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Risk analysis

Results of a comparative application of QRA methodology for road tunnels in Germany

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ABSTRACT: Based on the requirements of EC Directive 2004/54/EC a quantitative risk analysis method was developed for road tunnels in Germany. The risk model focuses on the risk of tunnel users and investigates risks due to car accidents and fires. Based on this method the safety level of several model tunnels with different properties were determined and compared. Additional sensitive studies on the calculation assumptions and the individual selected conditions such as varying tunnel geometry, ventilation and emergency exit distances show the specific impact on the outcome of the risk analysis.

1 Introduction

1.1 German risk analysis method for road tunnels

In Germany, the requirements for the operational equipment of road tunnels are regulated in the “RABT” (guidelines for the equipment and operation of road tunnels) [1]. The European directive 2004/54/EC [2] was implemented by an appropriate adaptation of the “RABT”. Risk assessment based on the method presented below now has to be used in specific cases. These include:

- road tunnels that have specific characteristics,
- determining the ventilation system for bidirectional tunnels and
- existing road tunnels, for which retrofitting according to the requirements would lead to disproportionally high costs.

Hence also in Germany a quantitative method for calculating monetarised expected risk values based on accident frequencies and fire simulations was developed. The German risk analysis method was published as final report “Assessing the safety of road tunnels” to the research project FE 03.378/2004/FRG[3]. This method covers the risk due to the following initial events:

- risk due to car accident
- risk due to fires

The German risk model does not include the risk due to transport of dangerous goods through road tunnels. This risk is covered by a separate approach based on the international ADR tunnel regulations, which is not presented in this paper.

The German risk model allows calculating two different risk indicators of societal risk for collision risk as well as for fire risk:

- Expected risk value (EV):
  statistically (in a long term perspective) expected number of fatalities per year and per tunnel (or per tunnel km).
- FN-curve:
  graph depicting the relationships between frequency and consequences (in terms of number of fatalities per event) of the investigated accident scenarios in a double logarithmic scale.

For fire risk as well as for collision risk the frequencies of the individual consequence scenarios are calculated by event trees defined in the risk model. Whereas the consequence values for collisions are also defined in the method (based on statistical accident consequence data), the consequence values for fires have to be calculated individually for the tunnel under investigation.

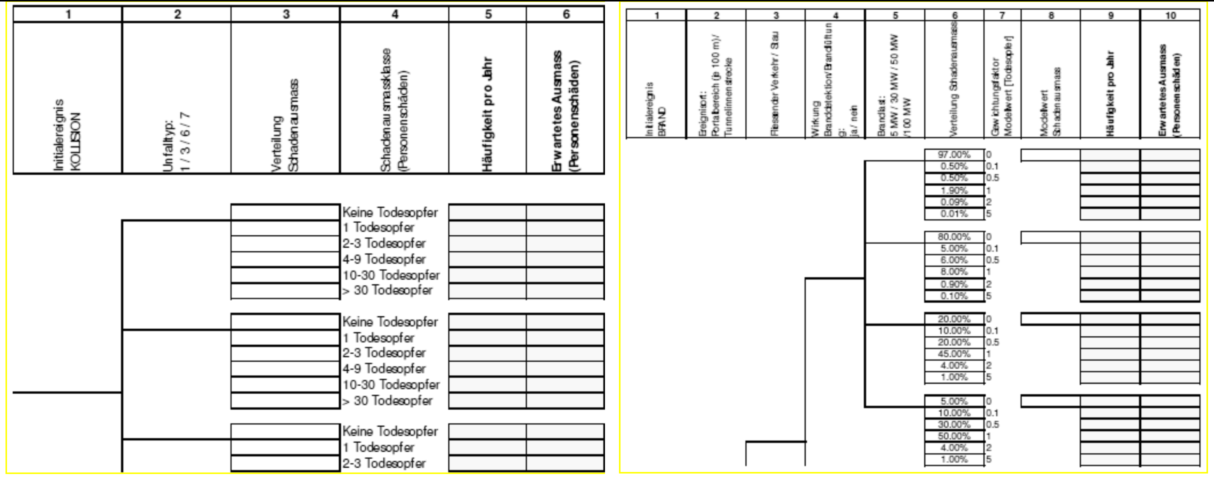


Figure 1. Structure of the event trees for scenario type collision and fire defined in the German risk analysis method

The consequence model for tunnel fires consists of two elements:

- A smoke propagation model to calculate the propagation of smoke in the tunnel, taking fire development and fire size, air flow conditions (including ventilation) and geometrical conditions of the tunnel into account. For this step commercial CFD-models can be applied.
- A simplified consequence model to calculate the consequence values for fires based on the results of the smoke propagation model; this model applies defined lethality rates in dependence of smoke concentration (different visibility zones).

The method has already been included in the regulations that determine practical applications. This procedure illustrated the challenge of implementing newly developed methods, which are based on a performance-based approach, in regulations that are traditionally made up of prescriptive specifications.

1.2 *New research work by applying German risk analysis method to different model tunnels*

Task of the research project “Sicherheitsbewertung von Straßentunneln auf Basis richtliniengerecht ausgestatteter Tunnel” [4] was to determine the range of risk values for different tunnel types (model tunnels). As basis for this investigation different model tunnels were defined. Safety related tunnel equipment of these model tunnels had to be according to the requirements of the regulation “RABT” (guidelines for the equipment and operation of road tunnels).

The basic tasks of this research project were:

- Determination of a range of safety values for tunnels equipped in a conforming way.
- Sensitivity analysis, to investigate the influence of various parameters on the results of the risk analysis.
- Derivation of recommendations

2 Conclusive assumptions for input variables

For the determination of consequence values for fire scenarios there are large numbers of assumptions which have great influence on the results. As there were no exact references in the risk analysis method about these assumptions, recommendations about theses input variables were determined and coordinated within the meetings of the management committee.

Table 1 shows reference values which can be used by applying the risk analysis method. Under special boundary conditions the values have to be adapted by expert assessment.

