ON THE FOUR ELEMENTS OF TUNNEL SAFETY: FIRE, AIR, WATER AND EARTH

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ABSTRACT

Based on an assessment of the tunnel safety in terms of the four elements: fire, air water and earth, some principal aspect regarding tunnel safety have been established.

With respect to tunnel equipment, it appears that rapid fire detection and the subsequent swift tunnel closure for incoming traffic is a main element.

In case of fire, it should be expected that active information of tunnel users is required and for this purpose the loudspeakers of the type SLASS are to be considered.

The emergency exists need to be attractive to use and should distinguish themselves from the service doors.

In case of unidirectional traffic that is never congested, longitudinal ventilation is appropriate for smoke management. Otherwise, smoke extraction is more favourable.

Fixed fire fighting systems can be installed to reduce the impact of tunnel fires on the tunnel structure and in order to increase the level of safety for the tunnel users.

Keywords: tunnel safety, self rescue, tunnel fire, fixed fire fighting systems FFFS

1. INTRODUCTION

Tunnel safety is the subject of numerous papers and the idea behind the concept of the present one is to view this from the perspective of the four elements: fire, air, water and earth. A new organization could lead to other conclusions than in the past.

In certain areas, tunnel safety is little different from conventional safety. However, this paper focuses on aspect where the nature of the tunnel environment becomes important i.e. when there is limited to time to conduct egress. In such circumstances, self rescue by the tunnel users has to be assumed and the typical incident is a tunnel fire.

2. FIRE

2.1. Introduction

Other accidents than tunnel fires result in many more annual casualties, see e.g. PIARC (2012) [1]. Although rare, tunnel fires may lead to exceptional dimensions of the impact and are therefore given particular attention when assessing the tunnel safety.

2.2. Tunnel design fires for tunnel safety

For the design of the integrity of the tunnel structure in case of fire, time-temperature curves are normally used. However, for the assessment of the user safety, the design fire is normally described in terms of its heat-release rate (HRR). As shown in **Table 1**, there is a wide range of HRR for road vehicles.

Table 1: Typical peak heat-release rates (HRR) from different road vehicles from PIARC 2011 [2] according to Ingason [3].
* Depending on the quantity and nature of the load.

Vehicle type	Peak HRR [MW]
Passenger car	5 – 10
Light Duty Vehicle (LDV)	15
Coach, bus	20
Lorry, heavy-goods vehicle (HGV) up to 25 tonnes*	30 – 50
heavy-goods vehicle (HGV) 25 - 50 tonnes	70 – 150
Petrol tanker	200 - 300

The decision which design fire to assume is implicitly a cost-benefit consideration. In case of longitudinal ventilation systems, the additional costs when deciding on a higher HRR is much lower than in case of smoke extraction. As a rough estimate, the size of the smoke extraction duct is proportional to the HRR of the design fire.

It is important to note that a tunnel ventilation system also is of benefit, when it is used for fires larger than the design fire.

Moreover, it is not evident that a tunnel with a smoke extraction designed for a 30 MW provides a lower level of safety than a tunnel with longitudinal ventilation that is designed for a 200 MW fire.

2.3. Fire mitigation methods

The best mitigation method is the prevention of the fire. Firstly, this is done by having a tunnel that is not prone to the occurrence of accidents. Secondly, the prevention of overheated vehicles from entering the tunnel is a valued method. This is done for the Mont-Blanc, Fréjus and the Gotthard tunnel by thermo scanning of the trucks approaching the tunnel. It is being said that up to 30% of the brakes of the trucks due not comply with the requirements.

From a perspective of the structural design of a tunnel, a passive fire protection seems the evident choice. However, thermal isolation of the tunnel walls reduces the heat transfer through the walls and results in higher temperatures in the traffic space, which again worsens the tenability i.e. deteriorates the conditions for self rescue.

