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Evacuation from a complex structure – The effect of neglecting heterogeneous populations

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Abstract

How is the total evacuation time of a mixed population and its subgroups predicted by the evacuation tool STEPS? Simulation using STEPS is compared with experimental data and evaluated based on individual total egress times. It was found that the total egress times were similar for the simulation and experiment, but the human behavior occurring in the experiment was not reproduced in the simulations.

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Keywords: egress; heterogeneity; disability; population; behavior; evacuation process; modeling; human behavior

1. Introduction

Societies increasing demand for complex buildings and structures requires more flexible building design in general as well as a flexible fire safety design. Performance based fire safety codes provide solutions for an adaptable design. Hence, these codes are increasingly implemented around the world as a supplement to the existing prescriptive codes. The use of performance-based codes enables the use of tools, such as computer models, to prove that the safety level in the current building is sufficient. The focus of the current study is common evacuation models, in particular STEPS, and the need for valid input data (e.g. walking speeds and delay times for a realistic population) to predict representative and realistic evacuation times. The majority of studies on walking speeds and delay times from literature evaluates the evacuation behaviour of homogeneous groups, often able-bodied adults, and applies normative standards for the choice of population (Gwynne et al. (2005); Boyce et al. (1999a)). It appears that the safety level in buildings is not the same for individuals of vulnerable part of the population, as for able-bodied indi-

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viduals. Research has shown that people with physical and cognitive disabilities, individuals aged younger than 5 years or older than 64 years as well as people impaired by drugs, are more likely to die in fires, compared to able-bodied individuals (Marshall et al. (1998); Leth (1998)). This makes it of high concern to focus on the fire safety provided in buildings for this group of people.

1.1. Literature review

A series of studies describing the evacuation processes from buildings and vehicles (ITSRR (2004); Gwynne et al. (2003); Tubbs (2009); Kuligowski (2009); Grindrod et al. (2011)) have been undertaken. The evacuation of high-speed trains has been studied by Capote et al. (2012). It has been shown, that the effect of the action of the train crew was more important for a smooth and fast egress, than the self-preservation of the passengers. Furthermore, it was found that the flow predicted using the empirical model by Nelson and Mowrer (2002), was conservative compared to the average of the data found in the experiment. The study also involved wheel chair users, and it was concluded that the need of assistance by the crew was essential for the evacuation of this subpopulation. The evacuation flow was likewise studied by Galea and Gwynne (2000) for an overturned rail carriage. Here it was shown that presence of smoke almost doubled the total evacuation time from the overturned rail carriage. In a study conducted by Oswald et al. (2010) the floor height in trains was investigated to clarify how the evacuation flow and behaviour were affected. There are several other studies on the evacuation from airplanes and boats (Gwynne et al. (2003); Galea et al. (2004)), where the evacuation efficiency has been shown to increase with number of cabin crew (Galea et al. (2008)).

A number of models describing the evacuation process can be found in literature (Kuligowski et al. (2010)). Some of the assessed models are not validated, while others are validated using different methods; see Table 1 in Kuligowski et al. (2010) for details. The methods range from comparison with full-scale fire drills to other people movement experiments (Kuligowski et al. (2010)). Furthermore, literature on past evacuation experiments, code requirements, validation against other models or third party validation are used in the validation process (Kuligowski et al. (2010)). The method of validation helps defining the limitations of the applicability of the model. Studies have found that age, gender, time of day (Weidmann (1993)), as well as interpersonal distances and densities (Dabbs and Stokes (1975)) affect the average walking speeds during an evacuation. Furthermore, it has been shown that some modelling approaches are based on “inaccurate assumptions about the way humans respond during emergencies”, which may lead to the production of inaccurate results according to Kuligowski (2011).

Kuligowski et al. (2010) reviewed 26 egress models and found that 21 allow a description of the evacuation capabilities of disabled people. There are different ways of accounting for the heterogeneity of a real population and including disabled people in the building environment. Campanella et al. (2009) showed that an increasing heterogeneity in the population affects average speeds, densities and more likely lead to break down of the flow.

1.2. Objectives

The current work centre on the evacuation modelling tool STEPS, which allows the description of people with impairments in the evacuation process. STEPS is chosen among other modelling tools. STEPS is a behavioural model, which means it is capable of modelling occupants performing actions and their movement towards a specified goal. The setup of these experiments and the hypothesis to test is whether the model is able to predict the behavioural patterns of each of the subgroups. This specific model is validated according to code requirements, fire drills and other people movement experiments as well as literature on past experiments (Kuligowski, et al. (2010)). However, it is known that there exists limited information and literature on the evacuation capabilities of people with disabilities (Boyce et al. (1999b)).

