Modelling of tunnel ventilation’s influence on fire risk – a detailed comparison of model assumptions and their potential influence

S Frey, N Riklin, R Brandt
HBI Haerter AG, Switzerland

O Heger, B Kohl
ILF Consulting Engineers Austria GmbH, Austria

ABSTRACT

Risk models are important tools to support decision making for road tunnels. Risk-analysis tools can be used to assess and compare different risk mitigation measures. A situation that commonly requires assessment is the case of bidirectional traffic in longitudinally ventilated road tunnels, as evacuating persons inherently would be located on both sides of a tunnel fire. The selection of the most appropriate ventilation strategy is not straightforward.

Two independent studies were conducted and presented at the ISAVFT symposium 2017, investigating the effect of different longitudinal ventilation strategies during congested or bidirectional traffic. In both cases, well-established risk assessment models have been used, however, the conclusions were in disagreement. In order to investigate the reasons for the different conclusions, the authors of the two mentioned papers have joined forces with the overall objective to compare the capabilities and assumptions of the different risk models.

It is found that the investigated risk models are in good agreement, when common risk-mitigation measures are applied on a representative road tunnel in the event of congested traffic. In addition, the applied CFD models have been validated against full scale fire test results and the smoke propagation predictions were confirmed in general for both models. However, an in-depth analysis of the underlying sub-models reveals subtle differences, which can potentially explain the disagreements in the conclusions of the prior studies.

1 INTRODUCTION

In case of a fire in a unidirectional road tunnel without traffic congestion, it is straightforward to decide on the longitudinal ventilation strategy, (i.e. the longitudinal target airflow velocity). Due to the absence of evacuating persons on one side of the fire, longitudinal ventilation is usually controlled to minimize or prevent the back-layering of smoke. Consequently, the egress area can be kept free of smoke by achieving sufficiently
large longitudinal flow velocities, which is generally reflected in national safety- and design guidelines.

In contrast, the choice of the appropriate target airflow velocity is much more complex when evacuating persons are present on both sides of a tunnel fire. This situation can occur in unidirectional tunnels during traffic congestion or in bidirectional tunnels, when the accident or the fire is blocking both driving lanes or driving directions.

In such cases, if the produced smoke is ventilated with a longitudinal flow velocity above the average egress speed, evacuating persons downstream of the fire will get caught up by the smoke and thus are exposed to fire hazards. On the other hand, the longitudinal ventilation system can be controlled to minimize the rate of smoke spread by keeping the longitudinal flow velocity close to zero (zero-flow ventilation). Thus, the smoke-filled area will be reduced but the smoke concentration in the vicinity of the fire will be much higher and the chance of survivability will decrease significantly for persons staying in this area, not able to evacuate in time.

Numerous studies regarding the assessment of mechanical longitudinal ventilation have been conducted in the past. However, systematic comparisons of the two latter mentioned ventilation strategies (critical-velocity ventilation / zero-flow ventilation) are scarce. Two studies, which were presented at the ISAVFT symposium 2017, [1] and [2], investigated the performance at different airflow velocities for tunnel fires in congested unidirectional tunnels and bidirectional tunnels. In [1], the Austrian tunnel risk model (TuRisMo) was applied on a unidirectional urban road tunnel for different fire sizes and traffic states. The expected benefits of critical-velocity ventilation in case of a tunnel fire during free-flowing traffic were confirmed. Yet, zero-flow ventilation was found to be favourable in case of tunnel fires during traffic congestion. In [2], the quantitative risk model consisting of SPRINT [3] and ODEM [4] were used to assess rural bidirectional tunnels with sparse safety equipment and, typically without emergency exits. Here, in contrast to [1], a longitudinal flow velocity of at least 1.5 m/s was found to be the best strategy. Consequently, the general question for the optimal longitudinal flow velocity in case of evacuating persons on both sides of a tunnel fire could not be answered consistently.

