Generic quantification of consequences of road-tunnel fires

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1 ABSTRACT

To an adequate degree of accuracy, the number of fatalities and injured due to road-tunnel fires can be determined based on characteristic parameters: total length of the tunnel, local inclination of the tunnel section, distance between emergency exits, fire heat-release rate, traffic regime, ventilation system and strategy.

The data generated to interpolate the dedicated response surfaces are based on about 2 million representative scenarios that were computed with the programs SPRINT and ODEM.

Consequently, this generic approach is applied in the new risk analysis methodology of road tunnels in Switzerland. Project specific 3D CFD with egress modelling is not foreseen.

2 INTRODUCTION

2.1 Motivation: Risk analysis of tunnels on national roads in Switzerland

Instructions by the Federal Department of the Environment, Transport, Energy and Communications (ASTRA 74001 (4)) specifies the safety requirements that comply with the EU-directive 2004/54/EC (5). A series of national norms and guidelines specifies the design of the Swiss tunnels and the requirements that are higher than those specified in the EU-directive (5).

An annual update is conducted of the tunnel-safety screening TUSI (6) regarding the need for refurbishment in order to meet the significant current safety-design criteria. In 2014, it was estimated that in total 1660 million CHF need to be invested. The main requirements are related to tunnel ventilation (49%) and to egress routes (44%).

The Federal Road Administration (FEDRO / ASTRA) is responsible for the national roads in Switzerland. 2010, FEDRO pre-qualified five consortia that then could conduct a pilot risk-analysis study and propose the development of the future Swiss risk analysis methodology. 2011, the winner (HBI Haerter, Matrisk and HOJ Consulting) was awarded the contract to write a guideline and to develop a methodology, which was conducted in close cooperation with the authorities. 2015, it was published (see (1), (2) and (3)) and is hence compulsory to use. The risk analysis uses Bayesian Probabilistic Networks (BPN) in order to cater for the interaction between various parameters, see (13), (14).

Amongst others, the risk analysis had to be transparent and give unambiguous results. Firstly, the new Swiss guideline (1) clearly identifies when a risk analysis has to be carried out in case of differences to national norms and guidelines or if according to exact criteria there is a special characteristics in terms of (4) and (5).

The consequences of a tunnel fire depend on many factors and therefore most risk analysis models require a dedicated CFD-analysis with egress modelling to be carried out. The drawback with this approach is that the results are likely to be user dependent and the results will therefore not be unambiguous. One mayor reason for this is that the assumptions, which need to be made in the CFD analysis, influence significantly the results. It was therefore decided to develop a generic model in order to quantify the consequences. The analysis showed that such a model can be based on the information on:

- the tunnel ventilation system and its application,
- the distances between the egress routes,
- the main tunnel characteristics: longitudinal inclination and overall tunnel length, and
- traffic regime

This information can be seen as a set of indicators governing the consequences due to road-tunnel fires.

Details of this study are reported in (11). It should be noted that the objective was to develop a model for Switzerland, which might not be directly applicable for other countries. A specific set of indicators have been used here. It is always possible to increase the number of indicators if necessary. This would, however, not impair the general methodology described in this paper.

2.2 Flow and Egress Modelling: SPRINT+ODEM

2.2.1 Flow simulation: SPRINT (Smoke PRopagation IN Tunnels)

SPRINT (**S**moke **PR**opagation **IN** **T**unnels, (8)) computes the flow field in the tunnel by means of a one-dimensional time-dependent model, based on the governing equations describing the conservation of mass, momentum and energy, as well as the additional relations for smoke propagation. The tunnel is defined as a single tube with constant cross-section, which is discretized lengthwise. Traffic, uni- or bi-directional, can be specified in terms of velocity, number of vehicles and percentage of trucks. The fire is modelled as a heat and smoke source. Smoke concentrations (0 to 100 %), CO concentrations and temperatures are computed assuming a stoichiometric fuel fire.

Each lengthwise element is divided vertically into a hot layer that covers the upper part of the tunnel and a cold layer of tunnel air underneath. Heat is transferred to the tunnel walls by means of convection and radiation.

As long as the smoke front is very close to the fire, it is very hot and travels at high velocities. With increasing distance from the fire, the smoke is cooled down and the smoke front velocity becomes very small. These effects are reproduced by the model.

2.2.2 Egress modelling: ODEM (One-Dimensional Egress Model)

The results from the 1D flow computations are used in the deterministic egress model ODEM (**O**ne-**D**imensional **E**gress **M**odel) that is described in (7).