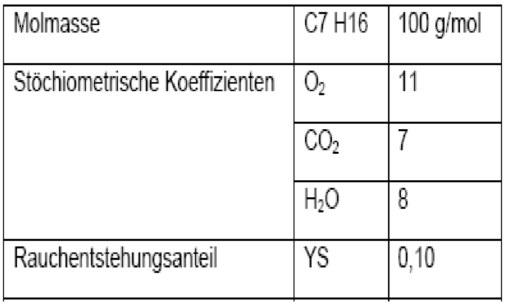
Subject	**Assumption, Comment for risk analysis**
Density of cars during congested traffic	150 passenger car per km (rural) 160 passenger cars per km (urban) Length of 2 passenger car = 1 truck
Assumption for starting time of evacuation and closing of tunnel	1 minutes after starting fire (theoretical value for determining the extent of damage with self-rescuing areas)
Average number of persons in a vehicle	1,2 persons in a passenger car 1,0 persons in a truck
How to handle buses?	No special branch in the event tree or for the risk potential. The scaling factor in the risk model already includes an average bus rate.
Effect of no fire detection (branch 4 of the event tree fir)	The fire ventilation fails and the closing of the tunnel will also fail
Model value for extent of damage "fire"	The procedure described as "Selbstrettungsbereiche" in the research report using the following values for estimating the fatalities as a function of the self-rescue conditions: - No self-rescue: 100% fatalities - Conditional self-rescue: 50% fatalities - Self-rescue: 0% fatalities
Estimation of visibility ranges	1,8 m above road at tunnel axes
Location of fire scenario within tunnel	Always use the case "fire in front of the emergency exit"
Longitudinal air velocity at the time of the beginning of the fire	Bidirectional traffic 1,5 m/s Unidirectional traffic 4,0 m/s
Reaction time of ventilation	1 Minute from detection to full operation
Fire characteristics	 Molmasse · C7 H16 · 100 g/mol Stöchiometrische Koeffizienten · O_2 · 11 CO_2 · 7 H_2O · 8 Rauchentstehungsanteil · YS · 0,10
Fire growth	Within 60 seconds to full fire size
Heat release rate	1.25 MW/m²

Table 1: Calculation assumptions and input values

3 Risk level of 8 different model tunnels

The German design guidelines RABT cover a wide range of different tunnel types – in terms of traffic value and traffic composition, traffic type (unidirectional or bidirectional), tunnel length, tunnel cross section etc.

Therefore, of course the risk values of these tunnels are quite different. For the purpose of the investigation all safety relevant parameters of the model tunnels were set at limit values according to RABT.

In order to determine the range of safety values 8 different model tunnels were assessed.

The selection of the model tunnels was made in coordination with an advisory board of external experts based on experience.

Parameter	TUNNEL 1	TUNNEL 2	TUNNEL 3	TUNNEL 4	TUNNEL 5	TUNNEL 6	TUNNEL 7	TUNNEL 8
Type	bi-directional	uni-directional	uni-directional	bi-directional	bi-directional	bi-directional	bi-directional	uni-directional
Length	1.200 m	3.000 m	600 m	1.200 m	1.200m	400 m	400 m	600 m
AADT	20.000	70.000	70.000	20.000	20.000	20.000	20.000	70.000
Cross Section	vaulted	vaulted	vaulted	rectangular	rectangular	rectangular	vaulted	rectangular
Ventilation	longitudinal	longitudinal	natural	longitudinal	smoke extraction	natural	natural	natural

Figure 2. Key parameters of investigated model tunnels

In practice, the results of a quantitative risk analysis can be depicted in 2 different ways: either as “risk per tunnel” or as “risk per tunnel km”. The risk levels of the model tunnels are presented in these two different ways in figure 3 and figure 4.

Comparing the overall risk values of the whole tunnel, model tunnel 2 shows the highest risk. The risk of tunnel 2 is dominated by collision risk, which is high due to the high traffic (aadt 70.000 vehicles / day) and the high tunnel length (3 km). The risk of tunnel 6 and 7 seems to be low, but is based on the tunnel length of 400 m. The overall risk of the other tunnels is quite similar, however, the fire risk varies considerably (by appr. a factor 3 between tunnel 3 and tunnel 2 and 5 respectively), which can be explained by the influence of the ventilation system (tunnel 3 – no ventilation, tunnel 5 - ventilation with smoke extraction, tunnel 2 - unidirectional tunnel with longitudinal ventilation).

