Safety Concept and Quantitative Risk Analysis for US Road Tunnel Projects

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ABSTRACT

The experience from road tunnel incidents in Europe has substantially improved tunnel safety since the late 1990s. Those findings can be applied in road tunnel projects to increase safety and sustainability, and reduce costs, including projects in the US. A holistic safety concept serves as a basis of design for road and structural design, systems and equipment. Hazards are evaluated and assessed, safety goals are defined and measures are evaluated in order of their effectiveness, prioritizing prevention, while also complying with codes and guidelines that focus on fire life safety. A quantitative risk analysis (QRA) is developed based on proven methods and adapted to US road tunnel conditions. The proposed road tunnel QRA approach focuses on accident risks based on statistical data, and on fire risks based on an event tree analysis for different scenarios. Simulations of smoke spread and egress are to be conducted for many critical scenarios under varying initial and boundary conditions and traffic scenarios. The effects of particular safety measures can be evaluated and compared. The QRA is a comprehensive Engineering Analysis for approval by the Authority Having Jurisdiction (AHJ), as required by the governing code NFPA 502.

Keywords: Road Tunnel Safety, Holistic Safety Concept, Quantitative Risk Analysis

INTRODUCTION

The United States have the largest road network in the world, and abundant experience with road safety in general, but there are relatively few road tunnels. According to the FHWA national tunnel inventory (NTI), there are only approx. 185 road tunnels over 1000 ft (300 m) and only 30 road tunnels in the whole US are over one mile long. In contrast, in Europe there are approximately 4000 road tunnels over 1000 ft and much longer road tunnels than in North America. Major tunnel fire catastrophes in the 1990s and the subsequent development, implementation and operational experience of new road tunnel safety standards, as documented e.g., in World Road Association documents (PIARC, Lit. 4 - 13), has led to substantially improved tunnel safety. The key feature is a risk-based approach that may be applied to increase safety and sustainability, and reduce costs of road tunnel projects also in the US. Safety measures with the highest efficiency may be identified by means of a probabilistic risk assessment, to answer the questions: Is a risk worth the benefit? Are risk mitigation measures worth the resulting risk reduction?

The following quote from David Okrent, Professor Emeritus of Engineering and Applied Science at the University of California, Los Angeles and world renowned physicist and expert on nuclear reactor safety (1922 – 2012), brings the argument to the point: *'... if our priorities in managing risks are wrong, if we are spending the available resources in a way that is not cost-effective, we are, in effect, killing people whose premature deaths could be prevented'* (Lit. 33).

SAFETY CONCEPT

The safety concept serves as a basis of design for road and structural measures, systems and equipment. Hazards are evaluated and assessed, safety goals are defined and safety measures are evaluated in order of their effectiveness, prioritizing prevention, while also complying with codes and guidelines that focus on fire life safety. A systematic road tunnel hazard analysis approach addresses the following incidents:

- Collisions
- Fires
- Explosions
- Natural disasters
- Structural collapse
- Toxic material release

and combinations of the above.

The hazards can be assessed in terms of:

- Damage to health and life of drivers, maintenance personnel, and emergency services
- Damage to vehicles
- Damage to infrastructure (road, structure, equipment)
- Damage to the environment (e.g., spillage of contaminated fire suppression water)
- Indirect economic damage, e.g., traffic disruption due to incidents

Safety goals must be defined and prioritized, such as:

1. Protect the life and health of motorists and people in and around the tunnel.
2. Protect the life and health of personnel and responders.
3. Maintain availability of the tunnel for traffic operation.
4. Protect assets (vehicles, equipment, roadway, infrastructure, environment)

Safety measures to achieve the safety goals are prioritized in the order of effectiveness:
1. Prevention
2. Mitigation
3. Evacuation
4. Rescue

Collisions impose the most significant risk to drivers on roads. The risk is largely related to driver behavior and vehicle properties, but can be reduced by tunnel safety measures.

The probability of a collision or fire hazard on a defined road section is in first order correlated to its length and traffic load, with a correction for increased accident risk of short tunnels due to influence of portal zones (Lit. 8). There is an increased likelihood of collisions in the tunnel portal zones, same as under wide bridges, due to changing light conditions. In contrast, the interior of tunnels provides safe, uniform conditions. Inside a tunnel, drivers are not exposed to glare and changing light, and unfavorable environmental conditions such as rain, snow and ice, that may lead to accidents on open roads. Therefore, the collision risk in long road tunnels is lower compared to open roads.

Fires on roads happen less often than collisions. Most vehicle fires result from technical defects and are limited in size and potential damage. According to the PIARC report (Lit. 11), the proportion of fires in which “there is neither personal injury nor damage to property” is between 80% and 90%. Collisions are the leading cause of large fires that may lead to fatalities and structural damage (Lit. 17). Therefore, any safety measures that reduce the collision risk also reduce the fire risk. The governing NFPA 502 standard (Lit. 2) focuses on mitigation, evacuation, and rescue measures to reduce the fire risk.


[redacted]

Figure 1 Car fire and large truck fire in tunnels

Collision and fire hazards may happen during the regular road operation, or they may occur during maintenance or construction work with lane closures, which obstruct the traffic and increase the risk.

Risks from natural disasters depend on the local conditions, and may be reduced in first order by appropriate design features, e.g. flood prevention (Lit. 9). Structural collapse must be prevented by adequate design, strict quality control, and regular inspection, maintenance, and repair (Lit. 1, 13).

SAFETY MEASURES

Prevention

Prevention measures have the highest priority, and apply both to open roads and tunnels, such as:

- Driver education
- Measures to improve driver awareness and avoid distraction.
- Well maintained vehicles in good condition with on-board safety systems (e.g., driver assistant systems).
- Traffic concept and road alignment providing a smooth, constant travel through the tunnel as far as possible (e.g., by adequate lane & shoulder width, avoiding impact surfaces, avoiding lane merges in tunnels, avoid weaving, etc.).
- Speed limit, adequate to sight distance and traffic conditions, that may be enforced.
- Traffic management, avoiding congestions.
- Traffic restrictions (permanent or temporary, e.g., on hazardous goods).
- Future connectivity to enable communication between vehicles and to road systems (V2X)

Tunnel specific prevention measures are:

- Bright tunnel walls, shielding drivers from distraction, separating roadway directions, and serving as fire compartmentalization.
- Wide shoulders.
- Tunnel lighting, which is directly related to the permitted speed and sight distance. Appropriately designed and controlled lighting is especially important to reduce the collision risk in the portal zones.
- Floor guidance lights reduce the probability of accidents and serve as wayfinding lighting for egressing motorists in case of a fire.
- Regular inspection and maintenance of structure, systems, and equipment. Since any traffic obstructions increase the collision and fire risk, lane closures for maintenance and construction works should be limited as far as possible.