To provide a better understanding of the interaction between quantitative risk model parameters and assessment of longitudinal ventilation performance in situations with evacuating persons on both side of the fire (i.e. congested tunnels), the authors of the above mentioned papers decided to conduct a joint study and investigate the differences in the respective risk models. The present paper summarizes assumptions, fundamentals, approaches and findings of this joint effort.

1.1 Outline

The remainder of the paper focuses on the comparison of the detailed version of the Austrian tunnel-risk model and the basic model behind the Swiss tunnel risk methodology, which is the combination of the 1D-CFD model SPRINT and the egress model ODEM. The sub models for fire-consequence analysis of the two quantitative approaches (Austria and Switzerland) are summarized in section 2. The generic model tunnel, on which all investigations were carried out, is also presented there. To provide a common basis for further investigations the CFD sub-models are validated against real scale fire tests in section 3. The performances of both risk models, with respect to established risk mitigation measures (i.e. reduced emergency exit distance, reduced emergency response time) are compared in section 4. The influences of model basis, like mesh resolution, vehicle modelling and the modelling of toxicity on the assessment of longitudinal flow velocities in case of a tunnel fire during traffic congestion are presented in section 5.
2  ASSESSMENT METHODOLOGIES

2.1  Austrian tunnel risk model
The Austrian tunnel-risk analysis methodology (TuRisMo) as defined in the national guideline [5], uses a fully integrated approach which combines a quantitative frequency analysis based on statistical evaluations (event-tree approach) and a quantitative consequence analysis that includes a collision-only (mechanical) part and a distinct fire consequence model. Details on the frequency part as well as on the collision-only consequence part can be found in [5], [6], [7] and [8].

The presented study focuses on the comparison of fire-consequence models and their sensitivity during the assessment of longitudinal ventilation strategies. The fire consequence model used in TuRisMo can be summarized as follows:

- For each detailed fire scenario, a transient one-dimensional airflow simulation is performed, taking all important influencing factors such as traffic volume, fire location, ventilation design and meteorological boundary conditions into account;
- 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 (i.e. for gravity driven smoke propagation) such as back-layering and smoke stratification, local cross-section peculiarities or the influence of present vehicles in the cross-section are examined;
- Visibility-, heat- and toxic-gas concentrations (CO, CO2 and HCN) generated in the three-dimensional CFD simulation are then combined with person-exposure distributions that depend upon the traffic configuration after the incident;
- Tunnel users are presented by means of evacuating agents which vary in evacuation speed and evacuation behaviour and reflect the emergency response timeline;
- Based on the superposition of evacuees and hazardous concentrations the effects of fire hazards on evacuation speed and survivability of persons is described by the use of an accumulation and intoxication model [9]. As a result, the expected total number of fatalities can be computed for each scenario.

2.2  Swiss tunnel risk model
The model approach used within the Swiss quantified risk analysis for road tunnels is described by [10] and [11]. The method is based on Bayesian Probabilistic Networks, which also permits to cater for inter-dependencies of parameters. The injured and fatalities due to accidents, fires and transports of dangerous goods are computed for each homogenous section of the tunnel and for the portal zones.

One particular aspect of the risk analysis method is its generic model regarding tunnel ventilation and egress routes. The developed generic model estimates the expected number of fatalities and injured in case of a road-tunnel fire. This model has been elaborated by HBI examining a large range of parameters using the simulation tools SPRINT [3] and ODEM [4].

The model SPRINT has been validated and in use for more than a decade. The effects taken into account are the piston and drag effect of the vehicles, jet fan thrust, tunnel-wall friction, pressure losses at the portals, the meteorological pressure differences and the influence of transverse ventilation on the momentum of the tunnel air. The temperature distribution in the tunnel is computed, incorporating the stack effect. Additionally, gravity driven smoke propagation due to the thermal stratification in the tunnel is accounted for.
by using a semi-empirical model. The programme also entails the implementation of various control philosophies regarding traffic control (tunnel closure, traffic stop) and the ventilation setting.

