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Evacuation experiment in a road tunnel: A study of human behaviour and technical installations

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ABSTRACT

An evacuation experiment was performed in a road tunnel in order to investigate how motorists behave and emotionally respond when exposed to a fire emergency, how information and wayfinding systems are perceived and whether green flashing lights can influence exit choice. The participants believed that they were taking part in a study about driving behaviour. Approximately 1 km inside the tunnel participants encountered an accident, i.e., cars and smoke. The fire alarm, which consists of a pre-recorded alarm and information signs, was also activated and green flashing lights at emergency exits were started. The results show that it was difficult to make out what was said in the pre-recorded alarm. However, an acoustic signal was positive since it alerted motorists and made them look for additional information. The information signs were also important for the decision to leave the vehicle. Social influence was found to be essential, both with regards to the decision to leave the vehicle and the choice of exit. The results also suggest that arousal level influences the amount of information noticed by motorists, which implies that technical installations, e.g., wayfinding systems, should be tested under stressful conditions before they can be relied upon in a real tunnel fire.

1. Introduction

Disastrous fires in road tunnels, such as the fire in the Mont Blanc tunnel and the fire in the Tauern tunnel, have clearly shown the importance of effective and prompt evacuation. An important finding in this regard is that motorists do not necessarily evacuate their vehicles [1,2]. This is exemplified by the fire in the Mont Blanc tunnel where most of the victims were found inside or near their vehicles.

It has been argued that the tendency not to evacuate the tunnel, i.e. to stay in one's vehicle, results from person and place affiliation [2]. According to the theory of *affiliation in fire entrapment settings* people will be attracted to and move towards familiar persons and places during evacuation [3]. In a tunnel it is possible that the vehicle constitutes something familiar, whereas the tunnel is an unfamiliar environment. Another possible explanation of the reluctance to leave the vehicle is that people do not initially want to abandon their property. A car or truck is often a large investment that people might not want to leave unattended inside a road tunnel if the situation is not perceived as being dangerous.

Thus there appear to be behavioural constraints that must be dealt with to ensure that as many motorists as possible leave their vehicles. Provision of clear information about the emergency and instructions about how to act would probably do much to improve motorist response. Research about information to motorists during tunnel fires is at present very limited. A substantial amount of research has, however, been carried out on evacuation from buildings [4–6]. This research has shown that information is vital during evacuation. Proulx and Sime [4] have explicitly demonstrated the importance of clear information, showing that clear messages that conveyed what had happened in an underground railway station led to shorter evacuation times than did less informative alarm bells.

Studies of evacuation from buildings have shown that evacuees do not always use the closest emergency exit [6]. According to the previously mentioned theory of affiliation, one explanation for this phenomenon is that people move towards familiar places in the event of a fire emergency [3]. In most cases the emergency exits are unfamiliar and seldom used by the occupants of a building. The emergency exits in a tunnel may similarly be even more deterring and unfamiliar than the tunnel itself. Different types of wayfinding systems have been proposed as means for influencing exit choice in emergencies [7,8]. Flashing lights at emergency exits is one example of a relevant system that has been evaluated in several studies [9–11]. It has been argued that green

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lights should be used since green is associated with safety and *go*, whereas the colour red and orange should be avoided [9]. Various types of systems are used to inform motorists in case of fire emergencies in tunnels, including information signs and pre-recorded alarms [12]. Although such systems have been installed in many new as well as older tunnels, research is limited regarding motorists' perception of the systems and the information conveyed.

Fires are perceived as very stressful and in an emergency situation people's emotional state is likely to influence how the individual interprets the situation and acts upon emergency information [13,14]. Emotional state can be described as the individual's immediate reaction to a situation. Theories of environmental psychology assume a continuing interaction between human and environment [15]. The Human–Environment Interaction model (the HEI model) provides a suitable tool to understand individual responses in a certain situation in a specific environment since it offers a holistic perspective [16]. The HEI model accounts for characteristics both of the physical and the social environment, and the individual's responses is further assumed to be mediated by personal factors such as demographic characteristics and personality traits. In the event of a tunnel fire the individual responses may be behavioural, e.g., exit choice and pre-movement time, perceptual, e.g., perception of technical installations, and emotional, e.g., emotional state.

