# VENTILATION CONTROL OPTIMISATION FOR SHORT LONGITUDINALLY VENTILATED ROAD TUNNELS IN CASE OF TEMPORARY BIDIRECTIONAL TRAFFIC OPERATION

Oliver Heger, Gregor Schmölzer

*ILF Consulting Austria GmbH, AT*

DOI 10.3217/978-3-99161-087-8-013 (CC BY-SA 4.0)

## ABSTRACT

Maintenance closures in modern tunnel infrastructure often require temporary bidirectional operation of short, longitudinally ventilated road tunnels, creating significant challenges for ventilation control and fire safety. These tunnels, originally designed for unidirectional traffic, face increased risk during such phases, particularly when regulatory requirements cannot be fully met due to spatial and operational constraints. This paper examines optimization strategies for ventilation control under these conditions using a representative two-lane motorway tunnel as a case study. The Austrian TuRisMo risk assessment methodology was applied, combining quantitative scenario analysis with coupled 1D–3D smoke propagation modeling. A key focus was the impact of jet fan activation near fire locations, which can destroy smoke stratification and impair evacuation. To address this, an adapted modeling approach approximating jet fan-induced destratification was introduced. Results show that natural ventilation—deactivating jet fans in smoke-filled areas—can significantly reduce expected fatalities in certain scenarios compared to configurations involving temporary overblowing. However, controlled longitudinal ventilation remains advantageous in other cases. The findings highlight the need for flexible, risk-based approaches and performance-based design principles to balance safety, regulatory compliance, and operational feasibility during temporary bidirectional operation.

*Keywords: tunnel ventilation, risk-based design, ventilation control optimisation*

## 1. INTRODUCTION AND REGULATORY REQUIREMENTS

Short unidirectional tunnels are generally regarded as relatively safe components of underground transport infrastructure. This is primarily due to their enhanced accessibility for emergency services and shorter egress paths to open areas compared to longer tunnels. Their comparatively lower risk potential is also reflected in tunnel safety regulations, which—depending on tunnel length and traffic volume—typically permit longitudinal ventilation (either natural or mechanical) for short tunnels with free-flowing unidirectional traffic.

However, due to spatial constraints, designing ventilation systems for short tunnels can be challenging. Ventilation zones must be compact, and jet fans as well as anemometers are often installed at short intervals. Under normal conditions—such as moderate gradients and typical meteorological influences—these challenges are generally manageable. In recent years, however, many road tunnels, constructed or significantly upgraded following the implementation of EU Directive 2004/54/EC [1], have entered their next major maintenance cycle. As a result, numerous tunnels, including short unidirectional ones with mechanical longitudinal ventilation, require extended maintenance, often necessitating the closure of one tube for prolonged periods. In such cases, it is practical to operate the remaining tube with bidirectional traffic to minimize the impact on overall traffic capacity. However, this temporary shift to bidirectional operation in a tunnel, designed for unidirectional flow, typically results in increased risk. Experience shows that this risk increase can often be mitigated by optimizing the longitudinal ventilation system for bidirectional traffic. This usually involves loop-controlled low-speed ventilation, maintaining the original airflow direction, and ensuring that jet fans are not activated in smoke-filled areas. Additional risk mitigation measures—such as significant speed reductions, traffic metering systems, or optimized maintenance scheduling (e.g., during night hours)—are also commonly implemented.

For short tunnels, however, the options for optimizing longitudinal ventilation control are significantly limited. Due to the short spacing between jet fans, it is often not possible to meet all regulatory requirements simultaneously. In some cases, jet fans located in potentially smoke-filled areas must be activated to maintain airflow control. Achieving full regulatory compliance would formally require the installation of a semi-transverse ventilation system. However, this is typically neither cost-effective nor feasible, as implementing such an upgrade would necessitate closing one tube—thus requiring bidirectional operation in the remaining tube in the first place. Therefore, the only viable approach is to optimize the existing longitudinal ventilation system and control strategies as much as possible, while reducing risk through supplementary safety measures, accepting a residual risk increase for a limited time. Current tunnel safety frameworks acknowledge this challenge and often permit cost-effectiveness analyses and ALARP (As Low As Reasonably Practicable) justifications in such scenarios.

