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# Movement speed and exit choice in smoke-filled rail tunnels

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ABSTRACT

An evacuation experiment including 100 individuals was performed inside a tunnel in order to study the effectiveness of different way-finding installations and to collect data on movement speeds and human behaviour. The participants took part in the experiment individually, and no group interactions were studied. The experiment tunnel was 200 m long and an emergency exit was located 180 m into the tunnel. In addition, emergency signs including distances to nearest exits were located every eight meters on both sides of the tunnel. The tunnel was filled with artificial smoke and acetic acid, which produced a mean light extinction coefficient of 2.2 $m^{-1}$. Participants had been told that they would participate in an evacuation experiment, but they had not been informed about the layout of the tunnel or the technical installations. The average movement speed was found to be approximately 0.9 m/s, independent of tunnel floor material examined. The experiment also demonstrated the importance of the emergency exit design. A loudspeaker, which provided people with an alarm signal and a pre-recorded voice message, was found to perform particular well in terms of attracting people to the exit, independent of which side of the tunnel the participants were following.



## 1. Introduction

The severe consequences of fires in underground rail transportation systems, such as the Baku subway fire of 1995 [1,2] and the Kaprun funicular fire of 2000 [1,3,4], have led the scientific community to investigate people's behaviours in tunnel fires, and evaluate the best design solutions in order to reduce the time to reach a safe place. Tunnels represent an environment that is not familiar to most people, and often staff is not immediately on site to provide help. For these reasons, more and more studies are focusing on improving the means of egress and on learning more about the behaviour of tunnel users in evacuation situations [5–13].

A key aspect during evacuation in underground rail transportation systems is the impact of the smoke on human behaviour and performance; people may need to change their initial choice of exit and/or perform different types of behaviour, e.g., reduce their speed or crawl. The current literature on movement speeds includes two main experimental data sets based on experiments by Jin [14,15] and Frantzich and Nilsson [16,17], which provide two different correlations on the relation between visibility, i.e., extinction coefficient, and movement speed. The results illustrate that the movement speed decreases with increasing extinction coefficient. Jin's [14,15] study included investigations of both irritant and non irritant smoke, providing speeds between 0.3 and 1 m/s for irritant smoke and 0.5–1 m/s for non-irritant smoke. In case of irritant smoke, people were not able to keep their eyes open, which caused them to walk in zigzag paths or use the wall as an aid. The minimum observed movement speed of 0.3 m/s corresponds to the walking speed in complete darkness. Movement during conditions with a broader range of extinction coefficients was investigated in experiments by Frantzich and Nilsson [16,17], and the obtained movement speed range was approximately 0.2–0.8 m/s. In both experiments the wall was found to be of great importance to the participants, who used it as an aid during the evacuation.

In accordance with affiliative theory [18], people tend to evacuate towards places or people of familiarity. In the case of rail tunnels, this is reflected in the likelihood that people will try to evacuate via a familiar place, e.g., the tunnel entrance or exit, even if they are in the middle of the tunnel. A questionnaire study by Gandit et. al [19] highlights that although many users know about emergency exits, many of the same people will not use them, i.e., emergency exits may be considered even more deterring than the tunnel itself [20]. Accident reports [21,22] also confirm this statement. Ineffective use of emergency exits may cause prolonged evacuation times, and could lead to tragic consequences due to the rapid development of untenable conditions in these types of facilities [19].

Different solutions can be applied in order to improve people's ability to orient themselves in smoke-filled environments [23,24]. Signage can for example be used to impact exit choice [5,25,26]. The influence of signage on exit choice is dependent on different

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factors [5], which include whether the sign is visible or not, given the visibility conditions and the sign design, and the cognitive processes that affect the evacuees to notice, understand and use the information provided by the signage [27].

Way-finding systems are an alternative measure to make evacuation from underground rail transportation systems easier, and many experiments have been performed to test the performance of different systems [5,12,28–31]. For example, Nilsson [5] performed evacuation experiments on the use of green flashing lights, demonstrating the effectiveness of green to attract attention to the sign which informs people about the exit. Furthermore, Boer and Veldhuijzen van Zanten [32], Nilsson [5], and Proulx and Sime [12] describe how the passivity of tunnel users can be overcome through the use of vocal messages by the tunnel operator. In particular, their studies focused on the type of instructions that should be given to evacuees. They concluded that people reacting to a clear announcement spent less time hesitating than those reacting before the announcement was made. Also, if an informative message were given rapidly, the evacuation process was faster.

The discussion above demonstrates that a fire in an underground rail transportation system can result in devastating consequences in terms of loss of life. But the experimental studies discussed above also show that there are means of reducing the total evacuation time in underground rail transportation systems. However, evacuation data are generally affected by behavioural uncertainty [33], and a single experiment may not be representative of a full range of the behaviours of the occupants. Further experimental data appear necessary in order to increase the knowledge on evacuation behaviours and responses in underground rail transportation systems. In addition, there is a need to explore variables that were only partially investigated in previous studies, e.g., the influence of different floor surfaces on occupants' movement speed, the impact of different inclinations on movement speeds and different emergency exit designs.

In order to address the above-mentioned issues an evacuation experiment was performed in a smoke-filled tunnel. The choice of research strategy was dictated by the main objectives of the experiment, which were:

1. To study the effectiveness of different way-finding systems in a smoke-filled tunnel
2. To collect data on human performance and movement speeds in a smoke-filled tunnel, focusing on the different variables affecting the movement, e.g., floor inclination and surface materials

In the present paper, the main focus is evacuation in underground rail transportation systems. However, much of what is presented can also be applied to other underground transportation systems, e.g., road tunnels.

## 2. Method

On May 30–31 and June 1 2011 an evacuation experiment was performed in Stockholm, Sweden. The experiment was performed in a single bore tunnel that previously had been used in the construction of a road tunnel in Stockholm, namely the Southern link (Södra länken). The tunnel was provided with technical installations typical for rail tunnels. However, there were no rail tracks inside the tunnel. In the following sections the participants, the layout of the experiment, the procedure, the scenarios, the data collection and the analysis of the experiment are described.

### 2.1. Participants

A total of one hundred participants were recruited among the general public and among employees at the Traffic Administration Office in Stockholm. The means of recruitment and participants' characteristics are presented in the following sections.

#### 2.1.1. Recruitment

Two months before the experiment, information about the study was published on an online portal, used by researchers who want to get in contact with potential test participants for their studies. Anyone that was interested in participated in the experiment could apply online. The information included a description of the experiment, i.e., the participants were going to walk through a real tunnel, environmentally similar to the Stockholm Metro tunnels, in dense artificial smoke, that acetic acid would be used to create an irritating environment, that the participants would undergo a questionnaire study related to the experiment, and that some of the participants would be interviewed. The information also included formal details on the location and the dates of the experiment, compensation for participation and the duration of the experiment. No information was given on the tunnel features, e.g., the tunnel layout, emergency exits or other technical installations.

Participants were recruited from the general public and among employees at the Traffic Administration Office in Stockholm. Both groups received the exact same information about the experiment, but the employees at the Traffic Administration Office in Stockholm applied by sending an email to the researcher in charge of the experiment instead of applying online. In order to exclude sensitive individuals, each person that had applied for the experiment had to undergo a so-called Hospital Anxiety and Depression (HAD) test [34]. This was done 2–3 weeks before the experiment and only persons that received a score of less than eight for both anxiety and depression were included in the experiment. In addition, persons who were younger than 18 years, had asthmatic health problems or were active within the field of fire safety, e.g., as fire protection engineers or fire fighters, were not allowed to take part in the experiment. The persons that were selected for the experiment received additional information after having passed the HAD test, which was distributed at latest a week before their participation. The information included details on the procedure, risks, benefits, treatment of data, publication of results, casualty insurance and the researcher in charge of the experiment.