Details on the evacuation experiment and the evacuation model build up in STEPS are explained in the following section. Results on total evacuation times for the real exercises and for the simulations, differentiated for the six subpopulations: mobility-, visual-, auditory-, and cognitive impaired people as well as able-bodied people are presented. In the conclusion the main highlights of the current work is presented.

2. Full scale experiment

The study contains two parts: an experimental part, where full-scale evacuation exercises are performed from a train in a tunnel and a comparative study between the experiment and simulations of the same experiment.

Firstly, the method applied for the setup of the experiments is presented. Secondly, it is described how the associated evacuation calculations are performed using the program STEPS 5.1. The average unimpeded walking speeds are found for each subpopulation in the experiment, and are added into STEPS 5.1 together with measured delay times to start moving. This is done in order to perform simulations of the experiment that uses exact values from the experiment combined with default options.

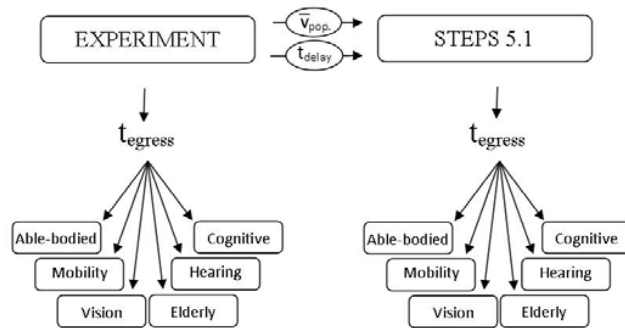


Fig 1. Relation between the experiment and simulations.

The linkage between the experiment and the simulations performed with STEPS is displayed in Fig. 1. The mean velocities for each subpopulation, v_{pop} , obtained for the unimpeded walking in the experiment serves as input to the STEPS model. In addition the delay time to start moving is measured in the experiments and is also an input parameter to the model. Two different evacuation times, t_{egress} , is obtained. These evacuation times will then be decomposed to a representation of the individual egress times for each member of the subpopulations.

Table 1. Distribution of people in the reference scenario and mixed scenario, the demographic profile of Denmark, (Agerskov and Bisgaard (2013), Bengtsson (2008)), and number of participants recruited from each subpopulation (n) and the mean unimpeded free walking speed horizontally.

Subpopulation	Scenario		Demographic profile of Denmark	n	Mean speed [m/s]
	Reference	Mixed			
Able-bodied (16-64 years)	46(39)	28	64.5%	58	1.69
Elderly (65+ years)	-	8	18.1%	12	1.43
Hearing impaired	-	3	1.4%	3	1.81
				4	1.55
Cognitive impaired	-	2	6.7%	2	1.53
Visually impaired	-	2	0.8%	3	1.02
Reduced mobility	-	3	7.4%	-	-
Children (<16 years)	-	-	17.4%	-	-

The evacuation experiment is performed from a full-scale IC3 train in a tunnel. The train has a capacity of 23-seated and 13 standing passengers in the carriage, and further 10 standing passengers in the entrance lobby, see Fig. 2. The longest evacuation route is approximately 24 meters. The exercises are initiated with a spoken warning message informing passengers to evacuate the train immediately. The experiment is performed without the influence of fire hazards such as smoke, heat or flames. The individual total egress time is then measured as the time from the completion of the message until the person has left the transversal tunnel.

During the experiment two different compositions of the test group were applied – homogeneous of able-bodied adults (scenario 1) and mixed (scenario 2). The composition of the test groups was matched as close as possible to the demographic profile of Denmark, however excluding children (Agerskov and Bisgaard (2013); Bengtsson (2008)). Table 1 gives an overview of the number of person for each type of subpopulation in the two scenarios. The mean unimpeded walking speed for each sub-group is also given in Table 1 together with the number of recruited participants. These walking speeds serve as input to the STEPS model. Each scenario was replicated five times resulting in a total of 10 evacuation exercises. The participants were not familiar with the test location and received oral information prior the experiments about the procedure. The experiments were recorded with temporarily installed 54 video cameras. The total evacuation time for each of the scenarios were determined by manually register when the participants passed predetermined check points.