The egress model ODEM is based on deterministic behaviour of individuals. It includes decisions triggered by visual impression of the smoke front and/or high temperatures. The model includes the influence of reduced visibility, toxic gases, and temperatures determined by SPRINT. The exposure related to the toxic environment was originally incorporated in one single, generic pollutant but was recently extended to include CO, CO2 and HCN. In order to be deterministic, the individuals do not have individual characteristics (e.g. walking speed, response time). Furthermore, no people-to-people interaction is considered.

2.3 Model tunnel for current investigation

Usually a considerable number of different fire scenarios is assessed during the application of both risk-assessment methodologies in order to cover a significant area of the incident sample space. However, to work out subtle model differences with respect to parameter dependencies and basic model assumption, the presented fire-consequence models are applied to a single fire scenario during fully congested traffic in a generic tunnel. The relevant parameters of the 1,200 m long unidirectional generic tunnel are presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Generic tunnel – relevant parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel system</td>
</tr>
<tr>
<td>Tunnel length</td>
</tr>
<tr>
<td>Emergency exits</td>
</tr>
<tr>
<td>Gradient</td>
</tr>
<tr>
<td>Tunnel cross section</td>
</tr>
<tr>
<td>Traffic conditions</td>
</tr>
<tr>
<td>Traffic density</td>
</tr>
<tr>
<td>Traffic mix</td>
</tr>
<tr>
<td>Ventilation system</td>
</tr>
</tbody>
</table>

A medium sized fire with a maximum heat release rate (HRR) of 30 MW, e.g. truck fire or multiple passenger car fire, serves as basis for the comparison. Fire development and production rates have been chosen according to the Austrian guideline for quantitative road tunnel risk analysis [5]. The according parameters together with the emergency control timeline can be found in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Model fire- and emergency response parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire position</td>
</tr>
<tr>
<td>Maximum heat release rate</td>
</tr>
<tr>
<td>Time to reach maximum HRR</td>
</tr>
<tr>
<td>Production rates</td>
</tr>
<tr>
<td>CO</td>
</tr>
<tr>
<td>CO₂</td>
</tr>
<tr>
<td>HCN</td>
</tr>
<tr>
<td>Soot</td>
</tr>
<tr>
<td>Emergency ventilation activation</td>
</tr>
<tr>
<td>Latest start of person evacuation</td>
</tr>
</tbody>
</table>
3  SMOKEPROPAGATION MODEL VALIDATION

In order to assess potential differences in the prediction of smoke propagation determined by TuRisMo/FDS and SPRINT/ODEM, the smoke propagation models were compared and validated using the Memorial full-scale fire tests [12]. Knowing that natural ventilation is difficult to simulate, the test 502 was used to validate the two smoke-propagation models. The maximum heat release-rate in this test was about 50 MW, the average air velocity varied from 0.75 m/s to 2.5 m/s during the test.

The following two figures show the direct comparison of the normalized smoke concentrations obtained by SPRINT and FDS. Furthermore, the corresponding full-scale fire test results (smoke dispersion as well as 70°F temperature contour) are presented. One can see that the smoke fronts determined by the two models are consistent to the experimental data both in the main flow direction (right to left) as well as in the back-layering section. Therefore, both, SPRINT and FDS, are concluded to be appropriate for the modelling of smoke and pollution propagation of a tunnel fire.

Figure 1: Comparison of the normalized smoke density for SPRINT and FDS and validation against the full-scale fire test (smoke / temperature); 90 s after fire ignition

Figure 2: Comparison of the normalized smoke density for SPRINT and FDS and validation against the full-scale fire test (smoke / temperature); 150 s after fire ignition

4  ASSESSMENT OF STANDARD RISK MITIGATION MEASURES
Since their development, both risk models have been used and tested in an extensive way with respect to the effectivity of standard risk-mitigation measures in road tunnels. However, direct comparison of assessment results for different quantitative risk models are rare and not common practice. Therefore, the application of both risk models on the same fire scenario with identical boundary conditions is chosen to serve as common basis for the present study.

