

Engineering egress data considering pedestrians with reduced mobility

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To quantify the evacuation process, evacuation practitioners use engineering egress data describing the occupant movement characteristics. This data are typically based to young and fit populations. However, the movement abilities of occupants who might be involved in evacuations are becoming more variable - with the building populations of today typically including increasing numbers of individuals: with impairments or who are otherwise elderly or generally less mobile. Thus, there will be an increasing proportion of building occupants with reduced ability to egress. For safe evacuation, there is therefore a need to provide valid engineering-egress data considering pedestrians with disabilities.

Gwynne and Boyce recently compiled a series of data-sets related to the evacuation process to support practitioner activities in the chapter Engineering Data in the SFPE handbook of fire protection engineering. This paper supplements these data-sets by providing information on and presenting data obtained from additional research related to the pre-movement and horizontal movement of participants with physical, cognitive- or age-related disabilities. The aim is to provide an overview of currently available data-sets related to, and key factors affecting the egress performance of, mixed ability populations which could be used to guide fire safety engineering decisions in the context of building design.

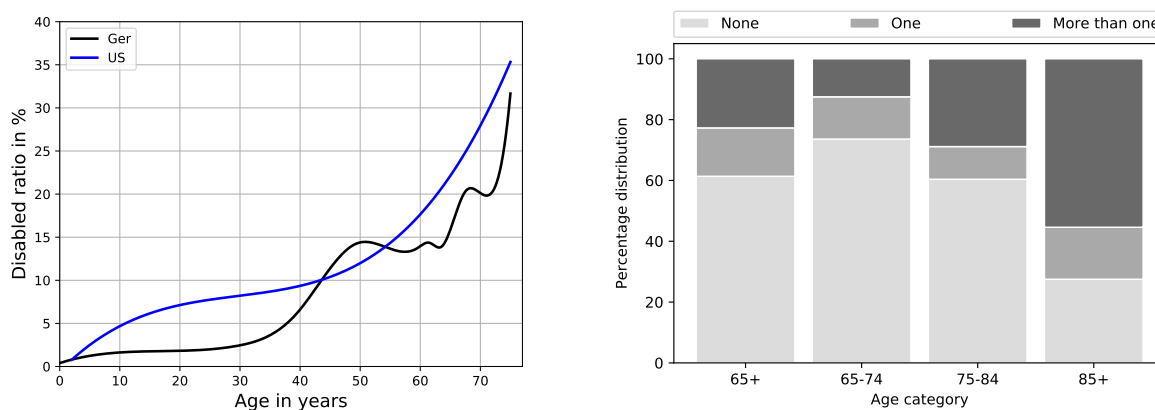
Keywords: egress, disability, movement, pre-movement, evacuation, mobility, pedestrians, engineering data

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1. Introduction

Evacuation practitioners need to identify and employ data to characterise occupants and their occupancy for the evaluation of the overall evacuation time of buildings. Establishing the overall evacuation time for a number of fire scenarios is a key component in performance-based design. This time is typically compared to the time where the environmental conditions become untenable [1], [2]. Performance-based design represents one of the two key regulatory approaches to life safety, where the other is a prescriptive approach. As part of performance-based design, engineering data relating to evacuee movement are necessary to establish building safety in response to representative emergency scenarios [3]. Practitioners employ calculations and simulation tools to quantify evacuation performance using such data ([4], [5]). In addition, this data is key both in the development of engineering calculations and simulation tools and in the testing of such tools ([6], [7]). This is a challenging task that is made more difficult as data are typically scarce, partial and often detached from context. This context is required for the practitioner to make an informed assessment and, without it, data might be employed that are inappropriate to the scenario being examined.

Many of the data-sets used today (like [8], [9], [10], [11] and [12]) were developed or collected some decades ago. It is debatable whether these data-sets are still representative given the limited data collection techniques employed at the time, a less mature understanding of the evacuation process and also changing scenario conditions (e.g. changes in the population dynamics, building designs, procedural measures, etc.) [13]. For instance, examining populations ages in Canada, UK, Japan, US, France and Germany we see the median has moved from 35-40 years in 2000 to 40-45 years in 2017 [14]. This change is also reflected in the 'population barrels' (formerly known as 'population pyramids') for Germany, Canada and the UK where an obvious ageing of the population is apparent when comparing statistics for 1995 and 2015 (see Fig 2). As well as being an ageing society, obesity increases in developing countries [15] where obese individuals are subjected to a higher risk of having a mobility disability [16]. Furthermore, the prevalence of single- or severely disabled increases with age, especially in an age older than 50 years (Fig 1).



(a) Ratio of severely disabled persons in Germany and the United States. (b) Population aged 65+ by number of disabilities in the United States.

Figure 1: Percentage with disability across the life span. Ratio of severely disabled persons in Germany [17] and the United States (2013) [18] (left). Population aged 65+ by number of disabilities depending on age (2008-2012) [19] (right).

These demographic changes have complex impacts on society and on the evacuation process. Such impacts might include increased number of elderly people living in mixed occupancy buildings affecting the relevance of emergency procedures [20], increased social pressures on neighbours and fellow evacuees to provide assistance during an incident, increased proportion of the population with a movement disability that affects evacuation performance (both of those with the disabilities and those around them) and an increased requirement for responders to rescue residents.

Gwynne and Boyce [21] recently compiled a series of data-sets related to the process of evacuation to support practitioner activities in their SFPE handbook chapter entitled Engineering Data. This included data collected between 1985 - 2012 which were presented in a standardized manner in conjunction with core background information. Although comprehensive, such actions are always limited by the time at which they are conducted and therefore necessarily excludes research since that time. Whilst it is acknowledged that some data-sets described by Gwynne and Boyce focused on people with disabilities and that they presented some data on assisted movement, most data sets neither involved people with disabilities or reduced performance, e.g. children, or they did not adequately document the disability-status. Most data sets focussed on those without reduced mobility or did not adequately document the particular limitations of those involved. Data regarding people with disabilities was categorised by assisted and unassisted unimpeded (free) movement speeds on the horizontal, ramps, ascending or descending stairs and door traversals.

To summarise, social-demographics in western societies are changing as the way of living and the kind of dwellings. Particularly in the context of these developments and associated lack of data, it is pertinent to extend the understanding of movement behaviour of heterogeneous pedestrian groups. This paper gives a brief review of the established structure of the evacuation process (Sec 2). After an extended review of literature (Sec 3), a comprehensive update of data-sets considering pedestrians with physical, mental- or aged-related disabilities and reduced performance (Sec 4.1, Sec 4.2 and Sec.4.3) are presented. This analysis enables the identification of key factors influencing sensitive subprocesses of an evacuation for building designers, fire safety- and safety engineers.

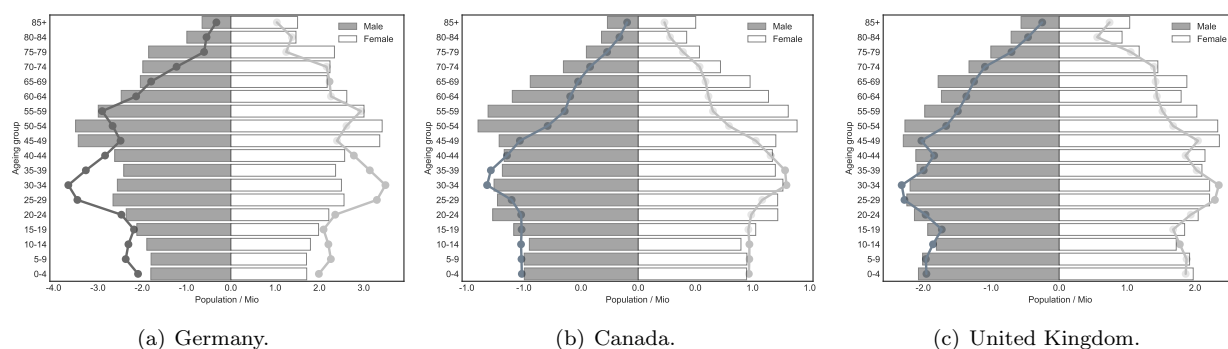


Figure 2: Ageing pyramid depending on gender for the population of Germany, Canada and the United Kingdom. Current demographic trends mean that societies in developed countries are growing older. The ratio between inhabitants older than 65 years and between the age of 15 and 65 (ageing quotient) is increasing as well. Data of the census 2015 is plotted by bars, line plots representing the data of the census 1995. Source: [22].

2. Background

2.1. Evacuation process

Evacuee response to an incident is a combination of individual attributes, decisions and actions, social factors, procedural factors, spatial factors, and environmental conditions [23] which interact in many ways and influence the evacuation. It is arguably not practical for engineering models (calculations or simulations) to address all these elements. Calculation methods require a reduction of reality, thus making assumptions in the development of a model. This applies to all types of models, e.g. an evacuation training tool or calculation software for pedestrian movement which has implemented a model comprising agents, their interactions, responses, movement etc. A well established model of the evacuation process is called the 'engineering timeline' [1], [2], [24], which is also implemented by BS PD 7974-6 [25] and ISO TS 29761:2015 [26]. The engineering time line compares the RSET (Required Safe Escape Time) i.e. the time required from ignition of a fire until all occupants can reach an area of safety with the ASET (Available Safe Egress Time),

i.e. the time available between ignition of a fire and the time at which tenability criteria are exceeded in the means of egress. The aim of this comparison is to ensure that the ASET should be longer than the RSET by an acceptable margin of safety. The RSET is separated into two main parts: the pre-movement and the movement phase. The pre-movement time relates to the interval between the time at which a general alarm signal or warning is given and the time at which the first deliberate evacuation movement is made. The movement time is the time needed, once movement toward an exit has begun, for all occupants to reach a place of safety. The influence of each part on 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 surroundings of the building, characteristics of evacuees and technological boundaries.

As a baseline, evacuation assessment addresses the physical movement involved in the evacuation process. The assessment typically employs factors like expected travel speeds, flow, and densities [27]. These factors are related through, so called, fundamental diagrams which allow achievable travel rates (speeds and flow) to be established based on route capacity and population size (e.g. [28], [29], [30], [31], [32], [33]). The physical movement is initiated after a delay period (pre-movement time¹) based on the evacuee reception, perception and interpretation of the conditions faced, e.g. fire conditions, actions of others, alarm type, proximity to incident, etc. This is typically characterized by a delay time that captures the numerous factors. Data is therefore required to represent these delays and travel rates.

