

THE INFLUENCE OF INDIVIDUAL IMPAIRMENTS ON CROWD DYNAMICS

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ABSTRACT

Emergency exits as bottlenecks in escape routes are important for designing traffic facilities. Especially the fundamental diagram is a crucial performance criterion for assessment of pedestrians' safety in facilities and an important basis for calculation methods. For this reason, several studies were performed during the last decades which focus on the quantification of movement through bottlenecks. These studies were usually conducted with populations of homogeneous characteristics to reduce influencing variables and for reasons of practicability.

Studies which consider heterogeneous characteristics in performance parameters are rarely available. In response and to reduce this lack of data a series of well-controlled large-scale movement studies considering pedestrians with different disabilities was carried out.

As result it is shown that the empirical relations $v(\rho)$ and $J(\rho)$ are strongly affected by the presence of participants with visible disabilities (such as wheelchair users) and the perception of the disability by the non-disabled participants. An adaption of movement speeds to movement speeds of participants using a wheelchair was observed, even for low densities and free flow scenarios. Flow and movement speed are in a complex relation and do not depend on density only. In our studies, the concept of specific flow does fit for the non-disabled subpopulation but it is not valid for the disabled participants.

KEYWORDS

human behaviour | engineering egress data | evacuation egress | heterogeneity | fundamental diagram

LIST OF ABBREVIATIONS

Symbol	Description	Unit
A_i	Individual required space (area of a Voronoi cell)	m ²
BOT	Bottleneck	
J	Flow rate	s ⁻¹ or (ms) ⁻¹
$J(\rho)$	(individual) relation of movement flow rate and density	s ⁻¹ or (ms) ⁻¹
$\bar{J}(\bar{\rho})$	Fundamental diagram flow-density	s ⁻¹ or (ms) ⁻¹
KDE	Kernel density estimator	
l_i	Length of a wheelchair	m
max	Maximum	
min	Minimum	
mix	Study with a subpopulation of participants with mixed (multiple severe) disabilities	
μ	Averaged value	
N	Numbers of participants	
NDP	Non-disabled participants	
persID	Unique identification number of a participant in a run (number of trajectory)	
PWD	Participants with disabilities	

pwdID	Unique identification number of a participant with disability for all studies	
ref	Study with reference population without any disabilities	
$\bar{\rho}$	Pedestrians' density	m^{-2}
RNA	Regarding the need for assistance	
σ	Standard deviation	
SiME	Safety for pedestrians with disabilities	
t	Time (step)	s
$\bar{v}$	Movement speed	ms^{-1}
v_o	Unimpeded (free) movement speed	ms^{-1}
$v(\rho)$	(individual) relation of movement speed and density	ms^{-1}
$\bar{v}(\bar{\rho})$	Fundamental diagram speed-density	ms^{-1}
w	Passage width	m
w_w	Width of a wheelchair	m
wal	Study with a subpopulation of participants with walking disabilities	
whe	Study with a subpopulation of wheelchair users	
x,y	Cartesian coordinates	m

INTRODUCTION

Experimental investigations of pedestrian movements and dynamics have 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. Frequently such studies were conducted under laboratory conditions with a homogeneous configuration of the participating groups (see more comprehensive reviews in [1], [2], [3] or [4]). Movement dynamics in bottlenecks are of particular interest because of the high relevance when assessing the performance of a facility (e.g. [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]).

It is debatable whether those data are still representative in terms of transferability to diverse, inhomogeneous and more realistic populations. Given the fact, that the demographic transformation process is already in progress ([25], [26]), movement characteristics and functional relationships may be out of date [27]. Until now, only a few studies considered a more heterogeneous characterisation of participants. This topic is recently addressed by a comprehensive literature and data review on the influence of reduced mobility on movement characteristics [28].

To summarise, social-demographics in western societies are changing as the way of living and the kind of dwellings is. Particularly in the context of these developments and the associated lack of data, it is necessary to improve the understanding of movement behaviour of heterogeneous pedestrian groups. We present a deep analysis of a series of well-controlled movement studies with focus on characteristics on pedestrians' movement and assessment of performance of a facility, the so-called fundamental diagram. The structure is organised as follows: in Sec 2 the setting of the movement studies, the data extraction techniques and the used calculation methods are introduced. The data analysis follows in Sec 3. First, we present a comparison of unimpeded (unrestricted, free) movement speed of different subpopulations (Sec 3.1). Second, the impact of the presence of subgroups of participants using a wheelchair, participants with walking disabilities and participants with mixed disabilities on movement in a group is discussed. Especially the effect on fundamental relationships $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho}) = \bar{\rho} \cdot \bar{v}$ is examined in more detail (Sec 3.2). The conclusion is made in the last section (Sec 4).

METHODS

Study settings

The movement studies were conducted as a part of the interdisciplinary research project SiME. SiME is an acronym for the German meaning of ‘Safety for all people’ and funded by the German Ministry of Education and Research (BMBF). Twelve studies with more than 145 single runs and overall 252 participants with and without disabilities were performed in an industrial hall in Wermelskirchen-Dabringhausen (Germany) in June 2017.

Participants without disabilities were recruited by public call while participants with disabilities were recruited from a sheltered workshop. For defining the type of disability and to consider and select participants with disabilities, we used the Score RNA-approach, which is a method to weight potentially critical indicators for egress (for details we refer to [29] and [30]). The Score RNA considers disabilities in reception (blindness, deafness), perception (cognition) and ability of movement (walking impairments, requirement on assistance devices) and in addition a cross-section variable (age). This Score evaluates the influence of the individual ability to evacuate autonomously. Here we present the influence on movement through a bottleneck (Fig 1) by absence and presence of subpopulations considering wheelchair users (Bot_whe), walking disabled (Bot_wal) and multiple severe-disabled participants (Bot_mix). This configuration follows the concept of increasing complexity of individual characteristics: first, a subpopulation of walking disabled represents the simplest case of complexity, because the movement pattern is quite similar to the reference population. A more complex situation because of static space requirements (wheelchairs) does follow. These subpopulations are therefore a necessary simplification for the design of a persona 'participants with single disability'. For details of applying a persona we kindly refer to [31]. Afterwards, a subpopulation of multiple severe-disabled participants (considering blind, deaf and wheelchair users) was analysed. In addition, all studies were replayed without a subpopulation with disabilities (reference studies – Bot_ref).

