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Capacity of Doors during Evacuation Conditions

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Abstract

In this paper, we show how the capacity of evacuation doors is affected by the evacuation door width, population composition, the presence of an open door and evacuation conditions. For this, laboratory experiments have been performed. Varying door opening widths showed that only the experiment with the widest door opening (275 cm) resulted in a capacity lower than the threshold capacity from the design guidelines (2.25 P/m/s). 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, while the lowest capacity is, as expected, found for the experiment with 5% disabled participants. The presence of a door opened in the escape direction in an angle of 90 degrees for a door opening of 85 cm results in a 20% capacity reduction.

Keywords: emergency doors, capacity estimation, laboratory experiments.

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1. Introduction

Since 1992, the Dutch national building code ("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 1 meter is sufficient to let at least 135 persons pass during the period available for safe escape (1 minute). This value corresponds to research of Peschl [1].

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.

Therefore, the aim of the research project described in this paper is to perform experimental research to collect new information on the capacity of emergency doors. Here, capacity relates to the maximum number of persons that can pass through a door under prevailing conditions.

A literature research has been performed to find other research related to similar bottlenecks. In 2002, the department Transport & Planning of the Delft University of Technology performed laboratory experiments with a

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narrow bottleneck. This resulted in a capacity of 1.77 P/m/s [2], which is closer to the capacity recommended by the fire brigades than in the design guidelines. However, the narrow bottleneck a short hallway of five meters long, whereas a doorway usually has a length of 10-40 centimeters. This will most likely lead to a higher capacity for doorways, since pedestrians may accept short headways for a short period of time.

Kretz et al. [3] performed bottleneck experiments as well. In these experiments, the bottleneck was a thick wall of 40 cm with an opening the pedestrians had to pass. Different widths for the opening have been considered (40 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm, 100 cm, 120 cm, 140 cm, and 160 cm). The participants consisted of healthy students; the experimental conditions were normal. A linear decrease of the capacity is shown with increasing bottleneck width as long as only one person at a time can pass (from 2.2 P/m/s for 40 cm to 1.78 P/m/s for 70 cm width). A constant value of the capacity of around 1.8 P/m/s is shown for larger bottleneck widths (70 cm, 80 cm, 100 cm and 120 cm). Only the very narrow bottleneck thus shows a capacity slightly lower than the capacity indicated in the design guidelines, the other bottlenecks width result in lower capacities.

Experimental research by Müller [4] and Nagai et al. [5] indicated much higher capacities for bottleneck widths varying between 80 cm and 160 cm, namely between 2.29 P/m/s and 3.23 P/m/s. These high values can be explained by the very high densities at the start of the experiments. Also, the configuration of the bottleneck is slightly different, which affects the measured capacities [6]. These values correspond to the threshold indicated in the design guidelines.

In many more researches observations have been performed on corridors and in areas with many pedestrians present (e.g. stations, inner cities and stadiums), for overviews see [7,8]. The capacities found vary between 1.03 P/m/s and 1.67 P/m/s, thus much lower than the design guidelines. However, these capacities are found in normal conditions, which most likely will lead lower capacities than in evacuation conditions.

The next section describes the set up of the experiments in more detail. It also gives a short impression of the day of the experiments. Then, the methodology is described to calculate the capacities, the results of which are shown in the following section. We end with conclusions and recommendations for future research.

2. 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, the emergency door is represented by an opening: 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, which means 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 diverse physical conditions. This condition both depends on their age and on their constitution. Since physical fitness as well as constitutions are difficult to measure quantitatively, we use the approximate indicator age to discriminate. Here, we distinguish three categories: children (under 18 years of age), adults (between 18 and 65 years of age) and elderly (over 65 years of age). With these age categories, we are able to compose populations corresponding to a variety of situations, see Table 1. In addition, we added a category ‘disabled persons’, who are represented by three persons in wheelchairs and three blindfolded persons. Obviously, many varieties of physical disabilities exist, but it is impossible to include these all in the experiments. The objective was therefore to include a representative number of disabled persons to discover whether the varieties of physical disabilities should be investigated in more detail.

