Fire Safety Journal xxx (2017) 1–11

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

A tunnel evacuation experiment on movement speed and exit choice in smoke

Enrico Ronchi [a,*], Karl Fridolf [b], Håkan Frantzich [a], Daniel Nilsson [a], Anders Lindgren Walter [c], Henric Modig [d]

[a] Department of Fire Safety Engineering, Lund University, Lund, Sweden
[b] WSP Sverige AB|WSP Brand & Risk, Malmö, Sweden
[c] MTO Safety, Stockholm, Sweden
[d] The Swedish Transport Administration, Stockholm, Sweden

ARTICLE INFO

Keywords:
Evacuation
Experiment
Human behaviour in fire
Walking speed
Road tunnel
Smoke
Emergency exit
Design
Exit choice

ABSTRACT

In order to increase the knowledge on human behaviour in smoke, an evacuation experiment was performed in a road tunnel in Stockholm in July 2014. Sixty-six participants, who were instructed to individually evacuate the tunnel, took part. Participants' walking speeds were measured in a smoke-filled section, as well as in a smoke-free section, of the tunnel. The walking speeds in non-irritant smoke were measured for extinction coefficients in the range of 0.5–1.1 m^{-1}, which corresponds to approximately 2–4 m of visibility (for light reflecting signs). In addition, way-finding and exit choice in smoke were also investigated. Particularly, different emergency exit portal designs were evaluated in the smoke-filled section of the tunnel. The novel data-set on walking speed in smoke is presented, including coupled data on obstructed (movement in smoke) and unobstructed (smoke-free movement) walking speed. Results show that there is a weak relationship between an individual's ability to walk in smoke and the unobstructed walking speed, but more research is needed in this area. In addition, the results relating to way-finding and exit choice demonstrated that the emergency exit portal design in the experiments was appropriate for the intended use. However, in order to increase the performance of the design, the portal may be complemented with information signs on the wall opposite to the exit, namely way-finding signs including distances to the closest emergency exits on both tunnel walls, and a loudspeaker installation that can inform evacuees about the location of available exits.

1. Introduction

Human behaviour in road tunnel fires is of particular interest in the fire safety engineering community given the dramatic consequences of tunnel fires on life safety [22]. Fires may quickly become devastating due to the confined tunnel environment and the fire development may be rapid causing a quick deterioration of evacuation conditions [10,12]. In this context, the time component is critical when assessing the safety conditions of a road tunnel.

Two main research areas within road tunnel evacuation are walking speed and route/exit choice. Previous research has, for example, focused on different issues concerning the impact of smoke on tunnel evacuation safety and how this can impact the time needed to safely evacuate a tunnel in case of emergency. This includes the investigation of the influence of different way-finding installations on exit choice [6,11,16,24,26], group dynamics in dark environments [5] and the representation of walking speed and behaviour in smoke-filled environments [2,3,25]. Way-finding installations may include different types of signage or lighting systems. Examples of such systems that have been proved to be effective include dynamic signage [15,21] or stripes of lights [6]. In this paper, the term *obstructed walking speed* is used to describe the walking speed of people in smoke-filled environments, i.e., with reduced visibility, while the term *unobstructed walking speed* is used to describe the walking speed of people in smoke-free environments. It should be noted that the term obstructed speed is by no means to be confused with the impact of physical obstacles (i.e. it refers to movement in smoke).

Since the early studies conducted in the nineteen seventies in Japan, which today are summarized in a chapter of the Society of Fire Protection Engineering Handbook [30], it appeared evident that reduced visibility

* Corresponding author.
E-mail address: enrico.ronchi@brand.lth.se (E. Ronchi).

http://dx.doi.org/10.1016/j.firesaf.2017.06.002
Received 28 November 2016; Received in revised form 23 May 2017; Accepted 1 June 2017
Available online xxxx
0379-7112/

(generally expressed in terms of a light extinction coefficient [20], which refers to the intensity of monochromatic light of a certain wavelength to the intensity of light transmitted through the path-length of the smoke) is generally associated with a reduction in walking speed. Over the years, further experimental studies have investigated obstructed walking speeds at different visibility levels [1,4,8,11,12,16,17,27–29]. Nevertheless, to date there is no final interpretation on how smoke affects walking speed in smoke-filled tunnels. This issue is also exaggerated by the fact that it is unknown if, and to what extent, different experimental studies may be combined in order to generate more generalizable conclusions about movement in smoke. This is associated with several possible differences concerning the experimental conditions in which the data were collected. This includes: 1) the environment in which the experiment was performed, 2) the type of smoke used, 3) presence of physical barriers, 4) information to the participants prior to the evacuation, 5) participant demographics, 6) lighting conditions, 7) techniques for measuring and analysing walking speeds and visibility conditions, and 8) the visibility range during the experiments. As a general statement, it is possible to argue that data-sets on obstructed walking speed exist, but the uncertainty associated to the data is significant. For this reason, further data collection efforts are deemed to improve the current understanding of this issue.