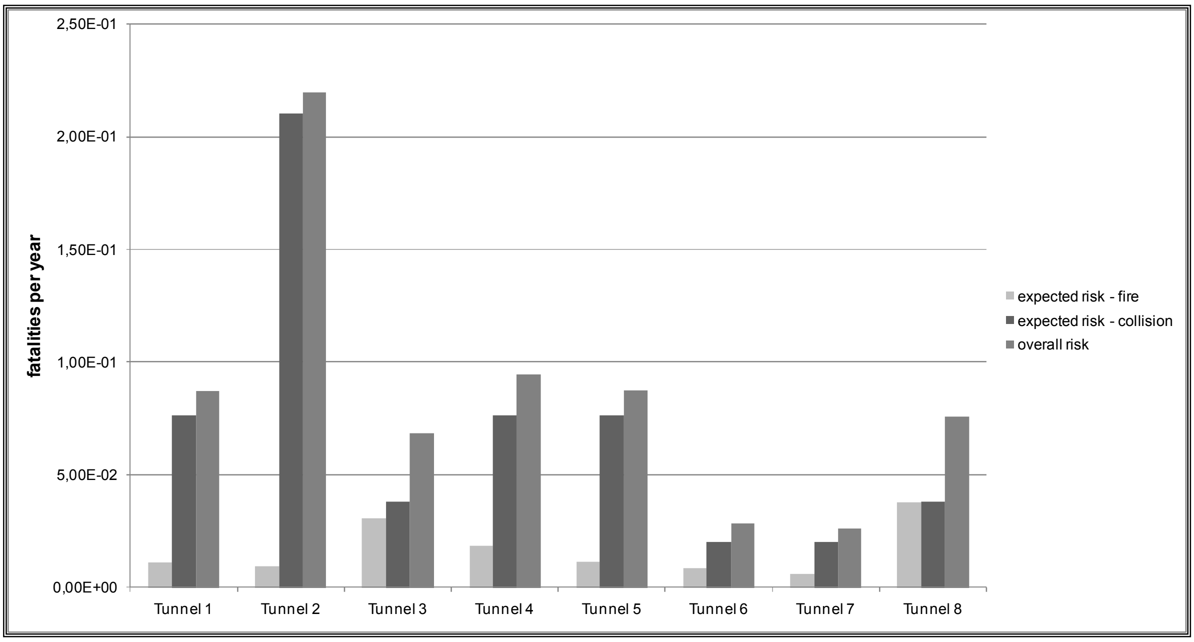


Figure 3. Expected risk values for 8 model tunnels per tunnel

Comparing the risk values per tunnel km it can be seen, that the tunnels with the highest risk are now model tunnel 3 and 8 (due to high fire risk of this tunnels), whereas the overall risk of the other tunnels is quite close together.

Looking at the collision risk per tunnel km, it can be seen that the values differs only slightly between the various model tunnels. This is remarkable, as the traffic of tunnel 2 (aadt 70.000 vehicles / day) is more than 3 times higher than the traffic of tunnel 1 (aadt 20.000 vehicles / day).

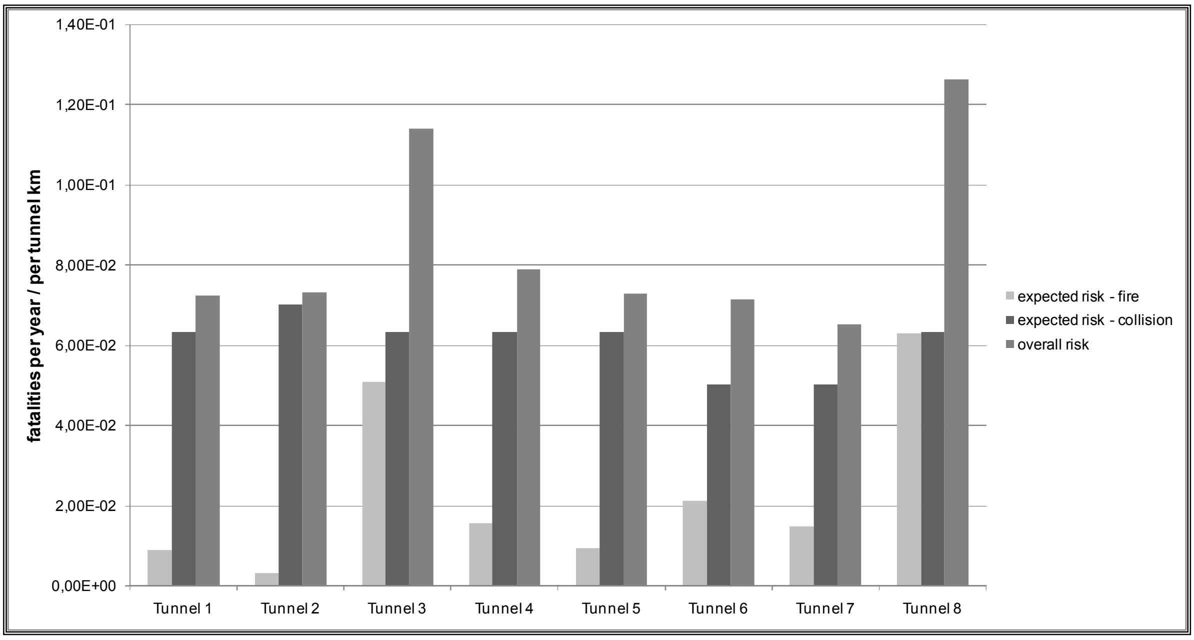


Figure 4. Expected risk values for 8 model tunnels per tunnel km

The fire risk values (see figure 5) show considerable differences, which can be explained once again by the different ventilation systems of the model tunnels. In tunnels with unidirectional traffic a longitudinal ventilation can blow the smoke away from the vehicles stopping behind the fire location (tunnel 2 – low fire risk); in bidirectional tunnels with smoke extraction smoke can be sucked off in most situation (tunnel 5 – low fire risk), however in a unidirectional tunnel without mechanical ventilation (tunnel 3 and 8) there may be a high fire risk (even if the tunnel is short), because smoke propagation cannot be controlled.

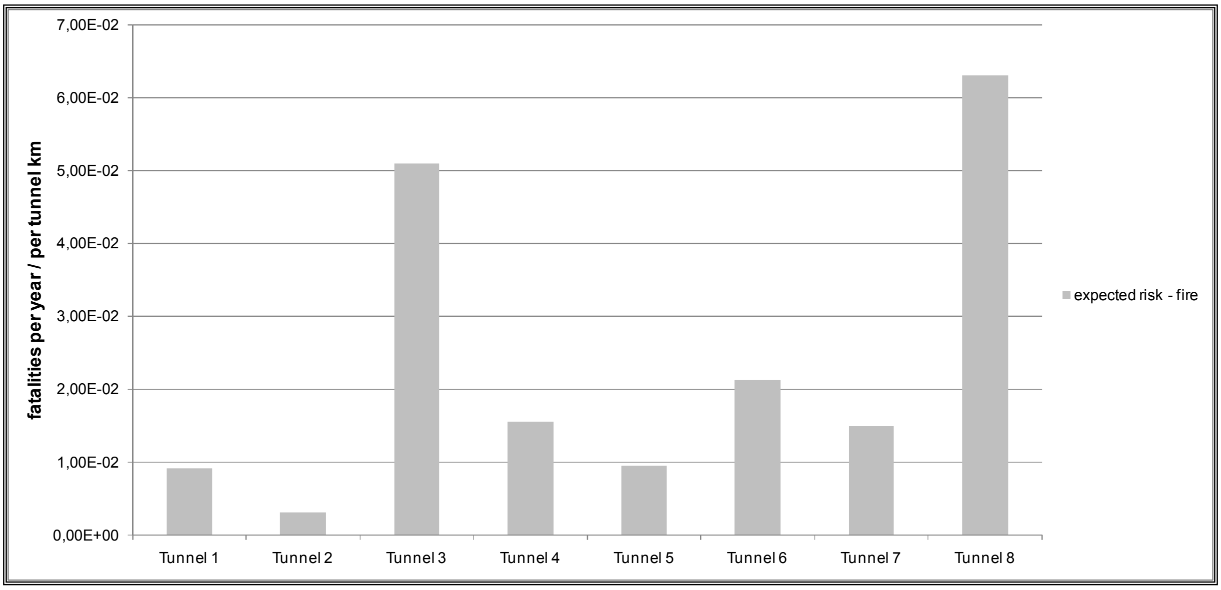


Figure 5. EV of fire risk of 8 model tunnels (risk per tunnel km)

