The benefit of event tree analysis for the ventilation design of railway tunnels

Verena Langner, Gruner GmbH, Vienna (Austria)
Bernd Hagenah, Gruner GmbH, Vienna (Austria)
Petr Pospisil, Gruner AG, Basel, (Switzerland)

Abstract

The design of the emergency ventilation system for rail tunnels is usually based on a restricted number of critical scenarios, leading to a ventilation system designed for these specific cases. The question is, what is a reasonable design scenario, and what is the adequate ventilation system which has a good performance in the vast majority of fire scenarios.

The performance of a ventilation system in scenarios more and less critical than the original design scenario should be assessed by a scenario analysis with a fast, easy applicable simulation tool.

The event tree analysis methodology allows to assign values for the probability of the different scenarios. By that, a well founded evaluation of the optimal, reasonable ventilation design can be worked out.

1 Introduction

There is currently no accepted standard for use and hence, the dimensioning of tunnel ventilation systems for rail tunnels. The design and dimensioning of ventilation systems is thus in practice based on specific protection goals which can vary for different projects / countries. E. g. no German rail tunnel is ventilated whereas the long alp traversing tunnels like Gotthard- or Loetschberg have tunnel ventilation equipment which is used in case of train incidents in the emergency stops and in the tunnel. Additionally, design criteria are for example minimum flow velocity through open cross-passages or critical velocity in the incident tube, etc.

A common approach for ventilation design of rail tunnels is to define one particular critical scenario in which the protection goals must be fulfilled. This strategy leads to a ventilation system which might be optimized for that particular case, but less attention is paid to the performance of the ventilation system in other cases.

Obviously, if only one critical case is considered it cannot be assured that the dimensioning is adequate for a broad variety of other cases. Hence several scenarios are often defined to design the emergency ventilation. In order to not only concentrate on the rare / unrealistic cases sometimes not 'worst case scenarios' but 'worst credible scenarios' are used (4).

The approach presented in this paper takes into account not only a few selected scenarios but many possible cases using event tree analysis for the assessment of the ventilation design.

By means of a risk based approach

- the impact of a hot train incident is known for nearly all possible scenarios – with ventilation,
- the entire system with regard to the flow conditions in the tunnel bores and cross passages during self-rescue can be optimized,
- oversizing of the ventilation plants can be avoided and
- the residual risk can be estimated at the same time.

The following chapters present this approach using the example of the New Semmering Base Tunnel.

2 The Ventilation System of the new semmering base tunnel

2.1 Tunnel system

The New Semmering Base Tunnel is part of the Baltic-Adriatic Corridor and is situated between Vienna and Graz in Austria. The basic geometrical parameters are shown in Table 1, the tunnel is schematically shown in Figure 1.

Table 1: Basic geometrical tunnel parameters

Parameter	Value / Description
system	double bore single-track / no crossover
length [m]	27'300
free cross-sectional area [m²]	42
slope (from east to west) [‰]	8.4
number of cross-passages	56
cross-passage distance [m]	maximum 500
emergency stop	approx. in the middle of the tunnel
ventilation shafts	vertical exhaust and supply air shaft at the emergency stop
ventilation plant	in the ventilation centre which is situated at the shaft head (at the surface)

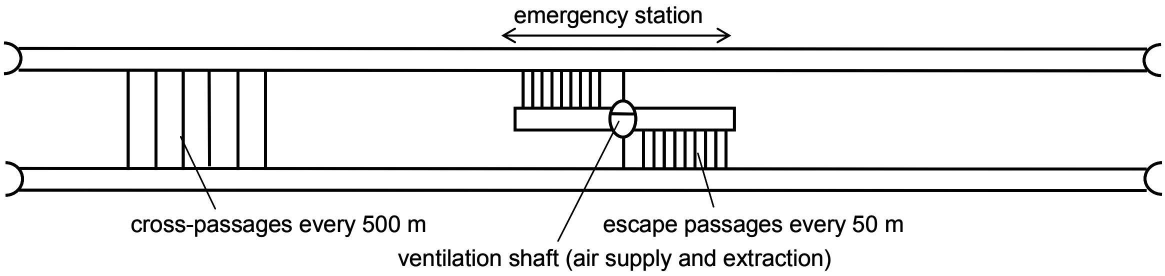

Figure 1: Schematic of the New Semmering Base Tunnel

2.2 Safety concept and ventilation requirements

The Tunnel Safety Concept of the New Semmering Base Tunnel is based on the regulations for Austrian rail tunnels, which are being designed at the moment or have been established in recent years (for more information see (1)). Within the safety concept of the New Semmering Base Tunnel a range of specific protection goals were defined. The protection goals which concern the ventilation concept include:

- The creation of a safe area in the middle of the tunnel system (emergency station).
- Emergency station, non-incident tube and portals are safe areas (6) and should remain free of smoke for at least 180 minutes.
- Avoiding further danger to following trains in the incident tube.
- The prevention of the simultaneous entry of smoke into both tubes as a result of a fire in a technical room.