It should be noted that whether early experiments performed in the '70s [17] considered smoke produced by actual fires (e.g. wood cribs), this is not the case in the experimental research conducted over the following years, i.e. artificial cold smoke is generally employed. The use of such type of smoke leads to consider such experiments as an indication of the reduction of walking speed due to reduced visibility conditions rather than representing the whole impact that irritant smoke might have on occupants. This limitation should be taken into account when applying data-sets obtained with such type of artificial cold smoke.

Another problematic aspect relates to the representation of peoples' walking speed in smoke. Since the above-mentioned experiments have only measured obstructed walking speed, it is not known if the individual obstructed walking speed is somehow related to the individual's unobstructed walking speed. More specifically, it is unknown whether the obstructed walking speed in smoke should be represented as a fractional reduction of the unobstructed walking speed or as an absolute reduction only dependent on the visibility conditions [12,25].

Previous research has also investigated the exit/route choice of evacuees in case of tunnel evacuation. Among other things, it shows that evacuees generally tend to follow one of the tunnel walls on their way to safety [4,17]. Ideally, in a twin bore one-way road tunnel (regardless of the number of traffic lanes) with cross tunnel links (and assuming vehicles driving on the right hand side, e.g. as in most European countries and in the US), people should follow the left hand side of the tunnel. This should be the case for both passengers or drivers (who might get out on different sides of the vehicle) as this typically is where way-finding signs, escape lights and escape routes leading to a parallel tunnel tube are located. However, in many cases, people may be expected to start to move along the right hand side of the tunnel, and then keep to that side. Consequently, there is a risk that they may miss the emergency exits on the opposite side, especially if the smoke is very dense [8,11]. The design of emergency exit portals can play a significant role in the likelihood of people adopting an optimal (shortest) route/exit choice when evacuating [26]. This issue needs to be further investigated.

In order to increase the current understanding on walking speed and exit/route choice in smoke, an evacuation experiment was conducted in a road tunnel in Stockholm in 2014. In the experiment, individual measurements of obstructed and unobstructed walking speeds were made for 66 participants. At the same time, data on way-finding and exit choice in smoke was collected. The purpose of this paper is to describe the experiment, to present a novel data-set on walking speed in smoke, including individually coupled data on unobstructed walking speed, and to explore the relationship between these two speeds. In addition, the purpose is to present and discuss the results related to the participants' way-finding and exit choice. It should be noted that the contents presented in this paper is a based on the material presented in two conference papers, more specifically [13,14], but this is the first paper which comprehensively present and discuss all results of this experiment.

2. The tunnel evacuation experiment

On July 1–3, 2014, an evacuation experiment was performed in the Northern Link road tunnel in Stockholm, parts of which was filled with artificial smoke during the experiment. One purpose of the experiment was to investigate the effectiveness of evacuation installations for a future tunnel in the Stockholm area, the Stockholm Bypass. The Stockholm Bypass project includes a 21 km long motorway connection between the southern and northern districts of Stockholm, Sweden [19]. Just over 18 of the 21 km will consist of twin-bore, parallel tunnels, with three lanes in each direction, and an expected travel time of about 15 min. The experiment was, however, performed in the Northern Link tunnel, since its layout is similar to the future Stockholm Bypass tunnel. At the time of the experiment, the Northern Link tunnel had not yet opened for traffic, but had almost been finalized as the opening was only a couple of months away. Consequently, all the basic technical installations and equipment, e.g., light installations and ventilation systems, had already been installed. However, for the experiment most of the way-guiding installations were covered not to interfere with the installations used in the experiment. In this section, a short presentation of the following aspects is presented: 1) portal configuration, 2) tunnel configuration, 3) participants, 4) procedure, 5) evacuation scenarios, and 6) data documentation. The present trials went through the review of a Swedish Ethical Committee which needs to approve experiments involving human subject after reviewing their experimental plans. More detailed information on the experimental work conducted can be found in the full report associated with the project published in Swedish language [9]. It should be noted that while the portal design was taken into consideration in the tunnel safety design, dynamic signage was not considered. Nevertheless, experimental research [15,21] has shown that dissuasive signage has great potential to aid way-finding in evacuation emergencies.

2.1. Participants

The participants that took part in the evacuation experiment were recruited in a three-step process, of which the first step was initiated approximately one month before the experiment when a recruitment advertisement was published online. In the advertisement, explicit information about the true purpose of the experiment was not included. It did, however, include information about the fact that selected participants would have to walk in a smoke-filled environment. In the second step, participants applied to the experiment by providing information about themselves and by filling out a so called HAD questionnaire [31]. HAD is an abbreviation for Hospital Anxiety and Depression, and the questionnaire was used to rule out sensitive individuals who showed signs of anxiety and/or depression. These people had to be discarded from the experiments due to ethical restrictions. In total, 100 men and 48 women applied to take part in the experiment. Based on the submitted applications, selected participants were, in the third and final step, invited to take part in the experiment. At this point, they received additional information about the experiment, such as the background and purpose of the study, practical details about the execution of the experiment, associated risks, handling of collected data, where the results of the study would be published, insurance, compensation for participation (300 Swedish kronor), etc.

A total of 66 participants took part in the evacuation experiment, of which 20 were women and 46 were men. Their main characteristics are presented in Table 1, and are based on the answers that they gave in a questionnaire, which was filled out directly after each participant completed the experiment. Fifty-seven participants, i.e., 86%, stated that