#### 2.1.2. Participant characteristics

A total of one hundred persons participated in the experiment, namely 56 men and 44 women. The age ranged from 18 to 66 years, with an average age of 29.4 years. The height of the

**Table 1**
A summary of the participants' age and height.

| | Mean | Min | Max | Std. |
|---|---|---|---|---|
| Age (years) | 29.4 | 18 | 66 | 10.3 |
| Height (cm) | 175.1 | 153 | 198 | 9.4 |

**Table 2**
A summary of the participants' travelling frequency.

| Travel frequency | Participants (no.) |
|---|---|
| Several times per week | 78 |
| About one time per week | 11 |
| About one time per month | 10 |
| Less than one time per month | 1 |
| | 100 |

participants varied from 153 to 198 cm, with an average of 175 cm. See Table 1 for a detailed summary. No information on the participants' weight was collected. Eighty-three of the participants reported that they were right-handed and consequently 17 of the test participants were left-handed.

The majority of the participants, namely 89 persons, said that they used the Metro once, or more than once, every week, see Table 2. Thus, it was concluded that the majority of the participants had knowledge and experience of travelling with the Metro. Thirteen of the participants reported that they had received information on what to do in a fire in the Stockholm Metro on at least one occasion. Most of them had read the emergency information posters in the trains or at the Metro stations, some reported having seen the emergency evacuation signs above the train doors in the trains and one person even reported having seen “emergency stuff” inside the tunnel at one occasion when the train he was travelling in had been moving slowly.

A rather high proportion of the participants, namely 22 persons, stated that they had walked on the tracks inside a Metro or a rail tunnel on at least one occasion. The most common reason was work or education related, some mentioned it had been to obtain dropped belongings, e.g., a cell phone, and some said they had been “young and stupid” when they had done so. Considering the answers it seemed as only a few had been walking longer distances on the tracks, and also that the time elapsed since they had done so was long. Two persons reported that they had participated in a real evacuation in the Stockholm Metro before the evacuation experiment. Both persons had evacuated from a station platform due to fire, thus not from a train inside a tunnel similar to the evacuation experiment, but neither of the persons had actually seen the fire or the smoke.

### 2.2. Experiment setup

The experiment was carried out in a single bore tunnel in Stockholm. The tunnel was equipped with emergency signs and an emergency exit, and during the experiments the tunnel was filled with artificial smoke and acetic acid fumes. In the following sections the tunnel layout, the technical installations and the smoke properties in terms of visibility and concentration levels are presented.

#### 2.2.1. Tunnel layout

The evacuation experiment was carried out in a single bore tunnel in Stockholm previously used in the construction of a road tunnel in Stockholm, namely the Southern link (Södra länken). Due to the fact that the end of the tunnel was closed when the Southern link was taken into operation, the only way in and out of the experiment tunnel was the tunnel entrance, see Fig. 1. The experiment tunnel was at the time of the experiment not used for traffic, but occasionally the Greater Stockholm Fire Brigade used the tunnel for fire-fighting exercises. The total length of the tunnel was approximately 300 m, but during the experiments only the first part of 200 m was used.

The tunnel included two segments: one part (a) of 122 m with an inclination of 10%, and one part (b) of 76 m with no inclination, see Fig. 1. Generally, the floor surface was smooth and consisted of compact gravel. However, in order to enable an analysis of movement speeds on different materials, one part (c) measuring approximately 32 m long and 1.5 m wide, was covered with macadam of size 32–64 mm about 150 m into the tunnel, commonly used in rail tunnels. The tunnel width was about 8 m.

#### 2.2.2. Technical installations

After the Southern link had been built, the working tunnel used in the experiment was stripped of all technical installations. Thus, no signs or other electrical components were in place prior to the experiment. The installations described below were consequently the only installations active during the experiment.

Emergency signs were installed every eight meters on both sides of the tunnel at a height of about one meter, see Fig. 2. The signs were models of the emergency signage used in the Stockholm Metro and provided information on distances to the nearest exits as well as a source of light. During normal conditions, i.e., without the presence of smoke and other light sources, the light intensity from the emergency signs corresponded to 1 lx, measured at ground level at equal distance between two signs [35]. Apart from the emergency signs, no other illumination was provided inside the tunnel during the experiment.

One hundred eighty meters into the tunnel, an emergency exit was installed on the left side of the direction of travel, marked EXIT in Fig. 1. The emergency exit design is shown in Figs. 3 and 4.


**Fig. 2.** A picture of the emergency sign installed every eight meters inside the tunnel.

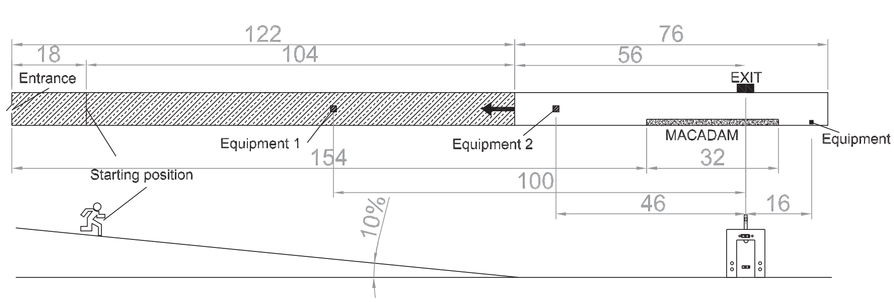


**Fig. 1.** A schematic top (above) and side view (below) of the tunnel geometry. Measurements in metres.

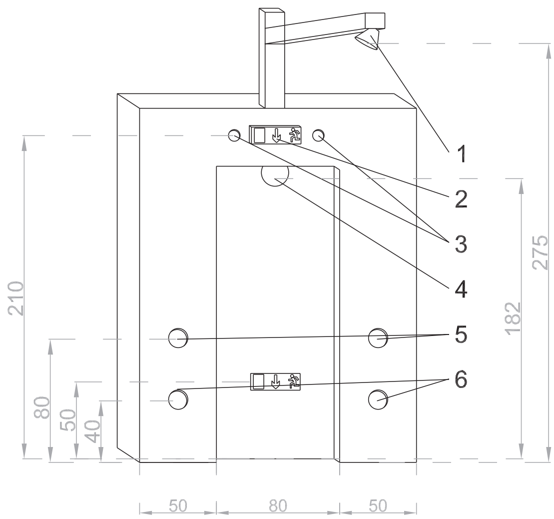


**Fig. 3.** A schematic drawing of the emergency exit inside the tunnel (measurements in centimetres).

**Fig. 4.** A picture of the emergency exit inside the tunnel.

The door represented the only exit inside the tunnel and was equipped with a number of way-finding installations, which were combined in order to study their effectiveness in terms of attracting people to the door. The six types of installations are numbered in Fig. 3 and are described in Table 3.

The selection of the way-finding installations was made in order to evaluate a set of systems (e.g., flashing or continuous lights, loudspeakers, etc.), which may be representative of typical alternative safety design solutions. The use of the performance based design approach allows exemptions from some of the prescriptive legal requirements if safety is not impaired. Hence, new systems can replace other safety features, which may result in an equivalent level of safety. In this context, way-finding installations were selected in order to evaluate their effectiveness in providing stimuli to the use of emergency exits.