These examples clearly demonstrate that the way how the risk values are presented – as risk per tunnel or as risk per tunnel km - considerably influences absolute results as well as relative comparisons. It is therefore essential to carefully consider this aspect when interpreting the outcome of a risk analysis.

As an example the FN-curve-diagram of the overall risk of 3 different model tunnels are given in the figure 6 (risk per tunnel km).

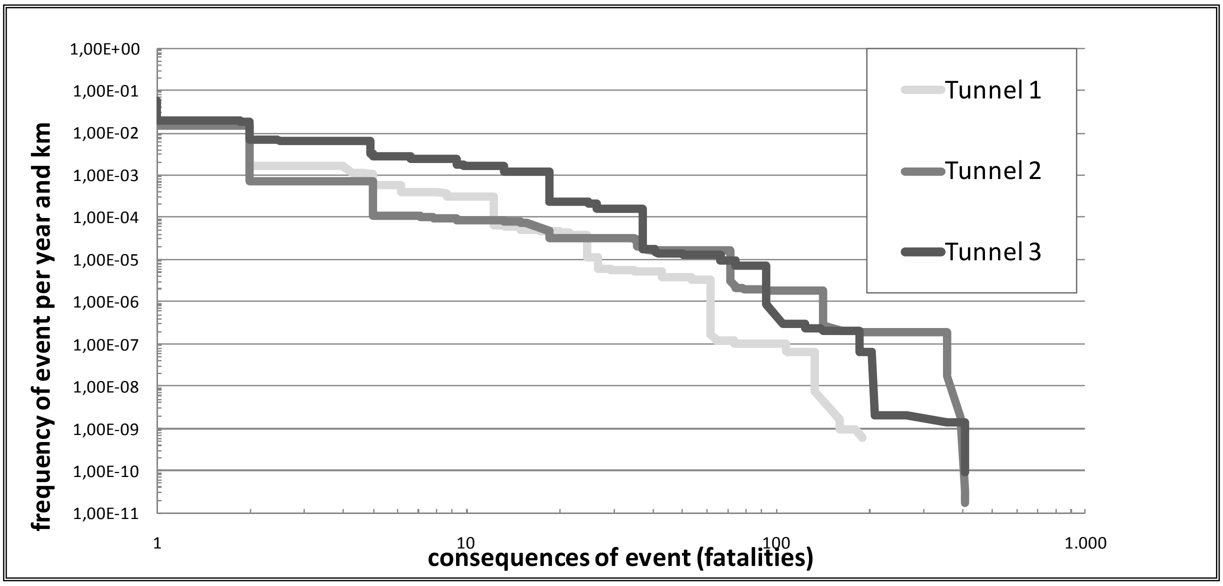


Figure 6. Comparison of the overall risk (risk per tunnel km) of 3 different model tunnels

This figure demonstrates clearly, that the 3 model tunnels show different characteristics in terms of fire risk:

The 3 km long unidirectional tunnel with longitudinal ventilation and high traffic (model tunnel 2, aadt 70.000 vehicles / day) shows the lowest risk up to accidents with 20 fatalities, but at the same time the highest risk potential for accidents with many fatalities (> 100). This is due to the fact that many people may be effected if a fire accident happens in a traffic jam situation; however, this is very unprobable hence the corresponding frequencies are very low.

On the contrary, the 600 m long unidirectional tunnel with high traffic and natural ventilation (model tunnel 3; aadt 70.000 vehicles / day), shows a much higher fire risk for accidents with consequences up to 50 fatalities, which is due to the fact that also in normal traffic situations (without congestion) the smoke propagation cannot be controlled and consequently vehicles stopping behind the accident location may be effected as well.

In comparison the 1,2 km long bidirectional tunnel with longitudinal ventilation (model tunnel 1; aadt 20.000 vehicles / day) is located between the FN-curves of the other 2 tunnels up to accidents with appr. 20 fatalities, but shows a lower risk for accidents with higher consequences, which can be explained by a lower number of people effected in catastrophic events (due to lower traffic values).

These examples clearly demonstrates, that an un-ambiguous, interpretation of the results of such a risk analysis study is not a simple straight-forward task but requires experience and specific expertise.

4 Results of sensitivity studies

Another objective of the research project was to study the influence of characteristic tunnel parameters mainly on the overall risk and specifically on fire risk. The following examples are presented in this paper:

- Influence of tunnel geometry (vaulted tunnel cross section versus rectangular tunnel cross section)
- Influence of mechanical ventilation (various parameters)
- Influence of reduced emergency exit distances

The study was performed by selecting one or two model tunnels, where the parameters investigated were expected to be relevant. The results were depicted as EV as well as FN-curves (risk per tunnel km) and evaluated by relative comparison. For these reasons the conclusions cannot be transferred to other types of model tunnel (e.g. from bidirectional to unidirectional tunnels).