Based on the protection goals the following main ventilation objectives have been derived:

- To prevent smoke propagation through open cross-passages (tunnel) and escape passages (emergency station) into the safe areas, there must be a sufficiently high over pressure in the non-incident tube and in the refuge room of the emergency station with respect to the incident tube. For hot incidents in the tunnel this objective is implemented by the requirement of a minimum flow velocity through open cross-passages (cf. test criteria in chapter 4.1).

- To prevent smoke propagation into the non-incident tube at the portal regions, the exit of smoke from the incident tube must be avoided or the outflow velocity from the non-incident tube must be high enough to prevent smoke entry. This objective is implemented by the requirement on the flow velocities in the tunnel tubes (cf. test criteria in chapter 4.1).

Further ventilation criteria / requirements include:

- not to exceed the maximum allowable flow velocity through open cross-passages (v_{max} = 10 m/s) to prevent a negative impact on the escape procedure,
- low air flow in the incident tube (to prevent a rapid smoke propagation and an impairment of the smoke layering),
- high reliability by low complexity of the ventilation system and its control.

2.3 Ventilation concept

During normal operation, ventilation is achieved by the train induced piston effect. Hence, no active ventilation is foreseen.

In case of a hot train incident the following two design scenarios have to be considered:

- **Incident in the emergency station:** When a fire is suspected due to a report from the driver or irregularities in operation, the emergency station will be prepared for train evacuation:
  - doors in the emergency station from the incident tube into the escape area are opened automatically,
  - fresh air is fed into the escape area (100 m^3/s) and
  - air is extracted at the emergency station (250 m^3/s).
  The air supply quantity is designed to produce a sufficient air velocity in all escape passages in the emergency station (v_{air} > 2.5 m/s) and thus prevent smoke entering the safe area. The extraction quantity is dimensioned to prevent further smoke propagation into the tunnel bores (see (1)). Three supply- and three extraction fans are foreseen.

- **Incident outside the emergency station:** If the incident train stops outside the emergency station:
  - the open doors in the emergency station (prepared for the case of an incident in the emergency station) from the incident tube into the escape area are closed,
  - fresh air (100 m^3/s) is fed into the non-incident bore and
  - air is still extracted at the emergency station (250 m^3/s).
  Simultaneous air extraction from the incident bore and air supply into the non-incident bore leads to a pressure difference between both tunnel bores (Figure 2). Hence, air flow from the non-incident bore into the incident bore through open cross-passages prevents smoke propagation into the safe area.