Whereas the growth rate of a fire is by and large proportional to the longitudinal flow in the tunnel, the maximum heat-release rate does not seem to be influenced by the flow rate in the tunnel [8]. Higher flow rates, however, can increase the risk of fire spread.

3. AIR

3.1. Ambient conditions

The external ambient conditions are particularly important for the design of the tunnel-ventilation system, which also became evident in the Mont-Blanc fire. The requirements from different countries vary. In Switzerland [6], it is specified to dimension the ventilation system according to the annual average of the winds in the disadvantageous direction with respect to the orientation of the tunnel portals. In Austria [4], the requirements are more onerous, as it is based on the statistic of the half-hourly mean values and the tunnel ventilation has to cater for the 95 % percentile of the winds. In case of the highest risk category IV, even dimensioning for 98 % of the winds is required.

When a tunnel goes through a mountain, the difference in barometric pressure between the tunnel portals can be much higher than the wind pressure. The French guideline on the design of tunnel ventilation systems [7] provides a method to estimate this barometric pressure difference that though to our experience appear to lead to rather high values.

3.2. Control of the longitudinal flow

In order to have an efficient smoke management, the tunnel-ventilation system needs to cater for the ambient condition.

In case of smoke extraction, the simplest and most robust method is to specify the smoke-extraction rate so that the required conditions are inherently satisfied irrespectively of the ambient conditions. Similarly, in case of longitudinal ventilation and if there are no persons downstream of the fire, the adequate applied thrust need to be engaged in case of fire. In both cases, it is considered that the high flow velocities that occur may be judged to be permissible.

In other circumstances, an active control of the longitudinal flow is inevitable. PIARC 2011b [10] gives advice on the operation strategies for emergency ventilation in road tunnel and also provides a description of various tunnel-ventilation systems.

With respect to the ventilation control routine, Altenburger et al. (2013) [9] concluded that a PI-regulator with the parameters according to the Ziegler/Nichols criteria and incorporating anti-windup is the best applicable scheme.

The main difficulty in the control of the longitudinal flow during a fire is that the desired flow velocities, which depending on the application are between 1 and 3 m/s, are close to the accuracy of the flow measurements in the tunnel. In a laboratory, an anemometer may have an accuracy of ±0.1 m/s but in a tunnel application, it is difficult to envisage accuracies better than ±0.3 m/s. Erroneous measurements inevitably lead to a wrong control of the longitudinal flow which can have fatal consequences. Therefore plausibility tests based on several independent measurements are required ([4], [6], [10]). In order to do this, at least three measurements need to be available. Considering that the average flow velocity is of importance, anemometers that measures the flow across the tunnel cross section e.g. based on the ultra-sonic technique are favoured.

In particular in long tunnels, an additional difficulty controlling the longitudinal flow based on velocity measurements is that the flow can initially be driven by the moving traffic. One solution is to base the control of the longitudinal flow on to measurements of the barometric pressures at the portals, as it is done in the Fréjus tunnel [11]. The difficulty is that the barometric pressures are of the magnitude of 100 000 Pa which should be compared to typical wind pressures of 20 Pa. Based on three measurements at each portals of 13 km long Fréjus tunnel that experiences barometric pressure differences between the two portals of up to 600 Pa, it is therefore possible to conduct a first response to the atmospheric conditions immediately subsequent to the fire detection.

3.3. Smoke management with tunnel ventilation

3.3.1. Longitudinal ventilation

With longitudinal ventilation, the smoke is blown towards one tunnel portal and the tunnel user upstream of the fire are then in a safe haven. In case of fluent unidirectional traffic, this is the simplest smoke management. As long as it can be ensured that nobody is downstream of the fire, there is no obvious maximum length for a tunnel using this ventilation concept. Moreover, the view could be adopted that there is no need to control the velocity of the longitudinal flow as long as the velocity is adequately high to prevent backlayering of smoke i.e. avoiding that smoke flows against the direction of the main flow. Therefore, longitudinal ventilation is envisaged for the 18 km Fehmarnbelt tunnel that is to establish the fixed link between Denmark and Germany. This is characterised by low traffic figures, an emergency lane and the fact that the connecting road work is not expected to cause traffic congestion in the tunnel.