In accordance to the reported 10 % of inhabitants with disabilities in Germany [32] and the estimated prevalence of high and medium disabilities world wide of 15 % [33], a similar population was configured. This is in accordance to the prevalence of disability (approximately 15 % for EU-27 [34] and 19 % for the US [35]).

Participation was absolutely voluntary for everybody and a 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 anonymous data were used for the studies and the methodological design, data storage process and the access authorisation for data was approved by the ethics committee of the Bergische Universität Wuppertal. No ethical concerns were mentioned. The mean age of the disabled participants was 47.57 ± 6.99 , the mean age of non-disabled participants was 35.93 ± 16.26 . The mean age of the reference population was 32.07 ± 15.20 . The body heights of all participants range from 1.45 m to 2.04 m with a mean of 1.74 ± 0.1 m.

The aim of the studies was to investigate the impact of a heterogeneous characterised crowd (non-disabled participants and disabled participants) on performance criteria for movement in built environments under laboratory conditions. In this context, the passage width w was varied in steps of 0.1 m from 0.9 m up to 1.2 m. The length of the bottleneck was constant with a length of 2.4 m (see Fig. 1) and each run was repeated (see Tab. 1). The geometry was built from wooden three-layer panels with a height of 2.0 m. To buffer starting conditions and minimize the effect of the entrance, a waiting zone of approximately 30 m² was located at a distance of 15.0 m in front of the bottleneck entrance. The initial density was about 3.0 m⁻².

Table 1: Controlled boundary conditions and characteristic of each run. Note that some participants have to rest after a run due to their disability and that volunteers without tasks participated run-wise.

Bot_whe	Run	00	01	02	03	04	05	06	07	08
	Width	0.9 m			1.0 m		1.1 m		1.2 m	
	N (NDP)	77	81	80	80	80	83	83	85	83
	N (PWD)	7	7	7	7	7	7	7	7	7
Bot_wal	Run	00	01	02	03	04	05	06	07	08
	Width	0.9 m			1.0 m		1.1 m		1.2 m	
	N (NDP)	70	79	80	80	80	79	80	81	81
	N (PWD)	5	5	5	5	5	5	5	5	5
Bot_mix	Run	00	01	02	03	04	05	06	07	08
	Width	0.9 m			1.0 m		1.1 m		1.2 m	
	N (NDP)	71	71	71	71	74	73	79	73	71
	N (PWD)	12	12	12	12	12	12	6	12	12
Bot_ref	Run	00	01	02	03	04	05	06	07	08
	Width	0.9 m			1.0 m		1.1 m		1.2 m	
	N (NDP)	68	67	67	66	66	69	69	69	69
	N (PWD)	-	-	-	-	-	-	-	-	-

The participants were advised to move through the bottleneck without haste. It was emphasized not to push, and to walk with the preferred movement speed. A run was started by instructions of the experiment leader. When a participant leaves the geometry, he or she returns to the waiting zone for the next run. Each run was repeated twice and the performance criteria were measured in a measurement area of 4.0 m² located 4.0 m in front of the bottleneck entrance (see Fig 1 - Fig 4).

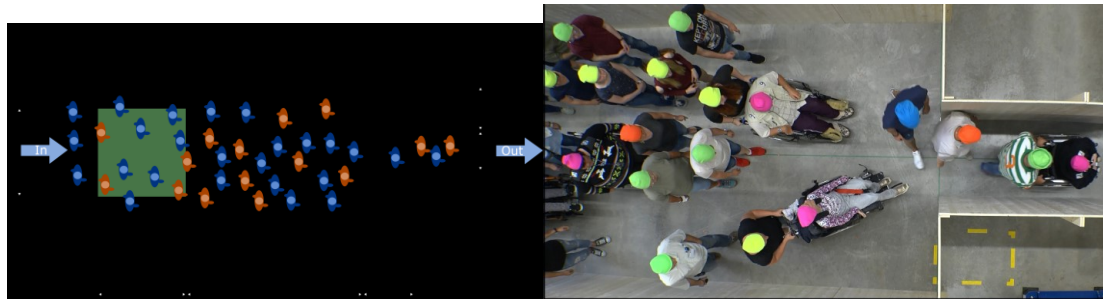


Figure 1. Sketch (left) and snapshot (right) of the study setup. The passage width has been varied in steps of 0.1 m between 0.9 m and 1.2 m. The measurement area is coloured in green.

Data extraction

The movement through the study setting was captured by nine high-definition cameras attached to the ceiling of the hall at a height of about 6.34 m. Each participant wore a coloured cap according to their individual body height. We used the PeTrack-Framework to determine the automatic extraction of positions at every time step (frame) from the video recordings [36]. PeTrack detects the centre of the coloured cap and tracks the position for the following time steps. The transformation from pixel coordinates into physical (world) coordinates was auto-corrected by taking the lens distortion, the perspective view and the height according to the colour of the caps into account [37].

We assume a coherent area of pixels in the middle of the coloured hats as body centre of a participant, so the resulting trajectories represent positions of the head projected on the ground. All resulting trajectories were checked and corrected manually. The trajectories are precise with a maximum error of approximately 0.092 m in the perspective of the centred camera (for details of the error calculation we refer to [37]). Fig 2 displays for instance the trajectories corresponding to a bottleneck configuration

with a passage width of 1.2 m with (Bot_whe_08) and without (Bot_ref_08) participation of wheelchair users. See Tab 1 for details of the run 08 indicated by the two-digit number. Participants with disabilities (in this case using a wheelchair) are coloured in orange. For more comprehensive information about the disabled participants see Tab 3-5 in App 1.

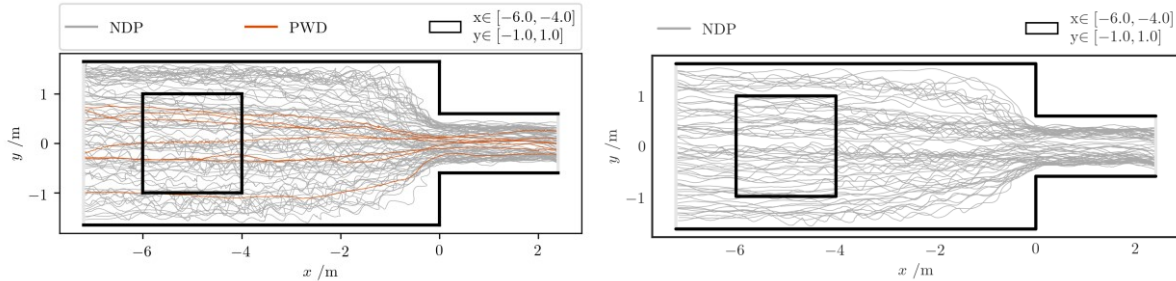


Figure 2. Trajectories for Bot_whe_08 (left) with approximate 10 % of participants using a wheelchair and trajectories for Bot_ref_08 without participants with disabilities. The passage width is 1.2 m and the measurement area is plotted by the black rectangle.