The objective is to determine the consequences of a tunnel fire in terms of injured and fatalities, which are computed using egress modelling. Firstly, the number of persons in the tunnel needs to be determined, which depends on the traffic flow and the average number of persons per vehicle. The vehicles enter the tunnel until the portals are closed. The vehicles continue moving either towards the exit portal or the fire, unless they are halted by a traffic light or encounters smoke. When stopped inside the tunnel, it takes the pre-movement time (here set to 120 s) until the persons leave the vehicles. It is, however, assumed that an immediate egress commences when the smoke is closer than 50 m to the persons or if the temperatures exceed 50°C. It is assumed that the people move according to the escape way signalization. Upon identification of smoke or hot air, egress direction is inversed, if the approached exit is more than 25 m away. No social interaction is implemented. When the persons have reached the exit, they are considered to be in a safe haven i.e. out of danger.

At zero smoke concentration, the walking speed is 1.2 m/s and at 100 % smoke concentration 0.2 m/s. Depending on the smoke concentration, a linear interpolation between the two is conducted.

The number of egressing persons in a road tunnel is relatively low and it is therefore assumed that they are neither hindered by other persons nor by standing vehicles. Passing from one side of the fire to the other is not possible in the model.

The toxicity of the smoke is modelled by the CO concentrations and the fatal limit is assumed to correspond to a dose of 900 ppm of CO during 30 min. This value is somewhat lower than in other models in order to cater for the stacked concentration levels observed in genuine tunnel fires; the hot gasses would in many circumstances result in higher concentrations in the upper half of the tunnel than in the lower half with the egressing persons. This value was selected based on initial computations. Persons that have reached a safe haven and with a dose lower than the fatal one are in the model determined as being injured. Another cause of fatality is exposure to a temperature of 100°C, which again is the average one over the tunnel cross section. Unlike CO, the exposure to temperatures higher or equal to the fatal limit leads to immediate death.

In the original egress model ODEM (7), it was assumed that the smoke was always mixed over the tunnel cross section. However, considering that the objective of some of the investigated ventilation strategies is to benefit from smoke stratification, a pseudo zone model was developed. It is assumed that the smoke at flow velocities of less than 1.5 m/s in a distance from 30 m to 300 m from the fire can be fully stratified, unless it is closer than 40 m from a jet fan or experiences flow reversal. At flow velocities between 1.5 m/s and 2.5 m/s, partial stratification is assumed. Moreover, it is assumed that the smoke can only sustain stratification for a duration of up to 5 min. Outside the stratified zones, it is assumed that the smoke is completely mixed over the cross section.

The assumptions regarding stratification has led to an adaptation of the egress model ODEM. It is hence the model-assumption that due to stratification, the tunnel user may not be exposed to CO and temperatures. On the other hand, visibility and egress velocity are not affected by stratification, see Table 1.

Table 1 Stratification model and egress

	No smoke	Stratified smoke	Partly stratified smoke	Non-stratified smoke
Flow velocity		< 1.5 m/s	1.5 m/s to 2.5 m/s	> 2.5 m/s
Egress velocity	1.2 m/s (maximal)	Linear interpolation depending on smoke concentration between 0.2 m/s (100% smoke) and 1.2 m/s (0% smoke)		
CO and temperature exposure	No exposure	No exposure	Linear Interpolation between none and full exposure	Full exposure

2.2.3 Example of SPRINT+ODEM simulation

Figure 1 shows a typical output of a simulation. At a distance of 800 m from the portal of a 2000 m long tunnel with an inclination of -3%, a fire ignites at the time t =0s. The maximum heat-release rate of 100 MW is reached at the time t=600 s. On the left hand side in the diagram, the flow velocity is shown; due to the piston effect of bidirectional traffic, at 80 km/h, the flow velocity is initially about 0.5 m/s. Fire detection occurs at 90 s (yellow horizontal line), which results in tunnel closure and the start-up of the tunnel ventilation. In this particular example, the ventilation strategy is to have a velocity of 1 m/s, which is selected to be in the negative direction, as this was the main flow direction at the time of detection.

In the right hand diagram, the smoke propagation is shown in grey. The zones with stratified smoke are shown as light grey. As vertical lines, the emergency exits are shown. The coloured lines indicate egress trajectories of selected persons. The green lines indicate successful egress. The purple lines show fatalities due to high temperature and the red ones due to toxicity.