#### 2.2.3. Artificial smoke and acetic acid

In order to create an environment that was as realistic as possible, but without putting the participants' health into danger, the tunnel was filled with both artificial cold smoke and acetic acid during the experiment. The cold smoke was similar to what is used during, for example, entertainment shows, and at nightclubs, and has no adverse physical effects on human beings. As an irritant, acetic acid was therefore introduced into the smoke. At the used concentration levels the acid may cause a burning sensation in the nose and throat, eye-irritation, and/or coughing, in a short-time perspective for those residing in the environment. These adverse physical effects are, however, acute and not long-term.

Two smoke machines, which were located at the end of the tunnel (equipment 3 in Fig. 1), produced the smoke using a mixture of polyglycole and distilled water. In addition, acetic acid was boiled in pots located in the beginning and the end of the tunnel. The smoke and the acetic acid were evenly distributed inside the tunnel during the experiment by a fan, which was turned off when there was a participant inside the tunnel.

Measurements of the light extinction coefficient were made with a device that consisted of a light source and a receiver, which were fixed 1 m apart in a steel frame. The light source was a laser diode and emitted light with the mean wavelength of 670 nm, and the receiver was a photodiode with a peak sensitivity wavelength of 710 nm. The measurements were made at two locations inside the tunnel, namely equipment 1 and 2 in Fig. 1, at a height of about 1.5 m. In the present study the light extinction coefficient was calculated according to Eq. (1), where $I$ was the intensity of the light as it had passed through path length $L$ of smoke and $I_0$ was the intensity without any smoke present. Measurements of the acetic acid was made manually with an accuro Gas Detection Pump, manufactured by Dräger [37]. As for the smoke density measurements the gas measurements were made at different locations inside the tunnel.

$$D_L = -(1/L) \times \ln(I/I_0) \quad (1)$$

The mean light extinction coefficient during the experiments was 2.2 m$^{-1}$, with a standard deviation of 0.54 m$^{-1}$. This can be translated into a mean visibility of about 1.4 m for reflecting signs, and 3.4 m for light-emitting signs [38]. The values are in line with the range of visibilities that can be encountered in an actual tunnel fire [39], and furthermore with the acceptance criteria of current regulations [40–42]. As an example, the Swedish tunnel regulations state that evacuees can be exposed to a visibility of less than 3 m for approximately 15 min [42], with the principle of self-evacuation still being met. The level of irritation during an actual fire is deemed to be higher than the experimental conditions under consideration. This is a limitation of the study that has been driven by ethical reasons, i.e., the mean gas concentration of acetic acid was 4 ppm during the experiments. This concentration is well below the Swedish Work Environment Authority's recommended level of short time exposure, i.e., 10 ppm for 15 min [43].

### 2.3. Procedure

On the days of the experiment the participants arrived in groups of about ten people. The actual evacuation inside the tunnel was, however, performed individually and the evacuation scenario was determined by the activated way-finding installations on the emergency exit, described above, and the initial starting position inside the tunnel. In the following sections the sequence of events at the days of the experiment, the scenarios, the data collection, and the analysis are presented.

#### 2.3.1. Sequence of events

The experiment was carried out on May 30–31 and June 1 2011. It was divided into 3-h periods, and at the beginning of each period a group of about ten people arrived at the site of the experiment. At their arrival the participants were led into a parked

**Table 3**
A description of the different way-finding installations on the emergency exit.

| Installation | Description |
|---|---|
| 1. Halogen lamp | A white halogen lamp of 500 W installed above and directed towards the door. Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 556 lux, measured 22 cm from the lamp. |
| 2. Emergency exit sign | Standard backlit European emergency exit sign. |
| 3. Green flashing lights | Green flashing lights, which consisted of two green light bulbs, installed on each side of the emergency exit sign above the door. The lights flashed with a frequency of approximately 1 Hz, i.e., one flash per second. |
| 4. Loudspeaker | Loudspeaker installed on the upper centre part of the door enabling analarm signal and a pre-recorded voice message to be broadcasted. The alarm signal consisted of an increasing signal, which was repeated three times within 1.5 s [36]. The frequency range was 800–970 Hz. The alarm signal was repeated twice before the pre-recorded voice message; a computer generated female voice that said (translated from Swedish): *The sound is coming from an exit. Follow the sound in order to get out.* The alarm signal and voice message could be heard approximately 25 meters from the door. |
| 5. Green lights | Green light bulbs installed on each side of the door on the lower part of the frame. Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 11 lux, measured 20 cm from the bulb. |
| 6. White lights | White light bulbs installed on each side of the door on the lower part of the frame. Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 63 lux, measured 20 cm from the bulb. |

**Table 4**
The experiment scenarios and number of participants for each scenario.

| Scenario | Way-finding installations | Initial location | Number of participants |
|---|---|---|---|
| 1 | 2 | A | 12 |
| | | B | 12 |
| 2 | 2, 3 | A | 10 |
| | | B | 10 |
| 3 | 1, 2, 5, 6 | A | 10 |
| | | B | 16 |
| 4 | 2, 4 | A | 10 |
| | | B | 14 |
| 5 | 1, 2, 3, 5, 6 | A | 1 |
| | | B | 5 |

bus in close vicinity to the tunnel entrance, which served as a gathering point during the whole experiment. The responsible researcher began by welcoming the participants and briefed them about the experiment and the safety procedures. The same information had been mailed to the participants a couple of weeks before the experiment and was merely a repetition.

The experiment was carried out with one participant at a time, and no group interactions were studied. Having received the instructions inside the bus the participants were selected one by one for the experiment, which began with the participant being led out of the bus and provided with protective clothes, more specifically, an overall, boots, gloves and a helmet. The participant was then led to the tunnel entrance where he or she was shown a short video film from the Stockholm Metro. The film, which was shown in a first person perspective, illustrated a person travelling in a train that eventually came to a stop inside a tunnel. When the film ended the participant was led into the tunnel and told to imagine that it was he or she in the video, and that he or she should find a way to safety.

A fire fighter was always present inside the tunnel to film the evacuation or to assist the participant if he or she signalled for help. The participant had been informed about the presence of the fire fighter during the introduction; however, due to the dense smoke inside the tunnel, the participant could not see the fire fighter during the evacuation. When the participant entered the tunnel the fire fighter led him or her to the first emergency sign of the tunnel. The participant was left approximately 2–3 m in front of the sign, and then told to initiate evacuation. Whether the

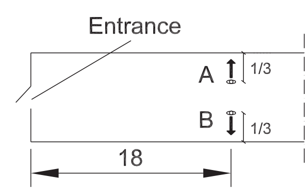


**Fig. 5.** Initial location of the participants inside the tunnel. Measurements in metres.

participant was left on the right or left side of the tunnel was dependent on the scenario, see Table 4. On the first sign the distances 160 and 268 m to the closest exit was printed, see Fig. 5. Note that the distance of 268 m, which pointed towards the tunnel entrance, was hypothetical, and only a way of encouraging participants to move into the tunnel.

The experiment ended when the participant either had found the emergency exit located inside the tunnel, or when the participant had walked past the emergency exit and reached the end of the tunnel. When the experiment had ended, the participant was led out of the tunnel by a fire fighter and returned to the bus where he or she answered a questionnaire about the experiment. Some participants also took part in an interview about the experiment after the questionnaire study. Note that each participant only participated in the experiment once, i.e., each participant only took part in one evacuation. The reason was to avoid learning effects in terms of familiarity with the environment, location of exits and walking in smoke.