Measurement

Based on the individual position and the time step, the participants can be represented as a set of points in the metric space, which can be transferred into a Voronoi diagram [38],[39]. The Voronoi tessellation assigns an individual required space $A_i(t)$ to each person (called Voronoi cell) which includes all coordinates of the Euclidean plane that are closer to the participant i than to the neighbours [39], [40], [41]. Then, the density inside a Voronoi cell of a participant is equal to the reciprocal of its area $\rho_i(x, y, t) = \frac{1}{A_i}$. The averaged Voronoi density $\rho(x, y, t)$ inside the measurement area is then defined as:

$$\rho(x, y, t) = \sum_i \rho_i(x, y, t) \quad Eq 1$$

with

$$\rho_i(x, y, t) = \begin{cases} \frac{1}{A_i}(t): & \forall (x, y) \in A_i(t) \\ 0: & other \end{cases} \quad Eq 2$$

The averaged Voronoi movement $v(x, y, t)$ speed inside the measurement area is then defined as:

$$v(x, y, t) = \sum_i v_i(x, y, t) \quad Eq 3$$

with

$$v_i(t_i, dt) = \frac{dx_i(t_i, dt)}{dt} \quad Eq 4$$

and

$$v_i(x, y, t) = \begin{cases} v_i(t): & \forall (x, y) \in A_i(t) \\ 0: & other \end{cases} \quad Eq 5$$

An example for the distribution of Voronoi density and movement speed over space at time step 21.24 s (similar to frame 531) for a study with wheelchair users obtained from Voronoi method is presented in Fig 3.

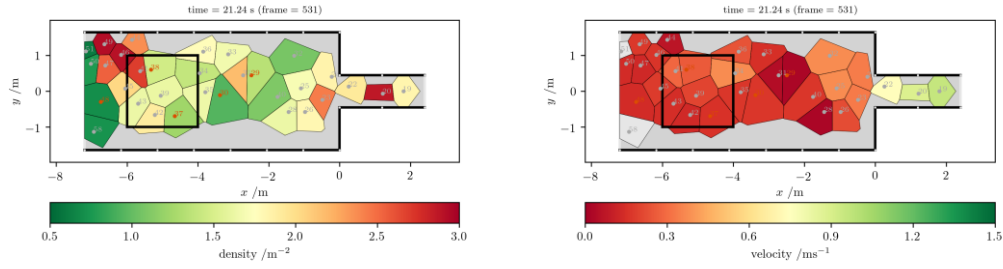


Figure 3: Individual Voronoi density (left) and movement speed (right) obtained from Voronoi tessellation. Unique identification numbers (persIDs) of participants with disabilities are coloured in red.

ANALYSIS AND RESULTS

Unimpeded movement speed

The unimpeded (free) movement speed v_0 was measured for each participant immediately before starting the studies (Tab 2). This was realised by single-file movement of the participants through the bottleneck configuration using a passage width of 0.9 m. The start of each individual was controlled by an instructor with respect to interpersonal distance of approximately 5 s which is similar to approximately 6 m interpersonal space (expecting a possible free movement speed of 1.2 ms^{-1}).

Table 2. Unimpeded movement speeds in ms^{-1} for different subpopulations. For a comprehensive description of the characteristics we kindly refer to [29]. Data is presented in the following format: mean [standard deviation, minimum - maximum] and reproduced from [42].

Study	N (PWD)	v_0 (PWD) / ms^{-1}	N (NDP)	v_0 (NDP) / ms^{-1}
Wheelchair	7	0.96 [0.35, 0.45 – 1.41]	77	1.45 [0.17, 0.63 – 1.82]
Walking Disabled	5	1.28 [0.12, 1.07 – 1.41]	70	1.44 [0.17, 0.88 – 2.08]
Mixed Population	5	1.33 [0.29, 0.29 – 1.65]	71	1.47 [0.18, 0.65 – 1.89]
Reference	12		68	1.47 [0.17, 1.08 – 1.86]

Overall, the observed unimpeded movement speeds of non-disabled participants are comparable with literature findings (see [1] or [28]), which indicates a working experimental setting. On the other hand, unimpeded movement speeds of the participants with disabilities depends strongly on individual characteristics such as the kind of movement ability which leads to high standard deviations. For this reason, it is difficult to derive general statements about movement characterisation [29]. Due to the small sample size for the disabled participants, the results represents in particular the relation of the individuals in this study and the results should be verified in further experiments.

Stationarity

To determine the fundamental diagram only data from stable conditions are used. This is particularly important since pedestrian dynamics experiments usually have significantly shorter running times than field studies of car traffic, which leads to relatively low densities and movements lower than the free flow state at the beginning and the end of a run.

Since a central objective of the investigation was the analysis of the influence of heterogeneous movement properties on the stability of the values of interest, an automatic detection, as for example the Cumulative Sum Control Chart algorithm [16], did not find the desired time periods. For this reason here steady states are defined by the relative stable condition of the time development [15]. In this work, the steady state conditions were detected manually selected by analysing the time series for movement speed, density and flow (in accordance to the work by [41], [15], [43], [44], [45], [46]). In result, the shape of the measurement area depends on space and time. In constant space-dimension we took the measurement in a rectangular area in a distance of 4 m to the bottleneck entrance (Fig 1, Fig 2). In variable time-dimension, the spread of the measurement area was adapted by the steady state definition

(see grey coloured areas in Fig 3).