Table 1. Overview of the 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 the sight 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 blacking out. Two alternative light situations are considered: full lighting (200 lux) and dimmed (1 lux, corresponding to emergency lighting).

In the experiment, 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.

The final experimental variable relates to whether or not the outflow of pedestrians after passing the door opening is free. In reality, doors cannot always open 180 degrees, but may be restricted to an opening of e.g. 90 degrees. The hinder of such an open door is investigated.

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, conclusions can be drawn 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	Sight	Open door	Start time
1	100	Average	200	No	9:58
2	220	Average	200	No	10:17
3	85	Home for elderly	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 video camera and an infrared camera are used to observe the experiments. The infrared camera observes LEDs, 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.

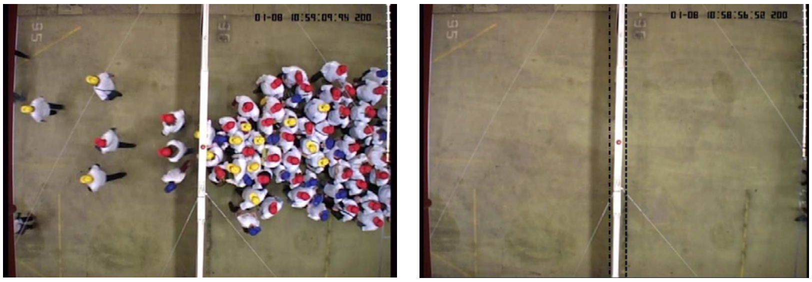
In total 75 children of 11 years old (blue caps), 90 adults (red caps) and 50 elderly persons (yellow caps) have participated in the experiments. This leaded to populations of between 90 and 150 persons, which are large enough to cause congestion upstream of the door to observe capacities.

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 Figure 1. To use the door opening 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.

Figure 1: Overview of the experimental site.

3. Methodology to calculate emergency door capacity

The images of 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. Figure 2a shows such an image of the reference experiment with a door opening of 85 cm wide, an average population, 200 lux, no open door and no stress.



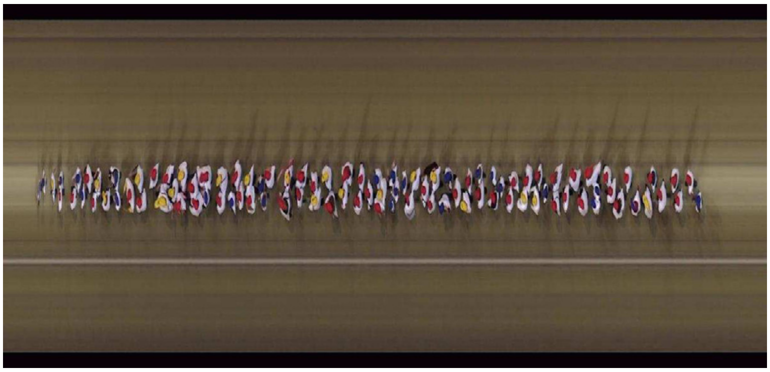
a. Overview of the pedestrians.

b. Cross sections to measure capacity.

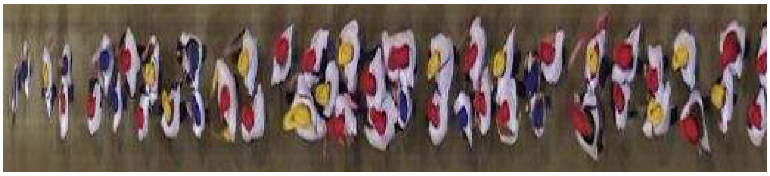
Figure 2: Digital video camera images of the reference experiment.

To calculate the capacity of the emergency door, the moments that the subjects pass a cross-section directly downstream of the door need to be known. Figure 2b shows the considered cross-sections: the stripe-dotted line indicates the cross-section to determine the capacity of the flow from right to left, while the striped line corresponds to the cross-section to determine the capacity of the flow from left to right.

