Appendix 1: Tools for Probabilistic risk assessment

Probabilistic risk 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.

Neither prescriptive guidance nor deterministic fire engineering is particularly good at high consequence/low frequency fire events that tunnels can experience. Quantitative risk assessment, however, considers the severity and frequency of a wide range of events. In other words: quantitative risk assessment treats the frequency and the consequence sides of the predicted risks with equal emphasis. It has the advantage that it assesses the level of risk more holistically considering a wide range of event scenarios including the reliability of safety measures and management procedures [8]. Quantitative risk assessment is a useful method to evaluate the influence of preventive safety measures on the total risk. Furthermore it is most suitable to perform cost/benefit analyses of these safety measures.

A probabilistic – quantitative - risk model comprises two parts: the probabilities and consequence model. Important techniques to quantify all relevant parameters and probabilities of failure modes are the fault-tree analysis and the event-tree analysis, which are also used for hazard identification. For the consequence model the requirements are similar to those for the deterministic approach, although in a probabilistic analysis the level of detail in the consequence model might be a bit lower.

The models described in this appendix for probabilistic risk assessment in tunnels are:

- TunPrim: a spreadsheet model for Road Tunnel Risk Assessment: a QRA tool for probabilistic risk assessment (section 1.3,[7])
- The TNO-tunnel model ([6], see example in Appendix 2)
- QRAM: Quantitative Risk Assessment Model for risk estimates relevant for transport of dangerous goods through road tunnels. The model is developed for harmonisation of restrictions on transport of dangerous goods during an OECD/PIARC study (section 1.1,[9]).
- TUSI: a model predicting traffic accidents in Norwegian Road Tunnels (section 1.4,[3]).
- Swedish Model for Quantitative risk analysis procedure for the fire evacuation of a road tunnel (section 1.2,[4])
- NASA method for probabilistic risk assessment [10]

Several tools for probabilistic risk analysis are evaluated and compared in this report.
1.1 QRAM for transport of dangerous goods through road tunnels: applications in France and Austria

1.1.1 Risk Analysis Comparison Scheme

| 1. Type of risk assessment method | QRAM, Quantitative Risk Assessment Model. Probabilistic risk analyses 2 important aspects:  
• frequency (probabilistic approach)  
• consequences (number of fatalities /injuries, damages)  
The method is suited for open air or tunnels sections, road or rail transport. |
| 2. Objective | QRAM is applied in France and Austria to assess the risks from the transport of dangerous goods in a quantitative way. The model evaluates the consequences and the frequencies of occurrences of possible accidents. This enables the quantitative assessment of societal risk and individual risk. |
| 3. Type of accidents | The model deals with accidents related to transport of dangerous goods. Types of accidents included are:  
• Fire  
• Explosion  
• Leakage of aggressive and toxic materials |
| 4. Methodology | a) Choice of a restricted number of dangerous goods  
b) Choice of representative accidental scenarios implying those dangerous goods  
c) Identification of physical effects of those scenarios for an open air or a tunnel section  
d) Evaluation of their physiological effects on road or rail users and on the local population taking into account of the possibilities of escape/sheltering  
e) Determination of yearly frequency of occurrence for each scenario |
| 4.1. Structure | A limited number of dangerous goods and a limited number of representative accidental scenarios is taken into account in the QRA. The risk assessment of each scenario is based on a different event tree leading to the major possible hazards that are pressure wave effect, thermal effect or toxic effect. |
| 4.2. Hazard Identification | The yearly frequency of occurrence for each scenario is taken into account. |
| 4.3. Frequency calculation | The consequences of a restricted number of scenarios is examined including:  
• Physical modelling of the effects: explosions, fire or toxic releases  
• Effects on road/ rail users and local population  
• Frequency of scenarios |
| 4.4. Consequence assessment | The method results in:  
• Societal risk (F/N curve)  
• Expected value (EV) : number of fatalities per year, obtained by integration of a F/N curve  
• Individual risk: risk to the local population due to an incident (frequency per year) |
| 5. Risk monitoring & evaluation | France: the result of the QRA method is an evaluation of risk levels obtained for a given set of alternative routes existing around a tunnel. The least risky route is |
selected on the basis of a quantified risk assessment. 

Austria: The results are compared to the threshold values for tolerable and non tolerable risk. Risk mitigating measures are suggested, alternative routes are investigated.

