ON THE SAFETY OF SHORT ROAD TUNNELS

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ABSTRACT

Many road tunnels are comparatively short and a large number of them are in the range of 500 to 1’000 m of length or shorter. Such tunnels are typically longitudinally or naturally ventilated and have emergency exits at a distance in the range of 300 to 500 m. The detailed specifications vary from country to country. Risk analysis and experience show, that the safety level of such tunnels is frequently unsatisfactory, particularly in case of bi-directional traffic and tunnel slopes in the range of 2-3% or higher. This is basically related to the short time scales characterizing such tunnels, which can result in extremely rapid smoke propagation. This was tragically demonstrated e.g. in the fire in the Viamala tunnel (16 September 2006), on the Swiss A13 motorway.

The present papers reviews some of the characteristics and safety-relevant weaknesses of the current design approaches for short tunnels, based on our design and design-support experience. We strongly feel that the current, guideline-oriented approaches need to be enhanced by genuinely risk-based methodologies, which allow for a clear identification of weaknesses and possible solutions. A further potential for improvement can be identified at the level of SCADA systems: faster and more integrated, “intelligent” automatic responses of all tunnel’s equipment will be provided by next generation’s SCADA technologies which are currently developed within the EU research project EMILI.

Keywords: short road tunnels, safety, ventilation, SCADA

1. INTRODUCTION AND OBJECTIVES

Most tunnels are short or very short, as illustrated in Figure 1. Roughly 75% of the Swiss tunnels are shorter than 1 km (representing roughly 30% of the total tunnel length) and 60% shorter than 500 m (representing roughly 15% of the total tunnel length). Data for other countries are provided e.g. by Lotsberg (2009). Such tunnels frequently represent a problem from the point of view of safety. Several quite obvious reasons are well know also laypersons: the higher accident rate in the immediate vicinity of the portals, where the environmental conditions for the driver change very rapidly, the reduced equipment (e.g. radio, ventilation, water supply, CCTV etc.), the sometimes reduced availability of escape routes etc.

More subtle reasons for this situation are related to the particularly small time scales characterizing short tunnels. The air velocity and smoke propagation patterns in the tunnel change very rapidly depending on traffic, ventilation modes, thermal effects, portal wind etc. Many short tunnels, particularly in the Alpine range, have a significant slope. They are therefore particularly sensitive towards the local heating by the fire, which can generate a violent “stack-effect”. As it will be shown below, these problems are accentuated by the limited usefulness of ventilation in very short tunnels. Tunnels with bidirectional traffic are obviously particularly challenging.

The risks related to short tunnels are frequently underestimated. Because of this misperception, joined with the objective difficulties raised by the large number of such tunnels, necessary upgrades are frequently delayed or reduced.
Some of the specific risks related to short tunnels are discussed in the present papers and possible paths for improvement are outlined.

![Graph showing the length distribution of Swiss tunnels](image)

**Figure 1:** Length distribution of Swiss tunnels, presented as the percentage (based on number and on length) of tunnels shorter than a certain value (data from Lotsberg 2009).

### 2. THE FIRE IN THE VIAMALA TUNNEL

The safety problems related to short, steep tunnels were tragically demonstrated during the Viamala tunnel fire, on the Swiss A13 motorway (16 September 2006). The key data of the tunnel - opened in 1967 and thoroughly retrofitted in the past few years – are not particularly unusual: length 760 m, slope 5% (North to South), bi-directional traffic on two lanes, about 8’000 vehicles/day, longitudinal ventilation, no emergency exits.

![Image of the Viamala tunnel](image)

**Figure 2:** The fire in the Viamala tunnel (16 September 2006).

The fire developed at about 100 to 150 m from the lower North portal. It was originated by a collision between a coach and a car and rapidly involved both vehicles and a second car. According to the whiteness’s reports fire was instantaneous and smoke propagation was extremely rapid (values up to 10 m/s were reported). 9 persons tragically died in the smoke (among them a young family and the persons who died while heroically trying to save them, Claudia Coduri and Francesco Franciamore). Nevertheless 21 persons from the coach and about 20 cars succeeded to escape from the tunnel. Numerous car drivers behind the accident site left the tunnel through the South-portal turning their vehicles. As the tunnel alignment is a long S-shape curve many people could not see the other portal and the accident site. Further details on the fire are reported e.g. by the Tiefbauamt Graubünden (2006) and Mundwiler (2007).
The most striking aspect of the Viamala fire is that the tunnel’s equipments were essentially in line with the current Swiss requirements (FEDRO 2000) and performed as expected. The fire was signaled at 13:13 by the fire-detection system and immediately confirmed by a phone call and the use of a fire extinguisher, the alarm was correctly transmitted and the automatic measures immediately initiated (maximum lighting, emergency lighting, tunnel closure, jet fans activation and CCTV images transmission). The radio broadcast of the alarm did not work properly. The rescue teams were on site about 10 minutes after the receiving the fire alarm and reported heavy smoke exiting from the southern (higher) portal and smoke-free conditions at the northern extremity (Mundwiler 2007).

