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The flow rate of people during train evacuation in rail tunnels: Effects of different train exit configurations

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ABSTRACT

An exploratory study of a train evacuation inside a tunnel was performed in order to study the effects of different train exit configurations on the flow rate of people through the exit. A total of 84 participants in the ages 18–40 years took part in the experiment, which was carried out on two separate days and involved 18 evacuation scenarios. The statistical analysis of the experiment demonstrated that the average flow rate capacity of the train exit was .3 persons per second and meter (p/s m) door width, including all scenarios. Four variables related to the train exit configuration were identified to significantly affect the flow rate of people: (1) a reduction of the train exit height increased the flow rate of people with on average .026 p/s m; (2) a change of tunnel floor material from concrete to macadam increased the flow rate of people with on average .015 p/s m; (3) an emergency ladder present in the train exit reduced the flow rate of people with on average .064 p/s m; and (4) a complete failure of the lighting inside the train reduced the flow rate of people with on average .029 p/s m. In addition, qualitative observations revealed a deferential behaviour among the participants in the train, caused by the people outside the train. It is therefore believed that the population density outside the train will significantly determine the flow rate capacity of the train exit during an evacuation.

1. Introduction

If a fire occurs on a passenger train travelling in an underground rail transportation system, the general principle is to move that train to a safe place, often the nearest station, and disembark its passengers (Burnett, 1984; European Commission, 2008). However, past incidents have shown that this is not always possible, and that train passengers sometimes are forced to self-evacuate the train inside a tunnel, i.e., evacuate the train and move to a safe place with no more help than instructions from the staff. Examples are the fire in the Hirschengraben Tunnel in 1991 in Zurich (Carvel and Marlair, 2011; Fermaud et al., 1995), the Baku subway fire in 1995 (Carvel and Marlair, 2011; Rohlén and Wahlström, 1996), and the Kaprun funicular fire in 2000 (Carvel and Marlair, 2011; Larsson, 2004; Schupfer, 2001). Taken together, these incidents demonstrate that evacuation in underground rail transportation systems due to fire may take considerable time, and may result in disastrous consequences in terms of loss of lives with many hundreds of dead and/or injured.

The time it takes passengers to reach a place of safety in an underground transportation system, i.e., the total evacuation time, is among other things dependent on the time it will take to leave the train. While evacuation through the side doors of a train at a platform can be fairly smooth and fast, the same type of evacuation inside a tunnel can be very problematic, and it is in turn likely that the evacuees will encounter many obstacles on their way to safety (Fridolf et al., 2013). The obstacles may create bottlenecks, i.e., locations where the flow of people is severely restricted. One example of such an obstacle is the exit height from train to track level (Frantzich, 2000; Galea and Gwynne, 2000; Norén and Winér, 2003; Oswald et al., 2008, 2005, 2011), which may be particularly difficult to overcome for children, senior citizens and persons with disabilities (Fridolf et al., 2012).

Typically, the number of people that passes a certain point in the evacuation route per unit of time is termed the flow rate of people. If also the width of the evacuation route is taken into consideration, the flow rate of people can be expressed in terms of persons per unit time and width (Gwynne and Rosenbaum, 2008). In combination with other variables, the flow rate of people can be used in engineering calculations and models of evacuation. Hence, this represents an important part of the puzzle in the fire safety design process of buildings as well as underground transportation systems, and the variable has been studied in a number of evacuation experiments (Frantzich, 2000; Galea and Gwynne, 2000; Norén and Winér, 2003; Oswald et al., 2008, 2005, 2011).

In terms of flow rate measurements of upright-standing trains inside tunnels, one of the few existing field studies to date was

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performed by Frantzich (2000), who carried out a full scale evacuation experiment in the Stockholm Metro. The study included a total of 143 participants, of which 115 were recruited among administrative personnel at the Stockholm Public Transport in the ages between 18 and 50+. About 42% of these participants were women. Frantzich (2000) observed flow rates varying from .08 to .17 persons per second and meter (p/s m) door width at the train exits, and explained the lower flow rate as an effect of the presence of an emergency ladder in the train exit. Similar results were reported by Oswald et al. (2008), who estimated the flow rate to be approximately .19 (p/s m) door width in an evacuation experiment involving 439 participants in a simulated tunnel situation. The participants, who were aged 11–60, had been recruited from the train depot in Vienna and were almost exclusively men. In addition to the flow rate measurements, Oswald et al. (2008) also identified three types of exiting strategies: "jumper", "sider" and "sitter". In both experiments, the participants had to overcome a height difference of more than 1 m between the train and the track level (1.4 and 1.15 m, respectively).