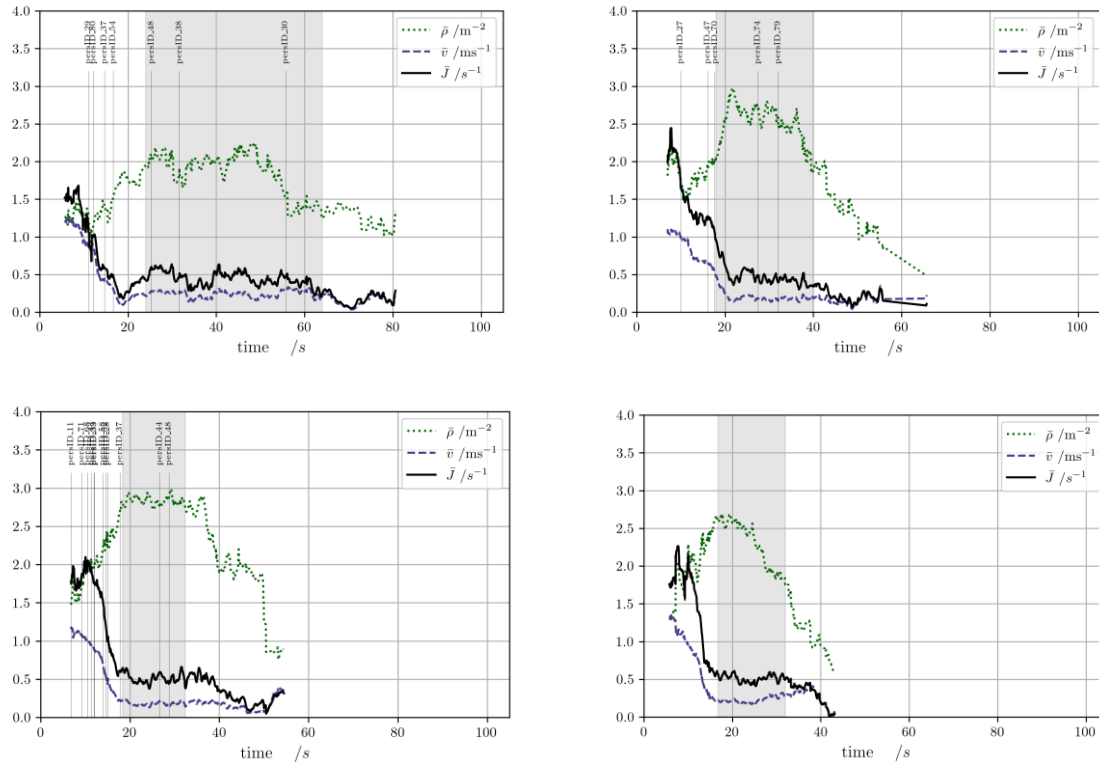


Figure 4. Time series of moving averaged measures $\bar{\rho}(t)$, $\bar{v}(t)$ and $\bar{J}(t)$ in a time interval of 2 s (which is corresponding to 50 frames) for bottleneck configurations with a passage width of 0.9 m and different subpopulations (top left: wheelchair users, top right: walking disabled, bottom left: mixed disabilities and bottom right: reference population without disabilities). The unique ID (persID) and the time of entrance of participants with disabilities into the measurement area is emphasised by the vertical lines. The period of stationary conditions is presented by the grey coloured area.

Overall densities in a range between 2.0 m^{-2} and 3.0 m^{-2} were observed in all configurations (varied width and subpopulations) with low averaged movement speeds and moderate flows. The ladder can be justified by a manageable number of participants and, as a result of a two-day-cooperation, a polite and considerate behaviour and the low motivation of the participants. Focussing the time development of the studies with the reference population, the measured performance criteria does not show remarkable fluctuations: the flow inside the measurement area increase after start, goes to a small steady state condition plateau of approximately 10 s and decreases afterwards. The appearance of the averaged values is harmonious without noticeable fluctuations (Fig 3, bottom line right). If subpopulations of participants with disabilities were considered, density increases within 25 s from initial density up to a local maximum and remains steady (but fluctuating) for approximately 40 s (considering wheelchair users), approximately 20 s (considering walking disabled participants) or approximately 10 s (considering mixed subpopulation and reference run). But the appearance of the time-dependent development changes, if subpopulations with disabilities were considered: remarkable fluctuations, especially in the average density and flow, are observed (see for instance time stamp 30 s or time stamp 55 s in Fig 3, top line left). In consequence, the process of obtaining the fundamental diagram is a balance between considering the data of disabled participants (fluctuating data) and the need for stable conditions (steady states).

In order to place the measurement area in a region of the study setup where stable conditions can be achieved, the spatiotemporal dependency of the measures were analysed. To implement this, a mesh grid of 600×600 cells was placed over the geometry and the values were linear interpolated for each frame during the steady state interval. Fig 5 shows the flow profiles for the four different populations in a bottleneck with a passage width of 0.9 m. The overserved maximum individual flow is approximately 2.5 s^{-1} for all populations. It is worth noticing that the maximum flow was observed at the entrance to the bottleneck and that the flow in front of the bottleneck is lower than inside the bottleneck (which is in accordance to the findings by [45]).

The flow is not homogeneous distributed over the entire space for all configurations: throughout analysing the study with a reference population (Fig 5, bottom right), walking impaired (Fig 5, top right), and mixed-population (Fig 5, bottom left), the flow decreases mainly near to the bottleneck entrance due to increasing density in front of the bottleneck. But, if a subpopulation using wheelchairs is considered, the situation is quite different (Fig 5, top left): a decreased flow is observable over the entire geometry which is independent from the observed passage width. Therefore, higher densities occur along the entry hall which confirms that the mode of movement is different. Concluding, the observed flow during the consideration of wheelchair users may not be the capacity of the built-environment.

