ requires assistance for ∨ self-initiative ∨ slightly annoyed ∨ sociable behaviour	high urge ∨ insecure ∨ introverted ∨ friendly / polite ∨ open-mindedness ∨ self-confident / cool ∨ tired ∨ difficulties ∨ hard to understand ∨ not possible ∨ slowly ∨ silent ∨ communicative ∨ by images ∨ only with trusted persons ∨ easy to ∨ undistanced ∨ distanced ∨ seeing ∨ hearing ∨ walking ∨ mental ∨ seeking attention from others ∨ environment ∨ other persons ∨ short distances ∨ long distances ∨ hardly any ∨	–

PWD_9: A *female* participant who *is not* assisted by an *assistive device.* Participants *body* is *not visibly impaired.* The individual motion style is characterised by *frequently swaying.* A third person *may* notice *an often tired appearance* in everyday life situations.

PWD_10: A *female* participant who *is not* assisted by an *assistive device.* Participants *body* is *not visibly impaired.* The individual motion style is characterised by *walking frequently bent.* A third person *may* notice *an impaired foot and hearing disabilities* in everyday life situations.

PWD_11: A *female* participant who *is not* assisted by an *assistive device.* Participants *body* is *not visibly impaired.* The individual motion style is characterised by *looking around frequently.* A third person *may* notice *an easily distraction* in everyday life situations.

PWD_12: A *male* participant who *is not* assisted by an *assistive device.* Participants *body* is *not visibly impaired.* The individual motion style is characterised by *a fast step frequency.* A third person *may* notice *no characteristic features* in everyday life situations.

PWD_18: A *female* participant who *is not* assisted by an *assistive device*. Participants *body* is *not visibly impaired*. The individual motion style is characterised by *orientation to others*. A third person *may* notice *a sociable behaviour* in everyday life situations.

PWD_19: A *male* participant who *is not* assisted by an *assistive device*. Participants *body* is *not visibly impaired*. The individual motion style is characterised by *distance to to others and oriented to a fixed neighbour*. A third person *may* notice *high urge to be active* in everyday life situations.

PWD_20: A *male* participant who *is* assisted by an *personal assistant*. Participants *body* is *not visibly impaired*. The individual motion style is characterised by *distance to to others and oriented to a fixed neighbour*. A third person *will* notice *seeking attention from others behaviour and an open-mindedness appearance* in everyday life situations.

PWD_21: A *female* participant who *is not* assisted by an *assistive device*. Participants *body* is *not visibly impaired*. The individual motion style is characterised by *tending to keep increased distances to other and talking to herself*. A third person *may* notice *a friendly, polite and introverted appearance* in everyday life situations.

PWD_22: A *male* participant who *is not* assisted by an *assistive device*. Participants *body* is *swinging forth and back*. The individual motion style is characterised by *playing with something in his hands for reassurance*. A third person *will* notice *no characteristic features* in everyday life situations.

PWD_23: A *male* participant who *is* assisted by an *personal assistant*. Participants *head and shoulder* is *hanging*. The individual motion style is characterised by *slow step frequency*. A third person *will* notice *a strong salivation flow* in everyday life situations.

PWD_24: A *male* participant who *is not* assisted by an *assistive device*. Participants *body* is *sporty*. The individual motion style is characterised by *fast step frequency and an upright gait posture*. A third person *will* notice *communication is only with trusted persons possible* in everyday life situations.

PWD_26: A *female* participant who *is not* assisted by an *assistive device*. Participants *body* is *adipose*. The individual motion style is characterised by *talkative behaviour and following behaviour to others*. A third person *will* notice *no characteristic features* in everyday life situations.

PWD_28: A *male* participant who *is not* assisted by an *assistive device*. Participants *hands and arms* are *gesticulating wildly*. The individual motion style is characterised by *spread out arms*. A third person *will* notice *no characteristic features* in everyday life situations.

PWD_30: A *male* participant who *is not* assisted by an *assistive device*. Participants *body* is *walking impaired*. The individual motion style is characterised by *limping and spasticity*. A third person *will* notice *difficulties in articulation due to spasticity, distanced behaviour to others and interested behaviour in environment* in everyday life situations.

PWD_32: A *male* participant who *is not* assisted by an *assistive device*. Participants *body* is *not visible impaired*. The individual motion style is characterised by *wobbling from one leg to the other leg and orientation to all directions*. A third person *will* notice *a curious behaviour* in everyday life situations.

PWD_34: A *female* participant who *is* assisted by an *manually operated wheelchair* (l_{whe} = 1.40 m, w_{whe} = 0.6 m) *with personnel assistance*. Participants *body* is *sitting in a wheelchair*. The individual motion style is characterised by *dependency to be pushed, orientation towards a contact person*. A third person *will* notice *articulation is not possible due to bilateral spasticity* in everyday life situations.

PWD_35: A *male* participant who *is* assisted by an *manually operated wheelchair* (l_{whe} = 1.16 m, w_{whe} = 0.74 m) *and the body often tilts to the side*. Participants *body* is *sitting in a wheelchair*. The individual motion style is characterised by *slow operating single-handed*. A third person *will* notice *the unilateral spasticity and interested behaviour in the environment* in everyday life situations.

PWD_36: A *female* participant who *is* assisted by an *electrical operated wheelchair* (l_{whe} = 1.23 m, w_{whe} = 0.64 m) *with chin steering*. Participants *body* is *sitting in a wheelchair*. The individual motion style is characterised by *slow movement*. A third person *will* notice *articulation difficulties and hard to understandable communication* in everyday life situations.

PWD_37: A *female* participant who *is* assisted by an *electrical operated wheelchair* (l_{whe} = 1.10 m, w_{whe} = 0.77 m) *with (sporadic) personnel assistance*. Participants *body* is *obese and sitting in a wheelchair*. The individual motion style is characterised by *jerking by operating with arms and feet and orientation towards environment*. A third person *will* notice *an open-mindedness appearance* in everyday life situations.

PWD_38: A *female* participant who *is* assisted by an *manually operated wheelchair* (l_{whe} = 0.92 m, w_{whe} = 0.66 m) *with personnel assistance*. Participants *body* is *sitting in a wheelchair and the the arms are very short*. The individual motion style is characterised by *fast and manoeuvrable*. A third person *may* notice *no characteristic feature* in everyday life situations.

PWD_39: A *female* participant who *is* assisted by an *manually operated wheelchair ($l_{whe} = 0.90$ m, $w_{whe} = 0.60$ m) with personnel assistance.* Participants *body* is *sitting in a wheelchair.* The individual motion style is characterised by *no specific feature.* A third person *may* notice *no characteristic feature* in everyday life situations.

PWD_40: A *male* participant who *is* assisted by an *manually operated wheelchair ($l_{whe} = 0.76$ m, $w_{whe} = 0.66$ m).* Participants *body* is *sitting in a wheelchair.* The individual motion style is characterised by *fast and agile; uses foot to push off and .* A third person *may* notice *no characteristic feature* in everyday life situations.

PWD_41: A *male* participant who *is not* assisted by an *assistive device.* Participants *arms* are *often angled and the hand to the sides.* The individual motion style is characterised by *delayed reaction times, obviously slow movement, orientation to neighbours.* A third person *will* notice *a easy to deflection* in everyday life situations.

PWD_42: A *male* participant who *is* assisted by an *personal assistant.* Participants *knees* are *characterised as knock-knees.* The individual motion style is characterised by *limping and contact searches to neighbours.* A third person *will* notice *an insecure appearance and difficulties in articulation* in everyday life situations.

PWD_43: A *male* participant who *is* assisted by an *personal assistant.* Participants *body* is *characterised by strong movement restrictions and a strong saliva flow.* The individual motion style is characterised by *no characteristic features.* A third person *will* notice *difficulties in articulation and communication by images* in everyday life situations.

PWD_44: A *male* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by a bilateral spasticity.* The individual motion style is characterised by *small steps and impaired vision.* A third person *may* notice *insecure appearance* in everyday life situations.

PWD_45: A *male* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by a bilateral spasticity.* The individual motion style is characterised by *wiggle walking activities, a slow communication with difficulties in articulation.* A third person *may* notice *no characteristic features* in everyday life situations.

PWD_48: A *female* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by strong limitation of vision.* The individual motion style is characterised by *a slightly bended gait posture and fast step frequency.* A third person *may* notice *a good orientation* in everyday life situations.

PWD_49: A *female* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by severe hearing impairment.* The individual motion style is characterised by *orientation to neighbours and hardly any self-initiative.* A third person *may* notice *no characteristic features* in everyday life situations.

PWD_51: A *male* participant who *is* assisted by a *manually operated wheelchair* (l_{whe} = 1.10 m, w_{whe} = 0.80 m) *and personnel assistant.* Participants *body* is *characterised by sitting and fixed to a wheelchair.* The individual motion style is characterised by *no characteristic feature.* A third person *may* notice *an open-mindedness appearance* in everyday life situations.

PWD_52: A *female* participant who *is* assisted by a *personnel assistant.* Participants *body* is *heavily bent.* The individual motion style is characterised by *difficulties in orientation and dependence on hand-guidance by others.* A third person *may* notice *no characteristic features* in everyday life situations.

PWD_54: A *female* participant who *is* assisted by a *white stick and personnel assistant.* Participants *body* is *characterised by no characteristic features.* The individual motion style is characterised by *orientation by hand and usage of arms for orientation.* A third person *may* notice *no characteristic features* in everyday life situations.

PWD_55: A *female* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by no characteristic features.* The individual motion style is characterised by *no characteristic features.* A third person *may* notice *a insecure appearance and supportive behaviour* in everyday life situations.

PWD_56: A *male* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by no characteristic features.* The individual motion style is characterised by *fast step cycle and a tendency to seeking for contact to neighbours.* A third person *may* notice *a slaggy appearance* in everyday life situations.

PWD_57: A *male* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by no characteristic features.* The individual motion style is characterised by *no characteristic features.* A third person *may* notice *good orientation and a tendency to deflect by many stimuli* in everyday life situations.

PWD_58: A *male* participant who *is not* assisted by an *assistive device.* Participants *shoulders* are *bent forwards.* The individual motion style is characterised by *fast step frequency.* A third person *will* notice *no characteristic features* in everyday life situations.

PWD_59: A *male* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by no characteristic feature.* The individual motion style is characterised by *simply following neighbours.* A third person *will* notice *no characteristic features* in everyday life situations.

PWD_60: A *female* participant who *is not* assisted by an *assistive device.* Participants *body* is *characterised by no characteristic feature.* The individual motion style is characterised by *a self-confident gait posture.* A third person *will* notice *a talkative, open-mindedness appearance* in everyday life situations.

PWD_61: A *male* participant who *is* assisted by a *personnel assistant.* Participants *hands* are *weaving frequently.* The individual motion style is characterised by *orientation by holding the shoulder of a predecessor.* A third person *may* notice *a good orientation* in everyday life situations.

PWD_62: A *male* participant who *is not* assisted by an *assisted device.* Participants *knees* are *are strongly bent.* The individual motion style is characterised by *a cool and springing gait* . A third person *may* notice *no characteristic features* in everyday life situations.

PWD_63: A *female* participant who *is not* assisted by an *assisted device.* Participants *body* is *characterised by no characteristic feature.* The individual motion style is characterised by *a fast step frequency* . A third person *may* notice *a nervous behaviour* in everyday life situations.

PWD_64: A *male* participant who *is not* assisted by an *assisted device.* Participants *arms* are *are frequently stretched out.* The individual motion style is characterised by *large steps and fast frequency* . A third person *may* notice *a nervous behaviour* in everyday life situations.

PWD_65: A *female* participant who *is not* assisted by an *assisted device.* Participants *body* is *characterised by no characteristic feature.* The individual motion style is characterised by *maintaining distance to others.* A third person *may* notice *no characteristic feature* in everyday life situations.

PWD_67: A *female* participant who *is not* assisted by an *assisted device.* Participants *body* is *a noticeable walking impairment.* The individual motion style is characterised by *self-confident gait posture and orientation to others.* A third person *may* notice *to get quickly annoyed* in everyday life situations.

Table A.5: *Identification of participants with disabilities (PWD_ID) by personal identification numbers (persIDs). The numbering of the participants with disabilities is not continuous. Missing identification numbers mean that they have been used in another context, e.g. for a helper or caregiver.*

PWD_ID	persID in bottleneck trials									persID in in corridor trials							
	00	01	02	03	04	05	06	07	08	01	02	03	04	05	06	07	08
Considering **older** participants:																	
PWD_9	8	70	59	33	39	32	35	29	52	3	30	7	34	1	1	2	22
PWD_10	9	78	77	51	42	58	50	66	74	24	49	38	26	42	53	19	57
PWD_11	47	80	79	86	63	52	53	80	69	71	71	65	80	75	59	45	59
PWD_12	51	82	85	43	25	68	39	75	77	76	80	71	77	85	63	47	61
Considering **cognition disabled** participants:																	
PWD_18	[a]	73	88	60	92	70	71	63	80	18	79	4	92	32	45	70	83
PWD_19	4	82	19	20	18	12	33	18	49	20	52	22	19	50	16	30	26
PWD_20	97	28	60	45	74	59	96	37	72	52	31	35	88	42	22	63	2
PWD_21	6	69	83	52	41	53	69	80	73	22	89	70	78	73	91	74	78
PWD_22	7	86	86	59	85	76	91	70	82	19	86	5	93	30	64	71	84
PWD_23	8	85	56	27	27	79	51	81	61	44	37	51	91	62	78	81	72
PWD_24	9	40	62	49	31	16	45	[a]	15	27	48	20	27	23	33	2	19
PWD_26	11	75	38	11	71	24	28	11	84	9	98	95	46	40	25	31	80
PWD_28	30	58	68	55	84	61	23	33	26	74	34	45	41	6	68	50	70
PWD_30	10	30	32	34	22	15	35	24	38	8	26	6	29	3	14	19	30
PWD_32	[a]	[a]	76	90	32	62	74	87	20	38	88	7	95	60	74	77	87
Considering participants using a **wheelchair**:																	
PWD_34	3	37	65	52	6	62	84	16	49	8	55	72	61	33	48	31	65
PWD_35	40	38	54	11	60	2	65	1	48	50	35	5	69	22	26	8	35
PWD_36	42	54	26	70	84	20	45	32	34	29	85	10	48	14	43	7	31
PWD_37	43	48	71	82	74	14	42	9	32	28	45	9	45	43	32	11	48
PWD_38	44	30	38	50	12	49	61	53	68	33	43	26	59	90	33	1	93
PWD_39	46	80	41	76	38	8	56	41	36	36	40	38	80	63	1	60	59
PWD_40	65	29	6	86	70	81	66	4	63	21	27	29	92	1	82	68	53
Considering participants with **walking disabilities**:																	
PWD_41	72	27	48	84	27	78	72	20	18	73	84	45	31	70	51	43	58
PWD_42	47	47	2	36	55	35	75	30	32	25	25	35	42	18	31	51	2

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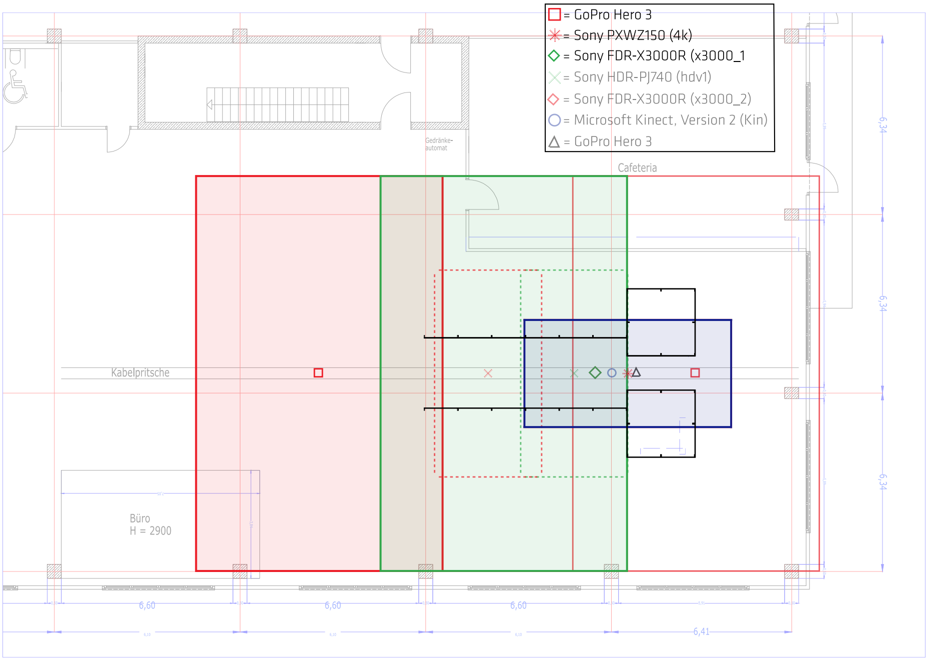
Table A.5 – continued from the previous page

PWD_ID	persID in trial bottleneck trials									persID in corridor trials							
	00	01	02	03	04	05	06	07	08	01	02	03	04	05	06	07	08
PWD_43	11	79	74	85	79	53	85	72	46	30	23	84	88	1	37	14	43
PWD_44	69	74	83	60	72	70	84	55	79	60	79	73	92	64	78	79	80
PWD_45	70	70	82	6	76	71	81	26	86	69	33	80	61	13	55	54	53
Considering participants with **mixed single disabilities**:																	
PWD_48	70	41	18	26	53	71	58	16	51	61	35	49	51	61	60	56	55
PWD_49	6	56	44	30	35	40	26	42	31	[a]	73	11	12	7	11	78	77
PWD_51	3	76	8	51	19	21	9	12	40	11	5	3	15	3	46	13	20
PWD_52	4	78	9	57	9	31	50	9	23	30	52	46	13	30	65	12	45
PWD_54	2	80	21	52	55	51	48	47	76	45	1	67	29	13	13	30	17
Considering participants with **mixed multiple (heterogeneous) disabilities**:																	
PWD_55	4	11	61	48	49	40	21	25	65	6	79	52	68	2	44	31	33
PWD_56	10	71	79	10	44	18	14	4	24	36	30	7	70	61	54	48	48
PWD_57	13	68	77	7	34	71	[a]	7	1	9	82	3	63	32	66	6	43
PWD_58	15	43	67	28	14	24	[a]	38	21	22	62	17	73	1	61	2	64
PWD_59	21	39	33	63	77	80	[a]	55	72	70	74	77	76	57	30	39	39
PWD_60	26	33	37	29	56	32	[a]	33	27	13	40	32	50	23	34	34	30
PWD_61	39	58	23	31	21	16	19	19	70	11	38	21	37	60	13	46	47
PWD_62	40	52	65	37	73	21	36	15	29	31	25	13	58	34	75	11	37
PWD_63	41	28	30	6	40	23	16	11	47	19	41	25	60	25	57	50	52
PWD_64	46	37	34	11	45	27	[a]	14	48	24	42	28	61	28	58	51	53
PWD_65	69	44	26	2	19	20	17	20	37	67	23	23	39	55	32	28	22
PWD_67	81	48	35	70	51	57	[a]	46	79	59	83	40	30	63	60	57	51

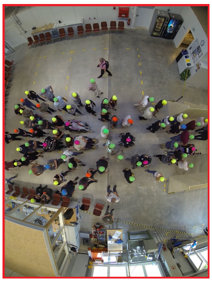
[a] No participation.

A.3.3 Data Capture and Trajectories Quality

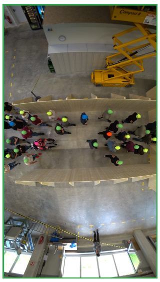
Footage of three camera perspectives was used to extract and combine individual trajectories (Fig. A.4). All cameras were mounted perpendicular to a height of 6.34 m above the ground floor. The recordings have a minimum resolution of 1920 x 1080 pixel and a frame rate of $25\,s^{-1}$. Assuming a participant's maximum speed of $2\,m\,s^{-1}$ leads to a spatial movement of 0.08 m between two successive frames.



(a) *Building layout, camera positions and covered area for video recordings.*



(b) *Perspective a: GoPro3_1.*



(c) *Perspective b: x3000_1.*

(d) *Perspective c: 4k.*

Figure A.4: *Overview of the study location (a) and sample images of camera perspectives used. Footage of (b) GoPro3_1, (c) x3000_1 and (d) 4k were used to track the individual positions and to combine trajectories. Frame colors of subfigures (b)-(d) correspond to covered areas of the cameras.*

Table A.6: *Camera perspectives used for trajectory extraction and data analysis.*

Name	Model	Resolution	Description
GoPro4-1	Gopro Hero 4	1920x1440	Bottleneck exit
GoPro4-2	Gopro Hero 4	1920x1440	Overview perspective waiting area and return path
4k[a]	Sony PXW-Z150	3840x2160	Central location above bottleneck entrance ($x, y = [0, 0]$), also captures bottleneck exit and approximately 3.5 m of the entrance geometry
x3000-2	Sony FDR-X 3000 R	1920x1080	Overview perspective
hdv1	Sony HDR-PJ740	1920x1080	Entrance geometry before bottleneck, bottleneck entrance
x3000-1[a]	Sony FDR-X 3000 R	1920x1080	Overview perspective entrance geometry
hdv2	Sony HDR-PJ740	1920x1080	Entrance of geometry and entrance bottleneck
GoPro3[a]	Gopro Hero 3	1920x1440	Overview perspective waiting area

[a] Camera perspectives used for trajectory extraction and data analysis. The combination of the trajectories resulting from different camera perspectives was realised by finding similar positions in overlapping areas. Couples of similar positions were tracked in space and time and combined over a weighting function (considering the more precise trajectories of the 4k-perspective). Starting with the 4k-perspective directly above the bottleneck entrance the combination was performed flow-upwards: 4k $\rightarrow$ X3000 $\rightarrow$ GoPro3. This procedure was developed by Juliane Adrian [209].

The image distortion has to take into account to get a constant pixel coverage. Transferring the coordinate system of the real world to a coordinate system of the image was done by optimisation of reference points and the projected image points. The approach is described in detail in [207, 208, 215] and in [265, Supporting Information 2].

Participants were asked to wear coloured caps according to their body height during study times to increase the tracking quality of the individual position. The unique colour coded pixel area of a cap was approximated by an ellipse, in which the centre represents the position of a participant. This assumed position is shifted according to the inclination of the view and projected through the body's centre of mass onto the ground floor. The error estimation of a participant's position consists of maximum detection error (e_{max}), systematic error caused by insufficient calibration (e_{cal}), systematic error caused by coloured cap markers (e_{mar}) and error variance of the position caused by wrong participant's height (e_{hei}) [207, pp. 3 sqq].

The maximal error (e_{max}) for the perspective of the 4k-footage was estimated by a linear combination (Eq A.1) of the single errors due to calibration (e_{cal}), marker detection (e_{mar}) and body height (e_{hei}).

$$e_{max} = e_{cal} + e_{mar} + e_{hei} \tag{Eq A.1}$$

Assuming a continuous detection and tracking of a participants' head, a sufficient auto-correction of the central position of the head-ellipses and given that an error between two measuring points is less than or equal to a reference point of calibration, the maximum total error e_{max} of the 4k-perspective is reached at the edge of the image at an angle of $\alpha = 42°$ and calculated with:

e_{cal}: 0.034 m for insufficient correction of the lens error and

e_{hei}: 0.058 m for not exact determination of participants body height.

