RISK ASSESSMENT GUIDELINES FOR TUNNELS

M. Molag, I.J.M. Trijssenaar-Buhre
TNO

ABSTRACT

This paper describes the Risk Assessment Guidelines for Tunnels that has been developed in the SafeT thematic network on tunnel safety. The objectives of the network are described and how the Guidelines support the EU tunnel safety directive. An overview of qualitative and quantitative deterministic and probabilistic methods for tunnel safety assessment is presented. It is indicated in this paper which methods are suitable for a risk assessment for a tunnel feasibility study, during conceptual, outline and detailed design and during tunnel operation and maintenance.

1. INTRODUCTION

The EU funded Thematic Network on Tunnel SafeT started in May 2003 and finished April 2006. The objective of the SafeT network was:

To develop comprehensive guidelines for pan European decision making on the safety of existing tunnels (primarily road but also rail) by investigating, identifying, assessing and proposing best practice solutions for (a) preventing incidents/accidents in existing tunnels and (b) mitigating its effects – for both people and goods – to ensure a high level of tunnel safety in Europe.

This objective was defined to support the implementation by the member states of the EU Directive on minimum safety requirements for tunnels in the trans-European network[1]. This directive was published in April 2004. In Article 13 „Risk analysis" of EU Tunnel Safety Directive it is stipulated:

1. Risk analyses, where necessary, shall be carried out by a body which is functionally independent from the Tunnel Manager. The content and the results of the risk analysis shall be included in the safety documentation submitted to the administrative authority. A risk analysis is an analysis of risks for a given tunnel, taking into account all design factors and traffic conditions that affect safety, notably traffic characteristics and type, tunnel length and tunnel geometry, as well as the forecast number of heavy goods vehicles per day.
2. Member States shall ensure that, at national level, a detailed and well-defined methodology, corresponding to the best available practices, is used and shall inform the Commission of the methodology applied; the Commission shall make this information available in electronic form to other Member States.
3. By 30 April 2009 the Commission shall publish a report on the practice followed in the Members States. Where necessary, it shall make proposals for the adoption of a common harmonised risk analysis methodology in accordance with the procedure referred to in Article 17(2).

In Article 3 “Safety measures”, e.g., it is required, that “the efficiency of these (risk reduction) measures shall be demonstrated through a risk analysis in conformity with the provisions of Article 13”. One of the guidelines that has been developed and discussed in the SafeT network was on risk analyses and finally resulted in the Guidelines on Harmonised Risk Assessment[2].

The procedure followed in the SafeT network was that first an inventory has been made of the used methods for tunnel risk assessment in the EU countries and risk assessment methods applied in other engineering areas. Based on an evaluation of the available methods and their application, proposals for the guidelines for risk assessment have been made.

2. TUNNEL RISK ASSESSMENT METHODS

In the literature two main categories of risk assessment methods can be distinguished:

1) Deterministic safety assessment: The consequences for loss of life of tunnel users and tunnel structure are analysed and assessed for possible accidents that can occur in a tunnel.
2) Probabilistic safety assessment: The consequences for loss of life of tunnel users and tunnel structure and the frequency per year that these consequences will occur are analysed. Consequences and the frequency of the consequences are multiplied and presented in risk for the individual tunnel user, a societal risk and a risk for tunnel damage.

Figure 1 shows the different stages in a probabilistic and deterministic safety assessment.