### *2.3.2. Scenarios*

The way-finding installations on the emergency exit were combined to give five experiment scenarios. In addition, the initial position of the participants inside the tunnel was varied for each scenario, i.e., the participants either started the evacuation on the same side of the tunnel as the emergency exit (A) or on the opposite side (B), see Fig. 5. The main purpose of the variation of the initial position was to study the differences in terms of exit usage for participants walking on the different sides of the tunnel.

A summary of the number of participants in each scenario is presented in Table 4, and the number describing the way-finding installations in each scenario is referring to Fig. 3 and Table 3. Due to an unexpected dropout of participants on the final day of the experiment, the number of participants in scenario 5 was much lower than in the other scenarios.

#### 2.3.3. Data collection

In order to enable an analysis of movement speeds, walking strategies, exit choice and other human behaviour activities, each evacuation was documented with a thermal imaging camera, namely an MSA Evolution 5600. The videos were recorded onto a memory card and transferred to a computer after each evacuation. A fire fighter managed the documentation by following the participants at a distance of 5–10 m throughout the evacuation, enough not to be seen in the dark and smoke filled tunnel.

As a complement to the video recordings each participant had to fill out a questionnaire after the experiment. The questionnaire consisted of 26 questions, some of which were divided into sub questions, and included both closed ended questions, i.e., yes/no, multiple choice or scaled questions, and open ended questions, i.e., the participants were asked to write freely. The questionnaire was divided into four parts and the first part included questions related to general information about the participant, e.g., gender, age and previous experience. The second part included questions related to the experiment and the participant's behaviour during the experiment, e.g., the degree of realism and the method used for orientation. The third part of the questionnaire included questions about technical installations and the perceived benefit of different installations. Finally, the fourth part of the questionnaire included questions related to the participant's feelings during the experiment, e.g., physical and psychological feelings. Care was taken during the formulation of the questions to make sure that the topic had been clearly defined, that the questions were relevant for the purpose of the study, that the questions were not biased and that the risk of misinterpretation was minimal. For this purpose, the framework suggested by Foddy [44] was adopted.

To further strengthen the reliability of the study, some participants were also asked to take part in an interview study. The interviews were semi-structured, meaning that the questions could be changed or adapted to the participant. Furthermore, the order of the questions was not fixed. In the interviews the participants were shown the video recording of their evacuation and asked to explain their behaviour and thoughts during different sequences of the evacuation. The interviews were recorded and were always performed after the participant had handed in the questionnaire.

#### 2.3.4. Analysis

The video recordings were analysed with the aim to reconstruct the evacuation paths of each participant, and finally to calculate the movement speed and document the exit choice of each participant. This was made by taking into consideration different factors contributing to the estimation of each participant's position during the passage of time, including (1) the position of the fire fighter filming each evacuation, i.e., the recording angle, and (2) the position of the participants in relation to the emergency signs, which could be seen on the thermal imaging camera due to the heat being generated by the lamps. In addition, if a participant changed his or her direction of travel, the position inside the tunnel was estimated by counting the number of steps made. The distance between a participant and the tunnel wall was used as additional information to estimate the participant's position inside the tunnel.

The above listed factors were used to draw the walking path of each participant in a CAD format. The CAD drawings were then used to reconstruct the movement pattern of each participant, i.e., the position of the participant inside the tunnel during the evacuation. Furthermore, the drawings included information of every change of walking direction, behaviour, type of floor material and tunnel inclination. This information was coupled with the participant's behaviour, i.e., the CAD drawings also included information on when and where inside the tunnel the participant performed a certain action. Hence, the final drawing enabled a derivation of information about each participant's movement speed and position inside the tunnel as a function of time.

The video recordings were also used to document the behaviour of each participant, e.g., walking and way-finding behaviour, use of visual and tactile information, and positioning of the hands. The type of walking posture was derived by analysing the position of the body in comparison with the emergency signs. As the height of the emergency signs was known to be approximately one meter, it was possible to estimate the position of the different parts of each participant's body in comparison with the reference of one meter from the ground.

The questionnaire answers were reproduced in a large matrix, and information relevant to the paper was statistically processed. Interviews were transcribed and read in order to find general trends.

## 3. Results

Data on experiences of the evacuation, movement speeds, movement patterns, and exit choice are presented in the following sections. The data is based on a combination of video observations, questionnaire answers and interview answers. Included quotes have been translated from Swedish. Due to an error, which occurred during one of the evacuations, only 99 of the 100 participants were included in the analysis of the video recordings. Furthermore, a technical problem that occurred in another evacuation permitted only half of the video recording to be analysed. All of the 100 participants took part in the questionnaire study, and 65 took part in the interview study.

### 3.1. Experiment experiences

In the questionnaire study the participants were asked about their experiences during the experiment. The majority of the questions were scaled, and the participants were for example instructed to express the perceived degree of realism in the experiment on a scale between 1 and 10. It is not believed that the participants answered the questions believing that “2” was twice as much as “1”, and it is therefore argued that the scale of the questions is ordinal. Hence, the results presented in this section are presented in box-plots rather than with mean values plus/minus a standard deviation.

The boxplots included in the presentation below should be interpreted in the following way:

- The tops and bottoms of each box are the 25th and the 75th percentiles of the samples.
- The line inside each box is the sample median, i.e., the 50th percentile of each sample.
- The lines extending above and below each box are the whiskers, and represent the sample minimum and maximum, excluding the extreme values, i.e., the outliers.
- The distances between the tops and the bottoms of each box are the interquartile ranges.
- The “+” are the outliers, i.e., sample values more than 1.5 times the interquartile range away from the top or bottom of each box. In order to make duplicate “+” available, the points have been uniformly randomized along the factor axis for each group.

The participants were asked to describe the degree of realism of the experiment by comparing the experiment to a real fire in a similar environment, see the left boxplot in Fig. 6. Alternative “1” corresponded to “not realistic” and alternative “10” corresponded

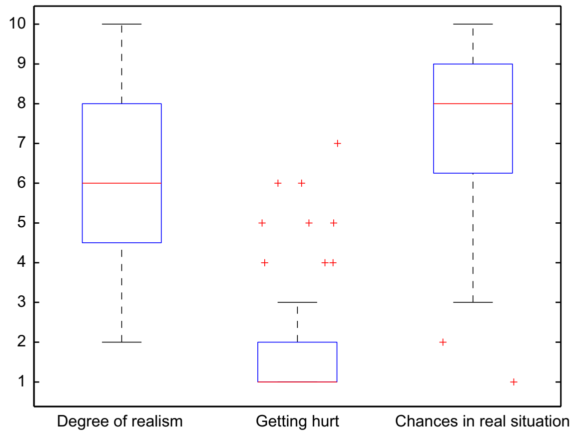


**Fig. 6.** Answers to scaled questions in the questionnaire study.

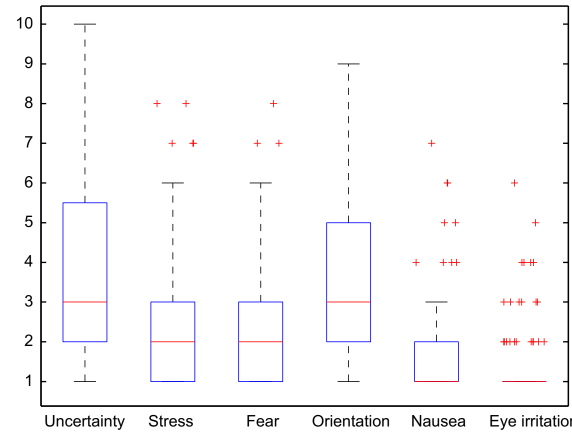


**Fig. 7.** Answers to scaled questions in the questionnaire study.

to "very realistic". Seventy-five percent of the participants graded the experiment "5" or higher, which strengthens the validity of the results. Some of the participants who were interviewed gave recommendations for future studies in order to raise the degree of realism. The recommendations included adding dummies to simulate unconscious evacuees, and increase the concentration of acetic acid in the air to make the environment more irritating. One limitation of the evaluation of the degree of realism made by the participants is related to the fact that they did not previously experience a real fire. Thus, their responses should be considered as an overall qualitative degree of perceived realism rather than a quantitative assessment of the realism of the experiment.