Given Eq A.1, the maximum error of a position in the 4k-footage during studies with crowd heterogeneities wheelchair, walking disabled and mixed is 0.092 m ($e_{max} = 0.034\,\mathrm{m} + 0.0\,\mathrm{m} + 0.058\,\mathrm{m}$) and for the homogeneous crowd conditons is 0.084 m ($e_{max} = 0.026\,\mathrm{m} + 0.0\,\mathrm{m} + 0.058\,\mathrm{m}$). Here, the following assumptions were made:

e_{max}: should be negligible for reasonably conducted laboratory experiments [208, p. 3].

e_{cal}: 0.034 m for Bot_whe, Bot_wal, and Bot_mix trials; 0.026 m for Bot_ref trials. The maximum calibration error was measured during the studies at head height on fixed reference points. It was calculated backwards by the distance between the real position and the difference of pixels.

e_{mar}: should be negligible for reasonably conducted laboratory experiments [208, p. 3]. Assuming a sufficient auto-correction process of $\beta \cdot 0.0012\,\mathrm{m}$, e_{mar} is set to 0. β is the angle of the camera view to the detected position.

e_{hei}: 0.058 m ($e_{hei} = \frac{d_h}{2 \cdot tan(\alpha)}$) with the maximum height variation of the same coloured participants of $d_{hei} = 0.13\,\mathrm{m}$ (and $\beta = 42°$).

Assuming a constant speed of a participant passing the entire camera perspective, the average error ($\bar{e}_{avg}$) over the perspective could be estimated by:

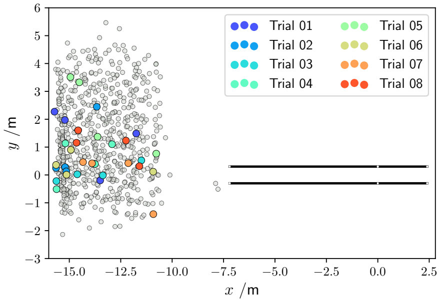
$\bar{e}_{cal}$: 0.015 m for insufficient correction of the lens error, and

$\bar{e}_{hei}$: 0.013 m for not exact determination of participants' body height,

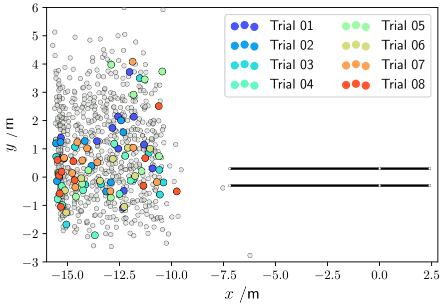
which results in an the average error ($\bar{e}_{avg}$) of a position for the 4k-perspective of 0.028 m.

A.3.4 Starting Position

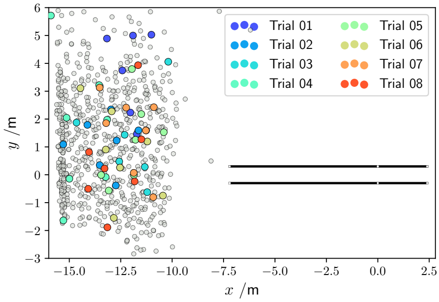
Since the reproducibility and stationarity of the measured values are sensitive to the presence of PWD inside the measurement area, the individual position of participants at the beginning of a trial was analysed. Fig. A.5 and Fig. A.6 compares starting position of PWD (coloured scatter) and NDP (grey scatter) inside the waiting area at the first frame before a study begins. The starting positions of the participants were not predetermined. However, care was taken to ensure that there were no huge clusters of people with disabilities.



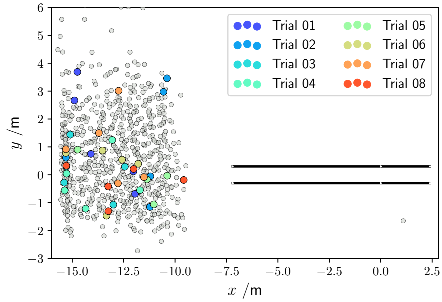
(a) *Cor_eld.*



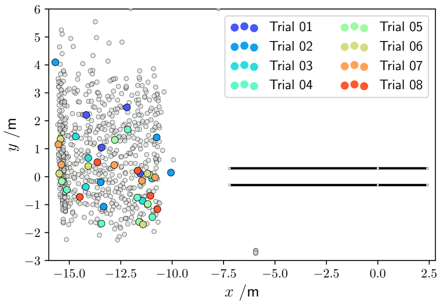
(b) *Cor_cog.*



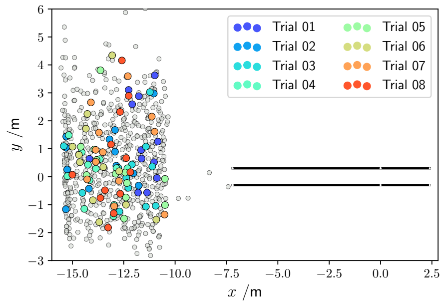
(c) *Cor_whe.*



(d) *Cor_wal.*

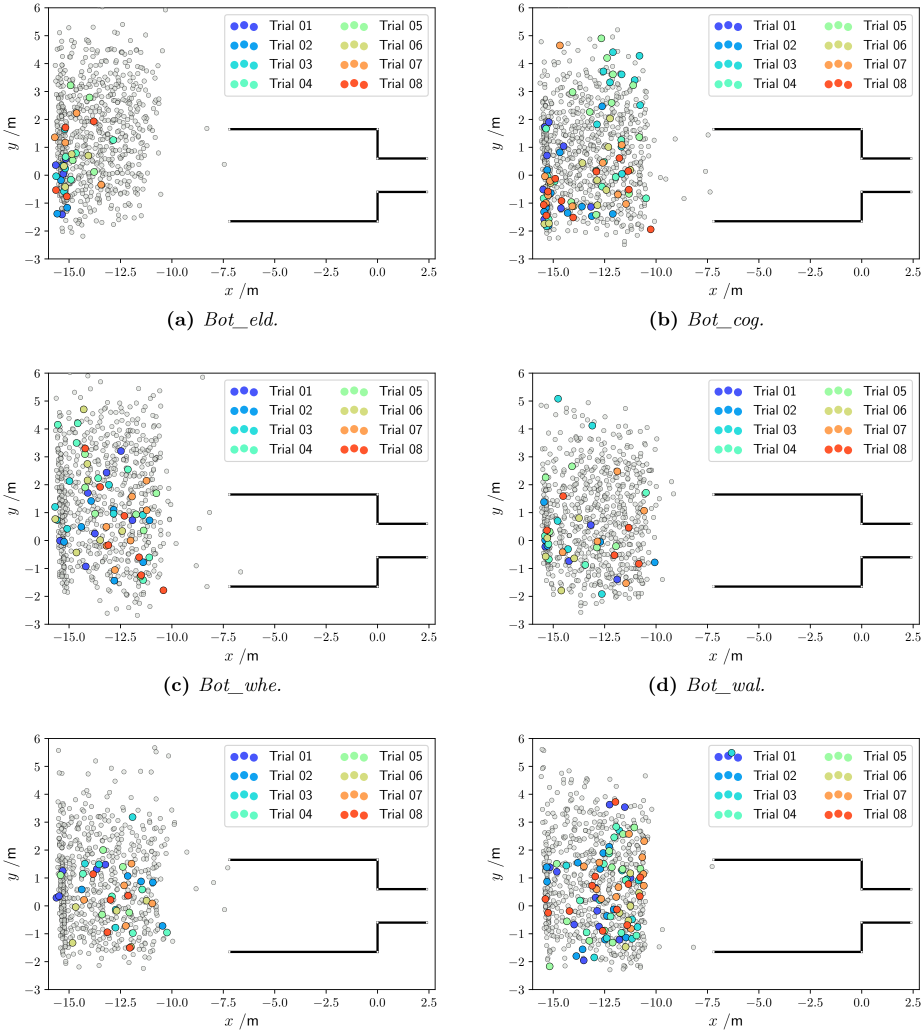


(e) *Cor_mix.*



(f) *Cor_het.*

Figure A.5: *Individual starting positions for PWD (coloured scatter) and NDP (grey scatter) in corridor studies.*



(a) *Bot_eld.* **(b)** *Bot_cog.*

(c) *Bot_whe.* **(d)** *Bot_wal.*

(e) *Bot_mix.* **(f)** *Bot_het.*

Figure A.6: *Individual starting positions for PWD (coloured scatter) and NDP (grey scatter) in bottleneck studies.*

A.3.5 Time Series Analysis

Tab. A.7 summarises the properties of stationarity for each trial. In particular, the time intervals set to be stationary as a result of the time series analysis (Sec. 5.4) are presented. The number of frames is following the combined trajectory files based on the video footage. Summary statistics for the flow rate J are presented for the three main phases of the studies – beginning-, stationary-, and ending phase – in Table A.8. They are related to the third step of time series analysis described in Sec. 5.4 on p. 56.

A comparison of flow rate J (orange line) and related rolling standard deviation σ_{SMA} (blue line) is exemplary presented in Fig. A.7. It clearly shows that an interval can be identified for both the mean and the standard deviation of the flow rate in which the values are independent of the time shift (stationary). This state is recognisable for the corridor but is even more apparent for the bottleneck.

Depending on the type of disability and the assistive devices used, the height and length of the fluctuations increases for corridor and bottleneck situations (see as an example the consideration of PWD using wheelchairs in Fig. A.7b and Fig. A.8b and consideration of heterogeneous disabled participants in Fig. A.7c and Fig. A.8c).

Table A.7: *Steady-state intervals and number of participants N with and without disabilities in each trial.*

Trial	Total frames		Steady state frames		N	
	First	Last	First	Last	PWD	NDP
Bot_eld_00[a]	97	11869	122	11765	4	81
Bot_eld_01	110	1988	580	1000	4	81
Bot_eld_02	136	2014	550	900	4	81
Bot_eld_03	114	1891	550	900	4	82
Bot_eld_04	89	1714	550	875	4	82
Bot_eld_05	88	1659	450	700	4	83
Bot_eld_06	81	1667	625	900	3	83
Bot_eld_07	109	1531	500	700	4	83
Bot_eld_08	97	1528	490	800	4	83
Cor_eld_01	71	2128	500	1550	4	79
Cor_eld_02	94	2237	500	1700	4	81
Cor_eld_03	98	2105	500	1550	4	81
Cor_eld_04	77	1936	480	1320	4	81
Cor_eld_05	59	1752	520	1380	4	81
Cor_eld_06	69	1783	575	1425	4	81

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Table A.7 – continued from the previous page

Trial	Total frames		Steady state frames		N	
	First	Last	First	Last	PWD	NDP
Cor_eld_07[b]	73	1621	320	1325	4	81
Cor_eld_08	77	1626	400	1200	4	81
Bot_cog_00[a]	68	14114	69	14030	9	88
Bot_cog_01	89	1460	680	1080	9	86
Bot_cog_02[b]	62	2322	500	1300	11	87
Bot_cog_03	63	2097	755	1050	11	87
Bot_cog_04	72	2204	480	875	11	88
Bot_cog_05	80	4947	580	980	11	88
Bot_cog_06	68	1992	550	1000	11	89
Bot_cog_07	64	1914	620	1100	10	90
Bot_cog_08	81	1812	550	750	11	89
Cor_cog_01	73	2836	600	2400	11	89
Cor_cog_02	73	2767	600	2400	11	89
Cor_cog_03	71	2473	675	1790	11	85
Cor_cog_04	96	2382	730	1900	11	88
Cor_cog_05	122	2455	620	2000	10	91
Cor_cog_06	73	2252	560	1940	11	89
Cor_cog_07	232	2142	500	1505	11	87
Cor_cog_08	83	1957	700	1540	11	87
Bot_whe_00[a]	271	13493	271	13493	7	77
Bot_whe_01	61	2554	600	1600	7	81
Bot_whe_02	82	2732	600	1800	7	81
Bot_whe_03	77	2400	570	1450	7	80
Bot_whe_04	71	2232	500	1200	7	80
Bot_whe_05	116	2291	700	1550	7	83
Bot_whe_06	65	2138	530	1250	7	83
Bot_whe_07	160	2229	750	1040	7	85
Bot_whe_08	74	1937	500	1100	7	83
Cor_whe_01	82	3437	600	2900	7	85
Cor_whe_02	91	2899	600	2100	7	83
Cor_whe_03[b]	99	3002	900	2580	7	85
Cor_whe_04	91	2787	600	2100	7	85
Cor_whe_05	113	2537	700	2050	7	84

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Table A.7 – continued from the previous page

Trial	Total frames		Steady state frames		N	
	First	Last	First	Last	PWD	NDP
Cor_whe_06	112	2480	400	1900	7	83
Cor_whe_07	105	2557	750	2100	7	85
Cor_whe_08	71	2454	400	2000	7	86
Bot_wal_00[a]	79	10981	90	10951	5	70
Bot_wal_01	90	2051	450	1000	5	79
Bot_wal_02	82	2063	600	1200	5	80
Bot_wal_03[c]	87	1810	450	800	5	80
Bot_wal_04[b]	80	1772	450	700	5	80
Bot_wal_05	71	1600	450	700	5	79
Bot_wal_06	70	1562	450	865	5	80
Bot_wal_07[b]	115	1577	400	700	5	81
Bot_wal_08	61	1489	480	750	5	81
Cor_wal_01	99	2429	500	2000	5	81
Cor_wal_02	63	2416	500	2000	5	85
Cor_wal_03	88	2225	370	1760	5	86
Cor_wal_04	88	2182	410	1740	5	87
Cor_wal_05	70	1897	400	1570	5	83
Cor_wal_06	73	1830	460	1410	5	81
Cor_wal_07	77	1796	405	1380	5	83
Cor_wal_08	99	1914	400	1175	5	84
Bot_mix_00[a]	202	14163	205	14160	5	74
Bot_mix_01[c]	79	1398	400	890	5	75
Bot_mix_02[c]	150	2548	700	1500	5	74
Bot_mix_03	121	2243	380	1000	5	74
Bot_mix_04	83	2242	500	1100	5	75
Bot_mix_05	110	2036	390	890	5	75
Bot_mix_06[c]	85	1958	500	1170	5	75
Bot_mix_07	81	1780	550	780	5	75
Bot_mix_08	75	1615	400	810	5	75
Cor_mix_01	77	2725	625	2450	4	75
Cor_mix_02	236	2772	700	2200	5	77
Cor_mix_03	94	2369	500	1760	5	76
Cor_mix_04	97	1446	350	2010	5	79

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Table A.7 – continued from the previous page

Trial	Total frames		Steady state frames		N	
	First	Last	First	Last	PWD	NDP
Cor_mix_05	83	2244	550	1775	5	79
Cor_mix_06	86	2163	530	1755	5	78
Cor_mix_07	84	2387	610	1920	5	78
Cor_mix_08	142	2098	790	1735	5	77
Bot_het_00[a]	65	14103	1505	14103	12	71
Bot_het_01	92	1958	460	810	12	71
Bot_het_02	81	1784	470	880	12	71
Bot_het_03	81	1789	510	800	12	71
Bot_het_04[b]	88	1760	510	650	11	74
Bot_het_05	98	1625	600	910	12	73
Bot_het_06[b]	86	1561	500	700	6	79
Bot_het_07	80	1469	490	810	12	73
Bot_het_08[b]	86	1427	500	700	12	71
Cor_het_01	80	2240	450	1890	12	73
Cor_het_02	81	2091	430	1800	12	73
Cor_het_03	74	1945	355	1545	12	74
Cor_het_04	68	1834	400	1410	12	74
Cor_het_05	82	1720	300	1300	12	73
Cor_het_06	57	1695	260	1290	12	71
Cor_het_07	72	1526	400	1195	12	71
Cor_het_08	63	1549	400	1150	12	71
Bot_ref_00[a]	70	11046	1383	11046	NaN	68
Bot_ref_01	82	1565	420	800	NaN	67
Bot_ref_02	71	1527	500	705	NaN	67
Bot_ref_03	83	1410	450	605	NaN	66
Bot_ref_04	83	1371	480	680	NaN	66
Bot_ref_05[b]	103	1354	450	550	NaN	69
Bot_ref_06	74	1320	580	760	NaN	69
Bot_ref_07[b]	105	1269	600	750	NaN	69
Bot_ref_08	54	1150	480	650	NaN	69
Cor_ref_01	98	1888	420	1100	NaN	68
Cor_ref_02	77	1717	500	1400	NaN	68
Cor_ref_03	91	1561	400	1230	NaN	69

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Table A.7 – continued from the previous page

Trial	Total frames		Steady state frames		N	
	First	Last	First	Last	PWD	NDP
Cor_ref_04	82	1480	380	875	NaN	69
Cor_ref_05	107	1549	500	950	NaN	70
Cor_ref_06	78	1429	400	980	NaN	69
Cor_ref_07	76	1349	500	950	NaN	68
Cor_ref_08	68	1167	350	900	NaN	69

[a] Trials ending by '_00' were designed to measure the unrestricted, free speed v_0. Because of the single passage of participants, no stationary state for $\bar{\rho}$, $\bar{v}$ or $\bar{J}$ could be reached. The time interval refers to the period between the first and last person in the recording interval.
[b] Trial did not considered for capacity analysis due to trend dependency in the flow rate analysis.
[c] No PWD has been passed the measurement area during the steady state interval.

Table A.8: *Time series analysis for the flow rate J /s^{-1}. Mean, Variance and Covariance at the beginning, steady and ending phase of a study are presented.*

Study	**Beginning phase**			**Steady phase**			**Ending phase**		
	Mean	Var	Cov	Mean	Var	Cov	Mean	Var	Cov
Bot_eld_01	1.88	1.49	69.11	0.94	0.01	-1.21	0.43	0.05	-29.31
Bot_eld_02	1.98	2.01	112.25	1.14	0.01	-6.13	0.39	0.06	-44.12
Bot_eld_03	1.84	1.86	115.68	1.08	0.01	3.57	0.42	0.08	-30.88
Bot_eld_04	2.15	1.65	76.41	1.12	0.04	-11.09	0.60	0.13	-32.59
Bot_eld_05	2.22	1.82	76.02	1.27	0.06	-7.22	0.73	0.27	-70.02
Bot_eld_06	2.17	1.89	30.47	0.98	0.05	-2.32	0.48	0.07	-17.12
Bot_eld_07	2.30	2.25	123.51	1.31	0.01	-0.48	0.56	0.06	-23.47
Bot_eld_08	2.32	2.12	89.98	1.04	0.01	-8.58	0.44	0.07	-27.56
Cor_eld_01	1.08	0.26	45.39	1.14	0.04	15.58	0.73	0.10	-33.69
Cor_eld_02	1.12	0.36	66.22	1.04	0.05	6.54	0.77	0.13	-33.06
Cor_eld_03	1.12	0.41	70.63	1.23	0.04	-5.71	0.78	0.16	-35.55
Cor_eld_04	1.30	0.41	62.23	1.35	0.04	-31.87	0.80	0.12	-37.95
Cor_eld_05	1.38	0.35	63.09	1.42	0.03	-11.01	0.77	0.15	-18.75
Cor_eld_06	1.29	0.72	76.69	1.41	0.07	-57.23	0.77	0.17	-16.72
Cor_eld_07	1.18	0.64	78.67	1.57	0.08	-43.09	0.89	0.23	-12.43
Cor_eld_08	1.51	0.62	72.83	1.60	0.02	-25.57	0.88	0.26	-29.65
Bot_cog_01	1.82	0.92	20.96	0.87	0.05	15.75	0.53	0.15	-66.25
Bot_cog_02	2.03	0.99	27.39	0.88	0.16	-80.91	0.43	0.06	-17.17

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Table A.8 – continued from the previous page

Study	Beginning phase			Steady phase			Ending phase		
	Mean	Var	Cov	Mean	Var	Cov	Mean	Var	Cov
Bot_cog_03	1.93	1.28	-77.49	0.82	0.02	7.34	0.27	0.05	-37.32
Bot_cog_04	2.09	1.19	60.45	1.04	0.06	-27.48	0.53	0.14	-42.60
Bot_cog_05	2.22	1.28	59.22	0.98	0.01	-3.88	0.55	0.06	-34.21
Bot_cog_06	1.97	1.03	13.50	1.07	0.05	-5.18	0.51	0.11	-50.64
Bot_cog_07	2.05	0.96	24.13	0.88	0.01	2.90	0.41	0.12	-33.79
Bot_cog_08	1.97	1.34	26.21	1.44	0.02	6.28	0.73	0.23	-70.43
Cor_cog_01	0.95	0.20	32.13	0.95	0.04	-27.44	0.80	0.12	-14.90
Cor_cog_02	1.13	0.29	22.54	0.94	0.04	-39.10	0.55	0.07	-12.17
Cor_cog_03	1.07	0.26	82.23	1.15	0.07	-53.67	0.80	0.12	-42.40
Cor_cog_04	1.19	0.28	51.09	1.14	0.03	8.09	0.85	0.07	-13.98
Cor_cog_05	1.10	0.39	103.97	1.18	0.03	-25.32	0.87	0.25	-31.36
Cor_cog_06	1.21	0.28	46.68	1.24	0.09	-72.00	0.71	0.16	-11.50
Cor_cog_07	0.93	0.87	168.73	1.55	0.04	-18.99	0.95	0.11	-30.79
Cor_cog_08	1.61	0.41	76.22	1.32	0.07	-52.83	0.85	0.15	-19.48
Bot_whe_01	1.22	0.81	-44.98	0.84	0.06	-28.11	0.32	0.06	-8.19
Bot_whe_02	1.27	0.50	24.08	0.67	0.03	-8.49	0.38	0.07	-39.28
Bot_whe_03	1.77	1.29	-7.28	0.54	0.09	-47.39	0.25	0.02	-15.23
Bot_whe_04	1.83	1.15	40.33	0.58	0.06	10.83	0.35	0.05	-25.31
Bot_whe_05	1.28	0.58	78.56	0.64	0.03	-1.49	0.41	0.06	-17.50
Bot_whe_06	1.57	0.82	-0.85	0.66	0.03	14.17	0.42	0.10	-29.44
Bot_whe_07	1.18	0.51	97.55	1.08	0.03	-2.48	0.46	0.06	-43.31
Bot_whe_08	1.48	0.97	14.09	0.89	0.10	-4.75	0.43	0.03	-10.40
Cor_whe_01	0.91	0.26	57.57	0.66	0.13	157.67	0.63	0.08	-17.88
Cor_whe_02	1.06	0.30	42.69	0.93	0.07	55.33	0.40	0.05	2.68
Cor_whe_03	0.52	0.15	49.59	0.95	0.14	120.55	1.00	0.30	-32.51
Cor_whe_04	1.25	0.32	68.37	0.77	0.11	-39.33	0.80	0.17	-24.83
Cor_whe_05	0.73	0.32	25.34	1.12	0.12	78.50	0.79	0.13	-28.28
Cor_whe_06	1.06	0.49	83.31	0.98	0.14	-0.67	0.86	0.13	-34.05
Cor_whe_07	0.66	0.27	73.69	1.15	0.11	58.09	0.97	0.16	-23.65
Cor_whe_08	1.47	0.58	74.78	0.95	0.17	74.62	0.82	0.26	-33.80
Bot_wal_01	2.24	1.80	101.73	0.90	0.06	-22.70	0.23	0.04	-31.84
Bot_wal_02	1.91	1.41	-3.06	0.72	0.03	-12.31	0.26	0.04	-16.93
Bot_wal_03	2.13	1.60	75.43	1.05	0.17	-35.70	0.39	0.04	-26.26

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Table A.8 – continued from the previous page