Why this tragic outcome, if almost everything worked properly? The main reasons could be identified as follows:

- Rapid fire evolution caused by ignited fuel during the collision (“Fire broke out in five seconds”).
- Extremely rapid smoke propagation (velocity up to 10 m/s) and complete loss of stratification.
- Wrong user’s behavior with fatal consequences was observed.

The main lessons to be learned from this tragic tunnel fire are:

- Self rescue by the concerned tunnel users is crucial and must begin very quickly.
- The involvement of a coach with many people on board had a huge potential towards higher consequences. Fortunately only two persons from the coach died. 6 victims traveled in a car, one was a truck driver.
- 150 m to walk in heavy smoke towards the north portal was a too long distance for some of the victims.
- Even the short reaction time of the fire services, of the order of 10’, was too long for most of the tunnel users.
- A public dispute about permissibility of U-turning cars and escaping from the tunnel rose. In the Viamala case this fact might have limited the number of victims.

3. SMOKE PROPAGATION

The key elements affecting smoke behavior in road tunnels are:

- Traffic.
- Thermal effects (natural temperature differences, fire heating).
- Meteorological effects (portal wind).
- Mechanical ventilation.

The influence of thermal effects increases with increasing tunnel slope. Tests and real fires showed that in case of fire the temperature increases significantly only over a distance of 500-1’000 m. Thermal effects act therefore faster and have a larger effect on the air and smoke motion in short tunnels, as illustrated in Figure 3. In shorter tunnels significant longitudinal velocities are achieved even with moderate slopes of the order of 2% (Figure 3 left). Similarly, the time scales for the velocity development are of the order of only 2’-3’ for short tunnels, as compared to 4’ and more for tunnels of 2 km and longer (Figure 3 right). Even faster developments can be expected in case of a faster fire dynamics, such as the one observed in the Viamala case. Similarly, short tunnels can be extremely sensitive towards external wind portal loads.
Figure 3: Longitudinal air velocity generated through a 30 MW fire (devel. time 5’), without mechanical ventilation. Left: Peak vs. tunnel slope; Right: Time development (slope 5%).

A simple example can illustrate the combined effect of traffic and thermal effects, Figure 4. Let us consider a 760 m long tunnel with a uniform slope of 5% and a moderate traffic volume, in both directions 600 vehicles/h, 80 km/h, 10% HGV. A “standard” HGV fire located at ¼ of the tunnel length is modeled as follows: 30 MW fire, with a linear increase of heat-release rate between 0 and 5’, followed by a 60’-long phase with constant heat-release rate. The traffic is stopped 2’ after ignition. Note that this setup does not correspond to the Viamala case.

The results, assuming no mechanical ventilation, are presented in Figure 4 (simulations were carried out using the 1D code TunSim, Bettelini, 2008). During the initial 1’-2’ the scenario is dominated by the traffic, but the “stack-effect” becomes rapidly dominant. Conditions for self rescue are clearly very unfavorable. On both sides of the fire smoke propagation is faster than the expected escape velocity.

Figure 4: Longitudinal air velocity in the tunnel (left) and smoke propagation (right).

The tunnel is rising from left to right, 30 MW fire, no mechanical ventilation.

The very short time constants relevant for tunnel aerodynamics and smoke propagation in short tunnels, of the order 2’, impose extremely strict constraints to all tunnel safety facilities: detection, system’s response, escape etc.
4. TUNNEL EQUIPMENT

The safety requirements for Swiss tunnels are stated in the norm SIA 197/2 (SIA, 2004) and in a number of directives developed by the FEDRO (Swiss Federal Road Authority). Full requirements are applicable for tunnels longer than 600 m, reduced requirements starting with 300 m. For tunnels between 300 and 600 m, CCTV equipments and radio (communication and broadcast) are not mandatory.

The minimum requirements from the European Directive 2004/54/EC apply only for tunnels longer than 500 m and full requirements are applicable only starting with 1'000 m. The situation in other countries was reviewed e.g. by Day (2004) and Kim et al. (2008). Details are not relevant for the present purposes.

