Emergency Door Capacity: Influence of Population Composition and Stress Level

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Abstract For the new version of the Dutch design guidelines for buildings, a threshold value for the capacity of emergency doors needs to be set. Innovative large-scale laboratory experiments have been performed to investigate the capacity of emergency doors during evacuation conditions. This paper focuses in particular on the relation between capacity and the independent variables population composition and stress level.

It turns out that the average observed capacities are for all widths lowest for the lowest stress level and highest for the highest stress level. The population with a greater part of children has the highest capacity (on average 3.31 P/m/s). This is mainly due to the smaller physical size of children compared to adults and elderly, which makes it possible that more children can pass a door at the same time than adults. The lowest capacity (on average 2.02 P/m/s) is found for the experiment with 5% disabled participants.

Introduction

Since 1992, the Dutch national building design guidelines ("Building decree") sets requirements to the width of emergency doors. Since 2003, these requirements depend on the number of persons that rely on an emergency door. According to the Building decree a door width of one meter is sufficient to let 135 persons pass during the period available for safe escape (1 minute). This value corresponds to research of Peschl [1], being similar to 2.25 P/m/s. The threshold of 135 persons per meter width during a safe escape time of one minute has been discussed for years between the Ministry for Housing, Regional Development and the Environment and the fire brigades that are used to allow a maximum of 90 persons per meter width during a safe escape time of one minute (1.5 P/m/s).

A literature research has been performed to find other research related to similar bottlenecks. This overview showed a wide variety of capacities ranging between 1.03 P/m/s and 3.23 P/m/s [2-8]. Most of the capacities found are lower than the capacities in the design guidelines (2.25 P/m/s), but the conditions differ

R.D. Peacock et al. (eds.), *Pedestrian and Evacuation Dynamics*,
DOI 10.1007/978-1-4419-9725-8_2,

widely. To collect further information on the capacity of doors during emergency conditions new, dedicated, experimental research has been performed.

In previous research, we developed a conceptual model of pedestrian behavior in relation to capacities of emergency doors. This model shows that doorway width, population composition, light intensity, the presence of an open door and stress level affect the capacity of emergency doors. This paper focuses on the relations between population composition and stress level and capacity.

The next section describes the set up of the experiments in more detail. In the third section the methodology is described to calculate the capacities, the results of which are shown in the subsequent section. We end with conclusions and recommendations for future research.

Experimental Set Up

The capacity of an emergency door depends on several aspects, among which the composition of the population using the door, the conditions under which the door is used and the door width. Before describing these experimental variables in more detail, some boundary conditions are set.

In the experiments, an opening represents the emergency door: subjects pass a free passage of a certain width. In this opening, no doorstep is present, to reduce hindrance and prevent possibly dangerous situations for participants. In addition, the pedestrian flow is one-directional, implying that no counter flows are present caused by fire fighters and people from emergency services. In reality, these people will rarely enter a building when the evacuation process is still going on.

The experiments performed by Peschl [1] have been based on a student population. However, in practice, the population will not consist of persons being in good shape, but the persons will have different physical conditions. In this research, we will use age as an indication for a person's physical condition. Here, we distinguish four categories: children (under 18 years of age), adults (between 18 and 65 years of age), elderly (over 65 years of age) and disabled persons. With these categories, we are able to compose populations corresponding to a variety of situations, see Table 1.

The disabled people are represented by three persons in wheelchair and three blindfolded persons.

Table 1. Overview of different populations in the experiments

	Population	Children	Adults	Elderly	Disabled
1	School	90%	10%	0%	0%
2	Station during peak hours	0%	100%	0%	0%
3	Home for the elderly	5%	20%	75%	0%
4	Work meeting	5%	90%	5%	0%
5	Shopping centre	30%	60%	10%	0%
6	Average	25%	55%	20%	0%
7	Disabled	23%	54%	18%	5%

The conditions under which an emergency door is used may vary considerably. In the experiments, both the stress level of the participants and ambient conditions are varied. Not much is known on how to introduce stress in an experiment. In the past two methods have been considered favorable: enforcing participants to hurry e.g. by rewarding participants according to their performance and exposing participants to noise. Here, we have chosen to use for the latter option by sounding the slow-whoop signal. In addition, the stress level of the participants is raised by a combination of the slow-whoop signal and stroboscope light. In total, participants have been exposed to three stress levels: none, a slow-whoop signal and a combination of a slow-whoop signal and stroboscope light.

The sight is reduced by reducing illumination to a low level. Two alternative light situations are considered: full lighting (200 lux) and dimmed lighting (1 lux, corresponding to emergency lighting).