4.1 Influence of tunnel geometry on fire risk

This study was carried out on the basis of model tunnel 1 and 4 (both bidirectional tunnels) and model tunnels 3 and 8 (both unidirectional tunnels). All parameters of the two model tunnels compared to each other (like length, traffic volume and composition, longitudinal inclination etc.) are exactly the same, the only difference being the tunnel cross section (vaulted cross section versus rectangular cross section). The results are shown in figure 7 and figure 8 respectively:

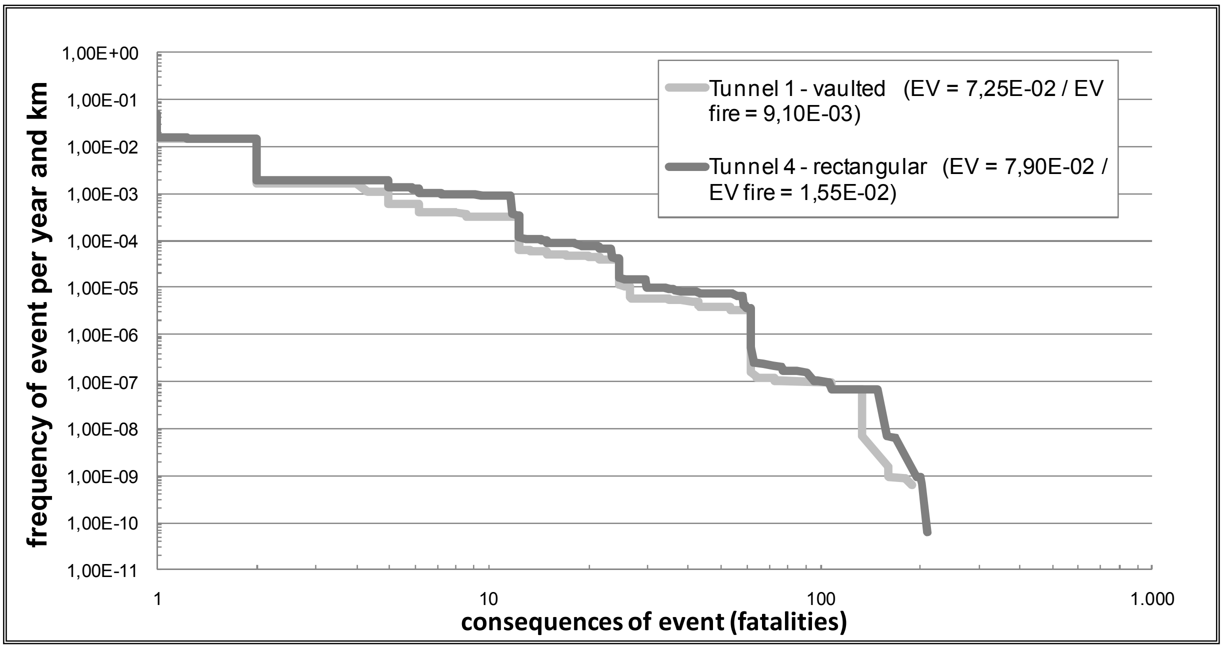


Figure 7. FN-curves (overall risk) and expected values (overall risk and fire risk) for model tunnel 1 and 4

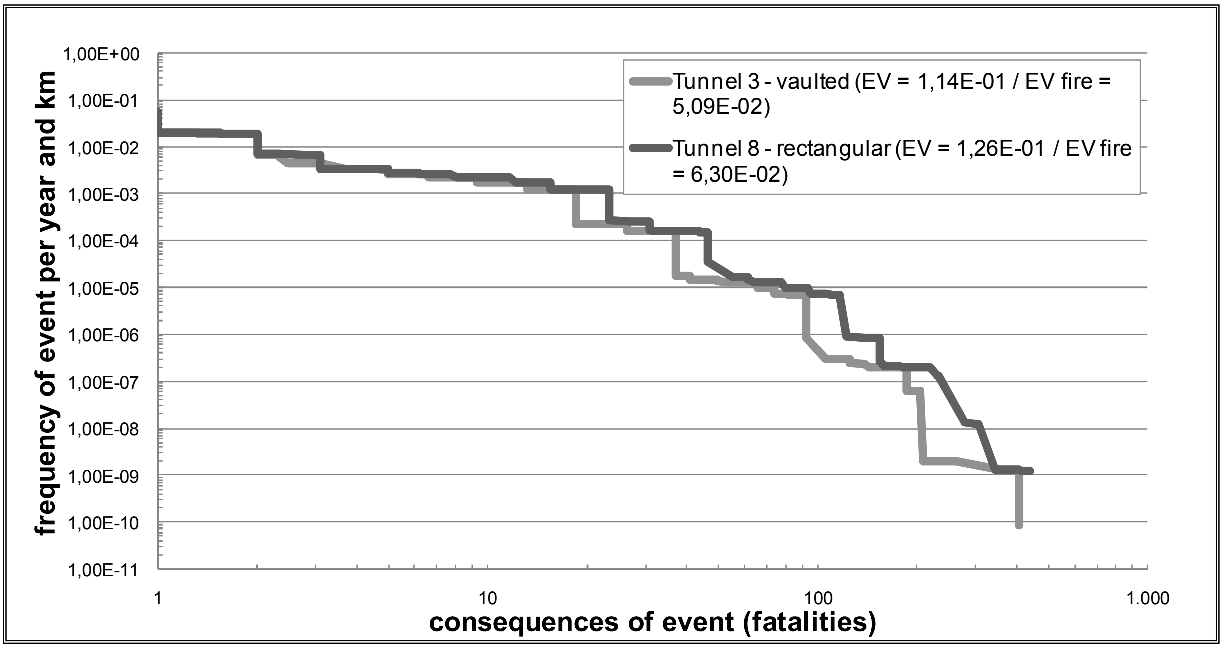


Figure 8. FN-curves (overall risk) and expected values (overall risk and fire risk) for model tunnel 3 and 8

Both comparisons show a clear influence of the cross section on fire risk, which can be seen in the expected value as well as in the FN-curves: The FN curve of the model tunnel with a rectangular cross section is clearly above the FN-curve of the model tunnel with a vaulted cross section. The explanation is that the storage volume for smoke in the vaulted cross section is bigger than in the rectangular cross section, so that lower parts of the tunnel cross section remain smoke free for a longer period of time. This effect can clearly be demonstrated when locking more into detail of the results of the risk analysis.

4.2 Influence of mechanical ventilation

One of the main objectives of the sensitivity study was the investigation of ventilation parameters; three characteristic results are presented in this paper.