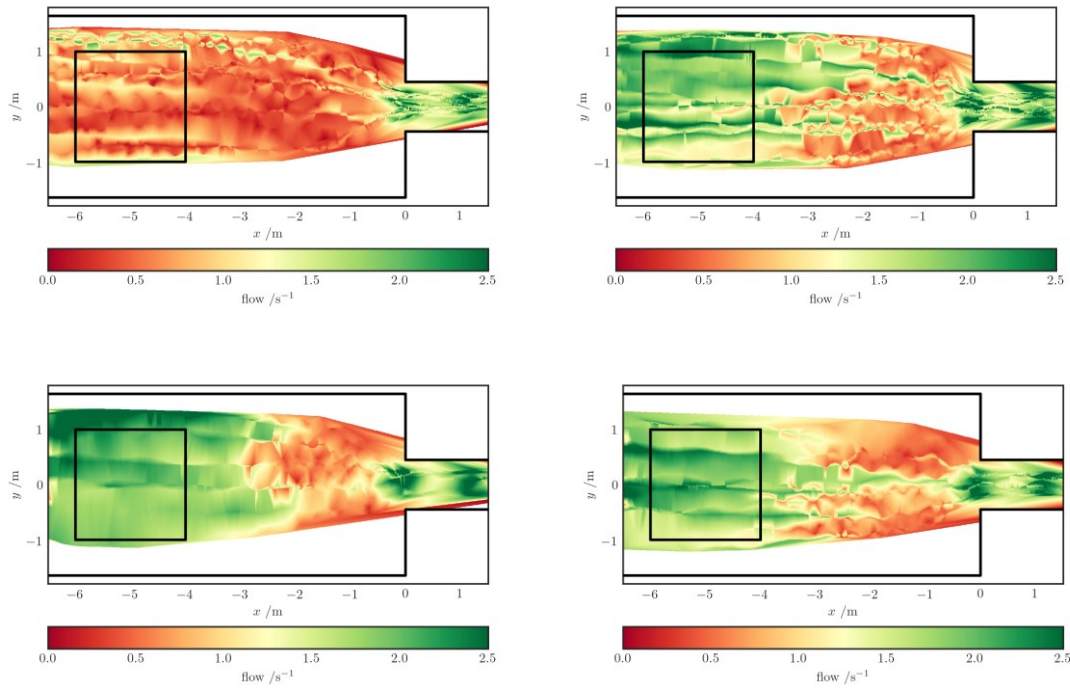


Figure 5. KDE-profile (mesh grid size: 600 x 600, linear interpolation method) of the flow in a bottleneck configuration (passage width of 0.9 m) for different populations during the stationary states. Approximately 10 % of participants using a wheelchair (top left), participants with walking impairments (top right) participants with mixed disabilities (bottom left) and a reference population without participants with disabilities (bottom right).

Density-Speed- and Density-Flow-relations (Fundamental diagrams)

We focus on the analysis of the fundamental relationship of $v(\rho)$ and $J(\rho)$ for unidirectional movement through the bottleneck geometries with different subpopulations. The derived fundamental diagrams for $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$ are determined by the stationary states resulting from the time series (see Fig 4). A time interval of 2 s (which is corresponding to 50 frames) was used to calculate the moving averages. Fig 6 presents individual speed-density-relations $v(\rho)$ depending on the considered subpopulations in comparison to the resulting fundamental diagrams $\bar{\rho}(\bar{v})$ during the steady state interval. A time-step of 12 frames (approximately similar to 0.5 s) and a density interval of $\rho_{min} < n < \rho_{max}$ with n as a multiple of 0.1 m^{-2} was used for plotting to make sure that the presented data is independent. As a result of the limited number of the participants, the observed density interval is in between 0.5 m^{-2} and 5.0 m^{-2} . The lower threshold of density located at 0.5 m^{-2} is due to the fact, that the size of Voronoi cells was limited to a maximum length (cut-off-radius) of 2.0 m to avoid infinitely long Voronoi cells at lower densities (given only one participant in a measurement area of 4.0 m^2 is lead to $\rho = \frac{MA}{A_i} = 0.5$). It is striking out, that participants with disabilities are likely to appear in all density regions (Bot_wal and Bot_mix), but this this does not apply to the results of the Bot_whe study, where wheelchair users are considered. Participants in wheelchairs tend to appear in density regions less than

2.0 m⁻² (compare the orange scatter on the left in Fig 6). Otherwise, participants with mixed disabilities are distributed over a density up to 4.0 m⁻². It is worth noticing that the observed average movement speed is low for all configurations (approximately 0.25 ms⁻¹). While considering participants with walking impairments and in mixed configurations, a slight dependency between movement speed and density is recognisable, the averaged movement speed in the measurement surface in a group considering participants in wheelchairs is independent from density. This is in contrast to the expected behaviour and data from previous studies with homogeneous populations (e.g. [47], [6], [2]) and the classic understanding of the fundamental diagram.

The comparison of individual flow-density-relations $J(\rho)$ to the deriving fundamental diagrams $\bar{J}(\bar{\rho})$ is presented in Fig 7. A time-step of 12 frames (approximately similar to 0.5 s) and a density interval $\rho_{min} < n < \rho_{max}$ with n as a multiple of 0.1 m⁻² was also applied here. A dependency of the flow on density was observed for all configurations. It is independent from the subpopulation but the capacity point $J_{s,max}$, where the density is maximum ($\bar{\rho}_c$), was not reached in any study. The observed flow increase linearly to a plateau of approximately 1.0 (ms)⁻¹ for all configurations. A slightly minor higher flow was observed in the studies with mixed- and reference population.