Study	Beginning phase			Steady phase			Ending phase		
	Mean	Var	Cov	Mean	Var	Cov	Mean	Var	Cov
Bot_wal_04	2.32	1.60	98.07	1.19	0.08	-19.77	0.40	0.04	-32.08
Bot_wal_05	2.16	1.27	67.86	0.94	0.02	-8.86	0.43	0.05	-21.47
Bot_wal_06	2.33	1.72	67.74	0.82	0.01	-10.12	0.33	0.01	-6.01
Bot_wal_07	2.03	1.98	174.91	1.83	0.31	-43.72	0.36	0.09	-31.50
Bot_wal_08	2.12	0.96	54.77	1.16	0.02	-7.41	0.59	0.10	-22.49
Cor_wal_01	1.22	0.44	83.37	0.91	0.03	-26.39	0.73	0.11	-18.64
Cor_wal_02	1.09	0.24	34.84	1.02	0.04	-44.27	0.67	0.07	-0.08
Cor_wal_03	1.08	0.47	76.47	1.20	0.06	-72.90	0.73	0.12	-21.79
Cor_wal_04	1.33	0.55	80.02	1.19	0.07	-46.80	0.63	0.07	-13.09
Cor_wal_05	1.21	0.37	50.59	1.35	0.07	-65.33	0.78	0.21	-17.73
Cor_wal_06	1.47	0.53	73.28	1.34	0.11	7.37	0.78	0.14	-21.63
Cor_wal_07	1.50	0.61	75.46	1.44	0.06	-11.17	0.86	0.29	-24.59
Cor_wal_08	1.46	0.83	94.36	1.59	0.03	-14.16	0.78	0.32	-70.77
Bot_mix_01	2.15	1.77	100.03	1.00	0.06	-0.80	0.28	0.04	-41.03
Bot_mix_02	1.03	0.49	131.41	0.86	0.13	-27.24	0.41	0.11	-51.45
Bot_mix_03	1.52	1.52	107.46	1.39	0.05	4.81	0.27	0.06	-25.20
Bot_mix_04	1.51	0.72	47.56	1.00	0.07	-24.01	0.24	0.03	-32.59
Bot_mix_05	1.47	1.06	101.42	1.15	0.10	24.80	0.55	0.17	-56.49
Bot_mix_06	1.80	0.97	111.92	0.78	0.11	-59.39	0.35	0.04	-19.02
Bot_mix_07	1.60	0.68	77.14	1.29	0.01	2.47	0.66	0.14	-57.86
Bot_mix_08	2.05	1.29	79.90	1.04	0.08	-25.49	0.44	0.15	-26.93
Cor_mix_01	0.96	0.22	48.73	0.70	0.06	4.29	0.53	0.06	-8.20
Cor_mix_02	0.44	0.15	88.20	0.97	0.03	5.14	0.82	0.13	-28.57
Cor_mix_03	0.92	0.28	73.42	0.99	0.16	-98.84	0.79	0.11	-29.70
Cor_mix_04	0.82	0.31	52.46	1.01	0.14	31.72	0.54	0.05	-8.72
Cor_mix_05	0.57	0.19	25.08	1.28	0.05	-13.62	0.81	0.11	-16.21
Cor_mix_06	0.70	0.39	-1.16	1.23	0.05	-32.25	0.97	0.18	-21.27
Cor_mix_07	0.66	0.18	22.44	1.06	0.10	79.74	0.77	0.12	-30.71
Cor_mix_08	0.90	0.39	65.45	1.29	0.02	-16.15	0.71	0.17	-17.30
Bot_het_01	2.02	2.25	86.60	0.84	0.01	-0.54	0.61	0.17	-55.88
Bot_het_02	1.97	1.41	48.28	1.00	0.05	-17.04	0.44	0.09	-22.32
Bot_het_03	2.00	1.47	19.91	0.83	0.03	-2.39	0.38	0.05	-22.21
Bot_het_04	2.00	1.33	65.57	1.11	0.03	-3.87	0.51	0.04	-17.44

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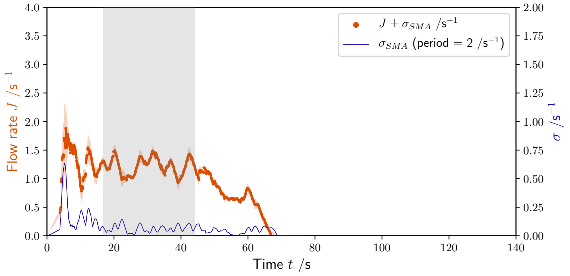
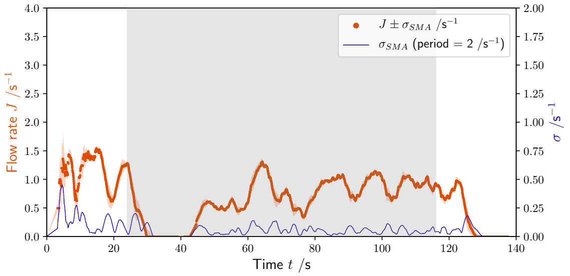
Table A.8 – continued from the previous page

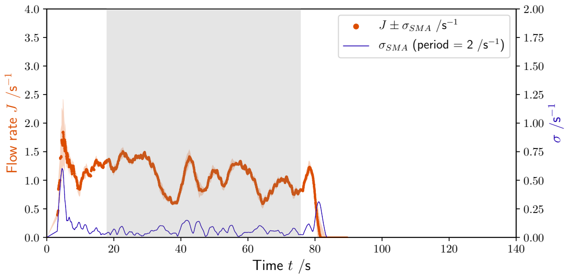
Study	Beginning phase			Steady phase			Ending phase		
	Mean	Var	Cov	Mean	Var	Cov	Mean	Var	Cov
Bot_het_05	2.03	1.33	50.91	0.95	0.01	-4.92	0.27	0.05	-15.97
Bot_het_06	2.10	1.42	77.03	1.13	0.08	-15.52	0.53	0.08	-27.31
Bot_het_07	2.26	1.75	32.36	1.13	0.04	-5.47	0.42	0.11	-25.84
Bot_het_08	2.14	1.42	67.76	0.89	0.07	-13.52	0.25	0.01	-7.94
Cor_het_01	0.99	0.26	46.62	1.06	0.06	-52.74	0.82	0.13	-10.27
Cor_het_02	1.20	0.37	63.39	1.10	0.05	-48.36	0.64	0.08	-8.07
Cor_het_03	1.27	0.52	61.90	1.27	0.03	-26.20	0.94	0.20	-19.45
Cor_het_04	1.47	0.53	67.36	1.33	0.07	-34.84	0.88	0.22	-21.60
Cor_het_05	1.16	0.65	76.45	1.55	0.06	-32.71	1.01	0.21	-24.80
Cor_het_06	1.21	0.50	45.95	1.48	0.04	-22.03	1.02	0.28	-26.56
Cor_het_07	1.59	0.65	69.08	1.59	0.05	12.07	0.86	0.29	-19.58
Cor_het_08	1.67	0.65	56.37	1.55	0.04	-22.09	1.13	0.30	-26.45
Bot_ref_01	1.98	1.78	62.28	0.99	0.01	-2.95	0.55	0.16	-29.85
Bot_ref_02	1.98	1.51	2.74	0.58	0.03	8.54	0.47	0.12	-33.38
Bot_ref_03	2.16	1.75	64.73	0.97	0.00	-1.05	0.64	0.30	-47.89
Bot_ref_04	2.12	1.56	68.05	0.62	0.01	-4.38	0.26	0.04	-17.46
Bot_ref_05	2.06	1.86	99.25	1.41	0.01	-2.85	0.60	0.10	-27.91
Bot_ref_06	1.82	1.08	-4.50	0.63	0.01	-4.88	0.17	0.02	-4.78
Bot_ref_07	1.92	1.25	65.38	0.52	0.07	-11.07	0.23	0.01	0.25
Bot_ref_08	2.07	1.12	11.39	0.68	0.01	-3.41	0.18	0.01	-3.51
Cor_ref_01	0.99	0.36	54.31	1.22	0.02	0.68	0.73	0.08	-42.96
Cor_ref_02	1.07	0.24	62.77	1.16	0.04	-43.51	0.67	0.16	-14.22
Cor_ref_03	1.18	0.50	76.55	1.29	0.06	-46.89	0.90	0.11	-11.33
Cor_ref_04	1.24	0.47	70.86	1.60	0.03	-12.63	0.99	0.11	-35.25
Cor_ref_05	1.19	0.45	84.64	1.45	0.03	-13.08	1.13	0.15	-30.44
Cor_ref_06	1.31	0.50	77.39	1.55	0.03	-15.76	0.94	0.18	-22.20
Cor_ref_07	1.64	0.57	63.87	1.45	0.01	2.69	1.05	0.19	-21.67
Cor_ref_08	1.64	0.78	69.43	1.72	0.05	4.10	0.82	0.19	-19.05



(a) *Cor_ref_01*

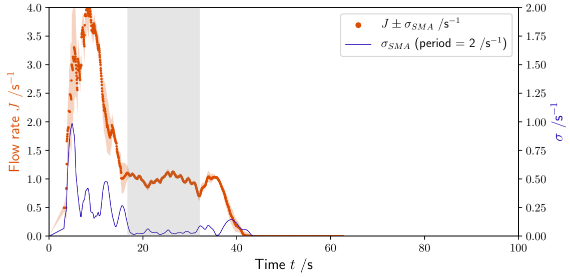


(b) *Cor_whe_01*

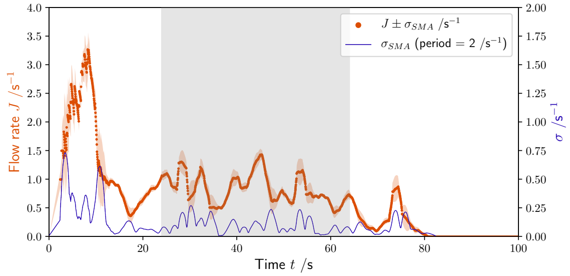


(c) *Cor_het_01*

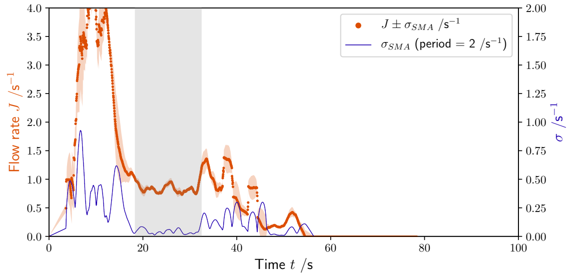
Figure A.7: *Example of a time series analysis of the dependent moving average of $\bar{J}(t)$ (orange) with a window size of 2 s for corridor configurations under homogenoues (considering the (a) reference population) and heterogeneous crowd conditions ((b) wheelchair and (c) s mixed). The corresponding SMA (blue) refers to the second y-axis.*



(a) *Bot_ref_01*

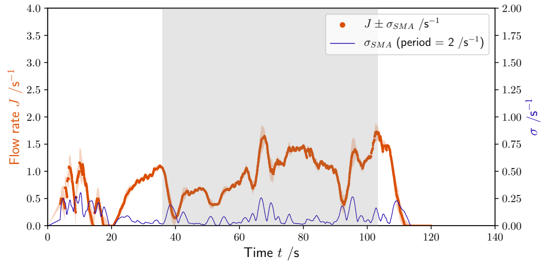


(b) *Bot_whe_01*

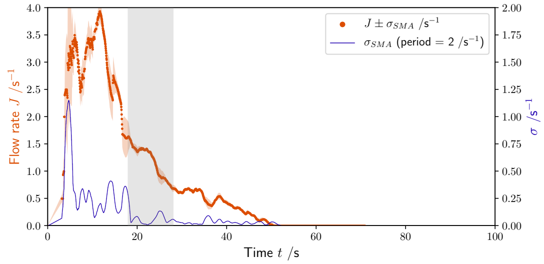


(c) *Bot_het_01*

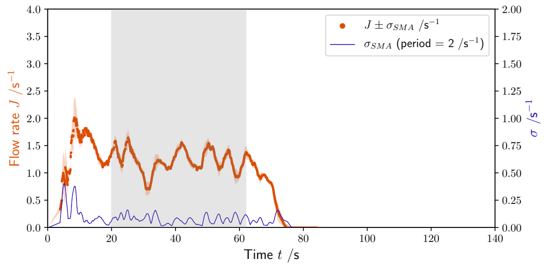
Figure A.8: *Example of time series analysis of the time dependent moving average of* $\bar{J}(t)$ *(orange) with a window size of* 2 s *for bottleneck configurations considering a (a) reference population, (b) subpopulation of wheelchair users and (c) subpopulation considering mixed disabled participants. The corresponding SMA (blue) refers to the second y-axis.*



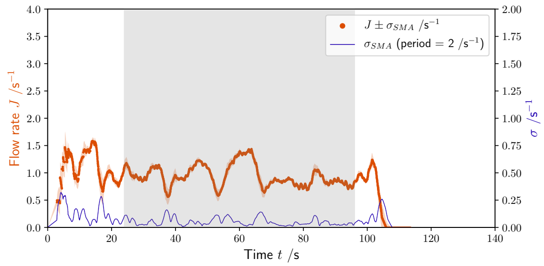
(a) *Cor_ref_03.*



(b) *Cor_wal_03.*



(c) *Cor_wal_04.*



(d) *Cor_eld_03.*

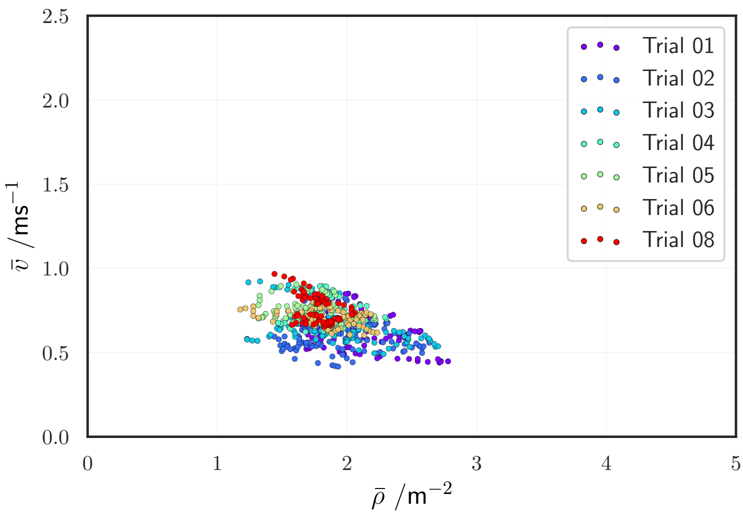
Figure A.9: *Example for trend dependency ((a) and (b)) and short-term fluctuations ((a) and (d)) in time series analysis of moving average measures of* $\bar{J}(t)$.

Appendix B

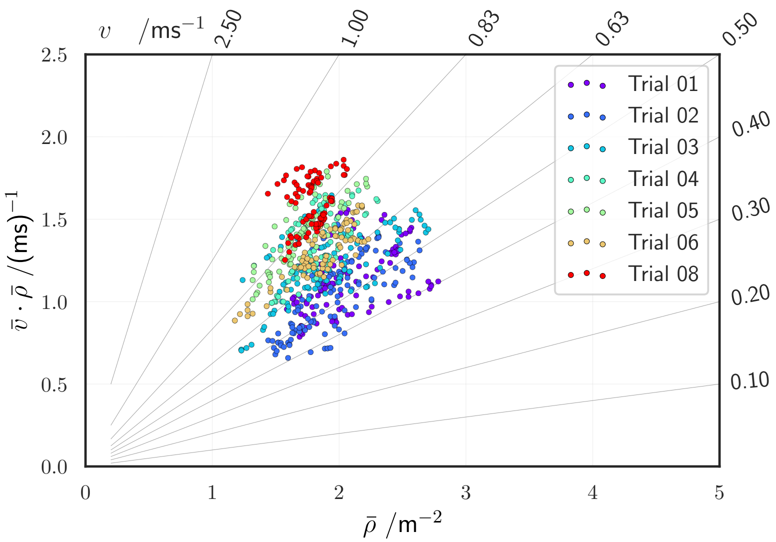
Fundamental Diagrams Depending on Populations

B.1 Fundamental Diagrams for Corridor Studies

B.1.1 Cor_old

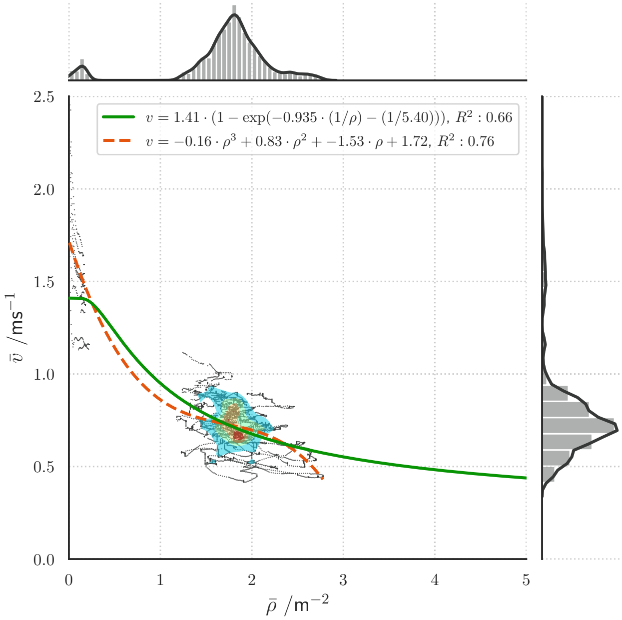


(a)

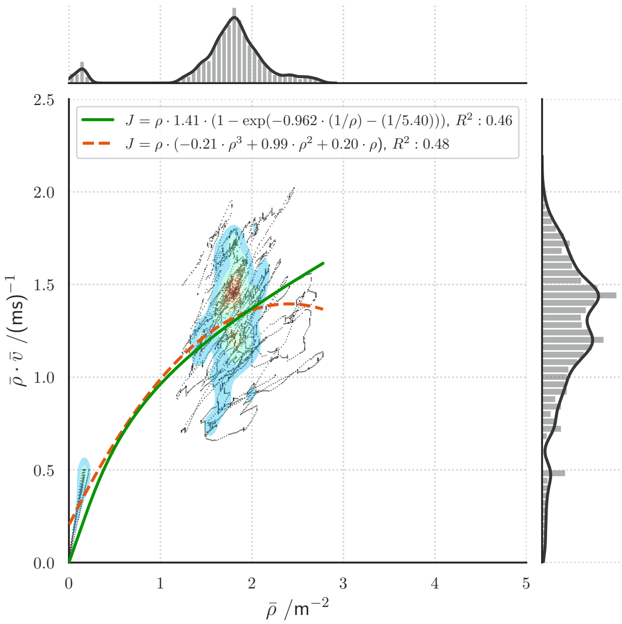


(b)

Figure B.1: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Cor_old. Grey dotted nomogram lines in (b) are associated with speed v.*



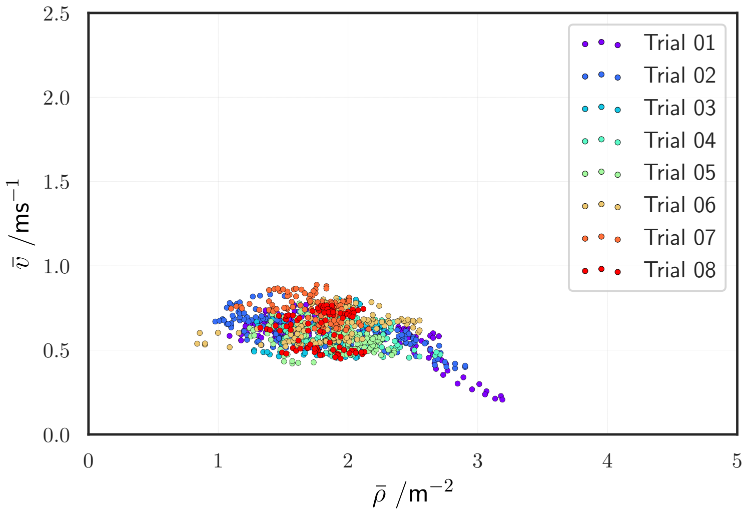
(a)



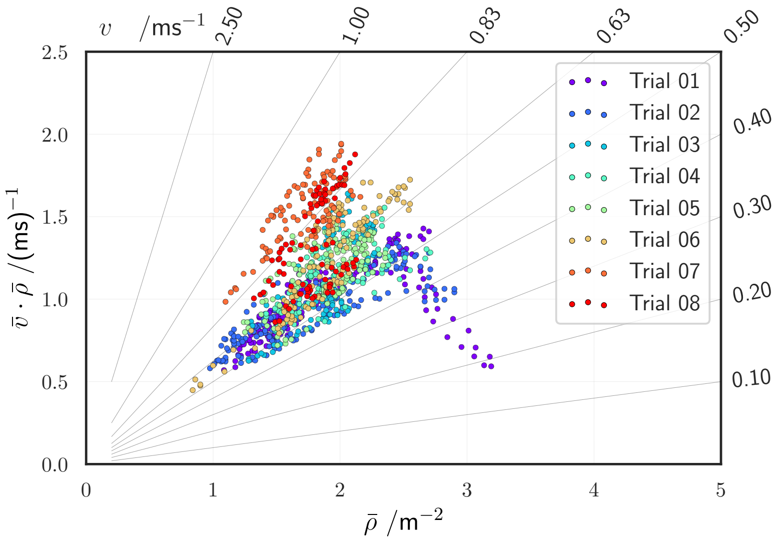
(b)

Figure B.2: *Capacity analysis of Cor_old for $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.1.2 Cor_cog

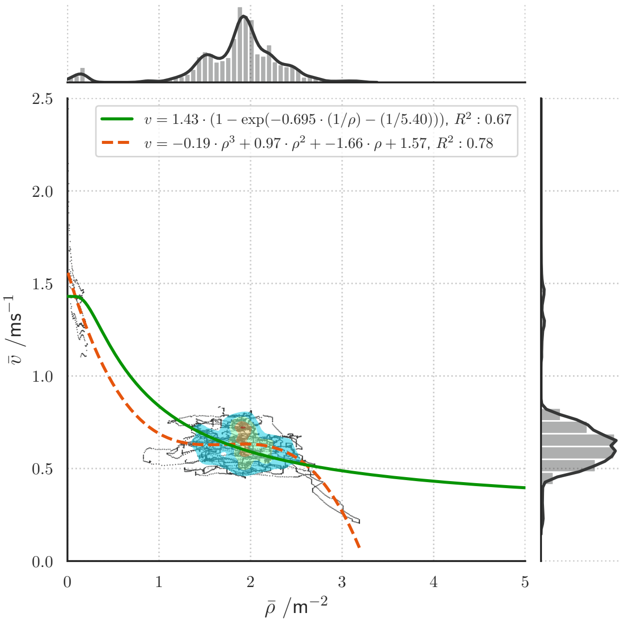


(a)

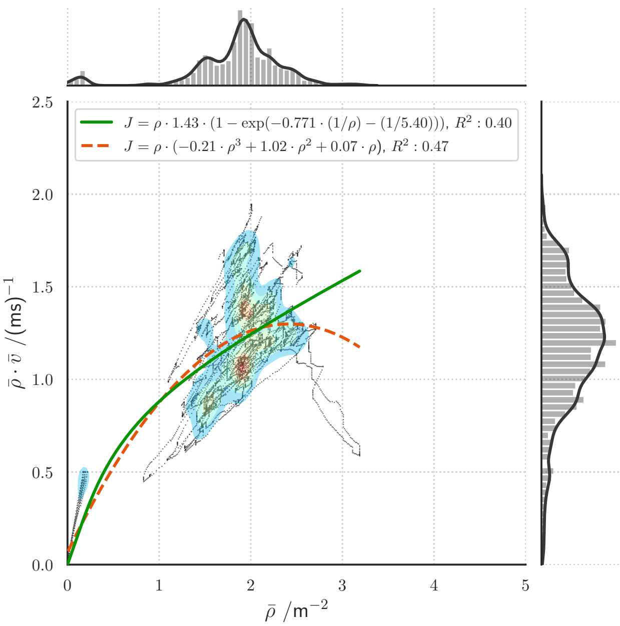


(b)

