Risk assessment of zero-flow ventilation strategy for fires in bidirectional tunnels with longitudinal ventilation

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ABSTRACT

Two generically different methods are used to assess alternative strategies for responding to the outbreak of fire in a road tunnel. One approach, common in Japan, follows a deterministic process that leads to strong qualitative outcomes, namely either "safe" or "fatal", for any chosen specific scenario. The other approach, developed in Austria, is a probabilistic, system-based process that leads to quantitative outcomes for any specific tunnel and that provides a method of comparing overall safety in different tunnels. The two approaches are used to provide independent assessments of the merits of (i) an actively controlled zero-airflow response to the detection of fire and (ii) a simpler response in which all fans are immediately shut down and the airflows are determined by conditions at the tunnel. Both assessment methods show that the active response constitutes a significantly lower risk strategy than the simpler response.

1. BACKGROUND

Modern road tunnels provide good opportunities for the self-rescue of people in the event of a tunnel fire. Usually this is achieved by a combination of smoke management and emergency exits located at distances below a maximum value defined in guidelines. For instance, for tunnels in the trans-European road network, the maximum admissible distance between emergency exits is limited to 500m. In national guidelines, even shorter thresholds between 250m and 350m are defined. However, in older tunnels, emergency exits may be missing and, especially in single tube tunnels, it may be very difficult and cost-intensive to retrofit this important safety feature.

Single tube tunnels in most cases are operated bi-directionally. If such tunnels are equipped with longitudinal ventilation, tunnel fires may become especially dangerous for tunnel users: as cars are queuing at both sides of the fire, no option for smoke management will completely avoid endangering some people and – if emergency exits are missing – the escape route to a place of safety may be quite long.

This type of tunnel is quite common, maybe not on motorways and other roads with high traffic, but on the secondary road network in mountainous areas or on roads with a limited traffic load. Examples of countries where this type of tunnel exists include Austria, Norway and in particular Japan.

Other situations with similar conditions include unidirectional tunnels that need to be operated bidirectionally for a limited time - because one tube must be closed down for reconstruction works, perhaps. Another example is highlighted by the response to the falling of a ceiling panel in the Sasago Tunnel in 2012. The removal of ceiling panels from this tunnel and many others requires their conversion from semi-transverse to longitudinal ventilation.

For such tunnels with longitudinal ventilation and bidirectional traffic, there are at present two main strategies for responding to fire: either (i) blow the smoke in a controlled direction at low speed (e.g. at 1.0-1.5m/s as is done in Austria) or (ii) switch off the ventilation system completely (as is done in Japan). Recently, a third strategy that was initially developed over 30 years ago has come into increasing use, namely actively controlling the air flow to reach zero flow rapidly. Thereafter the air velocity is maintained at 0 m/s, thereby minimising the rate of spread of smoke. Nakahori et al (3) demonstrated the feasibility of a suitable control strategy for this purpose. The present paper verifies the risk-reducing potential of this strategy, by applying state of the art risk assessment tools.

2. ZERO-FLOW VENTILATION STRATEGY

2.1 Invention of Zero-Flow Strategy

The Kan-Etsu Tunnel, which is 11km long and is the longest road tunnel in Japan, opened in 1985 as a single-tube, bidirectional tunnel. A second tube was added in 1991 and the tunnel is now operated as a two-tube, one way traffic tunnel with a dedicated evacuation tube connected to the main tube at intervals of 350m. The tunnel is ventilated longitudinally; it has 52 jet-fans and two intermediate shaft locations in each tube.

Mizuno et al (1) investigated several ventilation control methods for fire in the original bidirectional configuration of the Kan-Etsu Tunnel. They concluded that the “zero-flow control” was the best option and they developed cutting-edge simulation software to enable its implementation in the tunnel zone containing the fire. Ever since that time, zero-flow control schemes have been the preferred option in Japan for long expressway tunnels similar to the original configuration at Kan-Etsu.

The desirability and feasibility of zero-flow control was discussed in Nakahori et al (3). Although the above discussion focusses on bi-directional tubes, important applications also exist in uni-directional tubes. For example, if a fire breaks out at the upstream end of a zone of stationary or heavily congested traffic – because of a vehicle crash, for instance - neither direction of air-flow is preferable.

For simplicity, attention herein is focussed on horizontal tunnels. For completeness, however, it is noted that a slightly different implementation is appropriate in non-horizontal tunnels. The target is to control the air speed at a low value that will ensure equal rates of smoke propagation in both directions. The generic name "zero-flow" implicitly embraces this case too.

2.2 Technology for Zero-Flow Control

Although the zero-flow strategy is intuitively attractive, its implementation in short tunnels has not been practicable until quite recently. This is because most jet fans are operated either "on" at full speed or "off". In this case, the smallest possible change to an existing velocity of, say, 1 m/s in one direction might cause a velocity of 1 m/s in the other direction. As a consequence, control systems seeking to achieve zero flow are likely to cause hunting – and this can be dangerous as well as un-nerving for people in the tunnel.