To determine the passing moments on the specified cross-sections, the movie of a single repetition of an experiment is split into individual images. In each image, the picture line corresponding to the cross-section is selected. These picture lines are then placed next to each other, which gives a similar effect as a finish photo, see Figure 3a. Figure 3b shows a zoom of the picture lines in Figure 3a. This figure clearly shows that the first participants have passed the cross-section at high speed: their caps are very small, while the images of the following persons are larger.



a. Picture lines of a repetition of the reference experiment.



b. Zoom of the picture lines of a repetition of the reference experiment.

Figure 3: Picture lines of a repetition of the reference experiment.

In Figure 3, the horizontal axis indicates the time, while the vertical axis indicates the lateral position where the pedestrian passes the cross-section. To determine capacity, the passing moments of each pedestrian are important, implying that we need to find the centre point of the caps in the figure. The corresponding x-position indicates the corresponding passing moment of this person.

The next step is therefore to automatically recognize the caps using their clearly identifiable colors. In the 'photo finish' we look for pixels within a pre-specified color range (red, blue and yellow). The detected pixels that are closely related can then be combined to caps. Figure 4 shows the identified pixels (caps, white areas) for a repetition of the reference experiment.

For each cluster (cap) its centre point is calculated. As indicated before, the x-position of this point indicates the time moment when the participant passes the cross-section, while the y-position indicates the lateral position in the cross-section. A cumulative curve can be derived based on these passage moments, where the number of persons having passed the cross-section is plot against the passing moment, see Figure 5.

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 an experiment is then the average of the capacities of all repetitions. Since 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.

Figure 4: Overview of the identified caps of a repetition of the reference experiment.

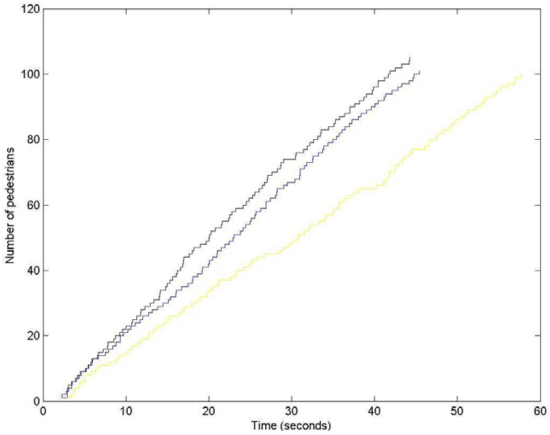


Figure 5: Cumulative curves of two repetitions of the reference experiment (black and blue lines) and a repetition of the experiment with the disabled persons (yellow line).

4. 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.

During the experiments the opening width has been varied between 50 cm and 275 cm. All these experiments have been performed with an average population, a normal light intensity (200 lux) and without the presence of an open door. Figure 6 shows the results of these experiments.

For each experiment, the observed capacity is shown in the figure. The type of marker indicates the stress level, while the green star represents the average capacity per experiment over all stress level. In addition, the current threshold capacity from the Building decree has been indicated (C = 2.25 P/m/s = 135 P/min).

The figure shows that only the experiment with the widest door opening results in an average capacity lower than the threshold value from the Building decree. Furthermore, the high capacity of the door opening of 220 cm is remarkable, as well as the large difference between the repetitions in this experiment. Figure 6 indicates that the repetitions without stress or with a low stress level result in the highest capacity for a door opening of 220 cm, while the experiment for a door opening of 100 cm contradicts this finding. Figure 7 gives more insight into the influence of the various stress levels.

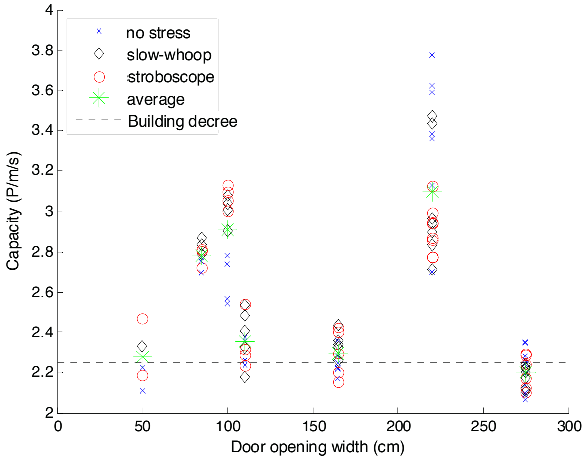


Figure 6: Capacity as a function of door opening width for an average population, a light intensity of 200 lux and no open door present.