Mitigation

- Fast incident detection, in particular relying on:
  - Acoustic Detection System (ADS)
  - Closed-circuit television (CCTV) camera system with Automatic Incident Detection (AID)
  - Smoke detection (Visibility measurement)
  - Fire detection (Linear Heat Detection system)

  Reliability of detection is essential, because automatic reactions to false alarms would have negative effects.
- Signals and barriers for lane or tunnel closures in case of an incident with adequate distance for lane changes and off-ramps for deviations.
- Signals inside long tunnels, to warn and prevent vehicles from approaching the incident site further.
- Traffic management in the adjacent road network, to allow for traffic leaving the tunnel in case of an incident.

- Fixed Fire Fighting System (FFFS)
- Fire Protection
- Drainage

Evacuation
- Wide shoulders to provide safe evacuation path
- Emergency exits in short distances, equipped with appropriate doors and signage
- Emergency lighting and floor guidance lights
- Public Addressing / Voice Alarm System (PA/VA)
- Fire ventilation / smoke control

Rescue
- Emergency Response Plan
- Emergency responder access routes
- Staging areas at portals
- Means of communication
- Standpipes with Fire Department connections (FDC)
- Staging areas at portals
- Rescue equipment
- Regular emergency responder training & exercises

The following systems are proposed as a novelty in the US, and substantially improve road tunnel safety:
- Floor Guidance Lights (Lit. 20)
- Acoustic Detection System (Lit. 21)
- Tunnel ventilation with active flow control (Lit. 29, 31)
- High pressure water mist FFFS (Lit. 25, 26).

Tunnel Ventilation

Tunnel ventilation system can be crucial to improve safety and reduce costs in road tunnels (Lit. 31). Transversal ventilation systems were developed in the US by the Pittsburgh Bureau of Mines more than 100 years ago to dilute the pollutants produced by the cars at that time, but transversal systems require high investment and operational costs. Due to massive decrease of vehicle emissions and an increasing percentage of electric vehicles, air quality in road tunnels is not an issue today, and transversal ventilation systems have become obsolete. Longitudinal ventilation systems with jet fans are much more cost effective and have been applied since the early 1960s in Europe.

Nowadays, tunnel ventilation systems are mostly designed for fire ventilation. A mechanical ventilation system is required by NFPA 502 (Lit. 2) for tunnels longer than 3,280 ft (1 km). In shorter tunnels, a mechanical ventilation system is not required if an adequate safety level can be demonstrated by an engineering analysis. However, mechanical ventilation does not necessarily improve tunnel safety but instead can even increase the risk. In practice, most fatalities in road tunnel fire incidents were caused by toxic smoke spread caused by the operation of the mechanical ventilation (Lit. 31).

The fire ventilation goal is to provide tenable conditions, which is particularly challenging when motorists are situated on both sides of a fire. The airflow and resulting smoke spread are determined by uncontrollable forces such as moving traffic, meteorological pressures and fire buoyancy. Therefore, an active dynamic flow control, based on precise and reliable in-tunnel airflow measurement, is required to achieve defined flow conditions (Lit 29, 30). That is not feasible in short tunnels.

Figure 2 Fire fighting of a large tunnel fire under controlled flow conditions

Delayed detection, signal processing and system reaction lead to a delay, while smoke spread is initially driven in first order by the piston effect of moving vehicles. The tunnel may be completely full of smoke before any systems, namely traffic management and fire ventilation, can react. To assess the usefulness of a mechanical ventilation for supporting the evacuation of motorists, means of egress must be considered. In particular, where motorist may be exposed to smoke downstream of a fire, providing emergency exits in short distances is crucial. This can be evaluated by simulations of smoke spread and egress for analysis of ASET = Available Safe Egress Time (time until conditions become untenable) and RSET = Required Safe Egress Time (time to evacuate the tunnel) as described in the following section on Quantitative Risk Analysis.

Structural Integrity

Bridges and tunnels may collapse due to deterioration and corrosion. The atmosphere in tunnels is wet and corrosive, therefore the protection of the tunnel structure and equipment from corrosion, as well as regular inspection is essential. Detected damages must be adequately repaired.

A large fire in a tunnel may cause substantial damage, leading to lengthy tunnel closure for repair work. In cut & cover structures or lids, even a structural collapse may result. In first order, tunnels rely on the fire department to control the fire and limit the damage. A Fixed Fire Fighting System (FFFS) may be useful when the tunnel operator cannot rely exclusively on the Fire Department, and the expected costs for tunnel closure and refurbishment after large fires, considering the probability of such events, are higher than the Life Cycle Costs (LCC) of the FFFS. This can be evaluated by a monetized risk assessment. Of particular interest is the comparison with LCC of structural fire protection measures such as protection boards. Fire protection boards need to be regularly removed for inspection of the underlying structure, which would require extended tunnel closures.

QUANTITATIVE RISK ANALYSIS (QRA)

Methodology

QRA has been developed in the US for a wide range of applications, e.g., nuclear facilities, chemical industry and NASA, but until recently has not been applied to US road tunnels. NFPA 502 (Lit. 2) requires conducting an 'engineering analysis' considering multiple relevant factors.