<table>
<thead>
<tr>
<th>5.1. Risk-informed decision making</th>
<th>France: A tunnel is authorised to accept transport of dangerous goods according to the ADR categorisation method.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2. Risk acceptability criteria</td>
<td>France: The least risky route is selected</td>
</tr>
<tr>
<td>Austria: threshold values for tolerable and non tolerable risk are available (Figure 5.1).</td>
<td></td>
</tr>
</tbody>
</table>

References:


1.1.2 Hazard Identification

In the table below are some main characteristics of the 13 representative scenarios.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HGV fire 20 MW</td>
</tr>
<tr>
<td>2</td>
<td>HGV fire 100 MW</td>
</tr>
<tr>
<td>3</td>
<td>Bleve of LPG in cylinder</td>
</tr>
<tr>
<td>4</td>
<td>Motor spirit fire</td>
</tr>
<tr>
<td>5</td>
<td>VCE of motor spirit</td>
</tr>
<tr>
<td>6</td>
<td>Chlorine release</td>
</tr>
<tr>
<td>7</td>
<td>Bleve of LPG in bulk</td>
</tr>
<tr>
<td>8</td>
<td>VCE of LPG in bulk</td>
</tr>
<tr>
<td>9</td>
<td>Torch fire of LPG in bulk</td>
</tr>
<tr>
<td>10</td>
<td>Ammonia release</td>
</tr>
<tr>
<td>11</td>
<td>Acrolein in bulk release</td>
</tr>
<tr>
<td>12</td>
<td>Acrolein in cylinder release</td>
</tr>
<tr>
<td>13</td>
<td>Bleve of liquefied CO2</td>
</tr>
</tbody>
</table>

*Representative accidental scenarios: 13 scenarios in QRAM versions 3.6

HGV = Heavy goods vehicle

1.1.3 Situation in France

Circular 2000- 82 describes a new procedure concerning the definition of the restriction for transport of dangerous goods through road tunnels. Main requirement: evaluation of risk levels obtained for a given set of alternative routes existing around a tunnel. The choice of the least risky route is made on the basis of a quantitative risk assessment.
QRA is to be considered for all road tunnels with a length of more than 300 m. In the past 3 years 20 tunnels have been evaluated. This procedure has shown to give a good level of applicability in the overall decision.

On the basis of the original OECD/Piarc model, Ineris has followed up the development process in order to enhance the user-interface performance of the original model and to extend its capacities to the study of longer routes. The work was funded by the French government.

A two steps development process was decided as follows:
- enhance the user interface
- Implementation of GIS in order to extend capacities

In France a classification or grouping of dangerous goods is used, which is based on the ADR (European agreement concerning the International carriage of Dangerous Goods by Road). The QRAM incorporates accidents scenarios representing each of the groupings. With the aid of the QRA model a tunnel authorization can be determined. For example when a tunnel is authorized to accept grouping A carriages the tunnel will be allowed to admit vehicles carrying the most dangerous goods.

<table>
<thead>
<tr>
<th>Grouping</th>
<th>Description</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grouping A</td>
<td>All goods including all dangerous goods carriages authorized on open roads</td>
<td>Least restrictive</td>
</tr>
<tr>
<td>Grouping B</td>
<td>All carriages in grouping A except those which may to lead a very large explosion (‘hot BLEVE’ or equivalent)</td>
<td></td>
</tr>
<tr>
<td>Grouping C</td>
<td>All carriages in grouping B except those which may lead to a large explosion (‘cold Bleve’ or equivalent) or a large toxic release (toxic gas or volatile toxic liquid)</td>
<td></td>
</tr>
<tr>
<td>Grouping D</td>
<td>All carriages in grouping C except those which may lead to a large fire</td>
<td></td>
</tr>
<tr>
<td>Grouping E</td>
<td>No dangerous goods (except those which require no special marking on the vehicle)</td>
<td>Most restrictive</td>
</tr>
</tbody>
</table>

1.1.4 Situation in Austria

In the year 2001 the Federal Ministry of Transport, Innovation and Technology initiated an Austrian tunnel safety board. The question of tolerable risk was extensively discussed in the Austrian tunnel safety board. The members of this committee agreed on threshold values for tolerable and non tolerable risk (Figure 0.1).