4.2.1 Influence of mechanical (longitudinal) ventilation in a (short) unidirectional tunnel

For that purpose model tunnel 3 (unidirectional traffic, 600 m long, aadt 70.000 vehicles / day) which showed a high fire risk (see figure 4) was equipped with a longitudinal ventilation (as additional risk mitigation measure).

The effect is a big reduction of fire risk which can be seen clearly in the expected value as well as in the FN-curve (see figure 9).

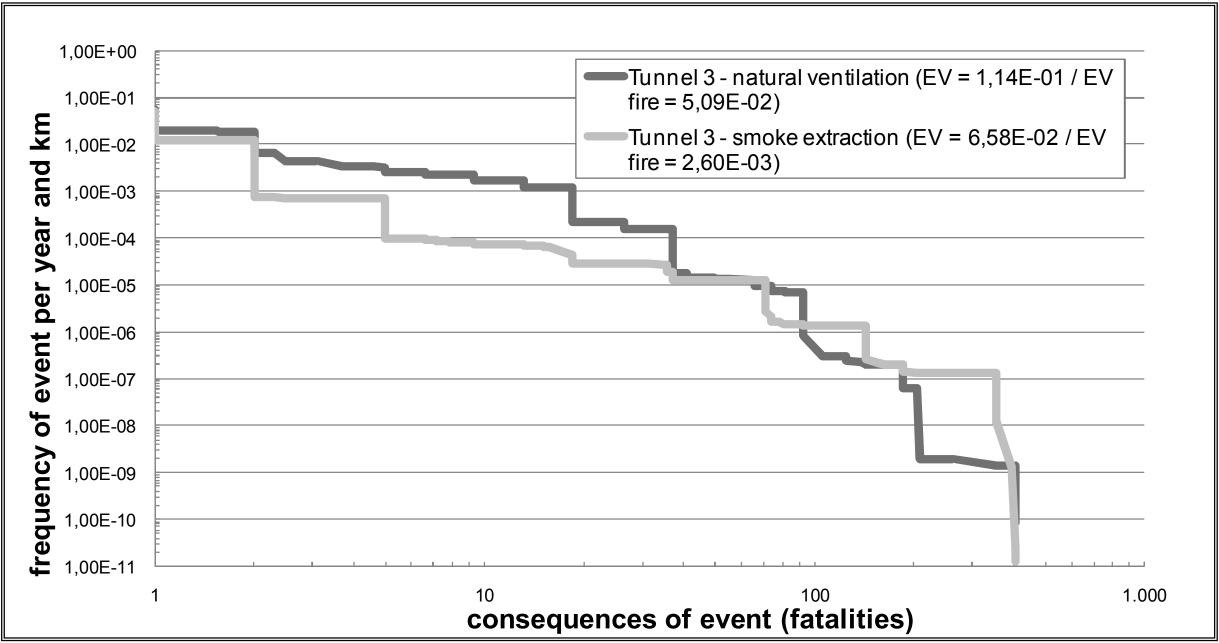


Figure 9. FN-curves and expected values of overall risk of model tunnel 3 without and with mechanical ventilation

The EV of fire risk is reduced by approximately 95 %. However, the FN-curve also shows an increase in risk for scenarios with high numbers of fatalities (which are very unprobable – however) – probably due to faster smoke propagation towards vehicles stopping in front of a fire in situations with congested traffic.

4.2.2 Influence of smoke extraction instead of longitudinal ventilation in bidirectional tunnels with rectangular cross section

Given the same tunnel cross section the positive effect of a smoke extraction can clearly be demonstrated in the expected value as well as in the FN-curves – see figure 10.

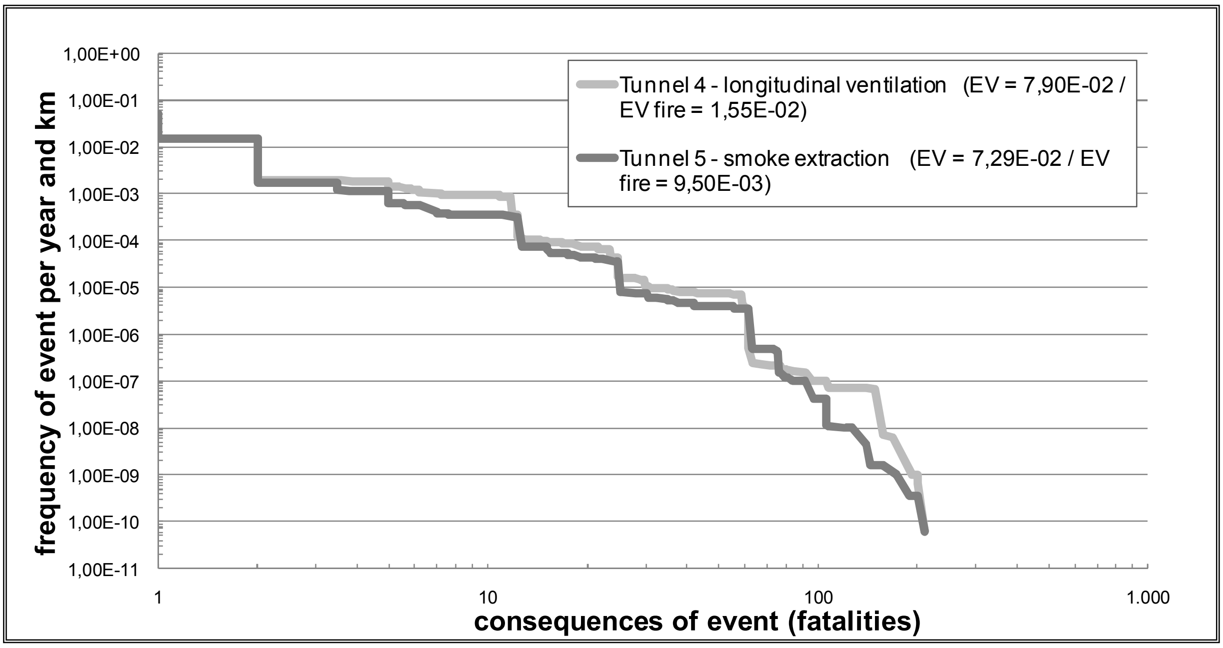


Figure 10. FN-curves (overall risk) and expected values (overall risk and fire risk) of model tunnel 4 (longitudinal ventilation) and 5 (smoke extraction)

The EV of fire risk is reduced by approximately 40 %; the FN curve of model tunnel 5 continuously lies below the one of model tunnel 4.