Nakahori et al (3) showed that this problem can be eliminated by using speed-controlled jet fans. Furthermore, Nakahori et al (4) showed that such control can be achieved reliably and cost-effectively using inverters. A suitable control system was developed to enable the achievement of any desired target speed (5) and the methodology has been implemented in an actual urban highway tunnel to control pollution emissions from the tunnel portal (6). The new methodology also enables a seamless and reliable transition from normal ventilation control to fire emergency ventilation control (7). The speed with which zero-flow can be achieved is illustrated in Figure 1, which is taken from Nakahori et al (5).

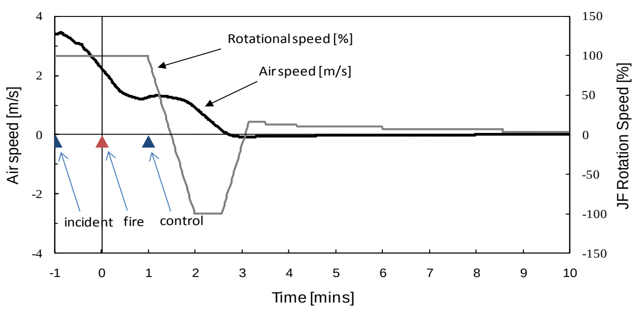


Figure 1. Rapid achievement of zero-flow by automatic control

Although the benefits of the zero-flow methodology are large, there is also a disadvantage, at least in comparison with the "all fans off" response. This is that, in common with all methods of automatic, responsive control, there is a need for reliable sensors in the tunnel during the response period. This need is addressed in the above-cited papers. Herein, it is important because of its influence on risk assessment. It is critically important to ensure that sufficient suitably-located sensors are provided to ensure that the large potential benefits of the zero-flow strategy can be realised reliably.

Another complication is the need for inverters (or other means of achieving reliable speed control). It will often be preferable for the inverters to be installed in equipment rooms, not in the main traffic tubes. In this case, long cables may be necessary between the inverters and the fans. This necessitates the use of electrical filters to avoid unacceptable electrical interference with other tunnel equipment. Kanazawa et al (6) showed that the Distancefree Surge Absorber (“DFSA”) system provides sufficiently high-grade filtering to enable the use of cables at least as long as 1,000m.

For completeness, it should be pointed out that the provision of jet fan speed control has important economic advantages in routine operation and in maintenance (4) as well as making possible an effective response to (rare) fires. Such benefits strongly outweigh the foreseen disadvantages of the resulting additional complexity even though account must be taken of such complexity in a comprehensive risk assessment process.

3. TUNNEL FIRE RISK ASSESSMENT - JAPAN

Two very different methods of risk analysis are used herein to assess the effectiveness of zero-flow ventilation strategy on fire life safety, namely:

- A scenario-based deterministic approach, based on simulations of a limited number of scenarios. This method is widely used in Japan. It is described in this Section.
- A fully integrated, system-based, semi-probabilistic approach that calculates an overall risk value for a tunnel based on a large number of fire scenarios. This method, designated the new Austrian tunnel risk model TuRisMo2, includes a systematic variation of relevant parameters. It is described in Section 4.

It is customary in Japan to choose a set of pre-fire conditions (scenarios) and to investigate the consequences of proposed control strategies for each individual scenario. The aim is to identify a strategy that does not expose drivers to fatal risks. A numerical simulation is conducted for each specific scenario to calculate the rate of smoke expansion and hence the smoke densities and temperatures, etc to which drivers will be exposed during evacuation. Driver safety is judged by comparing the simulation results with safety/fatality criteria determined from scientific data. Numerical simulation tools are vital to this method of tunnel safety analysis. Table 1 lists parameters that may be considered in the specification of a typical scenario.

Table 1. Parameters for Pre-fire Conditions

Parameter	Value
Fire Scale	passenger car fire, bus fire
Fire Location	near one end, midpoint, near the other end
Natural Wind	zero, downstream direction, upstream direction
Traffic Flow	light, normal, heavy
Vehicle Speed	normal, slow
Traffic Congestion	no congestion, congestion in one direction, congestion in two directions

3.1 Scenario-Trees

The overall purpose of the safety analysis is to assess risk mitigation strategies both *qualitatively* and *quantitatively*. The chosen strategies can include both design and operational options. For example, a *design* option could be a reduction in the distance between evacuation exits. The zero-flow control strategy is an *operational* option. The consequences of each chosen mitigation strategy are simulated for each scenario.

Each possible combination of the parameters in Table 1 is regarded as a terminal node in a scenario tree. For this particular Table, the total possible number of terminal nodes is 324 (= 2x3x3x3x2x3).

Not all terminal nodes in a scenario-tree necessarily proceed to numerical simulation. Some of the branches are trimmed *qualitatively* based on the safety analyst's knowledge and experience. For example, the analyst may recognise that one of the three listed fire locations will be far more critical than the other two. The objective of trimming the branch is to choose a limited number of terminal nodes that are screened as "potentially dangerous scenarios". These proceed to the *quantitative* simulation stage.

3.2 Tunnel safety simulator

Quantitative simulations are conducted using a tunnel safety simulator (Mizuno et al (1,2), see Figure 2) which has the following subsystems: a traffic simulator, a ventilation simulator and a ventilation control emulator. The ventilation simulator is includes an air-flow module and a smoke-density module. The air-flow module takes natural wind, fans, and traffic piston force as input and generates air-flow as an output. The density module takes fire/smoke growth and air-flow as input and generates smoke density as an output. The ventilation control emulator has a number of pre-programmed control algorithms including feedback control, feed forward control, Model-based Predictive Ventilation Control ("MPVC") (14), and constant/variable fan speed control. The tunnel safety simulator mimics driving behaviour and contains virtual instrumentation that performs data sensing. The simulator has 1D, 2D and 3D modules.