Figure B.3: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Cor_cog. Grey dotted nomogram lines in (b) are associated with speed v.*



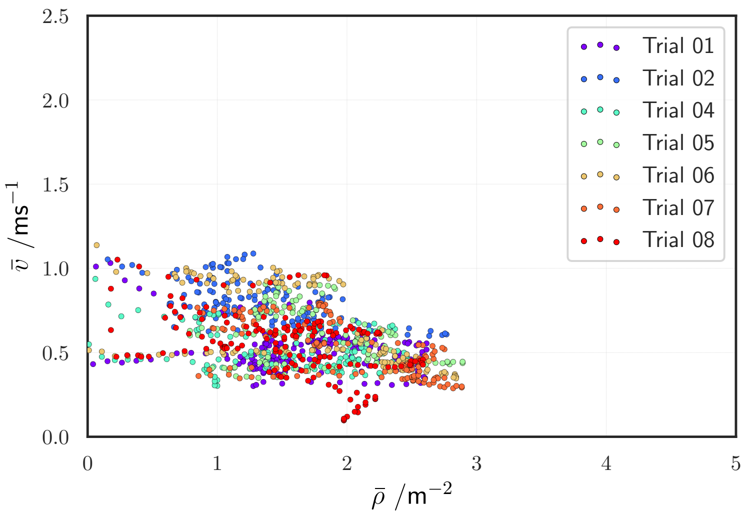
(a) *Cor_cog* $v(\rho)$



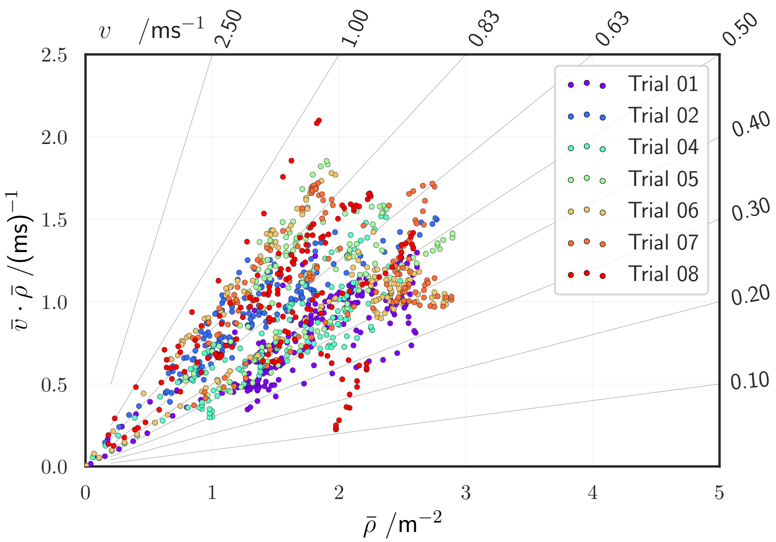
(b) *Cor_cog* $J(\rho)$

Figure B.4: *Capacity analysis of Cor_cog for* $\bar{v}(\bar{\rho})$ *(a) and* $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ *(b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.1.3 Cor_whe

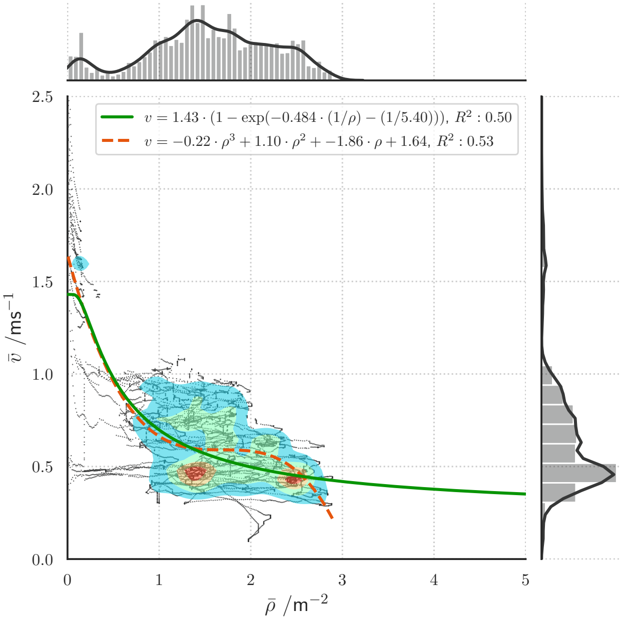


(a)

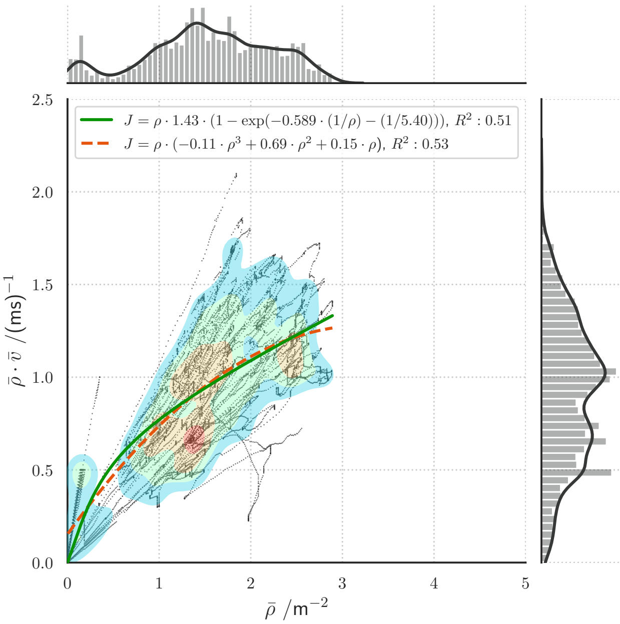


(b)

Figure B.5: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Cor_whe. Grey dotted nomogram lines in (b) are associated with speed v.*



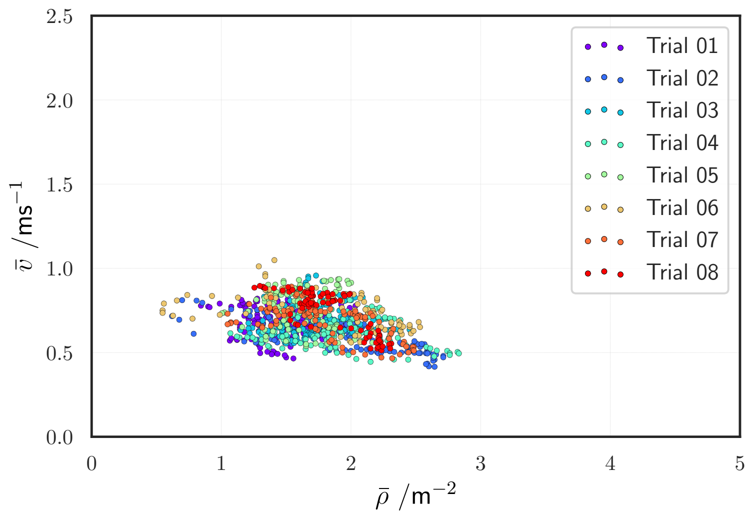
(a) *Cor_whe* $v(\rho)$



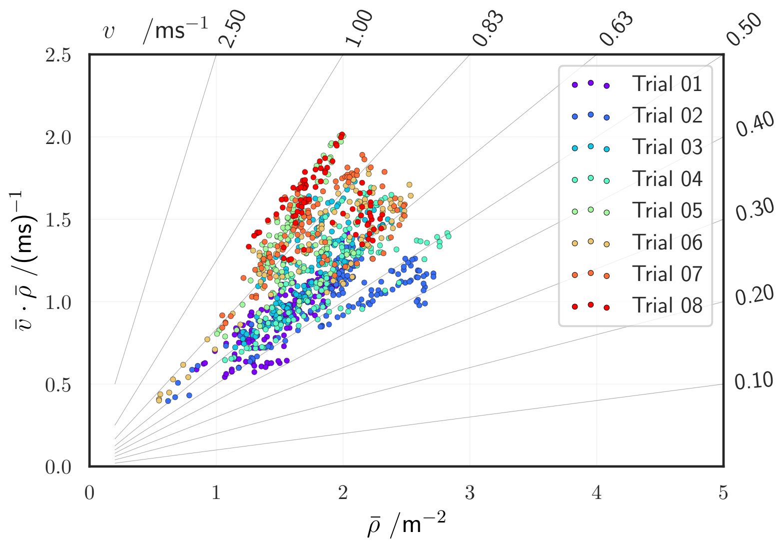
(b) *Cor_whe* $J(\rho)$

Figure B.6: *Capacity analysis of Cor_whe for* $\bar{v}(\bar{\rho})$ *(a) and* $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ *(b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.1.4 Cor_wal

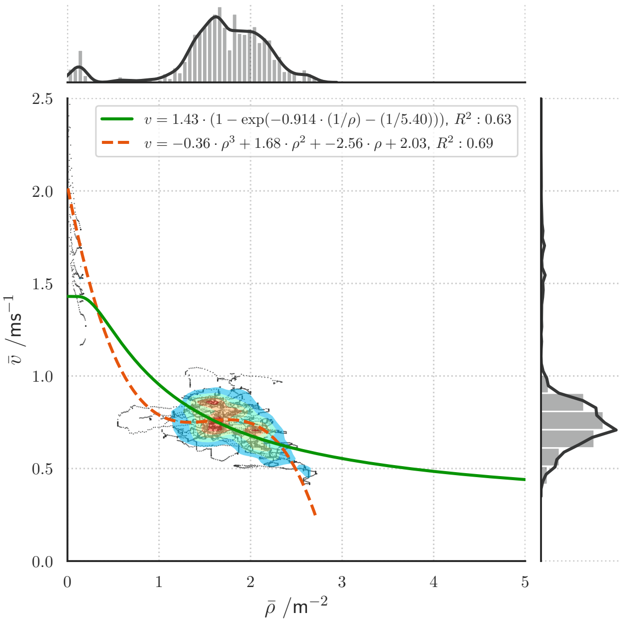


(a)

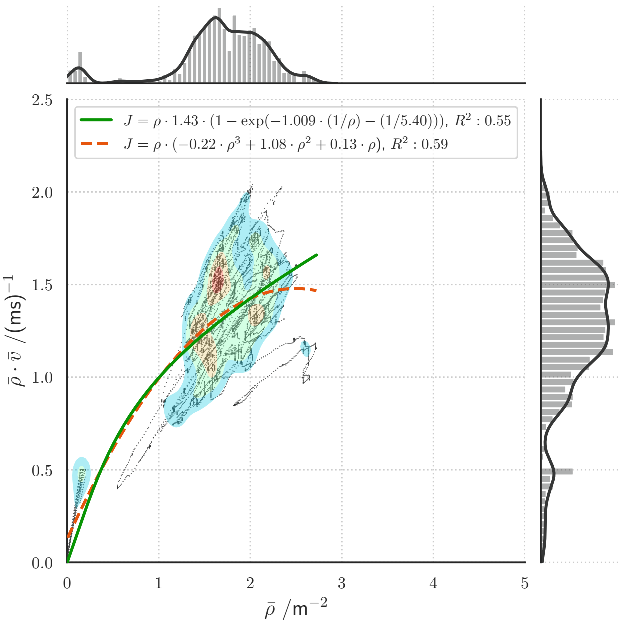


(b)

Figure B.7: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Cor_wal. Grey dotted nomogram lines in (b) are associated with speed v.*



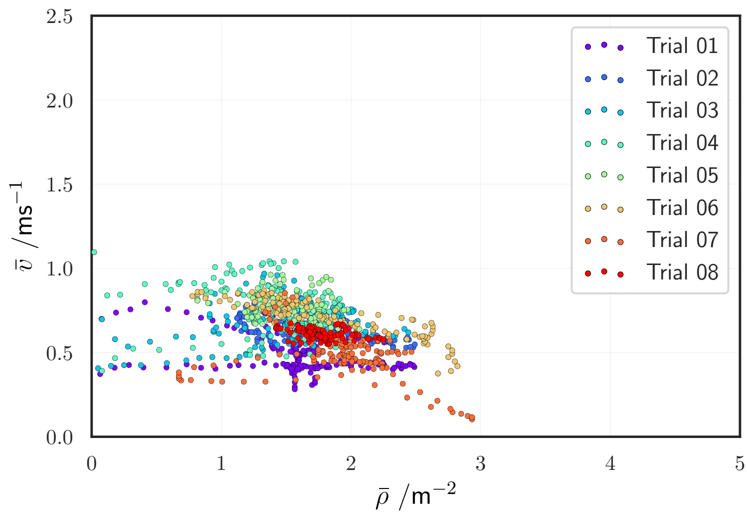
(a) *Cor_wal* $v(\rho)$



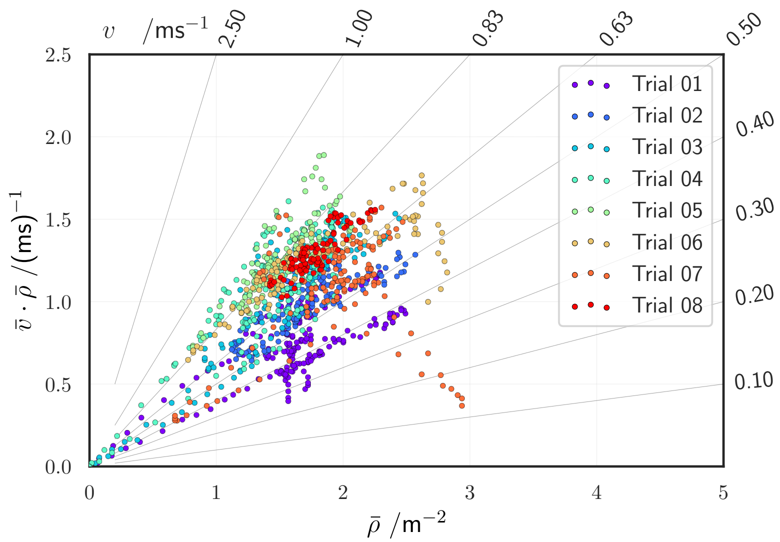
(b) *Cor_wal* $J(\rho)$

Figure B.8: *Capacity analysis of Cor_wal for* $\bar{v}(\bar{\rho})$ *(a) and* $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ *(b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.1.5 Cor_mix

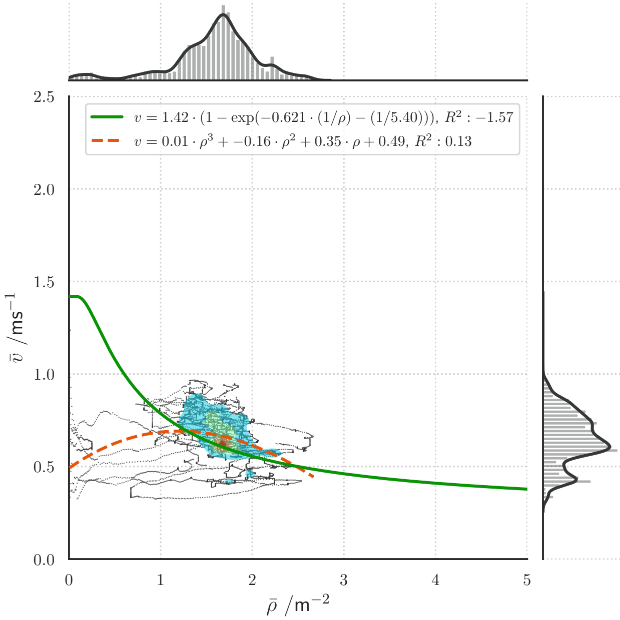


(a)

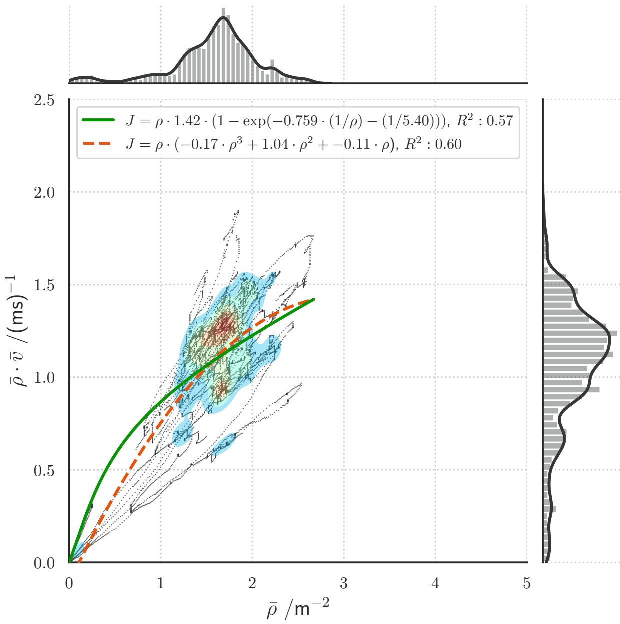


(b)

Figure B.9: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Cor_mix. Grey dotted nomogram lines in (b) are associated with speed v.*



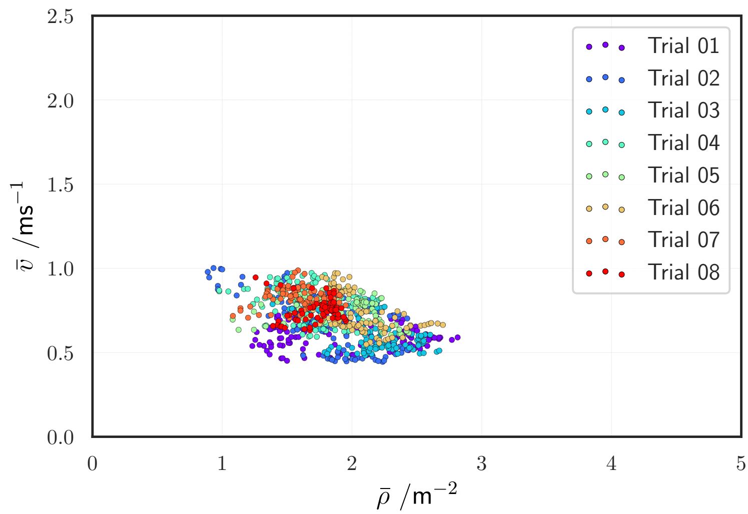
(a) *Cor_mix* $v(\rho)$



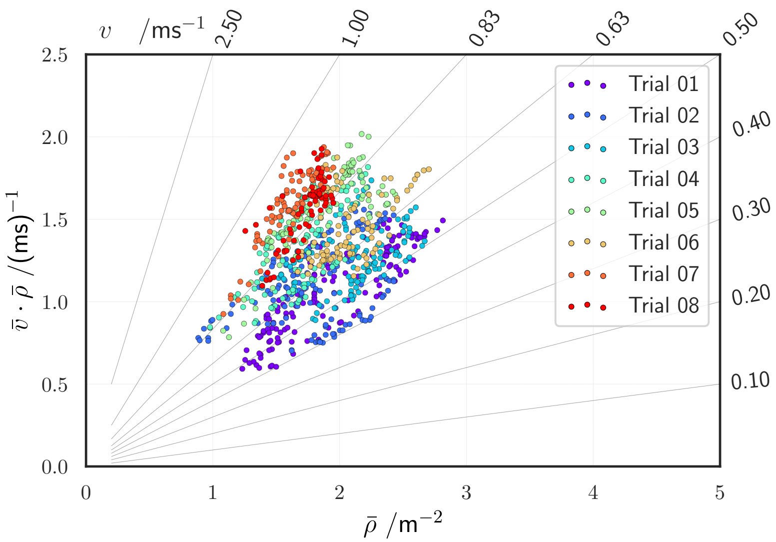
(b) *Cor_mix* $J(\rho)$

Figure B.10: *Capacity analysis of Cor_mix for* $\bar{v}(\bar{\rho})$ *(a) and* $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ *(b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.1.6 Cor_het

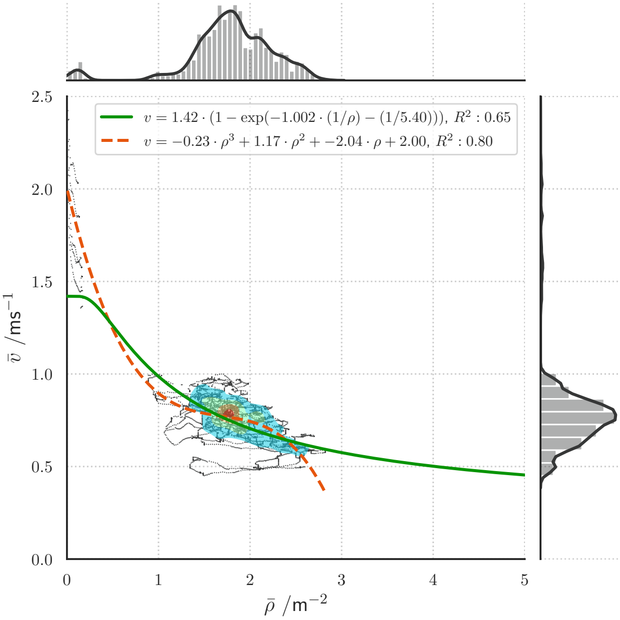


(a)

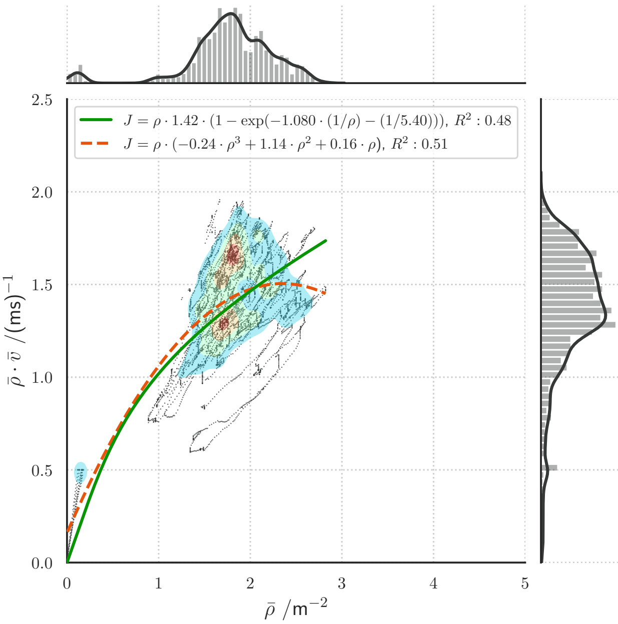


(b)

Figure B.11: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Cor_het. Grey dotted nomogram lines in (b) are associated with speed v.*