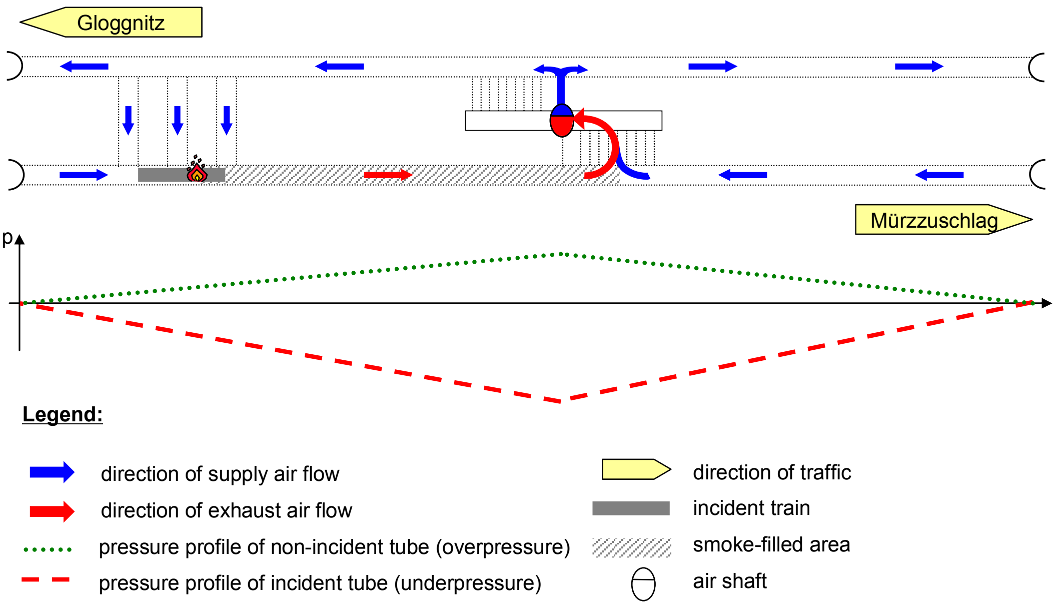

Figure 2: Ventilation scheme and pressure profile for an incident with a train stopping outside the emergency station (red dashed line = incident tube, green dotted line = non-incident tube)

During maintenance work, one tunnel tube will be completely closed. Pollutants produced by working machines, e.g. exhaust emissions from engines, will be sufficiently diluted and transported out of the tunnel system by the extraction fans (250 m^3/s).

3 Approaches for ventilation design and Control

3.1 Fundamentals

In principle the ventilation design process starts with the following steps:

- General and tunnel specific protection goals are defined in a safety concept (e.g. keeping the safe areas free of smoke for a certain time period).
- Based on the accepted protection goals, ventilation requirements are deduced (see also chapter 2.2).
- Critical scenarios and boundary conditions, for which the protection goals must be achieved, are fixed.
- On the basis of the ventilation requirements and critical boundary conditions, the ventilation system is chosen and the dimensioning process starts (e.g. air / smoke extraction quantities, etc.).

3.2 Ventilation design based on critical case

A common approach to design a tunnel ventilation system is to determine the air volume based on critical scenarios or based on combinations of unfavourable assumptions such as fire size, fire location, meteorological conditions, fan availability, train positions, etc. (3).

The choice of the design scenario is very difficult. It must be pointed out that the often used term 'worst case scenario' should be avoided. For each defined critical scenario, even worse scenarios are possible, leading to a residual risk, e.g., a second train entering the tunnel which starts to burn, explosions, extreme heat release rate, multiple fan failure, failure of power supply, several opened cross-passage doors, extreme storm on the portal, etc.

Even if the emergency ventilation has a very good performance for the defined critical scenario, it is not assured that it has a good performance / impact during other scenarios which are coincidentally more likely. Additionally, the residual risk is not quantified.

3.3 Advanced ventilation control

By using advanced ventilation control in order to cover the ventilation impact for a wide range of scenarios, the ventilation might be adapted to the current conditions. An example is the closed-loop control of longitudinal flow velocity applied usually in road tunnels.

A major drawback of advanced ventilation control is the increased degree of complexity (requiring sophisticated, complex control algorithms, reliable and precise air speed measuring devices, pressure control etc.). Thus, not only the time and costs for implementation and testing increase enormously, but also the possibilities for failure. Taking into account the lower probabilities of incidents in comparison to road tunnels, simple control modes are preferred for rail tunnel applications.

3.4 Use of event tree analysis

If a certain residual risk is admitted (which is a requirement of the tunnel safety concept), the ventilation design has to be based on credible cases and / or on additional ventilation requirements / criteria.
To confirm the effectiveness of the ventilation design and to prove that the defined residual risk is not exceeded, a systematic verification of the ventilation design is needed.

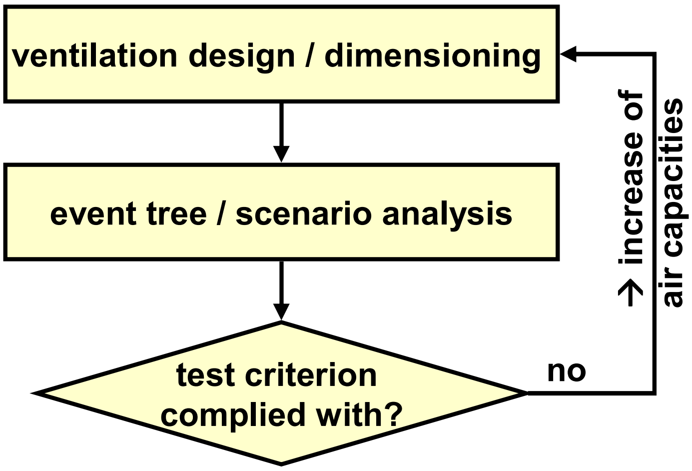

Figure 3: Use of the event tree analysis to verify the ventilation design

Principally event tree analysis is not reasonable / feasible in all cases. Possible reasons for the use of event tree analysis are:

- mutual exclusion design criteria (e.g. avoiding further danger to following trains in the incident tube which means a sufficient high flow velocity and prevention of smoke stratification in the incident tube, which means a sufficient low flow velocity),
- information about the performance of the ventilation in the majority of cases,
- optimization of the performance of the emergency ventilation for the majority of cases,
- quantification of the residual risk,
- minimization of the complexity of the ventilation system.

For the event tree analysis several combinations of relevant boundary conditions and further major impact parameters are taken into account respecting their differing probabilities of occurrence (cf. chapter 4.3).

The event tree analysis has been applied for the New Semmering Base Tunnel as shown in the following chapter.

4 Event tree analysis taking the New semmering base tunnel as an example

4.1 Test criteria and residual risk

For the New Semmering Base Tunnel the following two test criteria were defined to verify the compliance of the ventilation requirements for the cases with an incident train stop in the tunnel (outside the emergency station):

- To prevent smoke propagation through a cross-passage into the safe non-incident tube the flow velocity shall be at least 1.5 m/s (downstream of the fire) or at least 1.0 m/s (upstream of the fire) averaged over the free cross-sectional area of an open escape door when two cross-passages were opened simultaneously.

  This test criterion is based on 3D-CFD numerical investigations which were conducted to analyse the relationship between the minimum flow velocity in a cross-passage and the longitudinal flow velocity in the tunnel (1).

- To prevent portal recirculation the flow velocity in the tubes must amount to one out of the following values:
  - incident tube: at least 0.5 m/s in the direction of the emergency station (according to (7) the length of backlayering is considerably lower than 500 m for this flow velocity); exception: at least critical velocity in the direction of the emergency station for hot incidents between farthest cross-passage and portal)
  - non-incident tube: at least 0.5 m/s in the direction of the portal

Both test criteria must be reached in 95 % of cases where a train stops in the tunnel (not in the emergency station). It is therefore knowingly accepted that under unfavourable conditions a certain amount of smoke transfer to the safe area cannot be fully ruled out. In exchange, however, the velocities along the incident tunnel will be in a considerably more favourable range.

4.2 Parameters

The following parameters were varied in the event tree for the New Semmering Base Tunnel:

- **Location of the incident train in the tunnel:** Due the pressure profiles in the tunnel tubes (cf. Figure 2) the flow velocities through open cross-passages situated inside the tunnel are significant higher than near the portals. Five different positions of the incident train in the tunnel were investigated cf. Figure 4). The probability of stopping at each position was taken to be proportional to the section length (cf. Table 2). Only one tunnel bore is taken into account for the location of the stopped incident train.

Table 2: Values for the fire location used in the event tree

Description of fire location	Range in the tunnel (Class range)	Probability of occurrence
east portal	east portal to 2nd cross-passage	5 %
west portal	55th cross-passage to west portal	5 %
east branch	2nd to 8th cross-passage	15 %
west branch	49th to 55th cross-passage	15 %
middle of the tunnel	8th to 49th cross-passage	60 %

