Risk assessment of fire emergency ventilation strategies during traffic congestion in unidirectional tunnels with longitudinal ventilation

B. Kohl, O. Senekowitsch
ILF Consulting Engineers, Linz, Austria
I. Nakahori, T. Sakaguchi
Sohatsu Systems Laboratory, Japan
A.E. Vardy
University of Dundee, UK

ABSTRACT

Four possible strategies for ventilation response to fire in a unidirectional tunnel are compared quantitatively for three traffic conditions (congested, stop-and-go, free-flowing) and three fire sizes (5MW, 30MW, 100MW). The overall risk of each strategy for all nine combinations of traffic and fire are assessed using the Austrian tunnel risk model TuRisMo applied to a representative tunnel that is 3km long and has realistic gradients. It is found that commonly-existing strategies such as maintaining airflow in the original traffic direction are appropriate for free-flowing traffic, but that a zero-flow strategy previously proposed for bidirectional tunnels has strong advantages in the event of congested traffic or stop-and-go traffic.

1 INTRODUCTION

Unidirectional road tunnels have important advantages over bidirectional tunnels, especially dramatically lower damage-extents (number of fatalities/event) occurring as a result of an incident such as collision or fire. First, there is a lower risk of collision, mainly because of lower relative velocities. Second, there is a lower expected fire risk because of the absence of evacuating persons on one side of the fire. This often makes it possible to use a longitudinal ventilation system to prevent smoke entering regions with non-zero person densities (e.g. by preventing back-layering). In general, this can be achieved by means of sufficiently large longitudinal airflow velocities, e.g. above the critical-velocity. As a consequence, the emergency ventilation strategy for free flowing traffic in unidirectional tunnels is usually determined by the critical-velocity for the maximum design fire size.

Potentially very different conditions can prevail in the case of a tunnel fire during traffic congestion. Persons downstream of the fire may not be able to leave the tunnel using their vehicles and so may have to participate in the evacuation and self-rescue process. As a result, for this categorically different condition, traditional measures to mitigate fire risk need to be reconsidered. Standard emergency ventilation strategies that are widely used in unidirectional tunnels with free flowing traffic may yield suboptimal performance if applied during traffic congestions.

This situation is reflected in official regulations concerning ventilation design in unidirectional tunnels that have traffic congestion or very dense traffic on a regular basis. For example, German regulations for emergency ventilation in unidirectional tunnels differentiate explicitly between free-flowing and congested traffic. During free flowing traffic, a minimal longitudinal airflow velocity of approximately 3 m/s (i.e. the critical-velocity with respect to cross section, longitudinal inclination and design fire size) has to be achieved. During traffic congestion, however, the required velocity is reduced to 1.5 m/s. Furthermore, in tunnels longer than 1200 m, if traffic congestion is expected on a daily basis, a smoke extraction system must be provided. [1].

In contrast, Austrian regulations for unidirectional tunnels do not differentiate between traffic states. For all tunnels longer than 500 m, a minimum airflow velocity of 2 m/s must be achieved [2]. Additionally, for tunnels longer than 1500 m, a smoke extraction system is mandatory if traffic congestion or very dense traffic is expected on a regular basis.

Japanese regulations for unidirectional tunnels are broadly similar to the German and Austrian regulations. A minimal longitudinal airflow velocity of approximately 2 m/s has to be achieved. No special account is taken of congestion or dense traffic. It is implicitly assumed that persons in the region downstream of a fire will be able to leave the tunnel in their vehicles [3]. Smoke extraction systems are not required explicitly.

The availability of a smoke extraction system clearly adds to the range of possible responses to fire incidents. However, it would not be practicable to require them in all tunnels – due, for instance, to geographical or technical issues. Likewise, the cost of providing such a system retrospectively in an existing tunnel that did not previously require one might be prohibitive. This can happen, for example, when traffic growth has exceeded original expectations – perhaps because of exceptional economic growth or developments in the surrounding region. It can also happen when new regulations are more demanding than those that existed when the tunnel was built. In such cases, longitudinal ventilation may be the only available option.

In the event of congestion or especially dense traffic, the conditions in a unidirectional tunnel can resemble some of the characteristics of bidirectional tunnels which generically suffer the problem of requiring self-evacuating persons on both side of the fire. For such tunnels, a zero-flow ventilation strategy has been shown to perform better than emergency ventilation strategies such as shut-down ventilation [4]. Accordingly, design engineers, regulatory authorities and tunnel operators are interested in the applicability of zero-flow ventilation strategy to unidirectional tunnels.

1.1 Specific emergency ventilation strategies

The above regulations illustrate both similarities and differences between regulations in three specific countries. Other countries have their own requirements, but it is possible to summarise the international status for fire-emergency ventilation in unidirectional tunnels by the following four generic strategies.

Critical-velocity ventilation: “The airflow velocity must prevent back-layering”. Herein, this method is represented by assuming a critical-velocity of 3 m/s.