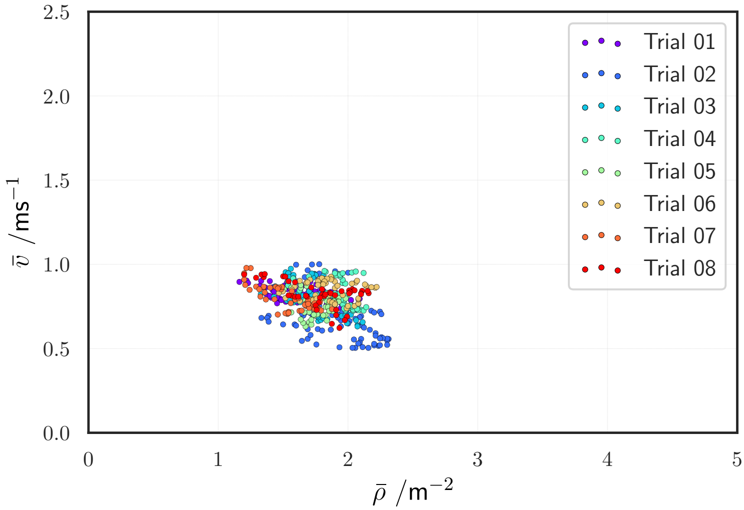
(a) *Cor_het* $v(\rho)$



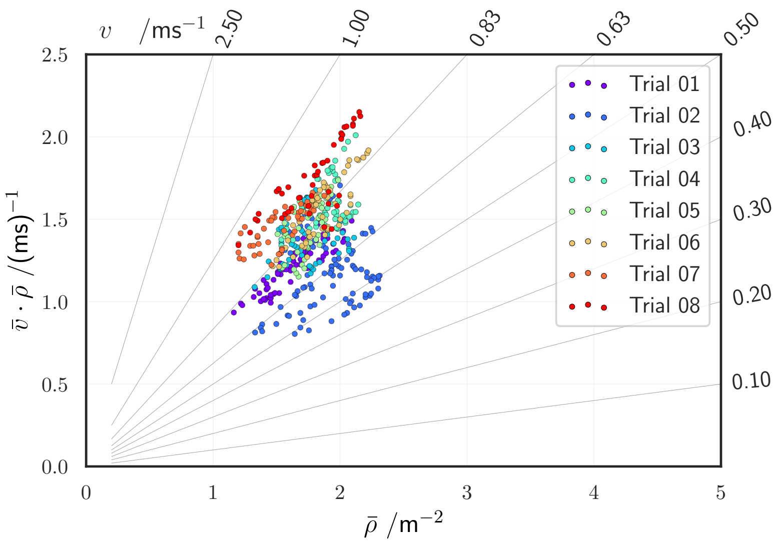
(b) *Cor_het* $J(\rho)$

Figure B.12: *Capacity analysis of Cor_het for* $\bar{v}(\bar{\rho})$ *(a) and* $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ *(b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.1.7 Cor_ref

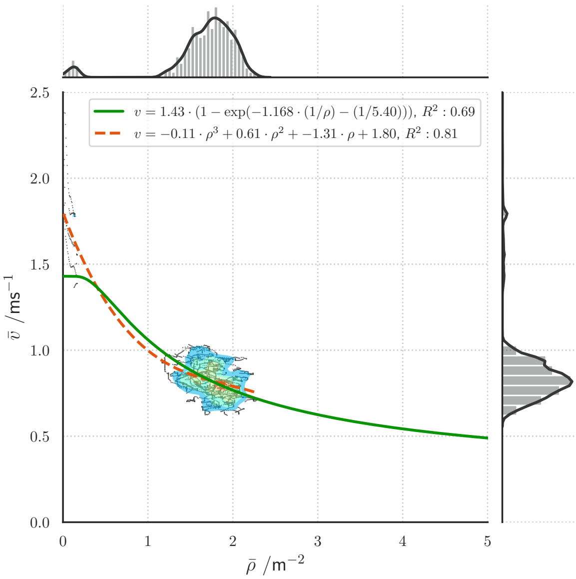


(a)

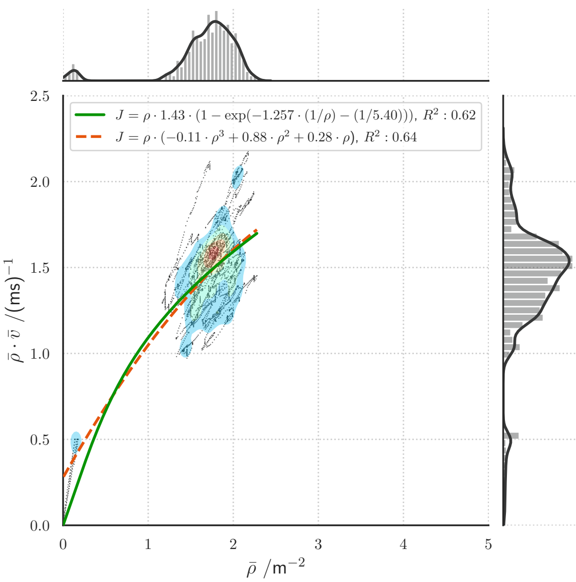


(b)

Figure B.13: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Cor_ref. Grey dotted nomogram lines in (b) are associated with speed v.*



(a) *Cor_ref* $v(\rho)$

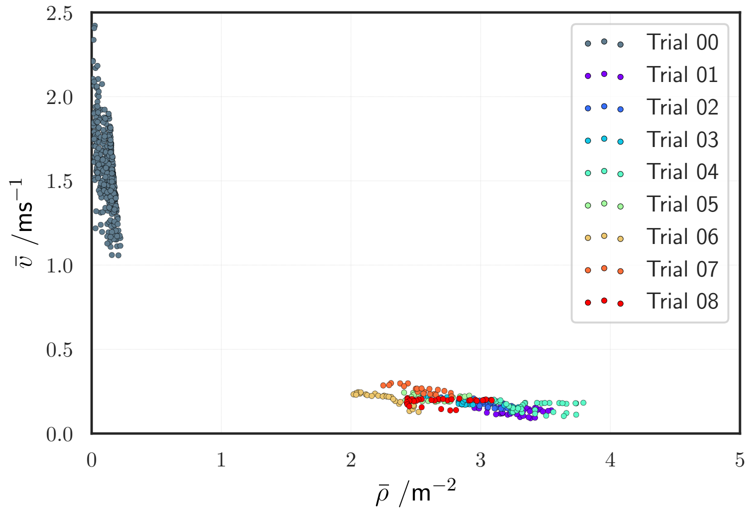


(b) *Cor_ref* $J(\rho)$

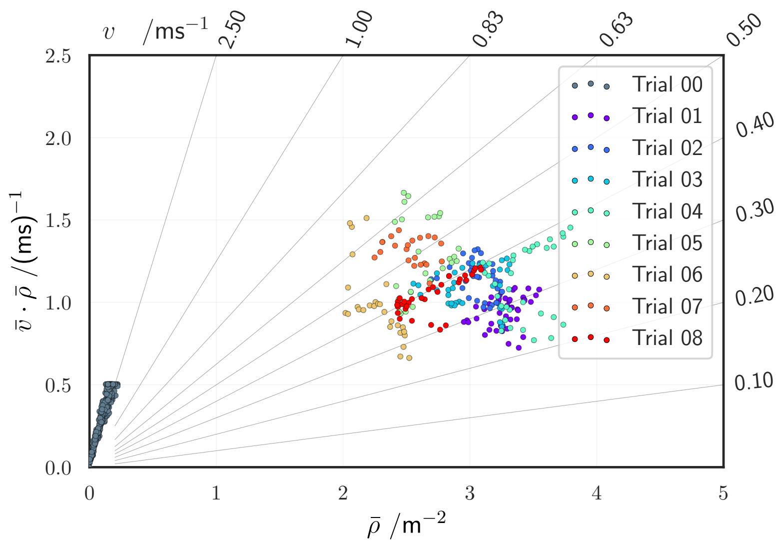
Figure B.14: *Capacity analysis of Cor_ref for* $\bar{v}(\bar{\rho})$ *(a) and* $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ *(b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.2 Fundamental Diagrams for Bottleneck Studies

B.2.1 Bot_old

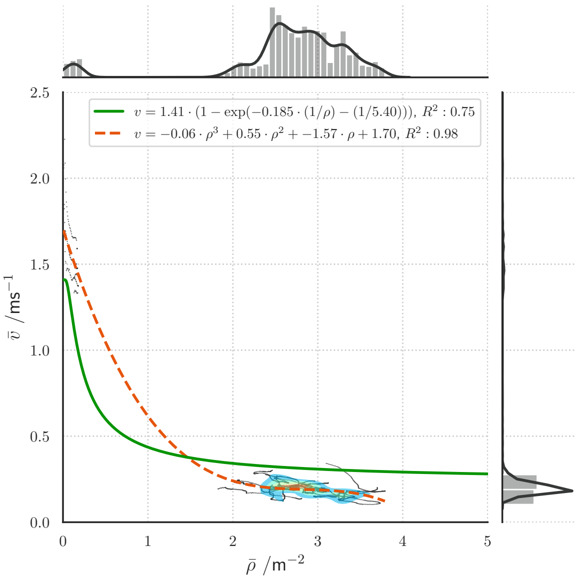


(a)

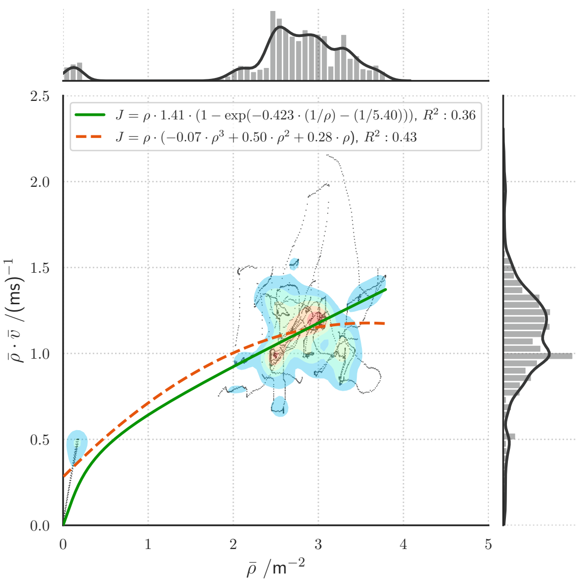


(b)

Figure B.15: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Bot_old. Grey dotted nomogram lines in (b) are associated with speed v.*



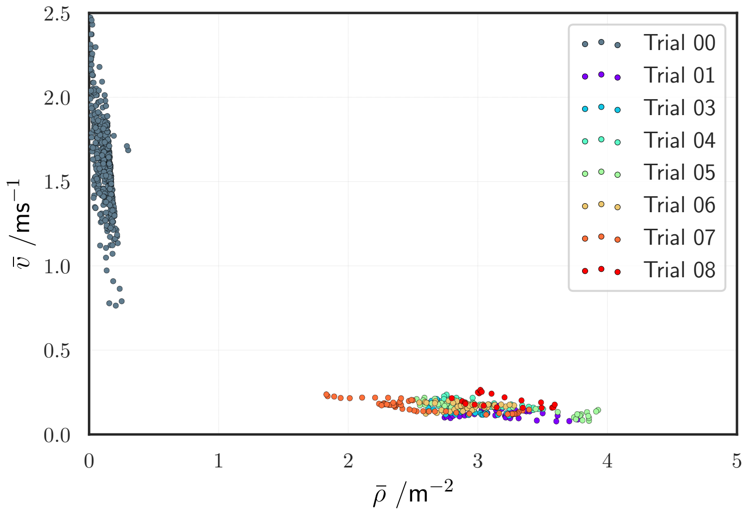
(a)



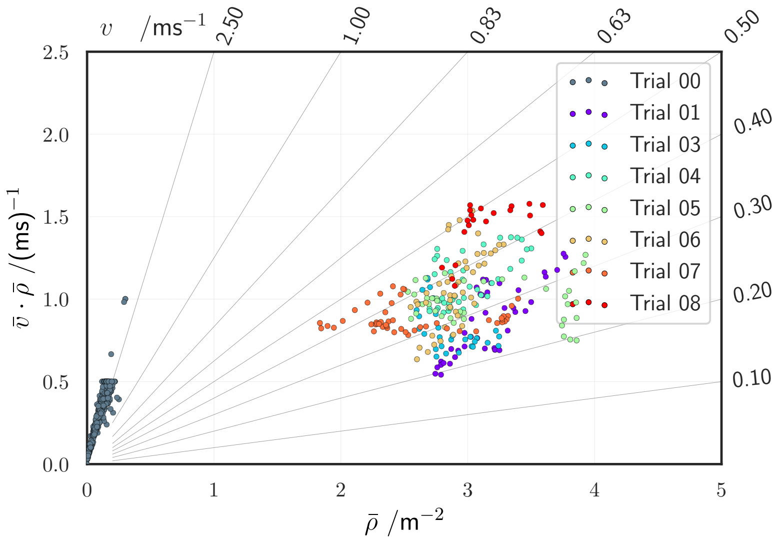
(b)

Figure B.16: *Capacity analysis of Bot_old for $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.2.2 Bot_cog

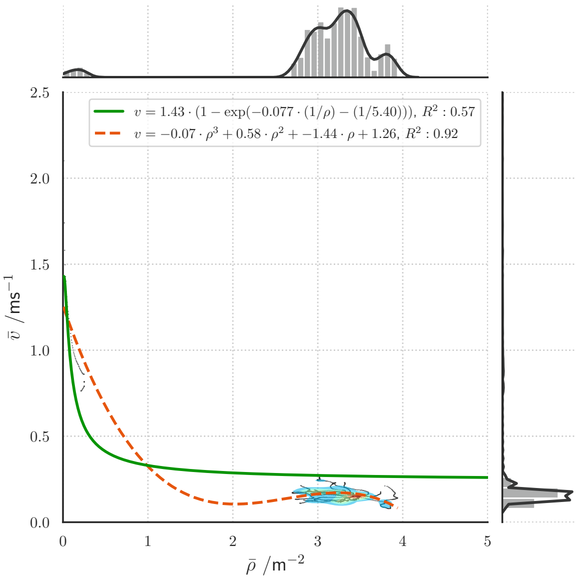


(a)

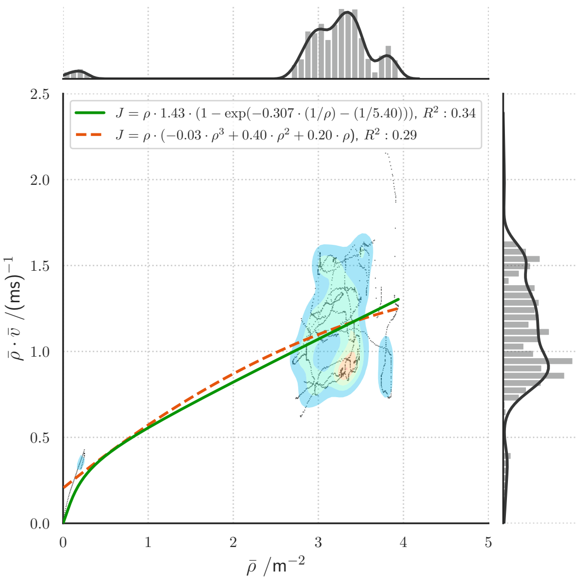


(b)

Figure B.17: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Bot_cog. Grey dotted nomogram lines in (b) are associated with speed v.*



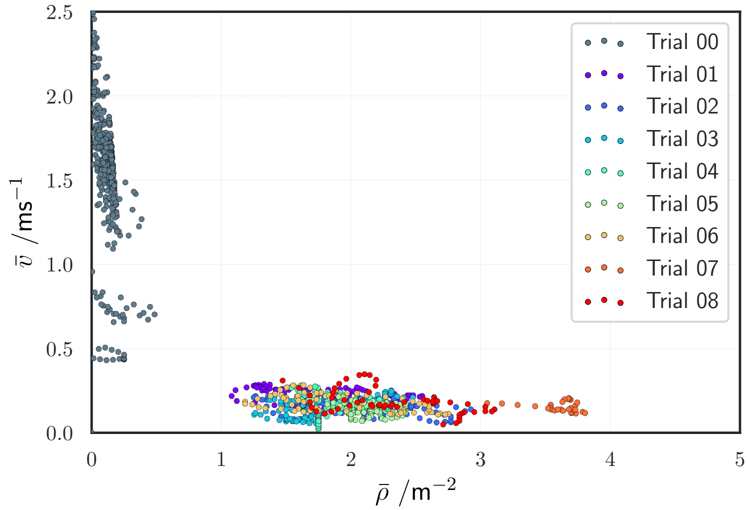
(a)



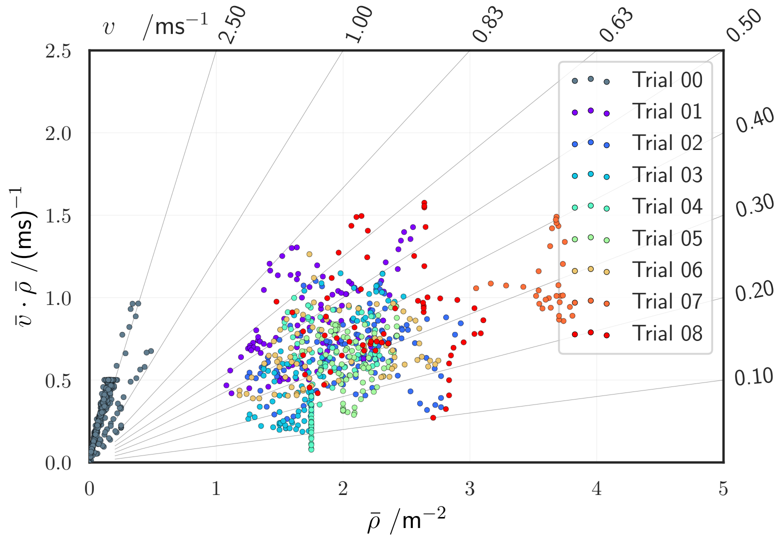
(b)

Figure B.18: *Capacity analysis of Bot_cog for $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.2.3 Bot_whe

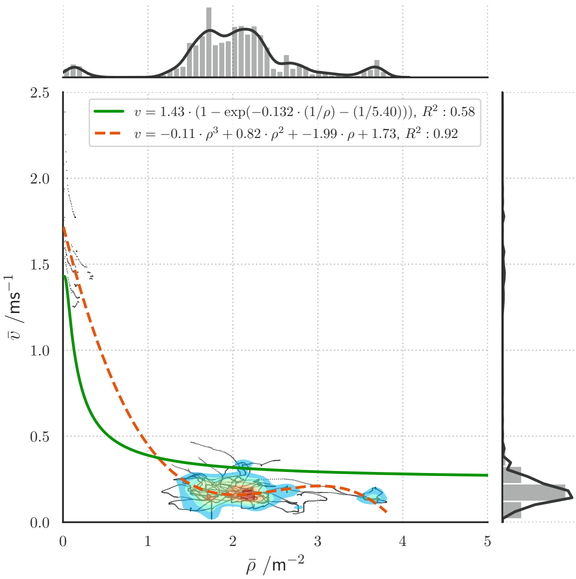


(a)

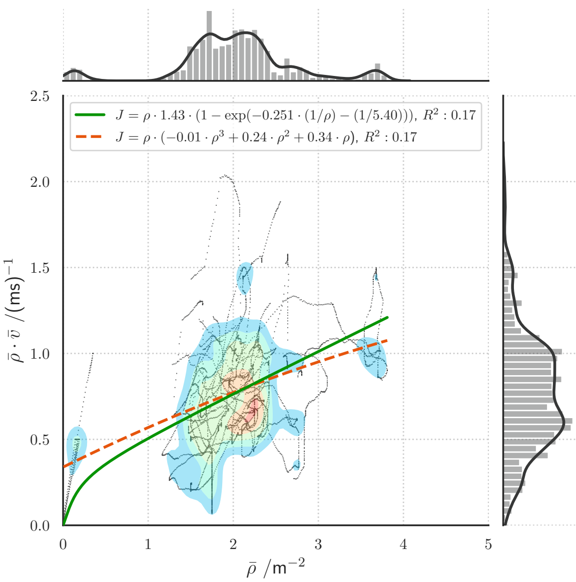


(b)

Figure B.19: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Bot_whe. Grey dotted nomogram lines in (b) are associated with speed v.*



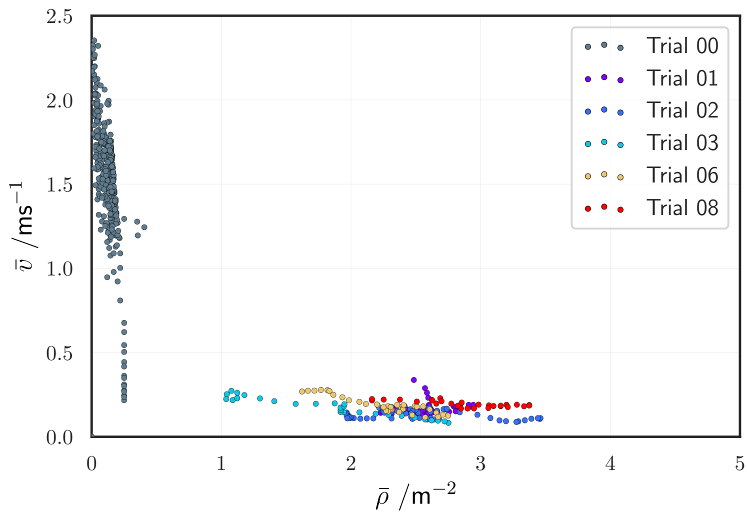
(a)



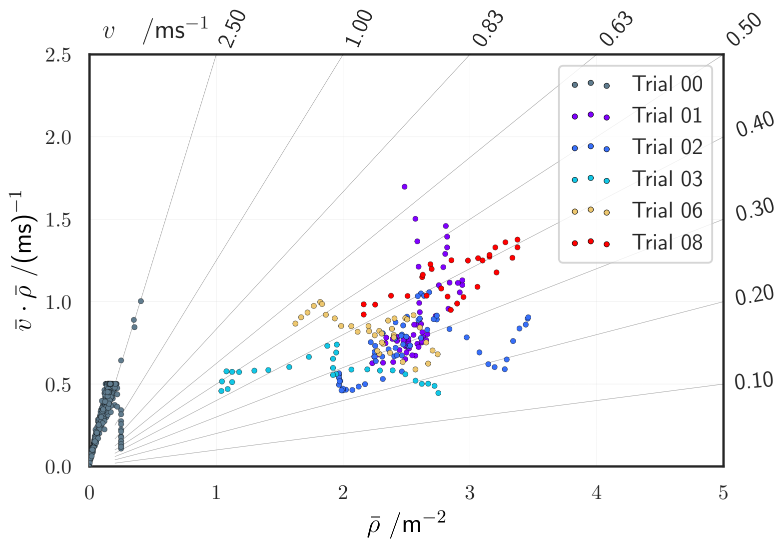
(b)

Figure B.20: *Capacity analysis of Bot_whe for $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.2.4 Bot_wal

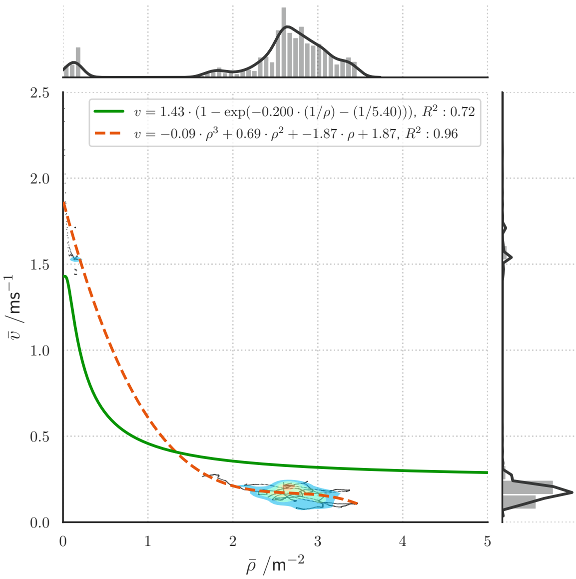


(a)

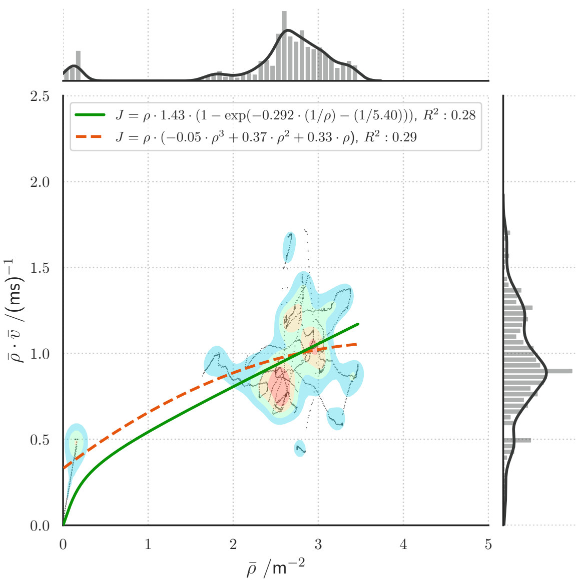


(b)