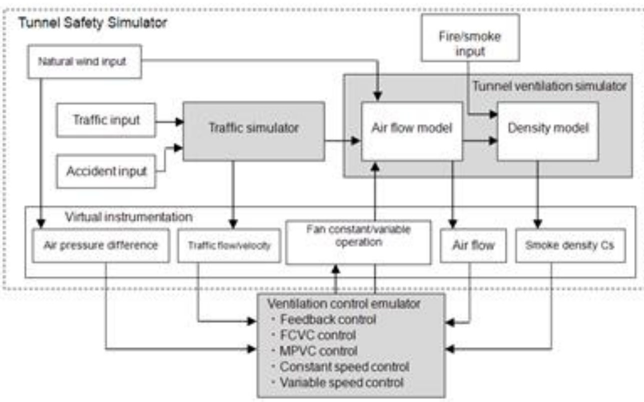


Figure 2. Tunnel Safety Simulator

The tunnel safety simulator has been developed over many years and is a comprehensive facility that is widely used and trusted. It can model fire emergencies in many different types of tunnel, e.g.

- Traffic flow: bidirectional and unidirectional, congestion and accident
- Tunnel length: up to 20km
- Tunnel structure: single tube, complex tunnel with multiple exit ramps

- Ventilation: longitudinal, concentrated portal exhaust, vertical shaft supply and exhaust, transverse, semi transverse
- Ventilation equipment: jet-fan, booster fan, electrical precipitator, vertical shaft supply and exhaust fan, transverse flow supply and exhaust fan
- Operation status: normal, fire emergency

3.4 Assessment of mitigation strategy

The use of the tunnel safety simulator is designed to evaluate alternative fire risk mitigation strategies – e.g. to compare zero-flow control with all-fans-off control. Each of the potentially dangerous scenarios identified in the qualitative assessment is analysed by the 1D models in the tunnel safety simulator to determine whether it is truly a significant risk when the selected control strategy is used. In particular, the prescribed path of the escaping driver is compared with the simulated path of the leading edge of the smoke front. If large numbers of scenarios are found to imply that drivers will be overtaken by the smoke, the control method is deemed unsuitable. If only a small number of cases are still considered as high risk, each proceeds to the next stage, namely simulation in more detail by the 2D or 3D models that can allow for effects such as smoke stratification and back-layering (see Figure 3, for example).

The 2D/3D simulations are time-consuming, but they enable a more realistic assessment than the simple longitudinal behaviour assumed by 1D methods. The stipulated requirement of a “safe” outcome is that all drivers can evacuate the tunnel without going into a region where the smoke density (= optical density) is 0.4/m or higher. Otherwise the outcome is classified as potentially fatal. Only when no driver fatality is predicted in any scenario is the mitigation strategy under the study accepted as an effective approach. The whole safety analysis is repeated with different risk mitigation strategies until at least one strategy is identified for which no driver fatality is predicted.

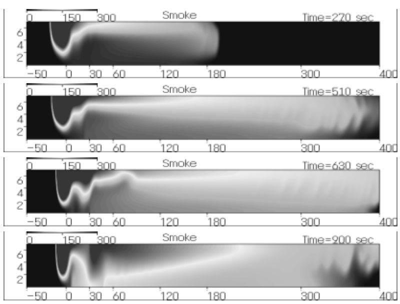


Figure 3. Predicted smoke density distribution at successive instants

4. TUNNEL FIRE RISK ASSESSMENT - AUSTRIA

4.1 Development of the Austrian Tunnel Risk Model TuRisMo2

In contrast with the deterministic approach that is usually followed in Japan, probability-based methods are gaining popularity in Europe. The Austrian Tunnel Risk Model TuRisMo was one of the first risk models specifically developed for road tunnels on the basis of the EC-Directive 2004/54/EC (8). It was developed by a working group of the Austrian Society for the Research on Road, Rail and Transport (FSV) and published in 2008 in the Austrian Tunnelling Guidelines RVS (RVS 09.03.11(9)). In order to widen the range of application of the risk model for addressing new and more complex problems – in particular with respect to fire risk – the model has recently been upgraded, taking into account practical problems identified by stakeholders (10). An enhanced version of the Risk model, namely RVS 09.03.11 was published in April 2015.

4.2 Basic risk concept and principles of risk evaluation

The Austrian Tunnel Risk Model is a system-based quantitative risk model in accordance with the definition of PIARC (12) comprising a range of methodical elements to analyse the whole tunnel system in an integrated manner (11). The model addresses the personal risk of individual tunnel users and hence calculates expected risk values for groups of persons using the tunnel. The risk value refers to the tunnel as a whole, reflecting issues such as the collective risk of all tunnel users and the expected average number of fatalities per year. Respective shares of risk due to mechanical effects, fires and hazardous goods are shown separately.

The method consists of two basic elements: A quantitative frequency analysis and a quantitative consequence analysis.