Figure 7 shows that the average observed capacities over all door opening widths are lowest for the lowest stress level and highest for the experiments with slow-whoop and stroboscope considered as the highest stress level. For all cases the average observed capacities are much higher than the value included in the Building decree. As well as in Figure 6 the figure shows some outliers for the experiments without stress and with only a slow-whoop signal for a door opening of 220 cm. An explanation can be found in the time of the day this experiment has taken place (see Figure 8).

Figure 8 indicates that both experiments with the largest variance in capacity have taken place at the beginning of the morning. Moreover, the figure shows that the stress level has 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. Although the number and the distribution of the participants over the three groups (children, adults, elderly) are equal for all experiments, other persons participated. 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 was happening. 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; this was clearly visible in the video images.

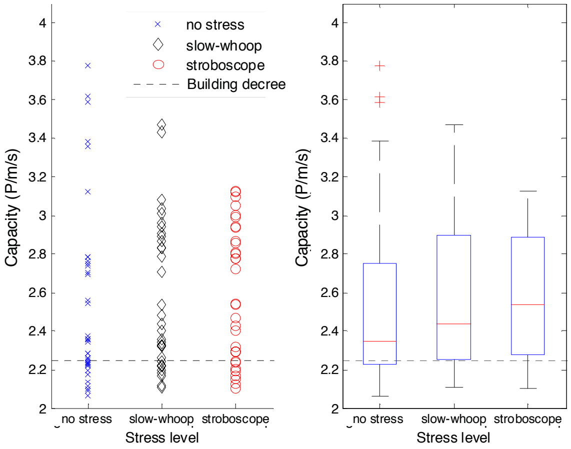


Figure 7: Capacity as function of stress level for the various door opening widths for an average population, a light intensity of 200 lux and no open door present.

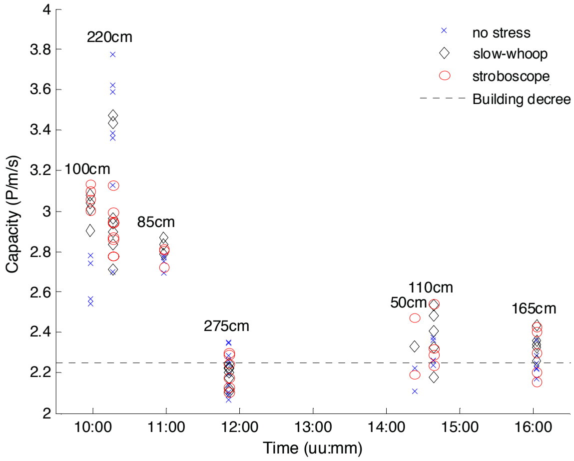


Figure 8: Capacity as function of time of day for various door openings for an average population, a light intensity of 200 lux and no open door present.

Figure 8 also shows the influence of time of day on the capacity. This is not contributed to the fact that participants have more experience with the experimental set up, but it relates to their physical fitness and mainly motivation. It appeared to be impossible to motivate the participants just as much for each experiment during the total day. Despite this fact, the capacity of almost all 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.

During the experiments also the population has been varied. These experiments have been performed with a door opening of 85 cm wide, a normal light intensity (200 lux) and without an open door. Figure 9 shows the results of these experiments.

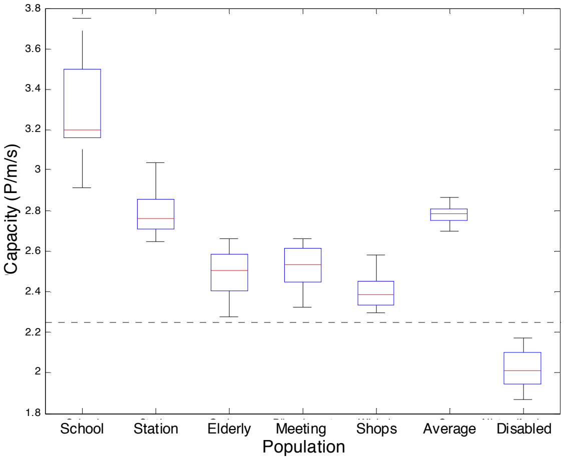


Figure 9: Box plot of the capacity as function of population at a door opening of 85 cm, a light intensity of 200 lux and no open door.