Engineering and computational models are generally employed to quantify an engineering time line for representative scenarios or some aspect of it . This time line typically represents an aggregate level of performance – at the level of the population – rather than the individual i.e. where a representative value or distribution for the initial delay and movement rates are employed to represent population performance. This simplification is necessary to generalize the time line across fire incidents. This time line can be characterised by several phases: the detection and warning phase, the pre-movement phase and the movement phase (e.g. [2]). The first phase is automated in many situations, i.e. is reliant on the activation time of technology and so is often represented by manufacturer information on device performance rather than human response data. In other situations, i.e. in the absence of automatic detection and alarm, reliance is on manual detection and activation which can be 'long and unpredictable' [25]. The pre-movement phase represents the time between the population becoming aware of the incident (e.g. through the raising of the alarm) and the time at which they initiate movement towards a place of safety. The travel phase represents the time between initiating movement to a place of safety and arrival at a place of safety (consisting of movement, queuing and non-evacuation activities).

2.2. Original work

Gwynne and Boyce [21] presented engineering data sets according to the key behavioural components that comprise the engineering time line in the chapter *Engineering Data* of the *SFPE handbook of fire protection engineering* [35] in a tabular format (Fig 3). The tables further describe the background and the key results of the data. Further information in the chapter of Gwynne and Boyce facilitates the interpretation and understanding of the context of the results and helps to differentiate between them.

The tables address data following the engineering timeline: detection, pre-movement time (with data distinguishing between occupant status/disability, i.e. awake or asleep, and by occupancy type), and travel time (horizontal and stair speed/flow, exit flow, escalator traversal, ramp traversal, and movement through smoke). For each key behavioural component, the tables provide information on the original scenario (called Observational Conditions). This comprised the original country or city in which the study or event of data collection took place, its nature, (whether an unannounced evacuation, an announced evacuation, laboratory experiment, etc.), the spatial environment, the environmental conditions, the participants and the variables examined. For further details on the structure of data presentation we refer to the original

¹The terms 'pre-movement time' and 'pre-evacuation time' are used interchangeably in the literature. Pre-movement, although not considered the most appropriate term as it may include movement, is used here because it is the term commonly used in regulations and guidance, e.g. in [4], [34].

work [21]. Furthermore, information on the sample size and make-up, the data collection approaches, and the results (mean, standard deviation, range are given). The tables had to be slightly customized to account for differences in the engineering data (Fig 3).

Occupancy	Source Author Year	Observational Conditions (L: Location, N:Nature, SC: Spatial Configu- ration, P:Participants, E:Environment, V:Variable)	Procedure			Sample		Results (sec)	Additional Information
	Strategy		Staff	Technology	Collection Method	Size	Mean [S.D, Range]		

(a) Pre-movement time / s table heading.

Source (author, year)	Observational Conditions (L:Location, N:Nature, SC: Spatial Configuration, P: Participants, E:Environment, V:Variable)	Sample		Results			Additional Information
		Collection Method	Size	Density Mean/Range of Means (persons/m ²)	Speed Mean [Range of Means] unless otherwise specified (m/s)	Relationship Speed and Density	

(b) Horizontal movement speeds / m s⁻¹ table heading.

Figure 3: Headings of the origin tables in the SFPE chapter [21] in [35] according to the key information.

The new data sets identified in this paper for pre-movement time, movement on the horizontal and empirical speed-density or speed-flow-relationships (movement phase) are presented in a similar form. The summary of the data as standardised format as possible is presented in App. 6.

3. Review process

The intention of the review by Gwynne and Boyce was to present data of pedestrian movement in a consistent and clear manner. To achieve this, journal publications, conference proceedings and additional (publicly available, written in English and published after 1985) sources were screened. Given the manner in which the data is typically employed, results were assigned to key behavioural components derived from the engineering timeline.

As noted previously, the work by Gwynne and Boyce presents data available up to the time it was initiated (i.e. up to and including 2013) and did not provide detail on the the range of disabilities that might affect evacuation performance as this was beyond the scope of the original work. In order to supplement the chapter of Gwynne and Boyce, an extended literature review has been performed in order to update the original work and to expand the focus and generate a more inclusive engineering data resource (Fig 4). We conducted the following steps to identify the items:

1. Definition of keywords and truncated terms for search (see Appendix II).
2. Literature search of material (drafted in English) in the following sources: ScienceDirect (www.sciencedirect.com), Scopus (www.scopus.com) and ISI Web of Knowledge (www.webofknowledge.com). By using these databases, it was possible to search a large number of subject related journals such as Fire and Materials, Fire Safety Science, Fire Safety Journal or Safety Science.
3. Source publications from proceedings of the following conferences: International Symposium on Fire Safety Science (IAFSS-Symposium (<https://iafss.org/symposium>)), Pedestrian and Evacuation Dynamics (PED), Human Behaviour in Fire Symposium (HBiF), Interflam and Traffic and Granular Flow (TGF).

4. Search for articles in the Journal of Fire Protection Engineering, Fire Technology, and Transportation Research Record were taken into account even if they were not listed in the research databases.
5. Lastly review, collection of relevant literature known by colleagues and from other sources reports or pre-prints, if it was publicly available.

This review process revealed 9675 results in total. After removing duplicates and screening titles in relation to relevance, 359 candidate publications remained. In a second step 178 publications were removed by screening abstracts, methods and results (see Fig 4). During the screening process we focussed on pedestrian movement, egress data and availability of data-sets. Similar to the procedure adopted by Gwynne and Boyce, we considered publications presenting results of experimental trials (hypothetical scenarios, controlled experiments, field investigations and case studies) and rejected publications dealing with simulation studies which did not present new empirical data. Data-sets identified for this extended review comprise both the pre-movement phase and the movement phase. The data-sets predominantly refer to circulation and (non-emergency) egress following the ICE-classification [36], which describes pedestrian movement and the nature of an event by distinguishing between ingress, circulation and egress. We filtered the data according to their accordance with the original work thus removed 107 publications. Review-publications were analysed and are summarised in Sec 4. Irrespective of the data available, all remaining data sets were considered disregarding the specific data collection methods used or boundary conditions of the experimental setting. As a consequence, we cannot ensure the consistency of the conditions present during the data collection approaches or the appropriateness or validity of the methodology applied. In order to enable the user in determining the validity or suitability of the data for their application, we documented the approaches to generate the data-sets in Appendix I. Finally, we analysed the remaining 74 publications in detail. 32 of these publications contained original research and engineering egress data considering pedestrian pre-movement and movement of the disabled and hence, are considered in this article.

We present the data sets of the 32 publications identified in the review process in the next section. Ten of these studies are related to the pre-movement phase and 22 studies are related to the movement phase. These studies had not previously been identified by Gwynne and Boyce, will be presented. Additionally, data providing important empirical speed-density and flow-density relationships, considering pedestrians with disabilities, was analysed and is presented in Sec 4.3.

For practical reasons and, in contrast to the original paper, in this article we differentiate between three study types: announced or unannounced evacuation, experiments and training exercises. In our understanding, evacuation (announced or unannounced) were conducted to collect data and understand the dynamics of movement during the evacuation of a number of people from a real building or space. Experiments, on the other hand, are artificial situations which are carefully designed to investigate the movement of a small number of participants moving individually without interactions with other persons. If the purpose of an evacuation or a experiment was training, the term 'training exercise' is used.

4. Results and discussion

Overall, the extended literature review identified 74 relevant publications. 32 of these publications have original engineering egress data addressing pedestrians with disabilities supplemented by previously published review publications.

The publications were classified according to their scope as review-articles (engineering methods, clinical test and multidisciplinary work) or new / unknown engineering data-sets considering pedestrians with disabilities in the pre-movement and movement phase. In order to extend the original work and to give an overview on the ongoing focus of research, Table 1 summarises the review publications involving people with disabilities and mixed abilities.

We structured the review articles in three main topics: engineering, clinical and multidisciplinary. The main area 'engineering' of the review articles deals with engineering data and the implications of disabilities on pedestrians' movement. These reviews deal with commonly used key performance parameters e.g. unimpeded movement speed or flow constraints as well as more complex factors like route choice or

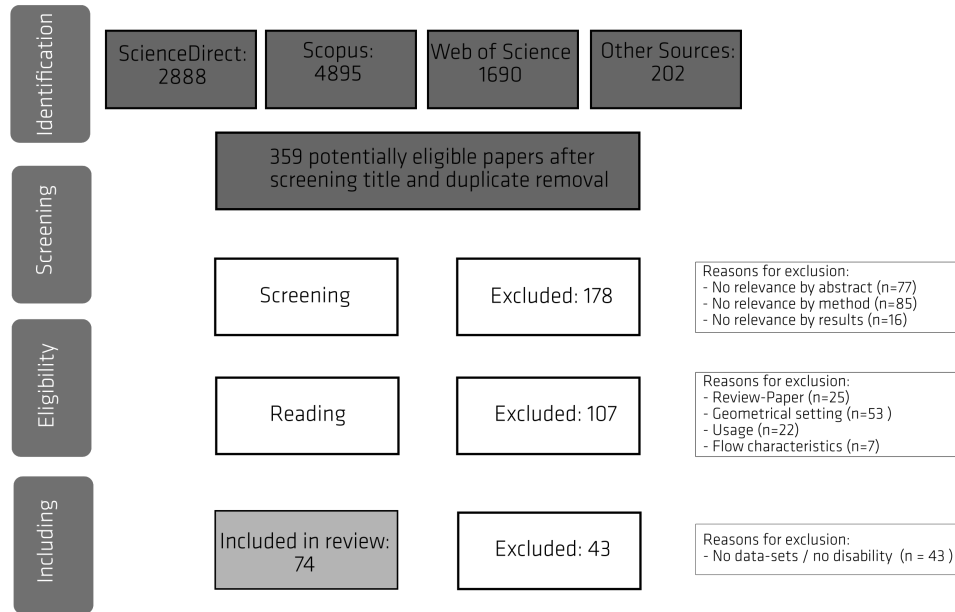


Figure 4: Methodical approach to indicate relevant publications (visualization according to [37], [38]). The review of 74 potential publications resulted in **eleven** additional data sets for the pre-movement and 21 additional data sets for the movement phase.

geometry-dependency. The second area 'clinical' provides an insight into studies on movement parameters in the context of clinical measurement methods. These reviews typically refer to studies that measure gait length, speed and swaying and the ability to walk over distance or time. The objective of the third area 'multidisciplinary' is to look cross-disciplinary and provide additional factors of interest for data collection, influencing factors and analysis. These three main topics constitute the starting point for updating engineering data for the pre-movement and movement phase.

