OPTIMIZATION OF ROAD TUNNEL REFURBISHMENT MEASURES BASED ON A COST-EFFECTIVENESS ANALYSIS

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ABSTRACT

The ventilation system of an existing Swiss twin tube road tunnel no longer meets the requirements of the current ASTRA (Bundesamt für Strassen, Federal Road Authority) ventilation guideline 13001 and several items of equipment have reached the end of their life cycle and need to be replaced. Adjusting the present ventilation system to the guideline requirements would be cost-intensive.

A quantitative risk analysis using the BAST and the OECD/PIARC CH models has been performed to determine an alternative system that is compliant with the guideline’s safety level (given by the ASTRA system) while having a good cost-effectiveness ratio.

Several measures were examined, but apart from the measure based on the guideline, only one of them met the required safety level. However, this measure had to be excluded due to various negative aspects, which cannot be quantitatively measured in the risk analysis. Based on the examination, the authors recommend a measure that can be implemented as an intermediate stage and later be adapted to the normative requirements.

Keywords: ventilation design, quantified risk analysis, cost-effectiveness analysis

1. INTRODUCTION

A Swiss twin tube road tunnel (length > 3km) with unidirectional traffic (low traffic congestion) and a transverse ventilation system (air injection and extraction distributed over the entire tunnel length) no longer meets the requirements of the current ASTRA (Bundesamt für Strassen, Federal Road Authority) ventilation guideline 13001 [1]. Moreover, several items of equipment have reached the end of their life cycles and need to be replaced. The tunnel name is not mentioned as ASTRA has not yet approved the results of the study.

The above mentioned ASTRA guideline specifies for this tunnel that a local smoke extraction system is required with remotely controlled mechanical dampers and control of the longitudinal ventilation with jet fans. Refurbishing the present ventilation system to the guideline requirements would be cost-intensive. Therefore, a quantitative risk analysis has been performed to determine whether the safety level according to the guideline can be achieved with lower-cost alternative ventilation systems. In addition, a structural measure has been evaluated which uses the present ventilation system but cuts the distances between emergency exits in half. The measure that meets the safety requirements set forth by the guideline, while offering a favorable cost-effectiveness ratio, will be implemented.

This paper aims to show the methods which have been used within the quantitative risk analysis and presents the results of the examination.
2. ASTRA GUIDELINE 13001 [1]

This guideline describes the system selection, sizing and equipment of tunnel ventilation systems for Swiss road tunnels. For a unidirectional tunnel with low traffic congestion, a simple portal-to-portal longitudinal ventilation system can be used in tunnels of up to 2000 m in length – possibly even of up to 3000 m in length, provided a) the daily traffic flow per lane is lower than 16’000, b) the daily truck flow per lane is less than 800, and c) the gradients in the tunnel are greater than +3.0% (uphill). Above a tunnel length of 3000 m, the emergency ventilation must have a local smoke extraction system with remotely controlled mechanical dampers. This is decisive for the tunnel in question.

3. QUANTIFIED RISK ASSESSMENT

3.1. Approach

In risk analyses for road tunnels, three types of scenarios are usually examined.

- scenarios with collisions (without fire)
- scenarios involving fire (without dangerous goods)
- scenarios involving dangerous goods

For this analysis, only fire scenarios and scenarios involving dangerous goods are relevant, since the examined measures cannot reduce the risk due to collision. This risk is therefore identical for all measures.

Within the scope of the system definition, practicable measures are identified and described in detail. As a boundary condition it is specified that the tunnel usage must not be changed after the implementation of the measure.

For each defined measure, a risk analysis is performed, using the German risk model from the BAST (Bundesanstalt für Strassenwesen) [2] for fire scenarios and the OECD/PIARC CH model [3] for dangerous goods scenarios. For each scenario, the frequency (events per year) and the consequence (fatalities) are determined and the risk, which is the product of the two, is calculated.

The aggregated risks for all damage scenarios (fire scenarios (BAST model) and dangerous scenarios (OECD/PIARC model CH)) determine the overall risk of the measure. This overall risk, also known as societal risk, can be expressed as an expected value (fatalities per year) or depicted in a frequency-consequence diagram (F-N diagram). This diagram illustrates the ratio of the frequency (per year and per 100 m of tunnel) and severity (number of fatalities) of all scenarios in each measure on a logarithmic scale, thereby cumulating the frequencies of the scenarios in each measure.
The evaluation of the societal risk of the defined measure is based on a comparison with the societal risk of a measure including all requirements according to the ASTRA guideline. In Switzerland there is an absolute risk limit available for dangerous goods. This limit is also included in the risk evaluation of each measure.