The greater majority of the participants were not worried that they would get hurt in the experiment, which is illustrated by the answers to the question "Were you worried that you would get hurt during the experiment?" in the questionnaire study. Alternative "1" corresponded to "No, not at all" and alternative "10" corresponded to "Yes, very much", and 91% of the participants answered "3" or lower, see Fig. 6. However, some of the interviewed participants mentioned being afraid of stumbling or falling inside the tunnel, some of whom also related this to getting hurt.

Most participants believed that they would have been able to evacuate the tunnel successfully if it had been a real fire when they answered the question "Had this been a real fire, what would the chance be of you evacuating the tunnel successfully?". Alternative "1" corresponded to "very small" and alternative "10" corresponded to "very high", and 80% answered "6" or higher, see Fig. 6. Note that one participant failed to answer the question and was therefore not included in the analysis.

The participants in the questionnaire study were also asked to estimate the perceived level of (1) uncertainty, (2) stress, (3) fear, (4) orientation problems, (5) physical discomfort in terms of nausea and (6) physical discomfort in terms of eye irritation during the experiment. Alternative "1" corresponded to "None" and alternative "10" corresponded to "High", and the result is presented in Fig. 7. Considering the boxplots, the overall impression is that most participants felt neither uncertain, stressed, were afraid, had orientation problems or experienced a high level physical discomfort. Statements made by the participants in the interview study furthermore reinforce this interpretation.

Some interview answers suggest that the perception of these types of feelings decreased with the increased time spent inside the tunnel. As an example, some participants, initially walking very close to the wall, later into the evacuation let go of the wall because they got acquainted to the environment. Consequently, the estimations presented in Fig. 7 may be estimations of the participants' feelings in the later part of the evacuation, and not

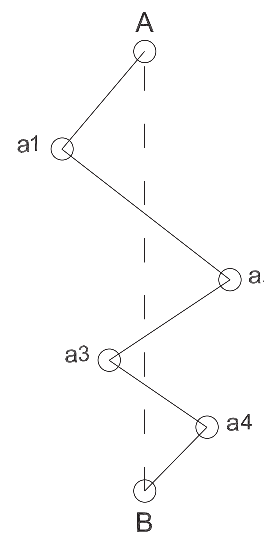


**Fig. 8.** Difference between total distance walked by a participant (A–a1–a2–a3–a4–B), and the distance between two points inside the tunnel (A–B).

averaged estimations of their whole evacuations, which to some extent could explain the, in general, low ratings.

### *3.2. Movement speeds*

The video recordings of the evacuations were used to determine the movement speeds inside the smoke filled tunnel. A distinction has been made between movement speed and modelling speed. This choice was driven by the current methods adopted by evacuation models to represent people movement. Current models do not include the possibility to explicitly simulate complex walking behaviours, e.g., "stop and go", zig zag behaviours, etc., unless the user is not implementing a deterministic set of actions of the occupants, i.e., models generally simulate people movement in non-stop straight lines. In this context, two different speeds have been provided in order to present information on both the actual speeds of the individuals as well as values of use for modelling purposes.

The movement speed was calculated for each participant by dividing the total distance walked in the tunnel by the time employed, i.e., the stops made by the participants were excluded in the analysis of the movement speed. The total distance walked is explained in Fig. 8 as A–a1–a2–a3–a4–B, in which the points illustrate a change of travel direction. In contrast, the modelling speed was calculated for each participant by dividing the distance

**Table 5**
Movement speeds in different parts of the tunnel.

| | Sample of participants (no.) | Movement speed (m/s) | | | |
|---|---|---|---|---|---|
| | | Min | Max | Mean | Std. |
| Part A | 99 | 0.42 | 1.42 | 0.91 | 0.23 |
| Part B | 98 | 0.51 | 1.45 | 0.91 | 0.22 |
| Part C | 52 | 0.50 | 1.82 | 0.94 | 0.29 |

**Table 6**
Modelling speeds in different parts of the tunnel.

| | Sample of participants (no.) | Modelling speed (m/s) | | | |
|---|---|---|---|---|---|
| | | Min | Max | Mean | Std. |
| Part A | 99 | 0.41 | 1.42 | 0.90 | 0.24 |
| Part B | 98 | 0.50 | 1.45 | 0.91 | 0.22 |
| Part C | 51 | 0.45 | 1.82 | 0.92 | 0.29 |

between two points inside the tunnel, i.e., A–B in Fig. 8, by the total time, including the duration of the stops made during the evacuation.

The movement and modelling speeds are presented in Tables 5 and 6. The speeds are presented for the respectively parts of the tunnel, which is illustrated in Fig. 1. All participants walked in the first part (a) of the tunnel, represented by a smooth floor material and an inclination of 10%. Also, all participants walked in the second part (b) of the tunnel, which consisted of a smooth floor material and no inclination. However, whether or not a participant walked on the third part (c) of the tunnel, which consisted of macadam and no inclination, depended on the initial position inside the tunnel at the beginning of the evacuation, and the participant's walking route.

The results presented in Tables 5 and 6 imply that neither an inclination of 10% or an uneven floor material consisting of macadam appear to have an impact on the movement speed. In fact, the movement speed was actually a bit higher on the macadam. Due to the small differences in the different parts of the tunnel it is hard to draw any far-reaching conclusions as to why. However, one possible explanation could be that learning effects may have been present, i.e., the participants got more used to the environment the longer they stayed inside the tunnel. Another explanation could be that neither floor material nor inclination will determine the movement speed in a dark and smoke filled tunnel, i.e., the impact becomes so trivial that the effect on the movement speed is insignificant in a dark and smoke-filled tunnel. The results also illustrate the small differences between movement and modelling speeds. This can be explained by the fact that only 25% participants actually stopped at some time during their evacuation, and that the average time stopped by a participant was short; 14 s (std. 14 s).