A 30 MW fire during traffic congestion in the generic tunnel, presented in section 2, is considered for this purpose. Target airflow velocities of 1.0 m/s before fire detection and 3.0 m/s after fire detection have been applied. Figure 3 and Figure 4 depict the assessment results of two standard risk-mitigation measures: reduced emergency exit distance and reduced fire detection time. Both risk-assessment approaches rely on relative assessment criteria. Thus, results are presented in a relative manner with the standard case (300 m emergency-exit distance, 120 s detection time) representing the baseline value for the number of fatalities per incident. To avoid the interference between fire location and emergency exit location, several fire locations, equally distributed along the tunnel, have been considered. The depicted results represent the arithmetic average.

Figure 3: Comparison of consequence results for different emergency exit distances (normalized to reference case)

Figure 4: Comparison of consequence results for different emergency response times (normalized to reference case)
In case of reducing the emergency-exit distances from 300 m to 200 m and 100 m, the results for both models are in good agreement. In addition to the consequence reduction due to reduced emergency-exit distances, also the considered variations in emergency response time lead to similar changes in consequence numbers for both models, see Figure 4. However, when longer emergency-exit distances are considered, the models predict different increases in fire consequences.

In general, the presented comparisons show good agreement of both risk-assessment models, if standard risk mitigation measures are assessed and considerable airflow velocities are applied. However, divergences for long emergency exit distances and divergences which emerged in prior studies suggest that significant differences can appear, if low airflow velocities are considered.

5 INFLUENCING FACTORS IN CASE OF LOW-SPEED VENTILATION

For the effectivity of longitudinal ventilation smoke stratification plays an important role, in particular if low longitudinal flow velocities are considered. Both CFD models account for possible smoke stratification. Because smoke layering is a two-dimensional buoyancy-driven effect, the stratification is directly taken into account in the three-dimensional FDS simulation. The 1D-CFD software SPRINT accounts for smoke stratification by means of an empirical sub-model that predicts a height-dependent smoke density as a linear interpolation between a smoke-free ground layer and a smoke-filled ceiling layer. The model is based on longitudinal flow velocity, propagation distance, smoke-layer age and temperature. To investigate the different stratification and propagation behaviour for low airflow velocities, smoke densities predicted with both CFD models are compared for the before defined fire scenario (1200 m model tunnel – 30 MW – congested traffic – fire located at 600 m). To consider the effect of model parameters, parameter variations with respect to reference height, mesh resolution and vehicle modelling were performed.

5.1 Reference height

One important model fundamental assumption that can influence the risk-assessment result is the reference height, at which the smoke density is evaluated and processed by means of evacuation models. Figure 5 and Figure 6 compare the development of smoke densities for different reference heights, for 3.0 m/s and 0.5 m/s target emergency airflow velocities. An initial airflow velocity of 0.0 m/s was applied in both cases. Prior to fire detection, the FDS results for smoke density at face level (1.6 m above ground) and cross-sectional average smoke density show significant differences as can be seen in the top graph in Figure 3 and Figure 6. Due to the low initial airflow velocity, a smoke layer is formed. This leads to a lower smoke density at face level compared to the cross-sectional volume average smoke density. The result generated with the 1D-model SPRINT is comparable to the volume-averaged value obtained by the 3D model. In case of 3.0 m/s airflow velocity smoke stratification is lost subsequent to engaging the emergency ventilation. Smoke density at face level as well as the cross-sectional density differ for low airflow velocities, see Figure 6. 300 s after fire breakout (centre curve) smoke stratification is preserved downstream and upstream of the fire. For the upstream region, this difference remains for the entire simulation time (bottom curve). Thus, smoke stratification is preserved over a considerable time and consequently the choice of reference height can influence the risk assessment result in case of low airflow velocities.
Figure 5: Comparison of smoke concentrations 120 s (top), 300 s (centre) and 900 s (bottom) after fire breakout for 3.0 m/s emergency target airflow velocity.