The connecting road work has an influence on the traffic flow in the tunnel and it is therefore often not to be expected that traffic congestion can be prevented at all times for tunnels in urban areas. In case of traffic at standstill, Ilg et al [12] concluded that the best ventilation strategy in case of longitudinal ventilation is to maintain the flow direction at a flow velocity of 1.0 to 1.5 m/s. At this velocity, there is a certain chance that smoke stratification occurs so that the tunnel users can escape below the smoke layer at normal walking speed. In case that there is no smoke stratification, it could be the better strategy to blow the flow at higher speeds e.g. 3m/s, which would keep on side of the fire smoke free and dilute the toxic gasses on the downstream side of the fire [13]. However, at such flow velocities, the visibility on the downstream side is bound to be very poor and therefore the walking speed reduced to a fraction of a meter per second (down to 0.2 m/s).

The use of longitudinal ventilation in a tunnel with bi-directional traffic is problematic and similar to the situation with unidirectional traffic at standstill. As an alternative to controlling the flow velocity, it is often decided not to engage the tunnel ventilation system at all and to hope that this results in smoke stratification i.e. provides the best tenable conditions.

3.3.2. Smoke extraction

A smoke extraction limits the smoke spread to the extraction zone. Tunnel users outside this are in a safe haven. This is therefore the favoured ventilation system in case of bidirectional traffic and for congested unidirectional traffic.

Considering that the smoke-extraction rate is similar to the smoke-production rate, it is important to have an active control of the longitudinal flow so that the smoke does not flow beyond the extraction zone.

3.3.3. Response time

Irrespectively of tunnel ventilation system, it is of paramount importance that it is activated quickly and that the tunnel portals are closed to incoming traffic [13]. The base line in [13] was to assume fire detection within 60 s when it had reached 5 MW, which corresponds to the criteria in RABT (2006) [5], and that the tunnel ventilation as well as the tunnel closure was initiated merely 20 s subsequent to the fire detection. If the fire detection took 600 s, the benefit of the tunnel ventilation was little different from assuming an infinitive fire-detection time.

4. WATER

4.1. FFFS – fixed fire fighting systems

There are two main types of water based FFFS installed in road tunnels today. These are water-spray systems and water-mist systems. The main mechanisms of fire suppression using these two types of systems are different. A water-spray system predominantly controls a fire mainly by fuel surface cooling, as well as taking heat out of the system by cooling surfaces directly adjacent to the fire site, whereas a water-mist system predominantly operates by gas cooling.

The benefit of the water spray systems is their simplicity. On the other hand, the water-mist systems require much less water. Moreover, it is advocated that water mist is better in dealing with pool fires (see discussion in section 4.2).

In contrast to earlier concerns, PIARC 2008 [15] concluded that FFFS under certain circumstances could be beneficial for the safety in a road tunnel. In spite of some concerns about the tenability, where in particular the potential negative influence of FFFS on the visibility is being argued, the predominant current thinking is that using FFFS has a positive net effect on the tunnel safety.

In the two large tunnel project in Stockholm (Norra länken and Förbifart Stockholm), FFFS is being introduced as a remedy against traffic congestion. As a consequence in Förbifart Stockholm, the design fire for the dimensioning of the tunnel-ventilation system was reduced from 100 MW to 50 MW.

4.2. Drainage and pool fires

The necessity to have an efficient drainage system has been recognised for decades. Longitudinal slots are more efficient than drainage at individual points.

