RISK ANALYSES OF THE SAFETY LEVEL OF GALLERIES

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ABSTRACT

Today the German tunnel directives (RABT) are not only applied to tunnels but also to open overhead noise barriers, such as galleries and partly covered troughs. Therefore, galleries have to be equipped with the same operational and safety equipment as tunnels.

Existing project-specific studies indicate that even if single predefined operational equipment elements are abandoned, a safety level can be reached that meets the requirements of a comparable tunnel with full operational and safety equipment.

Thus, a research project was initiated by the Federal Highway Research Institute (BASl) on behalf of the German Federal Ministry of Transport, Building and Urban Development to determine possible adapted requirements concerning the equipment of open overhead noise barriers by means of a risk-based analysis. It aimed at defining constructional and operational minimum standards for different types of open overhead noise barriers. The procedure was broken down into three steps:

• Comparative hazard analysis for tunnels and galleries
• Definition of representative construction types of galleries
• Risk-based, comparative analysis of representative scenarios and determination of the corresponding safety level for different types of galleries and reference tunnels.

The results of the project have revealed that for galleries with specific constructive conditions minor requirements regarding operational and safety equipment could be admissible.

Keywords: overhead noise barriers, galleries, tunnel safety, comparative risk analysis

1. INTRODUCTION

At present the German „Directive for the Equipment and Operation of Road Tunnels (RABT)“ is fully applied to open overhead noise barriers, such as galleries and partly covered troughs. This means that galleries have to be equipped completely with the same operational and safety equipment as tunnels. An analysis of relevant guidelines in many European countries and the US showed that in most cases no or comparatively few concrete specifications have been defined at regulatory level concerning lower requirements for (open) overhead noise barriers, which may differ from the requirements for tunnels.

However, existing project-specific studies indicate that even if single predefined operational equipment elements are abandoned, a safety level can be reached that meets the requirements of a comparable tunnel with complete operational and safety equipment.

Therefore, a research project by the Federal Highway Research Institute (BASl) on behalf of the German Federal Ministry of Transport, Building and Urban Development [FE 15.492, 2010], [4] was initiated to determine possible adapted requirements concerning the equipment
of open overhead noise barriers by means of a risk-based analysis. It aimed at defining constructional and operational minimum standards for different types of open overhead noise barriers. Its results can be incorporated as recommendations when updating the regulations or respectively in specific project work to ensure a more efficient construction and operation of open overhead noise barriers.

2. METHODOLOGY

The objective of the project was to derive constructional and operational minimum requirements to be met by the different types of overhead noise barriers on the basis of comparative risk-based studies.

In the first step the aspects to be considered in the analysis were substantiated and existing risk-based examinations were analysed in view of the question. In addition, a scheme was developed regarding the handling of the issue abroad on the basis of a comparison of different international regulatory provisions as regards the safety equipment of noise barrier structures.

Since - due to the varying equipment options - there is no clearly defined safety level neither for tunnels nor for galleries which are equipped according to the relevant guidelines, a typification was undertaken in the second step which defined characteristic open overhead noise barriers in terms of design features and possible significant influencing factors regarding user risks.

The focus was especially on provisions which contribute significantly to the risk reduction in relevant partial scenarios and/or which require considerable efforts (investment and maintenance costs). For simplification, in the following examinations a distinction was made between two types of overhead noise barriers as depicted in Fig. 1:

- Noise barriers with lateral openings: Galleries with lateral openings on one side, like noise barrier galleries or protective galleries (against rock fall etc.), for example
- Noise barriers with ceiling openings: Overhead noise barriers with openings in the ceiling, e.g. designed with light grids or longitudinal openings (for example partly covered troughs).

One examined sub-type was “partly open”, which means the combination of open sections with closed tunnel sections.