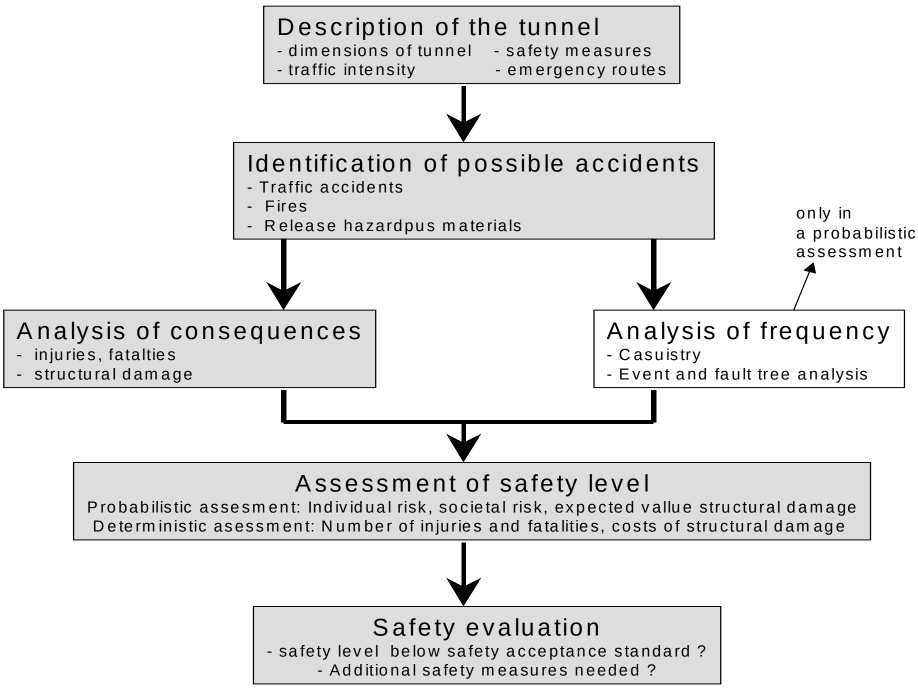

Figure 1 Main steps in a tunnel risk assessment. The frequency analysis is not part of the deterministic risk assessment.

Detailed descriptions of the different steps of deterministic and probabilistic risk assessment methods are presented in the SafeT report on the risk assessment guidelines[2]. In the following table an overview of the available methods is given:

Method	Accident types							Model aspects					
	Traffic disturbance without damage	Collisions	Fire	Explosion	Leakage of aggressive and toxic materials	Nature (earthquakes, flooding)	Accidents for submerged tunnels (dropped anchors, sunken ships	Hazard Identification	Frequency calculation	Physical effects	Damage	Evacuation	Economics
Hazard identification													
Checklist	Generally applicable methods							√					
Casuistry								√					
Fault tree analysis (FTA)								√	√				
Event tree analysis (ETA)									√	√	√		
Cause-consequence analysis								√					
What-if analysis								√					
Hazard and operability analysis (HAZOP)								√					
Failure mode, effects and criticality analysis (FMECA)								√					
Deterministic safety assessment													
Maximum credible accident analysis (MCA)	Generally applicable method												
Dutch road tunnel scenario analysis	√	√	√	√	√			√		√	√	√	
TNO- tunnel consequence model			√							√	√	√	
SIMULEX		√		√								√	
Probabilistic risk assessment													
Fault tree analysis (FTA)	Generally applicable methods							√	√				
Event tree analysis (ETA)									√	√	√		
QRAM			√	√	√			√	√	√	√		
TUSI	√	√	√						√				
QRA Procedure by Persson			√	√				√	√	√	√	√	
TunPRIM	√	√	√	√	√				√	√	√	√	
TNO- tunnel probabilistic model			√	√					√	√	√	√	

Table 1: Overview of risk assessment methods[5-12]

3. APPLICATION OF TUNNEL RISK ASSESSMENT METHODS

3.1 Current state of practice

An overview of experience and practical applications in several countries is made by PIARC[3] and presented in table 2.

	Canada	France	Great Britain	The Netherlands	Sweden	USA
Applied Method	Qualitative risk analysis Determini-stic analysis	Quantitative risk analysis	Qualitative analysis of risks affecting design and operation of road tunnels Deterministic analysis of scenarios e.g. using CFD	Probabilistic risk analysis Deterministic scenario analysis	Probabilistic risk analysis Deterministic scenario analysis	Probabilistic risk analysis Deterministic analysis
Objective	Comparison /ranking	Assess risk related to transport of dangerous goods	Risk based design Optimisation of incident response procedures Regulation of dangerous goods transport	Acceptability of safety performance Optimisation of incident response procedures Establish safety objectives	To contribute to high safety standard with reasonable means	Minimize fire related injuries and structural damage. Provide adequate conditions for evacuation
Applied Model	"home made", not standard	QRAM	Different models, methods can be adapted depending on the focus of the activity.	Guideline on scenario analysis TUNPRIM model for QRA	Different models can be used	No model

