Tools for safety management – Effectiveness of risk mitigation measures

Bernhard KOHL
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Background

Traditional approach to tunnel safety – prescriptive approach

- Framework of guidelines and regulations for design, construction and operation of road tunnels
- **Focus on technical design specifications** to establish a certain level of standardization and guarantee an adequate performance of technical systems
  - The resulting **safety level might differ** from tunnel to tunnel
  - Does not take into account **effectiveness of safety measures** in a particular tunnel
  - Does not address the **residual risk**
Background

Modern safety standards take into account the evaluation of effectiveness of safety measures

- **EC Directive 2004/54/EC**
  - Introduces risk assessment as practical tool for the evaluation of tunnel safety
  - Includes a list of safety measures, thus defining a minimum safety level
  - Introduces the principle of equivalence: alternative measures allowed if they provide the same or higher safety level
Tools for risk-based decision making

Risk assessment process

Start

Definition of the system

Hazard identification

Probability analysis
Consequence analysis

Risk estimation

Risk analysis

Risk criteria

Risk evaluation

Risk evaluation (additional)

Risk reduction

(additional) safety measures

Acceptable risk?

No

Stop

Yes

Stop
Tools for risk-based decision making

Principle of risk evaluation

**RELATIVE APPROACH**

- The assessed tunnel is **compared to a “reference tunnel”**
- This “reference tunnel” **defines the acceptable risk level** (because it meets all prescriptive requirements, represents acceptable conditions etc.)
  - In Europe: tunnel of same geometry and traffic fulfilling EC-Directive requirements
- **Additional risk** of the assessed tunnel to be **compensated** by alternative risk mitigation measures
Tools for risk-based decision making
Typical application of quantitative risk assessment

To support decision making
- For design decisions in planning phase (tunnel structure & equipment)
- For decisions on additional risk mitigation measures (in case of deviation from prescriptive requirements, to compensate specific characteristics etc.)
- To decide on operational strategies for emergencies (operation of ventilation, traffic management etc.)
- To decide on safety requirements for upgrading of existing tunnels

To demonstrate a sufficient level of safety
- In case of deviation from prescriptive requirements
- Demonstrating compensation of specific characteristics by alternative measures
- In construction phase of upgrading of existing tunnels

To select the best suitable combination of risk mitigation measures
- By combining results of risk assessment with cost-effectiveness analysis for safety measures
Safety measures
Hierarchy of tunnel safety measures

PREVENTION  MITIGATION  SELF-RESCUE  EMERGENCY RESPONSE

Source: BASi
Safety measures
Holistic approach

- A safe tunnel environment requires a optimized and balanced interaction of all aspects influencing safety.

- Additional safety measures need to be integrated into this complex system – taking interaction effects into account.
Safety measures
Practical example: Lay-Bye

(lied) positive effects:
- Safe place for vehicles not able to continue
- Drivers can leave their car without being exposed to traffic
- Broken down vehicle does not impede traffic
- Risk of subsequent incident (collision) reduced

(unintended) negative effects:
- End wall could aggravate consequences of collision, if a vehicle crashes into it
- Hence additional mitigation measures required (e.g. crash cushion)

Necessity of proper assessment of all positive and negative effects of measure on safety within a specific tunnel, together with other aspects like operation or cost
Safety measures
Assessment process for tunnel safety measures

1. **Specific safety problems** of an individual tunnel must be defined
2. **Suitable measures** need to be **found** which are able to mitigate or compensate the problems identified
3. For the tunnel in question it is necessary to **analyze how the measure acts on the risk** caused by the specific problems, including interaction effects
   - This step must be performed **qualitatively**, but quantification is highly beneficial
   - The **quantification** of the effects on a detailed level can be based on data (measurements, statistics), on theoretical considerations, on practical experience or on expert judgement
   - For more complex problems – like the response to a fire incident – the use of complex simulation tools like CFD smoke propagation simulation or egress simulation may be indispensable
4. After having assessed the effectiveness of a risk mitigation measure on a detailed level, **the effect of the measure on the overall safety level** of the tunnel is studied (e.g. by application of **professional risk assessment tools**)


