 DOI: 10.3217/978-3-85125-883-7-18

UPGRADE OF THE GERMAN METHODOLOGY FOR TUNNEL RISK ASSESSMENT

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ABSTRACT

The currently used methodology of safety assessment of road tunnels in accordance with BASt booklet B66 "Sicherheitsbewertung von Straßentunneln" [1] dates from 2009, extensive knowledge has been gained when implementing and applying the developed method in risk analysis studies. Numerous research projects have provided new findings on parameters previously not considered. As some methodological elements and basic assumptions no longer correspond to the state of the art, it became necessary to re-analyze the methodology and to develop appropriate adjustments. The updated holistic approach is based on the current evaluation of incidents in German road tunnels as well as the state of the art regarding the assessment of road users' risks in tunnels. The upgrade suggested as output of the BASt research project FE15.0663/2019/ERB[1] funded by the German Federal Ministry of Digital and Transport deals with risk evaluation, frequency analysis as well as the consequences of collisions and fires in tunnels. The implementation of the proposed adjustments allows analyzing tunnel risks more realistically and improves the evaluation of a large number of safety measures. The present paper summarizes the main adaptations developed and their influence on the risk assessment of road tunnels.

Keywords: Tunnel risks, risk analysis methodology, frequency analysis, risk assessment, evaluation of safety measures, Computational Fluid Dynamics (CFD), evacuation simulation

1. INTRODUCTION

With the introduction of the RABT 2006 [2] and the publication of the EABT-80/100 [3] in 2019, the requirements of the EC-Directive 2004/54/EC [4] on the use of risk analyses for the assessment of safety of road tunnels were transferred to German regulations. So, risk analyses are required if a road tunnel either has special characteristics or deviates from the specifications laid down in the regulations as regards its geometric design or safety-related equipment. Risk analyses also become necessary to verify if longitudinal ventilation for bi-directional tunnels and tunnels with daily congestion is admissible.

The required depth of risk analyses (qualitative/quantitative) as well as the verification of whether there is a special characteristic and/or a significant deviation from guideline specifications is determined according to the procedure described in Leitfaden für Sicherheitsbewertungen von Straßentunneln [5] gemäß RABT 2006 [2]. The methodology how to carry through quantitative risk analyses is described in the BASt booklet B66 Sicherheitsbewertung von Straßentunneln [1].

Since its publication in 2009, extensive knowledge has now been gained in the implementation of the procedure and its practical application in risk analysis studies. In addition, numerous research projects on special issues were carried out and significant new findings were made on parameters that were previously not taken into account. Among other things, the underlying accident statistics (event database) has been updated in the meantime and provides additional information on the frequencies of collisions and fires in road tunnels.

Therefore, both the methodological approach and the basic parameters and assumptions of the method no longer reflect the current state of the art. For the reasons mentioned above, it is necessary to re-

[1] FE15.0663/2019/ERB „Überprüfung der Annahmen und Parameter für Risikoanalysen für Straßentunnel (review of the assumptions and parameters for risk analyzes for road tunnels) im Auftrag des Bundesministeriums für Digitales und Verkehr (BMDV) vertreten durch die Bundesanstalt für Straßenwesen (BASt), 2020-2022.

analyze the currently applicable methodology for the safety assessment of road tunnels and to suggest appropriate adjustments.

For this purpose, in a first step, new statistical bases were collected, accident rates were updated and influencing factors were determined. In addition, previously used input parameters and assumptions of the methodology, which affect the tunnel safety level as a whole as well as individual equipment features, were further completed, their influence on the risk checked and adjusted.

In addition, the methodology was expanded to include parameters that were previously not taken into account. This comprises, for example, the influence of speed on the accident rate and severity, fire development rates differentiated according to faster or delayed progression, a more detailed consideration of reaction times and human behavior during evacuation processes, the positive effects of third-party rescue, etc. From the investigation of the parameters mentioned with regard to their influence on risk, statements were derived regarding the need to take these parameters into account in risk-oriented studies in the future.