The internal ethical codex developed at the Department of Civil Engineering at the Technical University of Denmark is followed in the current work (Sørensen and Dederichs (2014)).

3. Simulation – STEPS

The modelling software STEPS 5.1 was used to simulate the evacuation exercises. The following section describes the settings used to simulate the exercises.

3.1. Constructing the model

The geometry of the train and tunnel was imported to the software to create the foundation for the simulations. The grid applied to the model is tested for grid sizes of 250 mm, 300 mm and 500 mm. Assessment of the total egress times using the three different grid sizes shows that the spread around the average total egress time overlaps each other and it is therefore not possible to determine which one is better. It has only been possible to test the grid size for the scenario where walking speeds are reduced based in the speed/distance relation. Smaller grid sizes than 500 mm entails difficulties in using the speed/density relation to reduce the walking speed. STEPS calculates the density based on the neighbouring cells to the assessed person. The speed/density is based on the curve presented in the SFPE Handbook (DiNenno (2002)), where the walking speed is 0 m/s for densities larger than 3.8 p/m². If a smaller grid than 500 mm is applied, the density calculations results in larger densities and therefore no movement. The maximum possible density for a grid of 500 mm is 4 p/m². Based on the tests it is chosen to work with a grid size of 500 mm, which has entailed minor changes to the train dimensions in order to fit the grid, see Fig. 2a.

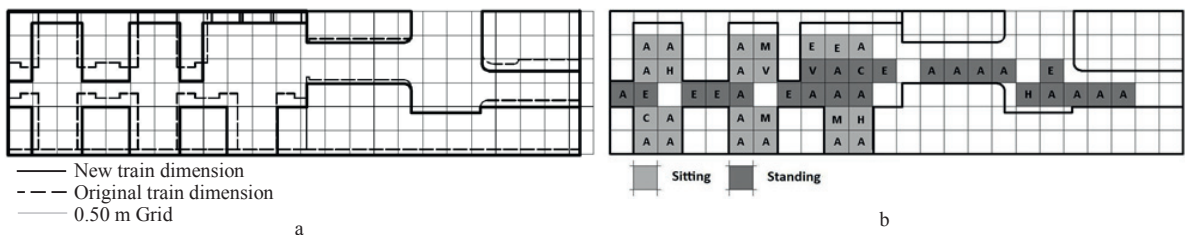


Fig. 2. (a) Modification in train dimensions based on grid size. (b) Seating of subpopulations in the train for the mixed scenario and display of the grid system.

3.2. Agent characteristics

The heterogeneity of the experimental population can be modelled in varies ways, e.g. body size, velocity, need of assistance, ability to negotiate terrain, group formation etc. (Christensen and Sasaki (2008); Schneider and Könnecke (2012)). In the current study the heterogeneity of the population is modelled based on variations in body size, unimpeded walking speed and delay times to start moving. The horizontally projected body sizes are based on the results from Predtechenskii and Milinskii (1978) for people wearing mid-summer street dress, which corre-

sponds to the time of the year where the experiments were held. The heights of the participants are determined based on the average for the Danish population and accounting for age (Hesse (2007)).

STEPS offers pre-defined default values for the walking speeds for each type of person. In the current simulations walking speeds for each subpopulation was obtained from the exercises and the measured values (Table 1) are used as input to the model. Observed delay times from the experiment are likewise used as input, where a mean delay of 13.7 seconds is representative for all subpopulations. It is assumed that the standing agents will start moving without delay.

Agents are seated as in the experiment according to Fig. 2b and assigned the free speed given in Table 1. Thus, the default Fruin distribution is not applied (Fruin (1971)). The seating was randomly determined for each replication of the exercises. However, the seating from the first run was used as reference for the simulations. It is chosen not to use random seating in the simulations and therefore use the exact same seating as applied in the experiment for all simulation replications. The chosen grid size implies a maximum capacity of 52 persons. However, it was chosen to follow the experimental setup and occupy the train with 46 passengers.