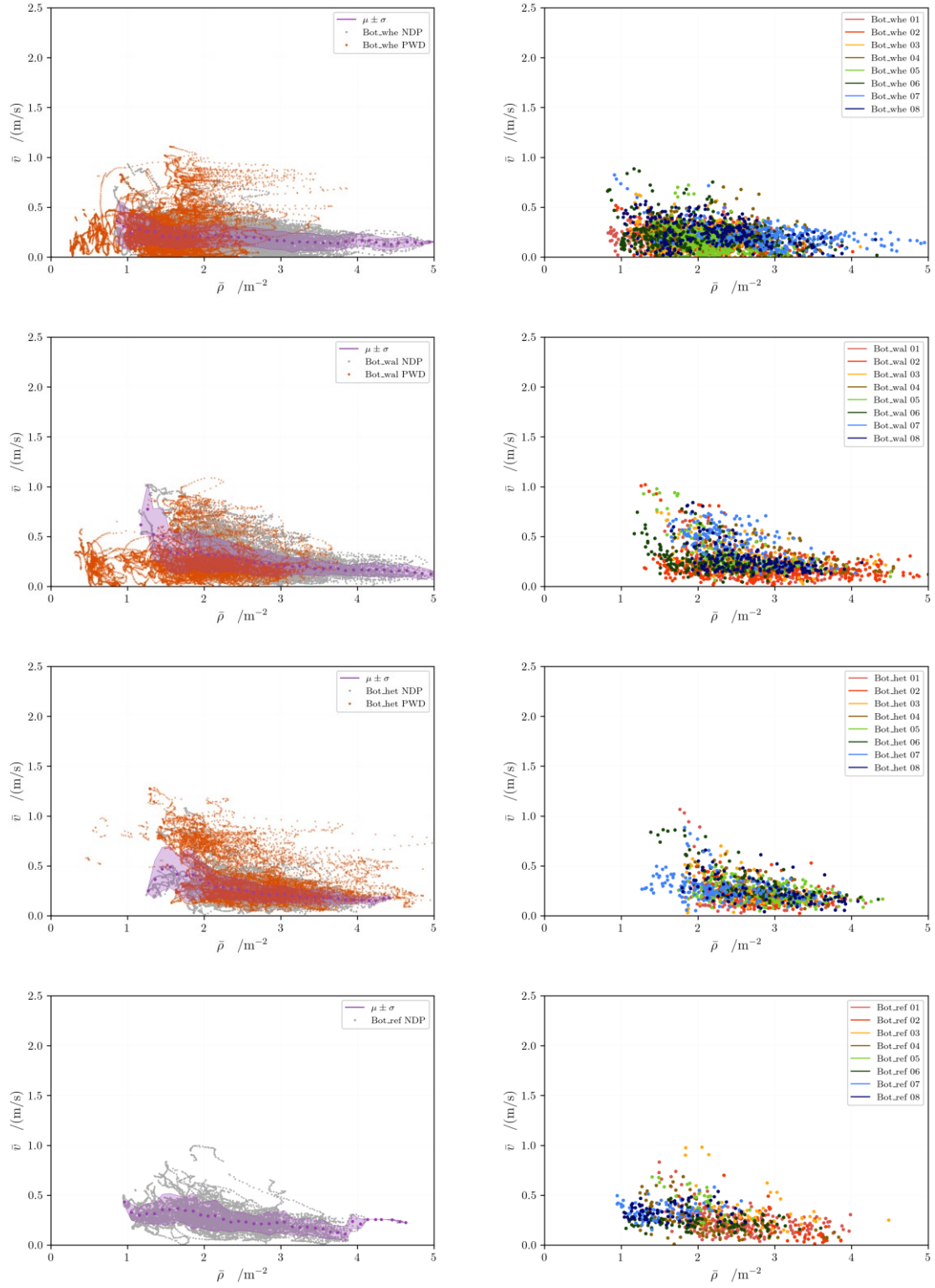


Figure 6. Individual speed-density-relations $v(\rho)$ (left) derived from data of all runs considering different subpopulations and fundamental diagrams $\bar{v}(\bar{\rho})$ for different runs (right). Left: individual values for participants with disabilities are coloured in orange, the 1σ -interval and a rolling mean is coloured in violet. Right: colours are indicated by different runs (see Tab 1). Starting from the top: Bot_whe, Bot_wal, Bot_mix and Bot_ref.

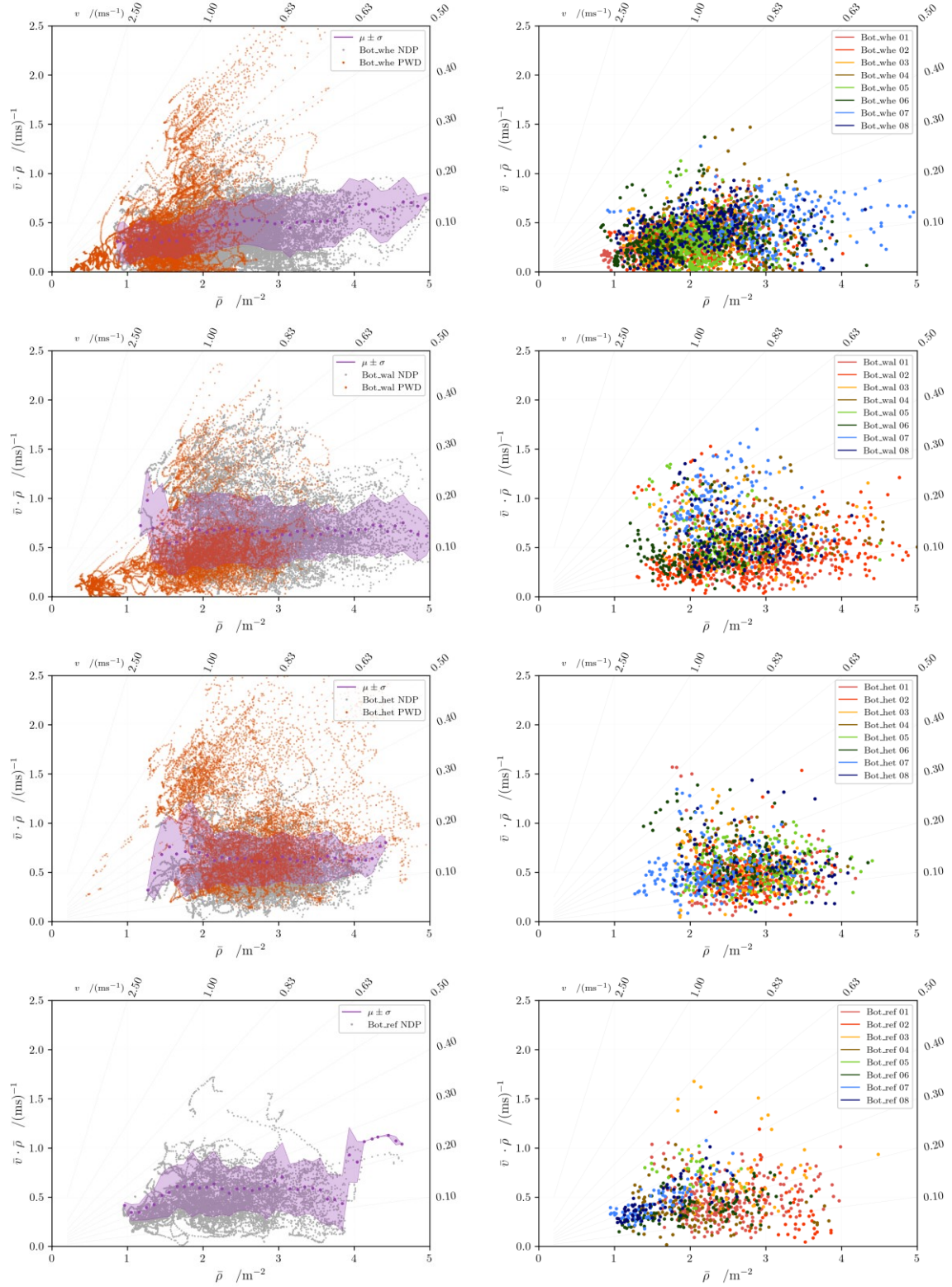


Figure 7. Individual flow-density-relations $J(\rho)$ (left) derived from data of all runs considering different subpopulations and fundamental diagrams $\bar{J}(\rho)$ for different runs (right). Left: individual values for participants with disabilities are coloured in orange, the 1σ -interval and a rolling mean is coloured in violet. Right: colours are indicated by different runs (see Tab 1). Starting from the top: Bot_whe, Bot_wal, Bot_mix and Bot_ref. The grey dotted nomogram lines are associated movement speeds v .