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1 Please note that the groupings shown here are an example of how QRAM is used in France, this is not a harmonized European classification.
The basis for the threshold of non tolerable risk is that the risk in tunnels must not exceed that on open road. The threshold for tolerable risk is about the same magnitude as getting killed by a lightning or a similar natural disaster. Between these two thresholds there is an area of conditional tolerable risk. This is given the name ALARP-region (As Low as Rational Possible). Another principle is that each fatality is valued equally, i.e. the tolerated frequency for an incident causing ten fatalities is one tenth of that of an incident causing one fatality. This assumption defines the slope of the tolerance curves.

The software in combination with this definition makes it possible to assess the risk in existing tunnels. If the F/N curve of a tunnel is completely in the range of tolerable risk, no action is required. If the F/N curve touches the area of non tolerable risk, immediate action is required no matter what it costs. If the F/N curve is situated in the ALARP region, mitigation measures are necessary, but cost effectiveness can be taken into account.

The QRAM software in combination with this definition makes it possible to assess the risk for existing and planned tunnels. If the F/N curve of a tunnel is in the range of tolerable risk, no action is required. If the F/N curve touches the area of non tolerable risk, immediate action is required independent from costs. If the F/N curve is situated in the ALARP region, mitigation measures are necessary, but issues of cost effectiveness can be taken into account.

In a project funded by the Federal Ministry of Transport, Innovation and Technology the Institute for Transport Planning and Traffic Engineering carried out a QRA study for 13 selected Austrian tunnels. The tunnel length ranged from about one to ten kilometres. The selection covered uni- and bi-directional tunnels as well as a broad range of different ventilation systems. None of the analysed tunnels reaches the area of non tolerable risk. All F/N curves are situated more or less within the ALARP region. None is lying exclusively in the area of tolerable risk. Suggestions for risk mitigating measures were made.
1.2  Quantitative Risk Analysis Procedure for the Fire Evacuation of a Road Tunnel

1.2.1  Risk Analysis Comparison Scheme

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Type of risk assessment method</td>
<td>Quantitative risk analysis for a unidirectional road tunnel</td>
</tr>
<tr>
<td>2.</td>
<td>Objective</td>
<td>Using the described methodology gives the decision makers a good idea of the risk level in the tunnel. The results can suitably be used by decision-makers when deciding which resources should be spent on further safety installations for the tunnel.</td>
</tr>
</tbody>
</table>
| 3. | Type of accidents | Types of accidents included are  
* Fire  
* Explosion  
Fire accidents for cars and fire and explosion accidents for transport of flammable and explosive hazardous goods (gasoline, propane, and TNT) are included. |
| 4. | Methodology | The methodology consists of the following steps:  
* Definition of the tunnel  
* Identification of representative accident scenarios  
* Frequency determination  
* Consequence assessment, including a basic queue model and evacuation analysis  
* Risk mapping and interpretation  
* Risk reduction, ranking system for risk reducing measures  
* Tunnel Safety Management System |
| 4.1. | Structure | Several hazard identification methods are possible:  
* A simple procedure based on a literature study on information from tunnel fires and how they initiated and developed  
* More complicated methods such as Hazard and operability (HAZOP) analysis and What-if Analysis |
| 4.3. | Frequency calculation | The frequency per year of each scenario is determined. The procedure is based on the Swedish VTI model. A simple event tree is constructed including scenario’s and frequencies. Data sources of statistical information are:  
* PIARC 1999 [11], initial frequencies for scenarios involving passenger car and HGV fires  
* Information available for highways in Germany are used to determine the initial frequencies for each scenario involving hazardous goods[12].  
* Germany, Ernst Basler, 2001 [13]  
* Sweden, Räddningsverket, 1996 [15] |
| 4.4. | Consequence assessment | Consequences resulting from a flash fire, vapour cloud explosion, and a BLEVE, pressure wave resulting from a TNT explosion.  
* Consequences of fire on humans by  
  o Heat and direct radiant heat  
  o Concentrations of carbon monoxide, carbon dioxide, and low concentrations of oxygen  
* Evacuation possibilities from a tunnel |
4.5. Risk calculation

- Evacuation time: awareness time, reaction time and movement time
- Simple queue model

The frequency for each scenario is calculated as well as the consequence measured in number of casualties. The final societal risk is displayed in an F/N Curve.