3.3. Modeling assumptions

Known from previous studies the walking speed is affected by the surrounding person density (Predtechenskii and Milinskii (1978); Fruin (1971); Pauls (1980)). STEPS offer two different possibilities for walking speed reduction as a consequence of person density; one by the use of the speed/density curve given in the SFPE handbook (DiNenno (2002)), and another with the use of the interpersonal distance curve developed by Thompson (Thompson and Marchant (1995)). The evacuation exercises are modelled using both these two methods to investigate the differences, and to determine which one of the options that gives the most appropriate result for a mixed population. The total evacuation flow is affected by the speed reduction methods. In addition, the flow through the train exit is controlled. Danish Guidelines provide a prescribed value of 1 p/s/m as the maximum flow through an exit, and this value is used as input for the simulations (Erhvervs og Boligstyrelsen (2004)).

To account for variability of evacuation simulation results each scenario ran 50 simulations. The number of simulations is based on recommendations given by the Maritime Organization for evacuation analysis of passenger ships (National Maritime Organization (2007)).

4. Result and discussion

In the following section the results from the study is presented and discussed. The section is divided into two parts. The first part presents results for the total egress time for the entire population from the experiment and the two different simulations. The second part contains a detailed quantitative assessment of the individual egress times for the subpopulations.

4.1. Total egress times

The total egress time for the complete test population is presented in Fig. 3. The figure consists of two graphs, a and b. The left graph is the total egress flow for the mixed population for the experiment and the two simulations of the same experiment. It is seen that the simulation using the speed/density relation fits the experimental result best. However, the total egress time is longer for the simulation. The three curves have similar trends for the first 30% of the exiting population after this point the curve for the experiment and the speed/density relation breaks and continues with a less steep slope.

Fig. 3b shows the results obtained from the experiment and simulations for the reference group of able-bodied adults. It is seen that the simulation using the speed/distance relation is the most representative for the reference group. It should be noticed that the curve for the experimental results is shorter. This is due to limitations in the recruitment process and only 39 able-bodied persons were available for this scenario. The total egress time differs with 14 seconds for the 39th person. A part of the difference might be explained by the exit time for the first person, which gives an initial difference of 5 seconds. The trend for the experiment and the speed/distance-simulation is however similar and results in comparable total egress times.

The results presented in Fig. 3 for the reference group and the mixed group shows that the simulations using the optional speed/density relation gives the best results compared with the experimental findings for the mixed population. Contrary, the optional speed/distance relation is the best fit for the reference group. On that basis, it is decided to use the speed/density relation to assess the individual egress times for the subpopulations in the mixed group.

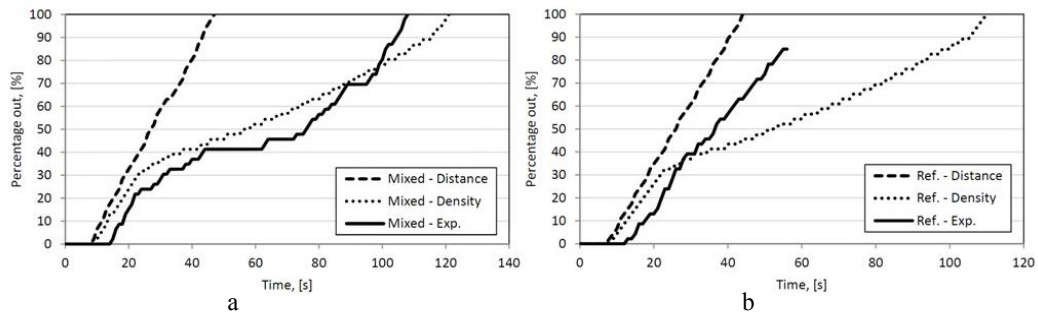


Fig. 3. Total egress flow for the mixed population (a) and the reference group (b). The black line represents the experiment (Exp.) and the dotted lines represent the simulations.

4.2. Egress time for subpopulations

In the following section the individual egress times for the subpopulations are presented and discussed. The experimental results and the simulation using the speed/density relation are compared. In cases where differences between the experimental results and the simulations are detected the cause are evaluated based on the video recordings from the experiment.

Fig. 4 presents the results for the chosen four subpopulations: hearing (a) and mobility (b) impaired test persons, elderly (c) and able-bodied test persons (d), respectively.

The individual egress times for the three hearing impaired participants are presented in the middle left graph in Fig. 4a. It is seen that the difference between the simulation and experiments is two and five seconds respectively for the first and second person. For the third and last person there is detected a difference of six seconds between the experiments and the simulation. For the first person the simulation predicts a faster egress time compared to the experiments, however the difference is negligible. The simulation predicts a longer evacuation time for the remaining two agents. Overall, the total egress time for the three hearing impaired participants are comparable between the simulation and the experiment.