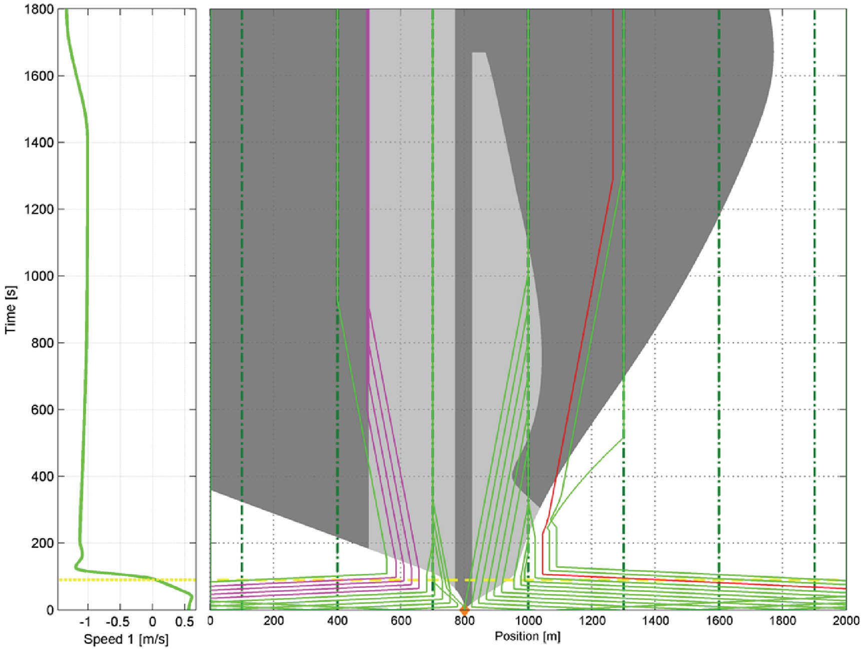

Figure 1 Example of computed scenario showing the development of smoke and egress patterns (right diagram) with time (y-axis) and flow velocity (left diagram). Light grey show zones with smoke stratification. Emergency exits every 300 m, 150 person in tunnel: 114 injured but manage to egress (green lines), 29 fatalities (22 due to temperatures (purple lines) and 7 due to toxicity (red lines)). Only every fifth egress trajectory is shown.

2.3 Investigated parameter range

The number of fatalities and injured due to a fire was computed for various ventilation systems and ventilation strategies. About 2 million scenarios were computed for all combinations of following parameters:

- 5 heat-release rates: 0 MW, 5 MW, 30 MW, 100 MW and 300 MW
- 3 external portal pressures differences: -20 Pa, 0 Pa, +20 Pa
- 1 length profile: continuous (monotonous) longitudinal inclination
- 7 longitudinal inclinations: -8%, -3%, -1.5%, 0%, 1.5%, 3%, 8%
- 5 tunnel lengths: 1000 m, 2000 m, 3000 m, 5000 m and 7000 m
- 5 distances between emergency exits: 50 m, 100 m, 300 m, 500 m and 1000 m
- 5 reference ventilation systems:
    1) Natural ventilation
    2) Longitudinal ventilation without control of the flow velocity
    3) Longitudinal ventilation with control of the flow velocity
    4) Smoke extraction without control of the flow velocity
    5) Smoke extraction with control of the flow velocity
- 3 traffic scenarios combined with 2 ventilation strategies:
    - Fluent unidirectional traffic (100 km/h, 1000 veh/h,lane)
    - Fluent bi-directional traffic (80 km/h, 1000 veh/h,lane)
    - Traffic standstill for uni- and bi-directional traffic (150 veh/km,lane)

- 2 ventilation strategies for each traffic scenario
    - ventilation strategy for fluent traffic
    - ventilation strategy of standstill

Idealised fire curves were used, where the peak heat-release rate (HRR) was reached 10 min after onset, see Figure 2. This maximum HRR was maintained for 60 min. Reduction to 0 MW takes 30 min. In all cases, it was assumed that the fire was detected and the portal immediately closed for traffic 60 s after the fire had reached 5MW.

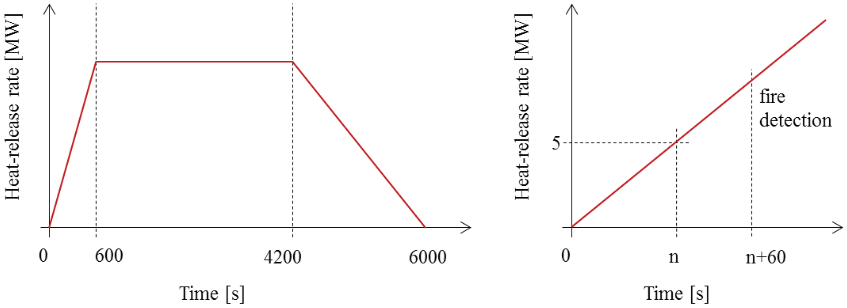

Figure 2 Idealised fire curves (left) and detection principle (right).

A traffic flow of 1000 veh/h,lane was assumed with 8 % heavy-goods vehicles. For fluent traffic, the traffic speed was 80 km/h for bidirectional traffic and 100 km/h in case of unidirectional traffic. 150 veh/km,lane was assumed at standstill. In all computations, a density of 1.5 persons per vehicle was considered.

The geometry of a typical Swiss two-lane tunnel was assumed with a tunnel width of 9 m and a cross section of 45 m^2 in case of smoke extraction (systems 4 and 5) and of 50 m^2 in case of natural and longitudinal ventilation (systems 1 to 3). The dimensioning of the ventilation system was in accordance with the Swiss guideline on tunnel ventilation (9) with a wall friction factor (λ) of 0.015 and a portal pressure of ±10 Pa. High frequency of traffic congestion (determined RV2 in (9)) was assumed.