- ***Frequency analysis***
  An event tree analysis is used to evolve a set of characteristic incident scenarios (collisions and fires) and to calculate the frequencies of these scenarios.
- ***Consequence analysis – collision***
  To estimate damage resulting from collisions, the method includes default values for individual collision scenarios (depending on vehicle involvement), which were derived from statistical data of tunnel collisions.
- ***Consequence analysis – fire***
  To estimate damage resulting from to fires, the method includes a set of integrated simulation tools based on various fire scenarios (in particular smoke propagation and evacuation).

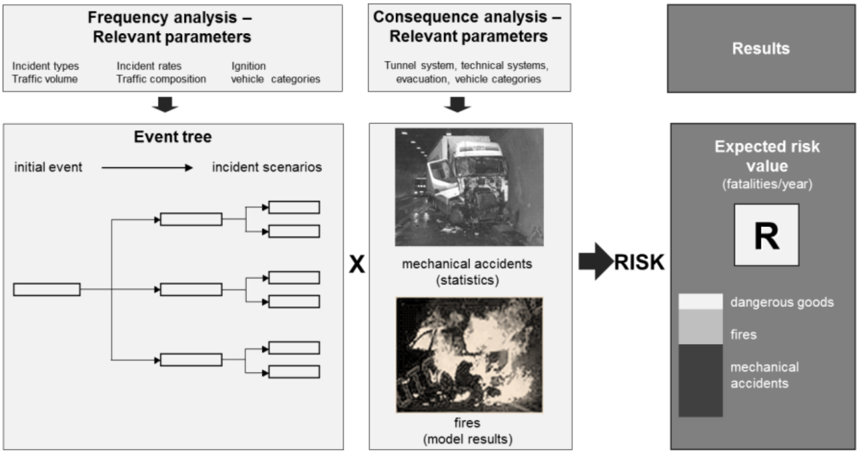


Figure 4. Structure of the Austrian Tunnel Risk Model TuRisMo

The basic information and data used for the development of TuRisMo have been derived from an analysis of a large number of incidents, fires and collisions with casualties in Austrian motorway and expressway tunnels during the years 1999 to 2012.

Typically, TuRisMo is applied in a relative approach in which the risk analysis is performed twice. First, it is undertaken for the actual or proposed tunnel under investigation. Then, parameters describing, for example, the effects of an implemented risk mitigation measure are changed in the model and the risk calculation is repeated. The influence of the changes to the mitigation measure is evaluated by comparing the two outcomes.

4.3 Basic incident scenarios and frequency analysis

The following basic incident scenarios are implemented as part of TuRisMo:

- Breakdown or malfunction of a vehicle, causing a fire
- Breakdown or malfunction of a vehicle, causing a collision (with or without fire as a follow-up event)
- Single-vehicle collision (with or without fire as a follow-up event)
- Collision between vehicles driving in the same direction (with or without fire as a follow-up event)
- Head-on collision (with or without fire as a follow-up event)

All incident scenarios are differentiated in terms of vehicle type (car, HGV, bus) and involvement of dangerous goods. However, dangerous goods are covered only by a simplified approach. The frequency of a number of pre-defined damage scenarios is calculated by means of an event tree analysis. Starting from an initial event (for which the frequency is known) alternative chains of events leading to different consequence scenarios are developed step by step (branches of the event tree). These consequence scenarios differ with respect to scenario type, involvement of vehicle types, damage effects, etc. By quantifying the event tree (initial event as well as bifurcations of the individual branches), it is possible to estimate the frequency of each follow-up scenario.

4.4 Consequence analysis – the new fire model

The method of determining the sequence of each follow-up scenario is dependent upon the nature of the incident:

- *Collisions with exclusively mechanical consequences*: calculation based on values derived from a database on collisions with casualties in road tunnels.
- *Collisions or vehicle breakdowns resulting in fire*: application of a consequence model combining a smoke propagation model with an evacuation model.
- *Incidents involving dangerous goods*: use of a simplified approach based on the results from the fire consequence model.

The new version of the risk model, TuRisMo 2, includes a new fire risk model, which consists of the following sub-models:

- **Unsteady, one dimensional air flow simulation**
  This sub model gives the development of the longitudinal airflow in the tunnel for a set of influencing parameters. As this can be performed in a really efficient way, a large number of cases can be handled, resulting in a range of possible flow cases.
- **Three dimensional CFD simulation**
  Based on the flow fields calculated in the one dimensional simulation process, a (smaller) number of representative scenarios is derived (and projection coefficients are

set). These are simulated in a three dimensional CFD environment to deduce concentrations of smoke and toxic gases in the vicinity of the fire location.

- **Accumulation based evacuation simulation**
  The calculated gas concentrations and visibilities are then used as input for an evacuation simulation. In this sub model, an accumulation based intoxication model (13) is used to determine the maximum distance a person can cover after starting to evacuate from a given location at a given time. Comparisons of this distance with the distances to the various emergency exits enables risk values to be determined for each possible fire zone.
- This distance and the representative configuration of emergency exits calculated from their given location results in zones with risk for life.
- **Exposure simulation and data projection**
  Projecting these zones with risk for life with the zones occupied by congested traffic (exposure) gives the resulting risk for the assessed tunnel system. This projection is performed for the full number of scenarios again.