Low-speed ventilation: "The airflow velocity must be close to a prescribed target value (smaller than the critical velocity)". Back-layering will occur, but the smoke downstream of the fire will propagate at a smaller speed than with critical-velocity ventilation. Herein, this method is represented by a target airflow velocity of 1.5 m/s.

Zero-flow ventilation: "The airflow velocity is controlled to be as close as possible to zero". This minimises the speed of smoke propagation, but allows it to occur in both directions.

Shut-down ventilation: "All fans are shut down". The resulting movement of air and smoke is determined by conditions inside the tunnel such as residual traffic movement and smoke buoyancy.

1.2 Outline of paper

The remainder of the paper focuses on quantitative analyses of the consequences of these four general ventilation strategies on the degree of risk connected with tunnel fires. Direct comparisons are made for a range of traffic conditions and fire sizes. To provide a common basis for comparison, these traffic and fire scenarios are considered in a notional tunnel (the "model tunnel") specified in accordance with consequence analysis of the Austrian tunnel risk model TuRisMo [3]. This system-based, fully quantifiable risk assessment process is summarised in the following section, the chosen model tunnel is defined in Section 3 and the traffic and fire scenarios are presented in Section 4. The remainder of the paper describes the assessment process and uses the outcomes to demonstrate strengths and weakness of the four ventilation strategies.

2 ASSESSMENT METHODOLOGY

The Austrian methodology uses a fully integrated approach that allows for the detailed analysis of many kinds of safety measures and for interactions between different safety measures. Factors such as the installed equipment and boundary conditions such as traffic conditions are taken into account rigorously. The method combines a quantitative frequency analysis based on statistical evaluations and a quantitative consequence analysis that includes (i) a (mechanical) collision-only part and (ii) a distinct fire consequence model. Figure 1 shows a schematic representation of the overall structure of the method. Details of the various sub-models of the overall method have been given elsewhere [4], [5] and [6] and are not reproduced herein

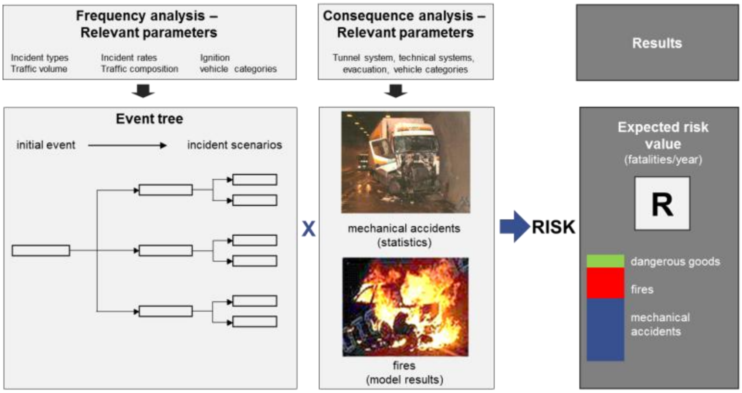

Figure 1: Schematic representation of the TuRisMo methodology

The fire consequence model used in the investigation of emergency ventilation strategies can be summarized as follows:

- Each distinct fire scenario is considered explicitly in an event tree and a set of detailed scenarios with varying local parameters is generated based on the probability distribution of the influencing parameters;
- For each of these detailed fire scenarios, a transient one-dimensional airflow simulation is performed, taking into account all important influencing factors such as traffic volume, fire location, ventilation design and meteorological boundary conditions;
- 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. The whole process is then repeated for the next detailed scenario.

The superposition of hazard distributions and person density together with the resulting distribution of expected fatalities is depicted in Figure 2. The interaction of fire hazard and evacuating persons is evaluated dynamically. That is, in each time step, the evacuation speeds of the considered persons are modified according to the local smoke concentration and temperature, thus determining the position of the persons in the next timestep. This dynamic interaction is illustrated in Figure 2 in which the smoke density along the tunnel is depicted at two specific instants.

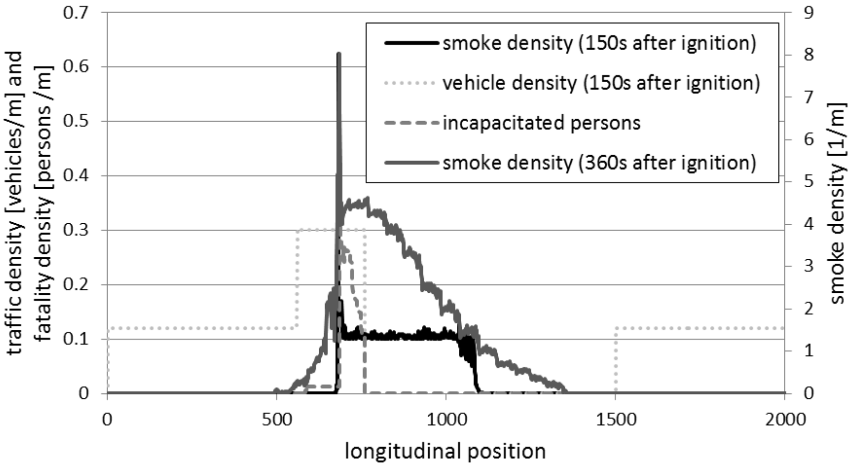

Figure 2: Smoke density- (solid line), vehicle density- (dotted line) and fatality density distribution (dashed line) for one exemplary fire scenario (30 MW/stop and go/zero flow ventilation)