In the experiments, the opening width is varied between 50 cm (the minimal free passageway of an escape route in the Building decree for existing buildings) and 275 cm. In addition to an opening of 85 cm wide (minimal free passageway of an escape route in the Building decree for new estates) openings are a multiple of 55 cm. Furthermore, an opening of 100 cm is tested to see the correspondence with the normative capacity expressed as the number of persons passing an opening of one meter wide in one minute.

Ideally, all combinations of experimental variables should be investigated. Since this is not feasible due to time restrictions (the experiments should not last longer than a single day), for each experiment one variable is changed, while for the other variables the default value is maintained. By interpolation of the results of the various experiments, pronouncements can be made on the not performed experiments. The stress levels are varied for all experiments.

Each experiment will be performed multiple times to guarantee the reliability of the observations. To determine the number of repetitions, a total time of congestion of three minutes should be achieved. Since the time of congestion for wide doors is shorter than for narrow doors, more repetitions are performed for the wide doors. An overview of the experiments is shown in Table 2.

Table 2. Overview of the performed experiments

Experiment	Opening width [cm]	Population	Light [lux]	Open door	Start time
1	100	Average	200	No	9:58
2	220	Average	200	No	10:17
3	85	Elderly home	200	No	10:43
4	85	Average	200	No	10:58
5	165	Average	1	No	11:25
6	275	Average	200	No	11:52
7	85	Work meeting	200	No	12:49
8	85	Disabled	200	No	12:23
9	85	School	200	No	13:48
10	85	Average	1	No	14:08
11	50	Average	200	No	14:24
12	110	Average	200	No	14:39
13	85	Shopping centre	200	No	15:19
14	85	Average	200	Yes	15:40
15	165	Average	200	No	16:03
16	85	Station	200	No	16:24

A digital video camera and an infrared camera are used to observe the experiments. The infrared camera observes LED's, attached on top of the caps of the participants. This technique guarantees good observations for the dimmed conditions. For the other experiments a digital camera is used, which is attached to the ceiling next to the infrared camera.

In total 75 children of 11 years old (blue caps), 90 adults (red caps) and 50 elderly persons (yellow caps) have participated in the experiments. This leads to populations of between 90 and 150 persons, which are large enough to cause congestion upstream of the door to observe capacities.

To represent an emergency door, a wall has been built in the middle of a large hallway, perpendicular to the sidewall. In this wall, an opening is made, whose width is easy to vary. At the side of the wall, some space is left to walk from one side of the wall to the other without using the opening. Above the centre of the opening an emergency exit sign has been hung up. An overview of the experimental site is shown in

Fig. 1. To use the doorway more efficiently the participants use it in two directions: in the first experiment, they walk from one side of the wall to the other and in the next experiment they walk back again.

Fig. 1. Overview of the experimental site

Methodology to Calculate Emergency Door Capacity

The images from the digital video camera form the basis to calculate the capacity of an emergency door. The movie of each repetition of an experiment is split into separate images with a frequency of 25 images per minute.

The flow through the door can be calculated by counting the number of pedestrians passing the door during a specific time period. When during this time period congestion occurs, the observed flow is equal to capacity. In our case, in all repetitions of the experiment this congestion occurs, so we will not mention this aspect further. To determine the capacity, we identify the passing moments of pedestrians at a cross-section directly downstream of the door using the similar idea behind a finish photo. From all images of a repetition, we take the part that corresponds to the indicated cross-section. By placing all these parts next to each other for increasing time moments, we see what happens at the cross-section over time (horizontal axis). On this new image, we then identify the persons (caps). The x-pixel of this cap indicates the time moment when the participant passes the cross-section, while the y-pixel indicates his lateral position.

Assuming that the capacity of the door does not change during a repetition of the experiment, a straight line is fit through the cumulative curve. The derivative of this line corresponds to the average capacity of this door during this repetition. The average capacity of the experiment is then the average of the capacities of all repetitions. If the average capacity of each experiment is known, the relations between the capacity and the various experimental variables (door width, population, stress level, etc.) can be determined.

Relations between Capacities and Experimental Variables

Based on the methodology described in the previous section capacities have been calculated for all repetitions of all experiments. In this section, the influence of the experimental variables population composition and stress level are discussed.

Stress Level

Fig. 2 shows that the average observed capacities over all doorway widths are lowest for the lowest stress level and highest for the experiments with slow-whoop and stroboscope considered as the highest stress level. The figure on the right shows some outliers for the experiments without stress. An explanation can be found in the time of the day this experiment has taken place (see also Fig. 4).