The risk limit for dangerous goods is illustrated by graphs in an F-N diagram (see chapter 3.4), which divides the diagram into three ranges (given by the Schweizerische Störfallverordnung StFV [4]): The acceptable range is the range in which risks are considered negligible; the transition range is the range in which risks should be reduced, if operationally, technically and economically reasonable; and the unacceptable range, where measures absolutely need to be taken to shift the risk at least to the transition range.

Within the scope of the cost-effectiveness analysis for all measures, the societal risks are monetized (marginal cost for preventing one fatal victim is set to 5 million CHF) and the appropriate expected investment, operating and maintenance costs per year are determined. The cost-effectiveness ratio is calculated as shown in the following formula, which considers the monetized risks and costs with regard to the actual state (distributed supply air and exhaust ventilation along the tunnel).

\[
\text{cost-effectiveness ratio} = \frac{\Delta C}{\Delta R_m}
\]

\(\Delta C = \text{cost difference; } \Delta R_m = \text{monetized risk difference}\)

The measure to be implemented meets the safety level according to the normative requirements and features an efficient cost-effectiveness ratio of less than 1.

3.1.1. BAST model [2]

Currently there is no official risk model for Swiss road tunnels to calculate fire scenarios. Thus, to enable a quantitative calculation of risks in road tunnels, in 2011 ASTRA launched a research project for the development of a respective model. Until the implementation of this model, ASTRA has determined that the BAST model should be applied.

The BAST risk model was developed for German road tunnels and features a standardized event tree for the frequency analysis of fire scenarios. In the event tree, the event location (portal area and tunnel inside), the traffic conditions (flowing traffic or congestion), the functioning of the fire detection / ventilation system and fire load (5 MW, 30 MW, 50 MW, 100 MW) are considered. The branches in the event tree result in 32 different paths (subsequent scenarios), which all characterize a possible scenario involving fire.

In the consequence analysis, the extent of the damage expressed as fatalities is calculated for the 32 damage scenarios. This requires the use of ventilation and evacuation simulations, which the user of the model needs to perform. Based on the various visibility ranges, tunnel areas are defined from which people can or cannot save themselves.

3.1.2. OECD/PIARC CH model [3]

The QRAM standard model by OECD/PIARC [5] allows for a quantitative determination of the risk to people due to the transportation of dangerous goods in tunnels and on open roads. For the OECD/PIARC CH model, the standard model was adjusted to Swiss conditions (for example dangerous goods ratio) and refined in various aspects based on experience and findings (e.g. the evacuation model). The parameters and respective mathematical calculation models are in line with each other in order to meet the StFV evaluation criteria. The risk analysis covers scenarios involving flammable and toxic liquids and gases (propane, acrolein, ammonia and CO₂). Unlike the standard model, the OECD/PIARC CH model does not
consider chlorine, since the respective release scenarios included in the standard model do not apply to Switzerland.

The model is mirrored in the software and is less methodically accessible to the user than the BAST model. The calculation of frequency and consequences of dangerous goods scenarios are based on event trees and probit functions. Probit functions are used to relate the level of injury (fatality) and exposure duration to a dangerous goods event of a given intensity.

3.2. Tunnel data and some key parameters

The tunnel with unidirectional traffic consists of two parallel tubes of >3000 m in length. The two tubes, each with two lanes, are interconnected at set intervals (maximum distance between interconnections approximately 360 m). Apart from the portal areas an exhaust duct is located above the lanes as well as a fresh air duct and a service duct below the lanes. The exhaust ducts are separated approximately at mid-tunnel. The tunnel is not subject to limitations regarding dangerous goods transportation. Due to maintenance work and functional tests, the tube is operated with bidirectional traffic for approximately 70 h per year.

Figure 2: Unidirectional tunnel

Further key parameters for the risk analysis are listed in the table below.

<table>
<thead>
<tr>
<th>TUNNEL, TRAFFIC and ACCIDENT DATA</th>
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<tbody>
<tr>
<td>Tunnel length</td>
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<tr>
<td>Tunnel cross section</td>
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<tr>
<td>Longitudinal gradient</td>
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<tr>
<td>Annual average daily traffic (AADT) per tube</td>
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<tr>
<td>Traffic congestion frequency</td>
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<tr>
<td>Accident rate (unidirectional traffic)</td>
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<td>Accident rate (bidirectional traffic)</td>
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<table>
<thead>
<tr>
<th>VENTILATION AND EVACUATION DATA</th>
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</thead>
<tbody>
<tr>
<td>Response time of fire detection system</td>
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<tr>
<td>Response time of the ventilation system</td>
</tr>
<tr>
<td>Visibility</td>
</tr>
<tr>
<td>Peoples' reaction time after fire detection</td>
</tr>
<tr>
<td>Escape speed of a person</td>
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</tbody>
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<tr>
<th>FIRE DATA</th>
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<tbody>
<tr>
<td>Fire load [6]</td>
</tr>
<tr>
<td>in 5 min with linear increase</td>
</tr>
<tr>
<td>in 10 min with linear increase</td>
</tr>
<tr>
<td>Yield soot (5 MW) [7]</td>
</tr>
<tr>
<td>Yield soot (30, 50, 100 MW) [7]</td>
</tr>
</tbody>
</table>