We compare the joint distribution of $v(\rho)$ and $J(\rho)$ and its marginals at once in Fig 8. The counts of the observations that are located in small hexagonal bins are colour-coded from little (blue) to much (red). In addition, the distribution of density ρ , movement speed v and flow J is presented. It summarises the dependency of movement speed and density inside the measurement area for each population configuration except the consideration of wheelchair users (Fig 8, top line, left). A weak negative, linear Bravais-Pearson-correlation (persons_r) on a scale of 0.2 - 0.3 was calculated for Bot_wal, Bot_mix and Bot_ref (Fig 8, left column). The linear relationship for Bot_whe was even weaker (0.15). Focusing the relationship between density and flow, a dependency for all population settings attracts attention which is also reflected in the persons_r on a scale between 0.3 and 0.5. A small scatter in the distribution of movement speed and flow for the studies considering participants in wheelchairs are striking out (see histogram on the y-axis in left column at the top of Fig 8): this subpopulation is characterized by participants whose disability is visible to others (see Tab 3 – 5 in the supplementary data of App1). Such a combination of participant's familiarity and visibility of 'need for assistance' to others leads to a communicative, considerate behaviour between participants in wheelchairs and non-disabled participants. In result the movement speed of all participants were anticipated to the movement speed of the slower wheelchair users [42]. Both subgroups interact and solve priority of movement by communication. In addition social norms, individual behaviour and degrees of freedom in movement and the influence of technical assistance devices and accompanying persons may affect the passageway [48]. This behaviour by non-disabled participants was only observed - qualitatively by video analysis and reflecting in results of fundamental relationships $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$ – if wheelchair users were considered.

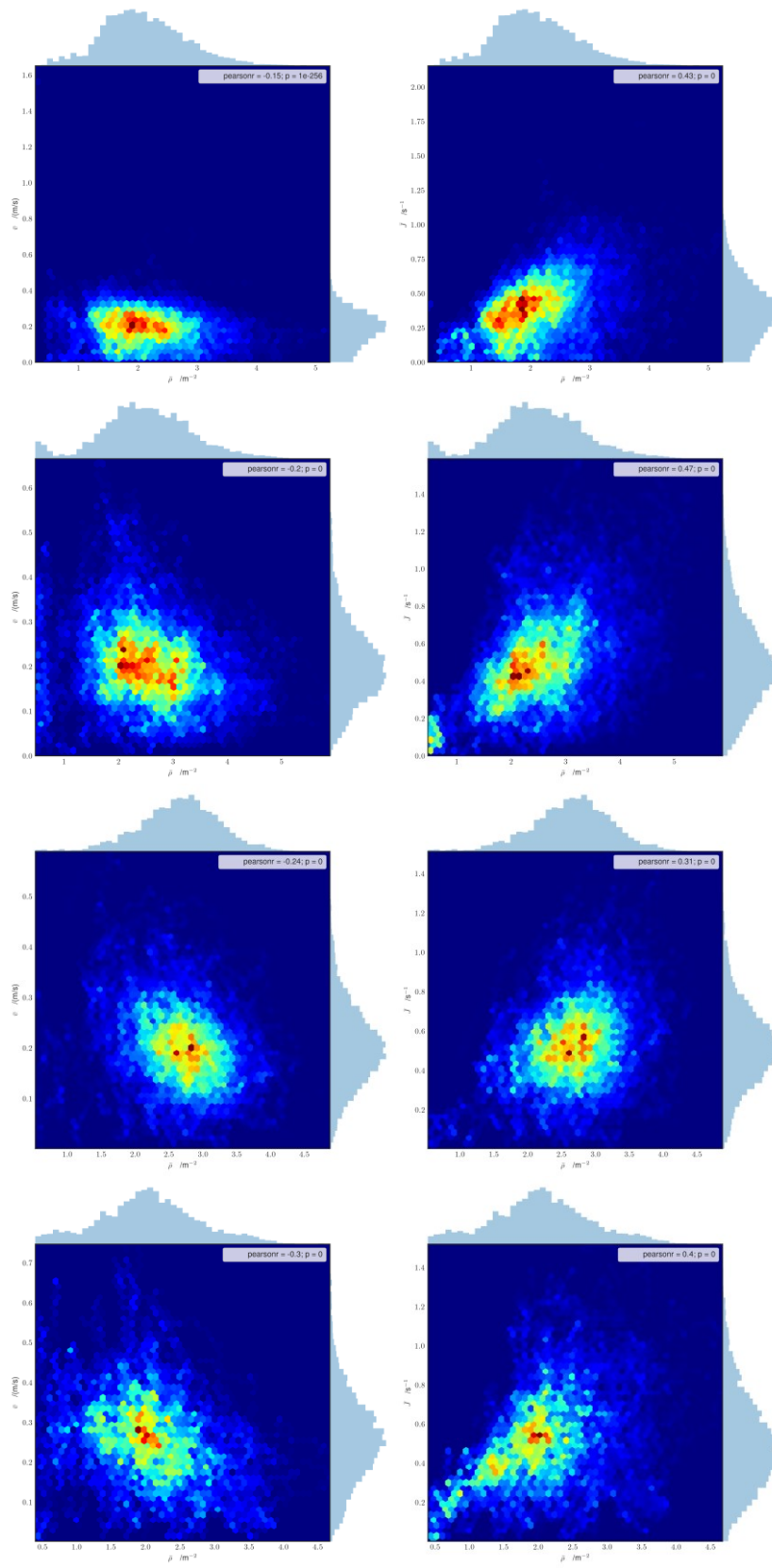


Figure 8. Joint plot of the fundamental relations $v(\rho)$ (left column) and $J(\rho)$ (right column) including data from the unimpeded movement speed runs as contour plots with joint histograms with density estimates. From top to bottom: Bot_whe, Bot_wal, Bot_mix and Bot_ref.