The graph to the right in the middle of Fig. 4b presents the egress flow for the three persons with reduced mobility. The first person exits two seconds faster in the experiment compared to the simulation. The following two persons exit the tunnel 13 and 18 seconds faster in the experiments compared to the simulation, respectively. All three participants are initially positioned in the carriage. The characteristics of the three participants with reduced mobility differ. One is using crutches and takes up space in the egress path, which restricts overtaking and queuing is therefore formed. The two other persons are leg amputated and their body sway during movement is larger compared to the other participants in the experiment. Assessing the video recordings, it is found that the mobility impaired person, using crutches is the first of the three to exit the tunnel. The second mobility impaired person is caught within the queue formed by the first person. This might explain the faster evacuation time for the second person. The third and last participant is not enclosed in the first queue and is himself subject for formation of a queue. None of the three participants received assistance from a fellow participant during horizontal movement. However, the one with crutches receive help to negotiate the stair.

The bottom left graph in Fig. 4c shows the exit flow for the subpopulation consisting of elderly participants. The individual total egress time for the first three members of this group is comparable for the simulation and experiment. The difference is in the range of seven seconds between the experiment and simulation, which is considered reasonable. The fourth person exit the tunnel after 80 seconds in the experiments compared to 40 seconds in the simulations. This indicates that something in the total flow has influenced the fourth person and consequently the

rest of the flow of elderly people. Examining the video footage it could be seen that the first three persons exit the tunnel before the mobility impaired participant with crutches, who causes the formation of a queue because he uses the whole width of the egress path, and is not overtaken by anyone. Even though there is a time span of 42 seconds in the experiment where no elderly people are exiting, the final difference between the simulation and experiment is 13 seconds. It is seen from the graph that the time interval between the persons in the simulations is much more constant compared to the experiment. On the other hand the queuing in the experiment results in very small time interval for the fourth to the sixth persons. These three persons exit within 5 seconds. The last two persons, seven and eight, are positioned in the queue formed behind the second mobility impaired person and they exit within a time span of 2 seconds. The exit times are more evenly distributed in the simulations compared to the experiments, where individual behaviour influences the total evacuation flow.

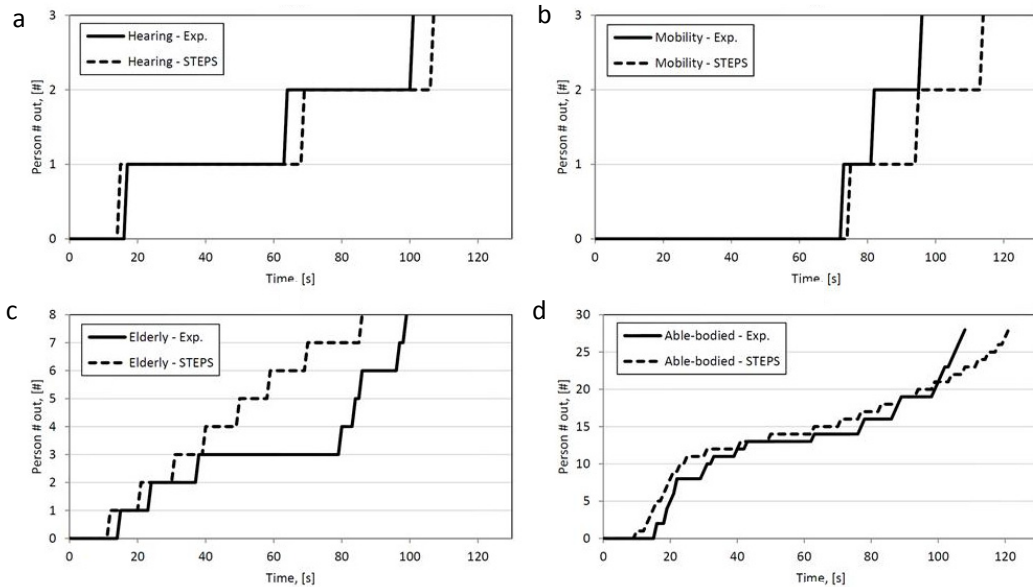


Fig. 4. Individual egress times for each of the six subpopulations. The black represents the experiment and the dotted line the average simulation. (a) Hearing; (b) mobility; (c) elderly; (d) able-bodied.