In case of smoke extraction (systems 4 and 5) and in accordance with the Swiss design guideline (9), a smoke extraction rate of 4 m/s times the cross section applied over an extraction-zone length of 200 m was assumed.

Only the ventilation systems (3) and (5) comprised an active control of the longitudinal velocity to a certain set point. This control objective could only be fully achieved if the dimensioning was adequate and it should be recalled that the design fire for the dimensioning was 30 MW.

The control of the ventilation system was conducted following the ASTRA instruction (10) according to stationary fire detection (in (10) referred to as “Hauptalarm stationär”) with two exceptions: In case of unidirectional fluent traffic, maximum ventilation capacity was engaged instead of controlling the flow velocity to 3 m/s and jet fans were not switched off when they were in smoke.

3 VENTILATION SYSTEM & STRATEGY AND TRAFFIC REGIMES

3.1 Strategy and Traffic Regimes

When selecting the ventilation system, it also has to be decided which type of ventilation strategy to apply with respect to the traffic flow:

- correct application of strategy for either fluent traffic or standstill
- application of ventilation strategy for standstill also for fluent traffic
- application of ventilation strategy for fluent traffic also in case of standstill

The combination of ventilation systems, ventilation strategies and traffic regimes is shown in Table 2 below using abbreviations e.g. 1_NLRFS meaning: Natural Ventilation (NL), Unidirectional traffic (R), fluent traffic (F), ventilation strategy standstill (S). The number "1" is the strategy relating to traffic regime and ventilation strategy.

The table also shows the effect of the longitudinal inclination (*i*):

$-8\% < i < 0\%$	the inclination only has an influence within this range; at positive inclinations, it is not expected to have any fatalities.
$\| i \|$	means that the absolute value of the inclination matters.

Moreover, the table indicates two heat-release rates. The first value (e.g. 0 MW for 1_NLRFS) shows that injured are expected down to HRR; the second value (e.g. 5 MW for 1_NLRFS) means that fatalities are only expected from the corresponding HRR e.g. 5 MW. The non-white colours show combinations, which conclude in the same results. The 30 possible combinations can in the modelling therefore be reduced to 17.

Table 2 Combinations of analysed of traffic regimes, ventilation systems and strategies. Dependency of inclination (i); minimum HRR for injured and fatalities

<table>
<tr><td>Traffic</td><td colspan="4">Unidirectional</td><td colspan="2">Bidirectional</td></tr>
<tr><td>Traffic regime: standstill / fluent</td><td>Fluent</td><td>Standstill</td><td>Fluent</td><td>Standstill</td><td>Fluent</td><td>Standstill</td></tr>
<tr><td>Ventilation strategy</td><td>Stand still</td><td>Fluent</td><td>Fluent</td><td>Stand still</td><td colspan="2">Bi-directional</td></tr>
<tr><td>1) Natural ventilation</td><td>1_NLRFS
$-8\%< i <0\%$
0 MW /
5 MW</td><td>2_NLRSF
$|i|$
0 MW /
5 MW</td><td>3_NLRFF
$-8\%< i <0\%$
0 MW /
5 MW</td><td>4_NLRSS
$|i|$
0 MW /
5 MW</td><td>5_NLGFG
$|i|$
0 MW /
5 MW</td><td>6_NLGSG
$|i|$
0 MW /
5 MW</td></tr>
<tr><td>2) Longitudinal ventilation without flow control</td><td>1_LORFS
$-8\%< i <0\%$
0 MW /
5 MW</td><td>2_LORSF
$|i|$
0 MW /
5 MW</td><td>3_LORFF
$-8\%< i <0\%$
30 MW /
30 MW</td><td>4_LORSS
$|i|$
0 MW /
5 MW</td><td>5_LOGFG
$|i|$
0 MW /
5 MW</td><td>6_LOGSG
$|i|$
0 MW /
5 MW</td></tr>
<tr><td>3) Longitudinal ventilation with flow control</td><td>1_LMRFS
$|i|$
0 MW /
5 MW</td><td>2_LMRSF
$|i|$
0 MW /
5 MW</td><td>3_LMRFF
$-8\%< i <0\%$
30 MW /
30 MW</td><td>4_LMRSS
$|i|$
0 MW /
5 MW</td><td>5_LMGFG
$|i|$
0 MW /
5 MW</td><td>6_LMGSG
$|i|$
0 MW /
5 MW</td></tr>
<tr><td>4) Smoke extraction without flow control</td><td>1_AORFS
$-8\%< i <0\%$
0 MW /
25 MW</td><td>2_AORSF
$|i|$
0 MW /
30 MW</td><td>3_AORFF
$-8\%< i <0\%$
0 MW /
25 MW</td><td>4_AORSS
$|i|$
0 MW /
30 MW</td><td>5_AOGFG
$|i|$
0 MW /
30 MW</td><td>6_AOGSG
$|i|$
0 MW /
30 MW</td></tr>
<tr><td>5) Smoke extraction with flow control</td><td>1_AMRFS
$|i|$
0 MW /
30 MW</td><td>2_AMRSF
$|i|$
0 MW /
30 MW</td><td>3_AMRFF
$|i|$
0 MW /
30 MW</td><td>4_AMRSS
$|i|$
0 MW /
30 MW</td><td>5_AMGFG
$|i|$
0 MW /
30 MW</td><td>6_AMGSG
$|i|$
0 MW /
30 MW</td></tr>
</table>