CONCLUSIONS AND OUTLOOK

A series of well-controlled studies on movement through a bottleneck was performed. The influence of variably composed subpopulations and a varied passage width on the fundamental relationships $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$ was analysed.

The unimpeded movement speed of all participants was measured and analysed with respect to the individual abilities. Expected unimpeded movement speeds of $1.47 \pm 0.17 \text{ ms}^{-1}$ were observed with the non-disabled reference population which is consistent with the literature [28]. Focusing on the unimpeded movement speed of the subpopulations with different disabilities, a slower, in case of the subpopulation consists of wheelchair users (Bot_whe: $0.96 \pm 0.35 \text{ ms}^{-1}$) or comparable (Bot_wal: $1.28 \pm 0.12 \text{ ms}^{-1}$ and Bot_mix: $1.33 \pm 0.29 \text{ ms}^{-1}$) averaged unimpeded movement speed was measured.

Further on, the fundamental relationships $\bar{v}(\bar{\rho})$ and $\bar{J}(\bar{\rho})$ were studied. Because of the experimental boundary conditions, a maximum flow point (capacity) was not reached. Thus the free flow branch of the fundamental diagram was studied. It was found that the shape of the speed-density relation is different to previously research in case of participation of wheelchair users. This uncommon characteristic results from a polite and considerate (social) behaviour of non-disabled participants, if participants whose disability is visible to others participate (e.g. wheelchair users). Additional space in case of larger passage widths has no effects of performance criteria of wheelchair users because the additional space is to leak for overtaking or passing the line simultaneously. The relationship $\bar{J}(\bar{\rho})$ results in a slightly linear correlation which is independent of the considered subpopulation and even true in case of consideration of wheelchair users. This effect results from an increased individual density at a given (anticipated and constant) movement speed.

It is worth mentioning that the number of data for the wheelchair users is limited and that usage of larger steps of additional widths (e.g. a multiple of a wheelchair width) may have an impact on the flow. The presented results may be used to improve engineering egress calculations for different configurations of populations in design and planning process of facilities. Further research, especially on the comparison between different processes in movement and different ratios of populations, is required.

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APP 1 - SUPPLEMENTARY INFORMATION

Tab 3 – 5 describe the identification and narrative description of participants with disabilities for a better understanding. Each participant is represented by an identification number (persID) which is unique for a single run and similar to the ID of a trajectory. The unique identification number for participants with disabilities (pwdID) is unique for the entire study. The assignment of pwdID and persID is shown in Tab 3-5

The description is not objectified and reflects the impression of the authors. Leaving out a description means that no distinguishing features were observed and the movement of the participants with disabilities was homogeneous. In case of participation of wheelchair users, the length l_w and width w_w of the wheelchair is given.

Table 3: Identification (pwdID and the assigning run-dependent persIDs) and narrative description of participants with disabilities for the subpopulation of participants using a wheelchair. Leaving out a description means that no distinguishing features were observed and the movement of the participants with disabilities was homogeneous.

pwdID \ run	00	01	02	03	04	05	06	07	08	Description
pwdID_34	3	37	65	52	6	62	84	16	49	manually operated wheelchair, operated by pusher, $l_w = 1.40$ m, $w_w = 0.6$ m
pwdID_35	40	38	54	11	60	2	65	1	48	manually operated wheelchair, operated by pusher, $l_w = 1.16$ m, $w_w = 0.74$ m
pwdID_36	42	54	26	70	84	20	45	32	34	electrical operated wheelchair with chin control, $l_w = 1.23$ m, $w_w = 0.64$ m
pwdID_37	43	48	71	82	74	14	42	9	32	manually operated wheelchair, sometimes with personal assistance, $l_w = 1.10$ m, $w_w = 0.77$ m
pwdID_38	44	30	38	50	12	49	61	53	68	manually operated wheelchair, operated by pusher, $l_w = 0.92$ m, $w_w = 0.66$ m
pwdID_39	46	80	41	76	38	8	56	41	36	manually operated wheelchair, operated by pusher, $l_w = 0.90$ m, $w_w = 0.60$ m
pwdID_40	65	29	6	86	70	81	66	4	63	manually operated wheelchair $l_w = 0.76$ m, $w_w = 0.66$ m, used feet to gain movement speed

Table 4: Identification (pwdID and the assigning run-dependent persIDs) and narrative description of participants with disabilities for the subpopulation of participants with walking impairments. Leaving out a description means that no distinguishing features were observed and the movement of the participants with disabilities was homogeneous.

pwdID \ run	00	01	02	03	04	05	06	07	08	Description
pwdID_41	72	27	48	84	27	78	72	20	18	-
pwdID_42	47	47	2	36	55	35	75	30	32	supported by an assistant while movement
pwdID_43	11	79	74	85	79	53	85	72	46	accompanied by a confidant / assistant
pwdID_44	69	74	83	60	72	70	84	55	79	tend to move in the back
pwdID_45	70	70	82	6	76	71	81	26	86	-

Table 5: Identification (pwdID and the assigning run-dependent persIDs) and narrative description of participants with disabilities for the subpopulation of participants with mixed (multiple) disabilities. Leaving out a description means that no distinguishing features were observed and the movement of the participants with disabilities was homogeneous.

pwdID \ run	00	01	02	03	04	05	06	07	08	Description
pwdID_55	4	11	61	48	49	40	21	25	65	-
pwdID_56	10	71	79	10	44	18	14	4	24	-
pwdID_57	13	68	77	7	34	71	-	7	1	-
pwdID_58	15	43	67	28	14	24	-	38	21	-
pwdID_59	21	39	33	63	77	80	-	55	72	-
pwdID_60	26	33	37	29	56	32	-	33	27	carries handbag with him
pwdID_61	39	58	23	31	21	16	19	19	70	navigated/assisted by an assistant behind him
pwdID_62	40	52	65	37	73	21	36	15	29	-
pwdID_63	41	28	30	6	40	23	16	11	47	defensive and temporising movement, slight tendency to prefer movement near the wall
pwdID_64	46	37	34	11	45	27	-	14	48	noticeable swaying
pwdID_65	69	44	26	2	19	20	17	20	37	-
pwdID_67	81	48	35	70	51	57	-	46	79	noticeable walking impairment