### 3.3. Movement patterns

The video recordings also enabled an analysis of the participants' movement patterns inside the tunnel. Previous studies have demonstrated the importance of walls during evacuation in smoke filled tunnels, in terms of facilitation of way-finding and orientation [17,38]. The same type of observations was made in the present study. Ninety-one percent of the participants followed one of the tunnel walls at least 75% of the total distance walked during the evacuation. One possible explanation of this behaviour could be to facilitate orientation inside the dark and smoke filled tunnel. This was mentioned by many of the interviewed participants, for example Participant 61, who in the interview said:

> *Yes, the visibility was minimal. You could at best see one to one and a half light forward [8–12 m, authors comment]. And… My strategy was to stick to a wall, in order to be able to orient myself.*
>
> *Participant 61, 1 min 12 s into the interview.*

Another possible explanation for the participants' tendency to follow the tunnel walls is the emergency signs, see Fig. 2, which were installed every 8 m. Ninety-six percent of the participants reported in the questionnaire study that they had seen the signs sometime during their evacuation, 82% said that they had seen the signs already in the beginning of the evacuation. Not only did the signs help the participants to orient themselves in the tunnel by showing the distances to the closest exits, but participants in the interview study also expressed that it was comforting to see the signs inside the tunnel. This is illustrated by a statement made by Participant 81 in one of the interviews:

> *[…] And I felt relieved to have something like that [the signs, authors comment]. Not to think about my situation, but to think "Alright, I should follow these signs, I should check how many metres they have counted down, and when I have passed it I should start looking for the next one".*
>
> *Participant 81, 1 min 43 s into the interview.*

The emergency signs seem to have been very important to a large proportion of the participants. Especially the lamps installed on each sign, which provided the participants with orientation points inside the otherwise dark and smoke filled tunnel, were appreciated. Many of the participants adopted a technique where they moved close to one of the walls, looked for and walked towards a lamp, and then started to look for the next. The importance of the emergency signs and the lamps was shared by many of the interviewed participants, and can be summarized with this statement made by Participant 3:

> *I trusted… I just focused on the lamps with my eyes, did not look for anything else at all. The lamp, and the signs with the lamps, was the only thing that I was looking for.*
>
> *Participant 3, 2 min 19 s into the interview.*

In addition to the analysis of the participants' walking paths, an analysis was also made of the most frequent walking behaviours inside the tunnel. A classification was made with regard to the walking posture and the participants' position of the hands during the evacuation. Note that many of the participants changed walking posture and the position of their hands during the evacuation. The term most frequent walking behaviour therefore refers to the behaviour that a participant adopted the longest distance walked inside the tunnel.

The analysis revealed that the most frequent walking posture was upright; 79% of the participants adopted this behaviour. In other words, of all the filmed participants, 79% walked the longest distance in an upright posture during their evacuation. The second most frequent walking posture was a crouched posture, which was adopted by 20%. Examples of the upright and the crouched posture are shown in Figs. 9 and 10. One participant, i.e., 1% of all the participants, walked very carefully and off balance during the whole evacuation and a preferred walking posture could not be determined. Some of the participants that adopted a crouched posture during their evacuation were asked about this behaviour in the interview. However, it seemed as there was no consensus among the participants as to why they walked with a crouched posture. Among the mentioned reasons were that the participants wanted to keep the same level as the emergency lamps, that there

**Fig. 9.** A participant walking with an upright posture, with hands in a normal position alongside the body.

**Fig. 10.** A participant walking with a crouched posture.

**Fig. 11.** A participant walking with the hands in front of the body.

was an uncertainty about the tunnel height, that it was done to check if the smoke was less dense closer to the ground, and that it was done to improve the walking balance.

The video recordings also showed that many participants frequently used their hands during the evacuations. In fact, 52% of the participants walked with their hands in front of the body at some time during their evacuation, and 43% put one or two hands on the wall at some time. In terms of the most frequent position of the participants' hands, i.e., the longest distance walked by each participant with his or her hands in a certain position, most participants preferred to position their hands normally alongside their body, namely 38%. Thirty-one percent of the participants preferred to have their hands in front of their body, and 30% kept at least one hand on the tunnel wall during the major part of the walked distance. The normal position with hands alongside the body is illustrated in Fig. 9, with hands in front of the body in Fig. 11, and with at least one hand on the wall in Fig. 12.

The interview study gave some explanations as to why the participants choose to walk with their hands either in front of their body or on the wall. The most common used explanation was related to orientation, i.e., a large proportion of the interviewed participants answered that they used their hands to orient themselves inside the tunnel. Some of the interviewed participants also expressed that they kept their hands in front of themselves or on the tunnel wall in order to protect themselves. The uncertainty related to the tunnel wall design, and the need to reduce the risk of getting hit by an obstacle is for example illustrated in the following statement by Participant 57:

> *I held out my right hand so that I wouldn't walk into the wall, but I did not want to walk too close, because… I thought that there maybe was something… Something projecting, sort of.*
>
> *Participant 57, 1 min 19 s into the interview.*

Other reasons that were mentioned for walking with the hands in front of the body or on the wall was related to balance and safety. Some participants said that they kept one or two hands on the wall in order to support their walking balance. Others said that it was simply something that increased the perceived level of safety inside the tunnel.

**Fig. 12.** A participant walking with both hands on the tunnel wall.

**Table 7**
The participants' exit choice in the different scenarios.

| Scenario | End location | Number of participants | Number of participants that choose emergency exit |
|---|---|---|---|
| 1 | A | 12 | 12 (100%) |
| | B | 12 | 8 (67%) |
| 2 | A | 11 | 11 (100%) |
| | B | 9 | 7 (78%) |
| 3 | A | 8 | 5 (63%) |
| | B | 18 | 12 (67%) |
| 4 | A | 10 | 10 (100%) |
| | B | 14 | 14 (100%) |
| 5 | A | 1 | 1 (100%) |
| | B | 4 | 4 (100%) |

### *3.4. Exit choice*

The video recordings of the evacuations were, in addition to the analysis of movement and modelling speeds and movement patterns, also used to document the exit choice of each participant, i.e., if a participant chose the emergency exit or not. The results are presented in Table 7. During their evacuations, a total of six participants had moved across the tunnel section shortly before they reached the emergency exit. Consequently, the position in the initial and end location, i.e., the tunnel side preference, in the tunnel differed for some participants. Due to the fact that it, in general, can be hypothesized that people walking on the same side of the tunnel as the emergency exit will find and use it to a higher extent than people walking on the opposite side of the tunnel, the

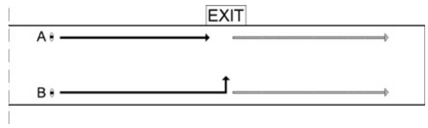


**Fig. 13.** The position of a participant inside the tunnel shortly before the emergency exit, i.e., the end location.

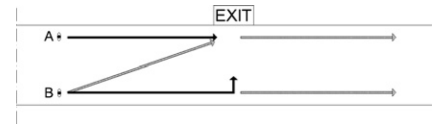


**Fig. 14.** An illustration of the walking path typical for participants that were walking on the opposite side (B) of the emergency exit in scenario 4.

end location in Table 7 refers to the participants' position inside the tunnel shortly before they reached the exit, see Fig. 13. Thus, there is a distinction between the end location as described in Table 7, and the initial position when the evacuation started, see Fig. 5.

As can be seen in Table 7, the probability of a participant choosing the emergency exit was generally higher for the participants that were walking on the same side as the exit in contrast to the participants that were walking on the opposite side. In fact, for all scenarios except scenario 3, 100% of the participants on the same side as the emergency exit used it. It could be argued that, irrespective of the way-finding installations employed, occupants on the same side of the exit are more likely to use it. Therefore way-finding installations on the emergency exit inside a tunnel are most beneficial for people on the opposite side of the emergency exit, in this experiment end location B, see Fig. 13.

It seems as if the introduction of green flashing lights, i.e., scenario 2, contributed to the usage of the emergency exit if compared with the standard design in scenario 1. This conforms to previous studies [45,46], and has been explained with the fact that flashing lights direct evacuees' attention and make them notice the emergency exit. In addition, it has been argued that the colour green is associated with safety and emergency exit [5].