Table 1: Identified thematic classification of review-articles.

Focus	Ref	Description
Engineering	[39]	Descriptive meta-analysis of normal (stratified) walking speed depending on age, gender and distance
	[40]	Evacuation of mixed ability populations: reviews the basis for current design guidance and explores the design options for persons with reduced mobility
	[41]	Focus on the design of the built environment and the ability of individuals with disabilities to egress in emergency evacuations; description of the behavior of the individual with a disability in response to the built environment, described almost solely by speed of egress
	[42]	Factors important for fire evacuation in underground transportation systems and summarise empirical research on pre-movement process, flow constraints, movement speed and way finding

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Table 1 – *Continued from previous page*

Focus	Ref	Description
	[43]	Literature overview on impact of building elements (stairs, lifts, doors, corridor, junction, bottleneck), population characteristics (children, disabled persons, stressed groups), specific environments (aircraft, trains, etc), decision-making and information processing as well as and modelling
	[44]	Review of studies on occupants' flow characteristics
	[21]	Review on engineering egress data depending on evacuation phase, built environment, kind of study and focussed parameter
	[37]	Relationship between movement ability at one point of (mid) life and cognitive decline; systematic review of 20 longitudinal studies
	[45]	Review on pre-movement time in the built environment with influencing factors; review on movement speeds depending on influencing factors and movement conditions; movement speeds for disabled occupants
	[13]	Reviews the influence of demographic change and the impact of body dimensions on speed and flow
Clinical	[46]	Acceleration of elderly patients
	[47]	Relation between well-being and movement
	[48]	Measurement of movement by accelerometry
	[49]	Collection of movement speeds linked to dependence, hospitalization, rehabilitation needs, discharge locations, and ambulation category
	[50]	Needs and challenges of occupants with cognitive disabilities in public transport
Multidisciplinary	[51]	Overview on the crowd motion simulation models of the last decades: cellular automata, social force models, velocity-based models, continuum models, hybrid models, behavioural models and network models
	[52]	Effects of ageing on occupants' vision, hearing, physical mobility as well as cognitive processes on road safety
	[53]	Human factors in evacuation including physical, cognitive, motivational and social variables
	[54]	State-of-the-art methods in crowd behaviour analysis inspired by physics and biology

4.1. Updating 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 others with reduced mobility. The extended literature review revealed ($n = 11$) additional publications regarding the pre-movement phase which had not been considered in the original work. Tab. 3 of Appendix I summarises the data collection methods, conditions and key results, as well as information relevant for the interpretation of these data-sets. Geörg et al. [55] and Schliephake et al. [56] carried out unannounced evacuations in a sheltered-workshop and an assisted living accommodation and documented it through video capture. Pre-movement times of occupants with different kinds of individual or multiple disabilities and assistive devices were analysed and published by interquartile range, median and range. Hall [57] carried out evacuation experiments using different kinds of transportation methods e.g. blanket, picky-back, bed, etc. in a hospital with trained and untrained staff. The average of the preparation time is presented for each transportation method.

Hunt et al. [58], [59] carried out evacuation exercises in a hospital with trained staff assisting occupants

with disabilities. The pre-movement time, horizontal and vertical movement speeds were determined in 32 trials with different technical assistance devices (stretcher, carry chair, evacuation chair, rescue sheet) being used by different teams. Preparation time is given by the mean and standard deviation depending on technical device and gender. MacCallum et al. [60] published data from six video-captured announced and one unannounced evacuation in different types of facilities and present preparation times (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.).

Shields et al. [61] 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. [62], [63] and Peacock et al. [64] collected data during five announced evacuations in office and residential buildings. These activities contained 160 data points from an able-bodied group and 170 data points from participants with disabilities. Data was presented by average and standard deviation. Hoondert [65] deals with evacuation experiments 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, was also presented. The influence of experience/lack of experience of the staff was displayed. A publication by Hamilton et al. [66] presents findings of twelve unannounced evacuations in primary schools in Ireland with participants in an age ranging 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 first activation to the time the first person exits the applicable room.

Although many studies have sought to determine 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 suggests a wide variation in pre-movement times with time periods from seconds up to half an hour (Fig 5). This time depends on the attributes of the population which is determined by the kind of usage, e.g. many occupants in a high-rise office building are characterised by a high variance of individual characteristics. But in contrast to residential buildings, occupants are not expected to be sleeping. Fig 5 presents pre-movement times for occupants with disabilities obtained from the additional publications identified in this review.

In general, data are often subjected to highly dispersed distributions because of most occupants initiating movement within a short pre-movement time and a few occupants initiating movement after a very long pre-movement time [2], [68]. 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 e.g. [21, Tab. 64.6].

All additional publications on occupants with disabilities described studies were carried out in formal settings with predominantly trained or instructed staff in familiar surroundings. The presence of a well-developed organisational setting (like in a sheltered workshop or health-care facility), availability of professional staff and extra assistance may reduce the times in the pre-movement phase [68]. Furthermore, occupants with disabilities may be aware of their own abilities and limitations and may profit from self-taught workarounds in daily life [69, Participant E]. For instance, asking a wheelchair user in one study for preparation strategies in case of emergency in daily life received the following answer: 'I will keep the mobile phone with me all the time to be prepared to get information' [70]. However, research investigating systematically this effect is rarely available.

Beyond well-developed 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 [5, p. 657 f]. For this reason, on the one hand, studies investigating the pre-movement phase should consider disabilities independently, e.g. a 'cognitively impaired' participant should not also be a wheelchair user because of difficulties in distinguishing the impact of the individual disabilities, to improve the statistical data base systematically. On the other hand, the combination of disabilities should be kept in mind to prevent misinterpretation and misspecification in performance-based

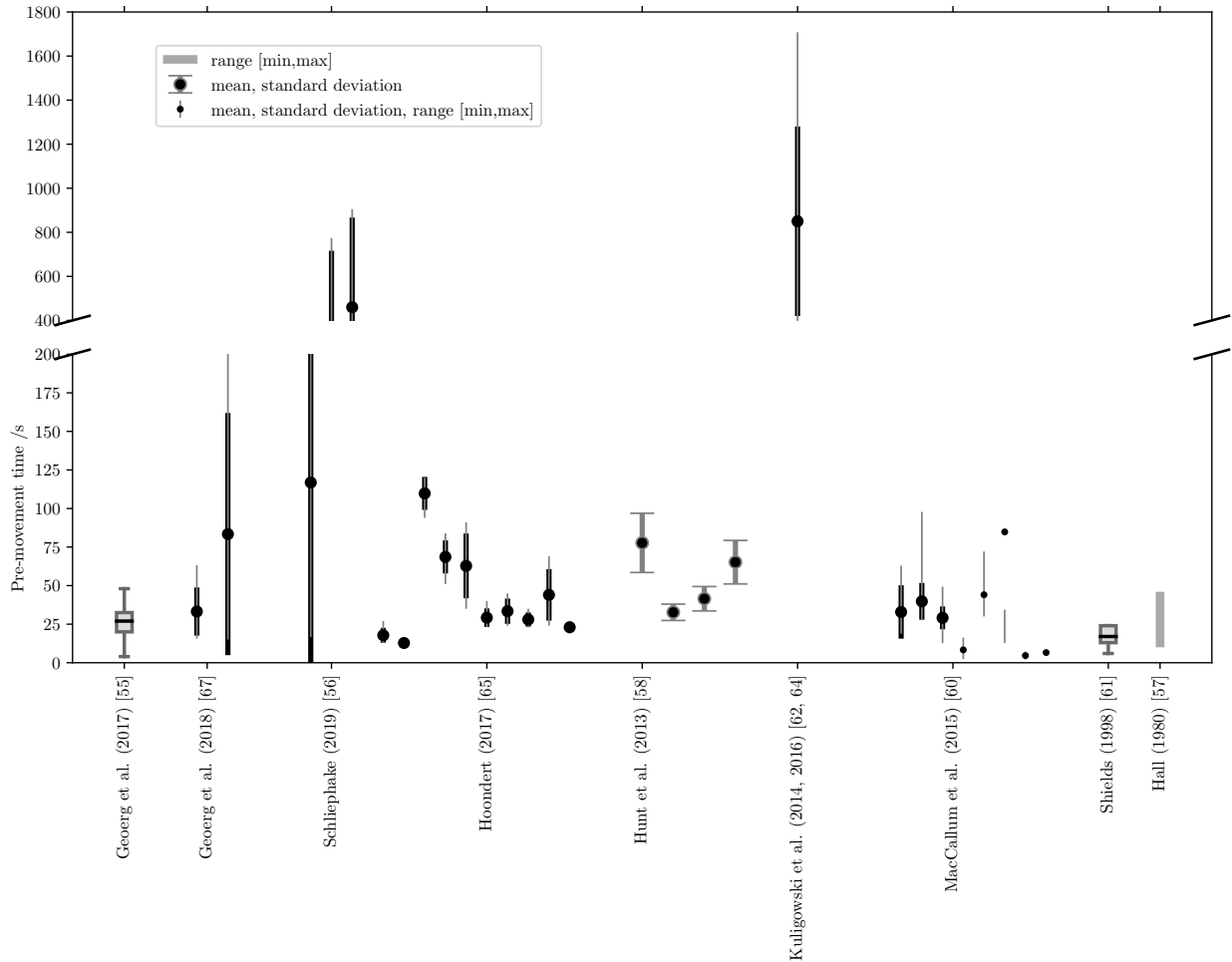


Figure 5: Pre-movement times for occupants with disabilities obtained from the additional publications (for the comprehensive data see Tab. 3). We used the following conventions to visualise different data types: the data published by [55] and [61] enables a box-and-whisker-plot with mean, interquartile range and range between minimum and maximum; the data by [58] gives mean and standard deviation represented by the gray pointplot with errorbars. Data only given by the range of minimum and maximum is represented by gray boxes, e.g. [57]. Data by [67], [56], [65], [62], [64] and [60] gives mean, standard deviation (point plot with black errorbars) and range between minimum and maximum with lightgray coloured errorbars. Please note the discontinuous axis for better visualisation of the data published by [56], [62] and [64].

design.