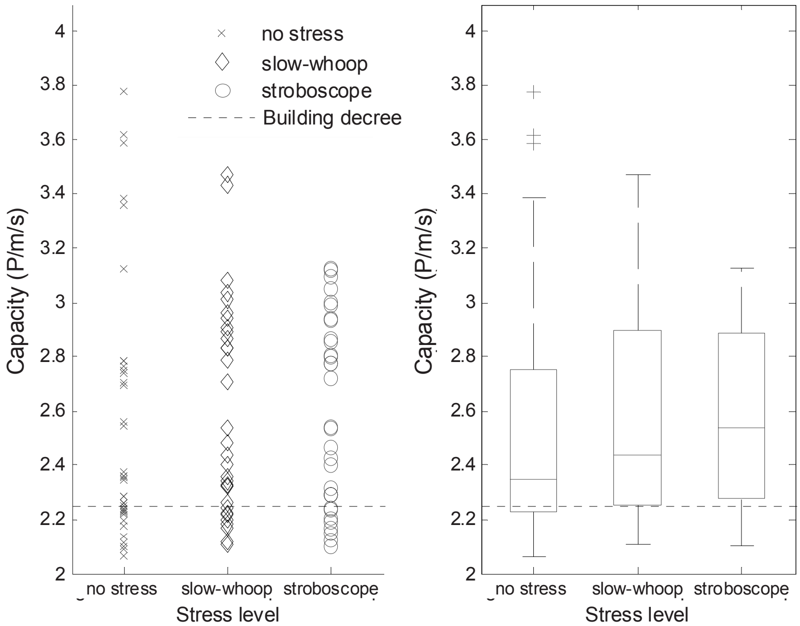

Fig. 2. Capacity as function of stress level for various doorway widths. On the left, observations are shown per repetition, on the Right, a box plot.

A closer look at the data shows that the experiments with the largest variance in capacity were the first two experiments performed. Moreover, the stress level appears to have an opposite effect for both experiments: for the first experiment the capacity is lowest for the lowest stress level, while in the second experiment the highest capacities occur at the lowest stress level. The other experiments do not show such a clear effect of the various stress level. This leads to the conclusion that the difference is not structural and can be attributed to the conditions (enthusiasm) during the first experiments. While the participants of the first experiment did not know what to deal with, the participants of the second experiment could wait and see what happened. Especially at the start of the experiment, these participants were very motivated and were in full focus to pass the door. In the first repetitions (without stress and with slow-whoop respectively) this lead to pushy behavior, which was clearly visible in the video images.

The capacity of most repetitions is higher than the capacity prescribed in the Building decree. Only most repetitions of the experiment with the widest opening are below the capacity threshold from the Building decree. Since the first experiments showed that the capacities appeared to be higher than the planned capacities all adults and elderly have joined the experiment. This lead to a slightly different population with more elderly participants than the average population, which has a negative effect on the capacity as will be shown in the following section.

Population Composition

During the experiments also the population has been varied. These experiments have been performed with a doorway of 85 cm wide, a normal light intensity (200 lux) and without an open door. Fig. 3 shows the results of these experiments.

The figure shows that five out of six populations result in a capacity higher than the capacity threshold indicated in the Building decree. Only the population with 5% disabled persons results in a slightly lower capacity (2.0 P/m/s versus 2.25 P/m/s). The population with mainly children has the highest capacity. This is mainly caused by the physical fact that children are smaller than adults, which makes it possible for more children to pass a door opening at the same time. The populations representing a retirement home, a meeting and a shopping centre do not differ much. Conversely, the capacity of the population ‘station’ varies considerably from the population ‘meeting’. The first population consists only of adults, while the second population consists of 90% adults, completed with 5% children and 5% elderly. However, the difference between both capacities is somewhat more than 8%. Also the population ‘shopping centre’ and ‘average’ have a substantially different capacity (15%), while the first population has only 5% more children, 5% more adults and 10% less adults. These differences might be explained by the moment of the day the experiment has been performed (see Fig. 4).