5. Risk monitoring & evaluation

5.1. Risk-informed decision making

5.2. Risk acceptability criteria

The subject of risk acceptability criteria is discussed. Dutch and Swiss Risk criteria are shown as an example.

6. Risk reduction

Possible approaches for risk reduction:
- Reduce the evacuation time
- Prolong the time until hazardous conditions occur
- Reduce the probability of an accident occurring

Furthermore the importance of a Tunnel Safety Management system is stressed and examples are given.


1.2.2 Introduction

The reference document [4] explains the methodology using an illustrative straightforward example. A lot of numbers, rules of thumb, and assumptions are given, so that the reader can understand and even recalculate the example.

The methodology is a good starting point for further developing guidelines and routines for performing a QRA for a road tunnel. The methodology is appropriate to use in the initial stages of a tunnel project. It is a good tool to use in order to get an overview of the risk level in the tunnel. The results are a good basis to decide which safety systems are required to have an acceptable risk level in a certain tunnel. If the results show that the risk is acceptable compared to a defined risk criteria it is a good signal that the tunnel does not present a greater threat than any other risk object in that specific society.

The methodology presented [4] is appropriate to evaluate the risk levels in road tunnels, which is not to say that it is the only way of doing this. The most important issue is however that there exists some standard methodology when evaluating the safety in tunnels. It is believed that the suggested methodology is not too complicated and does not require too many resources when carried out for every tunnel project. It is important that a benchmarking study is carried out, especially in countries with many tunnels, using a standard methodology, this enables the decision-makers to get a feel for the risk level that is present and enables them to compare the risk levels in different types of tunnel solutions. In turn this helps in the process of increasing the safety in tunnels.
The suggested methodology does however need further development in the following areas in order to make the results trust worthier.

- Choosing relevant scenarios with assigned design fires.
- Determination of relevant frequencies, better statistical information is required
- Evacuation procedure, determination of relevant pre-movement times. How should pre-movement times be chosen?
- Some sort of standardised risk acceptance criteria.

These are points that have to be further developed, and the more effort that is spent on developing these points the more accurate the actual risk estimations will become.

1.2.3 Methodology

Structure

The methodology consists of the following steps:

- Definition of the tunnel
- Identification of representative accident scenarios
- Frequency determination
- Consequence assessment, including a basic queue model and evacuation analysis
- Risk mapping and interpretation
- Risk reduction, ranking system for risk reducing measures
- Tunnel Safety Management System

Definition of the tunnel

The characteristics of a tunnel can vary considerably, and therefore the tunnel under study should be clearly defined. Many of the characteristics can influence the consequences in case of an accident. Characteristics to be described are:

- General information, such as geometric data, traffic loads and Speed limits
- Evacuation possibilities
- Ventilation system
- Fire detection/suppression system
- Communication systems
- Drainage system
- Warning signage

Hazard identification

Several hazard identification methods are possible:

- a simple procedure based on a literature study on information from tunnel fires and how they initiated and developed
- more complicated methods such as Hazard and operability (HAZOP) analysis and What-if Analysis
Each scenario that is chosen is associated with a certain design fire. The growth rate and maximum size of the design fire represents an actual fire scenario involving the relevant type of vehicle. The design fire is generally based on worst case data for that type of vehicle giving the results in the largest and fastest developing fire. Design fires are given for cars, heavy goods vehicle, and hazardous goods transport. For the hazardous goods transport fires of gasoline and propane are taken into account as well as an explosion of TNT.

**Frequency determination**

The frequency per year of each scenario is determined. The procedure is based on the Swedish VTI model. A simple event tree is constructed including scenarios and frequencies.

Data sources of statistical information are:
- PIARC, 1999[11]: initial frequencies for scenarios involving passenger car and HGV fires
- Information available for highways in Germany [12] is used to determine the initial frequencies for each scenario involving hazardous goods,
- Ernst Basler, 2001,[13];
- Räddningsverket, 1996 [15].