4.2. Updating engineering data for the movement phase

Numerous studies, which focus on several variables to describe the movement phase of pedestrians have been published in recent years. The publications often differentiate between the impact of geometry, e.g. junctions, or kind of movement, e.g. uni-, bi- or multi directional movement or building elements. However, few studies have considered truly heterogeneous groups or disabled pedestrians as evidenced by the small proportion of datasets presented in Gwynne and Boyce [21].

This review process, however, identified 22 additional publications focussing on unimpeded horizontal movement speed of occupants with disabilities (Fig 6).

The publication by Cabrera et al. [71] presents individual velocities of three groups of elderly participants with different ages. Movement was measured in a field study located in a public park. The impact of assistive

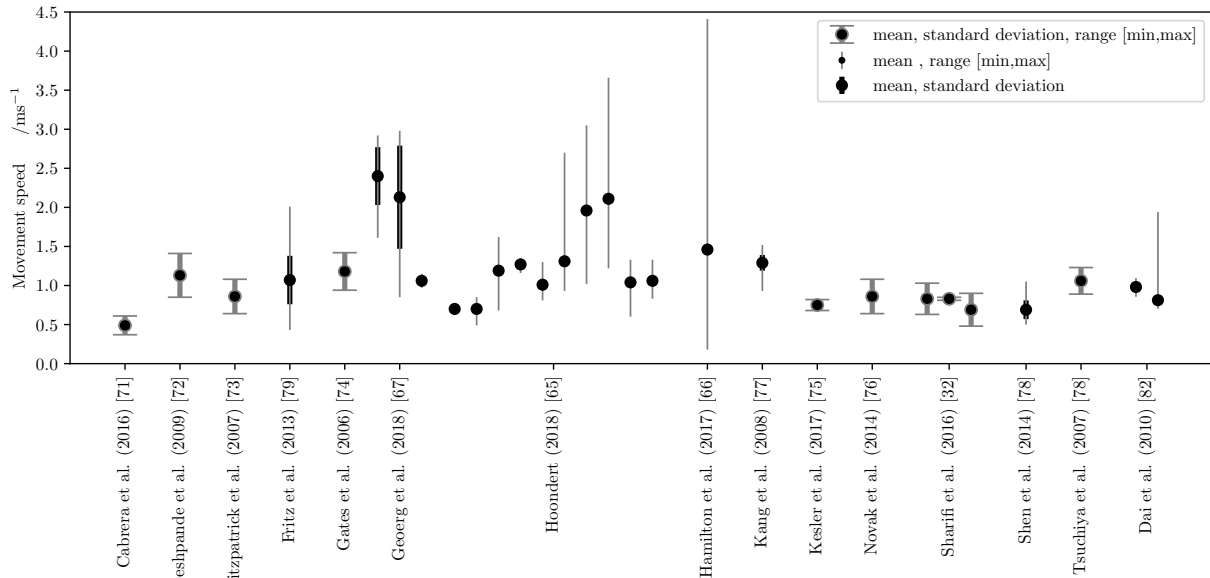


Figure 6: Selection of movement speeds regarding occupants with disabilities depending on the reviewed studies (for the comprehensive data see Tab. 4). We used the following conventions to visualise different data types: the data published by [71], [72], [73], [74], [75], [76],[32], [77] and [78] give mean and standard deviation represented by the gray pointplot with errorbars. Data by [79], [67], [66], [65], [80] and [81] gives mean, standard deviation (point plot with black errorbars) and range between minimum and maximum with lightgray coloured errorbars. The publication by [82] receive mean and range between minimum and maximum (black dot with gray coloured bar).

devices and grouping behaviour (group size and spatial orientation) was investigated and was compared with unimpeded walking. A publication by Hamilton et al. [66] presents horizontal movement speeds collected at 12 unannounced evacuation trainings in primary schools in Ireland with participants in an age ranging from 4-12 years. The numbers of participants varied in each exercise from 124 to 249. Deshpande et al. [72] examined walking performance presented by mental status and physical status of elderly participants. They concluded that normal walking is challenging in a neuromuscular manner while accelerated walking with simultaneous talking may be challenging with cognitive decline. Fitzpatrick et al. [73] report gait speed measured in a laboratory setting and compared the results with the cognitive function of the participants. They focus the prediction of early cognitive decline indicated by individual movement speed, but they provide also a comprehensive data set of movement speeds depending on different variables (e.g. age, gender, education, body mass index, etc.). Fritz et al. [79] investigated age-related changes in mobility and balance by backwards walking measures. For comparison, they also provided gait characteristics of forward walking (movement speed, gait length, swing percent, etc.) for different age groups. Furthermore, the variability across elderly groups is presented. The research of Kang et al. [80] compared the effect of movement speed, strength and range of motion on gait measures of young and elderly participants in a laboratory. Gates et al. [74] also presented a data set of movement speeds in a field study involving persons of different ages and gender; the effect of the group size was also investigated. Research by Novak et al.[76] presents the impact of ageing on body and segmental control of functional body parts. Kinematic data was collected from participants walking along a pathway and passing an obstacle. Movement speed, gait length and stepping frequency is compared for young and old participants. A short publication by Dai et al.[82] deals with the findings of a field study comparing movement speeds depending on age groups in public spaces of a shopping center. The impact of visibility and gender on movement speed was investigated in a controlled study in a classroom presented by Shen et al. [81]. Reduced visibility (zero or full visibility) was simulated by an eye-mask and the impact on movement speed of young participants was compared to similar studies. Movement speed, depending on different visibility scenarios, were presented. Samoshin et

al. [83] present flow-density- and velocity-density-relationships depending on the familiarity with the route and the influence of the kind of traffic facility. They considered blind and visually impaired participants in the field observations.

Walking in a group including wheelchair users was investigated by Tsuchiya et al. [78]. They compared individual unimpeded movement speed, movement speeds in homogeneous groups and movement speeds of wheelchair users in groups. Additionally, behavioural observations such as spatiotemporal needs of participants and overtaking procedures were analysed. Soong et al. [84] investigated the preferred movement speed for assessment of mobility performance of those with visual impairments. Movement speed depending on guidance by blind or seeing people for visually impaired participants was compared. Sharifi et al. [32], [77] presented findings on flow characteristics of heterogeneous pedestrian streams. Density and velocity of participants with differing categories of disabilities in a circuit of right-angles, oblique-angles, passageways and bottlenecks were collected and fundamental diagrams presented.

Kesler et al. [75] investigated the ability of persons with and without multiple sclerosis to walk along a 48 m path before and after a six-minute walk. More than twenty passive motion capture markers were placed on each participant to get gait parameters like step width and length. Velocity, oxygen consumption and gait width and length was compared. Jiang et al. [85] present a comparative analysis of movement speeds collected at typical observation points in hospitals and other public buildings. The impact of age and gender was investigated as well as the influence of 'healthiness/sickness'. Hoondert [65] carried out studies under laboratory conditions in a hospital. Movement speeds of different types of patients (e.g. dialysis, intensive care, neonatal incubator) were presented. The influence of the level of experience of the staff was also investigated.

Individual abilities, measurement methods and environmental conditions (e.g. age, gender, health status, motivation, facility, familiarity, time of day) influence the attainable movement speed [12], [40]. For this reason, the individual movement speeds of pedestrians on horizontal surfaces vary widely ranging from 0.3 m s^{-1} to 2.5 m s^{-1} [21], [40]. Based on the original work by Fruin ([10]), Predtechenskii and Milinski [11], Weidmann [12] and Pauls [86], international design codes and recommendations either suggest movement speeds of around 1.2 m s^{-1} [87], [88] or do not provide specific values [89], [90].

Data sets of movement speed that consider occupants with disabilities vary in comparable ranges ($0.23 \text{ m s}^{-1} - 1.95 \text{ m s}^{-1}$). Since occupants with disabilities often use technical assistive devices (wheel-chairs, canes, sticks, crutches) or require personnel assistance, the differences in speed between occupants with and without assistive devices or assistance (by another person) may partly be explained by the need for increased coordination and concentration regarding the use of assistive devices and/or the concentration on communicating with the assistor. Individual requirements such as response capacity, familiarity and social norms may also affect the movement speed in heterogeneous groups [91], [92].

Currently, the available data are too scarce to determine the variables that effect movement speed. All research studies are a simplified version of a more complex reality and they depend on boundary conditions [93, p. 2118]. The choice of participants in movement studies, which may be limited due to ethical considerations, reduces the the number of variables for better analysis, but also leads to limited comparability among multiple studies.

4.3. Using the flow-density or the velocity-density relationship?

Occupants' flow and movement speeds both depend on the occupant density [94]. Hence, the flow-density or velocity-density relationships² are important for traffic engineering and are often used in calculation methods or for validation of such methods. The fundamental diagrams representing flow-density or velocity-density relationships help to characterise the capacity of facilities [95].

²The terms flow-density- or the velocity-density relation means the whole data of the studies without focussing on steady states to account for the limited available data.

Both relationships depend on various variables like building type, cultural ([96]) or gender ([12]) impacts and socio-demographic factors. A considerable amount of research has been attempted to develop the flow-density or velocity-density relationships. This research has focussed mainly on different building types and variations in geometries such as bottlenecks, stairs and corridors as well as the influence of different flow types (uni- and bidirectional (e.g. [97], [98], [99], [100], [101], [102], [30], [28]), merging (e.g. [103]), transition (e.g. [100]) and crossing (e.g. [104])).

Fundamental diagrams considering participants with disabilities or heterogeneous populations are rare. Fig 7 compares the flow-density and velocity-density relationship of unidirectional movement determined in studies involving people with disabilities to the fundamental diagram. Note that the focus and methods differ among the publications: e.g. [98] used a towel fastened in front of the face to simulate a vision loss of participants, whilst [105] compared the relationship of velocity and flow on a stairway in front and behind a wheelchair user in an unannounced evacuation. The disabilities represented in currently available flow-density and velocity-density relationships can be classified as 'blind/visually impaired', 'age-related impact' and 'usage of assistive devices'.