The introduction of the strong halogen lamp above the emergency exit, and the continuous lights at each side of the exit, i.e., scenario 3, does not seem to increase the usage of the emergency exit. In fact, the design did not only avert participants walking on the opposite side of the tunnel, but also three persons that were walking on the same side as the exit. The reason for this cannot be expressed with certainty, but interview statements by some of the participants provide clues as to why the design was inadequate. Many participants actually interpreted the door as a train when they first identified it inside the tunnel. Consequently, this introduced an uncertainty in the decision making to choose the door or stick to the participants' already chosen walking path. The misinterpretation of the exit for a door is illustrated by a statement made by Participant 43, where he explains that he initially chose to continue to follow the opposite side of the tunnel because he thought it was a train on the other side:

*Yes, I thought it was supposed to be a train. So I did not go there. Otherwise I would have done that directly* [*gone to the exit, authors comment*].

*Participant 43, 3 min 43 s into the interview.*

Studying Table 7 reveals that the exit design in scenario 4, with a standard backlit European emergency exit sign and a loudspeaker, was very efficient in terms of getting the participants to use the exit. All 24 participants, independent on their location, used the door. An analysis of the walking paths of the participants in scenario 4 also reveals that the participants located on the opposite side of the emergency exit seem to have changed their walking direction, i.e., started to move towards the other side of the tunnel, earlier inside the tunnel than in the other scenarios. This behaviour, typical for scenario 4, is illustrated in Fig. 14. Furthermore, the perceived rating of the combined alarm signal and voice message was rated high in the questionnaire study by the 24 participants included in the scenario, and received a median score of 8.5 of 10.

In addition to the exit design in scenario 4, the design in scenario 5, which included all installations but the loudspeaker, was also effective in terms of attracting participants to the exit. Before the experiment it was hypothesized that the door would repel the participants by providing too much information, but this does not seem to have been the case. However, the number of participants in the scenario was small, and the results should therefore be treated carefully.

Fisher's exact test [47] was used in order to investigate the significance of differences between the observed frequencies in each scenario where the participants had been walking on the opposite side of the emergency exit inside the tunnel. The test was used to investigate if one or more of the emergency exit designs were significantly better in terms of attracting participants to the exit (among the group of participants that walked on the opposite side of the exit). One test was carried out for each combination of scenarios, and the exact $p$-values (one-sided) are presented in Table 8. Note that Scenario 5 was excluded in the analysis due to the low number of observations, i.e., participants, and the fact that all participants used the emergency exit.

In terms of emergency exit usage, Table 8 shows that the emergency exit design used in scenario 4 was significantly better ($p < .05$) than the designs used in scenario 1 and 3. The same conclusion can be drawn if scenario 4 is instead compared with a combination of scenarios 1, 2, 3 and 5. The calculated one-sided $p$-value then becomes 0.022 ($p < .05$).

## 4. Discussion

The results of the evacuation experiment provide detailed data on movement speeds and movement patterns inside a dark and smoke filled tunnel. In addition, the study illustrates the importance of technical installations along the evacuation route, and how an exit design may affect the usage of the exit during evacuation in underground rail transportation systems. The results presented in this paper may not be generalized for a situation with, for example, no smoke. However, it is argued that the results are of great importance in the fire safety design of underground rail transportation systems, as evacuation assessments of these facilities will include analyses of people moving in smoke.

Underground rail transportation systems are unique environments with a set of specific characteristics. For instance, the effectiveness of way-finding systems can be affected by occupant's lack of familiarity with the environment, and walking speeds are studied on surface materials, which are typical of underground transportation systems. Results presented in this paper are therefore deemed to be applicable in the study of environments that present similar characteristics to the scenarios under consideration. This means that the results on the effectiveness of different way-finding installations are related to scenarios where the occupants are not familiar with the environment. In this context, much of what is presented can also be applied to other underground transportation systems, e.g., road tunnels.

The movement speeds presented in this paper are in line with the data that has been presented in previous studies [16,17]. The

**Table 8**
Exact *p*-values of Fisher's exact test for consistency when comparing the scenarios pairwise.

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|
| Scenario 1 | – | 0.477 | 0.656 | 0.033 |
| Scenario 2 | 0.477 | – | 0.450 | 0.142 |
| Scenario 3 | 0.656 | 0.450 | – | 0.020 |
| Scenario 4 | 0.033 | 0.142 | 0.020 | – |

analysis suggests that neither inclination nor tunnel floor material significantly affects the movement speed, and this is illustrated by the small differences in movement speeds in the different parts of the tunnel. It is instead hypothesized that the smoke and the lack of lighting will be the limiting factors on the movement speed in a fire evacuation in underground rail transportation systems. A modelling speed has also been presented in the paper, in which the duration of the stops of a participant has been included. It is suggested that this so called modelling speed should be employed when using evacuation models that do not take into account stops made by the agents during the simulation of their evacuation paths.

Evacuation experiments in this type of environment, in which the participants have had to walk for as far as 160–180 m, are rare. In for example the study by Jin [14,15] the distance walked by the participants was only 20 m, and in the experiment by Frantzich and Nilsson [16,17] the tunnel length was 37 m. Walking in a dark and smoke filled tunnel for over 160 m could mean that participants are subject to fatigue, affecting the movement speed negatively, or that participants adapt to the environment, which could affect the movement speed positively. However, no significant differences were identified in terms of movement speeds related to the distance walked inside the tunnel. This observation is particularly important as it suggest that the movement speeds presented in the article can be generalized for a real situation, thus improving the external validity of the results.

In the present experiment, some factors may have an impact on the lack of the effects of fatigue on the walking speeds observed. Occupants may learn and understand a simple environment (a straight tunnel) quickly, thus having a positive effect on their speed over time. Other factors may be the time the participants spent in the dark after leaving the bus, which may have permitted them to get used to the dark, or the length of the tunnel in comparison with the population type. The population did not include a significant number of participants with mobility impairments, i.e., the population was mainly made by healthy participants.

The importance of the tunnel walls was demonstrated in the evacuation experiment. The video recordings revealed that 91% of the participants followed one of the tunnel walls at least 75% of the total distance walked during the evacuation. The primary reason was that it facilitated orientation inside the otherwise dark and smoke filled tunnel. Many of the participants also kept one or two hands on the wall in order to not lose their orientation. To provide tunnels with handrails, which have been suggested in previous studies [17], therefore appears to be a good solution that may improve the ability to orient during an evacuation inside a rail tunnel. It is argued that the availability of handrails would provide additional help on directing the evacuation and affect movement speeds. Further studies on the effectiveness on handrails and the impact of the sense of touch during evacuation are, however, needed.

Another reason as to why the participants choose to follow one of the walls was the emergency signs, which were positioned on the tunnel walls every eight meters. The signs were very appreciated by the participants as they included information on the distance to the closest exits. This information confirmed that the participants were walking in the right direction, and also gave them clear and detailed information on how much further they had to walk, which could be related to the remaining time they had to stay in the tunnel. Furthermore, the lamps installed on each sign provided the participants with orientation points inside the otherwise dark and smoke filled tunnel. It is argued that these signs are very important in a real evacuation, and future research should study if the design could be further improved.

The evacuation experiment also demonstrated that certain emergency exit designs are better than others in terms of attracting people during an evacuation inside a tunnel. Furthermore, it was shown that the usage of the emergency exit depended on the position of the participants inside the tunnel. Participants that walked on the same side of the tunnel as the emergency exit used it to a greater extent than those who walked on the opposite side. It could therefore be argued that the type of way-finding installations on the emergency exit inside a tunnel is most beneficial for evacuees on the opposite side of the emergency exit inside the tunnel.