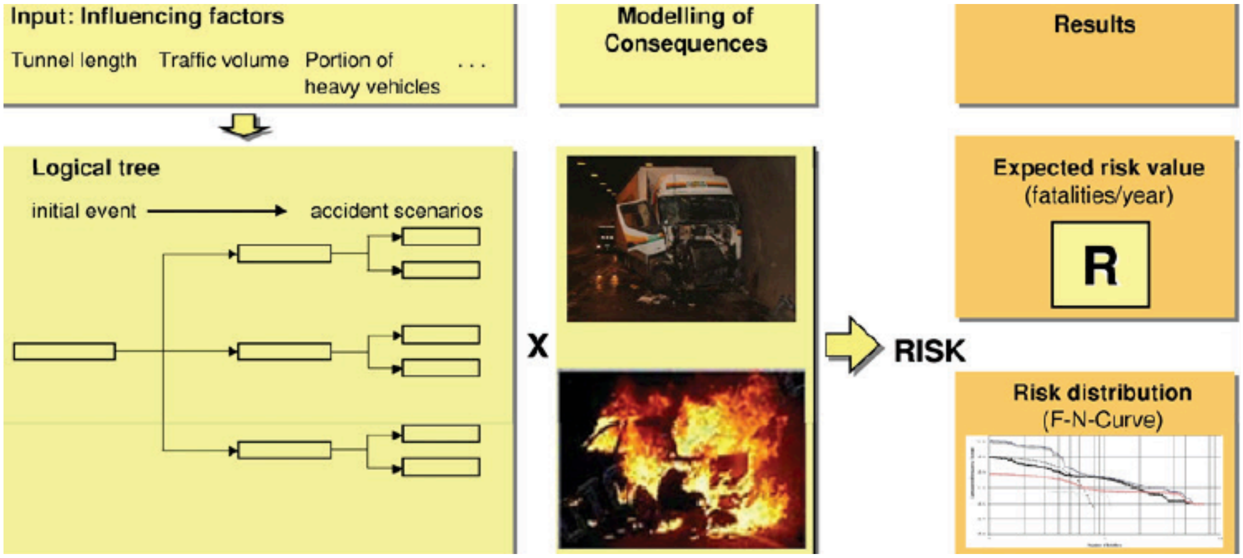

Figure 3 Road tunnel QRA procedure (from Lit. 8)

The operational risk of a road is in first order directly proportional to its length and traffic load. A tunnel QRA focuses on accident risks based on statistical data, and on fire risk based on an event tree analysis for different scenarios. With the QRA, the effect of particular safety measures can be evaluated by comparing life cycle costs of safety measures with the monetized risk of incidents. Such assessments take into account the impact on life and health of motorists and residents, material damage, and economic damage resulting from road closure for repair works multiplied with the likelihood of a particular incident.

The accident risk is calculated based on available accident statistics for a particular road where the tunnel will be, and comparison to US state and nationwide accident rates. The fire risk is based on simulations of smoke spread and egress for different scenarios. The scenarios are developed into an event tree, assigning probabilities to each scenario, as explained below.

Modeling

Safe evacuation of motorists is evaluated by an analysis of ASET/RSET. ASET is assessed by modeling the smoke spread, which depends on the type of fire, meteorological conditions, particularly wind on tunnel portals, fire buoyancy, and the flow induced by moving traffic. For RSET, evacuation is modeled based on simple assumptions about evacuee behavior, in particular the delay of egress and assumed walking speed.

In building fire life safety applications, ASET/RSET is evaluated only for one or a few ‘worst case’ scenarios. In contrast, in tunnels, varying longitudinal flow conditions determine smoke spread, therefore ASET/RSET must be evaluated for many different scenarios under varying boundary and initial conditions. Scenarios with and without operating safety systems, such as mechanical ventilation or FFFS, are to be simulated, since all systems can fail. Modeling is based on simplifications about aerodynamics and thermodynamics, using assumptions, physical parameters, and boundary conditions. numbers of required simulations. A one-dimensional (1D) model does not consider local three-dimensional (3D) effects, e.g. smoke stratification and asymmetric flow profiles. Since there is no smoke stratification in a 1D model, the results are considered conservative. 3D modeling is very elaborate. A major disadvantage of 3D models is that moving traffic, which has the most important influence on airflow and initial smoke spread, cannot be modeled with justifiable effort. However, 1D models are not applicable for complex geometries, such as buildings and underground garages, and when the tunnel length is short in comparison to the width.

One-dimensional (1D) methods model the airflow and smoke spread in a tunnel considering:

- A model of the tunnel geometry for the complete tunnel network, e.g., both tunnel cells and all cross passages in a twin tube highway tunnel.
- An aerodynamic model for incompressible flow with variable density
- A fire model with heat and smoke production
- Losses from surface drag, tunnel entry and exit, obstructions, standing vehicles
- Meteorological pressure (Wind on portals, buoyancy, barometric pressure)
- Forces induced by moving vehicles
- Forces induced by ventilation system (e.g. jet fans)
- Forces induced by the fire (Buoyancy, throttling effect)

Dynamic development of a fire incident is modeled as follows:

- Start and development of fire
- Vehicles stopping in front of fire, other vehicles moving until they stop at the end of the queue
- Vehicles downstream drive through, unless they are blocked, which would impose the most dangerous scenario
- Vehicles on adjacent lanes keep on driving
- Incident detection (based on temperature threshold or smoke reaching positions of smoke detectors)
- System reaction time (signal evaluation, plausibility check, positive alarm sequence)
- Signals on tunnel portals turn red, ideally preventing further vehicles from entering but there is no guarantee that motorists will not enter the tunnel regardless
- Alarming of motorists (PA/VA system) and emergency services
- Start of ventilation, with appropriate start-up time, and dynamic achievement of target flow by active flow control, which can take several minutes.
  (sidenote: In short tunnels, active flow control is hardly feasible)
- Activation of FFFS

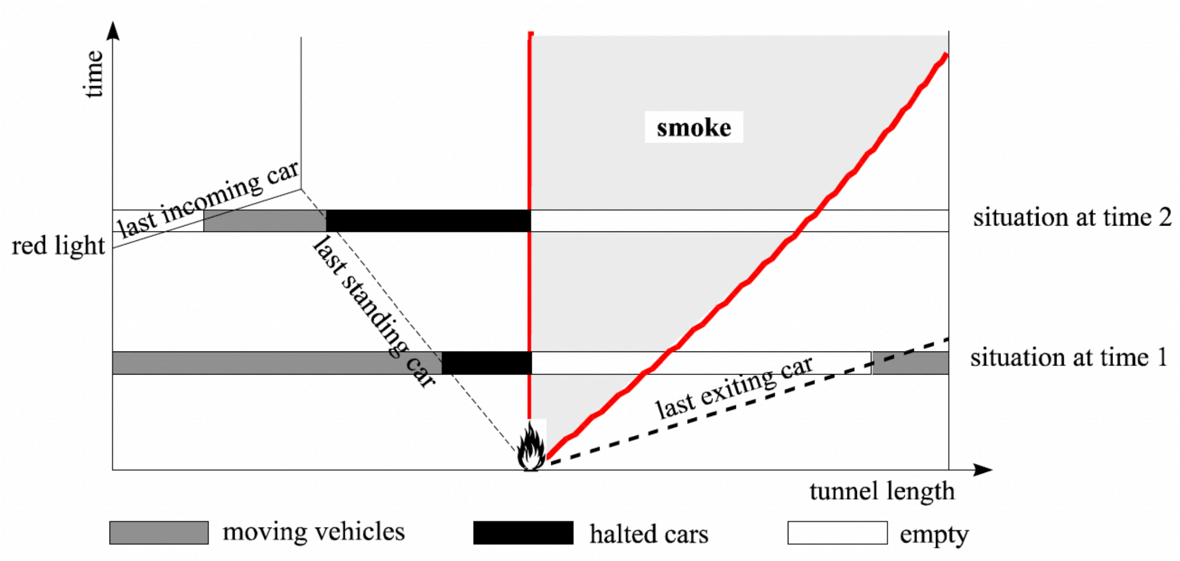

Figure 4 Dynamic traffic and smoke spread model (from Lit. 24)

Simulation time is usually until egress has been completed and a steady state flow has been achieved. Arrival of emergency services on site, assisted evacuation and fire fighting usually occur after completion of self evacuation and is not considered in the modeling, but is an important aspect of the safety concept.