The last graph, bottom right in Fig. 4d, shows how the able-bodied adults exit the tunnel. The first person exits after 10 seconds in the simulation compared to 16 seconds in the experiment. This difference is sustained until the eighth person has left the transversal tunnel. After the eighth person has evacuated, there is observed a plateau for the experimental curve, a time span where no one exits. From the video recordings two reasons for this first plateau are detected. First, the eighth able-bodied adult is the last person situated in the entrance lobby, and the ninth person is therefore situated in the carriage. Second, a cognitive impaired participant controls the first part of the flow from the carriage, due to his/her slower walking speed. She places both feet on every stair tread, which is the reason for her velocity. Furthermore, no overtaking is observed. Longer plateaus are likewise observed between the 13th and 14th able-bodied and again between the 14th and 15th person. The cause of the first plateau is found in the video recordings to be the first mobility impaired participant who occupies the stair and is subject for a queue formation. There are no specific incidents that can be addressed as a reason for the second plateau. The last ten persons in the experiment exit within a time span of 10 seconds, which corresponds to 1 p/s, which is considered reasonable. In the simulation it takes 38 seconds for the last ten persons to evacuate, and this is the reason for the difference in total egress time.

The results show that in three out of four sub-populations the simulations give a conservative total egress time for the subpopulations respectively. However, STEPS is not capable of predicting the interactions and differences in behaviour observed in the experiments.

None of the available sub-models provided in STEPS are capable of taking into account the altruistic behaviour observed in the experiments. The results from the current study show differences in the egress flow for the subpopulations between the simulation and experiment. The heterogeneity of the population is seen to have an influence on the evacuation flow. The amount of data is still scarce for vulnerable people even though there have been an increasing focus on this population in the past decades. It is therefore important that engineers and designers do not fully rely on results from simulations when predicting the evacuation of buildings and other structures. Attempts to create an on-line database with data on human egress behaviour are made within the last ten years. Such database could serve as a tool for designers, modellers, engineers, fire consultants etc. to increase the reliability of and development of evacuation models (Gwynne (2013)). Hence, representative data might produce a stronger bond between simulations and real emergencies.

Various aspects of human behaviour (discussed elsewhere) were neglected in the modelling.

The participants recruited were taking part in more than one exercise during the day of the experiment. It is therefore assumed that personal relationships among the members of the different subpopulations were established and have affected the results. The optimum experimental setup would be a completely new cast for each replication of the exercises.

5. Conclusion

The influence of the composition, with altering heterogeneity of the population on egress times during real fire drills were investigated in the current work. The results were compared to the total escape times using the software STEPS. Besides able-bodied adults, members of the reference group, the participating population consisted of subpopulations covering hearing, visually, mobility and cognitive impaired people as well as elderly people. The study has the following findings:

The total egress times from the experiments are twice as long for the mixed groups as for the able-bodied group. The application of the, in the STEPS manual, speed/distance relation does not give conservative predictions of the total egress times in both cases. However, it results in better predictions for the able-bodied group, compared to the mixed population. Results found, when applying the speed/density relation in STEPS that this matched best with the experimental results for the mixed test population. Hence, the speed/density relation was used to assess the individual egress times for the subpopulations in the mixed group.

Assessing the results in relation to the speed/density relation, the individual egress times for the subpopulations in the mixed group leads to the following findings:

The model over-predicts the egress times for five of the six subpopulations except for the elderly subpopulation in the evacuation process of the heterogeneous group. The egress time of the visually impaired sub-population is affected by the assistance by an able-bodied adult, guiding the impaired person, and letting them pass freely. The egress time for the hearing-impaired subpopulation was affected by queuing in the heterogeneous group. Furthermore, the total flow was affected by mobility-impaired participants due to walking speeds horizontally and on stairs as well as lower densities due to the movement and the use of crutches. Overtaking was rarely observed in the heterogeneous group. However, overtaking was observed in the simulations. In addition, assistance by able-bodied adults led to an increase in the speed of the impaired subpopulation. Overall the results indicate that it is necessary to account for heterogeneity, when describing the evacuation of mixed populations. The first step of using corresponding input velocities of the subpopulation leads to a reasonable description of the evacuation, but not a conservative prediction of the total egress times. Furthermore, it appears that human behaviour and the processes affect the flow and the total times.

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