As the smoke density increases along the tunnel, persons at successively increasing distances from the fire begin to evacuate. At each location, the density of evacuating persons is directly proportional to the vehicle density at this position, as is also depicted in Figure 2. The success or failure of evacuation of each person is evaluated based on the accumulation of toxins. This leads to a total number of expected fatalities originating from each particular location along the tunnel. The resulting distribution of expected fatalities as a function of longitudinal starting position is shown in Figure 2. The figure shows a case in which the average traffic speed is sufficiently high to prevent persons in the far downstream regions being exposed to smoke. Non-zero traffic density exists only in the vincinity of the fire (approx. 600m – 750m) and therefore it is only in this region that person densities overlap with significant smoke density and lead to fatalities.

By means of statistical superposition of the distinct scenarios, combined damage-extent values are generated for each global scenario in the event tree. This enables the evaluation of an overall risk-expectation value for the tunnel based on the statistically expected number of fatalities per year. However, to examine the detailed influence of emergency ventilation strategies, the distinct damage-extent values of the individual scenarios are discussed first, without integration in the event tree. The overall risk expectation values for the assumed model tunnel with respect to emergency ventilation strategie are presented thereafter.

3 MODEL TUNNEL

A 3,032m long, unidirectional tunnel with a generic longitudinal profile is used as a model tunnel. Its longitudinal topology is depicted in Figure 3. The tunnel is equipped with a longitudinal ventilation system consisting of 16 jet fans located in tunnel-region 4. An average hourly traffic of 1,435 vehicles is assumed. To allow for frequent traffic congestion, 1 hour of stop-and-go traffic per day and 1 hour of heavily congested traffic per day are assumed. The relevant input parameters are presented in Table 1.

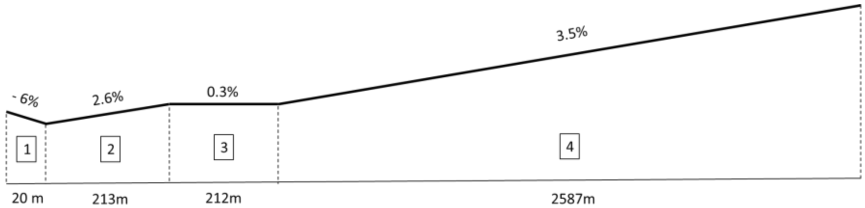

Figure 3: Longitudinal profile of the model tunnel

Table 1: Model tunnel – relevant parameters

Tunnel system	Unidirectional tunnel with 2 lanes
Tunnel length	3,032 m
Emergency exits	4 (401m, 951m, 1751m, 2351m)
Gradient	See Figure 3
Tunnel cross section	Vaulted, 50.4 m^2

Maximum allowable traffic speed	60 km/h
Average traffic volume	34,440 vehicles/24 hours
Traffic mix	92.0% Passenger cars 7.5% Heavy good vehicles (HGV) 0.5% Busses
Traffic conditions	22 hours free-flowing traffic, 1 hour stop-and-go traffic and 1 hour heavily congested traffic
Ventilation system	Longitudinal ventilation (16 jet fans, thrust = 900±10% N, diameter = 1.0 m)

4 SCENARIO SPECIFICATION

The various emergency ventilation strategies and the associated target airflow velocities (except for shut-down ventilation) are shown in Table 2.

Table 2: Emergency ventilation control strategies

Emergency ventilation control strategy	**Target airflow velocity**
Critical-velocity ventilation	3.0 m/s
Low-speed ventilation	1.5 m/s
Shut-down ventilation	No active airflow-speed control after fire detection
Zero-flow ventilation (*)	0 m/s

(*) Side note: In practice, in the case of non-horizontal tubes, small target airflow velocities are prescribed instead of zero velocity to ensure equal rates of smoke propagation in both direction of the tunnel. However, a target airflow velocity of 0 m/s has been applied in this paper even though the tunnel is not horizontal.