Evacuation experiments have also been conducted in derailed trains. For example, Galea and Gwynne (2000) made flow rate capacity measurements of an overturned rail carriage end exit. The experiment included a total of 32 participants, namely 16 men and 16 women in the ages 19–74, none of which had previous experience of evacuation from a train. Galea and Gwynne (2000) reported the average flow rate through an end door, for a carriage lying on its side, to be .08 (p/s m) door width, and .04 (p/s m) door width in the presence of non-toxic smoke. Lying on its side, the end door measured .8 m in height and 1.96 m in width, and was reachable at a height of approximately 1 m.

It has been suggested that the flow rate of people through train exits are influenced by the distance between the exit sill and the ground level outside, i.e., the train exit height (Norén and Winér, 2003; Oswald et al., 2005). However, in a tunnel environment with a narrow sideway parallel to the train, it is also likely that the flow rate of people is influenced by the interference of people walking alongside the train. This was suggested by Oswald et al. (2008, 2011) who observed more or less identical exit times for different exit heights (.65 and 1.0 m). In addition, they observed that the limited space along the pathway and a one-directional evacuation caused flow rates through some exits to be approximately half of the flow rates through the exits that on the outside were free from people.

The evacuation experiments discussed above provide valuable information on the flow rate capacity of train exits during evacuation in underground rail transportation systems, and demonstrate that evacuation of a train inside a tunnel may take considerable time. However, no experiments have yet been performed with the purpose to identify the relative importance of variable(s) that will limit the flow rate of people through a train exit when evacuation is necessary inside a tunnel. As a first step, an exploratory evacuation experiment was therefore performed in order to investigate how different train exit configurations affect the evacuation efficiency. The purpose of the study was to examine if any of the following variables influence the flow rate of people through the train exit: (1) floor material inside the tunnel; (2) train exit height; (3) presence of an emergency ladder in the train exit; (4) lighting conditions inside the tunnel; and (5) presence of extra handles in the train lobby. In addition, the study aimed to qualitatively describe important observations related to human behaviour and interactions among the participants, for example deferential behaviour among participants about to exit the train. A second part of the study included elderly and senior citizens, but due to ethical aspects, mainly the increased risk of injury, this part was performed as an interview study and the results have been presented elsewhere (Fridolf et al., 2012). The present study is the first in a series of evacuation experiments that will be carried out in the Swedish METRO research project. The results drawn from this exploratory study will complement future full-scale experiments in real tunnel environments with a mixed population.

2. Method

On the 3rd and 9th of December 2010 an evacuation experiment was performed at Lund University, Sweden. The experiment was carried out in a model of a train, which was linked together with a sideway tunnel. Different train exit configurations were used in order to study the effects on the flow rate of people through the train exit. In the following sections the participants, the layout of the experiment, the scenarios, the procedure and the analysis of the experiment are described.

2.1. Participants

Participants were recruited among students at the Faculty of Engineering, Lund University. Information about the experiment and instructions on how to sign up was given on information screens, posters and orally before lectures. The information was short and did only specify that participants were needed for an experiment involving evacuation from a train inside a tunnel, that the experiment was going to last for up to 3 h, and that the participants would be reimbursed with a cinema ticket and a free lunch.

The experiment was performed on two separate days. Forty-six participants took part the first day, namely 26 men (57%) and 20 women (43%). The age varied from 18 to 40 years, with an average of 22 years and a standard deviation of 4 years. Thirty-eight participants took part the second day, namely 23 men (61%) and 15 women (39%). The age varied from 19 to 31 years, with an average of 23 years and a standard deviation of 2 years. See Table 1 for a summary of the participants' age and gender.

On the first day of the experiment, 27 (59%) of the participants were students at the Fire Protection Engineering programme at Lund University; the corresponding number of participants on the second day was 14 (37%). The remaining percentages of participants were recruited from other programmes at the Faculty of Engineering, Lund University, and included both Swedish and international students.

The participants did not wear any protective clothes during the experiment, and they had their regular indoor clothes and shoes on. Due to the fact that the experiment was performed indoor, the participants did not wear any jackets, nor did they carry any luggage, e.g., backpacks or briefcases. However, a few of the female participants did have their handbags with them during the experiment. During the experiment, the participants were covered with casualty insurance. Note that each student only was allowed to participate on 1 day of the experiment.

2.2. Layout

The experiment was carried out in a model of a train, which was linked together with a tunnel with a width of .85 m. The design of the train was based on the Swedish X1 train, a commuter train

Table 1
Information about the total number of participants, their age and gender.

Day	Age (years)				Number of participants (–)		
	Mean	Min	Max	Std.	Women	Men	Total
1	22.5	18	40	3.6	20	26	46
2	23.4	19	31	2.4	15	23	38
Total	22.9	18	40	3.2	35	49	84