A door equipped with a loudspeaker, thus enabling an alarm signal and a voice message to be broadcasted to evacuees, was found to perform very well in the experiment and attracted all participants to the exit. In contrast, a combination of green and white continuous lights and a strong halogen lamp was misinterpreted as a train by many of the participants. Although the lights got noticed through the dense smoke, this introduced an uncertainty and made the participants unsure of how to respond, i.e., to continue follow the wall or to walk towards the door. These observations clearly demonstrates the importance of not only coming up with an exit design, but also to test it in an environment similar to the one it is intended to be used in.

It is not obvious that an emergency exit equipped with a loudspeaker will increase usage of it in a building. The number of walking routes may be many, as may the number of exits. However, inside a rail tunnel where evacuees generally only have two options, either to walk in the tunnel direction or to choose an exit in the wall, the loudspeaker may be essential if the evacuees are to notice the emergency exit at all. The loudspeaker is deemed especially important for those walking on the opposite side of the exit. As the distances between two emergency exits may sometimes exceed many hundred meters in underground rail transportation systems, the consequences of an evacuee missing an exit could be devastating. It is therefore suggested that future research should study the effects of loudspeakers on exit choice in underground rail transportation systems further, and also test the performance of different combinations of alarm signals and voice messages.

In the present study, a combination of data collection techniques has been used in order to improve the reliability of the results. Video recordings were used in order to enable the analysis of the participants' movement speed, behaviour and exit choice inside the tunnel. The great benefit of video recordings is that they permit an analysis of the material several times, with a subsequent increase in the reliability of the results. In addition, a questionnaire study that included all participants and an interview study that included 65 of the participants have been used in order to find explanations as to why the participants moved and behaved the way they did. The questionnaire and interview answers are believed to hold invaluable information, and have provided information on for example why certain exit designs were more appreciated than others. In relation to the purpose of the experiment it is therefore argued that the reliability of the results is high.

The evacuation experiment that has been described in the paper has been an attempt to describe a real world phenomenon. As it is an attempt, the evacuation experiment is intimately associated with both uncertainties and limitations, which evidently affects the external validity of the results, i.e., the generalizability. One limitation of the experiment is for example that people may behave differently in a real situation in which they would be subject to a real fire, toxic smoke and higher stress levels. The artificial setting of the experiment, including the fact that the participants knew that they were participating in a test, that protective measures were taken to minimize the risks, and that they knew that a fire fighter was always present to help them, altogether means that the participants probably were more relaxed and felt that they could take their time to evaluate the situation at all points of the experiment, simply because there was no time limit. It could, for example, be questioned whether evacuees in a real tunnel fire would stop to look at every single emergency sign to verify the distance information. In a stressed situation, evacuees may instead focus on the arrows and the first sign, and then continue in the direction that was decided after having looked on the first sign. Movement speeds could consequently be argued to be higher in a real fire situation; however, in a real fire situation the irritant effects of the smoke, which could not be reproduced in the present experiment, may outweigh this phenomenon. Another limitation of the experiment is related to the social influence [48–50], which will affect the reactions and actions of people in a real fire evacuation. No such observations have been made in the present study as the experiment was carried out individually. Future research should therefore try to verify the results in the present study with results from evacuation experiments in which participants evacuate together.

## 5. Conclusions

The analysis of the evacuation experiment showed that the average movement speed inside a smoke filled rail tunnel can be expected to be approximately 0.9 m/s in the case of a mean extinction coefficient equal to 2.2 $m^{-1}$ and no external sources of lights except the emergency signs. Neither macadam nor tunnel inclination of 10% have a great effect on the movement speed. The experiment also demonstrated the importance of both tunnel walls and emergency signs, which had been positioned every eight meters inside the experiment tunnel. Both of these features can be expected to facilitate orientation during an evacuation in a rail tunnel. Furthermore, the experiment illustrated the importance of the emergency exit design. Smoke produced by a fire in an underground rail transportation system may obscure way-finding light installations, especially for people walking on the opposite side of an emergency exit inside a tunnel. For this reason, the installation of a loudspeaker on the emergency exit, which can provide evacuees with a combined alarm signal and a pre-recorded voice message, may be particularly effective in terms of attracting people to an exit inside a rail tunnel, independent of which side of the tunnel they are walking.

## 6. Ethical considerations

According to the Swedish ethics act [51] all research that involves procedures that may be psychologically invasive to the participants must be subject to a review by a regional ethics board. The present study was reviewed and consequently approved [52,53]. The important ethical issues discussed below were identified and addressed within the project.

### 6.1. Preparation and precautions

A number of precautions were taken to avoid both psychological and physical injury in the experiment. The risk of psychological injury was minimised by preventing individuals who received a high score for both anxiety and/or depression according to the HAD questionnaire, see 2.1.1 Recruitment, from taking part. The HAD questionnaire was administered to everyone who responded to the advertisements about the experiment. Those participants who passed, i.e., who received a low score for both anxiety and depression, were then given a consent form and written information about the experiment.

The written information explained the background and aim, and also provided the participants with a description of the experiment. The description included information about the procedure, risks and benefits for the participants, handling of data and insurance. It was emphasized in the document that the experiment was voluntary, and that the participants could withdraw at any time. Information about how the participants could withdraw from the experiment was also included.

In addition to the written information, participants were also given oral information before the experiment was started. The oral information was given to each group of participants arriving at the experiment site. Written informed consent was then collected. Before each participant entered the tunnel, the most important safety information was repeated. More specifically, it was emphasized that the experiment was voluntary and it was pointed out again how they should act if they wanted to terminate their participation. The procedure for terminating the experiment was to give a signal to the fire fighter inside the tunnel by waving your arms.

A number of precautions were taken to minimize the risk of physical injury and to reduce the consequences of these injuries. During the preparation and installation of equipment the tunnel was checked several times to ensure that there were no spikes or other obstacles in the walls that people could bump into or get entangled in. The concentration acetic acid was also checked during test runs to make sure that it was below the threshold for short-term exposure specified in the Swedish legislation [43]. Checks of the concentration of acetic acid were also made several times during the experiments.

Before the participants entered the tunnel they were given protective clothes, namely an overall, boots, gloves and a helmet, in order to reduce the consequence of a fall or collision. In addition, all participants were followed by a fire fighter inside the tunnel. The fire fighter used a thermal imaging infrared camera that allowed him to see participants through the smoke. The task of the fire fighter was to intervene if he observed a potentially dangerous situation or signs of anxiety, and to help the participant out of the tunnel if he or she gave the termination signal. Finally, all participants were insured so that they would receive financial compensation and reimbursement of medical costs in case they got injured.

All participants were compensated for their participation in the experiment. From an ethical point of view, the compensation must be reasonable in relation to the type of exposure. Due to the type of exposure in the experiment, it was deemed reasonable, and also approved by the ethical committee, to compensate the participants with 300 SEK (approximately €34) for their participation. Note, however, that the employees at the Traffic Administration Office only were compensated in terms of leave from work during their participation by their employer.

### 6.2. Follow-up

Two months after the experiment, the participants were contacted to determine if they had suffered any injury or discomfort as a result of the study. Telephone calls were made to all participants and approximately 90% were possible to get hold of. The participants were asked if they had experienced any discomfort as a result of the experiment and they were also given the opportunity to freely point out other concerns related to the study. None of the contacted participants reported any injury or discomfort in the follow-up telephone interviews.

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