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Experiments of evacuation speed in smoke-filled tunnel

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ABSTRACT

Among tunnel fire safety strategies, evacuation speed in smoke, which is the basic evacuation performance characteristic, is one of the most important factors when assessing safety. An evacuation experiment in a full-scale tunnel filled with smoke has been done in order to clarify the relation between extinction coefficient up to $Cs = 1.0\ m^{-1}$, which includes $Cs = 0.4\ m^{-1}$ as a Japanese road tunnel fire prevention standard, and evacuation speed. The maximum, minimum and mean values of normal walking speeds are almost constant regardless of the extinction coefficient. As for the emergency evacuation speeds, the maximum speed is largely influenced by extinction coefficient, decreasing rapidly from 3.55 m/s at $Cs = 0.30\ m^{-1}$ to 2.53 m/s at $Cs = 0.75\ m^{-1}$ while the minimum and mean speeds are almost constant with a slight decrease as Cs increases. The maximum evacuation speed trends in the present experiments and those in Frantzich and Nillson (2003, 2004) and Fridolf et al. (2013), lie on the same decreasing logarithmic curve as a function of extinction coefficient.

1. Introduction

Smoke caused by tunnel fires flows stratified in the tube and large space during the initial fire, and after the stratification of the smoke is disrupted by the heat absorption by the ceiling wall, it starts to diffuse inside the tunnel, making evacuation activities, rescue activities and fire extinguishing activities extremely difficult. In particular, because of the many tunnels in Japan, many drivers use tunnels, increasing the importance of preventing tunnel fire disasters to a high degree, requiring accurate strategies.

One important point in the investigation of strategies to prevent disastrous tunnel fires is the clarification of evacuation behavior during tunnel fires. Tunnel space is around 10 m wide, from 5 m to 8 m high, and several hundred meters long, therefore it is clear that evacuation behavior will be different from that in normal building fires (Seike et al., 2012).

The authors have proposed a tunnel evacuation simulation model in which each evacuee influenced by smoke is analyzed using CFD based three dimensional smoke behavior (Kawabata et al., 1998), and the number of evacuees who cannot evacuate in a smoke-filled tunnel are calculated to assess tunnel fire safety (Seike et al., 2011).

In the evacuation model proposed in the paper (Seike et al., 2011), people start to evacuate when they see smoke or other people evacuating or hear emergency announcements, and after recognizing that they must evacuate, they evacuate at a constant walking speed. Hence walking speed during evacuation is not just the moving speed of evacuees but is also affected by the speed of information exchange, which alerts people to the need for evacuation. Thus, the maximum evacuation speed is one of the most important factors to consider to assess tunnel fire safety. Regarding walking speed in a tunnel, there have been few experimental instances. Therefore, evacuation simulations have, so far, used normal outside walking speed, not walking speed in smoke, to give the probability distribution function of walking speed. It is necessary to clarify the evacuation behavior in a tunnel fire and to perform a high quantitative assessment to use evacuation walking speed in diffusing smoke. Hence, the objective of the present study is to clarify simple walking speed in smoke and evacuation speed in smoke measured using a full-scale experimental tunnel as a method of investigating the basic evacuation performance characteristics during a fire.

Table 1 shows past experiments and research regarding walking speed in smoke in tunnel space. In Japan, no research using full-scale road tunnels has been conducted; only experiments using small sectional space such as corridors. Jin and Yamada (1985) has measured the walking speed in corridors filled with smoke, and reported that walking speed decreases rapidly at extinction coefficient, $Cs = 0.4\ m^{-1}$ in irritant smoke produced by burning wood. These results are generally used in Japanese road tunnel fire disasters prevention to assess fire safety as the inability of evacuees to evacuate at evacuee face height, which is 1.5 m high from

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Table 1
Summary of conditions in the present and literature experiments regarding walking speed in smoke in tunnel space.