Figure B.21: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Bot_wal. Grey dotted nomogram lines in (b) are associated with speed v.*



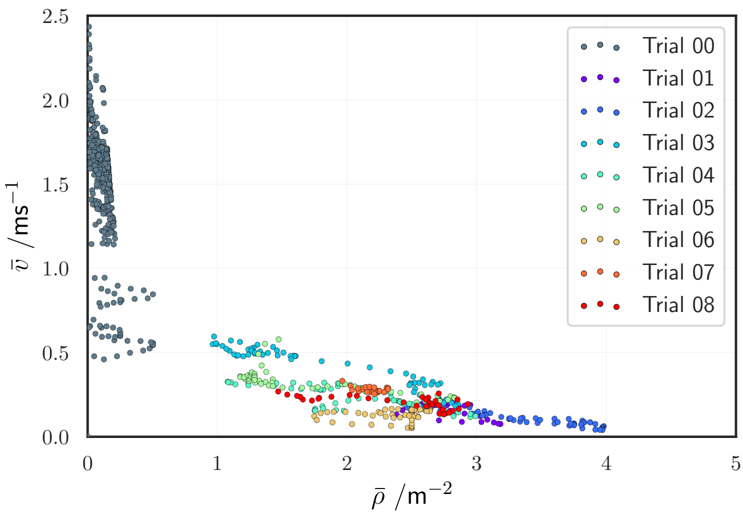
(a)



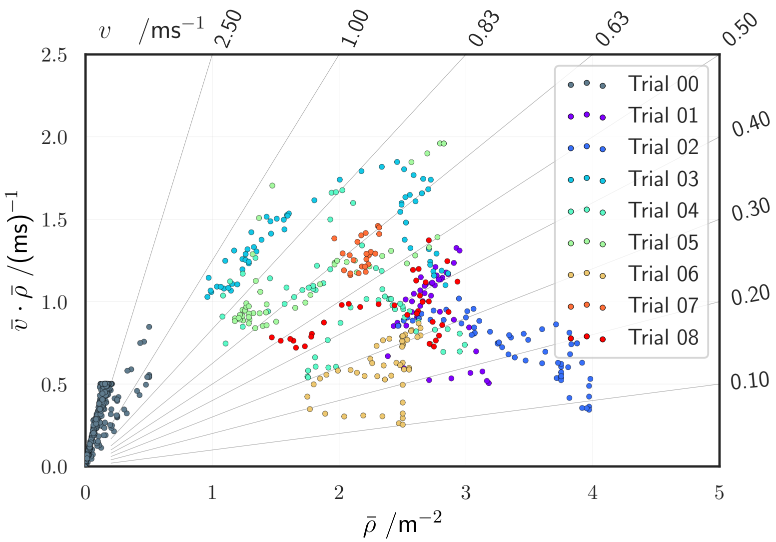
(b)

Figure B.22: *Capacity analysis of Bot_wal for $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.2.5 Bot_mix

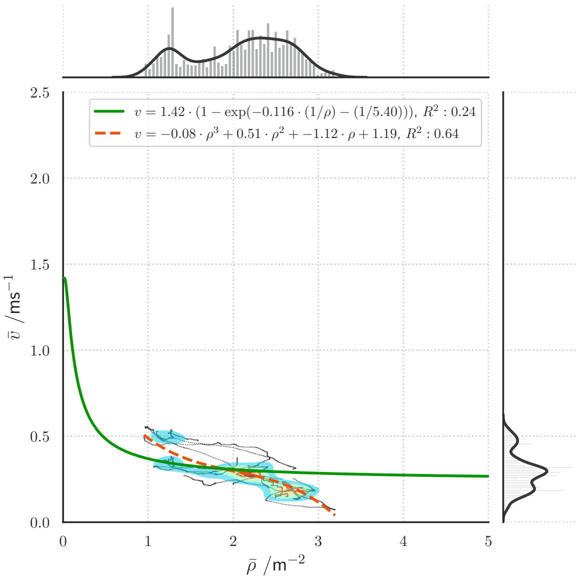


(a)

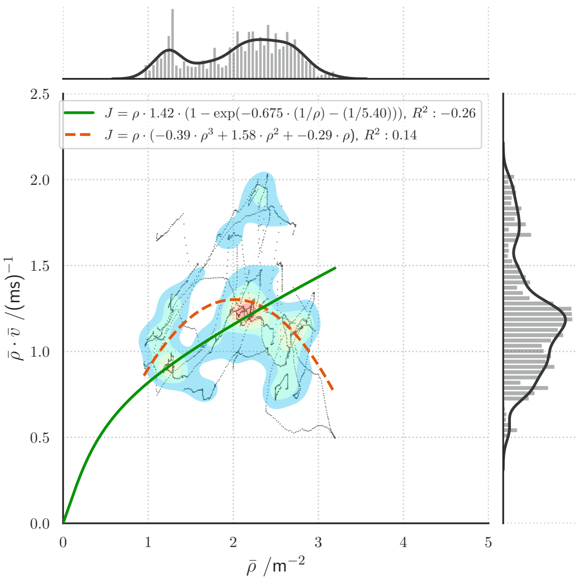


(b)

Figure B.23: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Bot_mix. Grey dotted nomogram lines in (b) are associated with speed v.*



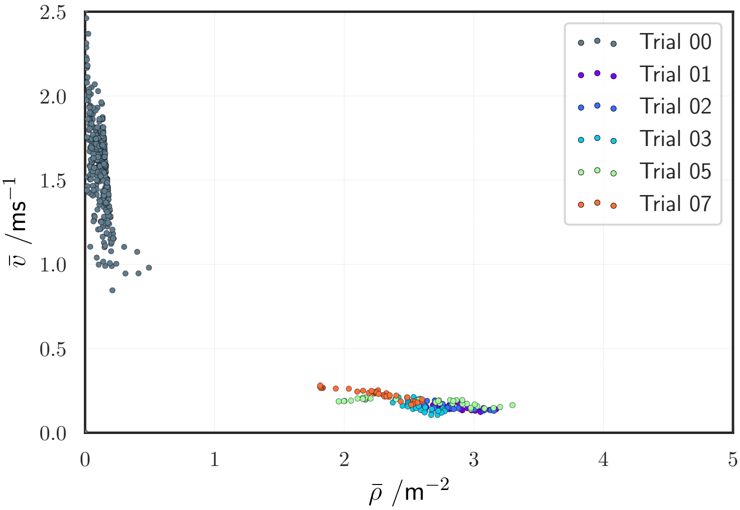
(a)



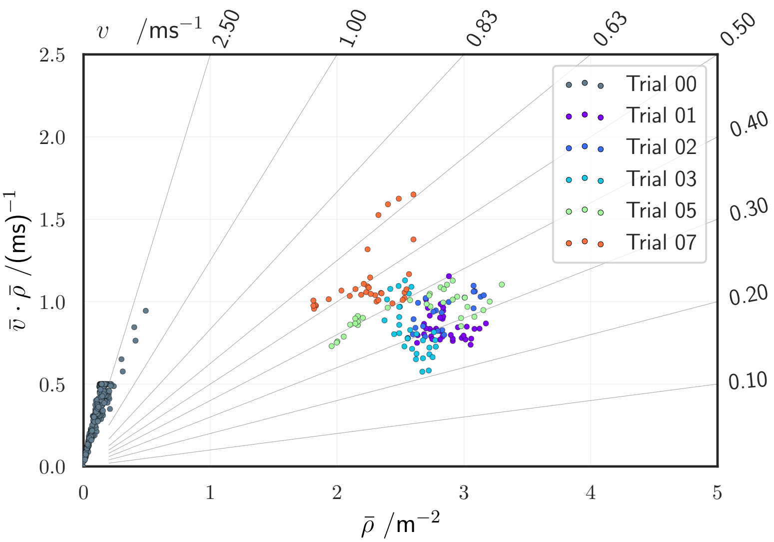
(b)

Figure B.24: *Capacity analysis of Bot_mix for $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.2.6 Bot_het

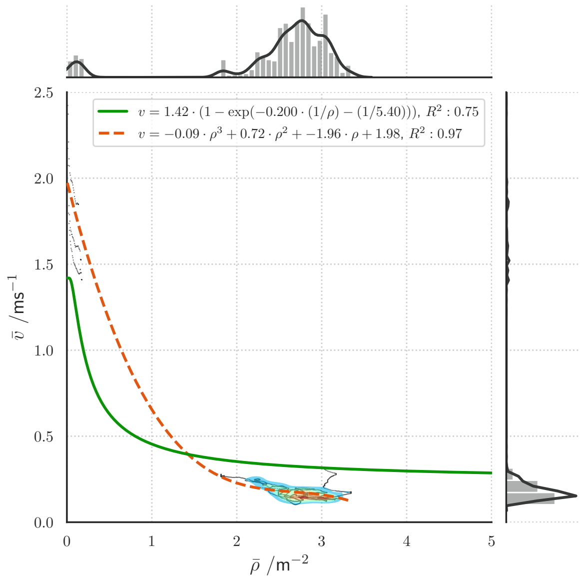


(a)

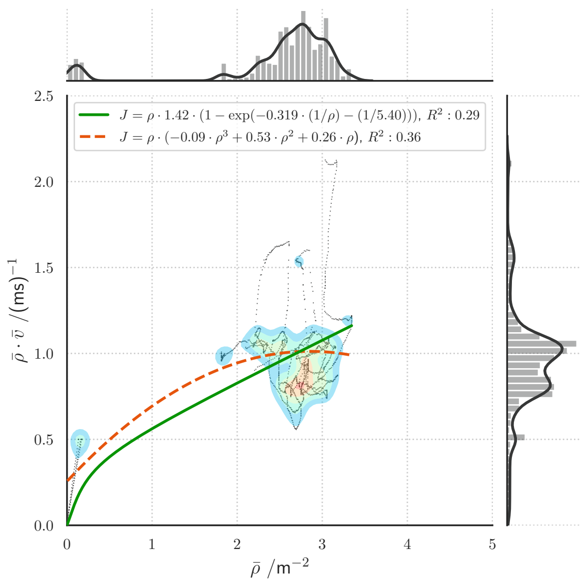


(b)

Figure B.25: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Bot_het. Grey dotted nomogram lines in (b) are associated with speed v.*



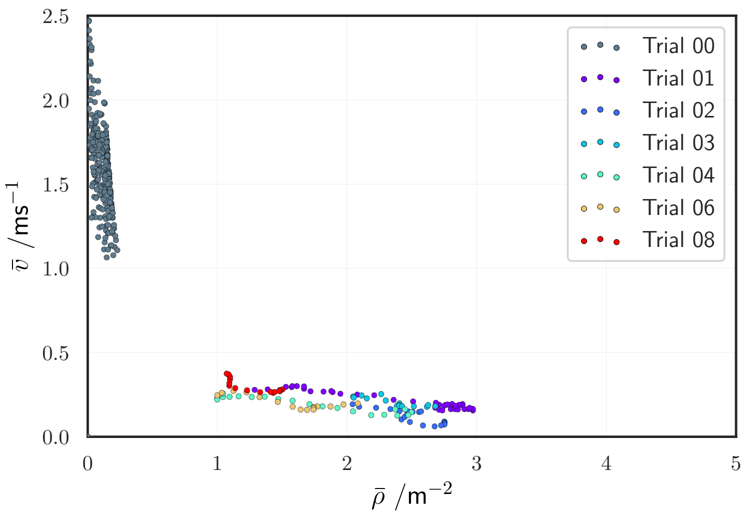
(a)



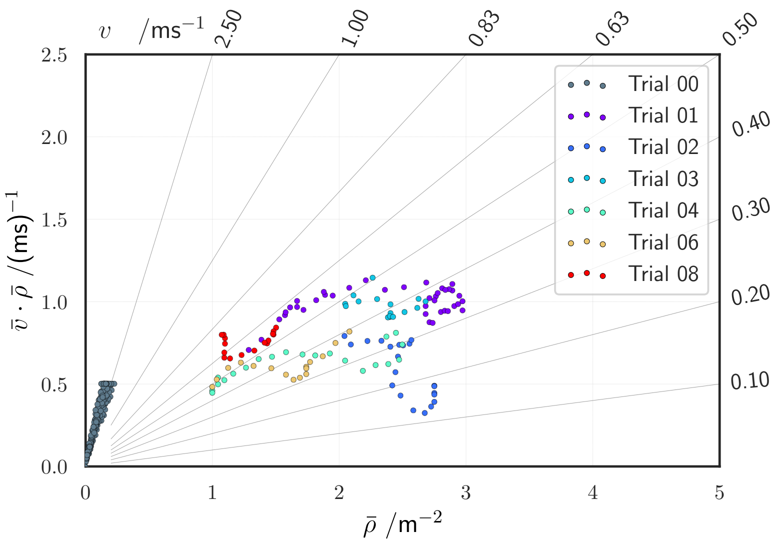
(b)

Figure B.26: *Capacity analysis of Bot_het for $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.2.7 Bot_ref

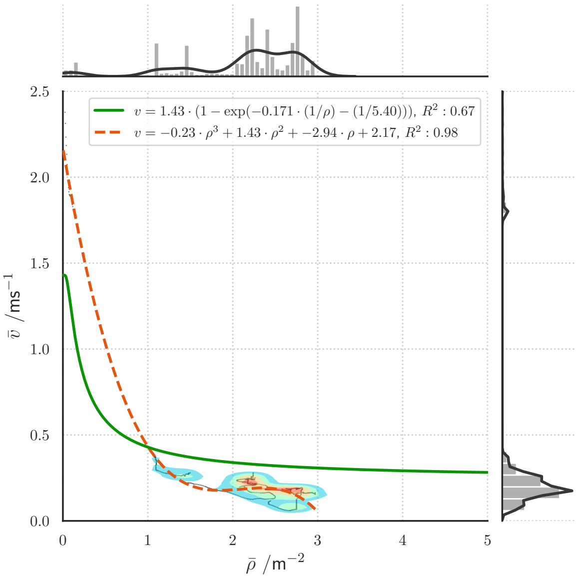


(a)

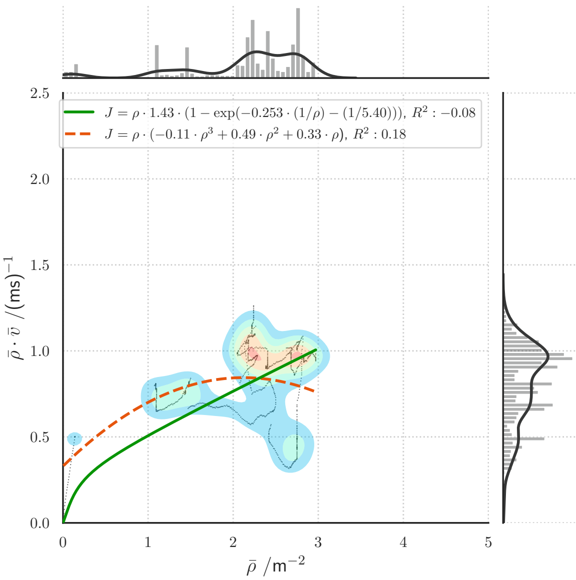


(b)

Figure B.27: *Empirical relations $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) for Bot_ref. Grey dotted nomogram lines in (b) are associated with speed v.*



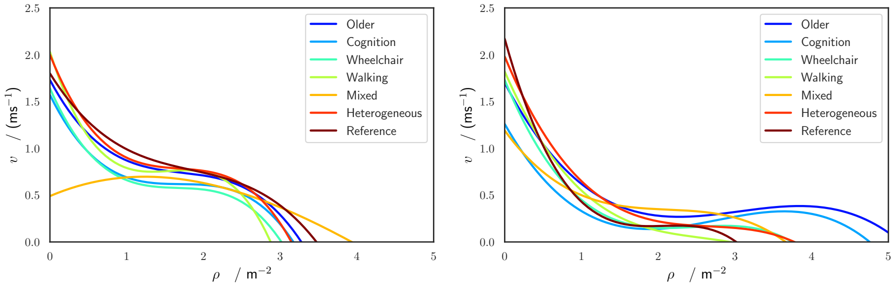
(a)



(b)

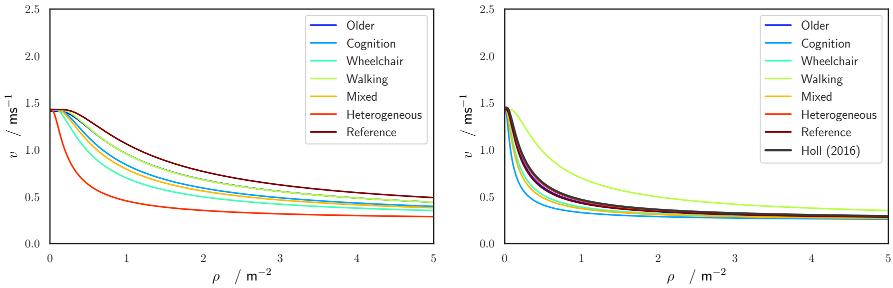
Figure B.28: *Capacity analysis of Bot_ref for $\bar{v}(\bar{\rho})$ (a) and $J_s(\bar{\rho}) = \bar{v} \cdot \bar{\rho}$ (b) including data from the unimpeded speed trials as contour plots with joint histograms and density estimates.*

B.3 Fitting Results



(a) *$v(\rho)$ for corridors.* **(b)** *$v(\rho)$ for bottlenecks.*

Figure B.29: *Comparison of empirical relations for corridor (left) and bottleneck (right) regarding to different subpopulations. The curves results from polynomial fitting method described in Sec. 5.7. Please note the low values for R^2 as presented in App. B.*



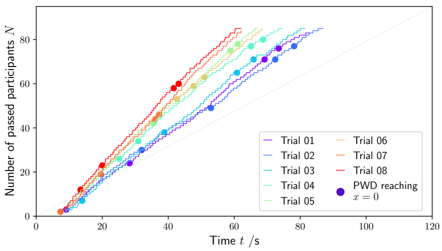
(a) *$v(\rho)$ for corridors.* **(b)** *$v(\rho)$ for bottlenecks.*

Figure B.30: *Comparison of empirical relations for corridor (left) and bottleneck (right) regarding to different subpopulations. The curves results from fitting method described in Sec. 5.7. Please note the low values for R^2 as presented in App. B.*

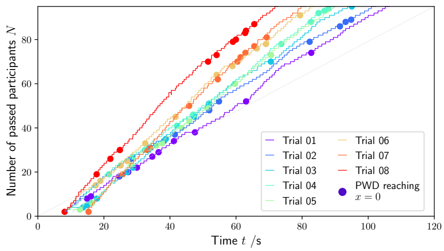
Appendix C

Individual Distances and Time Gaps

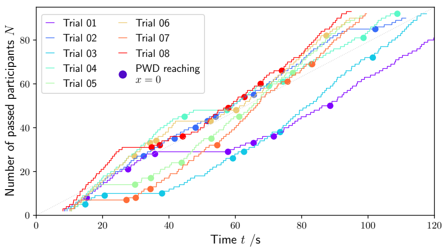
C.1 Time Gaps



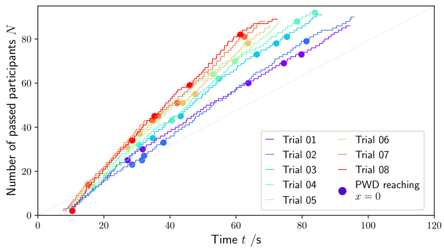
(a) *Older.*



(b) *Cognition.*

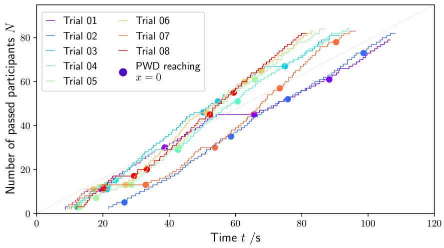


(c) *Wheelchair.*

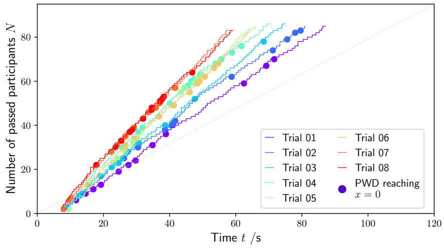


(d) *Walking.*

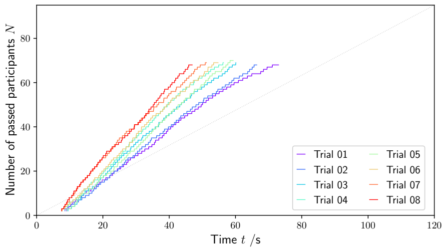
Figure C.1: *The cumulative number of passed participants $N(t)$ in a corridor for different conditions of crowd heterogeneity. The passage time of PWD at $x=$ is depicted by the scatter.*



(e) *Mixed.*

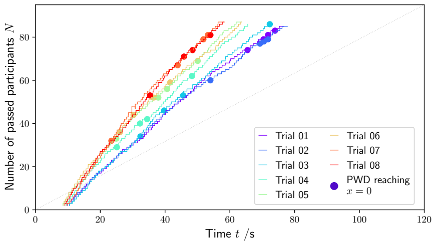


(f) *Heterogeneous.*

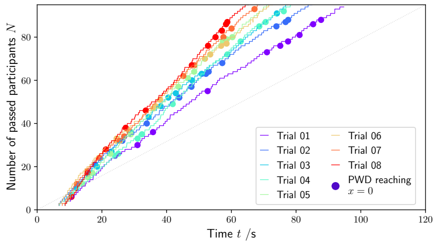


(g) *Reference.*

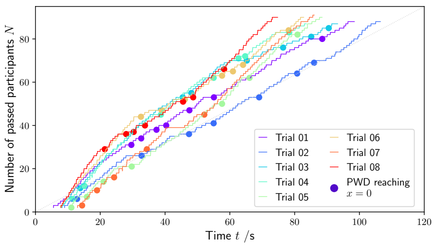
Figure C.1: *The cumulative number of passed participants $N(t)$ in a corridor for different conditions of crowd heterogeneity. The passage time of PWD at x= is depicted by the scatter.*



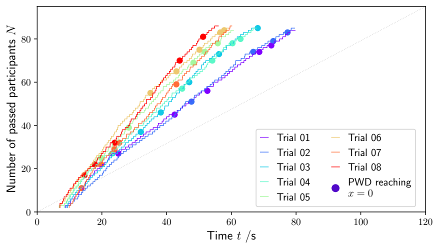
(a) *Older.*



(b) *Cognition.*

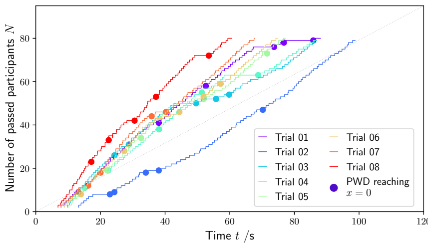


(c) *Wheelchair.*

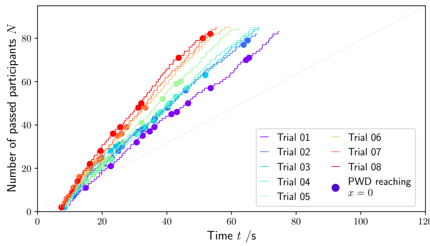


(d) *Walking.*

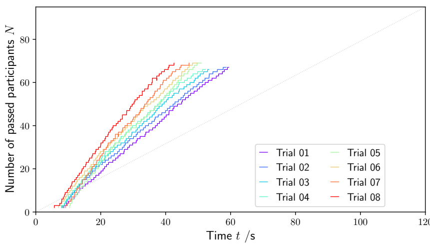
Figure C.2: *The cumulative number of passed participants $N(t)$ in a bottleneck for different conditions of crowd heterogeneity. The passage time of PWD at x= is depicted by the scatter.*