Figure 6: Comparison of smoke concentrations 120 s (top), 300 s (centre) and 900 s (bottom) after fire breakout for 0.5 m/s emergency target airflow velocity.
In addition, a quite different back-layering length results from the 3D-FDS model and the SPRINT model. A maximum upstream smoke spread of 200 m is predicted by FDS, whereas back-layering until the entry portal is predicted by SPRINT. The same smoke emission rates are applied in both models but the much farther smoke distribution in the SPRINT simulation leads to a lower smoke density between 200 m and 1200 m than FDS simulation. The diverging prediction of smoke back-layering clearly can influence the assessment of low speed ventilation strategies. Thus, potential causes for the different back-layering length results are discussed in the following.

5.2 Mesh resolution

One modelling parameter that can potentially account for different back-layering lengths is the chosen mesh resolution in the 3D-CFD analysis. The number of cells per dimension, in particular in vertical direction, determines the resolution of the vertical smoke and temperature layer. If the number of cells in the vertical direction is too small to account for a pronounced vertical temperature profile, the convection mechanism that governs the formation of a plume and hence drives back-layering may be underestimated. The effect may be amplified if obstacles, e.g. vehicles, are present in the simulation domain because of the reduced effective area available for convection. The influence of mesh resolution on vertical layer formation and back-layering is discussed in the following.

Figure 7 depicts the longitudinal smoke profile (left) and vertical smoke profile 50 m upstream of the fire location (right), 120 s (top), 300 s (centre) and 900 s (bottom) after fire breakout, for two different FDS mesh resolutions. Target airflow velocities of 0.0 m/s before detection and 0.5 m/s after fire detection were applied on the examined fire scenario presented in section 2.3.

For the chosen mesh resolutions of 2.0 m*0.5 m*0.5 m (standard FDS mesh resolution used in TuRisMo) and 1.0 m*0.5* m*0.25 m a subtle difference in smoke propagation length after 120 s can be perceived upstream and downstream of the fire, see Figure 7. The difference in the vertical smoke distribution, which is observed 50 m upstream of the fire location, is more pronounced. The higher number of computational cells leads to a sharper concentration transition from floor level to ceiling level, which is related to the formation of a more defined smoke layer. This sharper formation of a hot smoke layer at ceiling level and a cold fresh-air layer at ground level enhance longitudinal convection and therefore increase convection driven smoke propagation. The latter can be seen in the different smoke-propagation length 300 s (centre) and 900 s (bottom) after fire breakout in Figure 7. This effect is more important in upstream direction but also not negligible in downstream direction due to the small longitudinal nett airflow velocity of 0.5 m/s.

Although convection-driven smoke propagation is significantly increased for the denser computation mesh, a significant difference remains between 3D-FDS simulation and 1D-Sprint simulation. For the FDS simulation with a mesh resolution of 1.0 m*0.5 m*0.25 m the upstream smoke-front extension reaches 100 m after 120 s, 180 m after 300 s and 300 m after the total simulation time of 900 s. For the SPRINT simulation, however, the smoke front extends 180 m in upstream direction after 120 s and reaches a stable state 400 m in downstream direction after 300 s.

Preliminary tests with even higher FDS mesh resolutions did not increase the back-layering length significantly. Nevertheless, a further investigation on the effect of cell numbers on convection-driven smoke propagation in FDS could provide a better understanding of this effect.
5.3 Implementation of vehicles

The influence of computational mesh resolution on convection-driven smoke propagation is a computational inaccuracy rather than a physical effect. In contrast, the effect of congested vehicles on the convection mechanism is truly observable. The reduced effective cross-section area as well as the additionally introduced turbulences due to congested vehicles restrict the formation of convection and therefore reduce back-layering. Figure 8 depicts the longitudinal smoke profile (left) and vertical smoke profile 50 m upstream of the fire location (right), 120 s (top), 300 s (centre) and 900 s (bottom) after fire breakout, with and without the presence of vehicles in the FDS simulation domain. Only passenger
cars with an extension of 5 m x 1.5 m x 1.5 m and a vehicle density of 300 vehicles / km were considered. Target airflow velocities of 0.0 m/s before fire detection and 0.5 m/s after fire detection were applied on the model fire scenario presented in section 2.3. Based on the findings presented in section 5.2, an increased mesh resolution of 1.0 m*0.5 m*0.25 m has been used in both FDS simulations.