3.2 Application to other ventilation systems

Logical rules were developed in order to be able to interpolate between the different investigated systems in order to obtain results for any other ventilation system including such ones that are under dimensioned, as described in (2) and (11).

4 MAIN RESULTS

4.1 Initial analysis of results

In order to obtain an overview of the results, the impact on selected parameters was scrutinized, as shown below.

4.1.1 Heat-release rate

The number of fatalities increases about linearly with the peak heat-release rate but the influence on the number of injured is less significant, see Figure 3.

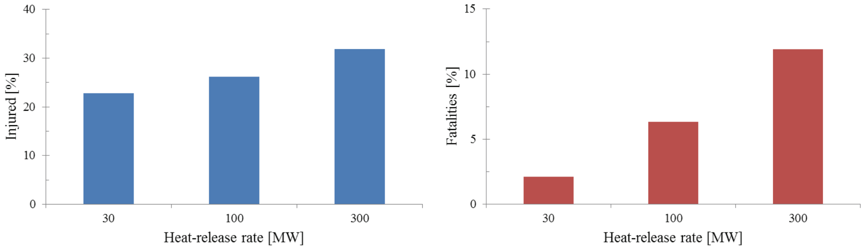

Figure 3 Influence of maximum heat-release rate. Average fraction of injured (left) and fatalities (right).

4.1.2 Tunnel length

At shorter tunnel lengths, the fraction of injured and fatalities decrease about linearly with tunnel length. However at larger lengths, this approaches an asymptotic value, as seen in Figure 4.

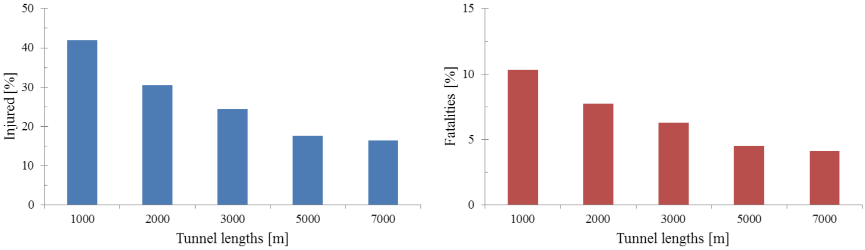

Figure 4 Influence of tunnel length. Average fraction of injured (left) and fatalities (right).

4.1.3 Longitudinal tunnel inclination

The influence of the longitudinal inclination is less pronounced in case of standstill or bidirectional traffic, as persons are situated on both sides of the fire, see Figure 5. On the contrary in case of fluent unidirectional traffic, the downhill inclinations can increase the consequences considerably compared with uphill gradients that are bound to be beneficial for the egress conditions, see Figure 5.

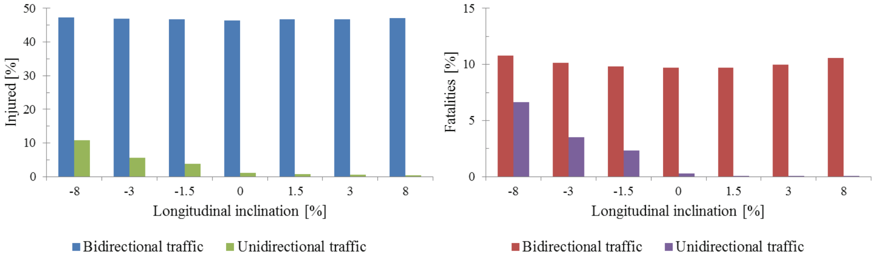

Figure 5 Influence of longitudinal tunnel inclination.
Average fraction of injured (left) and fatalities (right).

When developing the response surfaces (see section 4.2), it was decided to include this effect by considering the absolute value of the inclination i.e. $|i|$ for symmetric systems and to assume that there would be no fatalities at certain uphill inclinations, as shown in Table 2.

4.1.4 Distance between emergency exits

As expected, the distance between emergency exits have a large influence on longitudinally and natural ventilated tunnels but was of minor importance in case of smoke extraction, see Figure 6.

