VENTILATION AND DISTANCE OF EMERGENCY EXITS IN STEEP BI-DIRECTIONAL TUNNELS

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ABSTRACT

Experience from occurrences of fires in road tunnels shows that victims are usually found within a few hundred metres of the scene of the incident. The fatal consequences of a fire in a tunnel measuring only a few hundred metres can be comparable to those resulting from a fire in a long tunnel. In tunnels with considerable slope the hazard for tunnel users increases due to rapid smoke dispersion. In addition to an efficient alarm system, successful self-rescue requires tunnel users to be provided with measures that enable them to reach an emergency exit. When it comes to short, steep, bi-directional tunnels, the aerodynamic approach to avoiding or slowing down smoke dispersion reaches its limits. Longitudinal ventilation systems can cause additional danger by worsening visibility conditions. The largely passive safety system consisting of a parallel safety gallery featuring short distances between emergency exits promises great benefits in terms of safety in these particular constructions. But even here, the question is raised as to determining an appropriate distance.

Key words: Tunnel safety, distance of emergency exits, short and steep tunnels

1. INTRODUCTION

In countries with stringent exhaust regulations, even bi-directional tunnels of several kilometres in length can be navigated without requiring any mechanical ventilation. The purpose of built-in tunnel ventilation is often solely to contain vehicle fires. In the past, this has led to the installation of longitudinal ventilation systems in short, bi-directional tunnels even though the systems display only limited suitability for this purpose. Even today, national guidelines recommend the use of longitudinal ventilation for short, bi-directional tunnels despite the generally questionable benefit. The aerodynamic alternative featuring an extraction system is extremely costly, disproportionately so for short tunnels, both in terms of investment and maintenance.

The problem is clearly illustrated in tunnels with considerable slope. The special problems arising from those circumstances have been previously described in [10], [11].

In the following, requirements are outlined and approaches are described for determining the distance of emergency exits.

2. REQUIREMENTS

The requirements are illustrated on the basis of the EU-directive [1] as well as Swiss [2], Austrian [3] and German [4] guidelines and the standard [6].

2.1. Ventilation system

According to various guidelines, the ranges shown in Figure 1 for the primary ventilation systems natural ventilation, longitudinal ventilation and extraction are possible for bi-directional tunnels. Depending on the future traffic situation in a time frame of 10 to 15 years, the higher or the lower limits apply.

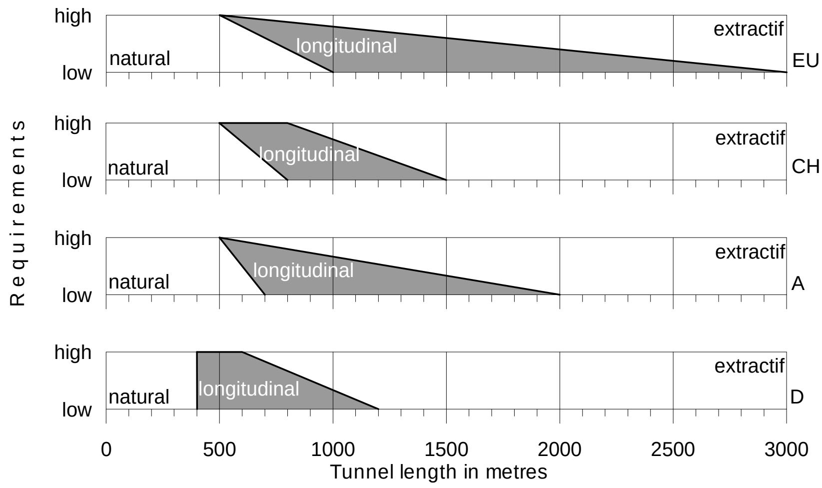

Figure 1: Examples of longitudinal ranges for the use of ventilation systems in bi-directional tunnels

Despite the obvious difference in the specifications at first glance, commonalities can be found:

- The total length of tunnels with natural ventilation lies within the range of the specifications for a maximum distance of emergency exits (section 2.3).
- In tunnels with high requirements, the range with longitudinal ventilation is strongly limited. According to EU and Austrian guidelines, the possibility of longitudinal ventilation is to be ruled out depending on the situation.

2.2. Slope

In accordance with the EU-directive, slopes of greater than 5 % are not permitted in new tunnels unless geographical conditions make it unavoidable. Special measures must be taken for tunnels with a gradient greater than 3 %.