Guo et al. [98] analysed the impact of reduced visibility conditions on uni- and bidirectional flow. They reported a reduced flow for both settings. Samoshin et al. [83] investigated the characteristics of blind and visually impaired people. Flow data for different types of route (horizontal, incline and door) and the influence of familiarity are presented. The publication by Sørensen et al. [106], [107] reports an effect of vision loss on movement speed. A strong influence of density-induced decrease of individual velocity is reported. Results from an evacuation study with pre-school participants were reported by Kholshchevnikov [108]. This study was designed as an extension of the empirical database of Predtechenskii and Milinskii [11]. Another publication by Kholshchevnikov et al. [109] reports findings from evacuation studies of elderly occupants at a senior citizen health care building. The impact of using different assistive devices was analysed and a decreased velocity was reported when participants used assistive devices. Larusdottir et al. [110], [111] and [112] report the flow of children aged from zero to two and three to six years through a narrowing corridor. They report a tendency to higher flows for children moving groups than the reference data for adults.

Shields et al. [105] examined the relationship between location of occupants in relation to wheelchair users and attainable movement speed during an unannounced evacuation. They reported a much greater mean movement speed ahead of wheelchair users, because participants following the wheelchair users tended to treat it as a slowly moving obstruction. A remarkable reluctance for overtaking wheelchair users during the unannounced evacuation was reported. Tsuchiya et al. [78] investigated the influence of the ratio of wheelchair users in a population and the width of an opening. The distribution of walking speeds for participants using wheelchairs is compared against the movement speed of non-disabled participants. Furthermore, the relationship between individual movement and moving in groups is presented.

Sharifi et al. [77] present results from large-scale studies considering visually impaired participants, motorised and -non-motorised-wheelchair users and participants without disabilities. They present individual movement speed, density and flow for movement in the horizontal, incline, corner, bottleneck and stair configurations. The resulting fundamental diagrams were based on the Kladek-equation [113, p. 89] (mostly known by Weidmann [12, p. 54]):

$$v_i = v_0 \cdot \left(1 - \exp\left(\gamma \cdot \left(\frac{1}{\rho} - \frac{1}{\rho_{max}}\right)\right) \right) \quad (1)$$

With

$$\begin{aligned} v_0 &= \text{unimpeded (free) movement speed} \\ \gamma &= \text{calibration constant} \\ \rho_{max} &= \text{jam density} \end{aligned}$$

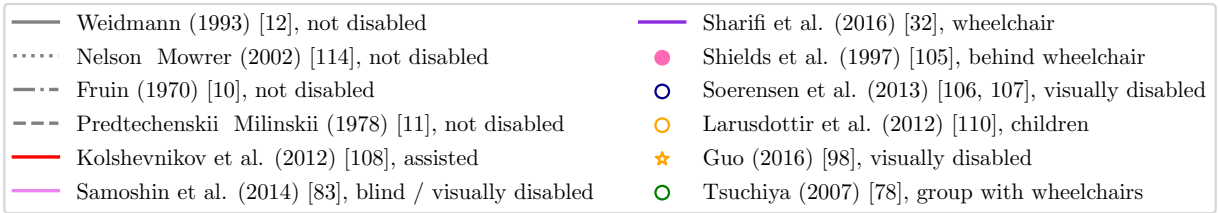
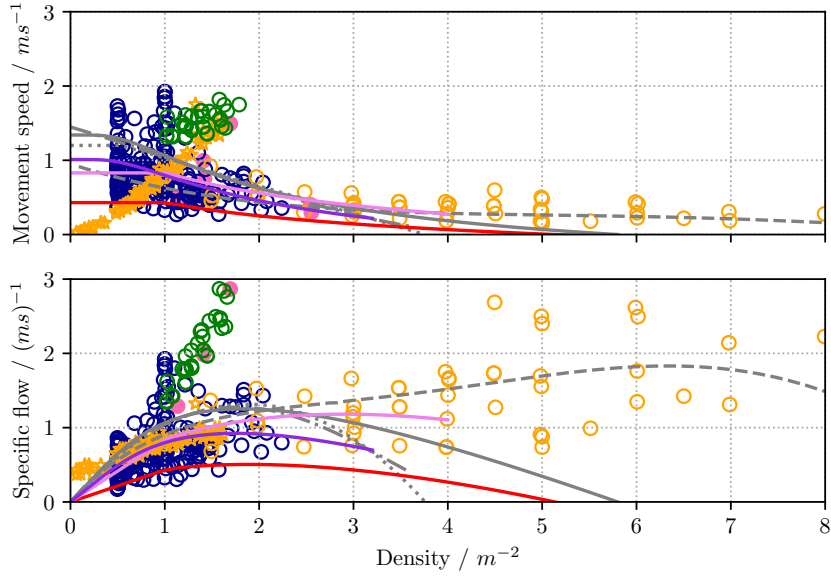
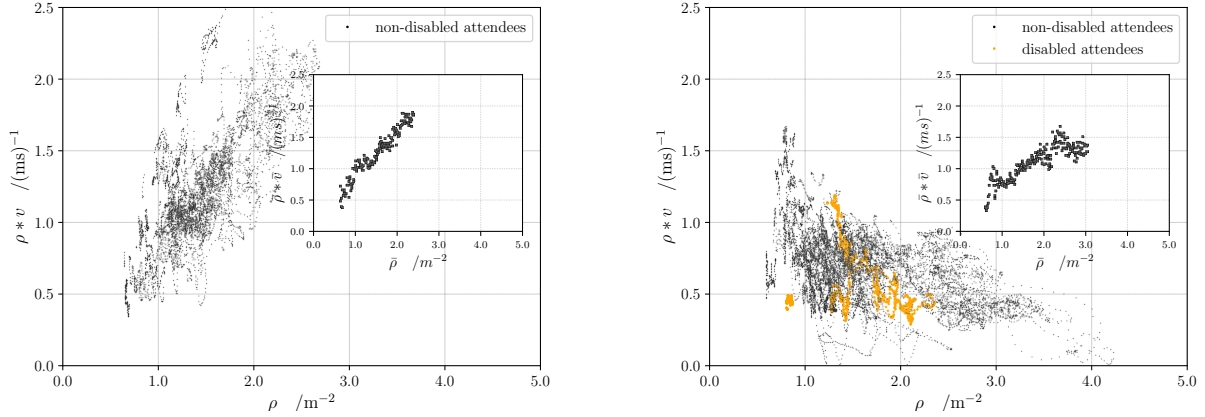


Figure 7: Velocity-density (top) and flow-density-relationship (bottom) of pedestrian movement through a bottleneck considering pedestrians with disabilities compared to the frequently referenced fundamental diagrams by [12], [114], [10] and [11] (with $f = 0.113 \text{ m}^2$).

Empirical data represent are collected from publications by: [108], [83], [32], [105], [106]/[107], [110], [98], [78]. Data picked up with Web plot digitalizer by the authors from publication. We refer the reader to Table 5 in App 6 for comprehensive details on data collection and measurement methods.

Overall, the consideration of occupants with disabilities further increases the number of variables which are important for flow-density and velocity-density relationships; for instance, the use of different devices to mitigate the impact of an impairment. Different kind of disabilities in heterogeneous groups may lead to interactions, fluctuations and transitions between different 'conditions of movement'. Social behaviour in groups, difficulties in accelerating/decelerating of individuals and the fact that some may occupying larger areas and might require more space (e.g. because of wheelchairs or crutches) become more important [91]. The type and severity of disability can have different effects on the movement, e.g. the movement of a blind person in a crowded place may be impeded by others [115] whilst the presence of a blind person assisted by a white cane may impede neighbours movement. The movement of a wheelchair user, on the other hand, may be unimpeded in low population densities (as exemplified in Fig 8). It should also be noted that different impairments may impede an individual's capacity to adapt to changing conditions around them. For instance, a wheelchair user may maintain comparable travel speeds to individuals without an impairment in clear well-defined spaces. However, their capacity to navigate around local obstacles or nearby occupants movement may be more restricted.

Notwithstanding, the analysis of the flow-density and velocity-density relations for occupants with disabilities confirm two important results: first, similar to the relations of populations without impairments, higher movement speeds are observed at low population densities, and second, the maximum flow seems to depend on the individual movement speed.



(a) Flow-density-relation of movement through a corridor without participation of participants with disabilities.

(b) Flow-density-relation of movement through a corridor with participation of participants with disabilities.

Figure 8: Individual fundamental diagram (Flow ($J_s = \rho \cdot v$)-density-relation for horizontal movement through a corridor with a width of 0.9 m) of a group without any disabled participants (left) and with $\approx 10\%$ wheelchair users (right). Movement in heterogeneous groups is often characterised by high fluctuation, phase transitions and interactions. Source: [91].

It is important to note that most of the observations focus on densities of $\rho \leq 2 \text{ m}^{-2}$. Furthermore, the studies differ in their measurement methods and environmental conditions (see Table 5 in Appendix I). The users of such data should be aware that the quantities of the functional relationship are highly sensitive to the user definition and the measurement methods used. For a comprehensive discussion on this issue, we refer to [116], [117]. Besides, the consideration of occupants with disabilities in high population densities adds additional challenges to the realisation of studies on movement (e.g. technical ability to collect the data, ethical concerns with the well-being of those involved and/or the number of factors that influence the results produced). Social norms, individual behaviour and ordering effects in movement as well as the influence of technical assistive devices and accompanying persons may impact individual movement and, if there is insufficient room for overtaking, may slow down the rest of the population [91]. Technical assistive devices like evacuation chairs or buddy systems for pre-identified persons with physical-, mental- or age-related disability may be perceived as constraints to movement [118, p. 159].

5. Conclusion

A significant proportion (approximately 20 %) of people in most industrial societies has a disability and this percentage is likely to increase in the future given current demographic trends relating to ageing and obesity [119], [22]. Together with increased accessibility, this means that building populations are becoming more and more diverse with a wider variety of movement abilities, i.e. it is no longer safe to assume that they only comprise able-bodied and fit individuals ([120], [121], [40]).

This paper has presented an extensive update on the comprehensive review given by [21] with focus on engineering data for the pre-movement and movement phase for occupants with physical-, mental- or age-related disabilities and reduced performance. It identifies differences for the design calculation and prediction of key values for egress if individual characteristics of individuals in a heterogeneous groups are taken into account.