For proof of fire resistance as required by NFPA 502, temperature loads on the structure are calculated conservatively with still standing air as an initial condition, for scenarios with and without FFFS. 3D simulations are useful to determine temperatures on structures in defined fire scenarios for the determination of required structural fire protection measures.

PRACTICAL EXAMPLE

The proposed methodology for concrete US projects is based on the German QRA BASt model (Lit. 14, 15), which can be adapted to US specific conditions.

Accident Risk

Statistical accident data on a particular highway provide probabilities of different accident types and initial collision rates. Those values can be compared with state and nationwide data for plausibility check.

The BASt methodology (Lit. 15) provides the probability distribution of fatalities across different accident types. Based on those data, the total accident risk is calculated, and displayed in an F-N curve.

Traffic Scenarios

1. Free flowing traffic

This traffic scenario is characterized by traffic moving at or near speed limit with no buildup of standing or slower vehicles. In case of a large fire, vehicles downstream of fire can leave the tunnel, and motorists upstream of fire are safe to escape. This is the most likely scenario, in particular for rural highway tunnels with low probability of congestions.

Usually, no casualties from fire to be expected. Serious damage from large fires is possible.

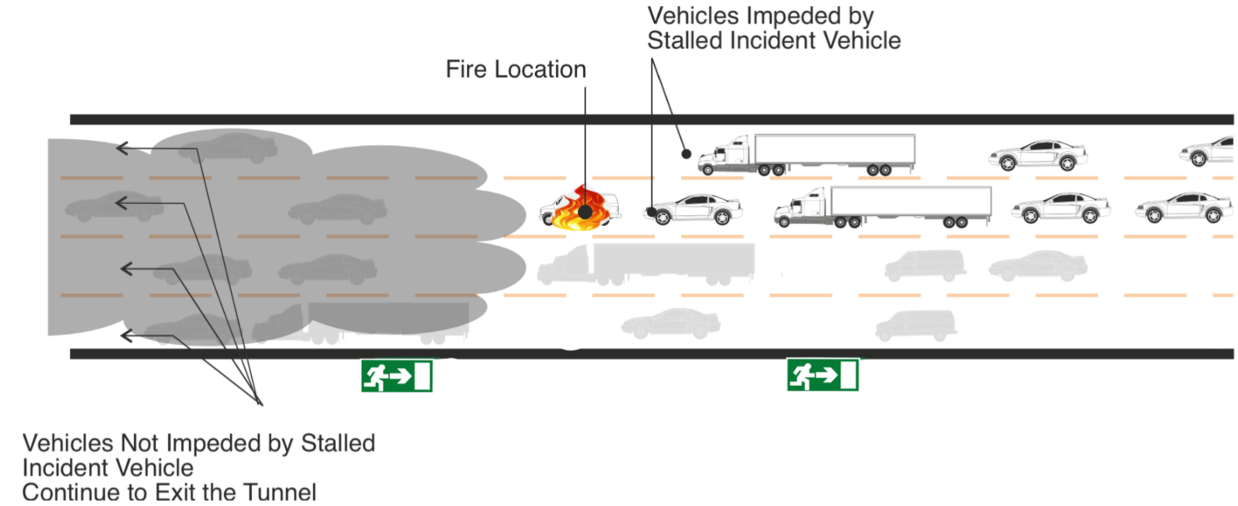

Figure 5 Free flowing traffic scenario

2. Buildup of lane of standing vehicles and rear-end crash resulting in a fire

In this scenario, traffic is moving at or near the speed limit in all lanes expect a lane with a buildup of standing vehicles due to an incident or congestion. A secondary incident then occurs at the rear of the lane of standing vehicles resulting in a fire. In case of a large fire, vehicles and motorists are exposed to smoke downstream of fire, even before incident is detected and safety systems can react.

This is considered a critical case because motorists being trapped downstream of the fire are exposed to smoke.

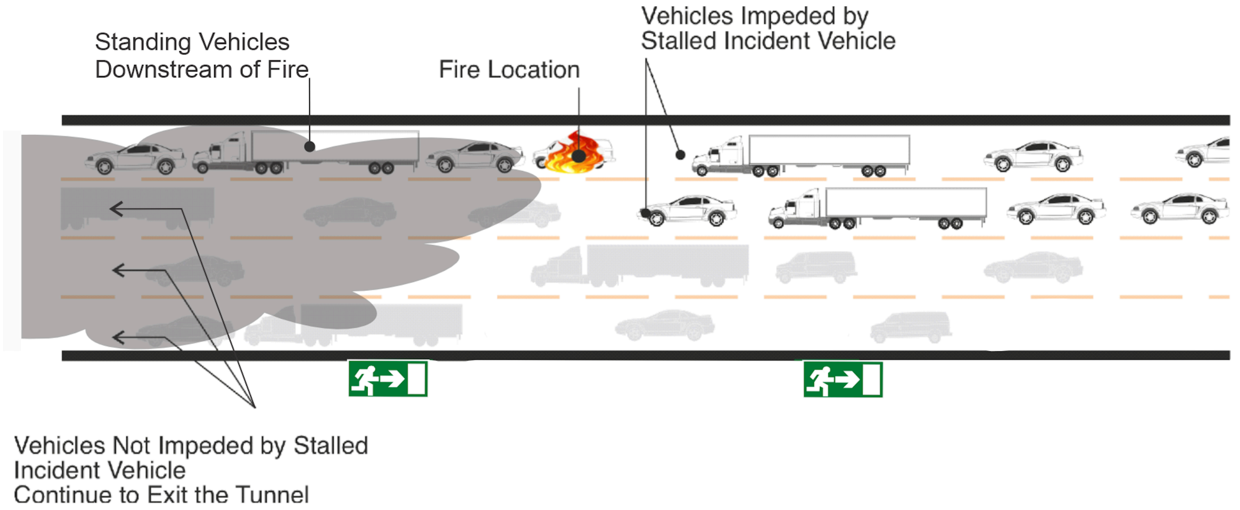

Figure 6 Scenario with vehicles blocked downstream of fire

3. Congestion / stop-and-go

Traffic is slowly moving, congested traffic resulting in a high density of vehicles in the tunnel. Fires from technical defects can occur, which usually develop slowly. Low-speed rear-end collisions are typically the only type of crash. No serious crashes / large fires resulting from crashes to be expected. Fires from technical defects may occur, and develop into large fires, although with a low probability.