Provided that sufficient computer resources are available, the application of this procedure enables a good coverage of possible scenario developments to be assessed and realistic fire risk values to be calculated.

4.5 Range of application

TuRisMo2 facilitates a systematic, quantitative risk assessment taking all relevant incident scenarios for road tunnels into account. In principle, it enables the investigation of the consequences of almost any relevant influencing parameter – i.e. specific tunnel characteristic or mitigation measure – on a quantitative basis provided that the required input data are available.

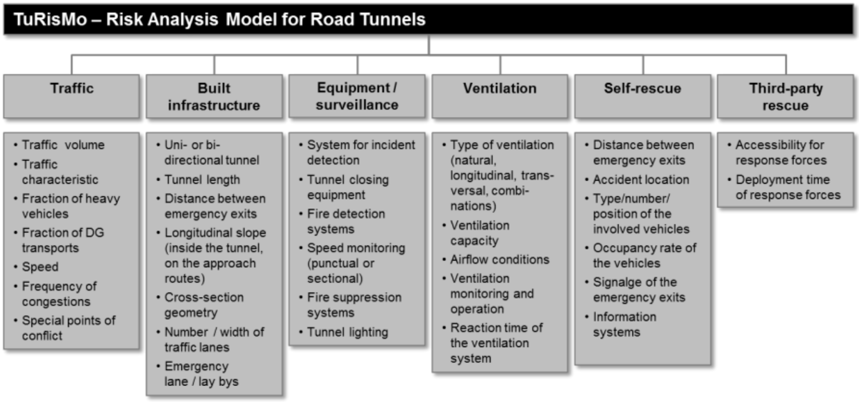


Figure 5. Overview of the influence parameters considered in the risk model

5. APPLICATION TO ZERO-FLOW STRATEGY

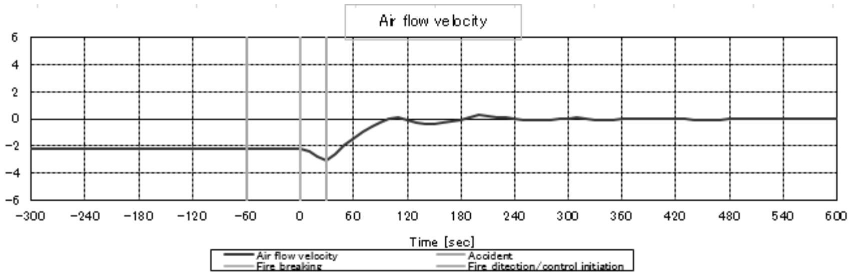
Both of the above methods of risk assessment are now applied to the assessment of the zero-flow strategy for responding to fire in a longitudinally-ventilated, bi-directional tunnel. Key parameters of the chosen (hypothetical) tunnel are listed in Table 2. These are broadly representative of many tunnels in Japan. A range of possible distances between emergency exits is considered, implying a range of possible numbers of such exits.

Table 2. Key parameters of model tunnel

Tunnel system	Bidirectional tunnel with 1 tunnel tube and 1 lane per direction
Tunnel length	2,990 m
Emergency exits	From 0 to 5
Gradient	+ 2,0 % (1,707 m) - 2,0 % (1,283 m)
Tunnel cross section	Vaulted, 71m² (8.4 m diameter)
Traffic volume	1,438 vehicles/hour
Traffic mix	69.5 % passenger cars 30.5 % HGV (incl. busses)
Traffic speed	80 km/h
Traffic signals	Traffic signals at both portals; possibility to stop traffic
Traffic condition	Asymmetric and symmetric traffic scenarios

5.1 Deterministic, scenario-based approach (Japan)

The scenario-based approach is illustrated for a "potentially dangerous" scenario with a 20MW fire breaking out 100m from a portal of the tunnel. It is assumed that an accident occurs at -60s, resulting in a fire starting at 0s. The fire is assumed to be detected at 30s and fire emergency ventilation is initiated immediately. The air velocity and jet-fan speed predicted by the 1D simulation for the zero-flow control case are shown in Figure 6. By inspection, the velocity at the fire location is quickly controlled to be close to 0 m/s. Figures 7 and 8 show the corresponding predictions of smoke density distribution for the zero-flow control strategy and the shut-down strategy respectively. They also show the assumed evacuation path of a driver attempting to escape from the original accident, assuming that he/she begins to evacuate immediately after the outbreak of the fire. In this particular case, the escapee has a large margin when the zero-flow control strategy is used, but is a potential fatality when shut-down control strategy is used.