For instance, the Austrian regulatory framework for tunnel ventilation design, the STSG [2] and the RVS guideline [3] formally require mechanical ventilation and, under normal bidirectional conditions, would not permit longitudinal ventilation without a risk analysis and/or compensatory measures for tunnels of a certain length and traffic volume (AADT). But RVS 09.11.03 explicitly allows for flexibility in temporary operational phases, enabling the use of longitudinal ventilation if equivalent safety can be demonstrated through a structured risk assessment or if additional measures would not be cost-effective with respect to the ALARP principle. Similar, also under the German guideline RE-ING [4], the use of longitudinal ventilation in bidirectional tunnels is conditionally permissible. For tunnels longer than 600 m and up to 1200 m, a risk analysis is required unless specific geometric and operational criteria are met. For tunnels exceeding 1200 m, smoke extraction systems are generally mandated. Actually, RE-lNG does not explicitly differentiate between permanent and temporary bidirectional operation. However, it is also common practice in Germany that longitudinal ventilation systems have been accepted for temporary bidirectional operation phases (e.g., during maintenance closures of one tube). For both regulatory frameworks, the use of longitudinal ventilation in permanent bidirectionally operated tunnels is restricted but there is regulatory and practical precedent for accepting longitudinal ventilation during temporary operational phases, provided that a comprehensive risk analysis is conducted, specific safety measures are implemented to mitigate the increased risk, and the equivalency of the residual risk, or alternatively the ALARP compliance of the temporary risk exceedance, is demonstrated.

Irrespective of the underlying directive, the regulatory requirements for longitudinal ventilation lead often to implementation issues in case of short tunnels (approx. 1.000 m). The spectrum of problems in such projects typically include undersized existing ventilation systems following expired guidelines or for downhill ventilation in case of tubes operated in uphill direction under normal (unidirectional) operation, short distances between fans and thus compact fire zones, spatial restrictions for installation, in particular small cross-sections and restricted options for adding more jet fans, as well as longer back layering due to low-speed ventilation during bidirectional operation. Due to these issues, it is often not possible to meet all regulatory ventilation control requirements simultaneously – i.e. achieving desired airflow velocities under design conditions for both ventilation directions, avoiding activation of jet fans in areas where smoke is potentially present (i.e. downstream the fire site or within the back-layering length in upstream direction), and avoiding flow reversal. Therefore, optimization of the ventilation control to minimize potential casualties is necessary as a part of the risk assessment and ALARP compliance demonstration procedure.

This paper is intended to illustrates a promising approach for this optimization procedure based on a scenario analysis, using a generic two-lane unidirectional tunnel with a typical longitudinal ventilation layout. The presented technique has been developed with broader risk assessment framework implementation in mind. Therefore, a simplified method to account for smoke destratification caused by jet fan activation in smoke-filled areas within quantitative tunnel risk analysis, relying on coupled 1D-3D smoke propagation modelling approaches, where jet fans are not specifically modelled in the 3D domain, has been adopted. In section 2 a generic two-lane unidirectional tunnel with a typical longitudinal ventilation layout, temporarily operated with bidirectional traffic, is presented as an demonstrative example and the possible options for optimizing longitudinal ventilation control are discussed. Section 3 presents the methodology used for the scenario analysis as well as the approximative approach to account for smoke destratification due to jet fan activation in smoke filled areas. The detailed results for one exemplary fire scenario as well as the overall result for the different fire detection zones for the considered model tunnel are finally presented in section 4.

## 2. EXAMPLARY MODEL CASE

As an example, a 675 m long, two-lane motorway tunnel with horseshoe profile, which is temporarily operated with bidirectional traffic during refurbishment, is selected. The given ventilation system is designed and optimized for one-way traffic and essentially complies with the requirements of the current Austrian guideline RVS 09.02.31. The tunnel has two accessible cross passages. A summary of the relevant parameters can be found in Table 1. Due to the steep gradient (-3.6%) against the normal operation direction, the tunnel has a total of 12 jet fans, spread across 6 locations. The resulting fire detection zone lengths are generally around 100 m, the only exceptions are the portal zones with 60 /185 m (see also Figure 1).

**Table 1:** Key parameters of the example tunnel

| Parameter | unit | value |
|---|---|---|
| Tunnel length | [m] | 675 |
| Gradient | [%] | -3,6 |
| Cross section | [m²] | 50,0 |
| Cross passages | [#] | 2 |
| Design fire | [MW] | 30 |
| Target velocity (bidirectional traffic) | [m/s] | ±1,5 |
| Portal pressure difference | [Pa] | 10 |
| Hourly traffic | [veh/h] | 2.200 |
| HG traffic share | [%] | |
| Number of jet fans | [#] | 12 |
| Static thrust per jet fan | [N] | 915 |