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<table>
<thead>
<tr>
<th>Noise barrier with lateral opening</th>
<th>Noise barrier with ceiling opening</th>
</tr>
</thead>
<tbody>
<tr>
<td>open</td>
<td>partly open</td>
</tr>
<tr>
<td>partly open</td>
<td>open</td>
</tr>
<tr>
<td>partly open</td>
<td>partly open</td>
</tr>
</tbody>
</table>

**Fig. 1:** Schematic depiction of different types of overhead noise barriers

In the third step the safety levels of open overhead noise barriers and of related reference tunnels were determined by a risk analysis. The risk-based studies and comparative calculations allowed determining the wide range of possible results for the respective safety levels. In view of the definition of future requirements for open overhead noise barriers those regulatory safety requirements which are necessary for tunnels and which have great savings potential concerning investment and maintenance costs were examined. Based on the comparison of the safety levels of variably equipped open overhead noise barriers the influence of infrastructural and technical characteristics of the respective constructions was investigated and the effectiveness of safety measures derived.
Methodically, the safety level was quantified by risks which were calculated using an event tree analysis. To assess the individual degree of damage the fire development was simulated three-dimensionally and the fatalities to be expected were determined by means of CFD calculations and escape models. The results were displayed and evaluated comparatively as monetized risks and cumulative distribution curves using reference tunnels with corresponding safety levels.

The procedure was broken down into the following sub-steps:

- Identification of decisive hazards and definition of relevant scenarios for the quantitative analysis of the safety level
- Risk assessment for different types of open overhead noise barriers, i.e. for defined types of open overhead noise barriers the resulting risk or respectively the safety level was determined.
- Risk assessment for reference tunnels, i.e. in order to be able to work out the differences with regard to risks between an open overhead noise barrier equipped according to the requirements set by the guidelines and the corresponding tunnel, comparative calculations were carried out. Hereby, the open overhead noise barriers examined in the previous step were modelled as tunnels, i.e. in the related model the open areas were modelled as closed areas.
- As a basis for the identification of criteria applied to the determination of minimum requirements concerning the equipment of open overhead noise barriers, the risk mitigating impact of different structure-specific characteristics and safety measures were investigated. From the point of view of the recommendations to be suggested for incorporation into the technical regulations, the focus was particularly on those measures which contributed significantly to mitigate the risk in the relevant scenarios or sub-scenarios and/or which involved considerable efforts (in terms of financing, realization etc.).

As far as the methodical basis for the quantitative analyses of the safety level was concerned, the proceeding was in accordance with the research project entitled „Safety Evaluation of Road Tunnels“ [FE 03.0378, 2004], [1].

3. RESULTS

In the course of the quantitative analysis comparative risk analyses, comparative to the safety level of a reference tunnel, were carried out for defined types of constructions. This means that not the absolute values of the risks resulting from the quantitative analyses were in the foreground but the differences for the different types of constructions and their equipment features.

To consider all relevant incident scenarios in the risk analysis, specific hazards had been identified qualitatively by means of a hazard analysis. Derived from this the following aspects were examined in detail:

- In view of possible modifications to regulatory bases, the focus of the safety level analysis and of the influence of specific elements of equipment lay on „typical“ open overhead noise barriers with a rectangular cross-sectional profile. These are laterally open (galleries) or open-ceiling structures (partly covered troughs). The characteristics of specific individual structures were not examined.
- The main focus of the analysis was on the safety of the tunnel users. In the quantitative analyses it was specified by the injury indicator “fatalities”.
- As regards the incident scenarios, the main focus of the quantitative risk-based analysis was on the fire scenarios, since the purpose of the greater part of the safety equipment required according to RABT 2006 is to reduce the extent of damage in case
of fire. Above all, such equipment elements involve immense costs and require complex implementation efforts, too.

- Priority of the analysis was attributed to fires with a thermal power between 5 MW and 100 MW. Fires with a higher thermal power (fires of hazardous goods transports, for example) were not taken into account.