Mostly no casualties, no serious damage to be expected.

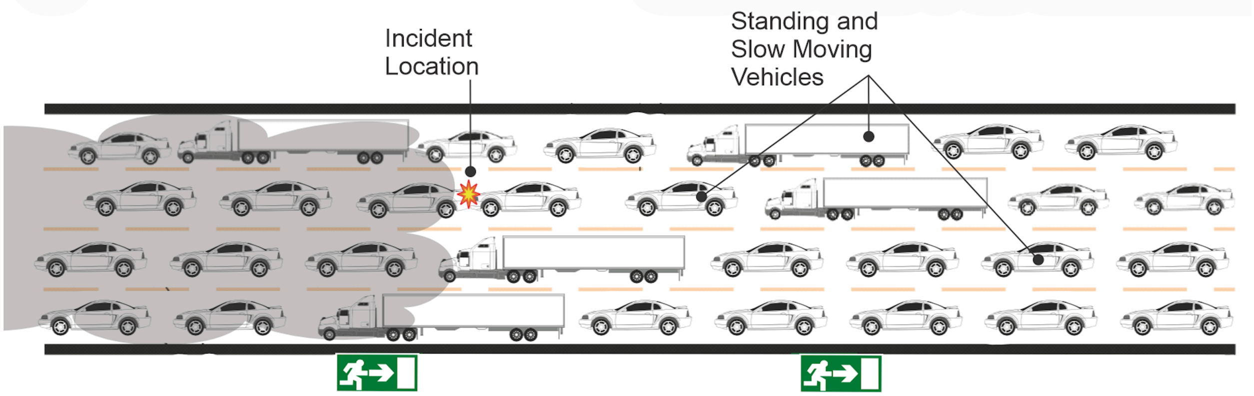

Figure 7 **Congested traffic scenario**

Fire Modeling

For modeling of design fires, the following fires are to be considered according to the BASt methodology (Lit. 15) for the ASET/RSET analysis:

- Car fire: 5 MW unsuppressed
- Truck/ bus fire: 30 MW unsuppressed
- Large Heavy Goods Vehicle (HGV) fire: 100 MW unsuppressed

The QRA methodology distinguishes between fires with immediate and with delayed development. Fires with immediate growth are considered to result from collisions, following an ultra-fast fire growth curve.

The delayed fire growth follows the growth curve up to a HRR of 5 MW and stays at that HRR until 5 minutes after which it continues along the ultra-fast fire growth curve. A delayed fire growth scenario is considered to result from technical defects, representing the majority of fire incidents.

It is assumed that the FFFS is able to limit the HRR of all fires to under 20 MW according to test data (Lit. 25, 26). The FFFS can also substantially reduce the smoke concentration, and reduces fire buoyancy. On the other side, the FFFS disrupts any smoke stratification in the application zone, which is detrimental to escape conditions.

Additionally, the following stress test scenarios have been evaluated for the fire durability assessment:

- Extra-large (overventilated) HGV fire: 200 MW unsuppressed, ultra-fast growth
- FLC fire: 300 MW fire unsuppressed, fast linear growth of 20 MW/Min.

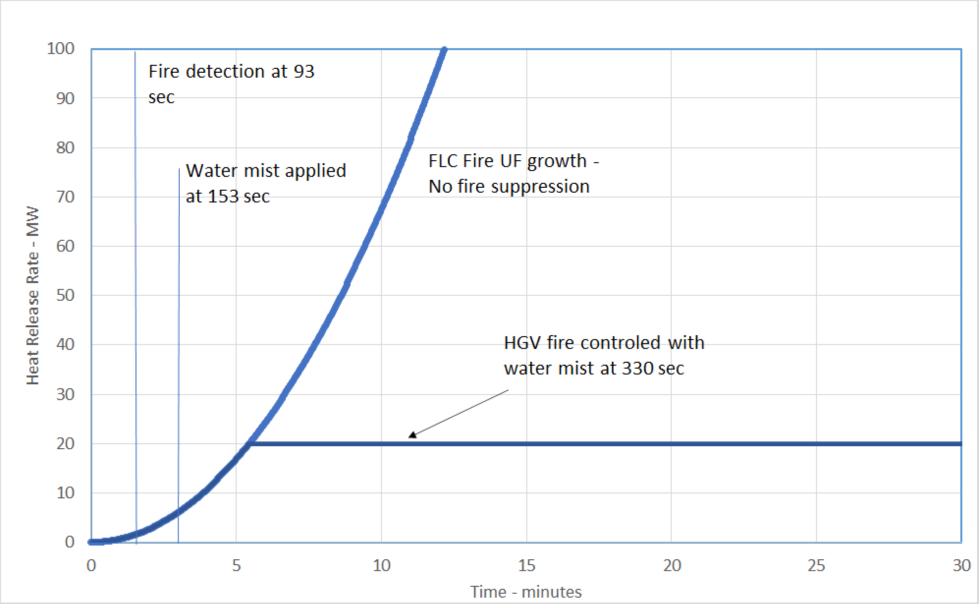

Figure 8 **Fire growth curve of large HGV fire**

Egress

A simplified egress model as developed for the BASt methodology (Lit. 14, 15) is applied:

- No evacuation prior to alarming and PA/VA initiation *(this is a pessimistic assumption)*
- People who evacuate after PA/VA initiation and reach an emergency exit before being overtaken by smoke (visibility limit of 16.4 ft / 5 meters) survive. Walking speed is 236 fpm/ 1.2 m/s *(this is an optimistic assumption).*
- People who cannot reach an emergency exit before being overtaken by smoke (visibility limit of 16.4 ft / 5 meters) are assumed to perish *(this is a pessimistic assumption)*.

Modeling of smoke spread and egress

For a particular US highway lid project, 556 different fire scenarios have been modeled with 1D simulations using the simulation software EQUA IDA Tunnel. Results were displayed on graphs, where smoke spread, and egress were compared. The air speed in cold air upstream of the fire is also displayed for comparison. It can be assumed that smoke stratification is likely for air speed below approx. 400 fpm / 2 m/s (Lit. 30), which may be expected as soon as the traffic slows down or has left the tunnel.