4.2.3 Influence of smoke extraction instead of longitudinal ventilation in bidirectional tunnel with a vaulted cross section

However, in a tunnel with a vaulted cross section the implementation of a ventilation system with smoke extraction changes the effective tunnel cross section from a vaulted cross section towards a rectangular one due to the construction of an exhaust air duct in the upper part of the tunnel profile. Examined by risk analysis the implementation of a smoke extraction system shows the following results:

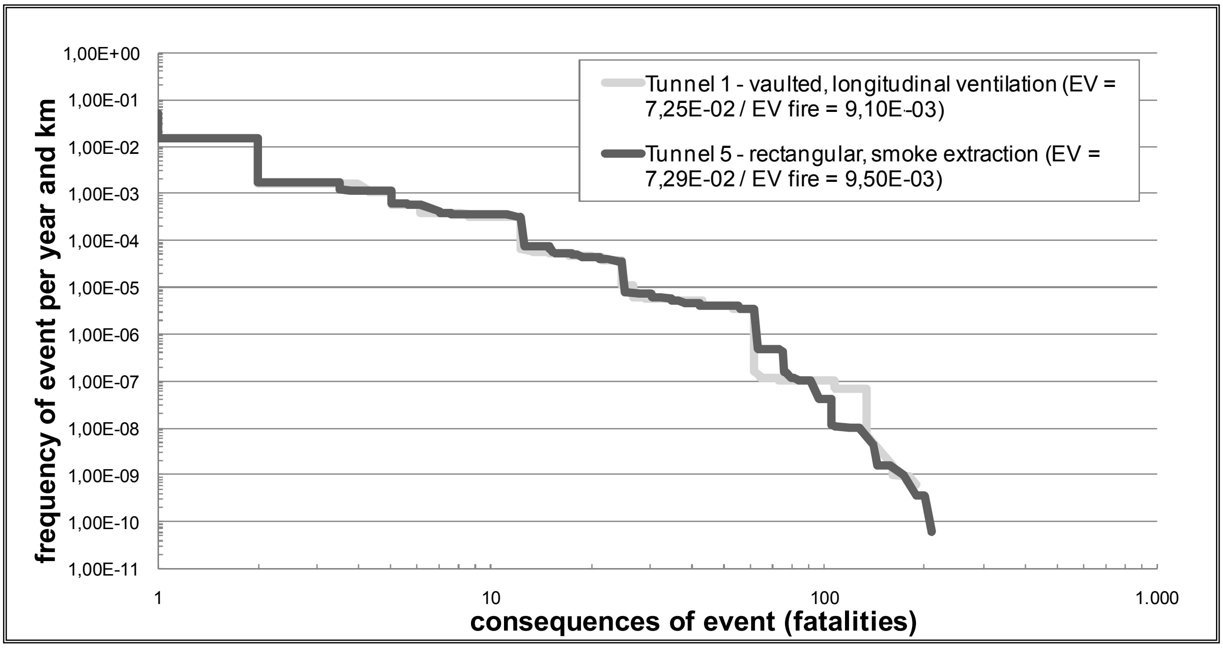


Figure 11. FN-curves (overall risk) and expected values (overall risk and fire risk) of model tunnel 1 (vaulted cross section with longitudinal ventilation) and model tunnel 5 (rectangular cross section with smoke extraction)

There is no relevant difference in risk, neither in the expected values nor in the FN-curves.

Obviously the positive effect of the smoke extraction (see figure 10) is compensated by the negative effect of a lower tunnel ceiling (see figure 7 and 8).

Considering the high cost of a smoke extraction system – these results may induce further studies on that topic.

4.2.4 Influence of longitudinal air velocity

The influence of longitudinal air velocity on the risk was investigated on the basis of a bidirectional tunnel with longitudinal ventilation (model tunnel 4). The standard value for the air flow in bidirectional tunnels in the self rescue phase (according to RABT: 1,5 m/sec.) was reduced to 1,0 m/sec.