Table 2 Overview of practices in different countries[3]

3.2 Risk analysis in the design stage and during tunnel operation

From table 2 can be concluded that different methods are applied. This is caused by preferences of the users for a specific method but is also caused by the availability of enough input data for a specific method. In the early design of a tunnel project is less input data available for a risk assessment than when the tunnel is operated. For that reason recommendations have been made for which model should be used from the early design stage till a tunnel that is in operation. Table 3 gives an overview of the design stages and requirements of a risk analysis[4]:

	Design/upgrading				
Stage	**Feasibility study**	**Conceptual design**	**Outline design**	**Detailed design**	**Operation / maintenance**
Degree of accuracy	Qualitative assessments	Rough estimate	estimate	Detailed estimate	Detailed calculation
Degree of detailing	Initial identification of hazards, risk and measures	Identification of hazards and risk Identification of reducing measures Initial qualification Initial acceptance criteria	Quantification of risk Study of risk reducing measures Acceptance criteria	Detailed evaluation of cost efficiency of risk reducing measures Evaluation of acceptance	Detailed evaluation of cost efficiency of risk reducing measures Evaluation of acceptance
Input	General experience	General experience Rough models General data	Experience Models Statistical information	Experience Models Statistical information Specific studies, tests, etc	Experience Audits Models Tunnel specific Statistical information Specific studies, tests, inspections,etc
Output	Evaluation of importance	Rough estimates of risks and costs as function of major design parameters.	Risk and costs as a function of basic design parameters Acceptability criteria	Basis for design and project documentation	Safety file Basis for new/adjusted measures, procedures

Table 3: Overview of design stages and requirements of a risk analysis

Table 4 shows which the use of risk assessments methods in the different stages of the life cycle of a tunnel. Table 4 is a combination of table 1 and 3. An explanation of the classification of each tool in this table is given in the following paragraphs.

3.2.1 Risk analysis in the feasibility study

In the feasibility study a general idea of the possible relevant risks and necessary safety measures or constraints on the design has to be obtained. The feasibility study deals with questions whether a tunnel is necessary or not, what the capacity of the tunnel should be, which safety aspects should be considered. In this stage a detailed safety analysis is not yet necessary and possible. With the use of checklists and the list of safety measures in the EU directive a good idea of the safety issues to be considered can be obtained. Using the knowledge and experience obtained in previous tunnel design projects a first estimate of the risks and necessary safety measures (and accompanying costs) can be made.

	Design/upgrading				
Method	**Feasibility study**	**Conceptual design**	**Outline design**	**Detailed design**	**Operation maintenance**
Hazard identification					
Checklist	√√				√√
Casuistry	√√	√			√√
What-if analysis		√	√		
Cause-consequence analysis		√	√		
Hazard and operability analysis (HAZOP)			√	√	
Failure mode, effects and criticality analysis (FMECA)				√	
Fault tree analysis (FTA)			√	√	
Event tree analysis (ETA)			√	√	√
Audits					√√
Inspections					√√
Deterministic safety analysis					
Maximum credible accident analysis (MCA)		√	√		√√
Dutch road tunnel scenario analysis		√	√√	√	√√
TNO- tunnel consequence model		√	√	√√	
SIMULEX			√	√√	
Probabilistic risk analysis					
QRAM		√√	√		
TUSI		√√			
QRA Procedure by Persson		√√	√		
TunPRIM		√√	√		
TNO- tunnel probabilistic model		√√	√		√

√ method can be applied in this stage of design
√√ method is very suitable for this stage of design

Table 4: Use of risk assessment tools in different design stages

3.2.2 Risk analysis during the conceptual design

In the conceptual design stage more accurate comparison between different tunnel design alternatives is made. In this stage a decision has to be made on aspects such as:

- the location and length of the tunnel
- the tunnel type, e.g. bored or immersed
- the number of tubes in the tunnel

- the dimensions of the tubes
- the number of cross-sections
- the type of traffic that can be allowed to use the tunnel

In this stage quantitative risk analysis (QRA) and deterministic safety assessments are very useful methods to compare the different concepts. The QRA can also be used to make a first check on the safety criteria are fulfilled.