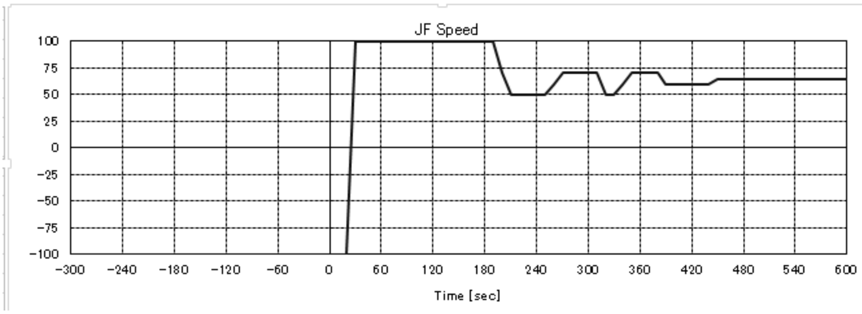


Figure 6. Air flow velocity and jet-fan speed in the 1D simulation (zero-flow control strategy)

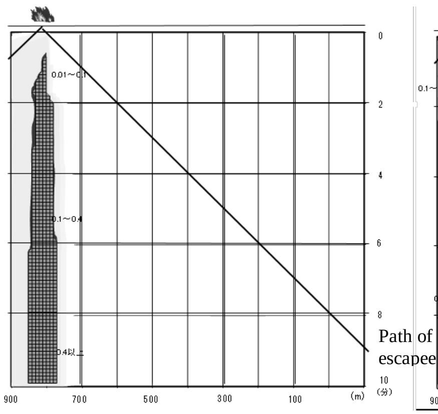


Figure 7. Smoke density distribution (zero-flow control)

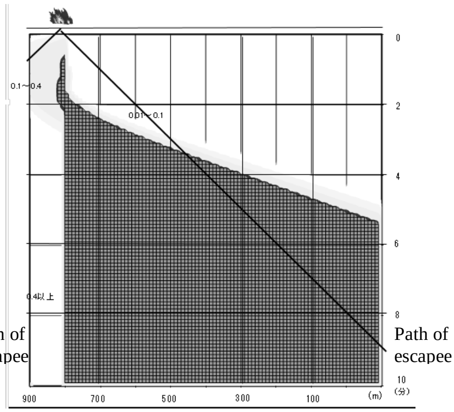


Figure 8. Smoke density distribution (shut-down control)

5.2 Statistical, system-based approach (Austria)

The hypothesized tunnel is now assessed using the system-based risk model TuRisMo2. The expected risk value for fire risk (expected number of fatalities per tunnel and year) for the ventilation strategies has been calculated and the outcome is summarised in Figure 9. It can be seen that, if the tunnel has no emergency exits, the active zero-flow strategy can reduce the fire risk calculated in the model to less than half of the value obtained by applying the shut-down strategy. However, the proportional advantage reduces when emergency exits exist. For example, in case of 5 emergency exits – which correspond to intervals of approximately 500m – the benefit of a zero-flow strategy reduces to 30%.

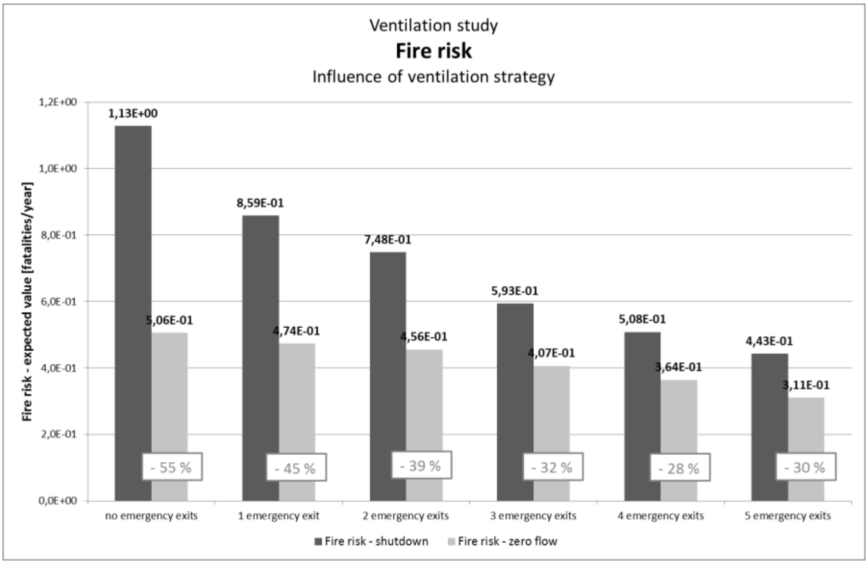


Figure 9. Influence of ventilation strategy on fire risk (System-based approach)

In the Austrian tunnel risk model, a broad range of many different scenarios with varying parameters is taken into account in a statistical manner. For the tunnel considered here, 135 cases were simulated, namely all possible combinations of:

- 3 fire sizes
- 9 traffic scenarios
  (3 different traffic loads combined with 3 different symmetry scenarios)
- 5 fire locations
  (three in the uphill section and two in the downhill section of the tunnel)

The differences between the two ventilation strategies are now highlighted by looking in more detail at one of the scenarios with a high predicted number of victims. In routine operation for this case, there is a high traffic volume with symmetric traffic conditions (same traffic value in both directions) and the ventilation system is operated to maintain a longitudinal air flow of approximately 1 m/s from right to left in Figure 10. A 30MW fire then develops in the middle of the tunnel (i.e. at 1,495m), implying initially downwards flow past the fire.