The relative performance of the four emergency ventilation control strategies is assessed by applying the consequence analysis to a variety of scenarios representing specific combinations of fire sizes (maximum heat release rates) and congestion states. In particular, three fire sizes (5MW, 30MW and 100MW) and three congestion states (heavily congested, stop-and-go and free-flowing) are considered as shown in Table 3. This approach allows for a systematic analysis of emergency ventilation control strategies. As indicated above, distinct transient 1-D CFD simulations (and also 3-D CFD simulations) are performed for all scenarios listed in Table 3 and for each emergency ventilation strategy under investigation. This leads to a total of 36 smoke-, temperature- and toxin-distribution patterns. The smoke distribution patterns together with the related traffic configurations are used in the evacuation and survivability simulation. Thus, distinct consequence parameters in terms of expected fatalitiescan be evaluated for all combinations of fire size, traffic state and emergency ventilation strategy, enabling a differentiated analysis of safety performance. In TuRisMo methodology, the fire location is varied with different precision in different levels of the simulation. For the 3D airflow simulations, only one fire location is simulated within regions with comparable global parameters such as inclination, cross section and ventilation design. In the current study, only Region 4 has been considered and therefore only one fire location had been simulated in the 3D simulation. In contrast, in the evacuation simulation, fire locations are considered at multiple intervals (every 50m in the current study). In the evacuation simulation, the consequences of different fire locations are assessed by shifting the smoke distribution resulting from 3D airflow simulation along Region 4.

Table 3: Scenarios considered

Traffic scenario	Fire size	Average vehicle velocity [km/h]	Traffic density [vehicles / m]
Heavily congested	5 MW	5	0.192
Heavily congested	30 MW	5	0.192
Heavily congested	100 MW	5	0.192
Stop and go	5 MW	15	0.120
Stop and go	30 MW	15	0.120
Stop and go	100 MW	15	0.120
Free flowing	5 MW	60	0.024
Free flowing	30 MW	60	0.024
Free flowing	100 MW	60	0.024

5 LONGITUDINAL AIRFLOW SPEED AND SMOKE PROPAGATION

In order to illustrate the characteristic airflow development, transient 1-D CFD simulations are used to deduce the consequences of the chosen emergency ventilation strategies. Results are shown in Figure 4 and Figure 5 for 5MW and 100 MW fires, respectively, during heavily congested traffic. The ventilation control algorithms are emulated in detail in the transient 1-D simulation by means of airflow-measurement/thrust-adjustment response. In Figure 4 and Figure 5, the airflow speed is measured 150m upstream of a fire located in the middle of Region 4 of the tunnel (see Figure 3). For all ventilation strategies, the target airflow velocity is achieved approximately 100 seconds after commencement of the emergency ventilation regime.

Although differences with respect to fire size can be seen to some extent for each emergency ventilation control strategy - i.e. the approach to the target velocity is coarser at higher heat release rates - the development of airflow velocity is generically different for the shut-down ventilation strategy only. With this strategy, the different heat release rates, leading to different buoyancy effects, result in different steady airflow states, characterized by a longitudinal airflow velocity of 0.6 m/s and 4.0 m/s for heat release rates of 5MW and 100MW, respectively. In contrast, with critical-velocity-, low-speed- and zero-flow ventilation, the buoyancy effect is compensated by the active use of jet fans, leading to invariant quasi-steady airflow states. Here, the term “quasi-steady” state is used even for flow velocities varying around a target velocity due to the periodical adjustment of jet fan states in response to changing pressures. It is obvious from Figures 4 and 5 that shut-down emergency ventilation may be problematic in general in tunnels with non-zero longitudinal inclination because non-deterministic behaviour of airflow conditions is undesirable during evacuation.