Figure 5: Typical equipments according to the Swiss guidelines for short tunnels (adapted from Tiefbauamt Graubünden, 2006).

Based on the considerations exposed in the previous chapters, the key elements for a successful emergency management in short tunnel are:

– Very early detection of fire principles certainly represents the most fundamental requirement. The currently used systems are: linear thermal detectors, discrete smoke detectors and CCTV with automatic detection. These systems reacts to different types of events (Liu et al., 2009) and the combination of such signals is certainly the key for rapid, error-free detection. At least two of the three systems should be present in every short tunnel.

– Rapid and precise user information represents the second key step. This is mostly based on radio broadcast of emergency information. While very effective, integration of this equipment with loudspeakers and VMP should be considered in short, steep tunnels.

– Ventilation and emergency exits are treated in separate chapters. The exigencies on other equipments are similar as for longer tunnels.
5. THE VENTILATION DILEMMA

Fire ventilation is straightforward in case of unidirectional traffic without congestion. All available jet fans are activated in the direction of traffic with the goal of exceeding the critical velocity and preventing smoke spread in the upstream direction.

A number of test cases were discussed by Zumsteg and Steinemann (2006) from the point of view of ventilation. As expected, the analysis showed that ventilation alone cannot meet the challenges imposed by short, high slope tunnels with bidirectional traffic. Effective fire ventilation in short bidirectional tunnels (or, similarly, in case of congestion in unidirectional tunnels) is almost impossible during the evacuation phase, for the following reasons:

– Rapidly changing forces acting of the tunnel’s air require a delicate control.
– Anemometer’s readings could be faulty because of the presence of smoke.
– The activation of jet fans will in many case destratificate the smoke and dramatically reduce the visibility level.

Numerical investigation of fire scenarios represents an instructive exercise. Figure 6 shows a possible ventilation strategy for the tunnel presented in Chapter 3, with minimization of the longitudinal air velocity. These and many other results are clearly not satisfactory.

![Figure 6: Longitudinal air velocity in the tunnel (left), smoke propagation and representative trajectories of escaping users (right). Conditions are as in Figure 4.](image)

Thus ventilation control during evacuation represents for many short, steep tunnels an irresolvable dilemma. In most cases it will be preferable not to ventilate during evacuation and use the jet fans only for supporting the selected firefighting strategy, after evacuation has been completed.

We therefore must fully agree with the conclusions by an estimated colleague (Day, 2004): “Mechanical ventilation is not a suitable mitigation measure for short road tunnels, particularly those with significant longitudinal gradients; the risks have to be mitigated using other measures such as reducing the spacing between emergency exits.”
EMERGENCY EXITS AND HUMAN BEHAVIOR

Emergency exits certainly represent the best and most expensive path for increasing the safety of many short tunnels. The directive 2004/54/EC prescribes emergency exits at least every 500 m. The requirements on the maximum distance between emergency exits in Switzerland are more differentiated and stricter (SIA 197/2):
- Maximum distance 500 m for slopes smaller than 1%.
- Linear decrease of allowable distance from 500 m to 300 m between 1% and 5%.
- Maximum distance 300 m in case of separate safety tunnel or cut and cover construction.

In the case of short, steep tunnels the applicable maximum distance between emergency exits will be typically in the range of 300-400 m, depending on slope. A number of older tunnels still suffer from much less stringent previous regulations (ASB, 1983), which prescribed, in case of longitudinal ventilations with jet fans in tunnels with bidirectional traffic:
- $L < 1$ km: no emergency exits required.
- $1 < L < 1.5$ km: one emergency exit or one point smoke extraction in the middle.
- $1.5 < L < 3$ km: two emergency exits or a smoke extraction over the whole tunnel length.

The distance between emergency exits has to be assessed based on the comparison between escape time and the time scales of smoke propagation discussed above. Assuming escape velocities in tunnel in the range of 1 m/s (good visibility) to 0.3 m/s (smoke), the escape times are in the range of 2.5’ to 8’ for a distance of 150 m (300 m between emergency exits) and 4’ to 14’ for a distance of 250 m (500 m between emergency exits). This simple estimate shows that the issue is not trivial for short tunnels and a specific analysis is required.