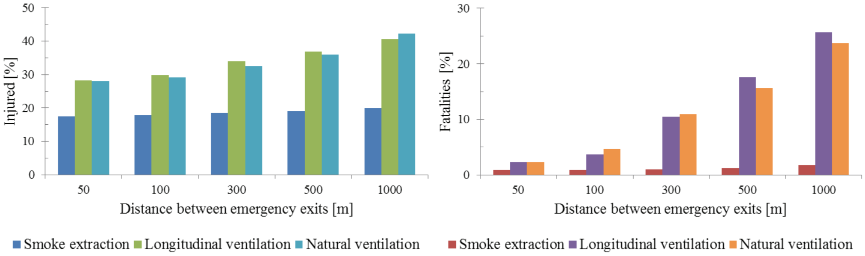

Figure 6 Distance between emergency exits for different ventilation systems.
Average fraction of injured (left) and fatalities (right).

It is found that the effect of the portal pressure difference that was varied from -20 Pa over 0 P to +20 Pa had a smaller effect even when considering the longitudinal inclination as a parameter.

4.1.5 Ventilation strategy and systems depending on traffic regime

In case of fluent unidirectional traffic, it is important to apply the correct ventilation strategy, see Figure 7. This is especially important in case of longitudinal ventilation at fluent traffic, where the consequences of the wrong strategy can be more severe than not having any ventilation at all. The consequences of using longitudinal ventilation with the correct strategy are even slightly lower than when using smoke extraction.

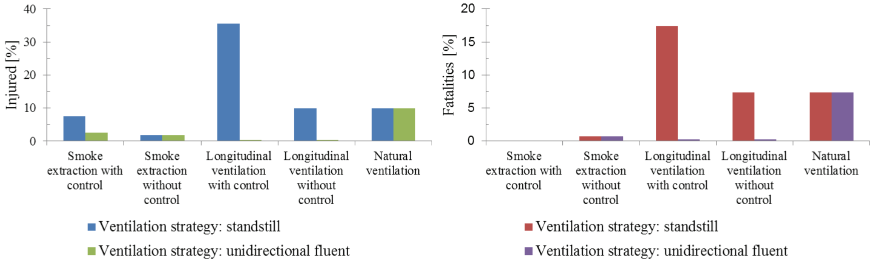

Figure 7 Effect of ventilation strategy in case of unidirectional fluent traffic for different ventilation systems. Average fraction of injured (left) and fatalities (right).

On the other hand, in case of standstill, the drawback from selecting the wrong ventilation strategy is less pronounced, see Figure 8. At standstill, smoke extraction is always the best ventilation system.

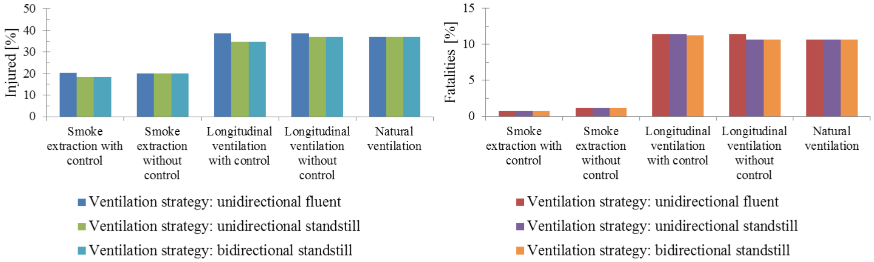

Figure 8 Effect of ventilation strategy in case of traffic standstill for different ventilation systems. Average fraction of injured (left) and fatalities (right).

In case of fluent bidirectional traffic, smoke extraction is always superior to longitudinal and natural ventilation, see Figure 9. Natural ventilation is better than longitudinal ventilation at low flow velocities.

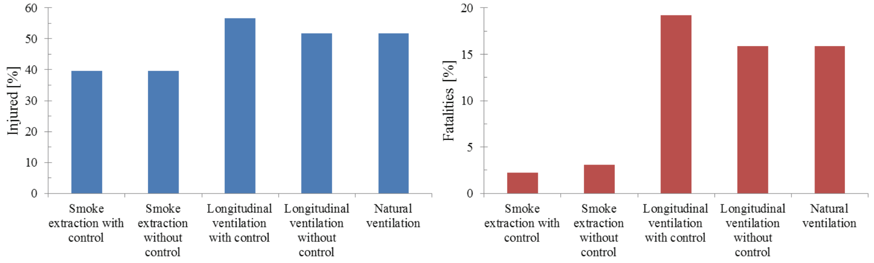

Figure 9 Fluent bidirectional traffic with different ventilation systems. Average fraction of injured (left) and fatalities (right).

4.2 Response surfaces

In order to be able readily to apply the results in the risk analysis, response surfaces were interpolated using the parameters shown in Table 3. Based on a student-t distribution, the quality of the regressions was assessed.

Table 3 Parameters in response surfaces

Variable	Unit	Variable	Coefficient	α–value	Interval
Longitudinal inclination	[%]	x_1	β_1	α_1	[*-100, 100*]
Heat-release rate	[MW]	x_2	β_2	α_2	[*0,inf*]
Distance emergency exits	[m]	x_3	β_3	α_3	[*0, x_4*]
Total tunnel length	[m]	x_4	β_4	α_4	[*0,inf*]

As shown in section 4.1.3, for symmetric systems the absolute value of the inclination needs to be considered. In other cases, the consequences depend mainly on the downhill inclination. Mathematically, this is handled by introducing an additional parameter g.