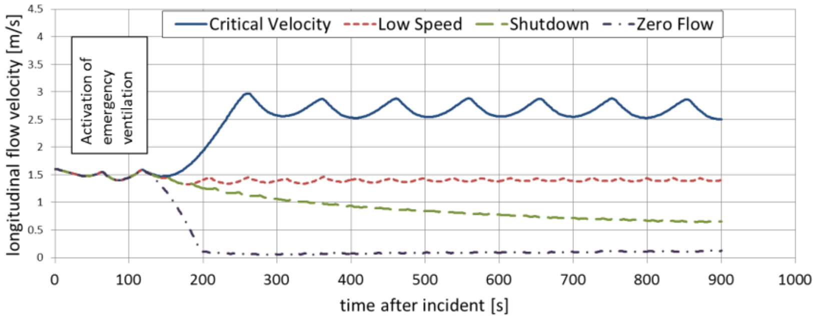

Figure 4: Development of longitudinal airflow velocity for a 5MW fire

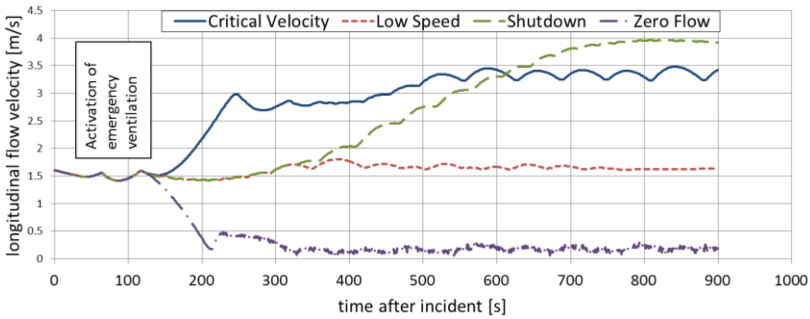

Figure 5: Development of longitudinal airflow velocity for a 100MW fire

In the model tunnel, the prescribed jet fan capacity is sufficient for all fire sizes considered, even during heavily congested traffic. Nevertheless, the longitudinal airflow velocity and the smoke distribution do depend (weakly) on the traffic state. Accordingly, distinct 3D-CFD simulations have been performed for all combinations listed in Table 3 for all four emergency ventilation strategies. Smoke distribution patterns for critical-velocity ventilation and zero-flow ventilation in the cases of 5MW and 100MW fires during heavily congested traffic are depicted in Figure 6 and Figure 7. The smoke front extends furthest in the direction of the exit (right) portal in the case of critical-velocity ventilation whereas the smoke density in the vicinity of the fire is greatest in the case of zero-flow ventilation. Thus, differences in smoke extension, smoke density, rate of propagation and back layering effects exist for the emergency ventilation strategies considered, depending especially on the achieved longitudinal airflow velocity. Nevertheless, since interactions between evacuating persons and fire hazards are non-trivial, none of the ventilation strategies can be preferred over the others based on qualitative considerations only. Whether lower smoke densities in extended downstream regions or higher but locally confined concentrations are preferable during self-evacuation, depends strongly on the velocity of smoke propagation, absolute smoke- and toxin densities and of course on the distribution and movement of persons in the tunnel. Therefore a sophisticated evacuation and survival model is used in the TuRisMo consequence analysis to account for interactions between evacuating persons and fire hazards (temperature, toxins, visibility).

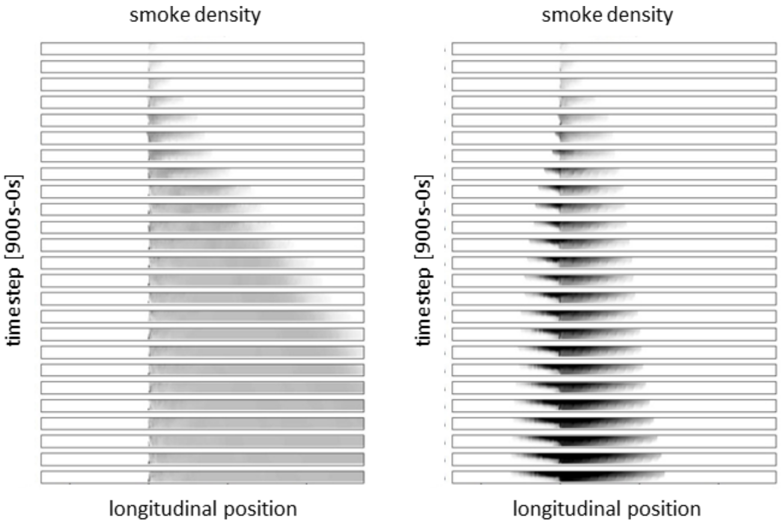

Figure 6: Comparison of smoke propagation for critical-velocity ventilation (left) and zero-flow ventilation (right) – 5MW

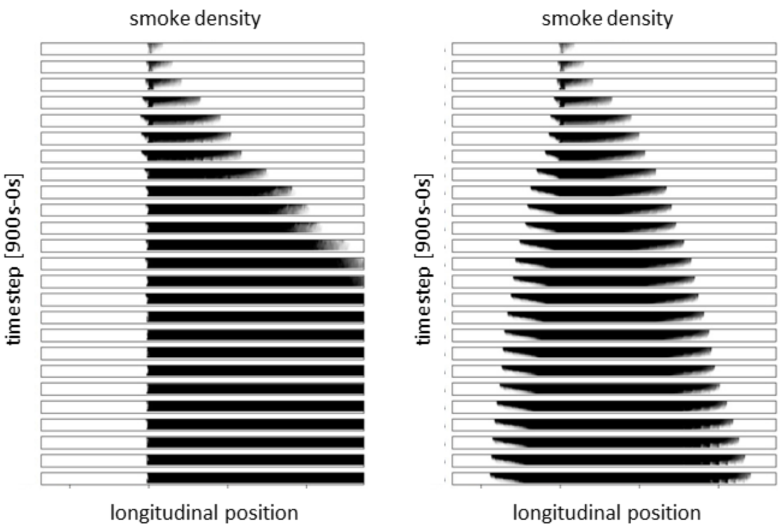

Figure 7: Comparison of smoke propagation for critical-velocity ventilation (left) and zero-flow ventilation (right) – 100MW

6 INDIVIDUAL RESULTS

The systematic application of the fire consequence analysis to all scenarios listed in Table 3 is now presented. The focus of the analysis is on the comparison of longitudinal emergency ventilation strategies for each combination of fire-size and congestion-state. No attention is paid in this part of the paper to the absolute probabilities of the individual scenarios. Figure 8 depicts expected damage-extent values for tunnel fires with differing combinations of traffic scenarios (row 1-3) and fire sizes (column 1-3). For ease of comparison, the same scale has been chosen for all charts within the figure. Although intuitively understandable, a few principal observations are discussed before specific comparisons of the results with respect to emergency ventilation strategies are made.