**Risk acceptability criteria**

In order to interpret the risk from a QRA results have to be compared with given risk criteria or have the expertise necessary to interpret the results and somehow come to a conclusion if the level of risk is acceptable, unacceptable or acceptable given certain modifications or risk reducing procedures. Since the risk criteria vary in different countries it is difficult to generalise and say if the results are acceptable or not acceptable. Currently, risk criteria exist in a number of countries (Holland, Great Britain, Hong Kong, New South Wales (Australia), Switzerland, Canada and Santa Barbara (USA)), in Figure 0.2 the Dutch and Swiss risk criteria are illustrated [14]. Figure 0.2 shows that in some areas the F/N curve enters the unacceptable region. If this were to be the information that was to be displayed to the management of a tunnel project it would thus show that the project would not be acceptable from a risk viewpoint. Thus a further analysis would be required where the effects of certain safety systems would have to be considered.
Possible approaches for risk reduction are:
- A- Reduce the evacuation time
- B- Prolong the time until hazardous conditions occur
- C- Reduce the probability of an accident occurring

The reference document focuses on the first two approaches (A and B). In order to get an overview of the positive effects of a certain safety system it is of great help to develop a ranking system. One approach when developing a ranking system is to analyse the two time components (A and B). A detailed analysis should be carried out on each relevant safety system to assign a certain value to each of these safety systems. The ranking system can be used to evaluate safety systems, and can be a good tool for decision makers when deciding upon which resources should be spent. In order to do this one has to additionally consider the economics (initial costs, maintenance cost, life length, etc.) associated with each safety system. The result of the analysis is a value for each safety system, for example between 1 and 5 where 1 is the best and 5 the worst.

A short description of the following safety systems is given in the paper as well as the effects they could have on the end results of a QRA:
- Ventilation systems
- Suppression systems
- A well-established tunnel safety management system

*Figure 0.2 Risk criteria in different countries*
# 1.3 Dutch risk assessment for road tunnels

## 1.3.1 Risk Analysis Comparison Scheme

<table>
<thead>
<tr>
<th></th>
<th>Type of risk assessment method</th>
<th>Probabilistic risk assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Objective</td>
<td>A conceptual framework supporting the decision making process by providing a common language for all parties involved. The objective is to have a basis to establish safety objectives and criteria for underground infrastructure. The TunPrim model is designed to calculate the internal safety in two-bore tunnels with uni-directional traffic in each bore during normal operation.</td>
</tr>
</tbody>
</table>
| 3. | Type of accidents              | - Traffic disturbance without damage  
- Collisions  
- Fire  
- Explosion  
- Leakage of aggressive and toxic materials |
| 4. | Methodology                    | 4.1. Structure:  
- Identification of initial events  
- Identification of accident scenarios in an event tree, each branch of the event tree is a scenario  
- Frequency calculation for each scenario  
- Consequence assessment for each scenario  
- Calculation of the overall risk  
4.2. Hazard Identification: A set of hazards is available in TunPrim, which was obtained by hazard identification. The basis for the hazard identification is the integrated tunnel safety philosophy of the Centre for Tunnel Safety in the Netherlands. Specifically the stages of an accident are used (see also Appendix and SafeT D1-report).  
4.3. Frequency calculation: Event tree analysis  
4.4. Consequence assessment: Consequences for each branch of the event tree are calculated as the number of fatalities. Three categories of fatalities: “mechanical” victims, deaths due to very serious injuries or entrapment (unable to escape), death due to fires, explosions and/or exposure to toxic substances. Evacuation possibilities:  
- Free fleeing distance  
- Traffic jam  
4.5. Risk calculation: The risk is presented as the Expected Value (EV, the average number of deaths per year) and Societal Risk (F/N-curves, a graph of the cumulative frequency of the occurrence of N or more deaths). |
| 5. | Risk monitoring & evaluation   | 5.1. Risk-informed decision making  
5.2. Risk acceptability criteria: For probabilistic QRA, risk acceptance criteria have been defined for tunnel users: an individual risk of $1.0 \cdot 10^{-8}$ and a societal risk of $1.0 \cdot 10^{-1}/(F^*N)$ have been defined. However, these are test values which at the moment do not have a legal status in the Netherlands. |

1.3.2 Objective

Tunprim is part of a conceptual framework supporting the decision making process by providing a common language for all parties involved. The objective is to have a basis to establish safety objectives and criteria for underground infrastructure. The TunPrim model is designed to calculate the internal safety in two-bore tunnels with uni-directional traffic in each bore during normal operation.

