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Overview of research on fire safety in underground road and railway tunnels

Ying Zhen Li*, Haukur Ingason

Safety and Transport – Fire Research, RISE Research Institutes of Sweden, Sweden

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ABSTRACT

In the past two decades, the interest in fire safety science of tunnels has significantly increased, mainly due to the rapidly increasing number of tunnels built and the catastrophic tunnel fire incidents occurred. This paper presents an overview of research on fire safety in underground road and railway tunnels from the perspectives of fire safety design. The main focuses are on design fires, structural protection, smoke control and use of water-based fire suppression systems. Besides, some key fire characteristics, including flame length, fire spread, heat flux and smoke stratification, are discussed.

1. Introduction

Urbanization stimulates the wide use of underground space for fast transportation in the cities. The numbers of underground road tunnels, subway tunnels and other railway tunnels are continuously increasing. Meanwhile, complexities of the infrastructure are also increasing, e.g. a roundabout in a tunnel, a metro transfer station connecting more and more lines, etc.

Despite the relatively low risk for large fires in tunnels, the increasing number of underground tunnels implies that more fire incidents may occur, unless more effective measures have been taken to reduce it. A fire incident in a critical infrastructure can be catastrophic. One example is the arson fire in a metro station in Daegu, South Korea, 2003, caused 198 deaths and 146 injuries (Ingason et al., 2015b). Another examples are the Channel tunnel fire incident in 1996 causing considerable damage to the tunnel lining over a length of approximately 480 m (Channel Tunnel Safety Authority, 1996) and the fire incident in the same tunnel in 2008 causing the tunnel lining destroyed over a length of 750 m (BEA-TT, RAIB, 2010). In recent years, reports on arson fires and terrorist attacks appear to be increasing. Special attentions should be paid to these issues.

This has forced the authority to reconsider the safety level of the underground tunnels and rethink the use of more active and/or passive fire protection systems. Nowadays tunnel fire safety has already become one of the key issues for any tunnel project.

In 2008, Ingason (2008) made an overview of the tunnel fire research. He summarized the important work conducted in tunnel fire community concerning critical velocity for smoke control in longitudinally ventilated tunnels, correlation between heat release rate and maximum ceiling temperatures, influence of ventilation on maximum heat release rate and fire growth rate and fire spread in and between vehicles. In the past decade, the interest in fire safety science of tunnels has significantly increased mainly due to the rapidly increasing number of tunnels built and the catastrophic tunnel fire incidents occurred as mentioned above. Much new knowledge has been obtained since 2008. There is a need to summarize these researches to provide sound knowledge and facilitate the foundation of the discipline of tunnel fire safety.

This paper presents an overview of research on fire safety in underground road and railway tunnels from the perspectives of fire safety design. The main focuses are on design fires, structural protection, smoke control and use of water-based fire suppression systems. Besides, some key fire characteristics are also discussed.

2. Fire incidents in underground road tunnels and railway tunnels

2.1. Underground road tunnels

A summary of some severe incidents in underground road tunnels obtained from the literature (Ingason et al., 2015b; Lönnermark, 2005; Carvel and Marlair, 2005) is presented in Table 1. It can be seen that in these severe fire incidents, collision and engine failure are key causes of these incidents. Heavy goods vehicles (HGVs) were involved in all of these severe fire incidents. These incidents are also characterized by the

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* Corresponding author.
E-mail address: yingzhen.li@ri.se (Y.Z. Li).

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Table 1
A list of some severe fire incidents in road tunnels.

Year	Tunnel, length	Location	Cause of fire	Duration	Consequences for		
					People	Vehicles	Structure
1968	Moorfleet L = 243 m	Hamburg, Germany	breaks jamming	1 h 30 min	none	1 HGV	Serious damage for 34 m
1976	B6 L = 430 m	Paris, France		1 h	12 slight injured	1 HGV	Damage for 150 m
1978, 11 Aug	Velsen L = 770 m	Velsen, Netherlands	Front-back collision	1 h 20 min	5 dead 5 injured	2 HGVs 4 cars	Serious damage 30 m
1982, 7 Apr	Caldecott L = 1083 m	Oakland, USA	Front-back collision	2 h 40 min	7 dead 2 injured	3 HGV, 1 bus, 4 cars	Serious damage, 580 m
2007, 23 Mar	Burnley L = 3400 m	Australia	Rear-front collision HGV/cars	1 h	3 dead 2 injured	3 HGV and 4 cars	Use of fire suppression system, no damage
2011, 29 Mar	Oslofjord, L = 7230 m	Norway	Engine problem	< 1 h	4 injured	1 HGV	
2011, 23 June	Oslofjord L = 7230 m	Norway	Engine breakdown	< 1 h	12 injured	1 HGV	Damage to tunnel linings

serious damage to the tunnel structure, which can be as long as several hundred meters. Lönnermark (2007) made an analysis of fires involving HGVs and found that fires in tunnels involving only one burning HGV very seldom lead to fatalities, but as soon two or more HGVs are involved, the fire most often leads to fatalities. These conclusions are reflected in what can be interpreted from Table 1.