The influence of disabilities is not confined to movement; some disabilities may have a more complex impact, e.g. obesity on stability [16] and individual space requirement [13] and a reduced movement speed [122] or cognitive disability on memory and gait speed [123]. Multiple factors may influence performance and little is known about the interaction between such factors, e.g. device, weight, age, terrain, etc. In addition, the presence of persons with impairments may have a physical and social impact on others around

them. Furthermore, there is a lack of data regarding the impact of the use of technical assistive devices, such as canes, crutches, wheelchairs, white stick, etc., and also the impact of the absence of such devices on movement. Whilst data exists related to access in relation to the static space requirements of people using assistive devices, e.g. in codes and standards, little data exists in relation to the space needed during movement, e.g. that of a crutch user or a user of a walking frame in taking a step forward in a crowd, and the impact on movement characteristics like gait length or frequency. Even if no physical assistance is needed, the likelihood that a person with a disability may be accompanied by others has until now rarely been considered in engineering calculations relating to movement.

This paper has reviewed the limited data related to occupants with disabilities and reduced performance that might be used in engineering evacuation calculation. It continues pioneering works on this topic by [21] and [40] and presents some new data sets and derived relationships. It is an attempt to highlight current challenges in considering mixed populations in the design of sufficient egress and the impact of expected demographic changes on egress performance. Design rules regarding capacities or flows generally assume relatively uniform and capable populations derived from data on largely unimpaired occupants [21]. It is therefore important to understand the impact of disabilities on pre-movement and movement. The supply in evacuation methods for this is certainly a challenge and focus should be on developing an understanding of movement of heterogeneous populations and quantify performance values in a form that can be used by practising fire safety engineers in analysis of buildings using a performance based approach.

Authors' contributions

PG, SG, KB, SH and FB carried out the problem identification and developed the method for the selection and evaluation of relevant material for the contribution. PG and FB carried out the analysis. PG and FB drafted the manuscript. SG, SH, KB and AB suggested modifications in the manuscript critically revising its content. All authors read and approved the final manuscript.

Acknowledgements

Part of this work has been performed within the research program Safety for people with physical, mental or age-related disabilities (SiME) supported by the German Federal Ministry of Education and Research - BMBF (grant numbers 13N13946 and 13N13950). The authors want to thank the two anonymous reviewers for enhancing the quality of this paper.

PG thanks the SFPE Foundation for financial support with the Dr. Guylène Proulx, OC Scholarship.

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6. Appendix I – engineering egress data

Table 3: Pre-movement depending on mobility characteristics.

Source	Observational conditions ^a		Sample			Results	
			Collection method	Description	Size	Mean /s [SD, range]	
Georg et al. 2017 [55]	L:	Germany	Video, observer	Movement disabled	4	29.8 [16.3, 5.0-48.0]	
	N:	Unannounced evacuation		Wheelchair user	6	42.3 [11.9, 25.0-61.0]	
	SC:	Sheltered workshop		Blind	1	68.0 [NaN, NaN-NaN]	
	P:	Employees of a sheltered-workshop		Deaf	2	34.0 [15.0, 19.0-49.0]	
	V:	Kind of disability		Aged > 65 years Cognition disabled	2 1	31.5 [0.5, 31.0-32.0] 36.0 [NaN, NaN-NaN]	
Georg et al. 2018 [67]	L:	Germany	Video, observer	Lying to seating	9	33.2 [15.6, 15.6-63.2]	
	N:	Evacuation experiments		Seating to seating	14	83.4 [78.5, 15.1-253.4]	
	SC:	Assisted accommodation					
	P:	Employees of a sheltered-workshop					
	V:	Kind of starting position					
Hall 1980 [57]	L:	UK	Observer	Anglia Sheet		46.0 [NaN, NaN-NaN]	Pre-movement time is similar to preparation time, some more assistive devices are investigated
	N:	Evacuation experiments		Blanket Sheet		38.0 [NaN, NaN-NaN]	
	SC:	Hospital		Ambulance Chair		19.0 [NaN, NaN-NaN]	
	P:	14 trained nurses, 40 ambulant patients		Wheelchair user		10.0 [NaN, NaN-NaN]	
	V:	Preparation, Kind of assistance					
Hamilton et al. 2017 [66]	L:	Ireland	Video		NaN	18.5 [10.8, 4.0-55.0]	Pre-movement time = time from first activation of the evacuation cue to the time the first person exits the applicable room
	N:	Unannounced evacuation					
	SC: P:	Primary school children in the age range 4-12					
Hoondert 2017 [65]	L:	The Netherlands	Video, observer	Dialysis trial 1		17.8 [4.8, 13.0-27.0]	Pre-movement time = uncoupling time
	N:	Evacuation experiments		Dialysis trial 2		12.8 [1.6, 10.0-15.0]	Pre-movement time = uncoupling time
	SC:	Hospital		Intensive Care trial 1		109.8 [10.7, 94.0-120.0]	
	P:	14 participants and 3 experienced staff members		Intensive Care trial 2		68.6 [10.7, 51.0-84.0]	
	V:	Multiple departments		Neonatal trial 1		62.8 [21.0, 35.0-91.0]	
				Neonatal trial 2		29.2 [6.0, 23.0-40.0]	
				Standard hospital ward trial 1		33.4 [8.2, 24.0-45.0]	
				Standard hospital ward trial 2		28.0 [4.6, 23.0-35.0]	
				Heart monitoring trial 2		44.0 [16.7, 24.0-69.0]	
				Heart monitoring trial 2		23.0 [3.0, 19.0-27.0]	
Hunt et al. 2013 [58], Hunt et al. 2015 [59]	L:	Ghent, Belgium	Video, observer	Stretcher	4	77.7 [19.2, NaN-NaN]	
	N:	Evacuation exercises		Evacuation chair	4	32.7 [5.3, NaN-NaN]	
	SC:	Hospital		Carry chair	4	41.5 [7.9, NaN-NaN]	
	P:	2 female, 2 male		Rescue sheet	4	65.2 [14.1, NaN-NaN]	
	V:	assistive devices					

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Source	Observational conditions ^a		Sample			Results	
			Collection method	Description	Size	Mean /s [SD, range]	
Kuligowski et al. 2014, [62], [63], Peacock et al. 2016, [62], [64]	L:	USA	Video	able-bodied	5074	160.0 [11.0, 41.0-255.0]	Pre-movement time = Pre-observation delay time
	N:	Announced Evacuations		with mobility disabled participants	170	850.0 [430.0, 398.0-1708.0]	
	SC:	Office and residential building					
	P:	5249					
	V:	Mobility					
MacCallum 2015 [60]	L:	Ireland	Video, server	Ob- Comfortable chair to wheelchair 1		32.9 [17.3, 18.9-62.9]	Staff simulated disabled participants; pre-movement time = preparation time
	N:	Announced / unannounced evacuations		Comfortable chair to wheelchair 2		19.4 [6.1, 11.1-36.8]	
	SC:	Hospital		Comfortable chair to wheelchair 3	NaN	20.7 [3.14, 16.2-24.6]	
	P:			Comfortable chair to wheelchair 4		19.5 [2.8, 10.8-26.0]	
	V:	Kind of assistive device, mode of evacuation		Toilet to wheelchair 1		39.8 [11.9, 28.0-97.8]	
				Toilet to wheelchair 2		50.7 [10.9, 30.5-81.5]	
				Toilet to wheelchair 3		42.1 [9.3, 30.9-70.2]	
				Toilet to wheelchair 4		57.2 [17.48, 39.7-138.0]	
				Bed to wheelchair 1		29.1 [7.4, 12.7-49.3]	
				Bed to wheelchair 2		62.0 [43.7, 26.4-131.2]	
				Bed to wheelchair 3		37.7 [25.0, 23.5-171.6]	
				Bed to wheelchair 4		62.1 [54.1, 23.6-124.0]	
				Bed		8.34 [NaN, 2.9-16.3]	
			Blank drag		44.07 [NaN, 30.0-72.1]		
			Ski Sheet		84.3 [NaN, 34.3-128.0]		
			Wheelchair		4.65 [NaN, 2.1-7.2]		
			Ambulant		6.6 [NaN, 3.6-9.5]		
Schliephake 2018 [56]	L:	Germany	Video, observer	Assisted	3	324.6 [391.7, 55.4-773.9]	Pre-movement time is similar to the time from first activation of the evacuation cue to the time the participant exits the applicable room
	N:	Unannounced evacuation		Wheelchair user	5	459.8 [407.1, 1.5-773.9]	
	SC:	Assisted accommodation		Walking frame	4	116.9 [151.4, 13.6-341.8]	
	P:	Employees of an assisted accommodation					
	V:	Kind of assistance					
Shields 1998 [61]	L:	Northern Ireland	Video, observer	Residence No. 1	16	NaN [NaN, 58.0-360.0]	Pre-movement time = time to evacuate bedroom from the alarm activation
	N:	Unannounced evacuations		Residence No. 2	12	43.7 [57.7, 6.0-160.0]	
	SC:	Residential care					
	P:	28 participants with learning disabilities					
	V:						

^a L: location, N: nature, SC: spatial configuration, P: participants, V: variable.

Table 4: Movement speed depending on mobility characteristics.