National and international directives dictate only minimum requirements, which must sometimes be exceeded e.g. in the case of large tunnel slopes. The “correct” distance for every particular tunnel must be established based on the overall tunnel setup. This point was made very well in the UNECE (2001) report: “Should the fire scenario analyses (smoke extension and spreading velocity under prevailing local conditions) show that the above-mentioned provisions are insufficient to ensure the safety of the road user, additional measures must be taken. These may involve emergency exits every 200 to 500 metres (or even less), using e.g. short perpendicular escape galleries to the open, when the topography so allows, or a parallel safety gallery.” Additionally, in countries, such as Switzerland, where the choice between different technical solutions for realizing emergency exits leads to different maximum distances (e.g. 300 m with safety tunnel and 500 m with separate exits), the choice must be risk-oriented.

The technical support for escape (lighting, signalization etc.) is a now well solved issue which does not call for additional comments. Nevertheless, because of recent disappointing experiences, a fundamental aspect must be stressed: emergency doors must be easy to open under all relevant conditions, independently on door type or technical details.

The issues related to human behavior, already treated in great detail by more qualified specialists, shall not be treated here. But it is important to state that in the Viamala fire, as in virtually every other fire, incorrect behavior by part of the user led to unnecessary loss of lives. It is therefore important to stress the importance of rapid and clear information of the users in case of emergency (see also Chapter 4). The awareness of being in a short tunnel could lead to a dangerous underestimation of dangers.
7. THE NEED FOR NEW TECHNICAL SOLUTIONS

Because of the specific needs and issues, short tunnels could greatly benefit from new approaches and innovative ideas. A systematic exploration would exceed the scope of the present work. We will therefore just sketch a few promising ideas:

- New concepts for alarming of the tunnel users, probably based on a combination of audio, voice and visual information would be important for shortening the delay between fire detection and escape.

- For fire cases it is important to reduce the fire intensity and the peak heat-release rate. This could be achieved by automatic fixed fire suppression systems (Bettelini and Seifert, 2009). In short tunnels water mist extinguishing systems have probably a good cost/benefit balance.

- Rapid smoke propagation in short tunnels could be counteracted also by setting up fire compartments. This could be realized by means of flexible solid curtains or by water curtain systems, which either block smoke propagation or reduce the longitudinal air velocity.

- New concepts for providing a fair chance for self-rescue in tunnels with inadequate escape facilities are under investigation. An example is GEPE (“Galerie d’Evacuation Paraffumée Escamotable”), which forms a protected escape corridor within the tunnel by means of folding down metallic curtain lamellae.

In our opinion these elements could be very helpful punctually, for solving specific problems, particularly in case of difficult renovations.

8. THE NEED FOR NEW APPROACHES

More advanced approaches are needed at two distinct levels: risk-oriented design and new-generation SCADA systems for the optimum exploitation of the complex tunnel equipments in case of emergency.

The current approach towards tunnel safety is in several countries strictly regulation-oriented. This means that the minimum normative requirements are strictly implemented, but the readiness to implement additional measures, on a case-to-case basis, is lacking. As a consequence, in deep investigations on the safety level are either not carried out or are carried out only in a qualitative manner. We strongly feel, that in-deep, quantitative investigations of scenarios are necessary for any tunnel with significant safety-relevant peculiarities. The software QRAM (OECD 2001), jointly developed by OECD and PIARC for the analysis of the transportation of dangerous goods through tunnels or alternative roads, is an adequate tool in all cases where dangerous goods are not the main concern. If fire is the main concern, this tool proved in the author’s opinion too less sensitive towards design optimization.

Existing SCADA systems allow mostly only for a comparatively basic exploitation of the existing tunnel infrastructure (Bettelini, 2008). The large amount of detailed sensor data and the operational flexibility allowed by modern tunnel equipment need an enhanced level of “intelligence” while dealing with emergencies. Because of the pressing time constraints, this can only partially be provided by tunnel operators. The main requirements on next generation’s SCADA systems will be (Bettelini, 2008):

- Use all available information, intelligently aggregated, for providing a precise, reliable view of the situation (event characterization, smoke extension and evolution, user’s location etc.).
- Make extensive use of rapid “what if” analysis for the (semi-)automatic assessment of different possible courses of action. The physical models shall be sufficiently accurate for allowing reliable investigations, but run within a few seconds. If necessary, the different options will be presented to the operator, with clear recommendations.

- Provide as much automation as possible and provide enhanced man-machine interfaces, for preventing excessive operator’s load through routine operations and allowing him to focus on the really safety-relevant aspects of the emergency.

- Improve the simulation capabilities required for training on real-life emergency situations.

This vision is being developed in the research project EMILI (“Emergency Management in Large Infrastructures”) as part of EU’s Seventh Framework Programme, Theme Security, FP7-SEC-2009-1.

9. REFERENCES

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