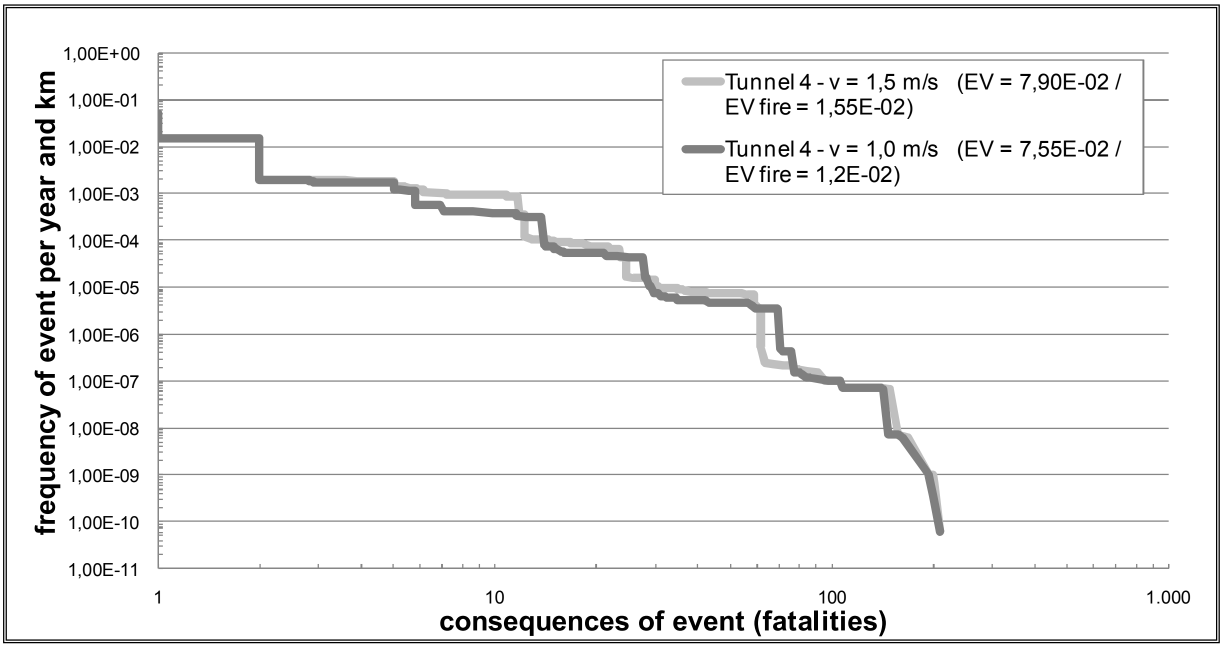


Figure 12. FN-curve (overall risk) and expected value (overall risk and fire risk) of model tunnel 4 with longitudinal air velocity of 1,5 and 1,0 m/sec.

A relevant influence can be seen in the expected value of fire risk (reduction appr. -20 %).

However, only a slight dislocation can be seen in the FN-curves. It can be concluded anyway, that the ventilation strategy in a longitudinally ventilated tunnel may influence risk to a certain extent.

4.3 Influence of reduced emergency exit distances

All model tunnels were analyzed with an emergency exit distance of 300 m (maximum admissible distance according to RABT). On the basis of model tunnel 3 (unidirectional tunnel, 600 m, high traffic volume – tunnel with high fire risk, see figure 4) the influence of a reduction of cross passage spacing was investigated. For this purpose the cross passage distance was reduced in two steps from 300 m to 200 m and then to 60 m. The results are shown in figure 13.

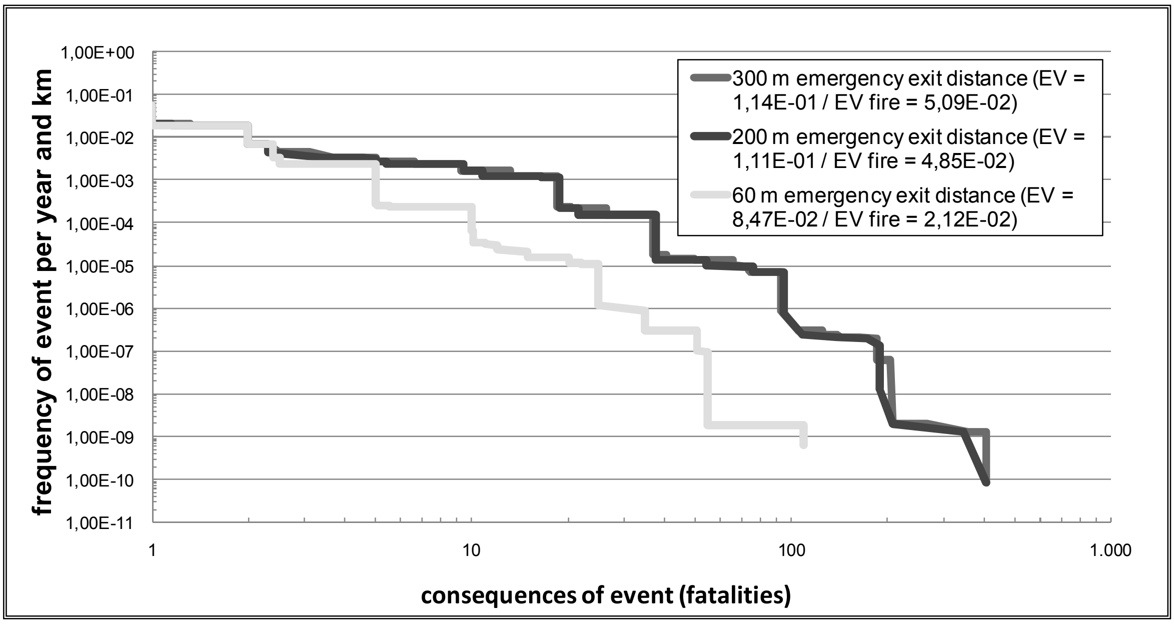


Figure 13. FN-curve (overall risk) and expected value (overall risk and fire risk) of model tunnel 3 with emergency exit distances of 300 m, 200 m and 60 m.

Whereas a reduction from 300 m to 200 m shows only a very small influence on risk (reduction of EV, of fire risk by 5 % minor effects in FN-curve), the effect of very short cross passage distances on fire risk is big (reduction of EV of fire risk by 60 %, clear difference in FN-curve).

The conclusion, that very short cross passage distances are a very efficient risk mitigation measure for tunnels with high fire risk whereas a variation at longer distances has only little effect, is in line with results of other risk analysis studies. However, it is assumed, that these specific results may also be influenced by model characteristics and specific assumptions (location of fire scenario in tunnel, local effects of smoke propagation).

5 Conclusions

Based on results of the research work the following conclusions can be drawn:

- The application of the German risk analysis method for road tunnels to 8 model tunnels showed comprehensible and traceable results
- The interpretation and evaluation of the risk analysis results, specifically of FN-curves, is not easy; specific attention has to be paid whether the quantitative risk values represent the whole tunnel or are scaled according to tunnel length.
- Different model tunnels, all strictly designed and equipped according to RABT, show not equal risk levels; hence it is not possible to derive clear and unique quantitative risk reference criteria on that basis.
- Vice versa it can be concluded that some definitions in the guidelines (for instance length criteria for the application of different ventilation systems) could be discussed on the basis of the results of systematic risk assessment studies.
- Especially the sensitivity study of various ventilation parameters lead to interesting results
- Tunnels with natural ventilation and high traffic volume show a high fire risk

- The expected influence of various ventilation systems can be clearly demonstrated
- If the implementation of a smoke extraction leads to the change of tunnel cross section (rectangular cross section due to intermediate ceiling instead of a vaulted profile) the positive effect of smoke extraction may be counterbalanced by the negative effect of a lower tunnel ceiling.

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