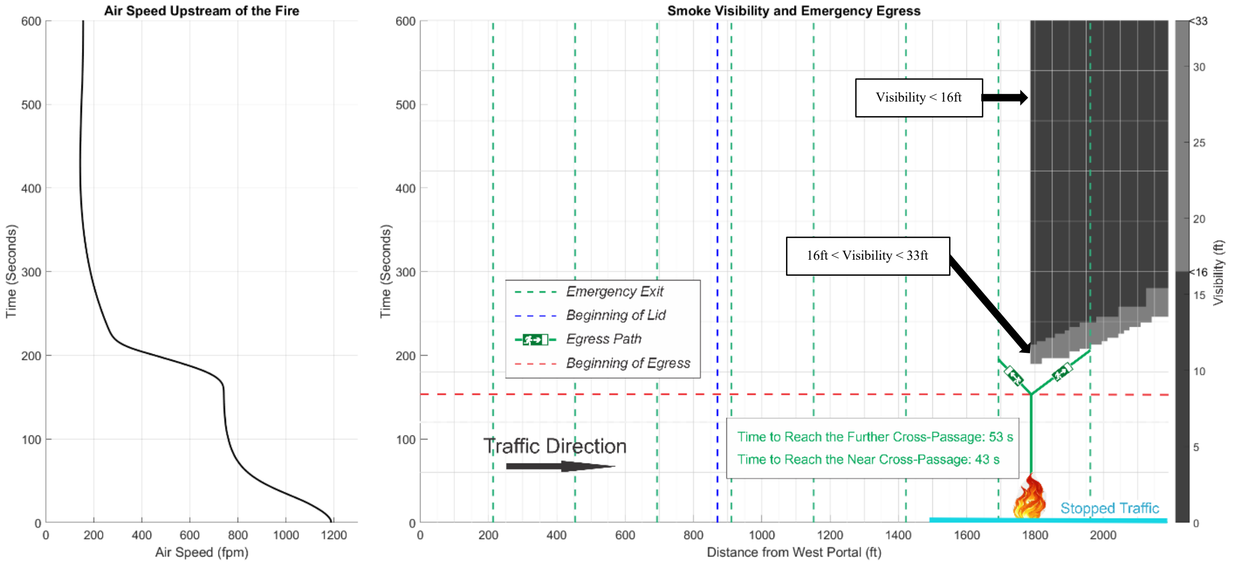

Figure 9 Graph of air speed (left) and smoke spread and egress (right) for one scenario

At four scenarios with vehicles and motorists blocked downstream of a fire according to Figure 6, motorists would be exposed to untenable conditions. However, since the flow velocity drops below 400 fpm, in practice conditions might be still tenable under a smoke layer.

The main benefit of a mechanical ventilation system would be to prevent flow reversal. However, scenarios with flow reversal due to natural forces such as wind or fire buoyancy against traffic direction, have been evaluated to not be critical when emergency exits in short distances are available. Rather, fast detection and alarming by the PA/VA system are essential to initiate self evacuation.

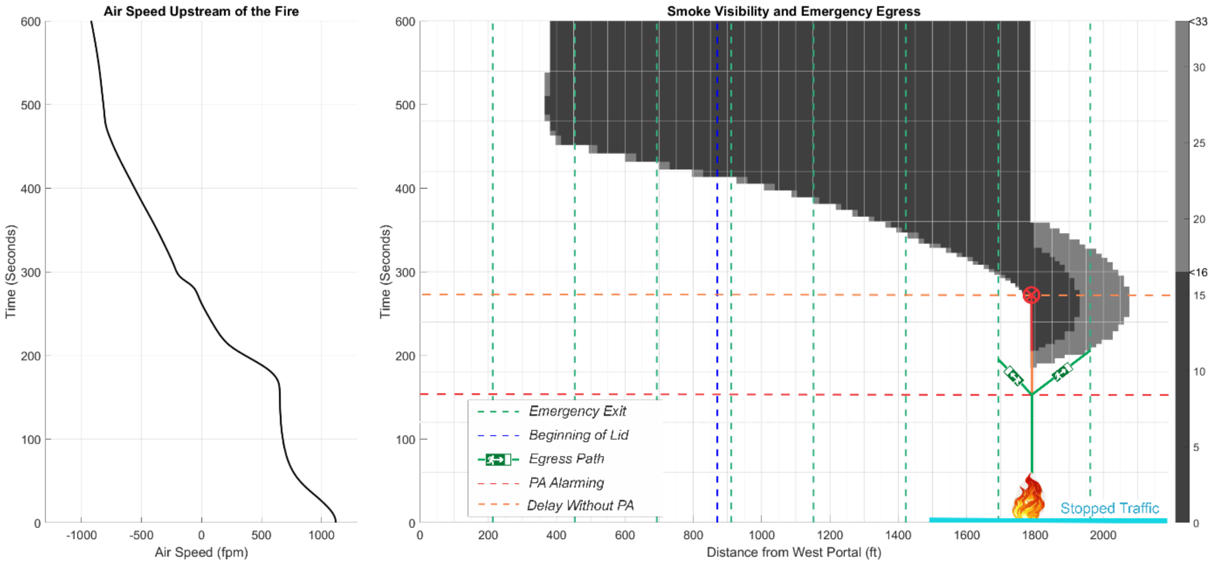

Figure 10 Scenario with flow reversal

In the 1D model, the effects of different safety systems, namely faster incident detection (by ADS) and alarming (by PA/VA), emergency exit distances, mechanical ventilation, and FFFS, can be directly simulated and displayed.

Fire Durability Assessment

Multiple fire durability simulations were conducted to evaluate the potential effects of a fire on the surrounding tunnel structures. These simulations focus on calculating the maximum air temperatures at the ceiling and on supporting structures, such as beams and walls. As a conservative assumption, the simulations were conducted with a 3D tool (FDS) with no airflow induced by traffic or wind which could provide a cooling effect.

The benefits of the water mist FFFS are evident when comparing the maximum temperature of gases on the tunnel ceiling. In the simulation without water mist, the maximum ceiling gas temperature above the fire was 2,525°F / 1,385°C, while in the simulation with water mist, it was only 530°F / 277°C, which is below the limit of 716°F / 380°C as determined by NFPA 502 (Lit. 2). In practice, most tunnels have no FFFS, and rely on the Fire Department to control and extinguish fires.