The indications in the Swiss guideline [2] apply to tunnels up to 5 %. For steeper tunnels, separate considerations are required to ensure compliance with required safety standards.

According to the RVS, a detailed risk analysis must be performed for tunnels with slopes greater than 3 %. Special considerations are also necessary as regards smoke dispersion and accidents.

Pursuant to RABT, special measures must be taken for tunnels with a gradient greater than 3 %. Slopes greater than 5 % are to be avoided.

On the basis of aerodynamic calculations and in accordance with the provisions in the guidelines laid out in [1], [3] and [4], a small slope is assumed to be up to 1.5 % and a steep slope starts at 3 %.

2.3. Distance of emergency exits

The EU-directive stipulates a maximum distance of emergency exits of 500 m. To reach the minimum safety standard, the distance of the emergency exits can be reduced.

The distances of emergency exits for tunnels in Switzerland are stipulated in the SIA standard [6]. The data is limited to slopes up to 5 %.

The standard distinguishes between emergency exits in a parallel safety gallery and safety galleries leading directly to the open. This distinction is based on the fact that emergency exits leading directly to the open are generally significantly more cost-intensive in terms of investment and maintenance.

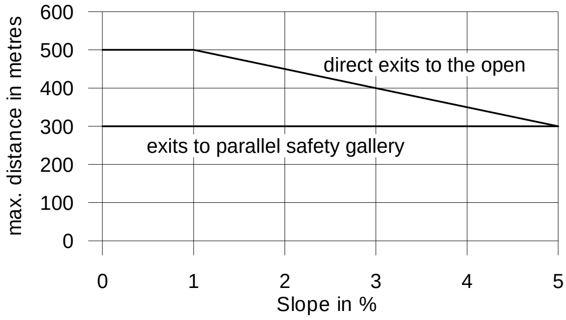

Figure 2: Distance of emergency exits as a function of slope for bi-directional tunnels according to [6]

Statistically speaking, about twice as many accidents per vehicle kilometres occur in bi-directional tunnels compared to tunnels with one-way traffic. For the latter a maximum distance of 300 m between emergency exits is stipulated. The specification for bi-directional tunnels and safety galleries leading directly to the open thus contains a rudimentary cost-benefit trade-off.

According to the Austrian Road Tunnel Safety Law, STSG, [7], and in accordance with the wording of the EU-directive, the maximum distance between emergency exits may not exceed 500 m.

In the RABT, the maximum distance between emergency exits is 300 m.

2.4. Emergency bays

The EU-directive stipulates 150 m as the maximum distance of emergency bays for new tunnels and 250 m for existing tunnels.

For bi-directional tunnels in Switzerland, niches for SOS equipment must be located on alternating sides every 150 m in accordance with the SIA standard. Hydrants are to be placed at the same distance and generally on one side.

In accordance with RVS, the distance of emergency bays may not exceed 150 m. In the case of tunnels in risk classes I and II as well as tunnels not subject to the STSG, the distance may be up to 250 m.

According to RABT, there must be emergency bays on one side of the tunnel at least every 150 m.

The cited guidelines are thus consistent in their stipulation of the 150 m regulatory distance.

2.5. Detection

A video system or automatic fire detection system must be installed in accordance with the EU-directive. There are no requirements pertaining to response times.

The Swiss guideline stipulates that new and refurbished tunnels are to be equipped with smoke detectors. Bi-directional tunnels feature smoke detectors every 100 m. A response time of 60 s is targeted.

In accordance with the RVS, a fire detection facility must be operated in tunnels if a ventilation system is present. When it comes to standard fires, the guideline stipulates response times of 90 s until the alarm at a rate of flow of less than 3 m/s or 150 s at 3 m/s or greater. In addition, a reliable alarm must be guaranteed as early as the smouldering phase. Video analysis for smoke detection is to be considered.

In accordance with RABT, tunnels with a ventilation system must also run a fire detection installation. Thermal line sensors are to be used. Opacity metres are to be comprised for fire detection (pre-alarm). Infrared cameras and suitable video devices may be permitted instead of fire detectors.

The requirements placed on detection systems are considerably different. The effectiveness and reliability of the Swiss approach with smoke detectors has already proven itself.