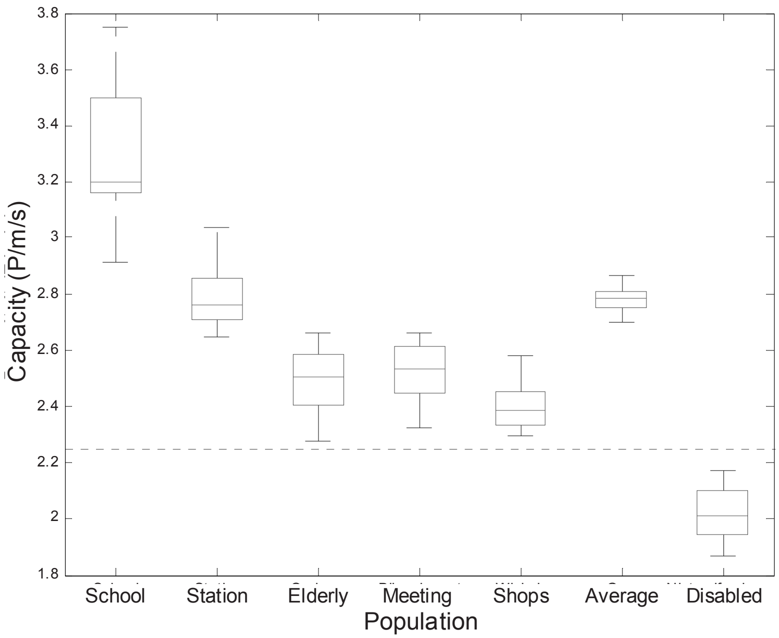

Fig. 3. Capacity as a function of the population composition

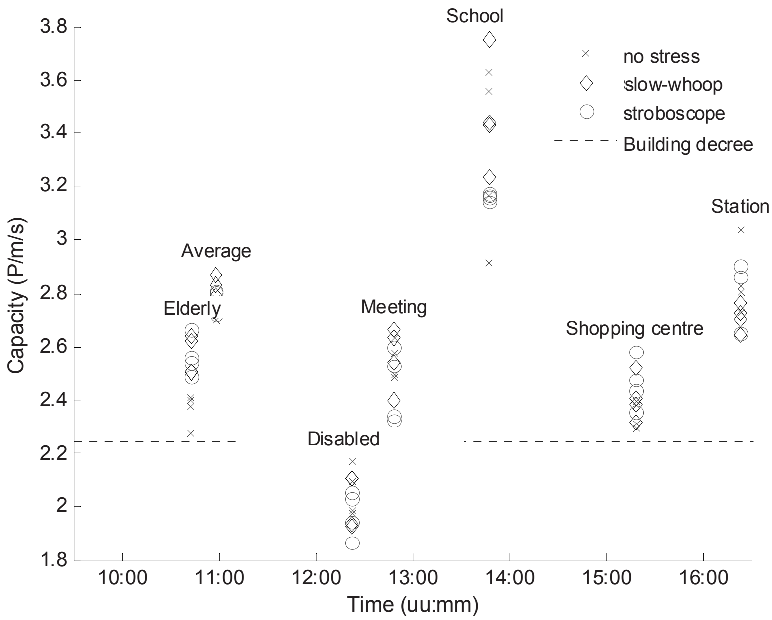

Fig. 4. Capacity as a function of population composition and time of day

For both situations mentioned above the performance moment of the experiment has a clear but opposite effect. The experiment with the average population was the fourth experiment of the day just before a short break, while the experiment with the shopping centre population occurred halfway the afternoon. At that moment the fatigue had increased considerably and the enthusiasm decreased, which lead to a lower capacity than the capacity of a comparable average population. Exactly the opposite causes the difference in capacity between the meeting population and the station population. The experiment with the meeting population occurred by one o'clock, when the participants were clearly in need of a lunch break, while the experiment with the station population occurred at the end of the day. To motivate the participants extra, the challenge was set to improve the highest capacity of the children. This led to a very strong motivation, resulting in a much higher capacity than the one of a similar population.

The variation in capacity is highest for the school population, which can be attributed to the fact that children strongly react to each other: if the first person passes the doorway very fast, the others will follow very fast as well, whereas if the first person passes the doorway very slow, the others will also take it easy. However, the variation between the experiments with the stroboscope was very small, probably because this unusual external condition makes the children focus more on the aim of the experiments (less distraction).

Conclusions and Recommendations

The main conclusion to be drawn is that the capacity of most experiments is higher than 2.25 P/m/s. The experiments with the lowest capacity have a population with disabled persons and a very wide doorway (275 cm) with less children than the other experiments with different doorway widths.

Another conclusion is that in the performed experiments, more pushing does not lead to the 'faster-is-slower' effect. In the experiments a higher urgency (higher stress level) leads to higher speeds and to a higher capacity.

Many differences between the observed capacities can be explained by the different experimental variables. The images of the experiments indicate that an explanation can also be found in the individual behavior of the participants. When this microscopic behavior can be predicted, also the capacities can be predicted for a larger variety of conditions. This will be subject of future research.

The research described here has explicitly been focused on the capacity of emergency doors. This is only part of the total evacuation process. The previous process (pre-evacuation, route choice, walking towards the exit) has a direct influence on the arrival pattern of pedestrians at the emergency door, and thus whether or not capacity of the door will be reached. This is also subject of future research.

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http://www.springer.com/978-1-4419-9724-1

Pedestrian and Evacuation Dynamics
Peacock, R.D.; Erica D., E.D.; Averill, J.D. (Eds.)
2011, XVIII, 910 p., Hardcover
ISBN: 978-1-4419-9724-1