Fire Risk

According to US NHTSA and NFPA data (Lit. 16, 17), it is assumed that 0.3% of accidents result in a fire, and 3 fires per Billion veh-km, are expected from technical defects. That refers to significant fires with at least 5 MW HRR. Smaller vehicle fires may occur more often but are not risk relevant (Lit. 11). As defined by the BASt model (Lit. 14, 15), an event tree was developed with the following assumptions on probabilities for a specific US highway lid:

1. Fire locations: FL1 = 25%; FL2 = 17%; FL3 = 25%; FL4 = 17%; FL5 = 17%

2. Wind Conditions: East to West = 20%; No Wind = 70%; West to East = 10%

3. Traffic Conditions: flowing 80%; congested or vehicles blocked downstream 20%

4. Fire size:
- 5 MW fires: 85%, resulting in 0.93 fires per year, or a 5 MW fire every year
- 30 MW fires: 14.1%, resulting in 0.15 fires per year, or a 30 MW fire every 6.5 years
- 100 MW fires: 0.9%, resulting in 0.01 fires per year, or a 100 MW fire every 102.5 years

5. Fire growth
19.2% immediate growth / 80.8% delayed fire growth.

6. Fire suppression (and ventilation)
FFFS reliability 95%, Ventilation system reliability 95% (in variants with ventilation), System reliabilities are based on an assumption of a failure on demand rate of 5%, which includes different possible failure causes such as power outage, failure of electrical or mechanical components, detection failure. That is a conservative assumptions; in practice, for instance for FFFS, a reliability of 99% is contractually required, to be demonstrated by a RAMS analysis.

Figure 11 Fire risk event tree

By multiplying the probabilities of each factor along a branch with the initial fire rate, the frequency of each specific scenario is determined. For most scenarios, zero fatalities can be assumed based on simple analysis. Some critical scenarios are simulated in the 1D model as explained above. The frequency of each scenario is multiplied by the expected number of fatalities, providing the level of risk for that scenario. Finally, the risks across all scenarios are summed to calculate the collective risk.

Based on the data and the described assumptions, the calculated collective risk is 0.0039 fatalities per year due to fires, which corresponds to a fire-related fatality mean frequency approximately every 255 years for a specific US highway lid. That is longer than the design lifetime of the lid, which is 100 years.

Total Risk

The total risk was calculated to be approx. 0.125 fatalities per year, which corresponds to a fatality approximately every 8 years. The results are displayed in an F-N curve. The x-axis represents the number of fatalities, while the y-axis shows the frequency of having N or more fatalities each year for each data point. For comparison, the acceptance curve from the PIARC Quantitative Risk Assessment Model for Dangerous Goods Transport through Road Tunnels (Lit. 4) is displayed.

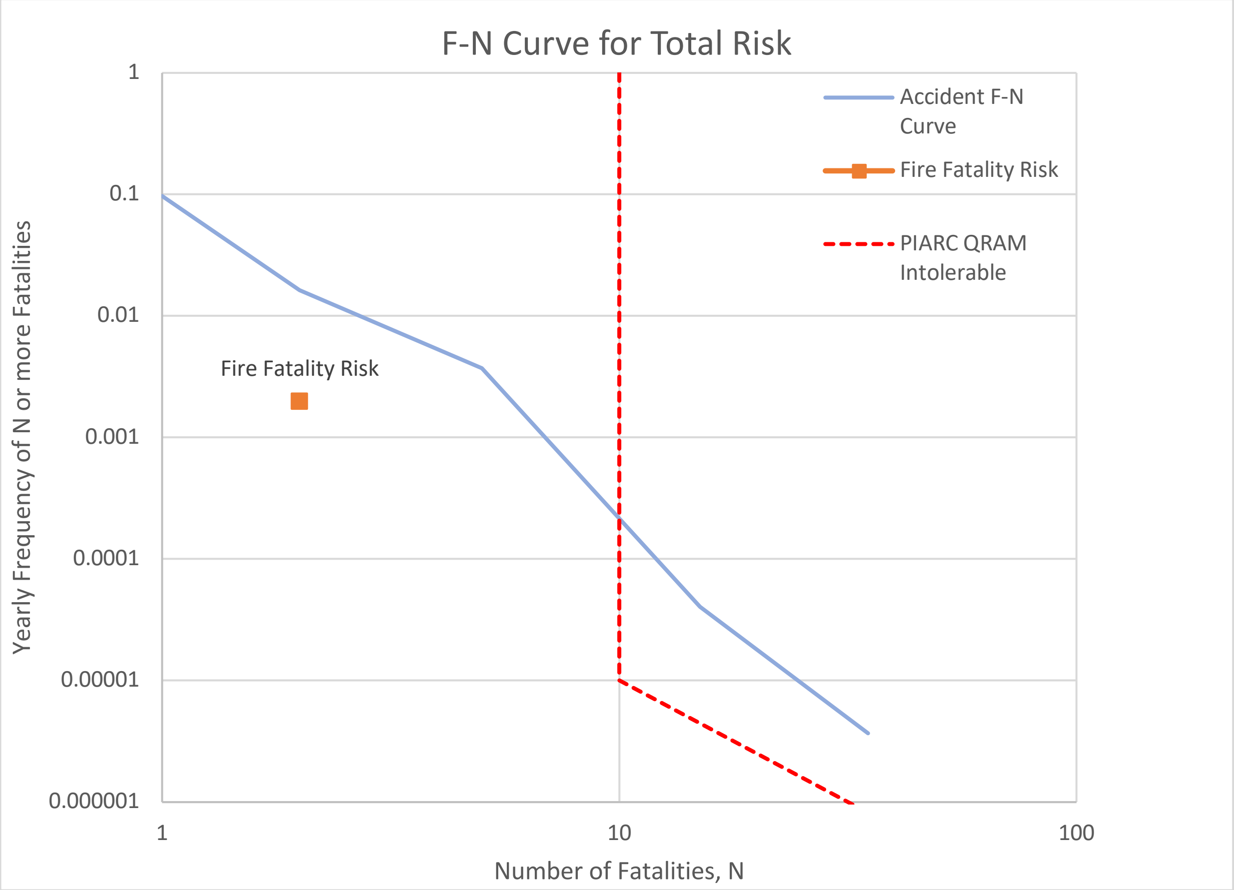

Figure 12 F-N curve for fatalities from accidents and fires – total risk

It can be seen that for this specific US highway lid the accident risk would partially exceed the tolerable threshold according to the PIARC QRAM methodology (Lit. 4), while the fire risk is tolerable. The ASET/RSET analysis shows that motorists have a good chance to evacuate in practically all evaluated scenarios. Critical cases are where vehicles are blocked downstream of a fire. In such cases, a mechanical ventilation without flow control would even make conditions worse.