Experiments in Törnskogtunneln [16] demonstrated that the drainage system was capable of removing the water by the FFFS envisaged for the Norra länken tunnel. Another spillage experiment examined the consequence of an immediate release of 2 m^3 of water. If the spillage had been gasoline, the HRR of a fire could be up to 150 MW. However, the fluid layer was so thin that it was concluded that the fire at this size would be of very short duration. Consequently, it appears that in a road tunnel, a pool fire will have limited duration unlike the ones in experiments that use pans to contain the liquid.

5. EARTH

5.1. Distance between emergency exits

In the Nordic research project on egress from tunnel fires in road tunnels [13], it was concluded that the potential number of fatalities was proportional to the distance between egress routes, which were at distances of 50 m, 150 m and 250 m. This is in line with the model by Vrouwenvelder [14] for such distances. In [14], however, it is predicted that the degree of deterioration of the chances for successful egress becomes much smaller when the distances between escape routes exceeds about 200 m.

5.2. Use of emergency exits

The prime question with respect to egress routes is, “will they be used”? Based on expert judgement [13], it was estimated that under normal circumstances, it should not be expected that in average more than about a third of the users would commence egress and use the egress routes. The reason for this behaviour is that people do what they are used to do. In case of traffic congestion or an accident, it is normal to stay in the car and normally nobody have experiences with tunnel fires.

This probability of egress could be increased to about 100 %, if a person of authority demands the tunnel user to leave their vehicles and to use the emergency exits. This is a good argument for having rapid response teams.

In any respect, the tunnel user need to be informed that they have to egress and the effect is larger when using multiple means of information. Conventionally, radio broadcast and information on variable message sings has been applied.

Due to reflections by the tunnel walls, messages from conventional loudspeaker systems are difficult to understand. However, with the new synchronised longitudinal announcement speaker systems (SLASS, see Figure 1), this is not the case. From personal experience driving through a tunnel in a vehicle with closed windows, the announcements were clear and easily understandable. When having such systems, it could even be considered no longer to use the broadcast system.

The likelihood that emergency exits are being used is increased if they clearly distinguish themselves from service doors. This can be done by colouring them green as the exit signs and have particular lights to attract them, see example Figure 2. The attractiveness of the egress door is increased , if it has a window and there is light on the other side. Moreover, the opening of the door should be intuitive. With this respect, some believe that panic bars are required. However, other mechanism work just as well and may lead the users to open even sliding doors. Sliding doors are mandatory in Switzerland, as the pressure differences in a road tunnel in most cases inhibits opening conventional swing doors applying the maximal permissible required force of 100 N

Figure 1: Illustration from [13] of SLASS loudspeaker system in the Elbe tunnel.

Figure 2: Illustration from [13] of emergency exit the Elbe tunnel.

6. CONCLUDING DISCUSSION

Rapid fire detection and closure of the tunnel for incoming traffic is the main feature in minimising the consequences of a tunnel fire. It is proposed to adopt the criteria in RABT (2006) that a tunnel fire of 5 MW in a tunnel at an air flow at 6 m/s shall be detected within 60 s. Shortly after this fire detection, the tunnel has to be closed to incoming traffic. Nevertheless, recognising that most fires are detected by the tunnel users and reported prior to the detection of a system, full coverage for the use of mobile telephones should be ensured. In Switzerland, smoke detectors are compulsory. Experiments in Sweden demonstrated that they are much faster in detecting the fire than conventional linear heat detectors.

The tunnel user need to be actively informed that they need to egress in case of fire. Several methods should be applied and a good system is the SLASS loudspeaker system.

Emergency doors should be easy to open i.e. by applying a force of no more than 100 N and attractive for egress: green with light around and having a windows showing with light in the space on the other side.

Longitudinal ventilation is a good system for smoke management of tunnels with unidirectional traffic as long as traffic congestion is avoided at all times. In other cases, smoke extraction is more favourable.

Fixed fire fighting systems can be installed to reduce the impact of tunnel fires on the tunnel structure and in order to increase the level of safety for the tunnel users.

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