1.3.3 Introduction

To support the internal safety evaluation of tunnels in the Netherlands, a Quantitative Risk Assessment (QRA) model named TunPrim has been developed. The risk assessment follows the well-known scheme consisting of (1) the identification of initial events/accident scenarios and their probability, (2) the calculation of the physical effects of each scenario and, (3) the calculation of the overall risk. This risk is presented as the Expected Value (EV, the average number of deaths per year) and Societal Risk (F/N-curves, a graph of the cumulative frequency of the occurrence of N or more deaths). The calculations are carried out in a spreadsheet (Excel).

Compared to fixed industrial facilities, the events leading to a traffic accident are relatively straightforward: collision or breakdown of one or more vehicles which may or may not carry hazardous materials. The most important scenarios appear to be vehicle fires and (to a lesser extent) the release of flammable or toxic gases or liquids. However, the course of events after the accident highly depends on specific circumstances such as the location within the tunnel, traffic conditions, detection and alarm, emergency response, etc. In order to keep track of all factors that should be taken into account, an event tree was constructed containing several thousand branches.

For each individual branch of the event tree, the frequency and consequences (i.e. number of deaths) are calculated based on the events that are relevant for that branch. Finally, frequencies and consequences are aggregated over all accident scenario’s (i.e. event tree branches), resulting in an Expected Value and a Societal Risk Curve.

1.3.4 Type of accidents

The types of accidents included in the model are:
- Traffic disturbance without damage
- Collisions
- Fire
- Explosion
- Leakage of aggressive and toxic materials
- Disturbance of regular traffic flow without damage or health effects;
- Collision with only material damage;
- Accident with casualties, no potential for accident development (escalation);
• Accident without casualties which may however develop to a serious calamity (escalation potential);
• Accident with casualties and with escalation potential

Fires and toxic or flammable releases have been taken into account in the scenario descriptions.

1.3.5 Methodology

Structure

• Identification of initial events
• Identification of accident scenarios in an event tree, each branch of the event tree is a scenario
• Frequency calculation for each scenario
• Consequence assessment for each scenario
• Calculation of the overall risk

Hazard Identification

A set of hazards is available in TunPrim, which was obtained by hazard identification. Application of a risk assessment by the user of TunPrim may lead to a smaller selection of hazards, but the set of hazards can not be increased by the user.

The hazard identification method used by the developer of TunPrim is described in this paragraph. To identify the key issues for safety improvement, the processes that occur in the pre- and post-accident phases were described, including accident generation, the accident itself and the accident development. The methodology describes the processes’ time dependency, the information exchange between the different entities involved (organisations, individuals and monitoring and communication systems), and the role and effectiveness of the different processes regarding prevention and mitigation of accidents.

Frequency calculation

The basic events (causes) of every system failure mode are assessed by a fault tree analysis. The frequencies are calculated using an event tree analysis.

Accident conditions

The TunPrim model is designed to calculate the internal safety in two-bore tunnels with unidirectional traffic in each bore during normal operation. The model distinguishes between the horizontal and the ascending/descending parts of a tunnel, to account for differences in accident frequencies and behaviour of pools of released hazardous liquids.

The accident conditions are further determined by the following “events”:
- a. period of the day (day, night or rush hour);
- b. uni- or bi-directional traffic;
- c. occurrence of traffic jams (in front of the accident, behind the accident or both);
- d. accident type (vehicle breakdown, only material damage, accident with casualties);
- e. type of vehicle(s) (car, bus or truck);
- f. cargo carried by trucks (not flammable -or empty-, flammable, or explosive cargos, or bulk transport.
of dangerous goods);
g. type of release of dangerous goods (none, instantaneous failure, large hole, small hole);
h. fire (yes/no).

**Accident response**
The model also describes the accident response phase, which includes:
a. detection and alarm,
b. alarm response (i.e. automatic or operator action),
c. artificial tunnel ventilation (at present only longitudinal ventilation is incorporated in the model) and
d. escape possibilities.

Four incident detection modes have been included in the model:
1. speed detection, i.e. the automatic detection of the reduction of the average speed or movement which is an indicator of some sort of traffic disturbance (within one minute after the incident);
2. detection of accidents by road users when communication equipment is present in the tunnel (5 minutes after the incident);
3. automatic fire detection (visibility measurements - within 5 minutes-, vs. carbon monoxide or temperature measurements - after 15 minutes-);
4. operator detection, considered to occur not later than 15 minutes after serious incidents.