(e) *Mixed.*



(f) *Heterogeneous.*



(g) *Reference.*

Figure C.2: *The cumulative number of passed participants $N(t)$ in a corridor for different conditions of crowd heterogeneity. The passage time of PWD at x= is depicted by the scatter.*

Table C.1: *Individual time gap Δt_i [s^{-1}] for disabled and non-disabled participants in crowd motion. Data is presented as mean (σ, min - max).*

Study	Width [m]	Time gap Δt_i [s^{-1}] PWD: Data per trial	PWD: Data per width	NDP: Data per trial	NDP: Data per width
Bot_eld_01	0.9	1.19 (0.38, 0.56 - 1.52)	0.27 (0.23, 0.11-0.44)	0.77 (0.33, 0.00 - 1.40)	0.78 (0.30, 0.08 -1.64)
Bot_eld_02		1.26 (0.09, 1.16 - 1.40)		0.77 (0.30, 0.00 - 1.64)	
Bot_eld_03	1.0	0.72 (0.17, 0.52 - 0.96)	0.85 (0.34, 0.48 - 1.48)	0.73 (0.38, 0.00 - 2.12)	0.71 (0.36, 0.00 - 2.12)
Bot_eld_04		0.98 (0.37, 0.48 - 1.48)		0.66 (0.34, 0.00 - 1.64)	
Bot_eld_05	1.1	0.84 (0.29, 0.56 - 1.32)	0.77 (0.34, 0.16 - 1.32)	0.63 (0.30, 0.00 - 1.64)	0.64 (0.32, 0.00 - 1.88)
Bot_eld_06		0.70 (0.34, 0.16 - 1.00)		0.63 (0.36, 0.00 - 1.88)	
Bot_eld_07	1.2	0.80 (0.38, 0.16 - 1.12)	0.73 (0.41, 0.12 - 1.16)	0.55 (0.34, 0.00 - 1.96)	1.11 (0.51, 0.04 - 2.04)
Bot_eld_08		0.66 (0.37, 0.12 - 1.16)		0.56 (0.31, 0.00 - 1.48)	
Cor_eld_01	0.9	1.02 (0.20, 0.72 - 1.24)	1.01 (0.31, 0.52 - 1.44)	0.91 (0.32, 0.00 - 1.88)	0.93 (0.31, 0.12 - 2.04)
Cor_eld_02		0.99 (0.35, 0.52 - 1.44)		0.92 (0.32, 0.00 - 2.04)	
Cor_eld_03	1.0	0.93 (0.37, 0.52 - 1.44)	0.97 (0.35, 0.52 - 1.44)	0.84 (0.40, 0.00 - 2.88)	0.82 (0.35, 0.04 - 2.88)
Cor_eld_04		1.00 (0.28, 0.52 - 1.16)		0.77 (0.32, 0.00 - 1.40)	
Cor_eld_05	1.1	0.67 (0.53, 0.00 - 1.48)	0.99 (0.39, 0.56 - 1.48)	0.72 (0.32, 0.04 - 1.80)	0.72 (0.32, 0.04 - 1.80)
Cor_eld_06		0.81 (0.52, 0.00 - 1.44)		0.72 (0.31, 0.04 - 1.72)	
Cor_eld_07	1.2	0.72 (0.15, 0.48 - 0.88)	0.69 (0.22, 0.32 - 1.00)	0.66 (0.37, 0.00 - 1.40)	0.66 (0.35, 0.04 - 1.80)
Cor_eld_08		0.67 (0.24, 0.32 - 1.00)		0.64 (0.33, 0.00 - 1.80)	
Bot_cog_01	0.9	1.36 (0.46, 0.72 - 2.04)	1.11 (0.51, 0.04 - 2.04)	0.88 (0.41, 0.00 - 2.04)	0.87 (0.39, 0.00 - 2.04)
Bot_cog_02		0.90 (0.42, 0.04 - 1.52)		0.84 (0.38, 0.00 - 1.92)	
Bot_cog_03	1.0	0.95 (0.28, 0.52 - 1.40)	0.95 (0.36, 0.28 - 1.56)	0.73 (0.32, 0.00 - 1.40)	0.75 (0.35, 0.04 - 1.84)
Bot_cog_04		0.95 (0.41, 0.28 - 1.56)		0.75 (0.38, 0.00 - 1.84)	
Bot_cog_05	1.1	0.82 (0.38, 0.36 - 1.72)	0.86 (0.47, 0.08 - 1.72)	0.66 (0.35, 0.00 - 1.68)	0.68 (0.38, 0.00 - 1.76)
Bot_cog_06		0.91 (0.53, 0.08 - 1.68)		0.68 (0.41, 0.00 - 1.76)	
Bot_cog_07	1.2	0.78 (0.37, 0.32 - 1.60)	0.74 (0.45, 0.08 - 1.92)	0.65 (0.30, 0.00 - 1.40)	0.63 (0.33, 0.04 - 1.44)
Bot_cog_08		0.72 (0.50, 0.08 - 1.92)		0.60 (0.36, 0.00 - 1.44)	
Cor_cog_01	0.9	1.37 (0.76, 0.24 - 3.04)	1.26 (0.72, 0.20 - 3.04)	0.99 (0.35, 0.00 - 2.40)	1.00 (0.32, 0.08 - 2.40)
Cor_cog_02		1.16 (0.63, 0.20 - 2.32)		0.98 (0.32, 0.00 - 1.80)	
Cor_cog_03	1.0	1.40 (1.14, 0.08 - 4.52)	1.26 (0.90, 0.08 - 4.52)	0.86 (0.36, 0.00 - 1.64)	0.85 (0.34, 0.04 - 1.72)
Cor_cog_04		1.12 (0.45, 0.08 - 1.80)		0.82 (0.34, 0.00 - 1.72)	
Cor_cog_05	1.1	1.13 (0.76, 0.12 - 2.52)	1.07 (0.74, 0.12 - 2.56)	0.82 (0.41, 0.00 - 2.40)	0.81 (0.39, 0.04 - 2.40)
Cor_cog_06		1.01 (0.69, 0.16 - 2.56)		0.78 (0.37, 0.00 - 1.56)	
Cor_cog_07	1.2	0.83 (0.45, 0.16 - 1.44)	0.84 (0.52, 0.04 - 1.84)	0.68 (0.39, 0.00 - 1.64)	0.68 (0.36, 0.00 - 1.76)
Cor_cog_08		0.85 (0.56, 0.04 - 1.84)		0.66 (0.34, 0.00 - 1.76)	
Bot_whe_01	0.9	2.51 (0.88, 1.64 - 4.28)	2.67 (1.00, 1.48 - 4.84)	0.93 (0.44, 0.00 - 2.28)	0.96 (0.49, 0.08 - 3.68)
Bot_whe_02		0.93 (0.44, 0.00 - 2.28)		0.97 (0.54, 0.00 - 3.68)	
Bot_whe_03	1.0	2.69 (1.08, 1.80 - 5.16)	2.53 (1.11, 1.36 - 5.16)	0.84 (0.51, 0.00 - 2.32)	0.80 (0.45, 0.00 - 2.32)
Bot_whe_04		2.38 (1.04, 1.36 - 4.28)		0.74 (0.40, 0.00 - 1.80)	
Bot_whe_05	1.1	2.45 (0.88, 1.52 - 4.28)	2.60 (0.85, 1.52 - 4.28)	0.74 (0.45, 0.00 - 2.44)	0.72 (0.40, 0.00 - 2.44)
Bot_whe_06		2.75 (0.73, 1.84 - 4.00)		0.68 (0.36, 0.00 - 1.52)	
Bot_whe_07	1.2	1.39 (0.80, 0.00 - 2.32)	2.00 (0.59, 0.92 - 2.68)	0.77 (0.68, 0.00 - 5.84)	0.70 (0.55, 0.00 - 5.84)
Bot_whe_08		2.23 (0.45, 1.40 - 2.68)		0.62 (0.36, 0.00 - 1.68)	
Cor_whe_01	0.9	5.21 (6.87, 1.64 - 22.00)	4.12 (5.43, 1.64 - 22.00)	1.07 (0.46, 0.00 - 2.84)	1.04 (0.42, 0.12 - 2.84)
Cor_whe_02		3.03 (2.26, 1.92 - 8.56)		0.99 (0.40, 0.00 - 2.68)	
Cor_whe_03	1.0	4.47 (5.24, 1.80 - 17.28)	4.11 (4.33, 1.80 - 17.28)	0.91 (0.51, 0.00 - 3.04)	0.90 (0.45, 0.04 - 3.04)
Cor_whe_04		3.76 (2.67, 1.96 - 10.12)		0.87 (0.40, 0.00 - 2.04)	
Cor_whe_05	1.1	3.27 (3.24, 0.00 - 10.88)	3.66 (3.38, 1.40 - 10.88)	0.79 (0.42, 0.00 - 1.88)	0.79 (0.42, 0.00 - 2.12)
Cor_whe_06		3.00 (3.26, 0.00 - 10.64)		0.79 (0.41, 0.04 - 2.12)	
Cor_whe_07	1.2	3.51 (4.21, 0.00 - 13.64)	3.56 (3.63, 0.68 - 13.64)	0.77 (0.40, 0.04 - 2.08)	0.77 (0.44, 0.00 - 2.56)
Cor_whe_08		3.10 (2.54, 0.68 - 8.92)		0.76 (0.47, 0.00 - 2.56)	
Bot_wal_01	0.9	1.62 (0.36, 1.12 - 2.12)	1.55 (0.36, 1.08 - 2.12)	0.80 (0.36, 0.00 - 1.72)	0.81 (0.33, 0.00 - 1.72)
Bot_wal_02		1.17 (0.64, 0.00 - 1.84)		0.81 (0.30, 0.04 - 1.64)	
Bot_wal_03	1.0	1.07 (0.52, 0.36 - 1.92)	1.10 (0.40, 0.36 - 1.92)	0.68 (0.32, 0.00 - 1.52)	0.69 (0.32, 0.04 - 1.52)
Bot_wal_04		1.12 (0.13, 0.92 - 1.32)		0.68 (0.34, 0.00 - 1.48)	
Bot_wal_05	1.1	1.12 (0.57, 0.52 - 2.16)	0.94 (0.51, 0.36 - 2.16)	0.61 (0.35, 0.00 - 1.56)	0.62 (0.32, 0.04 - 1.56)
Bot_wal_06		0.76 (0.29, 0.36 - 1.20)		0.61 (0.30, 0.00 - 1.56)	
Bot_wal_07	1.2	0.54 (0.43, 0.08 - 1.20)	0.65 (0.48, 0.08 - 1.40)	0.59 (0.32, 0.00 - 1.32)	0.58 (0.32, 0.00 - 1.32)
Bot_wal_08		0.77 (0.45, 0.12 - 1.40)		0.56 (0.34, 0.00 - 1.32)	
Cor_wal_01	0.9	1.25 (0.35, 0.68 - 1.76)	1.20 (0.55, 0.00 - 1.92)	0.97 (0.35, 0.00 - 1.80)	0.98 (0.38, 0.24 - 3.36)
Cor_wal_02		1.15 (0.65, 0.00 - 1.92)		0.97 (0.43, 0.00 - 3.36)	
Cor_wal_03	1.0	1.50 (0.43, 1.04 - 2.28)	1.39 (0.45, 0.76 - 2.28)	0.82 (0.38, 0.00 - 2.20)	0.87 (0.64, 0.04 - 7.76)
Cor_wal_04		1.27 (0.39, 0.76 - 1.84)		0.89 (0.83, 0.00 - 7.76)	
Cor_wal_05	1.1	1.10 (0.97, 0.00 - 2.84)	1.48 (0.82, 0.40 - 2.84)	0.73 (0.30, 0.04 - 1.56)	0.71 (0.32, 0.04 - 1.64)
Cor_wal_06		1.58 (0.65, 0.92 - 2.64)		0.69 (0.34, 0.00 - 1.64)	

Continued on the next page

Table C.1 – continued from the previous page

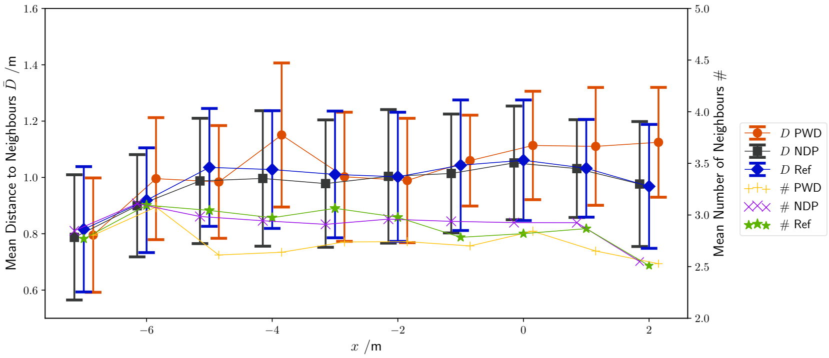
Study	Width [m]	Time gap Δt_i [s^{-1}]			
		PWD		NDP	
		Data per trial	Data per width	Data per trial	Data per width
Cor_wal_07	1.2	1.46 (0.56, 0.96 - 2.52)	1.06 (0.67, 0.08 - 2.52)	0.65 (0.38, 0.00 - 1.72)	0.68 (0.48, 0.00 - 4.44)
Cor_wal_08		0.66 (0.42, 0.08 - 1.04)		0.70 (0.55, 0.00 - 4.44)	
Bot_mix_01	0.9	3.96 (3.22, 1.16 - 9.08)	3.44 (2.70, 1.16 - 9.08)	0.81 (0.37, 0.00 - 2.24)	0.91 (0.38, 0.00 - 2.24)
Bot_mix_02		2.91 (1.48, 1.40 - 5.28)		0.98 (0.40, 0.00 - 2.20)	
Bot_mix_03	1.0	2.92 (2.36, 0.88 - 6.84)	3.14 (3.26, 0.88 - 10.56)	0.85 (0.49, 0.00 - 2.48)	0.85 (0.45, 0.04 - 2.56)
Bot_mix_04		3.37 (3.67, 0.88 - 10.56)		0.83 (0.43, 0.00 - 2.56)	
Bot_mix_05	1.1	1.82 (0.73, 1.12 - 2.80)	1.44 (0.85, 0.24 - 2.80)	0.77 (0.57, 0.00 - 3.40)	0.81 (0.53, 0.00 - 3.40)
Bot_mix_06		1.05 (0.68, 0.24 - 2.28)		0.82 (0.50, 0.00 - 2.68)	
Bot_mix_07	1.2	1.61 (0.97, 0.56 - 3.32)	1.68 (1.38, 0.08 - 4.52)	0.70 (0.37, 0.00 - 1.72)	0.66 (0.37, 0.00 - 1.72)
Bot_mix_08		1.76 (1.57, 0.08 - 4.52)		0.60 (0.36, 0.00 - 1.40)	
Cor_mix_01	0.9	4.50 (4.13, 0.96 - 11.36)	3.12 (3.48, 0.96 - 11.36)	1.08 (0.45, 0.00 - 2.92)	1.07 (0.38, 0.04 - 2.92)
Cor_mix_02		1.39 (0.86, 0.00 - 2.32)		1.05 (0.32, 0.04 - 1.88)	
Cor_mix_03	1.0	3.22 (1.81, 0.60 - 6.20)	2.96 (2.12, 0.60 - 7.00)	0.88 (0.48, 0.00 - 3.16)	0.91 (0.46, 0.00 - 3.24)
Cor_mix_04		2.70 (2.17, 1.28 - 7.00)		0.91 (0.45, 0.00 - 3.24)	
Cor_mix_05	1.1	2.00 (0.95, 0.48 - 3.48)	2.42 (2.36, 0.24 - 8.56)	0.87 (0.55, 0.00 - 3.32)	0.84 (0.48, 0.00 - 3.32)
Cor_mix_06		2.84 (2.95, 0.24 - 8.56)		0.78 (0.41, 0.00 - 1.96)	
Cor_mix_07	1.2	4.09 (4.60, 0.16 - 12.84)	3.30 (3.85, 0.16 - 12.84)	0.87 (0.58, 0.00 - 2.48)	0.82 (0.53, 0.00 - 2.48)
Cor_mix_08		2.52 (2.08, 0.84 - 6.44)		0.75 (0.47, 0.00 - 2.32)	
Bot_het_01	0.9	1.04 (0.38, 0.60 - 1.92)	0.93 (0.35, 0.52 - 1.92)	0.77 (0.36, 0.00 - 1.68)	0.76 (0.33, 0.00 - 1.68)
Bot_het_02 [b]		0.83 (0.25, 0.52 - 1.28)		0.72 (0.31, 0.00 - 1.40)	
Bot_het_03	1.0	0.82 (0.41, 0.20 - 1.64)	0.74 (0.38, 0.20 - 1.64)	0.70 (0.30, 0.00 - 1.40)	0.71 (0.30, 0.00 - 1.56)
Bot_het_04		0.65 (0.29, 0.32 - 1.28)		0.71 (0.31, 0.00 - 1.56)	
Bot_het_05	1.1	0.74 (0.39, 0.32 - 1.56)	0.65 (0.39, 0.04 - 1.56)	0.61 (0.35, 0.00 - 2.20)	0.63 (0.37, 0.00 - 2.20)
Bot_het_06		0.47 (0.31, 0.04 - 0.96)		0.63 (0.38, 0.00 - 1.80)	
Bot_het_07	1.2	0.65 (0.46, 0.08 - 1.68)	0.57 (0.45, 0.00 - 1.68)	0.55 (0.36, 0.00 - 1.44)	0.57 (0.36, 0.00 - 1.60)
Bot_het_08		0.50 (0.41, 0.00 - 1.40)		0.57 (0.36, 0.00 - 1.60)	
Cor_het_01	0.9	0.96 (0.33, 0.28 - 1.44)	0.97 (0.44, 0.00 - 1.80)	0.92 (0.36, 0.00 - 1.92)	0.90 (0.34, 0.04 - 1.92)
Cor_het_02		0.99 (0.51, 0.00 - 1.80)		0.84 (0.34, 0.00 - 1.52)	
Cor_het_03	1.0	0.78 (0.35, 0.12 - 1.28)	0.82 (0.34, 0.12 - 1.32)	0.77 (0.33, 0.00 - 1.40)	0.76 (0.33, 0.00 - 1.48)
Cor_het_04		0.87 (0.31, 0.36 - 1.32)		0.72 (0.35, 0.00 - 1.48)	
Cor_het_05	1.1	0.64 (0.31, 0.00 - 1.16)	0.77 (0.31, 0.12 - 1.28)	0.68 (0.35, 0.04 - 1.80)	0.69 (0.32, 0.04 - 1.80)
Cor_het_06		0.83 (0.33, 0.12 - 1.28)		0.68 (0.30, 0.00 - 1.32)	
Cor_het_07	1.2	0.67 (0.30, 0.00 - 1.20)	0.68 (0.35, 0.00 - 1.76)	0.61 (0.36, 0.00 - 1.40)	0.62 (0.34, 0.00 - 1.48)
Cor_het_08		0.68 (0.39, 0.12 - 1.76)		0.62 (0.32, 0.00 - 1.48)	
Bot_ref_01	0.9	–		0.77 (0.31, 0.00 - 1.52)	0.78 (0.31, 0.04 - 1.80)
Bot_ref_02		–		0.76 (0.34, 0.00 - 1.80)	
Bot_ref_03	1.0	–		0.69 (0.34, 0.00 - 1.48)	0.69 (0.36, 0.04 - 1.68)
Bot_ref_04		–		0.67 (0.39, 0.00 - 1.68)	
Bot_ref_05	1.1	–		0.61 (0.40, 0.00 - 1.48)	0.62 (0.36, 0.00 - 1.56)
Bot_ref_06		–		0.62 (0.31, 0.00 - 1.56)	
Bot_ref_07	1.2	–		0.56 (0.40, 0.00 - 2.48)	0.56 (0.38, 0.00 - 2.48)
Bot_ref_08		–		0.54 (0.37, 0.00 - 1.64)	
Cor_ref_01	0.9	–		0.95 (0.38, 0.00 - 2.68)	0.93 (0.34, 0.20 - 2.68)
Cor_ref_02		–		0.87 (0.33, 0.00 - 1.64)	
Cor_ref_03	1.0	–		0.75 (0.31, 0.00 - 1.44)	0.74 (0.30, 0.00 - 1.44)
Cor_ref_04		–		0.72 (0.31, 0.00 - 1.28)	
Cor_ref_05	1.1	–		0.72 (0.43, 0.00 - 2.16)	0.72 (0.40, 0.04 - 2.16)
Cor_ref_06 [a]		–		0.69 (0.39, 0.00 - 1.64)	
Cor_ref_07	1.2	–		0.63 (0.36, 0.00 - 1.52)	0.62 (0.321, 0.04 - 1.52)
Cor_ref_08		–		0.59 (0.29, 0.00 - 1.40)	

C.2 Distances between Neighbours

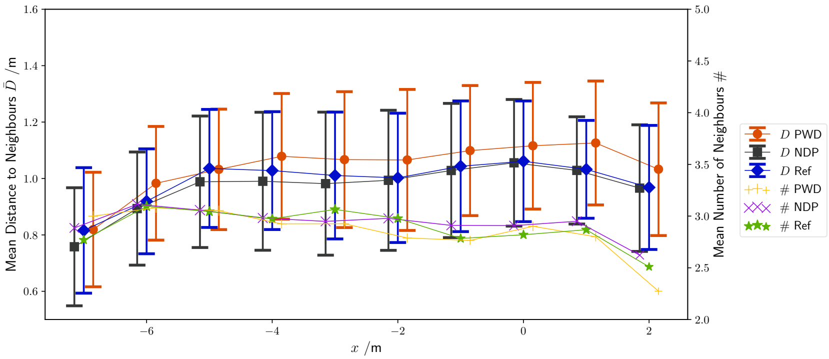
The analysis of neighbourhood relations in crowds is important for the characterisation of crowds dynamics. The distance D can be an indication of mutual repulsion due to specific characteristics. In contrast to the definition of the natural neighbour, which includes all points on a Delaunay circle [212, p. 74], in the following analysis all trajectory points of a point in time are understood as neighbours, which have a Delaunay connection and which are at most 2 m apart.

Since the averaged number of neighbours $\bar{N}$ as well as the averaged distance between a participant to the neighbours $\bar{D}$ is approximately constant according to the x-position in corridor studies (Fig. C.3) and independent of the crowd heterogeneity, remarkable differences were observed inside the bottleneck geometry (Fig. C.4).

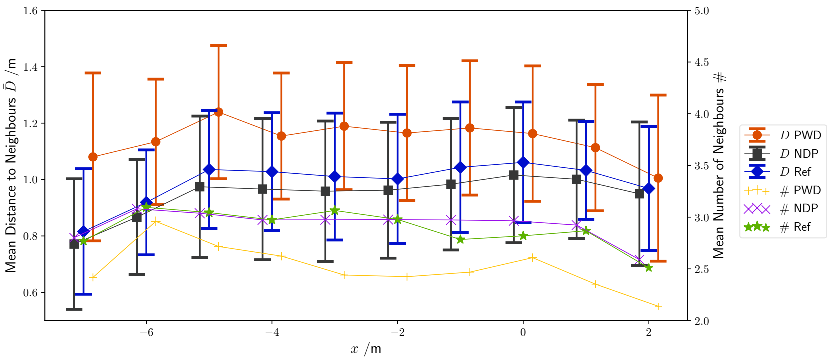
A noticeable smaller distance between neighbours and a decreased number of neighbours is observed for all heterogeneous crowd conditions. Furthermore, it can be observed that the location of the arrangement for the passage of the bottleneck already begins more than 4 m m before the bottleneck. For the crowd conditions wheelchair, walking, mixed, and heterogeneous, the distance between neighbours decrease significantly compared to the reference group. It is noticeable, that the number of NDP-neighbours remains approximately constant and independent from the location for homogeneous conditions, while the number of neighbours decreases in front of the bottleneck entrance in heterogeneous crowd conditions. Similar distances between neighbours for shares of NDP and PWD were found.