3. PROBLEM SHORT, STEEP, BI-DIRECTIONAL TUNNELS

In the alpine and prealpine region of the Swiss road network there is a significant number of tunnels with slopes of 3 % and greater. For example, the grade of the tunnels of the Gotthard ramps with a total height difference of 700 m is up to 5 %. The bypass route is the bi-directional A13 motorway via San Bernardino. Its north ramp in particular features a series of short, steep tunnels.

In what follows the authors focus on short, steep tunnels with slopes of 5 % or greater and lengths of up to 1.2 km. The longer Crapteig tunnel, located adjacent to the Viamala, Bärenburg and Rofla tunnels, is also quoted.

Table 1: Examples of bi-directional, steep tunnels

Tunnel	Grade	Length[1)]	ADT 2012	Speed limit	Ventilation	Emergency exits
Viamala	5.3 %	756 m	9'000	80 km/h	Longitudinal	PSG[4)] planned
Bärenburg	6.6 %	1031 m	9'000	80 km/h	Longitudinal	PSG planned
Rofla	5.6 %	1087 m	9'000	80 km/h	Longitudinal	PSG planned
Crapteig	6.5 %	2117 m	9'000	80 km/h	Extraction	PSG planned
Fieud	5.4 %	795 m	4'400[2)]	80 km/h	Longitudinal	Planned (2)
Soliwald[3)]	6.8 %	560 m	6'500	40 km/h	Natural	Planned (2)
Marzoli	11.0 %	870 m	2'700[2)]	80 km/h	Natural	None
Silvaplana	8.3 %	750 m	3'000	60 km/h	Natural	6, Δ = 125 m

1) including short, adjacent galleries
2) only accessible in the summer period
3) curve radius: 75 m
4) PSG: parallel safety gallery

Experience drawn from actual vehicle fires shows that the greatest danger to tunnel users comes from fires resulting from accidents with rapid heat development. In such cases, the fire spreads with smoke and buoyancy development within minutes. The available response time of tunnel users is very short and there is little time for self-rescue including alerting, orientation, reaction and escape. When the slope is significant the sequence is severely accelerated. During the Viamala tunnel fire in 2006, the buoyancy driven flow upward through the tunnel was reported to be around 7 m/s after the longitudinal ventilation was shut down. Some people fleeing to the upper portal on foot were overtaken by the smoke.

4. AERODYNAMIC APPROACH

The advantage of longitudinal ventilation in terms of safety in bi-directional tunnels is limited because the smoke can only move within the tunnel. An advantage comes with a fire near the portal and a rapid ventilation response, when the smoke can be blown out of the portal. Very rapid detection and automatic control are prerequisites in this case but the risk of an inadequate response is considerable.

As the slope increases, the buoyancy drastically reduces the available time for a useful ventilation response in a short bi-directional tunnel. In addition, the installable thrust is limited [10] in short tunnels. Smoke detectors are to be used to avoid operating jet fans in smoky sections, especially in tunnels without extraction.

Calculations have shown that when it comes to the geometry of the Fieud, Viamala, Rofla and Bärenburg tunnels, longitudinal ventilation no longer meets the requirements of the guideline [2]. However, jet fans installed by the upper portal might eject smoke developing near the lower portal. This decreases the effective buoyancy in the tunnel, gaining time for self-rescue. In the event of a powerful fire near the lower portal, these fans can slow down the upward flow. However, we must assume that even with the indirect effect of the jet fans on the smoke-filled zone, any existing smoke layer would be destroyed.

The effect of a decrease in the longitudinal flow can also be achieved using adjustable curtains (see [12]).

Systems featuring smoke extraction by way of adjustable dampers have been proven in steep tunnels (Gotschna tunnel, length 4 km, slope 5 %). To control smoke dispersion, sufficient thrust and large exhaust air flows have to be installed. When it comes to short tunnels, the issues of feasibility and suitability are raised.

5. RISK ANALYSIS AND STANDARD

Risk analyses are a useful tool for determining a balanced use of limited funds. In accordance with the requirement in the EU-directive, a number of national methods were developed and now serve as a basis for the equipping of safety installations. The EU's objective of defining a standardised method has not yet been met though.