Depending on ventilation and traffic scenario, fatalities are only to be expected within a certain range of heat-release rates. In order to cater for this, the regression is limited with another system-dependent parameter f.

Consequently, the formula of the resulting responses is:

$$P_j = \begin{cases} \min\left(\max\left(\left(\beta_0^j + \beta_1^j \left| x_1 \right|^{\alpha_1} + \sum_{i=2}^{4} \beta_i^j \cdot \left(x_i^j \right)^{\alpha_i} + E_j \right), 0 \right)^{\frac{1}{\alpha_{m,j}}}, 1 \right) & x_1 \geq g \quad x_2 \geq f \\ 0 & x_1 < g \quad \forall f \\ 0 & \forall g \quad x_2 < f \end{cases}$$

The corresponding target values are summarised in Table 4. In the computations, the fatalities are also considered to be injured and these therefore have to be subtracted.

Table 4 Target values in response surface

Target variable	Variable	α–value
Probability of fatality	P_1	$\alpha_{5,1}$
Probability of injured	P_2	$\alpha_{5,2}$

The regression coefficients, which were calculated for each of the ventilation systems and strategies listed in Table 2, are reported in (2).

As an example, the probability of injured for the scenario AORFF i.e. with smoke extraction (A), without flow control (O), at fluent unidirectional traffic (RF), and applying the ventilation strategy for fluent traffic (F), can be computed directly (here illustrated with a 2000 m long tunnel with distances between emergency exits of 250 m):

$$P_{injured\ and\ fatalities}^{AORFF} =$$

$$\min\left(\max\left(\left(-0.532 + 0.0191 \cdot \left| x_1 \right|^1 + 0.0185 \cdot x_2^{0.5} + 8.32 \cdot 10^{-8} \cdot 250^2 + 4.675 \cdot 2000^{-0.3} \right), 0 \right)^{\frac{1}{0.3}}, 1 \right)$$

where x_1 is the longitudinal inclination and x_2 the heat-release rate. In case of a longitudinal inclination of 6% and a 200 MW fire, the result is:

$$P^{AORFF}_{injured\ and\ fatalities} =$$

$$\min\left(\max\left(\left(-0.532 + 0.0191 \cdot \left|-6\right|^{1} + 0.0185 \cdot 200^{0.5} + 8.32 \cdot 10^{-8} \cdot 250^{2} + 4.675 \cdot 2000^{-0.3}\right), 0\right)^{\frac{1}{0.3}}, 1\right)$$

$$P^{AORFF}_{injured\ and\ fatalities} = 0.02379$$

This means that the probability that a person inside the tunnel is injured in case of a 200 MW fire is 0.024.

The corresponding response surface is shown in Figure 10.

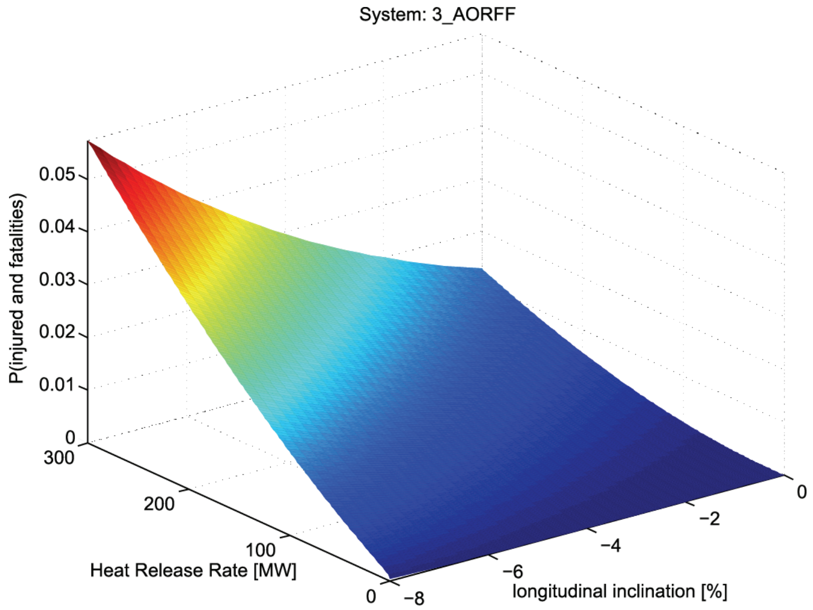

Figure 10 Response surface of a 2000 m long tunnel with 250 m between emergency exits having the system AORFF (traffic, ventilation system and strategy).