No vehicle influence is visible for longitudinal and vertical concentration distribution 120 s after the fire breakout. After 300 s a small difference manifests in the longitudinal profile of cross-sectional average concentration as well as in vertical concentration profile 50 m upstream of the fire location. Without vehicles in the simulation domain, the smoke front extends approximately 40 m farther in upwind direction. Still, a significant shorter back-layering length compared to the 1D-SPRINT simulation is obtained, where the final steady back-layering state is already reached. The difference in the back-layering length between 1D-Sprint simulation and 3D-FDS simulation significantly reduces at the end of the simulation time of 900 s after the fire breakout if no vehicles are considered in the 3-dimensional simulation. At the same time the difference in upstream smoke propagation for FDS simulations with and without vehicles grows to a total of 80 m. Vehicles cannot be taken into account directly in the one-dimensional model. It is therefore plausible that FDS results without vehicle consideration are in better agreement with SPRINT results. This generic difference between 3D-CFD simulation and smoke-spread models, where stratification effects are taken into account on a heuristic basis, has already been investigated in the past [13]. However, vehicles are present in a real fire, in particular during traffic congestion. Therefore, the potential uncertainty due to the partial negligence of vehicles in the application of 1D models has to be taken into account during the interpretation of risk assessment results obtained with such models.

It should also be mentioned that, if vehicles are considered in the computational domain, particular attention has to be paid, if the longitudinal flow is applied as velocity boundary condition. The velocity measurement to which the ventilation control algorithm refers is located in the area of traffic congestion. Therefore, a reduction factor has to be applied on the inflow boundary condition to account for velocity increase due to the reduction of the free cross-section. This effect is negligible for 2 lane unidirectional tunnels with a typical cross-section area (50 m²) and longitudinal ventilation, when only passenger cars are considered. However, the overestimated flow velocity at the fire location can lead to deviating results, if small tunnel cross-sections or high numbers of heavy-good vehicles are considered.
Figure 8: Comparison of back-layering length and smoke stratification with and without vehicle consideration, 120 s (top), 300 s (centre) and 900 s (bottom) after fire breakout – cross-sectional average longitudinal concentrations (left) – vertical concentration profile 50 m upstream of the fire (right)

5.4 Accumulation model
So far, model differences regarding the prediction of smoke propagation have been presented. In addition, also subtle differences in the modelling of person incapacitation were investigated. Generally speaking, two approaches exist to describe the incapacitation criteria. Accumulation-based incapacitation and threshold-based incapacitation modelling. In the two considered risk assessment methodologies, accumulation models are used to predict the point in time when evacuating persons get incapacitated due to smoke and heat. In the accumulation-based approach, the toxin dose which is accumulated for a given time duration is calculated according to the prevailing smoke concentration. The accumulated
doses for the evacuees are then summed up along their evacuation path, see Equation 1. If the accumulated dose reaches the maximum tolerable intoxication value before the smoke-free area is reached, incapacitation or death occurs.

\[ FID_{\text{Total}} = \sum_{t=t_0}^{t_{\text{Total}}} FID_t \]

Equation 1: Accumulated fractional incapacitation dose

Even tough general modelling approaches are the same, ODEM and TuRisMo evacuation and survivability sub-models differ in the explicit calculation of intoxication dose and maximum tolerable intoxication value. In the Austrian methodology, the intoxication model of D.A Purser is used [9]. The fractional incapacitation dose for an exposure time of 1 second is calculated according to Equation 2 - \( FID_{\text{TuRisMo}}^t \), where the intoxications related to carbon monoxide and hydrogen cyanide as well as carbon dioxide induced hyperventilation are considered. In the Swiss approach Equation 2 - \( FID_{\text{ODEM}}^t \) is applied to obtain the fractional incapacitation dose, which solely relies on carbon monoxide intoxication.

\[ FID_{\text{TuRisMo}}^t = \frac{1}{60} \times [FICO_t + FIHCN_t] \times VCO2_t \]

\[ FID_{\text{ODEM}}^t = \frac{1}{60} \times FICO_t \]