## Safety measures

### Examples for effectiveness tunnel safety measures

<table>
<thead>
<tr>
<th>MEASURE</th>
<th>DESCRIPTION OF MEASURE</th>
<th>INCIDENT TYPE</th>
<th>EFFECT DESCRIPTION</th>
<th>PREVENTION</th>
<th>MITIGATION</th>
<th>SELF</th>
<th>RESCUE</th>
<th>EVIREDG.</th>
<th>RESP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enforced speed control</td>
<td>Measurement of average speed on a defined road section; consequent punishment of violation</td>
<td>c</td>
<td>Prevention of speeding / reduction of average speed / speed difference between vehicles</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>Rumble strips</td>
<td>Edge of driving lane marked by “rumble” strips</td>
<td>c</td>
<td>Rises awareness of driver if vehicle is getting off driving lane</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Traffic guidance barriers</td>
<td>Traffic guidance barriers (e.g. jersey profile) are fixed on tunnel wall or located at critical points</td>
<td>c</td>
<td>Softens the impact of a collision with tunnel wall and guiding the vehicle back to driving lane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
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<tr>
<td>Immediate lane closure</td>
<td>Affected lane is closed by traffic management system (red cross) – requires reliable incident detection</td>
<td>c</td>
<td>Protects stopped vehicles on driving lane (breakdown) prevents uncontrolled evasive maneuvers and secondary collisions</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>Thermo-scanner</td>
<td>System which is able to identify lorries with a critical temperature pattern, when passing by (infrared cameras combined with specific evaluation software)</td>
<td>f</td>
<td>System detects and separates lorries which might be the cause of a fire due to any kind of overheating; for tunnels with high fire rates</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Fast intervention unit</td>
<td>Mobile unit of specifically educated staff with professional fire fighting equipment</td>
<td>f</td>
<td>Fast intervention allows fire fighting at an early stage of fire development; supports self-rescue on site</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Illustration of methodical approach
Example: Austrian Tunnel Risk Model TuRisMo

Frequency analysis – Relevant parameters
- Incident types
  - Traffic volume
- Incident rates
  - Traffic composition
- Ignition
  - Vehicle categories

Consequence analysis – Relevant parameters
- Tunnel system, technical systems, evacuation, vehicle categories

Event tree
- Initial event
- Incident scenarios

Results

Expected risk value
(fatalities/year)
- R
  - Dangerous goods
  - Fires
  - Mechanical accidents

Risk
- fires
- mechanical accidents
Illustration of methodical approach
Example: Austrian Tunnel Risk Model TuRisMo

**Event tree**

- **Initial event**
- **Incident scenarios**

**FREQUENCY ANALYSIS**

**Consequence analysis – Relevant parameters**
- Tunnel system technical systems

**Results**

**Basic incident scenarios**
- Breakdown of a vehicle causing a fire / a collision
- Single-vehicle collision
- Collision between vehicles driving in the same direction
- Head-on collision
- All collision types with fire as follow-up event
Illustration of method approach

Example: Austrian Tunnel Risk Model TuRisMo

CONSEQUENCE ANALYSIS

Fire development & smoke propagation simulation

- Time of closure
- Smoke Extraction
- Gradient
- Portal loss
- Jet Fans
- Portal pressure
- Vehicles entering the tunnel
- Number of driving vehicles
- Number of stopped vehicles
- Buoyancy
- Vehicles leaving the tunnel

Combined transient 1D/3D simulations

Egress model & exposure projection

simulating evacuation process & influence of smoke on people
Case study
Upgrading of existing tunnel - scope

- Tunnel 1.5 km long,
- Bidirectional traffic (13,000 veh/day; 5% HGV traffic)
- Longitudinal ventilation
- No emergency exits

- Tunnel does not fulfil minimum safety requirements
  emergency exits not feasible due to extreme topographical conditions