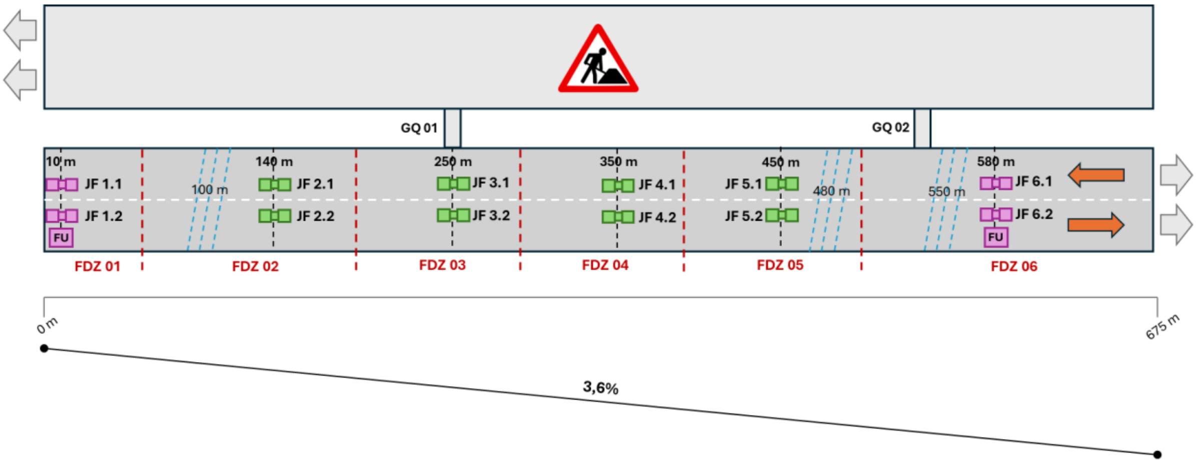


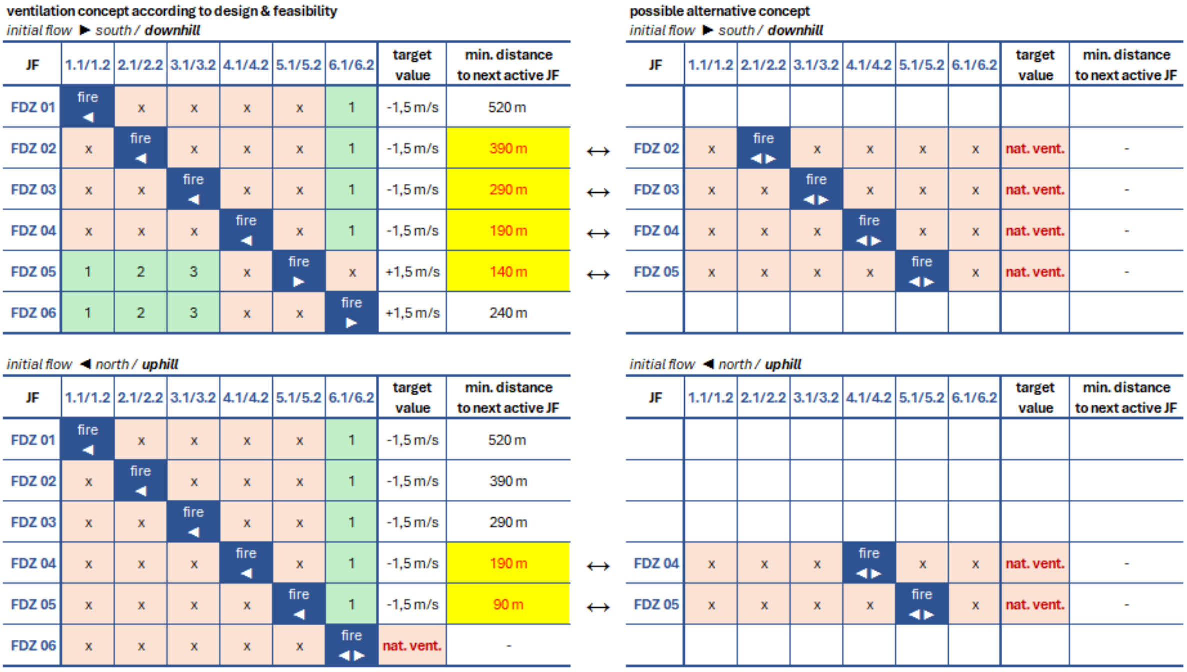
**Figure 1:** Ventilation scheme diagram for the example tunnel

In accordance with Austrian guideline RVS 09.02.31, during the temporary two-way traffic phase, the flow direction, prevailing in the tunnel at the time of fire detection, must be maintained, and an air speed upstream the fire of +/- 1.5 m/s must be achieved under design conditions. At the same time, jet fans in the smoke layer should not be activated to avoid unnecessarily and prematurely destroying any smoke stratification that may be present, which would significantly impair visibility and escape conditions. However, if this requirement is to be met, it means that all jet fans located between the fire and the respective exhaust portal must not be activated. Assuming that smoke is always extracted via the nearest portal in the portal zones, only 2 to 10 jet fans upstream of the fire are available for smoke extraction, depending on the location of the fire. Considering the system parameters for the selected tunnel (especially the steep gradient and short distances between jet fans), it can be assumed that it will not be possible to simultaneously meet all the requirements set out in the guideline, and consequently the following options, diverging from the regulatory requirements in one way or the other, remain:

- Full compliance with the required flow direction and velocity (according to RVS 09.02.31), but use of all jet fans that are not located in the immediate fire zone
- No use of jet fans downstream / too close upstream, but negative deviations in the achievable velocity (up to the extreme case of “natural ventilation”) are accepted
- Fixed smoke extraction direction (intentional flow reversal, if required) to take advantage of the gradient (thermal buoyancy) or to have more jet fans available upstream at a sufficient distance from the fire location

In a first step, calculations were performed for each fire detection zone (FDZ) to determine whether ventilation in both directions, at a minimum speed of 1.5 m/s, is possible under design conditions using only jet fans located upstream of the fire. In cases where this is not possible, fixed smoke extraction in the direction for which positive calculated proof could be provided is selected for the time being.