The figure above shows that five out of six experiments result in a capacity higher than the capacity threshold indicated in the Building decree. Only the population with 5% disabled persons (three blindfolded participants and three participants in wheelchairs) 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 not only caused by the enthusiasm of the children to be the first to pass the door, but also by the physical fact that children are smaller than adults, which makes it possible for more children to pass a door at the same time. The populations representing an elderly 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 Figure 10).

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 took place 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 leaded to a very strong motivation, resulting in a much higher capacity than the one of a similar population.

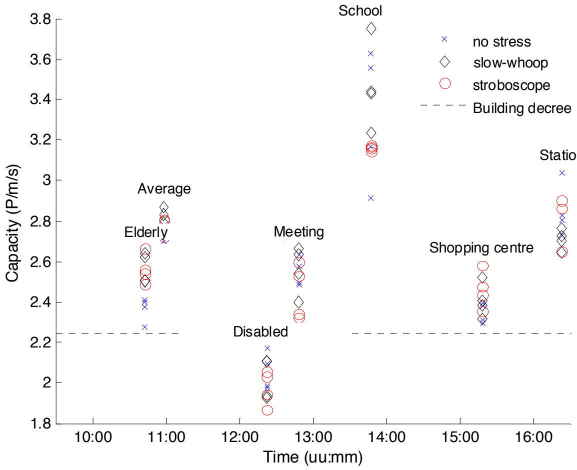


Figure 10: Capacity as function of the moment an experiment has been performed for various populations

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 door opening very fast, the others will follow very fast as well, whereas if the first person passes the door opening 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).

The last experimental variable discussed in this paper is the presence of an open door. Figure 11 shows the results for this experimental variable. From the figure it can be concluded that the capacity decreases up to 80% of the capacity threshold indicated in the Building decree when an open door is present in the door opening. This door does not physically narrow the door opening, but it reduces the outflow of the participants. At the location of the door some kind of narrow corridor exists, while on the other side participants are only hindered in their lateral movement at the moment of passing the wall. In the situation without a door participants fan out in all directions immediately after passing the door, which is not possible when a door is present. This is clearly visible in the trajectories for both situations (see Figure 12).

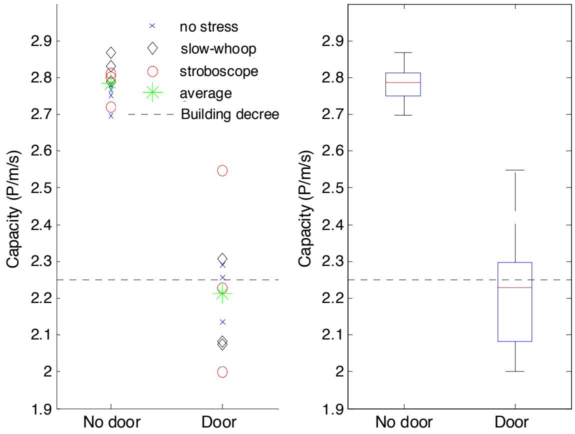
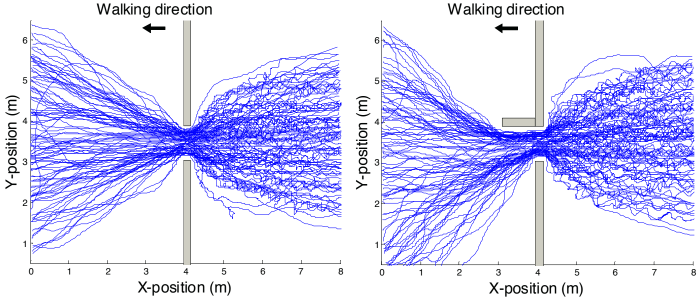


Figure 11: Capacity as a function of the presence of an open door for a door opening of 85 cm, an average population and a light intensity of 200 lux.