Another aim of the project was to standardize the procedures in order to be able to compare better the results of specific risk-oriented investigations on the features of safety-relevant equipment in road tunnels.

When working on the project, it was essential to obtain a broad, as comprehensive as possible view of the experience in the implementation and application of the procedure. To ensure this, a wide range of participants from practice and science were addressed in a workshop at the beginning of the project.

2. PRACTICAL EXPERIENCE

The analysis of the existing methodology shows that basically the methodology is still suitable for assessing the safety of road tunnels and, thanks to its modular structure, it is open to expansion. The fact that it does not focus on the use of special models guarantees a high degree of future viability.

In the last ten years, numerous different sets of rules have been developed or adapted in order to implement the requirements of the European directive. For the present research project, primarily the regulatory requirements of those countries were analyzed in-depth, in which the topic of tunnel safety is particularly important. The findings can be summarized as follows:

Degree of standardization: The current regulatory requirements or the established procedures for risk assessment in accordance with the requirements of EC Directive 2004/54/EC are (as expected) very different. Nonetheless, there are a number of methods comparable in terms of their basic principles. In comparison to the methods of other countries which have been evaluated in depth, it turned out that the method according to BASt booklet B66 [1] allows a greater degree of freedom in implementation. Other procedures have more detailed specifications for individual elements or their model consideration. Here, the evaluations show a general area of tension as to which extent which specifications should be made for risk-based evaluations or which extent of freedom is allowed in the implementation. In the first case, the comparability between different practical applications and the traceability are enhanced, in the second case there are more possibilities to map specific tunnel properties that can be mapped less or not at all in highly formalized procedures.

Risk analysis / model parameters: In comparison to the method according to BASt booklet B66 [1], some of the other established methods, e.g. the models in Switzerland [6] and in the Netherlands [7], take into account more / additional tunnel properties (design characteristics and measures) than the direct influencing variables and parameter values. This includes, for example, an increased number of lanes or curve radii. There are also, in some cases, more pronounced specifications and notes on the parameter values to be used. Furthermore, more specific instructions and specifications for modeling event sequences and models are taken into account (e.g. behavior of tunnel users).

There are several investigations and studies on many influencing factors that can be used for implementation in the further development of the process in accordance with BASt booklet B66 [1].

Risk evaluation: There is also considerable heterogeneity with regard to the criteria for risk assessment. While some procedures are based on comparative procedures with a reference tunnel (as often is the case in Germany today), others use absolute limit criteria relating to the level of safety or considerations of proportionality for any additional measures. There are also procedures that use not only collective risks but also individual risks for tunnel users as an evaluation measure.

Complexity and effort: The majority of the procedures established today tend to be complex. For practical application, in-depth specialist knowledge in the field of road tunnels and risk-based procedures is required. Today, there are software programs associated with several established processes that support implementation and thus reduce effort. However, even in these cases, the users have to be well familiar with the methodological basics and have to bring in system knowledge of tunnels in order to model the respective tunnel properties and possible event sequences realistically.

3. SUGGESTED UPGRADE FOR THE RISK ASSESSMENT METHODOLOGY

The suggested adaptations for the assessment methodology are divided into the following issues:

1. Risk evaluation
2. Frequency analysis
3. Analysis of the consequences of tunnel collisions
4. Analysis of the consequences of tunnel fires

When determining the adjustments, special attention was paid at the procedural level to the following general properties in the application of the methodology:

- Flexibility in use
- Minimum required level of complexity and effort
- Transparency, traceability and comparability of the (interim) results
- Process-related comparability of risk-reducing measures

In addition, the effects of the proposed adaptations were examined intensively. The previous safety level of a tunnel according to the specifications in booklet B66 [1] was compared with the calculations for a model tunnel, taking into account the new model parameters and evaluation approaches. The focus was on the comparative approach to assess differences in risk. The extensive results are presented in detail in the final report.