According to the HEI model the present emotional state will affect people's perception of various environmental factors and thereby influence their action in a certain situation. The performed behaviour may, with regard to the physical and social environment as well as personal factors, in turn induce a shift in the individual's emotional state [16,17]. In the event of an emergency it therefore seems likely that a person's perception of the situation, such as interpretation of emergency information and other people's actions, as well as his or her subsequent behaviour, i.e., decision to evacuate, choice of exit and pre-movement time, partly is a result of how he or she feels at the time. Similarly, if and how the person chooses to evacuate may influence his or her emotions after the evacuation.

The emotional state is described as a four-step basic emotional process linked to the neuropsychological operation of the central nervous system [16]. The process includes the components activation/arousal (the strength of the emotion), orientation (how directed the emotion is), evaluation (the hedonic tone of the emotion) and control (the control of the situation). In the HEI model emotions are seen as combinations of different levels of those four components. The HEI model has previously been applied in studies of people's response to various kinds of environments.

Although reports of actual tunnel fires offer valuable information about human behaviour, they usually do not provide in-depth data about the evacuation process. For more thorough and systematic studies, however, experimental methods are required that allow for observations of behaviour under realistic conditions. Such research involving evacuation experiments is scarce for road tunnels. One exception is the study performed by Boer [18,19] in which nine experiments were performed in the Benelux tunnel in Rotterdam, the Netherlands, in order to study human behaviour in the event of fire and to measure the time until motorists start to evacuate. The experiments in the Benelux tunnel revealed that social influence was an important factor, i.e., that motorists influence each other during evacuation, and that the closest emergency exit was almost always used [19].

In order to study human behaviour in road tunnels an evacuation experiment with partially informed participants was performed in the Göta tunnel in the city of Göteborg, Sweden [20,21]. The objective of the experiment was to:

(i) find out if motorists evacuate when exposed to a fire emergency,
(ii) quantify the evacuation time, particularly the time until people leave their vehicles,
(iii) obtain insight into factors influencing the decision to leave the vehicle and the choice of exit,
(iv) obtain information about motorists' perception of the fire alarm, namely information signs and pre-recorded alarm,
(v) obtain information about motorists' perception of green flashing lights at emergency exits and obtain insights into the ability of the lights to influence the choice of exit, and
(vi) find out if emotional state is linked to evacuation behaviour and response to evacuation information.

2. Method

2.1. Participants

The participants were recruited from among employees and external consultants working for the Swedish Road Administration (SRA). Care was taken to ensure that no participants had any direct involvement in the Göta tunnel building or planning process. The means of recruitment were posters on notice boards, e-mails and information at meetings. Everyone who signed up for the experiments filled out a Hospital Anxiety and Depression (HAD) questionnaire [22]. In order to exclude sensitive individuals, only those who received a score of less than eight for both anxiety and depression were included in the experiment.

Twenty-nine participants took part in the experiment, namely 27 men and two women. The age of participants spanned between 25 and 65 years, with one person not stating age. The average age was 44 years and the standard deviation was 13 years. SRA reimbursed participants by regarding the experiment as work activity. This meant that the participants and their vehicles were insured by SRA and that they received salary according to standard agency policy.

2.2. The tunnel

The Göta tunnel is a 1.6 km twin bore tunnel with 15 emergency exits (see Fig. 1). During normal operation the traffic flow in the two tubes is uni-directional. There are either two or three lanes in each tube depending on the exact location in tunnel. In addition, there is a wide shoulder where vehicles may stop in case of a breakdown. The experiment took place at a location where there were three lanes. Emergency exits are numbered from 1 to 15 from south to north. The distance between exits is 100 m. Since the tunnel is a twin bore tunnel, the exits are located on the left walls and lead to the other tube. Twelve of the emergency exits open out into traverse tunnels that connect the two tubes, and three lead directly to the other tunnel tube. The emergency exits closest to the participants in the experiment lead to traverse tunnels.

All emergency exits are clearly distinguishable (see Fig. 2). They are located in smooth alcoves in the tunnel walls, which are covered with white ceramic tiles. The area around an exit is covered with blue ceramic tiles. To the right of each exit are blue and white tiles showing large exit numbers, which are easy to distinguish when driving through the tunnel.

The wayfinding systems in the Göta tunnel consists of back-lit emergency exit signs on the left wall in both tubes and above