- Compensation by alternative measures required

Alternative measures investigated:

a) semi-transversal ventilation with smoke extraction
b) Alternative smoke management (zero-flow ventilation)
c) Implementation of FFFS
d) 24/7 fire brigade located close to tunnel portal
Case study
Upgrading of existing tunnel - results

Decision on alternative measures based on:
- Results of QRA
- Results of cost-effectiveness analysis of measures
- Qualitative Assessment of additional aspects (like compatibility with fire fighting activities)

Decision in favor of implementation of FFFS
Case study
Upgrading of existing tunnel - illustration

Measure: fire brigade located close to tunnel portal
Smoke propagation in time steps of 1 minute – with / without intervention of fire brigade

180 seconds
Fire brigade starts fire fighting within 3-5 minutes
Case study
Commissioning of new tunnel – Waterview Tunnel (NZL)

4,5 km long motorway project, closing a relevant gap in Auckland’s trunk road network, linking SH20 to SH16
Case study
Commissioning of new tunnel – Waterview Tunnel (NZL)

Waterview Connection Project

4,5 km long motorway project, closing a relevant gap in Auckland’s trunk road network, linking SH20 to SH16

Includes a 2,5 km long twin tube three lane motorway tunnel, high traffic load, high likelihood of congestion

High safety level: traffic management system, various incident detection systems, longitudinal ventilation, FFFS, emergency exit distance 150 m
Case study
Commissioning of new tunnel – Waterview Tunnel (NZL) - scope

Background of risk study:
- In earlier risk study the resulting risk level was classified as being “ALARP”, based on a frequency of congestion less than 1%
- a higher level of congestion should be avoided by traffic management measures
- however results of traffic studies indicated that a congestion frequency above the critical benchmark of 1% could occur

Objectives of risk study:
- Analyze the influence of a level of congestion > 1% on the personal risk of tunnel users (applying the Austrian tunnel Risk Model TuRisMo)
- as reference case, the risk level of the tunnel assuming a congestion level of 1% shall be taken – representing the acceptable risk level
- evaluate the differences in risk comparing the situation with increasing level of congestion (up to 8%) to the reference case
- identify and assess additional risk mitigation measures – as far as required
Case study
Commissioning of new tunnel – Waterview Tunnel (NZL) - approach

Effects of different types of congestion on risk:

- **Congestion as a consequence of a preceding incident**
  a queue is building up, which may induce secondary collisions and fires;
  vehicles in front of incident can leave tunnel

- **Congestion due to traffic overload**
  standing / slow moving queue caused by traffic bottlenecks / slow speed – collisions without casualties; sudden drop of driving speed at beginning of congestion may induce secondary collisions
  Vehicles in front of incident cannot leave tunnel
Case study
Commissioning of new tunnel – Waterview Tunnel (NZL) - results

- **Significant increase in collision risk** from “no congestion” to “regular congestion 1% of the time”
  - due to secondary incidents in the initial phase of a congestion, caused by the sudden drop in velocity
- **Increasing level of congestion reduces collision risk**, no casualties due to collisions in slowly moving traffic queue
- **Fire risk is very low** – due to high fire safety level of the tunnel
  - differences in fire risk due to the influence of congestion are low as well
- **Fire risk increases slightly** with longer-lasting congested scenarios - influence negligible in comparison to collision risk

- **No further risk mitigation measures required** to reach a safety level equal to or below the reference risk profile.
- **Collision risk** dominates the overall risk
Conclusions

- **Assessment of effectiveness** of risk mitigation measures requires systematic analysis of the functionality of a measure with respect to the specific safety characteristics of an individual tunnel.

- Although guidelines seem to provide a rigid framework, experience shows that there are a lot of opportunities to apply a concept for risk-based decision making.

- Risk-based approach in particular relevant for:
  - **Tunnels with specific characteristics** — to compensate risk-increasing factors.
  - **Upgrading of existing tunnels** — if requirements of modern guidelines can only be fulfilled at disproportionate cost.

- **Simple measures** can be very (cost)-effective.
Thank you for your attention!

contact: bernhard.kohl@ilf.com

For more information please visit
www.ilf.com / www.tunnelriskmodel.at