The technically feasible smoke extraction strategies derived from these calculations are summarized in Figure 2 (left-hand side), considering the basic flow at the start of the fire. Due to the steep incline, in zones FDZ 01 to FDZ 04 ventilation is only possible uphill / northwards. In zone FDZ 05, smoke extraction in both directions is mathematically possible in accordance with the guidelines. In zone FDZ 06, active ventilation is only possible in the direction of the nearby south portal since there are no more jet fans available upstream of the fire for ventilation northward. With a fire load of 30 MW and the desired air speed of 1.5 m/s, a significant backflow of smoke (back layering) is to be expected. Figure 2 (left-hand side) also shows the minimum distance between a fire and the nearest jet fan location required for ventilation. Depending on fire location and ventilation direction, this distance is 90 to 520 m. In some cases, under the given circumstances (slope, fire load, initial basic flow, forced flow reversal), it can be assumed that smoke backflow will temporarily or permanently, reach these locations. Scenarios where this could not be explicitly ruled out in advance are highlighted in yellow. For these cases, a possible alternative strategy has been defined as a potential optimization option to be assessed by means of a quantitative, simulation-based scenario analysis. The ventilation control alternatives for the affected fire zones are shown at the right-hand side of Figure 2. For the tunnel investigated, the only alternative still available in all affected zones is to dispense active, mechanical ventilation and to switch to natural ventilation instead.



**ventilation concept according to design & feasibility**

*initial flow* ▶ *south / **downhill***

| JF | 1.1/1.2 | 2.1/2.2 | 3.1/3.2 | 4.1/4.2 | 5.1/5.2 | 6.1/6.2 | target value | min. distance to next active JF |
|---|---|---|---|---|---|---|---|---|
| FDZ 01 | fire ◀ | x | x | x | x | 1 | -1,5 m/s | 520 m |
| FDZ 02 | x | fire ◀ | x | x | x | 1 | -1,5 m/s | 390 m |
| FDZ 03 | x | x | fire ◀ | x | x | 1 | -1,5 m/s | 290 m |
| FDZ 04 | x | x | x | fire ◀ | x | 1 | -1,5 m/s | 190 m |
| FDZ 05 | 1 | 2 | 3 | x | fire ▶ | x | +1,5 m/s | 140 m |
| FDZ 06 | 1 | 2 | 3 | x | x | fire ▶ | +1,5 m/s | 240 m |

*initial flow* ◀ *north / **uphill***

| JF | 1.1/1.2 | 2.1/2.2 | 3.1/3.2 | 4.1/4.2 | 5.1/5.2 | 6.1/6.2 | target value | min. distance to next active JF |
|---|---|---|---|---|---|---|---|---|
| FDZ 01 | fire ◀ | x | x | x | x | 1 | -1,5 m/s | 520 m |
| FDZ 02 | x | fire ◀ | x | x | x | 1 | -1,5 m/s | 390 m |
| FDZ 03 | x | x | fire ◀ | x | x | 1 | -1,5 m/s | 290 m |
| FDZ 04 | x | x | x | fire ◀ | x | 1 | -1,5 m/s | 190 m |
| FDZ 05 | x | x | x | x | fire ◀ | 1 | -1,5 m/s | 90 m |
| FDZ 06 | x | x | x | x | x | fire ◀▶ | nat. vent. | - |

**possible alternative concept**

*initial flow* ▶ *south / **downhill***

| JF | 1.1/1.2 | 2.1/2.2 | 3.1/3.2 | 4.1/4.2 | 5.1/5.2 | 6.1/6.2 | target value | min. distance to next active JF |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |
| FDZ 02 | x | fire ◀▶ | x | x | x | x | nat. vent. | - |
| FDZ 03 | x | x | fire ◀▶ | x | x | x | nat. vent. | - |
| FDZ 04 | x | x | x | fire ◀▶ | x | x | nat. vent. | - |
| FDZ 05 | x | x | x | x | fire ◀▶ | x | nat. vent. | - |
|  |  |  |  |  |  |  |  |  |

*initial flow* ◀ *north / **uphill***

| JF | 1.1/1.2 | 2.1/2.2 | 3.1/3.2 | 4.1/4.2 | 5.1/5.2 | 6.1/6.2 | target value | min. distance to next active JF |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |
| FDZ 04 | x | x | x | fire ◀▶ | x | x | nat. vent. | - |
| FDZ 05 | x | x | x | x | fire ◀▶ | x | nat. vent. | - |
|  |  |  |  |  |  |  |  |  |