Table 1: Key parameters

Notes on some key parameters:

For visibility ranges below 10 m, a drastic reduction of the escape speed can be expected and disorientation will begin. Below a visibility range of 5 m, movement is severely impaired. For the purpose of the evacuation simulation, it is assumed that people can save themselves if the visibility range is greater than 5 m, and the escape speed is set to 1.1 m/s. [2]

The soot yield values used in the analysis were deduced from fire tests involving vehicles. [7]
3.3. System Definition

For the risk analysis, five measures were examined. A brief description of these measures follows.

3.3.1. V0 (actual state)

V0 describes the current state of the ventilation system. The ventilation system is divided into two parts (north and south) in terms of aerodynamics. The supply air is fed into the traffic space through a supply duct and subsidiary pipes mounted approximately every 4 m. Generally, exhaust air is drawn through slots in the ceiling (every 14.5 m). A total of three supply and two exhaust fans are mounted as well as a reversible fan which can be operated as a supply as well as an exhaust fan. Several items of equipment have reached the end of their life cycle and need to be replaced or refurbished (ventilation control system, fans etc.). These are taken into account in the cost-effectiveness analysis.

3.3.2. V1

V1 covers the distributed exhaust air of the current state (V0). In addition, jet fans are mounted near the portals (north and south) in the sections without the false ceiling. The jet fans allow for easy control of the longitudinal flow.

3.3.3. V2 (target state)

V2 meets the ASTRA 13001 requirements. It contains jet fans in the portal areas (north and south) and a local smoke extraction system with remotely controlled mechanical dampers. The dampers are mounted 100 m apart. The smoke or gas is withdrawn from the traffic space close to the location of the fire event through dampers opened over a 200 m length of the tunnel. This means, in case of an event, three dampers need to be opened.

3.3.4. V3

V3 is similar to V2 with the existing exhaust fans (V0) being adapted to the required operating point. V3 features a number of negative aspects compared to V2 (for example no 100% tube separation, temperature resistance of exhaust fans, etc.), which cannot be quantitatively considered in the risk analysis. While V3 reaches the safety level of V2, it is not completely compliant with the guideline.

3.3.5. V4

V4 contains the ventilation system of the current state (V0), however, the distances between emergency exits are cut in half with regard to the existing situation. This results in 12 additional interconnections in addition to the 11 already existing.
3.4. Results

The following figure illustrates the expected societal risk values for all measures for the twin tube road tunnel. For all measures, the risk resulting from dangerous goods scenarios (OECD/PIARC CH model, lower bar) and the risk resulting from fire scenarios (BAST model, upper bar) are depicted. The risk aversion factor is not considered in the results from the BAST model, for the OECD/PIARC CH model does not include this factor. The figure shows that the societal risk for V0 is, as expected, the highest. V1 almost reaches the safety level of V2 (V3). The risk for V4 is only slightly lower than for V0. In V4, the risk due to fire is reduced by about 30%, while the risk due to dangerous goods scenarios is only reduced by about 3% compared to V0. V1 and V2 show a considerably higher risk reduction compared to V4 with respect to V0. The bars illustrate that for all measures, the dangerous goods ratio has a significant impact on the social risk.

The figure below illustrates the societal risk ratios with respect to V0 and to V2.

The societal risk in V0 can be reduced to approximately 28% for V1, to approximately 18% for V2 (V3) and to approximately 92% for V4. This means the safety level for V2 is 5.7 times higher than for V0, 1.6 times higher than for V1 and 5.2 times higher than for V4.

The societal risk of all measures in the F-N diagram is depicted in the following figure.
The figure shows that V0 and V4 almost reach into the non-acceptable range defined by the StFV. It needs to be specified that the StFV applies to risk involving dangerous goods only. However, in the graph, fire risks are included as well. Generally, V2 (V3 equal V2) is the lowest graph in the diagram with the exception of low frequencies (right hand area in the diagram). This is due to the OECD/PIARC CH model that ends the calculations for the individual measures at different extent levels, thus causing overlaps. The risks are very low in this area and have negligible influence on the expected societal risk values. When considering the results from fire scenarios only, V2 (V3 equal V2) is always the lowest graph.