Reference	Observational conditions ^a		Sample		Results		
			Collection method	Description	Size	Mean /s [SD, range]	
Cabrerera et al. 2016 [71]	L:	Peru		Walking alone (age 60-69)	120	1.15 [0.18, NaN-NaN]	
	N:	Field study		Walking alone (age 70-79)	120	1.08 [0.20, NaN-NaN]	
	SC:	Park		Walking alone (age 80-90)	120	0.87 [0.17, NaN-NaN]	
	P:	Pedestrians		Walking with a stick (age 60-69)	40	1.06 [0.17, NaN-NaN]	
	V:	Elderly		Walking with a stick (age 70-79)	40	0.75 [0.14, NaN-NaN]	
				Walking with a stick (age 80-90)	40	0.63 [0.12, NaN-NaN]	
				Walking with a walker (age 60-69)	30	0.85 [0.09, NaN-NaN]	
				Walking with a walker (age 70-79)	30	0.59 [0.06, NaN-NaN]	
				Walking with a walker (age 80-90)	30	0.49 [0.12, NaN-NaN]	
Dai et al. 2010 [82]	L:	China	Video	Female (15-55)	NaN	1.10 [NaN, 0.93-1.33]	Age of agents estimated by the authors
	N:	Field study		Male (15-55)	N/A	1.14 [NaN, 0.92-1.36]	
	SC:	Shopping center		Old man(55-70)	N/A	0.98 [NaN, 0.86-1.10]	
Deshpande et al. 2009 [72]	P:	Visitors		Child(6-14)	NaN	0.81 [NaN, 0.70-0.94]	
	L:	Italy		Overall, usual speed		1.23 [0.26, NaN-NaN]	Cognitive function was evaluated by the Mini-Mental State Examination (MMSE). It is a tool for measuring global cognitive disabilities across multiple domains (orientation, memory, concentration, language and praxis) with scores ranging between 0 and 30, higher scores indicating better cognition. A score < 24 points indicates cognitive disability.
	N:	Evacuation experiments		Overall, fast speed		1.49 [0.33, NaN-NaN]	
	SC:			Overall, walking-while-talking-speed		0.98 [0.28, NaN-NaN]	
	P:	660 participants aged over 65		MMSE 28 - 30 (Quartile I), usual speed		1.36 [0.22, NaN-NaN]	
	V:	Gait speed, cognitive decline		MMSE 28 - 30 (Quartile I), fast speed		1.66 [0.29, NaN-NaN]	
				MMSE 28 - 30 (Quartile I) walking-while-talking-speed		1.07 [0.26, NaN-NaN]	
				MMSE = 27 (Quartile II), usual speed		1.22 [0.22, NaN-NaN]	
				MMSE = 27 (Quartile II), fast speed		1.46 [0.26, NaN-NaN]	
				MMSE = 27 (Quartile II), walking-while-talking-speed		1.01 [0.25, NaN-NaN]	
				MMSE = 24 - 26 (Quartile III), usual speed		1.22 [0.24,]	
				MMSE = 24 - 26 (Quartile III), fast speed		1.48 [0.33, NaN-NaN]	
				MMSE = 24 - 26 (Quartile III), walking-while-talking-speed		0.99 [0.29, NaN-NaN]	
				MMSE < 24 (Quartile IV), usual speed		1.13 [0.28, NaN-NaN]	
				MMSE < 24 (Quartile IV), fast speed		1.35 [0.34, NaN-NaN]	
	MMSE < 24 (Quartile IV), walking-while-talking-speed		0.90 [0.27, NaN-NaN]				
Fitzpatrick et al. 2007 [73]	L:	USA		Age 75 - 79, usual gait	2014	0.97 [0.22, NaN-NaN]	Movement = gait speed; results from 15-foot-walk

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Reference	Observational conditions ^a		Sample			Results			
			Collection method	Description	Size	Mean /s [SD, range]			
	N:	Evacuation experiments		Age 75 - 79, fast gait	2014	1.39	[0.65, NaN-NaN]		
	SC:			Age 80 - 84, usual gait	838	0.92	[0.26, NaN-NaN]		
	P:	370		Age 80 - 84, fast gait	838	1.30	[0.41, NaN-NaN]		
	V:	Age, gender, race, education, BMI, several clinical aspects		Age 85+, usual gait	183	0.83	[0.22, NaN-NaN]		
				Age 85+, fast gait	183	1.16	[0.32, NaN-NaN]		
				Male, usual gait	1399	0.97	[0.23, NaN-NaN]		
				Male, fast gait	1399	1.41	[0.62, NaN-NaN]		
				Female, usual gait	1636	0.92	[0.23, NaN-NaN]		
				Female, fast gait	1636	1.28	[0.52, NaN-NaN]		
				BMI < 20.0, usual gait	79	1.00	[0.26, NaN-NaN]		
				BMI < 20.0, fast gait	79	1.46	[0.78, NaN-NaN]		
				BMI 20.1 - 25.0, usual gait	900	0.98	[0.24, NaN-NaN]		
				BMI 20.1 - 25.0, fast gait	900	1.38	[0.35, NaN-NaN]		
				BMI 25.1 - 30.0, usual gait	1393	0.96	[0.23, NaN-NaN]		
				BMI 25.1 - 30.0, fast gait	1393	1.36	[0.49, no - no]		
				BMI > 30.0, usual gait	654	0.7	[0.20, NaN-NaN]		
				BMI > 30.0, fast gait	654	1.26	[0.90, NaN-NaN]		
	Fritz et al. 2013 [79]	L:		USA	Motion analysis system	Young (24.1 ± 2.5 (21-31))	10	1.49	[0.18, 1.08-1.86]
		N:		Evacuation experiments		Middle-aged (47.3 ± 7.9 (35-61))	4	1.48	[0.22, 1.10-1.90]
SC:		Electronic walkway	Elderly (85.3 ± 6.7 (66-98))	12		1.07	[0.31, 0.43-2.01]		
P:		young, middle-aged and elderly age							
V:									
Gates et al. 1986 [74]	L:	USA		< 30 years	894	1.48	[0.20, NaN-NaN]		
	N:	Field study		30 - 64	662	1.44	[0.21, NaN-NaN]		
	SC:	Crossing at intersection		> 65	326	1.16	[0.26, NaN-NaN]		
	P:	Pedestrians		Disabled	10	1.18	[0.24, NaN-NaN]		
	V:	Age, group size, disability		Child with adult	55	1.22	[0.18, NaN-NaN]		
Georg et al. 2018 [67]	L:	Germany	Video, observer	Wheelchair	24	2.4	[0.37, 1.61-2.92]		
	N:	Laboratory conditions		Evacuation chair	8	2.13	[0.66, 0.85 - 2.98]		
	SC:	Assisted accommodation		Escape mattress	2	1.06	[NaN, 0.97-1.15]		
	P:	Employees of a sheltered-workshop							
V:	Kind of starting position								
Hall 1980 [57]	L:	UK	Observer	Anglia sheet		0.43	[NaN, NaN-NaN]		
	N:	Evacuation experiments		Mercury straps		0.32	[NaN, NaN-NaN]		
	SC:	Hospital		Mattress lines		0.20	[NaN, NaN-NaN]		
	P:	14 nurses,		Blanket		0.40	[NaN, NaN-NaN]		
	V:	Preparation, assistance		Bed		0.91	[NaN, NaN-NaN]		
				Two-handed lift		1.11	[NaN, NaN-NaN]		
				Three-handed lift		0.77	[NaN, NaN-NaN]		
		Four-handed lift		1.00	[NaN, NaN-NaN]				

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Table 4 – Continued from previous page

Reference	Observational conditions ^a		Sample			Results	
			Collection method	Description	Size	Mean /s [SD, range]	
				Australian lift		0.83 [NaN, NaN-NaN]	
				Fore-and-aft lift		1.00 [NaN, NaN-NaN]	
				Drunks lift		1.00 [NaN, NaN-NaN]	
				Pick-a-back lift		0.77 [NaN, NaN-NaN]	
				Pyjama		0.45 [NaN, NaN-NaN]	
				Dining chair drag		0.45 [NaN, NaN-NaN]	
				Armechair drag		0.56 [NaN, NaN-NaN]	
				Wheelchair		0.77 [NaN, NaN-NaN]	
				Ambulance chair		0.83 [NaN, NaN-NaN]	
Hamilton et al. 2017 [66]	L:	Ireland	Video			1.46 [0.58, 0.18-4.41]	
	N:	Unannounced Evacuations		walking		1.32[0.40, 0.18-2.59]	
	SC:	Primary school children in the age range 4 – 12		running male		2.47 [0.66, 1.12-4.41]	
	P:			female		1.48 [0.59, 0.18-4.41]	
Hoondert 2017 [65]	L:	The Netherlands	Video, observer	Dialysis trial 1		0.7 [0.1, 0.62-0.76]	Velocity = mean evacuation speed
	N:	Evacuation experiments		Dialysis trial 2		0.7 [0.1, 0.49-0.85]	
	SC:	Hospital		Intensive Care trial 1		1.19 [0.31, 0.68-1.62]	
	P:	14 participants and 3 experienced staff members		Intensive Care trial 2		1.27 [0.09, 1.16-1.35]	
	V:	Multiple departments		Neonatal trial 1		1.01 [0.17, 0.81-1.30]	
				Neonatal trial 2		1.31 [0.44, 0.93-2.7]	
				Standard hospital ward trial 1		1.96 [0.66, 1.02-3.05]	
				Standard hospital ward trial 2		2.11 [0.91, 1.22-3.66]	
				Heart monitoring trial 2		1.04 [0.29, 0.60-1.33]	
				Heart monitoring trial 2		1.06 [0.17, 0.83-1.33]	
Jiang et al. 2014 [85]	L:	China	Video observa-tion	Healthy (male, youth)	300	1.15 [0.06, 1.01-1.30]	N = Number of samples
	N:	Field study		Healthy (female, youth)	300	1.03 [0.06, 0.90-1.20]	
	SC:	Hospital		Healthy (kids)	300	0.95 [0.08, 0.81-1.10]	
	P:	300		Healthy (elderly)	300	0.69 [0.07, 0.50-0.81]	
	V:	Age, health status		Sick (male, youth)	300	1.00 [0.06, 0.75-0.95]	
				Sick (female, youth)	300	0.85 [0.06, 0.75-0.95]	
				Sick (kids)	300	0.60 [0.05, 0.54-0.70]	
				Sick (elderly)	300	0.50 [0.03, 0.45-0.60]	
Jiang et al. 2012 [124]	L:	China	Video	No aid	40	1.27 [0.19, 0.84-1.60]	
	N:	Evacuation experiments		Single crutch	20	0.87 [0.18, 0.52-1.11]	
	SC:	Underground public place		Double crutches	40	0.78 [0.22, 0.37-1.24]	
	V:	Disability grade, age, gender					
Kang et al. 2008 [80]	L:	United States of America	Motion analysis system	Younger adults	18	1.30 [0.10, 1.16-1.56]	
	N:	Evacuation experiments		older adults	18	1.29 [0.15, 0.93-1.52]	
	C:	Treadmill					
	P:	Young and elderly					
V:	Age						
Kesler et al. 2017 [75]	L:	USA	Video capture	Multiple sclerosis (age 54.3 ± 5.3)	15	0.75 [0.07, NaN-NaN]	6 minute walking test
	N:	Evacuation experiments		Age controls (age 49.7 ± 12.0)	15	1.98 [0.07, NaN-NaN]	
	SC:	Evacuation circuit		young controls (age 21.0 ± 1.2)	12	1.83 [0.08, NaN-NaN]	

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Table 4 – Continued from previous page