When an open door is present, not only less surface directly downstream of the door opening is used, but this surface is also used more intensely. The fact that the door opening is not fully used is not caused by pedestrians maintaining distance to the door, but because pedestrians cannot directly swerve to the right downwards of the wall. This is slightly compensated by pedestrians passing the opening at the left hand side swerving more to the left to give space to pedestrians passing the opening at the right hand side. The angle between the used surface on the left hand side of the wall and the wall is therefore smaller than in the situation that no door is present. Figure 12 also shows that a door not necessarily has to open 180 degrees, since the surface directly behind the wall is not used. A maximum opening angle of 150 degrees appears to be sufficient for a free outflow.

The intense use of the surface immediately downstream of the door results in many interactions between pedestrians, which leads to lower speeds and thus to a lower outflow (and thus capacity) at the door opening.



a. Trajectories without open door.

b. Trajectories with open door.

Figure 12: Trajectories for a door opening of 85 cm wide without (a) and with (b) open door.

5. Summary, conclusions and recommendations

This paper describes laboratory experiments to investigate the capacity of emergency doors in evacuation conditions. The aim is to identify the relation between the capacity and four experimental variables, namely the width of the door opening, population, light intensity and the presence of an open door in an angle of 90 degrees with respect to the wall. In addition the stress level of the participants has been influenced to imitate evacuation conditions by adding a slow-whoop signal and stroboscope light.

In all experiments, one of the experimental variables has been varied, while maintaining default values for the other variables. The reference experiment corresponds to a door opening of 85 cm wide, an average population, a light intensity of 200 lux and no open door.

Varying door opening widths showed that only the experiment with the widest door opening (275 cm) resulted in a capacity lower than the threshold capacity from the Building decree (2.25 P). The average observed capacities are for all widths lowest for the lowest stress level and highest for the highest stress level. Furthermore, the high capacity of a door opening of 220 cm (on average 3.09 P/m/s) is remarkable as well as the high variance in the repetitions of this experiment. This is most likely caused by the difference in behavior of the participants during the day. In the first experiments participants have a much stronger drive to pass the door than in the experiments later that day. This leads to much more pushing and higher speeds.

The population with a greater part of children has the highest capacity (on average 3.31 P/m/s). This is not only due to the large enthusiasm of the children, but also 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, as expected, found for the experiment with 5% disabled participants (3 blindfolded participants and 3 participants in a wheelchair). For all populations but the disabled population, a capacity has been measured higher than the threshold value in the Building decree. Finally, the difference in capacity for similar populations was remarkable. This depends on the moment of the day when the experiments have taken place.

The presence of a door opened in the escape direction in an angle of 90 degrees for a door opening of 85 cm results in a capacity reduction below the capacity threshold in the Building decree (2.21 P/m/s versus 2.25 P/m/s). The open door does not physically narrow the door opening, but it leads to interactions between participants reducing their speed and the corresponding outflow.

The main conclusion to be drawn is that the capacity of thirteen out of sixteen experiments is higher than the threshold value in the Building decree. The experiments with a lower capacity have a population with disabled persons, a very wide door opening (275 cm) or an open door. However, these capacities are only valid in undisturbed situations, similar to the one in the experiments. Obstructions, such as the presence of an open door, are shown to have a negative effect on the capacity.

Another conclusion is that more pushing behavior does not lead to the 'faster-is-slower' effect. In the experiments a higher urgency leads to higher speeds and to a higher capacity.

The results of the experiments are directly applicable in the assessment of the evacuation possibilities of buildings. Although the experiments have been performed in the Netherlands, the results are likely to be representative for most other European countries, due to the limited cultural differences. Furthermore, in countries with significantly different population demographics capacities are likely to be lower.

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.

For practical reasons the number of experiments has been limited. Additional experimental variables should be investigated in future research, such as very large door opening widths (double doors), open doors, effects of exterior walls instead of the thin wall from the current experiments, obstacles upstream and downstream of the opening, different conditions upstream and downstream of the opening and varieties of physical abilities in the population. These experiments should properly deal with the influence of the motivation of the participants on the capacity.

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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