Besides the characteristics by which the basic types of overhead noise barriers can be distinguished, a large number of further risk-relevant influencing factors are decisive for the safety level. These factors were included, or varied, in the quantitative analyses in order to be able to assess their influence on the risk. Examples of risk-relevant influencing factors are:

- Traffic volume (ADT)
- Type of operation (directional traffic / two-way traffic)
- Layout of infrastructural elements of the construction (size of the openings, lintel, roof pitch of galleries, …)
- Tunnel ventilation
- Environmental influences (e.g. wind)

For the type “Overhead noise barrier with lateral openings” the cases listed in Table 1 were distinguished:

**Tab. 1: Calculated cases for overhead noise barriers with lateral openings**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Overhead noise barrier, lateral openings, RV</th>
<th>Overhead noise barrier, lateral openings, GV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abbreviation</strong></td>
<td>RV-ESO 1</td>
<td>GV-ESO 1</td>
</tr>
<tr>
<td><strong>Infrastructure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of construction</td>
<td>1'200 m</td>
<td>1'200 m</td>
</tr>
<tr>
<td>Type of traffic</td>
<td>Unidirectional traffic</td>
<td>Bi-directional traffic</td>
</tr>
<tr>
<td>Number of lanes per direction</td>
<td>2 (RQ 26t)</td>
<td>1 (RQ 10.5T)</td>
</tr>
<tr>
<td>(standard cross-section, width b&lt;sub&gt;q&lt;/sub&gt;)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Section height, h&lt;sub&gt;q&lt;/sub&gt;</td>
<td>5.5 m</td>
<td>5.5 m</td>
</tr>
<tr>
<td>Longitudinal gradient</td>
<td>-3.0 %</td>
<td>+/-3.0 %</td>
</tr>
<tr>
<td>Ventilation system</td>
<td>Natural ventilation</td>
<td>Natural ventilation</td>
</tr>
<tr>
<td>Distance between emergency exits</td>
<td>300 m</td>
<td>300 m</td>
</tr>
<tr>
<td>Height of lateral lintel in longitudinal direction (top), h&lt;sub&gt;o&lt;/sub&gt;</td>
<td>0 m / 1 m</td>
<td>0 m / 1 m</td>
</tr>
<tr>
<td>Gradient of ceiling, α</td>
<td>0 % / 10 %</td>
<td>0 % / 10 %</td>
</tr>
<tr>
<td>Design of ceiling</td>
<td>No lintels / lintels across carriageway (height 1 m)</td>
<td>No lintels / lintels across carriageway (height 1 m)</td>
</tr>
<tr>
<td><strong>Traffic</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADT per tube</td>
<td>20'000 veh/d</td>
<td>20'000 veh/d</td>
</tr>
<tr>
<td>Percentage of heavy vehicles</td>
<td>15 %</td>
<td>15 %</td>
</tr>
<tr>
<td><strong>Event</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site of fire</td>
<td>Centre of structure</td>
<td>Centre of structure</td>
</tr>
<tr>
<td>Thermal power</td>
<td>5 MW / 30 MW / 100 MW</td>
<td>5 MW / 30 MW / 100 MW</td>
</tr>
<tr>
<td>Fire detection</td>
<td>120 s</td>
<td>120 s</td>
</tr>
</tbody>
</table>
Fig. 2 depicts schematically the definition of the cross-sectional parameters listed in Tab. 1.

Due to the influence of the various structural characteristics like lateral or ceiling openings the results were clearly different.

Fig. 3 and Fig. 4 show the resulting overall cumulative FN-diagrams for the calculated cases of unidirectional and bi-directional traffic.
With the indication of the extent (number of fatalities) the following parameters were determined in the event tree for each sub-scenario:

- Assessed (or "felt") collective risk \( R_e \)

\[
R_e = \sum H \cdot A \cdot \phi(A)
\]

- Monetized risk \( R_m \)

\[
R_m = \sum H \cdot A \cdot \phi(A) \cdot GK
\]

When monetizing the risks marginal costs of € 10 million per prevented fatality were assumed [FE 03.0378, 2004], [1].