3.1. Risk evaluation

According to the procedure described in booklet B66 [1], it is proposed that the (collective) risks determined in the course of the risk assessment are shown in the form of cumulative curves in a FN-diagram, using an absolute evaluation criterion to assess the acceptability. At the time of the development of the B66 procedure, however, it was foreseeable that it would not yet be possible to establish an absolute acceptability criterion. For this reason, it was recommended that the risk assessment be carried out based on a relative comparison between the planned case and the corresponding value for the theoretical case of a guideline-compliant design. As experience has shown, this comparative assessment of the risks largely has become established in practice. However, practice has also revealed that there is a need to sharpen the definitions with regard to the reference tunnel.

Basically, the reference tunnel is a theoretical tunnel similar to the real tunnel to be examined, but fully meets all requirements and conditions of the guidelines and regulations to be applied in the specific case. A relative assessment approach is made, in which compliance with the required safety level is determined by a relative comparison with this reference tunnel. Using a relative assessment approach, the influence of uncertainties on the assessment result can be minimized.

In the present research project, specifications for the reference tunnel were defined for all safety parameters relevant according to RABT [2]/ EABT [3] and compared with the tunnel to be examined. The focus was on setting parameters for the majority of tunnels in Germany. For tunnels that represent special cases, it is recommended that the reference tunnel be determined individually in consultation with the relevant decision-makers, depending on the objective of the investigation.

3.2. **Frequency analysis**

The suggested adaptation as regards the frequency analysis contains the findings from the evaluations of the nationwide event database, the definition of influencing factors for the accident rate as well as a proposal for updating the structure of the event tree.

The frequency of vehicle accidents and fires can be derived from long-term event statistics. In contrast to analytical methods, here statistical methods are clearly in the focus. Analysis is based on the nationwide event database consisting of the basic data for each tunnel and the event report for each reportable event. The database includes 168 tunnels and approx. 49,000 events (years 2006 to 2020).

After extensive data processing, numerous parameters could be derived directly from the database. The primary focus was on checking the current event rates and, if necessary, their updating based on new statistical data.

The analysis in the research project has revealed that the values from the BASt booklet B66 [1] for the (base) accident rate, the distribution of different accident types and the fire rate have to be updated. In addition to the new, updated values, the report includes a comparison with the values from BASt booklet B66 [1] and a comparison with event rates from other countries.

However, accidents in road tunnels are influenced by numerous geometric and traffic-related factors. Therefore, it is necessary to include these influencing factors when determining the frequency of accidents. For this purpose, corresponding correction factors for unidirectional and bidirectional road tunnels were determined, by which the respective base accident rate is multiplied.

Accident rates derived from the event database as well as expert estimates and comparison with approaches from other risk models form the basis for this factor model. Correction factors could be determined for the following influences:

- Existence of entrances / exits (f_{ZA})
- Tunnel length (f_{L})
- Number of traffic lanes (f_{FS})
- Traffic lane width (f_{FSB})
- Existence of break down lane (f_{SS})
- Traffic volume per lane ($f_{DTV / FS}$)
- Permissible speed (f_{V})
- Differential speed ($f_{\Delta V}$)

To determine the frequency, all possible intermediate states between the initial events up to the final system states are determined and quantified with regard to their expected frequency. The intermediate states are examined for system responses in the same way as those of the triggering event. In this way, until a final state is reached, different branches of the event sequence are created, which are provided with different branch probabilities.

The following branches are considered within the event sequence for mapping fire incidents:

- Event location (e.g. entrance area / inner tunnel section / center of the tunnel ...)
- Traffic volume (day / night / ...)

- Traffic status (free-flow traffic / congested traffic)
- Fire load (5/30/100 MW)
- Fire development (fast / delayed)
- Detection successful (yes / no)
- Tunnel user alert successful (yes / no)
- Tunnel closure systems activated (yes / no)
- Ventilation system activated (yes / no)
- Other security systems available and activated (yes / no)
- Increased extent of damage (yes / no)
- Start of third-party rescue measures

The report specifies standard values for the relative frequencies of the individual branches and explains specific differences to BASt booklet B66 [1].