Reference	Observational conditions ^a		Sample			Results		
			Collection method	Description	Size	Mean /s [SD, range]		
	P:	With/without disability						
	V:	Multiple Sclerosis						
MacCallum et al. 2015 [60]	L:	Ireland	Video, server	Ob- Bed		0.57 [NaN, NaN-NaN]	Velocity = mean over entire evacuation	
	N:	Announced / unannounced evacuations		Blanket drag		0.67 [NaN, NaN-NaN]		
	SC:	Hospital		Bed		0.36 [NaN, NaN-NaN]		
	P:			Ski sheet		0.52 [NaN, NaN-NaN]		
	P:			Ambulant / Bed		0.97 [NaN, NaN-NaN]		
				Bed		0.32 [NaN, NaN-NaN]		
Novak et al. 2014 [76]	L:	Canada	Video	Young adults, vision, no-GVS		0.92 [0.09, NaN-NaN]	4 conditions which included intact or blurred vision, and intact or perturbed vestibular information using galvanic vestibular stimulation; reduced visibility was simulated by blurring goggles	
	N:	Evacuation experiments		Old adults, vision, no-GVS		0.94 [0.17, NaN-NaN]		
	SC:	Obstacle crossing task		Young adults, blurred-vision, no-GVS		0.91 [0.11, NaN-NaN]		
	P:	Young and old participants		Old adults, blurred-vision, no-GVS		0.84 [0.18, NaN-NaN]		
	V:	Vision, vestibular status		Young adults, vision, GVS		1.02 [0.14, NaN-NaN]		
						Old adults, vision, GVS		0.94 [0.18, NaN-NaN]
						Young adults, blurred-vision, GVS		0.94 [0.13, NaN-NaN]
			Old adults, blurred-vision, GVS	0.86 [0.20, NaN-NaN]				
Samoshin and Istratov 2014 [83]	L:	Russia	Video observation	Familiar route		0.83 [NaN, NaN-NaN]		
	N:	Evacuation		Unfamiliar route		0.44 [NaN, NaN-NaN]		
	SC:	Indoor						
	P:	51 blind and visually impaired participants						
	V:	visual ability						
Sharifi et al. 2015, 2016 [32], [77]	L:	USA	Video analysis	Visually impaired participants		0.83 [0.20, NaN-NaN]	Number = Number of observations	
	N:	Evacuation experiments		Non-motorized wheelchair or rolling walker		0.83 [0.19, NaN-NaN]		
	SC:	Indoor		Motorized wheelchair		0.69 [0.21, NaN-NaN]		
	P:	180 participants without disabilities; 42 participants with disabilities		without disabilities		0.94 [0.21, NaN-NaN]		
	V:	disability, gender, assistance; level of service						
Shen et al. 2014 [81]	L:	China	Video	Female, good visibility		0.92 [0.18, 0.64-1.38]	Zero visibility was simulated with eye masks	
	N:	Field study		Female, zero visibility		0.42 [0.12, 0.23-0.95]		
	SC:	Classroom		Male, good visibility		0.91 [0.14, 0.64-1.32]		
	P:	96 students		Male, zero visibility		0.69 [0.12, 0.50-1.05]		
	V:	Gender, visibility						
Soong et al. 2000[84]	L:	Australia	taking time by walking behind the participants	Sighted guide technique		1.05 [NaN, NaN-NaN]	Raw data given in graphical form, figures extracted from graph by authors	
	N:	Evacuation experiments		Non-sighted guide technique		1.95 [NaN, NaN-NaN]		
	SC:	Corridor						
	P:	Visually impaired (elderly) adults						
	V:	sighted, no-sighted guide technique						

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Table 4 – Continued from previous page

Reference	Observational conditions ^a		Sample		Results		
			Collection method	Description	Size	Mean /s [SD, range]	
Tsuchiya et al. 2007 [78]	L:	Japan	Stopwatch	Non disabled, men		1.33 [0.17, NaN-NaN]	Wheelchairs were used by participants without disabilities
	N:	Laboratory Experiment		Non disabled, woman		1.27 [0.14, NaN-NaN]	
	SC:	Walkway in a campus		Wheelchair users, men		1.06 [0.17, NaN-NaN]	
	P:	College students, 202 male, 75 female		Wheelchair users, woman		1.06 [0.18, NaN-NaN]	
	V:						

^a L: location, N: nature, SC: spatial configuration, P: participants, V: variable.

Table 5: Fundamental diagrams considering pedestrians with disabilities.

Reference	Observational conditions ^a		Sample	Data points	Quantities		
					Measurement method	ρ/m^{-2}	v/ms^{-1}
Guo et al. 2016 [98]	L:	China	Method B as defined in [100]	74	0.85 (0.42, 0.06 - 1.62)	1.20 (1.01, 0.54 - 6.89)	0.74 (0.17, 0.37 - 1.32)
	N:	Laboratory Experiment					
Kholshchevnikov et al. 2012 [109]	L:	Russia	Method A as defined in [100]	-	Quantities were plotted by using Eq 1 with $v_0 = 0.43 m s^{-1}$, $\alpha = 0.43$ and $\rho_{max} = 1.028 m^{-2}$		
	N:	Evacuation training					
Samoshin et al. 2014 [83]	L:	Russia	Method A as defined in [100]	-	Quantities were plotted by using Eq 1 with $v_0 = 0.83 m s^{-1}$, $\alpha = 0.4919$ and $\rho_{max} = 1.03 m^{-2}$		
	N:	Evacuation training					
Sharifi et al. 2015 [32], [126]	L:	USA	Generalisation of Edie-method [125]	-	Quantities were plotted by using Eq 1 with $v_0 = 1.01 m s^{-1}$, $\alpha = 0.913$ and $\rho_{max} = 5.4 m^{-2}$		
	N:	Laboratory Experiment					
Shields et al. 1997 [105]	L:	Northern Ireland	Method A as defined in [100]	8	1.84 (0.57, 0.49 - 2.56)	0.66 (0.38, 0.30 - 1.49)	3.71 (2.20, 1.29 - 6.53)
	N:	Unannounced evacuation					
Soerensen et al. 2013, 2015[106], [107]	L:	Denmark	Method A as defined in [100]	210	0.92 (0.40, 0.49 - 2.24)	0.83 (0.36, 0.27 - 1.92)	0.72 (0.37, 0.17 - 1.92)
	N:	Laboratory Experiment					
Tsuchiya et al. 2007 [78]	L:	Japan	Method A as defined in [100]	34	1.36 (0.20, 1.02 - 1.79)	1.51 (0.14, 1.32 - 1.82)	2.06 (0.45, 1.34 - 3.13)
	N:	Laboratory Experiment					

^a L: location, N: nature, SC: spatial configuration, P: participants, V: variable.

^b Method A: Measuring mean values of flow and density in a time interval (Δt) at fixed position (x).

^c Method B: Measuring mean values of velocity and density over space (δx and time (Δt)).

7. Appendix II – Keyword and truncations

Table 6: Keywords and truncations used to find publications dealing with engineering egress data considering pedestrians with disabilities or reduced performance.

No	Boolean combination of keywords				
1	pedestrian evacuation	AND	parameter	OR	
2	pedestrian evacuation	AND	parameter	NO	sim*
3	pedestrian evacuation	AND	impair*		
4	pedestrian evacuation	AND	disab*		
5	pedestrian movement	AND	disab*		
6	pedestrian movement	AND	impair*		
7	pedestrian	AND	evacuation time		
8	pedestrian	AND	pre-movement		
9	pedestrian	AND	pre-movement	AND	time
10	pedestrian	AND	pre-movement	AND	phase
11	pedestrian	AND	pre-movement	AND	behavi*
12	pedestrian	AND	evacuation time	AND	reaction
13	evacuation	AND	mobility impaired		
14	movement	AND	mobility impaired		
15	mobility impaired	AND	evacuation		
16	vulnerable person*	OR	occup*	AND	evacuation
17	vulnerable person*	OR	occup*	AND	movement
18	vulnerable person*	OR	occup*	AND	pre-movement
19	pedestrian dynamics	AND	movement		
20	pedestrian dynamics	AND	pre-movement		
21	pedestrian	OR	occup*	AND	fundamental
22	pedestrian	AND	fundamental diagram	AND	diag*
23	pedestrian evacuation	AND	parameter	OR	heterogen*
24	pedestrian evacuation	AND	parameter	NO	sim*
25	pedestrian evacuation	AND	impair*		
26	pedestrian evacuation	AND	disab*		
27	pedestrian movement	OR	occup*	AND	disab*
28	pedestrian movement	OR	occup*	AND	impair*
29	pedestrian	OR	occup*	AND	evacuation time
30	pedestrian	OR	occup*	AND	pre-movement
31	pedestrian	AND	pre-movement	AND	time
32	pedestrian	AND	pre-movement	AND	phase
33	pedestrian	AND	pre-movement	AND	behavi*
34	pedestrian	AND	evacuation time	AND	reaction
35	evacuation	AND	mobility impaired		
36	movement	AND	mobility impaired		
37	mobility impaired	AND	evacuation		
38	vulnerable person*	AND	evacuation		
39	vulnerable person*	AND	movement		
40	vulnerable person*	AND	pre-movement		
41	pedestrian dynamics	AND	movement		
42	pedestrian dynamics	AND	pre-movement		
43	pedestrian	AND	fundamental diagram		
44	pedestrian	AND	fundamental diagram	AND	heterogen*
45	pedestrian evacuation	AND	parameter	OR	
46	pedestrian evacuation	AND	parameter	NO	sim*
47	pedestrian evacuation	AND	impair*		
48	pedestrian evacuation	AND	disab*		
49	pedestrian movement	AND	disab*		
50	pedestrian movement	AND	impair*		
51	pedestrian	AND	evacuation time		
52	pedestrian	AND	pre-movement		
53	pedestrian	AND	pre-movement	AND	time
54	pedestrian	AND	pre-movement	AND	phase
55	pedestrian	AND	pre-movement	AND	behavi*
56	pedestrian	AND	evacuation time	AND	reaction
57	evacuation	AND	mobility impaired		
58	movement	AND	mobility impaired		
59	mobility impaired	AND	evacuation		
60	vulnerable person*	AND	evacuation		
61	vulnerable person*	AND	movement		
62	vulnerable person*	AND	pre-movement		
63	pedestrian dynamics	AND	movement		
64	pedestrian dynamics	AND	pre-movement		
65	pedestrian	AND	fundamental diagram		
66	pedestrian	AND	fundamental diagram	AND	heterogen*