Different fundamental questions arise when applying risk analyses and the ensuing determination of the cost effectiveness of individual measures. Examples include:

- Object-specific adaptation
  On the one hand, a number of predetermined criteria are assessed on an object-specific basis and then integrated into the model. On the other hand, specific features hardly fit the rigid framework. Examples of this include the curviness and the traffic character: It can be assumed that the curviness of the tunnel was the crucial factor in the fatal event in the Viamala tunnel in 2006. On tourist routes with a high percentage of coaches and fully occupied cars (e.g. families with children) it must be assumed that self-rescue is difficult. Including such features is not appropriate for the method as the homogeneity and required comparability are then lost.
- Modelling
  Modelling the sequence of events during an incident often depicts reality in an optimistic way. If, in addition, the same methods are applied as were used, for example, when designing the ventilation, the result may be idealised and inappropriate. Risks and thus the consequences of incidents may be underestimated.
- Differences in the assessment of criteria
  An example would be the amount assigned to a fatality when calculating the cost effectiveness of a specific safety measure. In different analyses, values in the range of a factor of 3 were used. This directly affects the result.

Up until a few years ago, safety devices were dimensioned exclusively according to standard specifications. Following the fire in the Gotthard tunnel in 2001 Switzerland formulated the arguable somewhat optimistic policy that in the case of an incident every tunnel user should be given a *fair chance* to get himself to a safe area. In this case it is fairer to use the risk-based method which identifies that in certain scenarios fatalities are inevitable. The standard-oriented approaches applied already contained certain risk-based approaches. In hindsight it is clear that the cost-benefit ratio was not optimal and often still is not. In our opinion, the objective must be to use cost-benefit analyses to specify standards that approach the intended purpose and will be appropriately applied in an object-specific manner. In conjunction with risk assessments, this will enable more efficient use of the limited funds available. However, this process will still take some time. It is important to understand that optimum results cannot be achieved by using standard *or* risk-based methods alone but rather by using both methods together. The PIARC Technical Committee C4, Working Group 4 [13] also arrived at this consensus.

6. PRAGMATIC APPROACH

When constructing new tunnels in Switzerland, the specifications outlined in the publication of the SIA standard in 2004 are observed as regards the distance of the emergency exits (see Figure 2). 300 m is used as the standard distance between emergency exits. For the short, steep bi-directional tunnels now in need of retrofitting, deviations from this standard solution will need to be made.

6.1. Principles

The proposed pragmatic approach for steep tunnels is based on the following principles:

- Comparable safety standard to a tunnel with a slope of 3 % (section 2.2)
- Standardised distances which are easy for tunnel users to understand and remember
- Coordination of emergency exits with other safety devices as far as practicable
- Possibility to deviate from the specific requirements of the guideline when designing the ventilation
- Quick detection for signalisation, alarm and other reflexes

6.2. Viamala, Rofla and Bärenburg tunnels with parallel safety galleries

Parallel safety galleries are planned for the Viamala, Rofla and Bärenburg tunnels as well as for the longer Crapteig tunnel. Using so-called scenario analyses based on a tunnel in compliance with the guideline at a 5 % slope, a maximum distance of 260 m between emergency exits was determined for these tunnels. The cost of constructing the short links between the parallel safety gallery and the tunnel is approximately 5 % of the total cost of constructing the parallel safety gallery.

Based on the principles outlined in section 6.1, which correspond to the specifications in the EU-directive (section 2.3), the authors recommend aiming for 150 m between exits in these tunnels. The results are summarised in Table 2.

Table 2: Effect of the recommended approach on the distance of emergency exits and on the cost of the parallel safety galleries

	Original planning		Recommendation		Additional cost kCHF, %
Tunnel	Emergency exits	Distance	Emergency exits	Distance	
Viamala	2	252 m	4	150 m	500, +5 %
Bärenburg	3	258 m	6	150 m	750, +5 %
Rofla	4	217 m	6	150 m	500, +3 %

The three tunnels feature longitudinal ventilation and jet fans distributed over the length of the tunnel. A reassessment of these ventilations should be carried out separately from the considerations regarding the emergency exits.

6.3. Costoni di Fieud tunnel with safety gallery leading directly to the open

Another study, which applied the BAST method for safety assessment [14] to the Fieud tunnel, also arrived at a distance of approximately 250 m. However, the basic conditions are extremely different in terms of traffic for this tunnel on top of Gotthard Pass (open only in the summer period, hypothetical increase in traffic following refurbishment of Gotthard road tunnel, coach traffic, but no further heavy-duty traffic) and safety galleries leading directly to the open. Based on BAST, the sum of CHF 15 million was used for a fatality. The result was an additional emergency exit leading directly to the open and the renouncement on the existing, insufficient longitudinal ventilation.