3.3. Analysis of the consequences of tunnel collisions

In addition to the accident rate, the speeds driven in the tunnel also have an impact on the resulting extent of damage in the event of collision. Since no meaningful relationships could be derived from the event database, the influence was justified with the help of the Nilsson Power Model [8]. It is based on the direct relationship between the change in mean speed and the resulting change in the severity of the accident.

The different influence of the speed on these two sub-areas and equally on the frequency of accidents with different degrees of severity is represented by the numerical value of the exponent. Therefore, it is recommended to model the extent of damage for collisions with the exponent 1, also due to the good agreement with the statistically proven dependencies.

3.4. Analysis of the consequences of tunnel fires

In the event of a fire inside a road tunnel, smoke particles, heat and toxic gases can endanger road users. High concentrations of smoke particles lead to restricted visibility and to irritation of the respiratory tract and eyes, and thus hinder users in their orientation and movement. In order to be able to take these effects into account when determining the extent of the damage, a simulation model is required that enables the time and space-discrete calculation of the heat, smoke and toxic substances depending on the development of the fire and fluid-mechanical boundary conditions.

For the computer programs (CFD models) suitable for this purpose, essential parameters and boundary conditions were specified in the suggested adaptations in order to determine the impact models for estimating the consequences of fire. Approaches for simulating the effects of smoke, the effects of toxic gases and the effects of heat were defined.

An essential part of the revision of the damage scale model concerns the discussion and, if necessary, the definition of a detailed timeline on which the model is based. The focus was primarily on the definition of fire curves and the associated energy and pollutant release rates. A major innovation is the implementation of a fast and a delayed fire curve. They allow evaluating additional measures that have a significant influence on the individual time steps. These measures include, for example, the different behavior of detection devices, the reaction of operators, the activation of safety devices, and the degree of compliance with activated tunnel closure systems and the reaction of tunnel users.

One of the major innovations in the revised and upgraded methodology is the implementation of an accumulation-based escape mode. It aims at mapping the effects of a tunnel fire on people trying to escape as realistically as possible. The current risk model provides for the evaluation of successful or unsuccessful escape solely based on visibility. By implementing intoxication models (based on a "fractional effective dose" (FED) or a "fractional effective concentration" (FIC)) it is possible to model variable escape speeds as a result of restricted visibility or highly irritant gas concentrations. Another focus when revising the consequence model was the definition of model approaches and the requirements for models to analyze self-rescue processes. Possibilities were created to evaluate different escape velocities, the perception of security facilities or hazards in the tunnel, inadequate behavior during the self-rescue and the influence of people with restricted mobility. Approaches for evaluating third-party rescue activities, both concerning firefighting and rescue of people, were implemented, too.

4. SUMMARY AND CONCLUSION

Within the framework of the research project FE 15.0663/2019/ERB (Review of the assumptions and parameters for risk analyses for road tunnels), various recommendations for the further development have been made. They are based on the experience gained from practical application of the methodology described in BASt booklet B66 [1] and on the results of general developments in the field of risk analyses for road tunnels. The analysis of the presently used assessment method has shown that basically it is still suitable for safety assessment of road tunnels and that due to its modular structure it is open to expansions. Since the method does not focus on the use of special models, it features great sustainability. The method was expanded to include a factor model that allows further consideration of traffic-related and structural influences on accident rates. Furthermore, in order to represent more realistic fire processes, fire developments with both rapid and delayed progression were integrated into the procedure. In addition, an accumulation-based escape model was implemented to determine the impacts of fire on tunnel users. As a result, the extent of damage is now determined based on a "fractional effective dose" (FED) or a "fractional effective concentration" (FIC). Moreover, fire-fighting measures are now part of the procedure. By the implementation of the suggested adjustments, it is now possible to analyze the risks in tunnels more realistically and to better evaluate a large number of safety measures.

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