2.2. Underground rail tunnels and metro stations

A summary of some severe incidents in underground railway tunnels and metro stations obtained from the literature (Ingason et al., 2015b; Lönnermark, 2005; Beard and Carvel, 2012) is presented in Table 2. These severe fire incidents are in most cases originating from electrical fault. Compared to the severe fire incidents in road tunnels listed in Table 1, the consequences of these severe metro fire incidents are characterized by higher number of fatalities in a single incident. The number is expected to be related to the number of users but in reality it really indicates that the safety level of underground rail vehicles and stations/tunnels needs to be improved. Arson fires require special attention due the consequences of such fires in metro systems. Despite the small number of arson fires, the resulting consequences are clearly serious. The severe consequences in these metro station fire incidents are mainly due to rapid fire development in the wagon, and the large number of passengers on board and inside the metro station. Nowadays metro systems are becoming more and more complicated and constructed at numerous levels down to significant depths. Accordingly fire safety issues will require greater attention in the future.

Table 2
A list of some key fire incidents in underground railway tunnels including metro stations.

Year	Name country	Initial fire source location	Most possible cause of fire	Consequence
1903	Couronnes metro France		Electrical fault	84 dead
1972	Hokoriku tunnel Japan	Restaurant		30 dead and 690 injured
1979	San Francisco metro US	Underneath of a carriage	Electrical fault	1 dead and 58 injured
1987	King Cross station UK	Escalator in the Station	Cigarette	31 dead
1990	New York metro US	Inside the tunnel	Cable	2 dead and 200 injured
1991	Moscow metro Russia	Underneath of a carriage	Electrical fault	7 dead and over 10 injured
1995	Baku metro Azerbaijan	Rear of 4th car out of 5	Electrical fault	289 dead and 265 injured
2003	Jungangno metro Daegu, South Korea	In train	Arson, Petrol	198 dead and 146 injured

3. Design fires

The design fire is the most important parameter for describing the development and consequences of a fire. An overview of heat release rates (HRRs) for different vehicles driving through underground road and railway tunnels is presented. The focus is on understanding fire development and the influences of tunnel conditions (such as ventilation and tunnel geometry) on the HRR. The HRR describes the fire development in the form of energy release given in megawatts (MW) over a given time period.

In the following, the measured HRRs are summarized for each type of vehicle or fuel in graphs. In the underground road tunnels, the vehicles mostly consist of cars, buses and trucks. Fuel tankers are generally forbidden in the urban underground road tunnels and thus not considered. In the underground railway tunnels, the vehicles mostly consist of subway cars, although some railway stations are also located underground. The characteristics of fire development, i.e. fire growth and maximum HRR, will be depicted in detail, together with the influence of ventilation and tunnel structure.

3.1. Passenger cars

The measured or estimated HRRs from some passenger car fire tests are given in Fig. 1. The medium and fast t-squared curves (Karlsson and Quintier, 2000) are also plotted. These tests include the Fiat 127 test by Ingason et al. (1997), the Renault test in Eureka programme by Steinert (1994), the Citroen test by Steinert (2000), the Trabant test by Steinert (2000), the Citroen test by Shipp and Spearpoint (1995), the test Car2 by Mangs and Keski-Rahkonen (1994a, 1994b), and the tests Car1 and Car 2 by Lecocq et al. (2012). In the Fiat 127 test by Ingason et al. (1997), the car was placed in a blasted tunnel and ignited in the engine compartment with an electrical device. The peak HRR was 3.6 MW after 12 min. The fire was extinguished by fire fighters 13 min into the test. The Renault car fire test was carried out in EUREKA 499 test series (Fires in Transport Tunnels: Report on Full-Scale Tests, 1995; Steinert, 1994) and presented by Steinert (1994). The car used was a Renault Espace J11-II (1988) and was ignited in a transistor in the console in order to simulate a fire in the cable system. The peak HRR was 6 MW after 8 min. HRRs of different types of passenger cars in a car-park, all with different types of car bodies (plastic and steel) have also been