**Figure 2:** Possible smoke extraction strategies Variant I (left) and Variant II (right) for the example tunnel

# 3. ASSESSMENT METHODOLOGY

## 3.1. The Austrian Tunnel Risk Assessment Methodology

In many regulatory contexts risk assessment is the tool of choice to allow for a deviation from the ventilation requirements prescribed in the respective guidelines in terms of a performance-based design approach. In this model case example, the Austrian tunnel risk assessment methodology (TuRisMo) is applied for this purpose. The Austrian methodology uses a fully integrated quantitative approach that allows for the detailed analysis of many kinds of safety measures and for interactions between them. The method combines a quantitative frequency analysis based on statistical evaluations and a quantitative consequence analysis that includes a mechanical collision-only part and a distinct fire consequence model [5]. The primary output of TuRisMo is the expected number of fatalities per year for the tunnel under consideration which is assessed by comparison with a reference risk value. In this relative approach the reference risk profile is obtained by applying the same quantitative model (TuRisMo) to a suitable reference tunnel, which is defined as a tunnel as similar as possible to the tunnel under investigation while fully in line with all applicable design regulations and guidelines.

The methodological core of TuRisMo, which is also essential to the comparison of ventilation control strategies in this study, is the quantitative fire consequence model. The fire consequence model used further on in the investigation of emergency ventilation strategies can be summarized as follows: For each considered fire scenario, a transient one-dimensional airflow simulation is performed, considering all important influencing factors, such as traffic volume, fire location, ventilation design and meteorological boundary conditions. In this study the commercial software IDA RTV is used for this purpose. The predicted development of the longitudinal airflow velocities is then used as boundary condition in a three-dimensional CFD simulation (FDS) in which local effects such as back-layering and smoke stratification are examined. Visibility-, heat- and toxic-gas concentrations generated in the three-dimensional CFD simulation are then combined with person-exposure distributions dependent upon the traffic configuration after the incident. Based on this superposition and using an accumulation and intoxication model describing the effects of fire hazards on evacuation speed and survivability of persons [6], the expected total number of fatalities is computed [7].

### 3.2. Approximative Consideration of Jet-Fan Overflow

One of the central questions in the ventilation design of short bidirectionally operated tunnels is whether it is better to accept the fact that small distances between activated jet fans and fire location might lead to a destratification of smoke, or whether keeping stratification up as long as possible thus accepting deviations from the desired airflow target directions and velocities is preferable. To analyze the potential impact of jet fans on layer formation, the local impact of jet fans on the flow field or at least on the smoke layer, needs to be considered in the CFD simulations. According to the fire-consequence modelling technique, adopted in TuRisMo as explained above, active longitudinal ventilation components are not explicitly modeled in the 3D-CFD simulations, and only directly considered in the 1D part of the smoke propagation model. In the 3D-CFD simulations, the impact of jet fans is only considered implicitly by applying the longitudinal velocity development, that is a result of the consideration of jet fans in the 1D simulation, as velocity boundary conditions at the 3D domain inlet. This simplification of jet fan consideration in the 1D-3D coupled approach is legitim, if the distance between activated jet fans and region of interest is large enough for the high vertical velocity gradients, caused by the high discharge velocity of jet fans, to have decreased significantly so that the assumption of a relatively homogeneous velocity field acting on the smoke/fresh air layer formation is justified. For standard use case of tunnel risk assessment models (longer tunnels with sufficiently broad ventilation zones, where the distance between fire location and activated jet fan is often several hundreds of meters long), this assumption is typically applicable. In the present case, however, ventilation zones are very compact and no can be generally considered as smoke free due to the low target airflow velocities. Therefore the existing fire consequence analysis methodology, and in particular the (one-way) coupled 1D-3D smoke propagation model must be adapted and the direct impact of active jet fans on the smoke-layer formation potentially causing destratification considered.

The most intuitive and straight forward approach would be to consider jet fans in the 3D model directly. In principle, this is technically possible and several 3D studies, focusing on jet fan performance in tunnels, have indeed been carried out recently (cf. [8], [9]) . However, the large vertical gradients in the near-field of activated jet fans call for very high mesh resolutions in the 3D CFD analysis, at least in the respective region, which would lead to significant increase in computation time compared to the standard smoke-propagation simulation approach. In addition, the 3D CFD modelling of jet fans is typically restricted to steady-state problems, while the problem at hand is highly transient, as the time-dependent propagation of smoke is of relevance. In addition, it has been demonstrated that FDS might be rather inaccurate in predicting the impact of jet fans on upstream smoke propagation, which would necessitate the use of more adaptable CFD solvers like Ansys Fluent [8]. Due to these reasons and to be in line with the consequence analysis approach prescribed within the TuRisMo methodology, an alternative method to estimate the occurrence and impact of destratification due to effect of close active jet fans, at least in an approximative manner, has been adopted:

- In principle, the one-way coupling between the 1D and 3D CFD models is maintained, and the influence of jet fans on flow behavior is considered only in the transient 1D simulations. The results of the coupled flow simulation therefore do not include any consideration of 3D (or 2D) effects of the jet fans.