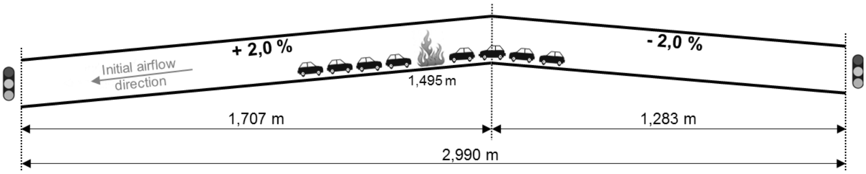


Figure 10. Schematic representation of Scenario

First, consider only the longitudinal mean airflow. Initially, the jet fans continue to be operated in the routine manner, thereby maintaining the downwards 1m/s. However, 150s after fire start, the fire emergency state ventilation control is activated. Thereafter, the two ventilation strategies have different outcomes.

- **zero-flow strategy:** After a short overshoot, the ventilation control rapidly achieves nearly zero flow and thereafter maintains this state (see Figure 11).
- **shutdown strategy:** The longitudinal airflow velocity is dependent on the buoyancy of the hot gases. As the initial airflow in the scenario is downward (negative) this leads to a change of the airflow direction about 430s after fire start (see Figure 12).

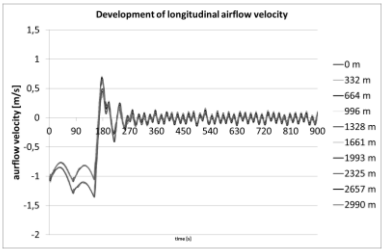


Figure 11. Development of longitudinal airflow velocity – zero-flow strategy

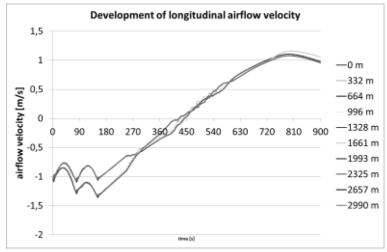


Figure 12. Development of longitudinal airflow velocity – shut-down strategy

Next, consider temperatures. Figures 13 & 14 show average temperature over the tunnel cross section. With the zero-flow strategy, hot smoke is mostly contained in a short region close to the accident location, but this leads to very high temperatures in this region (~800°C). With the shutdown strategy the smoke extends over a larger length of tunnel, but this results in lower temperatures, even close to the fire, except during the period of flow reversal when the predicted temperature temporarily reaches the same value as with the zero-flow strategy (~800°C). These outcomes are taken into account in the risk assessment process.

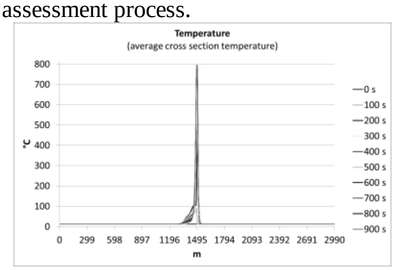


Figure 13. Average cross section temperature - zero-flow strategy

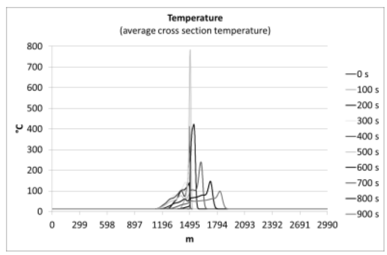


Figure 14. Average cross section temperature – shut-down strategy

Now consider visibility. Figures 15 and 16 show distributions of the extinction coefficient at one-minute intervals. In the zero-flow case, smoke propagates almost symetrically in both directions whereas, in the shut-down case, it intially propagates downstream (from right to left) and then propagates upstream. The existence of the change of direction is likely to cause confusion for some users, who might begin to evacuate uphill, only to be overtaken by the smoke front which, soon after reversal, is moving much more rapidly than in the case with the zero-flow strategy. For example, after 15 minutes, smoke in the zero-flow case extends approximately 500m on each side of the fire and the smoke fronts are moving at approximately 0.5m/s. At the same instant with the shut-down strategy, the smoke spread is again approximately 500m, but the speed of the upward-moving smoke front is much greater than with the zero-flow strategy. The difference between the speeds of propagation of the smoke front are potentially highly important for escaping persons, especially over long distances.

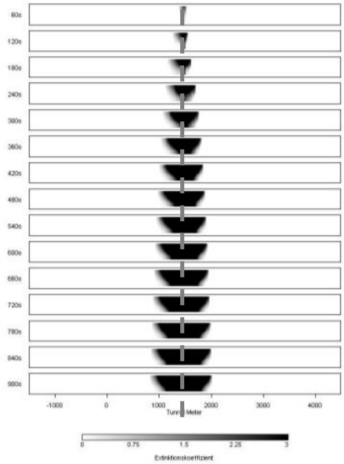


Figure 15. Smoke propagation along tunnel axis in time steps- zero-flow strategy (scenario 1)

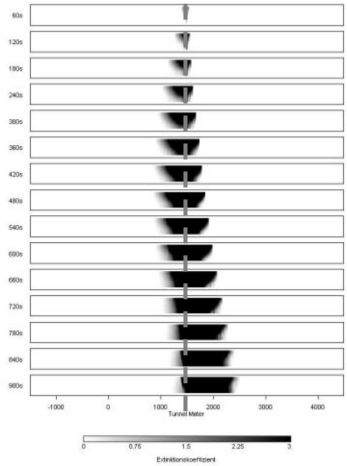


Figure 16. Smoke propagation along tunnel axis in time steps – shut-down strategy (scenario 1)

Figures 15 and 16 are applicable for just one particular scenario. The effects can be more pronounced in other scenarios. In the case considered in Figures 17 and 18, fire breaks out 2,238m from the portal of a 2,990m long tunnel. The initial direction of airflow is upstream (from right to left in the Figures). This differrence between the two scenarios has only minor consequences with the zero-flow strategy, but it has a big influence on the outcomes with the shut-down strategy. For example, after 15 minutes, the uphill-moving smoke front has propagated much further than in scenario 1 and smoke exists in a greater length of tunnel (approximately 1,500m). Furthermore, although not shown explicitly herein, the zero-flow strategy shows improved smoke stratification.