Even though the alternative measures (V1, V4) do not meet the required safety level of V2, a cost-effectiveness analysis with reference to V0 has subsequently been performed. The annual investment costs were determined by means of dynamic investment appraisal (annuity factor).

**Table 2: Cost-effectiveness ratio**

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<tbody>
<tr>
<td>V0 (actual state)</td>
<td>322'044</td>
<td>9.054E-04</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V1</td>
<td>352'532</td>
<td>2.489E-04</td>
<td>30'488</td>
<td>3'283</td>
<td>9.3</td>
</tr>
<tr>
<td>V2 (target state)</td>
<td>1'150'825</td>
<td>1.591E-04</td>
<td>828'781</td>
<td>3'732</td>
<td>222.1</td>
</tr>
<tr>
<td>V3</td>
<td>879'829</td>
<td>1.591E-04</td>
<td>557'785</td>
<td>3'732</td>
<td>149.5</td>
</tr>
<tr>
<td>V4</td>
<td>434'460</td>
<td>8.305E-04</td>
<td>112'416</td>
<td>375</td>
<td>300.2</td>
</tr>
</tbody>
</table>

The cost-effectiveness ratio shows that V1 offers the best ratio; however, the measure does not meet the required safety level of V2. The ratio in V3 is better than the ratio for V2.

All values are greater than 1, which means that, theoretically, no measure is cost-efficient. But meeting the required safety level takes precedence over cost-effectiveness (see Figure 1).

**4. DISCUSSION AND CONCLUSION**

The analysis reveals that V0 (actual state) offers the lowest and V2 (target state) generally the highest safety level. While V3 reaches the same safety level as V2, it contains non-quantifiable negative aspects. A sensitivity analysis (different moments of escape, traffic congestion frequencies, etc.), which is not the subject of this paper, came to the same conclusion. It needs to be specified, however, that parameter variations will result in a change in societal risks.

Furthermore, the results show that the acceptance level according to the StFV is met by all measures in question, even when taking into account fire scenarios. This leads to the conclusion that the ASTRA 13001 guideline requires a higher safety standard than the StFV.
This statement refers to the tunnel in question and the presumed parameter values only and shall not be understood as a general rule.

The OECD/PIARC CH model demonstrates that the risks from dangerous goods scenarios are crucial for the societal risk (fire and dangerous goods). This is due to the fact that the tunnel is predominantly operated with unidirectional traffic, and fire scenarios (the BAST model) only result in fatalities when there is traffic congestion (i.e. 50 h per year).

Halving the distance between the emergency exits compared to V0 does not lead to a significant change in societal risk. For fire scenarios (BAST model), this is mainly due to the fact that in the unidirectional traffic tunnels escape conditions with the chosen parameter values can be substantially improved only for the 50 MW and 100 MW fires. In the BAST model, these scenarios are not weighted heavily and therefore have little impact on the societal risk. The slight change with regard to dangerous goods can currently not be explained by the authors. Further clarifications by the developer of the model are required.

The cost-effectiveness analysis clearly illustrates that V2 is far from meeting the criteria on cost-effectiveness (about 220), meaning the low reduction in absolute risk compared to V0 comes at excessive costs. This holds true for V3 (about 150) as well. V1 offers the lowest ratio (about 9), V4 the highest (about 300), while both measures do not meet the required safety level.

The BAST method does not include certain parameters relevant for the calculation of the extent, which may have a significant impact on the results. Missing parameters include data on burnt material and soot yields as well as on the fire growth rate. The OECD/PIARC CH model can only be influenced by the user to a small degree, since the risk calculations for the scenarios are being performed within the system. Only fundamental presumptions such as traffic characteristic, ventilations system, etc. can be made by the user, for the program is calibrated to the acceptance levels of the StFV.

Based on these results, the authors recommend that, as an intermediate stage, V1 be implemented in the course of a tunnel renovation and later on be adapted to V2. The implementation of V3 does not appear to be advisable, since this variant does not meet various requirements set forth by the ASTRA 13001 guideline. Furthermore, V3 is not suitable as an intermediate stage since it generates disproportionate extra costs with respect to the adaptation to V2 as well as significant traffic obstruction during the construction period.

The decision which measure is to be implemented has not yet been taken by ASTRA.

5. REFERENCES

[1] „Lüftung der Strassentunnel“, ASTRA 13 001, Bundesamt für Strassen (ASTRA), 2008 V. 2.01