For tunnels equipped with automatic speed and/or fire detection systems coupled to automatic actions (starting ventilation, closing the tunnel, etc.), the possibility of overruling these actions by the operator (resetting of the command) is included in the model.
If the tunnel has no coupling of automatic detection and actions, the probability of the operator action depends on the type of detection, the presence and use of an emergency push button and the probability of manually starting the response actions.

The number of road users who have to escape from the tunnel is determined at the time when the accident bore is closed or –if this occurs sooner- when the effects for all road users occur. Fleeing is only possible when the emergency exits have been made available (unbolted).

**Consequence assessment**

In the TunPrim model the consequences are calculated as the number of fatalities, which complies with the broadly applied quantitative risk assessment approach. Three categories have been defined: deaths due to the accident itself (“mechanical” victims), and deaths in the accident vehicles, that can not escape due to very serious injuries or entrapment, or among other road users (i.e. those not involved in the accident) due to fires, explosions and/or exposure to toxic substances.

The algorithms to calculate the victims for the first two categories are relatively simple. The number of mechanical victims is derived from the data on the average number of casualties per casualty accident (tunnels and open roads).

The number of victims in accident vehicles is calculated from the number of injuries per casualty accident, the probability to be trapped or seriously injured and the probability to die from the
consequences of the scenario. The number of casualties among the other road users is calculated in a less straightforward manner. For each scenario of the event tree one or two maximum effect distance “upstream” and “downstream” of the incident are determined. The number of road users present in the tunnel is calculated from the length of the traffic jams in front of and behind the accident. “Free fleeing distances” have been determined, depending on the scenario (i.e. the effect distance) and the ventilation regime.

Within a “free fleeing distance” from the emergency exits, all road users are supposed to be able to escape the tunnel bore. The remaining road users in each effect distance (i.e. too far from an emergency exit) have a certain lethality probability while fleeing (this lethality percentage depends on the scenario). When an accident blocks an emergency exit road users near the accident will suffer a higher lethality, due to their increased fleeing distance. For certain scenarios there is also an effect distance outside the tunnel modelled.

The lethality probabilities for similar scenario’s depend on:

- the vehicle type and cargo load -except the dangerous goods- (representing the maximum fire load) and accident type (representing the time to reach the maximum fire load after ignition) for fires (all scenario’s lead to heat radiation and exposure to toxic fumes and smoke, at the time the maximum fire load of trucks with explosives is reached an explosion is assumed to occur);
- the release size, evaporation rate and toxicity of toxic liquids (all scenarios lead to toxic exposures);
- the release size, evaporation rate and time of ignition of flammable liquids (scenarios with direct ignition will lead to a pool fire; scenarios with delayed ignition can also lead to a gas cloud explosion);
- the release size (for jets also the direction of the release) and toxicity of toxic gasses (all scenario’s lead to a toxic exposure, for instantaneous releases also the pressure effects of the BLEVE – Boiling Liquid Expanding Vapour cloud Explosion- are taken into account).
- the release size (for jets also the direction of the release) and time of ignition of flammable gasses (instantaneous scenario’s with direct ignition will lead to a BLEVE, continuous scenarios with direct ignition will lead to flares -fire exposure-, delayed ignition will lead to explosions and scenarios without ignition can also lead to deaths when the gas replaces the oxygen in the tunnel).

Risk calculation

The risk is presented as the Expected Value (EV, the average number of deaths per year) and Societal Risk (F/N-curves, a graph of the cumulative frequency of the occurrence of N or more deaths).

1.3.6 Risk Monitoring and Evaluation

Risk-informed decision making

The exchange of information between the different actors in the processes is described in diagrams. Safety goals were formulated for representative information flow patterns.

Risk acceptability criteria
For probabilistic QRA, risk acceptance criteria have been defined for tunnel users: a personal risk of $1.0 \cdot 10^{-8}$ and a societal risk of $1.0 \cdot 10^{-7} / (F \cdot N)$ have been defined. However, these are test values that do not have a legal status in the Netherlands.
1.4 TUSI – a model predicting the frequency of traffic accidents in Norwegian Road Tunnels

1.4.1 Risk Analysis Comparison Scheme

<table>
<thead>
<tr>
<th></th>
<th>Type of risk assessment method</th>
<th>Frequency assessment method, based on statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Objective</td>
<td>To calculate the number of traffic incidents, accidents, and fires in new and existing road tunnels</td>
</tr>
<tr>
<td>2</td>
<td>Type of accidents</td>
<td>Types of accidents included: Personal injury accidents, material damage only accidents, fires in private cars and HGV and incidents (cases where a vehicle has stopped involuntary inside a tunnel).</td>
</tr>
</tbody>
</table>

4. Methodology

4.1. Structure

TUSI is a frequency assessment method

4.2. Hazard Identification

N.A.