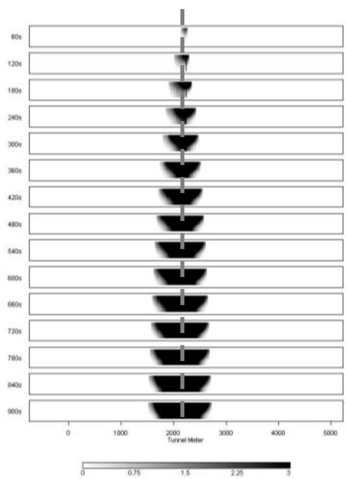


Figure 17. Smoke propagation along tunnel axis in time steps – zero-flow strategy (scenario 2)

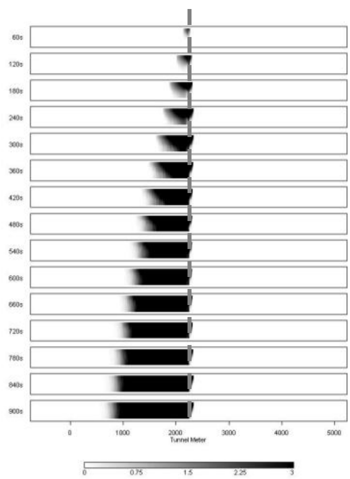


Figure 18. Smoke propagation along tunnel axis in time steps – shut-down strategy (scenario 2)

5.2.1 Wider considerations

The particular scenarios are informative, but they should not be interpreted as representative of all scenarios. Indeed, they demonstrate the importance of undertaking simulations independently for each scenario even when only relatively small differences are hypothesized. However, all 135 simulated scnarios are included in Figure 9, which expresses the outcome of the statistical approach. In this context, note that all outcomes are included in the composite overall result, including any that show negative effects. This is one of the major advantages of a system-based approch. Another advantage is that the effects of other safety measures can be assessed in the same systematic manner. So can interactions between various measures - as illustrated above in the discussion of distances between emergency exits.

A further advantage of the new Austrian tunnel risk model arises from the opportunity that it provides to look in detail at intermediate results leading to the overall results. The existence of the various graphs and diagrams is essential for the verification and interpretation of the results and, importantly, it greatly reduces the risk of the methodology being used as a “black box”.

However, one limitation of the risk model needs to be mentioned. In the present version, fire development follows a predefined curve and there is no feedback between fire growth and other parameters such as, for example, the longitudinal airflow velocity. Also, the production of flue gases cannot be taken into account in a rigorous manner. These limitations have the potential to distort the assessment of specific ventilation strategies. Similar limitations exist for nearly all other methods of assessing fire risk, of course, and much research might be needed before their importance can be reduced significantly. Nevertheless, they are re-iterated here to avoid giving a false impression of complacency in the new Austrian approach, even though it is considered to be a significant advance on previous methods.

6. CONCLUSIONS

Two approaches have been presented to assess zero-flow control as a risk mitigation strategy for tunnel fires in bidirectional, longitudinally ventilated tunnels. One is a scenario-based, deterministic approach that has been widely applied in Japan. The other is a system-based probabilistic approach that is now being applied in some EU countries.

The scenario-based, deterministic risk analysis is conducted using a scenario-tree that can be uniquely defined for individual tunnels and tailored to the specific needs of clients. It includes detailed analyses of scenarios identified as potentially dangerous and it shows the expected outcomes of each mitigation strategy explicitly. The method gives clear qualitative outcomes (“safe” or “fatal”) and it is easy for stakeholders to understand.

The system-based, probabilistic risk analysis is conducted for a standardized event-tree using statistical data applicable for tunnels in general. The result gives quantitative risk values describing overall risk such as the expected average number of fatalities per annum. In addition to providing quantitative comparisons for different mitigation strategies in any particular tunnel, it enables qualitative comparisons to be made of relative safety of different tunnels.

Both approaches have been applied to a "typical" tunnel case and have been used to compare the merits of a zero-flow control strategy and a switch-off-all-fans strategy. For this illustrative example:

- Both approaches have shown that the zero-flow strategy ensures more opportunity than the shut-down strategy for drivers to evacuate safely from a tunnel in the event of a serious fire.
- The system-based approach has shown that, if the (long) chosen tunnel has no emergency exits, the zero-flow strategy reduces the expected fatal risk by more than 50% in comparison with the shut-down strategy. The relative advantage reduces with increasing numbers of emergency exits, but it is still approximately 30% when the assumed distance between successive emergency exits is 500m.

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