	Jin and Yamada (1985)	Frantzich and Nilsson (2003, 2004)	Fridolf et al. (2013)	The present experiments
Experimental space	Corridor (20 m long)	Firefighting training tunnel 37 m long, 5 m wide and 2.6 m high	Full scale road tunnel 200 m long, including 122 m 10%, downslope, 8 m wide	Full scale road tunnel 700 m long, 9.8 m wide and 6.9 m high Inclination 0%
Occurred smoke	Irritant smoke (by wood) Non-irritant smoke (by crude oil)	Glycerol based artificial smoke and acetic acid	Glycerol based artificial smoke and acetic acid	Smoke machine Non-irritant white smoke
Experimental purpose	Visibility and walking speed Stop when participants can see the emergency sigh	Investigation of walking speed in tunnel and way finding and design of emergency exits	Investigation of walking speed in tunnel and way finding and design of emergency exits	Walking and evacuation speed in tunnel filled with smoke
Participants age	Unknown	18–29 Mean: 22	18–66 Mean: 29	23–62 Mean: 33.9
The number of participants	10	46 Man: 30 Woman: 16	100 Man: 56 Woman: 44	Total of 294 Man: 292 Woman: 3

the floor, at extinction coefficient higher than 0.4 m^{-1} (Dobashi et al., 2000).

Frantzich and Nilsson (2003, 2004) and Fridolf et al. (2013) performed evacuation experiments using full-scale tunnels, Frantzich and Nilsson (2003, 2004) while targeting extinction coefficient thick as Cs = 1.9–7.3 m^{-1}, and Fridolf et al. (2013) and also targeting excessively thick extinction coefficient Cs = 1.2–3.1 m^{-1}, but there exists no experiments targeting less than Cs = 1.0 m^{-1}, which includes Cs = 0.4 m^{-1} as the Japanese road tunnel fire prevention standard. Hence, the objective of the present paper is clarification of the relationship between walking speed and extinction coefficient less than Cs = 1.0 m^{-1}. Evacuation walking experiments in smoke have been performed using a full-scale experimental tunnel to investigate the basic evacuation performance characteristics during a fire.

2. Experiments

2.1. Experimental tunnel

Experiments were performed in a full-scale tunnel facility at the National Institute for Land and Infrastructure Management of the Ministry of Land, Infrastructure, Transport and Tourism in Japan in December 2013. The tunnel is horse-shoe shaped, its total length is 700 m, it is 9.8 m wide and 6.9 m high, and a 400 m long space in the tunnel that can be closed by shutters to fill it with smoke was used. The interval used for the experiments (longitudinal and transverse section) is shown in Fig. 1. In the present study, x means longitudinal direction and the origin point is set at checkpoint 1 in Fig. 1.

2.2. Methodology

Users involved in tunnel fire incidents decide to begin evacuating when they (1) see smoke along the ceiling or around them, (2) see other people evacuating and (3) hear an emergency announcement (Seike et al., 2011). Focusing on seeing evacuating people, evacuees' walking speed reaches information transmission velocity which indicates the need for evacuation to others, therefore the maximum evacuation speed is particularly important in clarifying evacuation performance. Thereupon, in the present study, to clarify simple walking speed and evacuation speed in smoke, evacuation and walking speed were measured using a full-scale experimental tunnel to investigate the basic evacuation performance characteristics in fires.

Participants in the experiments went in the x positive direction outward around 300 m from checkpoint 1–4, and then returned in the x negative direction homeward around 300 m from checkpoint 5–8 in Fig. 1. In the present experiments, participants were instructed to walk normally from checkpoint 1–4, and to perform emergency evacuation from checkpoint 5–8. The explanation was given as follows.

Normal walking: "Please walk in the tunnel as you normally walk."

Emergency evacuation: "Fire occurs in the tunnel and the present situation is considerably serious that an explosion could occur or the fire might spread, so please decide to evacuate, and do extremely urgently.": When the participants were instructed the emergency situation in this way, some participants considered it to be necessary to run and they did.

The speeds measured in the former and the latter are hereinafter referred to as "walking speed" and "evacuation speed", respectively. Additional explanations were given in earlier