- To determine whether the smoke layer might potentially be destroyed by upstream jet fans, the result of the 3D simulation is examined regarding the extent of “back-layering.” For this purpose, the cross-section-averaged temperature profiles at the boundaries of the influence zone of the nearest jet fan are analyzed, assuming an influence length of 60 m for a jet fan.

- If the cross-section-averaged temperature 60 m downstream of the jet fan closest to the fire site is elevated compared to the ambient temperature, it is assumed that the smoke stratification is destroyed for the duration of the temperature increase, and thus for the duration of the jet fan smoke-overflow

- To approximate the impact of a disrupted smoke stratification, the evacuation and survival simulations employ cross-section-averaged values for temperature and smoke gas concentration, rather than head-level values, for the duration of the jet fan smoke-overflow ($\bar{t}_1$) and the subsequent period required to purge the smoke-filled air column between the jet fan and the extraction portal at the prevailing flow velocity ($\bar{t}_2$) ).

- The time it takes for the smoke-filled air column between the jet fan and the smoke extraction portal to be removed from the tunnel is derived from the temporal progression of the flow velocity and the distance between the jet fan and the smoke extraction portal, cf.

$$\bar{t}_2 \colon \int_{\bar{t}_1}^{\bar{t}_2} u(t, x_{SV}) dt := x_{Portal} - \; x_{SV+60m}$$

**Equation 1:** Estimated time duration for removal of destratified smoke

## 4. RESULTS

The options for ventilation control for the described model tunnel application discussed in section 0 have been assessed based on a direct comparison of the two possible ventilation alternatives with respect to the expected number of fatalities resulting from the application of the adapted TuRisMo fire consequence model. The detailed results for fire zone FDZ 04, characterized by an initial airflow direction toward the south, are presented in Figure **3** and Figure **4** as a representative example to illustrate the applied methodology. In Variant I, the targeted longitudinal airflow velocity was successfully achieved, as shown in the left part of Figure **3**. To reach this velocity, both authorized jet fans were activated. In Variant II, natural ventilation was applied. The distance between the fire location and the activated jet fan in Variant I was 190 m. Results from the 3D CFD simulation using FDS (Fire Dynamics Simulator) indicate an increase in cross-section-averaged temperatures 60 m downstream of the relevant jet fan between 110 s and 320 s after ignition, compare Figure **3** (right part). After approximately 320 s, the back-layering was suppressed by the developing longitudinal airflow velocity of –1.5 m/s, leading to a re-establishment of smoke stratification.

This effect was incorporated into the evacuation and survival simulations by applying cross-section-averaged smoke gas and temperature values for the section between the smoke extraction portal (north portal) and the jet fan (580 m) during the period of expected smoke layer destruction (indicated as **CSA** Figure **4**- left**)**. For times before and after this period, Face-Level values were used (indicated as **FL** Figure **4** - left**)**. Since an instantaneous restoration of stratification after back-layering suppression cannot be assumed, the time required to purge the air column between the jet fan and the extraction portal (the zone of destroyed stratification) was also calculated. In a conservative approach, cross-section-averaged values were applied for this additional period as well. The integration of head-level and cross-section-averaged smoke gas and temperature values into a unified dataset for Fire Zone 04 is illustrated schematically in Figure **4**. Based on this dataset, evacuation and survival simulations were performed for three representative population groups, with different walking-speeds and pre-movement times considered.

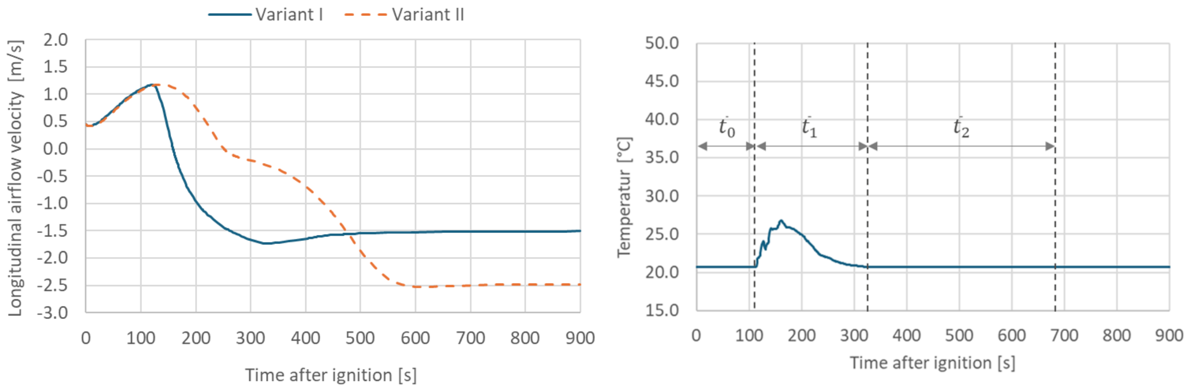


**Figure 3**: Time development of longitudinal Airflow (left): solid line Variant I vs. orange line Variant II, and temperature development 60 m downstream of activated jet fan for Variant I (right)