Quantitative risk analysis
Table 4 lists several models available for a QRA for a tunnel. Most models calculate the societal risk and the expected value of the number of fatalities per year. Questions to be asked in the choice of the model to be used are:
a) Are all relevant scenario's considered in the model (use table 1)?
b) Does the model include all important design parameters on which a choice has to be made in this stage and that are also relevant for safety (use table 5)?
c) Is the consequence modelling in the model adequate for this stage of the decision process (use data from casuistry, rough estimates, zone-models, sometimes CFD models)?
d) Are the failure frequencies in the selected model also fit for purpose in this analysis or should they be adjusted (use statistics, TUSI[9], sometimes fault trees)?

	QRA procedure for fire evacuation	**Dutch QRA road tunnels(Tunprim)**	**TNO train tunnel model**
Tunnel/traffic	Road	Road	Train
Traffic intensity	√	√	√
Type of traffic		√	√
Dimensions of the tunnel	√	√	√
Dimensions of the evacuation route in the tunnel	√	√	√
Distance and dimensions of the cross sections	√	√	√
Ventilation in the tunnel	√	√	√
Early detection systems	√	√	√
Sprinklers			√
The availability and use of manual fire extinguishers			√
Systems and procedures to prevent fires in the tunnel		√	√

Table 5: Overview of parameters included in different models

Deterministic safety analysis

A deterministic analysis is often a scenario analysis of the time sequence of events for representative accident scenarios that can occur in the tunnel:

- The initial cause of the accident
- The detection and alarm immediately after the accident
- The development of the consequences of the accident and the effect of mitigating measures
- The procedures and actions taken by operator
- The evacuation and possibilities for self-rescue actions by the tunnel users
- The possible actions of the emergency response workers

The scenario analysis will provide important information for the selection of preferred design alternatives. A scenario analysis also indicates which event of the accident has a major influence on the deterministic risks of a tunnel and will show where it is most effective to reduce the consequences of the accident.

3.2.3. Risk analysis during the outline design

In the outline design stage the level of detail increases. In this stage a decision on the general concept for the tunnel is already made. This concept will be worked out by a contractor who will focus on one or a limited number of solutions. In this stage the choice for the material becomes final and dimensions are calculated in more detail. Also more attention is given to the necessary installations and safety devices that have to be incorporated in the design. In this stage a quantitative risk analysis can be necessary to prove that the design meets the safety criteria. For this purpose it may be possible to use one of the models described in the previous section.

When the safety criteria are not met improvement of the safety is necessary. In that case safety improvements such as ventilation, sprinklers, early detection systems, more escape routes etc. can be introduced in the design. The need for additional safety measures can also be a result of a public discussion about safety or pressure from authorities. The effect of these safety measures on the design can be demonstrated with a quantitative risk analysis and/or a deterministic scenario analysis. In this stage of the design process (outline design) the risk assessment tools are almost the same as in the conceptual design stage. In this stage a higher level of detail and more accurate estimations of the frequencies and consequences can be necessary.

3.2.4. Risk analysis during the detailed design

In the detailed design the specifications and technical details are worked out. In this stage a risk assessment of the entire tunnel system should not be necessary anymore. The risk analysis should now focus on specific details, such as the reliability of the technical systems in the tunnel e.g. traffic control systems, ventilator capacity etc. Fault trees, a Hazard and operability analysis (HAZOP) or Failure mode, effects and criticality analysis (FMECA) can be useful methods to demonstrate the reliability of the technical systems in this stage.

In this design stage operating procedures, operating software and emergency response plans have to be worked out also. In this stage attention has to be given to the tasks and procedures for operators and emergency response workers in case of emergencies. A good understanding of these tasks can be obtained by writing out a number of representative accidents in a deterministic scenario analysis and describing all actions that have to be taken by these officials. A result of this exercise can be an emergency response plan and some extra features in the control room software.