The regression with response surfaces generally gave a very good fit to the simulation data. Due to the higher sample size, the correlation coefficients for the response surfaces for injured were higher than those for fatalities. However, even for the response surfaces for fatalities, the correlation coefficient was in most cases between 0.9 and 1.0 (which represents an excellent fit). Only in few cases, the correlation coefficient was in the range 0.7 – 0.8, which is still considered as acceptable.

4.3 Use on tunnels with variable inclination and at any length

Based on theoretical considerations, which are supported by the analysis in sections 4.1.2 and 4.1.3, it was argued that the total number of fatalities respectively injured depends on the local inclination of a tunnel section and the total length of the tunnel, see Figure 11. It can hence be computed as follows:

$$V_T = \sum_{j=1}^{n} V_j \frac{L_j}{L_{Global}}, \qquad T_T = \sum_{j=1}^{n} T_j \frac{L_j}{L_{Global}}$$

V_T = Number of injured, V_j = Number of injured in tunnel section j
T_T = Number of fatalities, T_j = Number of fatalities in tunnel section j
L_{Global} = Total length of tunnel, L_j = Length of tunnel section j

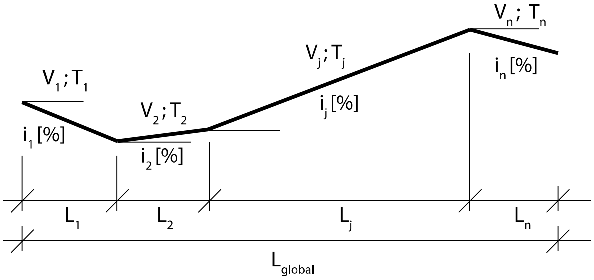

Figure 11 Tunnel with variable inclination.

In order to verify this relationship, 10 different tunnel shapes having 2 to 7 sections with different inclinations and lengths between 1.5 and 5 km were computed and the results compared with the ones deduced using the equations above. The distance between emergency exits and heat-release rate was varied. In total, about 10 000 scenarios were computed. As it can be seen in Figure 12, the overall correlation is very good and yielded a correlation coefficient of 0.949 for injured and 0.900 for fatalities.

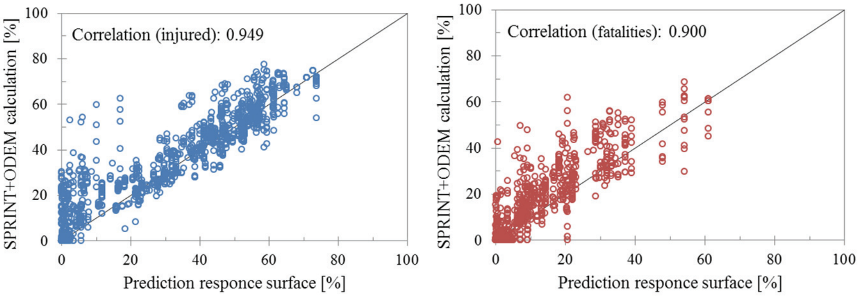

Figure 12 Correlation between computed scenarios of tunnels with variable inclinations and the values obtained based on local inclination and global length.

5 CONCLUSIONS

One main difficulty in Quantified Risk Assessments (QRA) is to determine the risk of fires, as this depends on numerous parameters such as: heat-release rate, tunnel geometry (in particular length and inclination), distance between emergency exits, tunnel-ventilation (system, capacity and usage), and traffic (quantity, unidirectional with/without congestion, bidirectional). Consequently, risk-analysis models either treat the risk due to tunnel fires in a rather simplistic manner or require dedicated CFD-modelling with egress analysis to be carried out.

The drawback using CFD and egress modelling in risk analysis is that no unique answer is obtained, as the results depend on computer program, parameter selection and user preferences. Therefore, the here presented generic model was developed for the risk analysis methodology of road tunnels in Switzerland.

The data required in order to interpolate the dedicated response surfaces is based on about 2 million representative scenarios that were computed with the programs SPRINT (**S**moke **PR**opagation **IN** **T**unnels) and ODEM (**O**ne-**D**imensional **E**gress **M**odel).

The analysis is based on five distinct tunnel-ventilation systems: natural ventilation, longitudinal ventilation with/without flow-velocity control and local smoke extraction with/without flow-velocity control. Other systems can be deduced from these according to rules of interpolation, which also have been established. In addition to the ventilation system, its use in conjunction with the traffic regime (unidirectional fluent/congested, bidirectional) are also characteristic parameters.

It was found that to an adequate degree of accuracy, the consequences due to fires can be determined based on: total length of the tunnel, local inclination of the tunnel section, distance between emergency exits, ventilation system, ventilation strategy, traffic regime, and heat-release rate.

The result of the generic model is the number of fatalities and injured.

The proposed model is tailored to be used in a risk analysis context, where the absolute consequences are often less relevant than the ability to distinguish adequately between changes in impact from various design options. It does not replace engineering of e.g. ventilation systems.

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