Equation 2: Fractional incapacitation dose for an exposure time of 1 s

The FID contributions, which describe the influence of carbon monoxide are comparable in both models. In both cases, the intoxication contribution is more or less linearly dependent on the CO concentration. The HCN and CO2 contributions, however, depend exponentially on the respective concentrations. Therefore, both accumulation models deviate in particular if small concentrations are considered. The comparison is given in Figure 9 where the time to incapacitation is plotted for a steady effective CO concentration, implicitly including HCN and CO2. Absolute incapacitation times are different for both approaches. However, since concentrations at different height levels are used, effective incapacitation times are similar. In addition, the comparison shows a very similar behaviour for high toxin concentrations due to the dominance of the CO contribution at high smoke densities. However, if CO is considered only, concentrations below 1200 ppm are insufficient for an incapacitation within 15 minutes, which is the typical timespan of an evacuation simulation (time needed to walk a distance of 1000 m). In contrast, concentrations of down to 400 ppm can be relevant, if the complete Purser model is applied.

This difference can affect the assessment of low-speed ventilation strategies. If low smoke concentrations are of little relevance, dilution is always preferable over smoke confinement. However, if already low smoke concentrations can lead to fatalities, distributing the smoke along the tunnel can be unfavourable because the dilution may be insufficient.
CONCLUSION

To provide a better understanding on the influence of risk-model assumptions on the assessment of low longitudinal flow velocities during traffic congestion, a detailed comparison of the Austrian and Swiss fire consequence model was started.

Good agreement was found when the results for 3D (Austria) and 1D (Swiss) CFD computations were compared with smoke spread and temperature profiles of the fire test 502 from the Memorial Test Programme. The assessments of standard risk-mitigation measures were also found to be in good agreement. Both models (1D and 3D) predicted similar risk reduction, when the distance between egress routes was reduced from 300 m to 200 m or 100 m and if the fire emergency response time was varied between 60 s and 180 s. However, if the distance between egress routes was increased to 600 m, the two model predicted the same trend but concluded rather different consequence values.

Subtle differences in smoke-propagation- and egress modelling where worked out. In 3D CFD-Analysis smoke density and temperature at face level are taken into account in the egress modelling, whereas cross-sectional average smoke density and temperature are considered in the Swiss model. Some grid dependency was found for the 3D model (FDS) that however appears adequately permissible. As expected, the presence of vehicles in the 3D CFD simulation influences the smoke spread, in particular back-layering length. Not only because of the sheer effects of vehicle blockage on longitudinal flow velocity, but also because of the introduced turbulences and the smaller available cross-section for convection. Regarding the egress models, an influence of the accounted combustion products on the survivability, in particular at low concentrations, was found. This influence strongly correlates with the applied toxin-production rates, which should also be discussed in parallel.

The found model differences could potentially contribute to the deviating assessment of low longitudinal flow velocities in case of tunnel fires in a congested environment, which emerged in prior studies, and for the different assessment of egress distances longer than 300 m. After increasing mesh resolution in the 3D-FDS simulation, the final back-layering length obtained with 1D and 3D simulation were comparable, when cross-sectional average concentrations are considered and the influence of turbulence and cross-section reduction due to vehicles is not taken into account explicitly. However, further investigation is needed to fully explain the differences. Subsequently, the egress models
will be scrutinised further and compared with other models developed to investigate the influence of behavioural parameters and model assumptions.

A final answer to the question for the best longitudinal ventilation strategy in case of a tunnel fire during traffic congestion cannot be given based on the obtained findings. The results emphasize that such an answer exists at best only on a case to case basis, but not in a general context. Model differences exist, but the good agreement over a major area of application as well as the qualitative similarity in model assumptions strengthen the confidence in the investigated risk assessment models.

7 REFERENCES

[12] „Test Report – Memorial Tunnel Fire Ventilation Test Program (MTFVTP),“ Highway Department, Boston Massachusetts, 1995