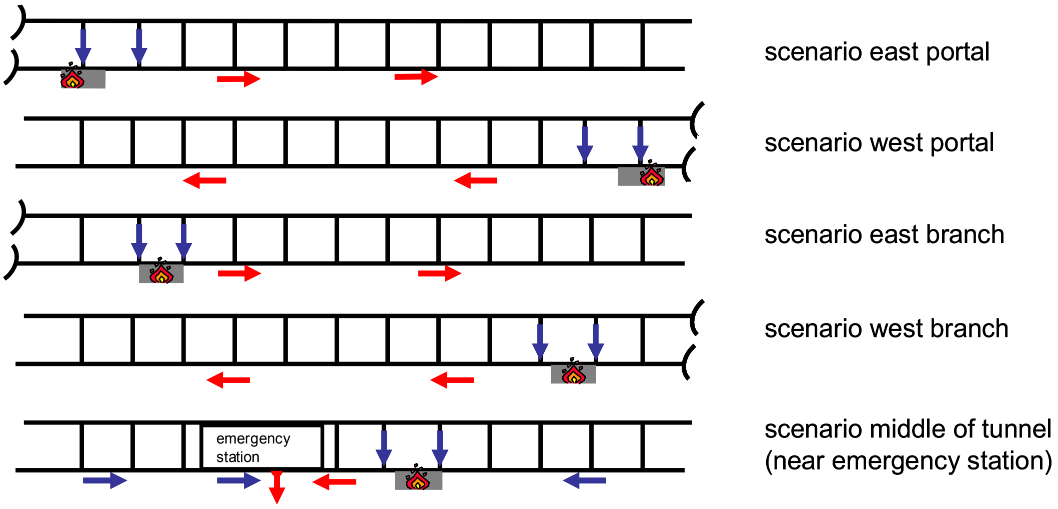

Figure 4: Fire locations for the event tree analysis

- **Heat release rate:** The level of the heat release rate determines the temperature difference between incident tube and the non-incident tube. The larger this difference, the more smoke transfer is to be expected. Additionally the heat release rate has an impact on the flow velocity in the incident tube (buoyancy and expansion). It is very difficult to determine the probabilities of different heat release rates, because of the low number of train incidents in rail tunnels that happened until now. E.g. same fire tests on metro cars delivered different results (8 MW and 16 MW). The fire development depends not only by the various sources of combustion, but as well on the specific fire scenario, e.g. when do the windows break, are the doors opened, etc. Thus the probabilities of occurrences are only assumptions. Because of the uncertainties it would be recommended to carry out the event tree analysis also for other probabilities for the heat release rate (parameter study). The calculations for the New Semmering Base Tunnel were carried out for four different heat release rates (5, 10, 20 and 28 MW). Table 3 shows the values used in the event tree, together with the relevant class range and the estimated probability of occurrence.

Table 3: Values for the heat release rates used in the event tree

Heat release rate	**Class range**	**Probability**
5 MW	< 7.5 MW	10 %
10 MW	7.5 - 15.0 MW	40 %
20 MW	15.0 - 25.0 MW	30 %
28 MW	> 25.0 MW	20 %

- **Meteorological influence:** The meteorological conditions (pressure difference between the portals and geothermal buoyancy) have a strong effect on the air flow in the tunnel and thus also on the pressure profile in the two tunnel tubes. Five different boundary conditions (combinations of portal pressure differences and geothermal buoyancy) were investigated (100, 300 and 490 Pa from east to west and 100 and 320 Pa from west to east). The probabilities of occurrence were determined from meteorological data. Table 4 shows the values used for the event tree together with the class ranges and probabilities of occurrence.

Table 4: Values for the meteorological influences used in the event tree

Values for the portal pressure difference and geothermal buoyancy (east → west)	Class range (east → west)	Probability of occurrence
100 Pa	0 to 200 Pa	60.0 %
300 Pa	200 to 350 Pa	20.5 %
490 Pa	> 350 Pa	2.0 %
-100 Pa	-200 to 0 Pa	16.5%
-320 Pa	< -200 Pa	1.0 %

4.3 Scenarios and 1D numerical analysis

To verify the compliance of the test criteria mentioned in chapter 4.1, steady state 1D simulations for various combinations of different meteorological effects (portal pressure difference and thermal buoyancy), heat release rates and fire locations were carried out.

A simplified graph of the event tree used for the New Semmering Base Tunnel is shown in Figure 5. In total 100 scenarios were taken into account to present an exhaustive set of possible scenarios for the New Semmering Base Tunnel. The key parameters selected are explained in detail in chapter 4.2. Two simultaneously opened cross-passages were taken into account as required in the test criteria (several opened doors were examined by additional transient 1D-simulations).