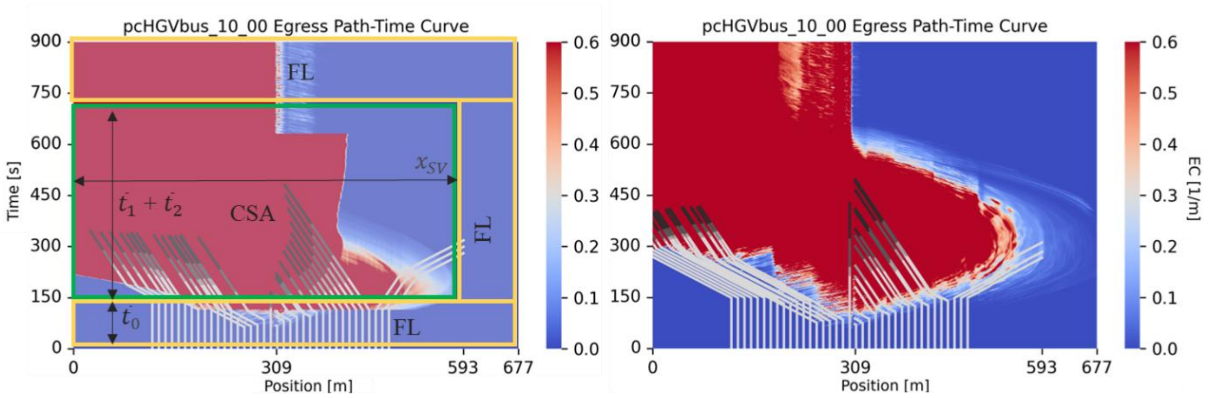


**Figure 4**: Temporal and spatial smoke density, along with path-time trajectories for one considered group of evacuating agents—Variant I (left) versus Variant II (right)

The spatial and temporal smoke density (expressed as extinction coefficient), together with the resulting path-time trajectories for one group of evacuating agents are also depicted in Figure **4**. Each trajectory represents an individual starting evacuation from a specific position within the vehicle queue. The trajectory color indicates intoxication level, ranging from light (no impairment) to dark (severe impairment). Agents whose trajectories terminate at an emergency exit—portal or cross passage—or who survive until the end of the simulation period (900 s) are classified as successfully evacuated. Conversely, agents whose trajectories end prematurely before reaching an emergency exit are classified as fatalities. Both the numerical data and qualitative visualizations clearly demonstrate the superior performance of natural ventilation (Variant II) compared to the configuration involving temporary overblowing of activated jet fans (Variant I) for the considered scenario.

Table 2 presents the quantitative results of the scenario analysis, expressed as the number of fatalities per scenario and ventilation variant. For Fire Zones FDZ04 – south and FDZ05 – south, the outcomes are unambiguous: natural ventilation (Variant II) offers significant advantages during the self-rescue phase. This benefit is primarily due to the anticipated destruction of the smoke layer caused by activated jet fans in Variant I. For Fire Zone FDZ02 – south, Variant II also results in a slightly lower number of fatalities. However, considering the inherent uncertainties in modelling and parameter assumptions, as well as the fundamental advantages of controlled longitudinal ventilation—particularly the ability to maintain a defined airflow state—Variant I is selected despite the marginally higher fatality count. Due to the similarity of fire zones FDZ 02 – south and FDZ 03 – south as well as FDZ 04 – north and FDZ 05 – north , quantitative results for scenarios FDZ 02 – south and FDZ 05 – north have been used as decision basis for fire zones FDZ 03 – south and FDZ 04 – north, respectively.