By means of a comparative analysis of the monetized risks and a further sensitivity analysis of relevant parameters, the significant differences and influencing factors were prepared and suggestions as regards criteria for minimum standards had been worked out in the fourth step. In doing so, aspects of the structure-specific differences of the safety level, the specific structure characteristics, the measure effect and implementation were discussed.

4. CONCLUSIONS AND RECOMMENDATIONS

As a last step based on the preceding quantitative and qualitative examinations regarding the safety level, recommendations were worked out concerning possible adaptations of regulatory requirements for open overhead noise barriers.

In connection with the discussions about possible, reduced requirements of RABT 2006 concerning the equipment of open overhead noise barriers compared to the present requirements, the specific hazards were analysed and the safety levels, subject to constructional characteristics, were determined and evaluated on the basis of comparable tunnels. The following recommendations were derived herefrom:

- The constructional characteristics of open overhead noise barriers generally have a risk-reducing effect in case of fire incidents because the flue gas can escape into the open, thus potentially spreading less inside the tunnel. But to a great extent this depends on the individual characteristic design of the structure. It is recommended to design the openings as large as possible to allow for a natural smoke dispersal into the open.

- A positive effect on the restriction of smoke propagation is achieved by transverse beams at the underside of the ceiling. The stronger smoke propagation is restricted in transverse direction, the lower can the special requirements of the ventilation system be, i.e. depending on the design of the transverse beams it may be possible to reduce the ventilation system requirements. Under certain conditions mechanical ventilation is not necessary at all.
• **Overhead noise barriers with lateral openings**

In case of overhead noise barriers with lateral openings it is recommended to keep the height of the boundary beam small (transverse beam functioning as smoke barrier) (< 0.5 m) or to do completely without it, if possible. In general cases such a fire-specific safety equipment will not be necessary. The same positive effect on the safety standard of the overhead noise barrier can be achieved by increasing the inner clearance substantially or by installing an inclined ceiling (ascending towards the lateral opening). In that case as regards the tunnel users’ risks the impact of the emergency exit distances, for example, on the safety level is reduced.

If the constructional features mentioned before cannot be met, the analysis has shown that certain parts of the safety equipment required according to RABT 2006 always have to be installed. In such cases it is recommended to provide risk-based, object-specific proof of the same safety level (comparison with a reference tunnel). Furthermore, on the one hand, overhead noise barriers with lateral openings offer another possibility to escape for people in good physical condition, and, on the other hand, they also provide for an additional rescue path for the emergency and rescue services. Here it is recommended for unidirectional traffic sections with single-sided noise barriers to examine the closing of the adjacent traffic lane in the case of an incident in the gallery.

• **Overhead noise barriers with ceiling openings**

Ceiling openings have a favourable effect on the restriction of the transverse propagation of flue gas and on the propagation reduction of thermal radiation. Therefore, in case of fire those road users who are close to the site of the fire are affected most. There are hardly any effective infrastructural or technical safety measures available for the tunnel users in this area. This means that the appropriate behaviour in case of fire is crucial for a successful self-rescuing.

The analysis has shown that the size of the ceiling opening has significant influence on the resulting risks. According to the results obtained it is possible to do without a ventilation system and a related detection system, given a ceiling opening proportion of at least 25 % and a width of 2.50 m respectively. A tunnel closing system and the distances between emergency exits have also only a minor effect on the safety level of the overhead noise barrier structure.

If the constructional characteristics mentioned above cannot be provided, the analysis has shown that certain parts of the safety equipment required according to RABT 2006 have to be installed. Here it is recommended to provide risk-based, object-specific proof of the same safety level (comparison with a reference tunnel).

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Risikoanalytische Untersuchungen zum Sicherheitsniveau offener Einhausungen (Risk-based analyses of the safety level of open overhead noise barriers)

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