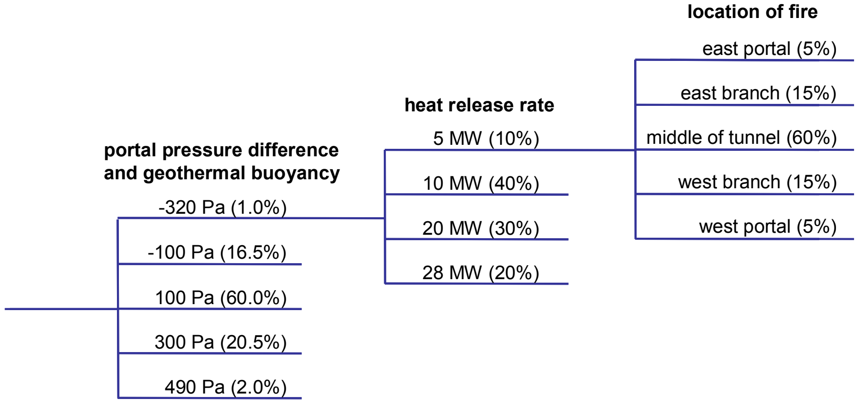

Figure 5: Reduced / simplified presentation of the event tree used for the New Semmering Base Tunnel, in total 100 scenarios were taken into account

For example the simulation case with a portal difference of 100 Pa (from east to west), a heat release rate of 20 MW and a fire at the east portal (probability of occurrence of that scenario is about 0.9 %) leads to air velocities of 2.8 and 3.5 m/s through the open cross-passages and to a flow velocity of 2.4 m/s between the location of fire and the adjacent portal in the incident tube.

Air velocity through open cross-passages and flow velocities in both tunnel tubes were evaluated for every single scenario to get the complete event tree.

4.4 Results for the New Semmering Base Tunnel

The chosen probabilities of occurrence lead to the following results:

- The air velocity through open cross-passages is higher than 1.5 m/s in 100 % of the cases when two cross-passages are simultaneously opened for all considered boundary conditions
- Portal recirculation can be prevented in 99.4 % of all cases by means of a sufficiently high flow velocity into the incident tube or a sufficient high flow velocity out of the non-incident tube.

Even if the individual probabilities of occurrence (e.g. the heat release rate) are varied, the general picture does not change significantly. The test criteria are thus complied with for the air quantities determined in the previous ventilation design process.

5 Conclusion

By admitting a defined residual risk, the performance of the ventilation system can be assessed and optimized by an event tree analysis for many scenarios, not only the critical one. Oversizing of ventilators or ventilation plants can be avoided, thus civil engineering costs, resulting power requirements and energy costs can be reduced.

Further remarks / conclusions:

- Due to the numerous scenarios to consider, using event tree analysis for ventilation design is only reasonable if the calculations can be done in a simple and efficient manner (such as for example using 1D simulations). In this case 3D-CFD simulations are considered to be rather unsuitable to be used extensively as part of the event tree analysis. 3D simulations are better used to give additional indications of the performance of the ventilation system for particular, special cases.

- As a further step, the application of the event tree analysis could be made more efficient (systematical determination of particular scenarios from the event tree that are sufficient to give an overall picture of all cases).

- In this particular example, event tree analysis has been used for verification purpose of the chosen air capacities in the design process. It would be also possible to use event tree analysis in the actual design development process.

- More application possibilities of the event tree analysis are for example
  - the examination of the various options for the ventilation system (e.g. with or without smoke extraction) as is proposed for road tunnels (5),
  - to check the influence of a smoke trail (smoke that is deposited in the tunnel in the wake of the burning train) on the design of smoke extraction systems of emergency stations,
  - to analyse the influence of other rolling stock (e.g. freight trains).

Acknowledgement

We would like to thank ÖBB-Infrastruktur AG for their kind permission to publish this work.

References

(1) The ventilation and tunnel safety concept for the New Semmering Base Tunnel, R. Bopp, V. Langner, C. Neumann, O.K. Wagner, Geomechanics and Tunnelling 3 (No.2), April 2010.

(2) Minimum flow velocity through open cross passages in twin bore rail tunnels, V. Langner, R. Bopp, P.R. Bailey, 5th International Conference 'Tunnel Safety and Ventilation' 2010, Graz.

(3) International Tunnel Fire-Safety Design Practise, P.C. Miclea, W.K. Chow, C. Shen-Wen, L. Jumei, A.H. Kashef, K. Kang, ASHRAE Journal, August 2007.

(4) Leitfaden Ingenieurmethoden des Brandschutzes, vfdb TB 04/01.

(5) A new approach to the ventilation and safety of road tunnels, P. Pospisil, December 2010

(6) TSI SRT, Safety in railway tunnels in the trans-European conventional and high-speed rail system, 2008/163/EC.

(7) The Handbook of Tunnel Fire Safety, Thomas Telford, 2005.