(a) *Crowd heterogeneity: older.*

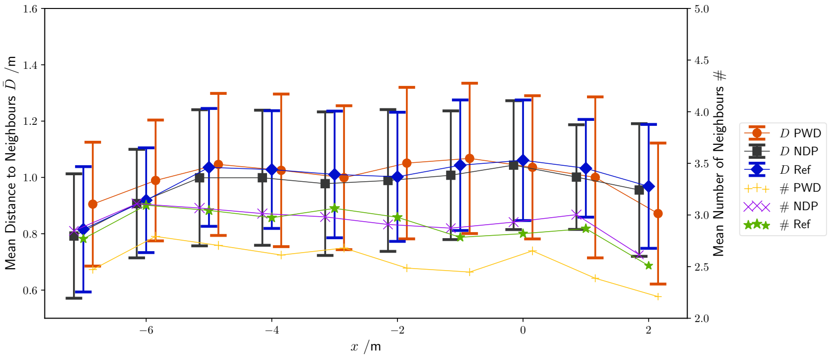


(b) *Crowd heterogeneity: cognition.*

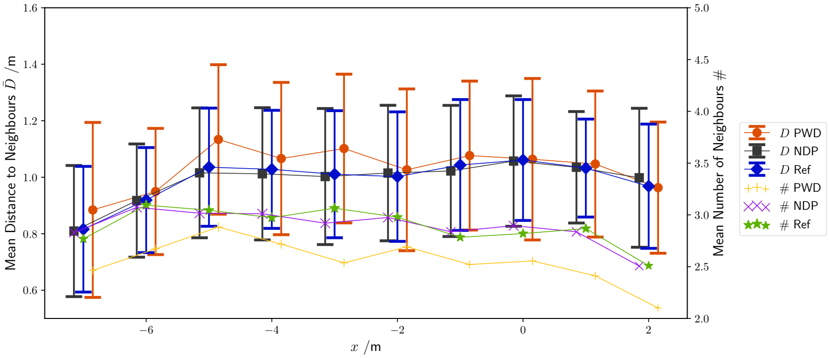


(c) *Crowd heterogeneity: wheelchair.*

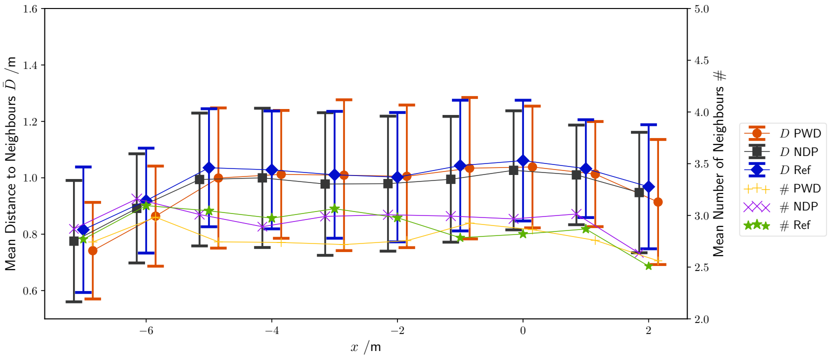
Figure C.3: *Analysis of averaged distances between neighbours and number of neighbours in a corridor for homogeneous (ref) and heterogeneous crowd conditions.*



(d) *Crowd heterogeneity: walking.*

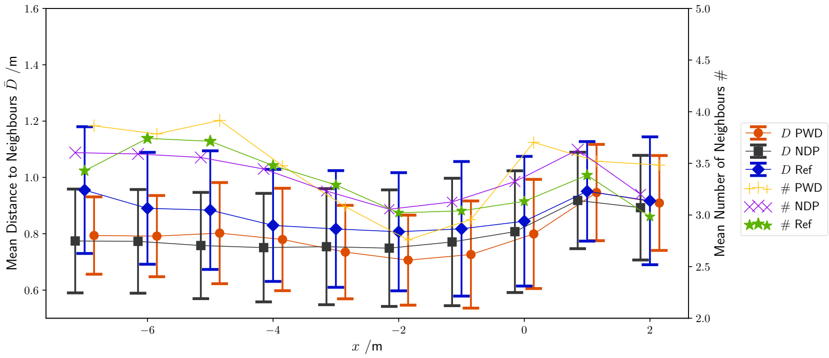


(e) *Crowd heterogeneity: mixed.*

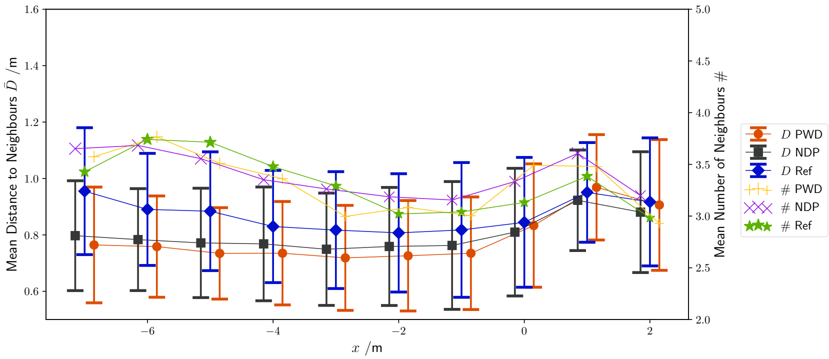


(f) *Crowd heterogeneity: heterogeneous.*

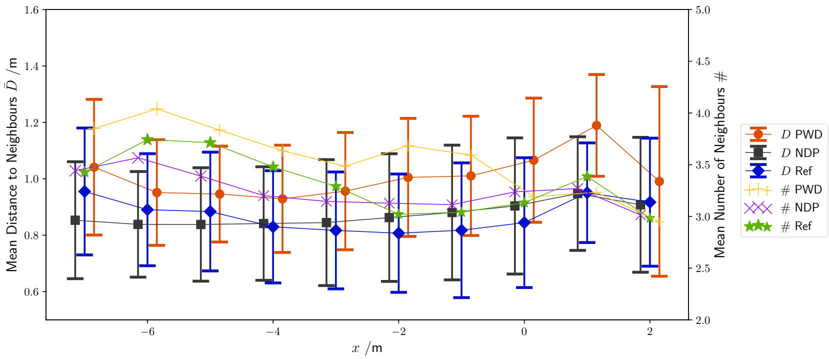
Figure C.3: *Analysis of averaged distances between neighbours and number of neighbours in a corridor for homogeneous (ref) and heterogeneous crowd conditions.*



(a) *Crowd heterogeneity: older.*

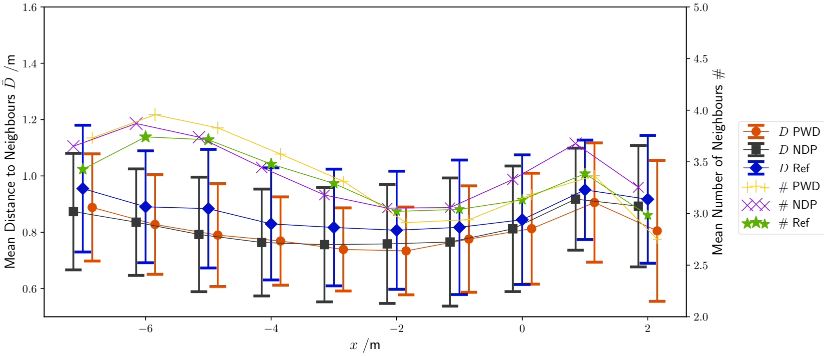


(b) *Crowd heterogeneity: cognition.*

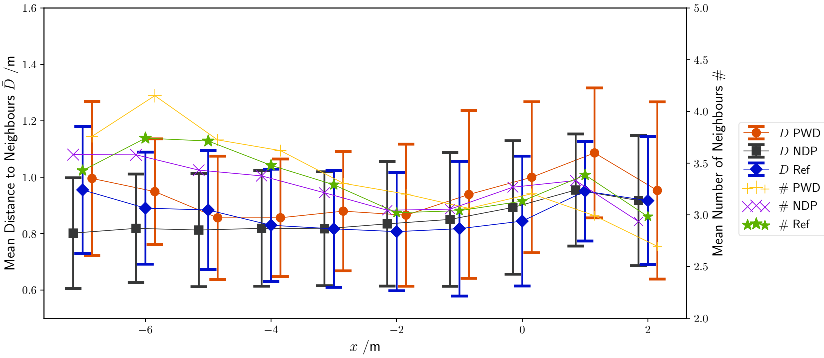


(c) *Crowd heterogeneity: wheelchair.*

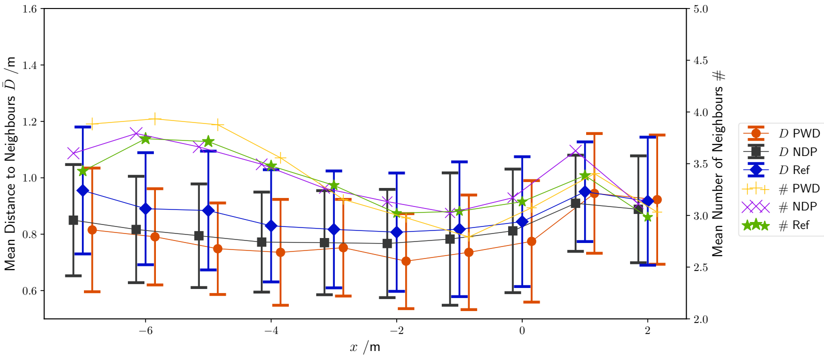
Figure C.4: *Analysis of averaged distances between neighbours and number of neighbours in a bottleneck for homogeneous (ref) and heterogeneous crowd conditions.*



(d) *Crowd heterogeneity: walking.*



(e) *Crowd heterogeneity: mixed.*



(f) *Crowd heterogeneity: heterogeneous.*

Figure C.4: *Analysis of averaged distances between neighbours and number of neighbours in a bottleneck for homogeneous (ref) and heterogeneous crowd conditions.*

Appendix D

Publications

Journal Article (peer review)

2. Paul Geoerg, Jette Schumann, Stefan Holl, Maik Boltes and Anja Hofmann. 'The influence of individual impairments in crowd dynamics'. In: *Fire and Materials* 2018.2 (2020), p. 1. ISSN: 03080501. DOI: 10.1002/fam.2789.

4. Paul Geoerg, Florian Berchtold, Gwynne, Steven, Karen Boyce, Stefan Holl and Anja Hofmann. 'Engineering egress data considering pedestrians with reduced mobility'. In: *Fire and Materials* 43.7 (2019), pp. 759–781. ISSN: 03080501. DOI: 10.1002/fam.2736.

5. Paul Geoerg, Jette Schumann, Stefan Holl and Anja Hofmann. 'The influence of wheelchair users on movement in a bottleneck and a corridor'. In: *Journal of Advanced Transportation* 2019.3 (2019), pp. 1–17. ISSN: 0197-6729. DOI: 10.1155/2019/9717208.

6. Paul Geoerg, Robert Malte Polzin, Jette Schumann, Stefan Holl and Anja Hofmann. 'Small-scale studies on evacuation characteristics of pedestrians with physical, mental or age-related disabilities'. In: *Journal of Physics: Conference Series* 1107 (2018), p. 072006. ISSN: 1742-6588. DOI: 10.1088/1742-6596/1107/7/072006.

Contribution to a Conference Proceedings

7. Paul Geoerg, Jette Schumann, Maik Boltes, Stefan Holl and Anja Hofmann. 'The influence of individual impairments on crowd dynamics'. In: *INTERFLAM 2019*. Ed. by Stephen Grayson. London: Interscience Communications, 2019, pp. 775–791.

8. Lea Schliephake, Paul Geoerg, Axel Pulm, Gina Sasse, Stefan Holl and Anja Hofmann. 'Die Berücksichtigung von Menschen mit Behinderungen in der Evakuierung'. In: *Proceedings of the 6th Magdeburg Fire and Explosion Prevention Day*. Ed. by Ulrich Krause and Michael Rost. 2019. ISBN: 978-3-00-056201-3.

9. Paul Geoerg, Robert Malte Polzin, Stefan Holl and Anja Hofmann. 'Berücksichtigung von Personen mit körperlichen, geistigen oder altersbedingten Beeinträchtigungen in der Evakuierungsforschung'. In: *Tagungsband der 65. Jahresfachtagung*. Ed. by Vereinigung zur Förderung des deutschen Brandschutzes. Köln: VdS Schadenverhütung GmbH Verlag, 2018.

11. Paul Geoerg, Jette Schumann, Maik Boltes, Stefan Holl and Anja Hofmann. 'The influence of physical and mental constraints to a stream of people through a bottleneck'. In: *Proceedings of Pedestrian and Evacuation Dynamics 2018*. Ed. by Anne Simone Dederichs, Gerta Köster and Andreas Schadschneider. Vol. 5. Lund, Sweden, 2020, pp. 246–252. DOI: 10.17815/CD.2020.57.

12. Paul Geoerg, Rainer Block, Werner Heister, Stefan Holl, Axel Pulm and Anja Hofmann. 'A score regarding the need for assistance: Considering pedestrians with disabilities in evacuation planning'. In: *Proceedings of the 5th Magdeburg Fire and Explosion Prevention Day*. Ed. by Ulrich Krause and Michael Rost. Magdeburg and Germany, 2017. ISBN: 978-3-00-056201-3.

13. Paul Geoerg, Anja Hofmann and Axel Pulm. 'Evacuation Dynamics Under Consideration Of Vulnerable Pedestrian Groups'. In: *INTERFLAM 2016*. Ed. by Stephen Grayson. London: Interscience Communications, 2016.

14. Paul Geoerg, Michael Rost, Ulrich Krause and Anja Hofmann-Böllinghaus. 'Vergleichende Untersuchung zur Personensicherheit am Beispiel eines Seminarraumes'. In: *Tagungsband zum 4. Magdeburger Brand- und Explosionsschutztag*. Ed. by Michael Rost and Ulrich Krause. Magdeburg: Eigenverlag, 2015.

15. Paul Geoerg, Anja Hofmann and Ulrich Krause. 'Comparative study of evacuation dynamics using a lecturer room'. In: *Proceedings of the 6th international Symposium on Human Behaviour in Fire*. Ed. by Karen E. Boyce. 2015, pp. 667–670. ISBN: 978-0-9933933-0-3.

18. Paul Geoerg, Michael Rost and Ulrich Krause. 'Vergleichende Untersuchung computergestützter Evakuierungssimulationen am Beispiel einer Engstelle'. In: *Tagungsband zum 3. Magdeburger Brand- und Explosionsschutztag*. Ed. by Michael Rost and Ulrich Krause. Magdeburg: Eigenverlag, 2013, pp. 1–12.

Journal Article (without peer-review)

10. Paul Geoerg, Laura Künzer, Robert Zinke, Stefan Holl and Anja Hofmann. 'Bewegung besonderer Personengruppen - Berücksichtigung von Barrierefreiheit'. In: *Technische Sicherheit* 1 (2018), pp. 38–43.

16. Marcus Marx and Paul Geoerg. 'Brand- und Explosionsschutz in Gebäuden und Anlagen landwirtschaftlicher Nutzung: Teil 2'. In: *Technische Sicherheit* 10 (2014), pp. 29–31.

17. Paul Geoerg and Marcus Marx. 'Brand- und Explosionsschutz in Gebäuden und Anlagen landwirtschaftlicher Nutzung: Teil 1'. In: *Technische Sicherheit* 9 (2014), pp. 30–33.

19. Rainer Block, Werner Heister and Paul Geoerg. 'Sicherheit in Werkstätten für Menschen mit Beeinträchtigungen: Ausgewählte Ergebnisse einer Onlinebefragung der Werkstattleitungen und Feuerwehren in der BRD zur Sicherheitsinfrastruktur in Einrichtungen der Eingliederungshilfe'. In: *FeuerTrutz Magazin* 6 (2017), pp. 38–41.

Conference Presentations

20. Paul Geoerg, Gina Sasse and Jette Schumann. *Sicherheit für Menschen Beeinträchtigung bei der Evakuierung - ein Bericht aus der Forschung.* Wermelskirchen, 2019-05-14.

21. Paul Geoerg. *Movement of pedestrians in heterogeneous crowds: Assessment of the unpredictable.* Berlin, 2019-03-30.

23. Paul Geoerg. *Sicherheit für Menschen mit Beeinträchtigungen bei der Evakuierung. Ein Bericht aus der Forschung.* München, 2018-11-10.

24. Paul Geoerg. *Sicherheit für Menschen mit Beeinträchtigungen bei der Evakuierung: Ein Bericht aus der Forschung.* Dresden, 2018-11-06.

25. Paul Geoerg, Jette Schumann, Maik Boltes, Stefan Holl and Anja Hofmann. *The influence of physical and mental constraints to a stream of people through a bottleneck.* Lund (Sweden), 2018-12-10.

26. Paul Geoerg. *Berücksichtigung von Menschen mit Beeinträchtigungen in der Evakuierungsforschung?!* Duisburg, 2018-05-29.

27. Paul Geoerg and Stefan Holl. *Considering pedestrians with special needs in evacuation: Predicting the unpredictable?* Rotterdam (The Netherlands), 2018-02-06.

28. Paul Geoerg. *SiME - Movement of the impaired?* Berlin, 2017-10-05.

29. Paul Geoerg, Rainer Block, Werner Heister, Stefan Holl, Axel Pulm and Anja Hofmann. *A score regarding the need for assistance: Considering pedestrians with disabilities in evacuation planning.* Magdeburg, 2017-03-23.

30. Paul Geoerg. *Score der Selbstrettungsfähigkeit? 2. Expertenworkshop des SiME-Verbundforschungsvorhabens.* Mönchengladbach, 2016-10-26.

31. Paul Geoerg. *Score der Selbstrettungsfähigkeit: Evakuierung von Gebäuden unter Berücksichtigung von Menschen mit Beeinträchtigungen.* Berlin, 2016-07-12.

32. Paul Geoerg. *Vergleichende Untersuchung zur Personensicherheit in Gebäuden*. Magdeburg, 2015-03-27.
33. Paul Geoerg, Michael Rost and Ulrich Krause. *Vergleichende Untersuchung computergestützter Evakuierungssimulationen am Beispiel einer Engstelle*. Magdeburg, 2013-03-23.

Scientific Poster

34. Paul Geoerg, Gina Sasse, Rainer Block, Stefan Holl and Anja Hofmann. *Sicherheit für Alle in der Bewegungsforschung: Abschlusskonferenz KOPHIS-Forschungsvorhaben: [Poster]*. Berlin, 2019.
35. Paul Geoerg, Gina Sasse, Rainer Block, Stefan Holl and Anja Hofmann. *Sicherheit für alle in der Bewegungsforschung: 4. BMBF Innovationsforum Zivile Sicherheit: [Poster]*. Berlin, 2018.
36. Paul Geoerg, Robert Malte Polzin, Jette Schumann, Stefan Holl and Anja Hofmann. *Evacuation characteristics of people with disabilities: 3. European Symposium on Fire Safety Science (ESFSS): [Poster]*. Nancy, France, 2018.
37. Paul Geoerg and Anja Hofmann-Böllinghaus. *Sicherheit für Menschen mit körperlicher, geistiger oder altersbedingter Beeinträchtigung: 3. BMBF Innovationsforum Zivile Sicherheit: [Poster]*. Berlin, 2016.
38. Paul Geoerg, Anja Hofmann and Axel Pulm. *Evacuation dynamics under consideration of vulnerable pedestrian groups: Interflam 2016: [Poster]*. London, 2016.
39. Paul Geoerg, Anja Hofmann and Ulrich Krause. *Comparative study of evacuation dynamics using a lecturer room: 6th International Conference on Human Behaviour in Fire: [Poster]*. Cambridge, 2015.

Reports and other Publications

40. Paul Geoerg and Anja Hofmann. *Sicherheit für Menschen mit körperlichen, geistigen oder altersbedingten Beeinträchtigungen: Einfluss heterogener Zusammensetzungen von Personengruppen auf die Personenbewegung: Schlussbericht*. Hannover (Germany), 2019.
41. Rainer Block, Werner Heister and Paul Geoerg. *Sicherheit in Werkstätten (und Wohnstätten) für Menschen mit Beeinträchtigungen: Ergebnisse einer Online-Befragung der Werkstattleitungen und Feuerwehren in der BRD zur Sicherheitsinfrastruktur in Einrichtungen der Eingliederungs- und Behindertenhilfe*. Mönchengladbach, 2017.

43. Paul Geoerg, Rainer Block, Werner Heister and Stefan Holl. *Pilotstudie zum Evakuierungsverlauf unter Berücksichtigung von Personen mit körperlichen, geistigen oder altersbedingten Beeinträchtigungen in einer Werkstatt der Wiedereingliederungshilfe*. 2016.

44. Forschungszentrum Jülich and Federal Institute For Materials Research and Testing. *Influence of individual characteristics: Extended documentation on large-scale movement studies*. 2019. DOI: 10.34735/PED.2017.1.

Co-supervised theses

45. Lukas Heydick. 'Explosionskenngrößen hybrider Dampf-Staub Gemische'. Bachelor thesis. Magdeburg: Otto-von-Guericke-Universität, 2020.

46. Tobias Hofmann. 'Variation der Gemischbildung für hybride Gemische im GG-Ofen'. Bachelor thesis. Magdeburg: Otto-von-Guericke-Universität, 2020.

47. Danny Regler. 'Literaturübersicht zu (historischen) sicherheitstechnischen Kenngrößen'. Bachelor thesis. Magdeburg: Otto-von-Guericke-Universität, 2020.

48. Daniel Ernst. 'Vergleichende Bestimmung der Mindestzündtemperatur von Gemischen und Reinstoffen'. Master thesis. Magdeburg: Otto-von-Guericke-Universität, 2020.

49. Abhishek Ellapu. 'Control and Measurement with LabView'. Master thesis. Magdeburg: Otto-von-Guericke-Universität, 2020.

50. Babette Tecklenburg. 'Zur Berücksichtigung von Menschen mit Beeinträchtigungen in der Evakuierungsplanung: besondere Bedürfnisse und Empfehlungen für Fachplaner'. Bachelor thesis. Magdeburg: Otto-von-Guericke-Universität, 2019.

51. Lea Schliephake. 'Vergleich des Bewegungsverhaltens von Menschen mit Beeinträchtigung sowie ohne Beeinträchtigung anhand einer unangekündigten Evakuierungsübung'. Bachelor thesis. Magdeburg: Otto-von-Guericke-Universität, 2018.

52. David Kirsch. 'Vergleichende Untersuchung zur Evakuierung des Magdeburger Hauptbahnhofs'. Bachelor thesis. Magdeburg: Hochschule Madeburg-Stendal, 2014.

Appendix E

Curriculum Vitae

The Curriculum vitae is not included in the online version for reasons of data protection.

Appendix F

Digital Appendix

- Phd thesis
  - Plots
    - Trajectories
    - Number of passed participants $N(t)$
    - Time series of ρ, v, J
    - Distance-time $d(t)$
    - Distance between Delaunay neighbours D
    - Acceleration a
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