Average damage-extent values increase strongly with increasing fire size. For fires with maximum heat release rates of 5MW, the expected damage-extent values are relatively small, namely approximately 0.004 fatalities/event for critical-velocity ventilation/free-flowing traffic and 0.07 for zero-flow ventilation/heavily congested traffic. For fires with much higher maximum heat release rates, however, the damage-extent values increase significantly. In particular, the expected damage-extent increases to 190 fatalities/event for critical-velocity ventilation and heavily congested traffic during a 100MW fire. Although not equally pronounced, this strong dependence on fire size holds for each combination of ventilation strategies and traffic scenarios. This characteristic is already known from prior assessments of free-flowing traffic in unidirectional and bidirectional tunnels and the rates of increase for free-flowing and stop-and-go traffic are comparable. However, due to much higher person densities, fires occurring during heavy traffic congestions lead to a significantly greater numbers of expected fatalities than fires in free-flowing traffic scenarios.

An increase in traffic density leads to an increase in expected fatalities for all fire sizes and emergency ventilation strategies. Damage-extent values of 0.004 to 1.65 for free-flowing traffic scenarios and 0.03 to 190 for heavy-congestion scenarios have been computed. Table 3 shows that higher levels of traffic congestion tend to be associated with higher traffic density and/or lower average speed. Higher traffic densities immediately lead to higher numbers of persons exposed to possible tunnel fires. Low average speeds, especially speeds comparable to smoke propagation velocities, imply increased numbers of vehicles (and therefore persons) close to fire hazards. Therefore, increased numbers of fatalities must be expected during high levels of traffic congestions. In addition to these general findings, detailed comparisons of the obtained results can yield more differentiated findings with respect to emergency ventilation strategies. Therefore, to achieve a systematic discussion, each traffic scenario is considered separately. The detailed results are summarized in Table 4 to Table 6.

In the case of free-flowing traffic, a critical-velocity emergency ventilation strategy leads to the lowest damage-extent values for fires with each heat release rate considered. For low heat release rates typical of passenger car fires, the predicted damage-extent values are very small for all four ventilation strategies, but critical-velocity ventilation leads to the lowest values. For higher heat release rates typical of HGV fires, critical-velocity ventilation shows a significant better performance than zero-flow ventilation. Therefore, critical-velocity ventilation would be recommended for all tunnel fires during free-flowing traffic in the model tunnel.

In the case of stop-and-go traffic, the relative performances of the emergency ventilation strategies depend strongly on fire size. For passenger car fires (5MW), the highest safety performance is achieved by the shut-down ventilation strategy followed by critical-velocity- and low-speed strategies. For these small fires, zero-flow ventilation strategy leads to damage-extent values approximately three times higher than for shut-down ventilation and two times higher than for critical-velocity and low-speed ventilation strategies. An important reason for this is a universal assumption of inappropriate behavior of tunnel users, namely that 3% of persons will stay inside their cars instead of participating in the self-rescue and evacuation process. For persons who stay in or next to their cars in a small fire, even relatively small dilution can be potentially life-saving. This is not the case with significantly higher heat release rates, however. For HGV-fires (30MW/100MW), the highest safety performance is obtained with the zero-flow ventilation strategy. It leads to almost 20 times lower damage-extent values than critical-velocity- and shut-down ventilation and 5 times lower than with low-speed ventilation strategy. Thus, the highest levels of passenger safety during stop-and-go traffic in the model tunnel are achieved with shut-down ventilation for passenger car fires and with zero-flow ventilation for HGV fires.

In the case of heavily-congested traffic, the relative performances of the various emergency ventilation strategies are similar to those for stop-and-go traffic, although slightly less pronounced. For passenger car fires (5MW) shut-down ventilation strategy leads to the lowest damage-extent value in terms of expected fatalitiesper event. The lowest performance is achieved for zero-flow and low-speed ventilation strategies, leading to damage-extent values being approximately 2 times higher than for shut-down ventilation and 25% higher than for critical-velocity ventilation. The reasons are the same as for stop-and-go traffic. Again, these findings are reversed in case of 30MW and 100MW fires where zero-flow ventilation leads by far to the lowest damage-extent values. Once again, the highest levels of passenger safety during stop-and-go traffic in the model tunnel are achieved with shut-down ventilation for passenger car fires and with zero-flow ventilation for HGV fires.