**Table 2:** Quantitative Results for selected fire zones and scenarios

| Fire Scenario | Fatalities Variant I | Fatalities Variant II | Suggested Variant |
|---|---|---|---|
| FDZ 02 – south | 8.7 | 7.7 | I |
| FDZ 03 – south | Not simulated | Not simulated | I |
| FDZ 04 – south | 56.9 | 27.8 | II |
| FDZ 05 – south | 16.5 | 3.4 | II |
| FDZ 04 – north | Not simulated | Not simulated | II |
| FDZ 05 – north | 6.0 | 2.2 | II |

## 5. SUMMARY AND CONCLUSION

This study addressed the challenges of optimizing ventilation control in short, longitudinally ventilated road tunnels during temporary bidirectional traffic operation, a scenario increasingly relevant due to maintenance cycles in modern tunnel infrastructure. Using a representative model tunnel and the fire consequence analysis part of the Austrian TuRisMo methodology, ventilation strategies, focusing on the trade-off between regulatory compliance, operational feasibility, and safety outcomes were systematically analysed. Based on a discussion of the Austrian and German regulatory framework and the application of related requirements on a representative model tunnel it was demonstrated that, in short tunnels with compact ventilation zones, it is often not possible to fully satisfy all regulatory requirements for ventilation control during temporary bidirectional operation. In particular, the activation of jet fans in close proximity to a fire can lead to smoke destratification, significantly impairing visibility and evacuation conditions.

To optimize the ventilation control with respect to the available options and to potentially inform a following ALARP discussion and full risk assessment treatment, an adapted fire consequence modelling approach, which approximates the impact of jet fan-induced destratification, was adopted, enabling a more realistic assessment of the contrary ventilation control approaches within the risk analysis framework. The results indicate that, for certain fire zones, natural ventilation (i.e., deactivating jet fans in smoke-filled areas) can substantially reduce the expected number of fatalities compared to configurations involving temporary overblowing by jet fans. However, in other scenarios, the advantages of controlled longitudinal ventilation—such as maintaining defined airflow and preventing smoke spread—may outweigh the risks associated with partial regulatory deviations.

Overall, the findings underscore the necessity of a flexible, risk-based approach to ventilation control during temporary bidirectional operation in short tunnels. By integrating quantitative scenario analysis and performance-based design principles, it is possible to identify ventilation strategies that achieve a maximum balance between safety, regulatory compliance, and operational constraints in the light of unavoidable safety requirement deviations and residual risk exceedance. The applied approximative approach to estimate the occurrence and impact of destratification because of activating close jet fans was particularly developed to be suitable for broader implementation in the full system-based risk analysis framework TuRisMo, which includes the quantitative treatment and simulation of hundreds of fire scenarios, and was thus kept this simple and approximative on purpose. This approach proved to be very efficient and produced overall plausible results. However, the utilization of 3D-CFD smoke propagation results, missing direct implementation of jet fans, in situations where jet-fan 3D-effects have the potential to severely impact the smoke-layer formation and thus the overall dynamics, is of course a strong oversimplification. This approach therefore bears the risk of leading to comparatively large uncertainties and modelling errors. It is therefore of utmost importance to attempt validation against experimental results or at least comparison to reliable 3D CFD simulations as part of the further development of the approach before integration of this approach in the overall risk analysis methodology.

## REFERENCES

[1] European Parliament and Council, „Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network,“ *Official Journal of the European Union,* pp. L 167, 39–91, 2004.

[2] Bundesgesetzblatt, *Gesamte Rechtsvorschrift für Straßentunnel-Sicherheitsgesetz, Fassung vom 30.05.2025. BGBl. I Nr. 54/2006 idF BGBl. I Nr. 123/2022,* 2006.

[3] Austrian Research Association for Road-Rail Transport, *RVS 09.02.31 Tunnel Equipment - Ventilation Systems: Basic Principles,* Vienna: Austrian Federal Ministry for Traffic, Innovation and Technology, 2014.

[4] Bundesministerium für Digitales und Verkehr, *Richtlinien für den Entwurf, die konstruktive Ausbildung und Ausstattung von Ingenieurbauten: RE-ING Teil 3 Tunnel – Abschnitt 1: Planungsgrundsätze; Abschnitt 2: Konstruktive Anforderungen und bauliche Durchbildung; Abschnitt 3: Technische Ausstattung,* Bonn, 2023.

[5] Austrian Research Association for Road-Rail Transport, *RVS 09.03.11 - Methodology of Tunnel Risk Analysis,* Vienna: Austrian Federal Ministry for Traffic, Innovation and Technology, 2019.

[6] Purser, D. A., McAllister, J. L., „Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat," in *SFPE Handbook of Fire Protection Engineerin (5th ed)*, Springer, 2016, pp. 2308-2428.

[7] Kohl, B., Senekowitsch, O., Nakahori, I., Sakaguchi, T., Vardy, A.E., „Risk assessment of fire emergency ventilation strategies during traffic congestion in unidirectional tunnels with longitudinal ventilation," in *Proceedings of the 17th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels*, Lyon, 2017.

[8] Beyer M., Stacey C., „CFD Validation for Tunnel Smoke Control Design," in *Proceedings of the 11th International Conference on Tunnel Safety and Ventilation*, Graz, 2022.

[9] Khodadadi, R., Abbas ,T., Scriven P., Waldron, T., „Analysing the significance of turbulence models in predicting the installation efficiency of jet fans in tunnels: A comprehensive investigation," in *Proceedings of the 20th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels*, Copenhagen, 2024.