3.2.5 Risk analysis during operation

Once the tunnel has been taken in operation an assessment of the safety performance is necessary periodically. In a periodic safety evaluation the following methods or tools could be used:

- checklists
- casuistry: for existing tunnels during operation all serious accidents should be evaluated. It should also be checked whether there are significant differences between the accident statistics of the tunnel compared to other tunnels and how these differences can be explained. If sufficient tunnel specific data is available, tunnel specific accident frequencies can be derived and implemented in a probabilistic risk analysis.
- inspections
- audits

The operating procedures and the safety management system should also be checked in an audit. An important issue to be checked is whether all initial conditions and principles are still the same as approved when the tunnel was initially designed and whether the safety provisions are still fit for purpose. An example can be that the traffic intensity can have changed dramatically in the past years or that the type of transport allowed through the tunnel has changed. In that case it can also be necessary to perform a probabilistic risk assessment to check if the tunnel still meets the safety criteria.

4. CONCLUSIONS AND RECOMMENDATIONS

From the literature search and the discussions in the SafeT network can be concluded that a lot of different methods are used to assess the safety during design and operation of a tunnel in EU member states and other countries. The applied methods vary from qualitative till quantitative methods, from probabilistic till deterministic methods.

Important for the selection of a tunnel safety assessment method is the level of detail in the available input for the method. In the early stage of the design of a tunnel it is recommended to apply more generic methods like checklists, casuistry of comparable tunnels. In the outline design more detailed methods can be used. In this stage it also recommended to use as well deterministic as probabilistic methods. In the detailed design phase the application of risk assessment methods should be used to proof that assumption made in earlier tunnel risk assessments are correct and that the reliability of tunnel technical systems meets the design criteria. During operation and maintenance of the tunnel it is important to use methods that assess if the actual safety performance of the tunnel meets the tunnel safety criteria. Also methods should be used that monitor possible changes in the use of the tunnel, changes in technical tunnel systems and changes in the tunnel operation.

5. REFERENCES

1. EU, “Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the trans-European road network”, Official Journal of the European Union, L 201/56-76, 7.6.2004.
2. I.J.M Trijssenaar-Buhre, T. Wiersma, M. Molag; Harmonised Risk Assessment, SafeT report, TNO apeldoorn april 2006.
3. PIARC “Management of Road Tunnel Safety, Subgroup 2- Risk Analysis for Road Tunnels, draft documents.
4. Durable and reliable tunnel structures, the comprehensive decision tool, DARTS R5.1, May 2004, ISBN 90 3760 4633
5. Weger D. de, “Scenario Analysis for Road Tunnels”, Safety and Reliability, ESREL, ISBN 90 5809 551 7, 2003.
6. Ruffin, E., Rault-Doumax, S., (2004), GIS interfaced OECD/PIARC QRA model for Road Transportation of Hazardous Goods, Loss prevention and safety promotion in the process industries, 11th International Symposium Loss prevention 2004 Praha Congress Centre 31 may-3 June 2004.
7. Circulaire interministérielle no 2000-82 du novembre 2000 relative à la réglementation de la circulation des véhicules transportant des marchandises dangereuses dans les tunnels routiers du réseau national
8. Knoflacher H., Pfaffenbichler P.C., Institute for Transport planning and Traffic Engineering, Vienna University of Technology, “A comparative risk analysis for selected Austrian tunnels”.
9. Amundsen, NPRA, “TUSI, A model predicting traffic accidents in Norwegian Road Tunnels”, 2003.
10. Persson M., “Quantitative Risk Analysis Procedure for the Fire Evacuation of a Road Tunnel –An Illustrative Example”, Lund University, Sweden, Report 5096, 2002.
11. Lynn Lee S.L., Bendelius A., “simulation of escape from road tunnels using SIMULEX”, Fifth International conference on “Safety in Road and Rail Tunnels”, p.411-420, 2003.
12. Weger D. de, Kruiskamp M.M., Hoeksma J., “Road tunnel risk assessment in the Netherlands - Tunprim: a spreadsheet model for the calculation of the risks in road tunnels”, Safety & Reliability International Conference ESREL 2001.