Table 4: Detailed results of consequence analysis for free-flowing traffic

Free-flowing traffic				
	3.0 m/s	1.5 m/s	shut-down	zero-flow
5 MW	0.004	0.02	0.03	0.02
30 MW	0.07	0.07	0.07	1.2
100 MW	0.16	0.16	0.16	1.7

Table 5: Detailed results of consequence analysis for stop-and-go traffic

Stop-and-go traffic				
	3.0 m/s	1.5 m/s	shut-down	zero-flow
5 MW	0.03	0.03	0.02	0.06
30 MW	36	8.8	34	1.3
100 MW	48	41	45	2.8

Table 6: Detailed results of consequence analysis for heavily congested traffic

Heavily congested traffic				
	3.0 m/s	1.5 m/s	shut-down	zero-flow
5 MW	0.05	0.07	0.03	0.07
30 MW	139	88	129	22
100 MW	195	180	182	93

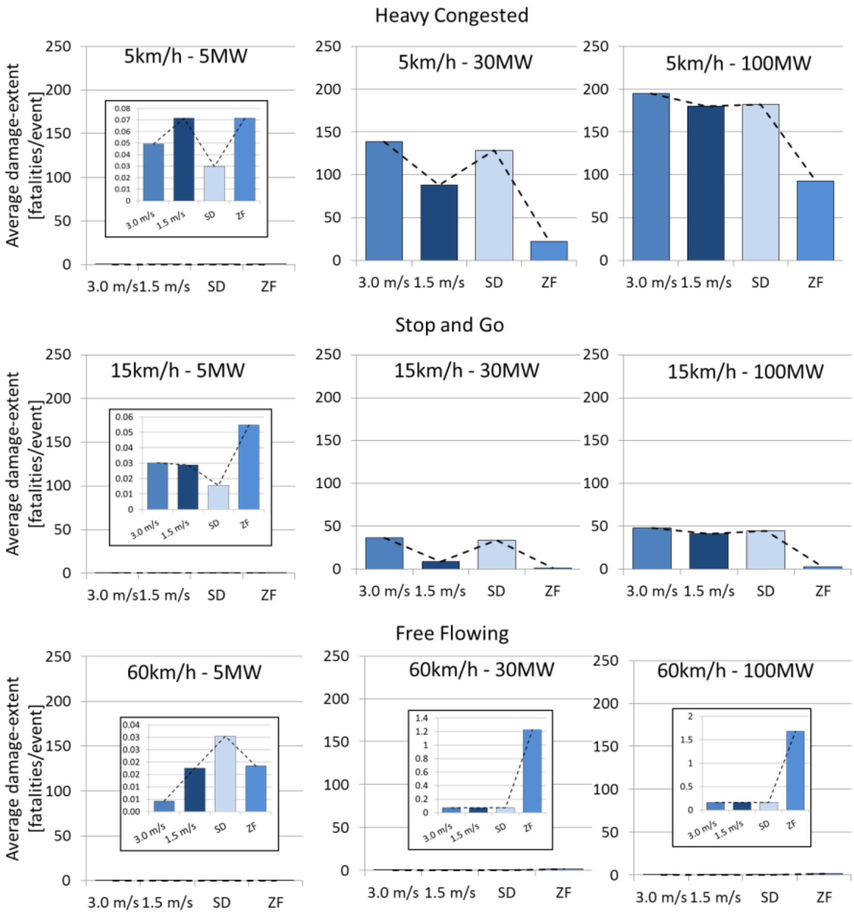

Figure 8: Collected results for damage-extent [fatalities/event] in the event of a tunnel fire. To facilitate comparisons, a common scale (0-250) has been chosen for the average damage-extent values for all scenarios. In addition, for scenarios with very low damage-extent values, figures with a smaller scale have been included

7 COMBINED RESULTS

TuRisMo is now used with the specific parameters shown in Table 7 in addition to the macroscopic traffic parameters in Table 3. The assumed frequencies of traffic congestion are 1 hour per day, 1 hour per week and 1 hour per month. The assumed daily durations for traffic congestions resemble tunnels in urban area with periodically congested traffic during rush hours (1h/day - 1h/week) as well as tunnels in rural areas with seasonal congestion effects (1h/week – 1h/month).

Table 7: Detailed traffic composition of the model tunnel

Congestion frequency [hours/day] case 1	0.5 stop and go 0.5 heavily congested
Congestion frequency [hours/week] case 2	0.5 stop and go 0.5 heavily congested
Congestion frequency [hours/month] case 3	0.5 stop and go 0.5 heavily congested
HGV-share / Bus-share	7.5 % / 0.5 %

Although the most effective emergency ventilation strategy varies with the maximum heat release rate, it is unlikely that this rate will be known when the response to a real fire is initiated. Accordingly, it is assumed that the choice of ventilation strategy will depend only on the traffic state. It is reasonable to tailor the response to the traffic state because real time evaluation of traffic states - i.e. measurement of traffic density and average speed - is common at critical points of infrastructure networks.

Figure 9 shows overall risk expectation values for the various emergency ventilation strategies, allowing for the probability of occurrence of an event as well as for its consequences (damage-extent). In each case, critical-velocity ventilation is used for free-flowing traffic scenarios, but different emergency ventilation strategies are used for congestion scenarios. With a congestion frequency of 1 hour per day, 4% of all vehicles passing through the tunnel are involved in traffic congestion. Likewise, with congestion frequencies of 1 hour per week and 1 hour per month, 0.6% and 0.14% of all vehicles experience traffic congestion. For each congestion frequency considered, low-speed emergency ventilation achieves a higher level of safety than strategies based on critical-velocity or shut-down ventilation. Thus, regulatory recommendations proposing to reduce target flow velocity in the event of fire during traffic congestion in a unidirectional tunnel are confirmed. The highest level of safety is achieved by zero-flow ventilation strategy. In the case of high frequencies of traffic congestion (1h / day) the overall risk value with respect to low-speed ventilation can be reduced by more than 50% if zero-flow ventilation strategy is used in the event of fire. Even for lower congestion frequencies of 1h/week or 1h/month the risk reduction is significant.