CONCLUSIONS

With a systematic safety concept approach, improved tunnel safety and cost savings are possible by focusing on measures with best effectiveness, in particular prevention. Safety measures with little or even negative benefit may be omitted. An important aspect of a safety assessment is to consider unwanted side effects and evaluate ‘what can go wrong’, considering practical experience.

An example is tunnel ventilation. Mechanical ventilation in unidirectional tunnels is typically used to prevent smoke from spreading against traffic flow, but inappropriate operation without flow control could also accelerate smoke spread and cause destratification, making conditions worse for motorists downstream of the fire. For facilitating egress even for situations when motorists are trapped in the smoke downstream of a fire, emergency exits on short distances are more effective. Another example is a high-pressure water mist FFFS, instead of structural fire protection, when large fires and delayed Fire Department access might otherwise lead to unacceptable damage.

ASET/RSET analysis with simulations of smoke spread and egress are a useful tool to assess the fire risk, however the approach is different than in buildings. Smoke spread in tunnels depends on many different factors, especially the longitudinal flow induced by moving traffic in the initial fire phase, and meteorological forces. Therefore, many simulations have to be conducted for different fire scenarios under different boundary and initial conditions.

With a Quantitative Risk Analysis, the risks can be brought in the right perspective. As on open roads, accident prevention measures are most effective. The fire risk is usually very low in short tunnels, and any Fire Life Safety measures may be questioned from the perspective of useful allocation of funds.

All safety systems must be suitable for tunnel conditions, diligently tested, and regularly inspected, tested and maintained during operation, to ensure reliable functionality. There is proven European tunnel equipment, which must be adapted to comply with US specific requirements such as UL or FM listing, and Buy America (BABA).

It is proposed to develop the applied QRA methodology into a US standard approach for the safety assessment of new tunnel projects, as well as refurbishments of existing tunnels.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: Safety Concept and QRA lead: P. Pospisil, Simulations: C. Santangelo, Event tree development: M. Mora, QC: B. Hagenah. All authors reviewed the results and approved the final version of the manuscript.

DECLARATION OF CONFLICTING INTERESTS

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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REFERENCES

1. TRB NCHRP Project 20-68A Best Practices For Roadway Tunnel Design, Construction, Maintenance, Inspection, And Operations, 2011

2. NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, 2023/2026

3. NFPA 551, Guide for the Evaluation of Fire Risk Assessments, 2022

4. PIARC, Dangerous Goods Quantitative Risk Assessment Model (DG-QRAM), 2001

5. PIARC 2008R15, Urban Road Tunnels, Recommendations to Managers and Operating Bodies for Design, Management, Operation and Maintenance

6. PIARC 2011R02, Road Tunnels: Operational Strategies for Emergency Ventilation

7. PIARC 2012R30EN, Social Acceptance of Risks and their Perception

8. PIARC 2012R23, Current Practice for Risk Evaluation for Road Tunnels

9. PIARC 2013R12EN, Risks associated with Natural Disasters, Climate Change, Man-made Disasters and Security Threats

10. PIARC 2016R35EN, Experience with significant incidents in road tunnels

11. PIARC 2017R01, Design Fire Characteristics for Road Tunnels

12. PIARC 2019R03, Prevention and Mitigation of Tunnel-related Collisions

13. PIARC 2021LR01, Improving Road Tunnel Resilience, considering Safety and Availability

14. BASt B66, Assessing the Safety of Road Tunnels – Final Report & Appendices, 2007

15. BASt B183, Assessing the Safety of Road Tunnels – Review of Assumptions and Parameters for Performing Risk Analyses, 2022

16. NHTSA, Motor Vehicle Fires in Traffic Crashes and the Effects of the Fuel System Integrity Standard, DOT HS 807 675, 1990

17. McGree T., Vehicle Fires, NFPA, 2024

18. Beard A., Carvel R. (editors), The handbook of tunnel fire safety, 2nd ed. 2011

19. Bettelini M., Rigert S., Ventilation and Escape Facilities for Short Cut-and-Cover Urban Tunnels, 7th International Conference 'Tunnel Safety and Ventilation' Graz, 2014

20. Rödiger Y., Escape Route Lighting in Road and Rail Tunnels, Swiss Tunnel Congress, 2016

21. Hoyer K. et al, Influence of Acoustic Tunnel Monitoring AKUT on Tunnel Safety, 12th International Conference ‘Tunnel Safety and Ventilation’ Graz, 2024

22. Riess I., On smoke stratification in a 1-D tunnel ventilation model, 11th International Conference 'Tunnel Safety and Ventilation' Graz, 2022

23. Riess I., Fixed fire Fighting Systems and Tunnel Ventilation, 2021

24. Riess I., Bettelini M., The prediction of smoke propagation due to tunnel fires, ITC Conference Tunnel Fires and Escape from Tunnels, Lyon, 1999

25. Lakkonen M., Sprakel D., Feltmann A., Comparison of deluge and water mist systems from a performance and practical point of view, 7th International Conference ‘Tunnel Safety and Ventilation’ Graz, 2014

26. Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems using the example of water based Fixed Fire Fighting Systems; Scientific Final Report of the SOLIT² Research Project, 2012

27. Oppenheim I., Oron Gilad T., Addressing the Information Needs of Road Users in Extreme Emergency Events - Utilizing New Technologies, XVI World Winter Service and Road Resilience Congress, 2022

28. Pospisil P., Hagenah B., Johnson D., Flow measurement for tunnel ventilation, BHR 20th ISAVT, Copenhagen, 2024

29. Pospisil P., Woodward D., Haydn S., Flow Control in Tunnels, North American Tunneling Conference, 2022, Philadelphia

30. Pospisil P., Road Tunnel Ventilation, Compendium and Practical Guidelines, 2nd ed. 2020, ISBN 978-3-9524178-4-3

31. Pospisil P., Tunnel Ventilation – The key to increase safety and save time and costs, 14th International Conference Underground Construction, ITA/AITES, 2019, Prague

32. Pospisil P., Reducing Costs and Improving Safety of Road Tunnels, Journal 'Tunnel', 3/2011

33. Okrent, D., Comment on Societal Risk, 'Science', Vol. 208, April 1980

34. FHWA National Tunnel Inventory *https://www.fhwa.dot.gov/bridge/inspection/tunnel/inventory.cfm*