Including other accompanying and in part temporary safety measures, the recommended distance of the two emergency exits seems justifiable.

6.4. Crapteig tunnel with extraction

The ventilation of the Crapteig tunnel will be refurbished and equipped with a powerful extraction system in compliance with the guidelines. In addition, a 2 km long parallel safety gallery will be constructed. The costs of these measures are in total around CHF 45 million.

The construction is found on the San Bernardino route with the Viamala, Rofla and Bärenburg tunnels. Despite the powerful ventilation that will be installed in the very steep tunnel Crapteig, arguments for homogeneity and understandability of the distances of emergency exits should still be highlighted.

Table 3: Effect of the recommended approach on the distance of emergency exits and on the cost of the parallel safety gallery

	Original planning		Recommendation		Additional cost kCHF, %
Tunnel	Emergency exits	Distance	Emergency exits	Distance	
Viamala	8	241 m	13	150 m	1250, +4 %

7. CONCLUSIONS

Based on the concerns described and in agreement with the guidelines of the EU, Austria and Germany, the authors recommend that the distance between emergency exits in short, steep, bi-directional tunnels with a slope above 5 % and with a length up to 1200 metres should be usually 150 m. By considering remarkable, object-specific features other distances might result on behalf of risk-analysis approaches. For constructions requiring long safety galleries leading directly to the open, larger distances may be permitted. Suitable measures should be used to observe the safety standard of a tunnel with 3 % slope and a distance between emergency exits of 300 metres.

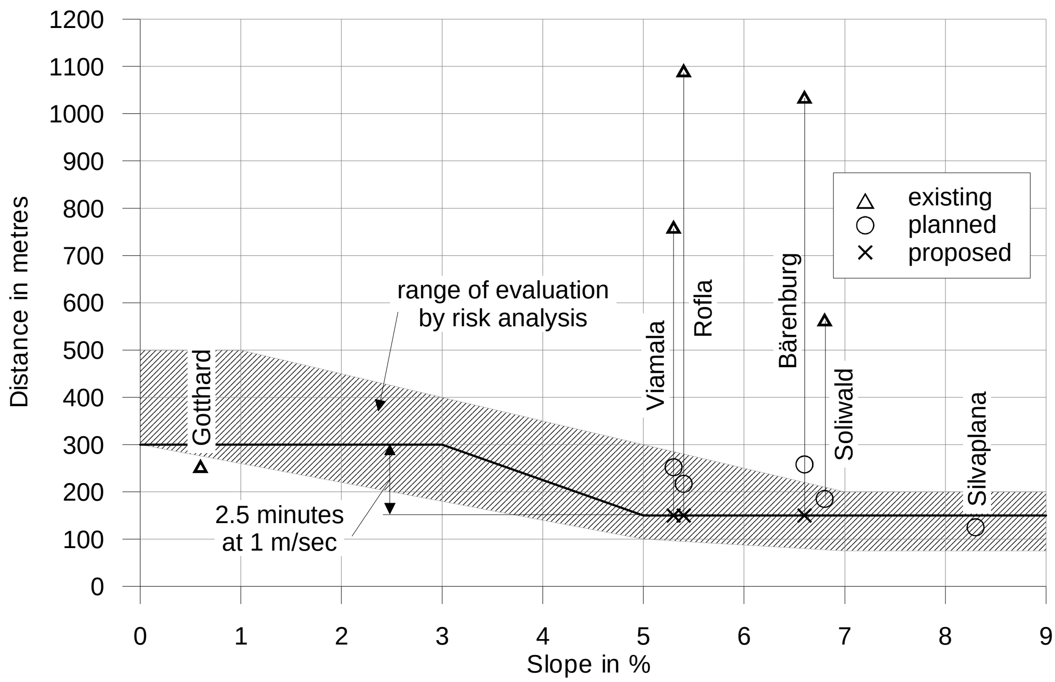

Figure 3: Proposed "guideline" and range for risk analysis for the distance between emergency exits in tunnels with bi-directional traffic displaying the described tunnels

The design of the systems and assessment of safety should take into consideration the particular, object-specific features of the tunnel.

With special tunnel geometries in particular, designs adhering to guideline specifications, standards or cost-benefit analyses should be critically questioned, justified and adapted if necessary. The generally formulated requirements should be used as a guiding, not hindering force for the art of engineering. Appropriate safety and economic solutions take precedence over pure legal considerations following the letter of the requirements.

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