Figure 9 compares expected risks for three congestion frequencies. Herein, attention is focussed on the fire risk which is seen to increase strongly in comparison with the case of free-flowing traffic (NB: Note that different scales are used in the four graph boxes). The figure provides a simple visual indication of the relative influence of the various ventilation strategies. Little attention should be paid to the collision risk shown in the figure because the potential effects of traffic congestion on collision risk have not been considered in detail. In particular, the increased probability of consecutive collisions during the early stages of development of traffic congestion has not been considered.

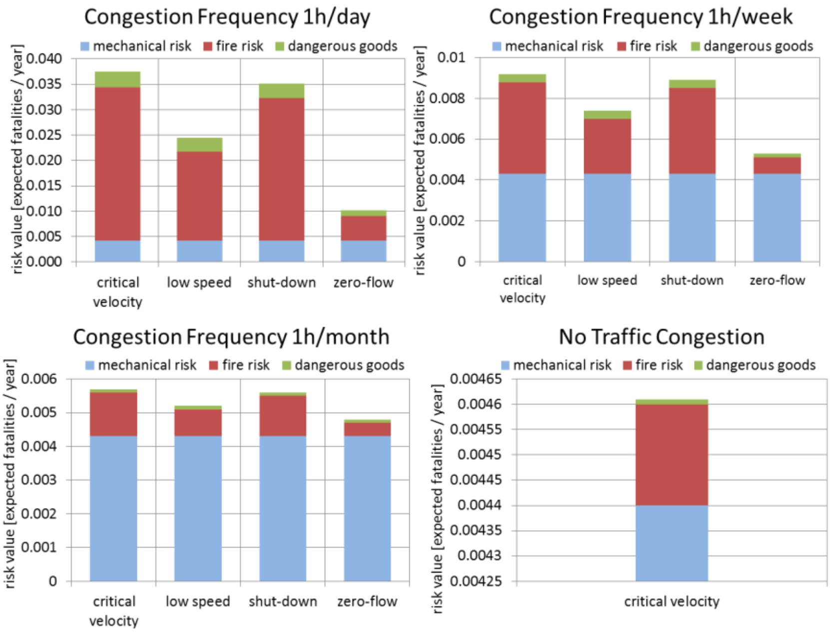

Figure 9: Risk expectation values with respect to emergency ventilation strategies for different congestion frequencies

8 CONCLUSIONS

The performance of four widely used emergency ventilation strategies for longitudinally-ventilated, unidirectional road tunnels during traffic congestion has been investigated by applying the fully quantitative Austrian tunnel risk method to a generic model tunnel. Comparisons of results obtained for the ventilation strategies have shown that the optimum emergency ventilation strategy depends strongly on fire size and traffic state. With free-flowing traffic, critical-velocity ventilation yields the highest level of passenger safety. During congested traffic, calculated average damage-extent values in small fires are close to zero for all four emergency ventilations. For this case, zero-flow ventilation has the poorest performance, but this is primarily because it is assumed that 3% of tunnel users will stay in or next to their cars instead of moving towards the next emergency exit. For such persons, other strategies perform better because they dilute the smoke. In contrast, with higher heat release rates, zero-flow ventilation has been shown to be the best of the four strategies, indicating that confinement of smoke is more beneficial than smoke dilution. The safety-gain due to the application of zero-flow ventilation during high HRR fires dominates the overall safety performance. This has been demonstrated by the comparison of overall risk expectation values.

In the calculation of the risk expectation values, it has been assumed that the choice of the emergency ventilation strategy is made in the knowledge of the current traffic state. In practice, this means that the best emergency ventilation strategy can be chosen if real-time traffic (flow and density) sensing capabilities are provided. Additionally, although not assumed in the calculation of the overall risk expectation values, an even better targeted selection could be made if knowledge of real-time fire sizes were available. The possibility of inferring this information based on the installation of linear temperature cables is discussed in [8].

Although dependent on real time estimations of traffic flow (and fire size), zero-flow emergency ventilation strategy has been found to perform better than common emergency ventilation strategies in the case of traffic congestion. However, this paper has focussed exclusively on the self-rescue phase immediately after the outbreak of a fire. Other ventilation strategies may be more suitable during subsequent assisted rescue and fire-fighting phases. It should also be noted that the influence of longitudinal airflow velocity on fire development and emission rates has not been considered – because it is not yet considered in the Austrian tunnel risk model – although it is the subject of current investigations [9].

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