4.3. Frequency calculation

This is the essence of the method. The following variables are taken into account in the model:

- Accident rate on equal road section i.e. sections with equal or similar geometry covering the tunnel itself and 50 m in front of the tunnels;
- Speed limit
- One or two way traffic
- AADT (average Annual Daily Traffic)
- HGV (% of AADT)
- Length of the tunnel
- Number of lanes in each direction
- Geometry (both horizontal and vertical)

4.4. Consequence assessment

N.A.

4.5. Risk calculation

N.A.

5. Risk monitoring & evaluation

Accident rate, number of accidents, number of car fires (private cars and HGV) as well as incidents are calculated.

5.1. Risk-informed decision making

N.A

5.2. Risk acceptability criteria

N:A technical risk acceptance criteria are not used in Norway


1.4.2 Introduction

TUSI² is a model predicting the frequency of traffic accidents in Norwegian road tunnels. The Institute of Transport Economics has developed the model for the Road Transport Safety Department of Public Roads Administration in Norway. The model is used for calculating number and frequencies

² “TUSI” is an Acronym for Tunnel Safety in Norwegian
of personal injury accidents, material damage only accidents, fires in private cars and HGV and incidents (cases where a vehicle has stopped involuntary inside a tunnel) in Norwegian road tunnels. The model is based on the experience from more than 700 existing tunnels on the National road network, with an accumulated tunnel length of almost 600 km. 400 tunnels are 500 m or shorter while 40 tunnels are longer than 3000 m. Data from other countries have also been used in the development process.

The model is developed to calculate the accident rate, the number of accidents and the number of car fires in new, planned, tunnels.

The following variables are taken into account in the model:
• Accident rate on equal road section, not in tunnel, in the same area
• Speed limit
• One or two way traffic
• AADT (Average Annual Daily Traffic)
• % HGV traffic
• Length of the tunnel
• Number of lanes in each direction
• Geometry (both horizontal and vertical)

In the model the tunnel can be divided into up to 11 more or less “similar” zones on basis of vertical or horizontal geometry (or number of lanes). Special calculations are made for a zone 50 m outside the tunnel (zone 1), the first 50 m inside the tunnel (zone 2), and the next 100 m inside (zone 3) and the rest of the tunnel (zone 4 – the mid-zone). A tunnel with two-way traffic and two entrance zones at each end then has the maximum of 7 different zones in the middle where the number of lanes and geometry can differ from one zone to the other.

Figure 0-3 shows an example of a model-calculation of a new 7260 m sub-sea tunnel between two counties on each side of the Oslo fjord.

The average accident risk for the whole tunnel is 0,041 accidents per mill vehicle-km, while it in the zone 50m outside the tunnel (zone 1) is 0,108 acc/mill vehicle-km. Within the tunnel the accident rate varies between zones from 0,039 in the safest mid-zone to 0,087 in the entrance zone (zone 2). The table in the middle shows detailed results from each of the 11 zones within the tunnel, and for the two zones 50 m outside the tunnel in both directions.
## Results Oslofjorden

<table>
<thead>
<tr>
<th>Lane</th>
<th>Acc rate</th>
<th>Acc/year</th>
<th>Year/acc</th>
<th>Travel X 1000 vehkm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra 1</td>
<td>0.029</td>
<td>0.064</td>
<td>15.6</td>
<td>2205.52</td>
</tr>
<tr>
<td>1</td>
<td>0.043</td>
<td>0.243</td>
<td>4.1</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.052</td>
<td>0.179</td>
<td>5.6</td>
<td>5649.90</td>
</tr>
<tr>
<td>Extra 2</td>
<td>0.054</td>
<td>0.145</td>
<td>6.9</td>
<td>2699.18</td>
</tr>
<tr>
<td>1</td>
<td>0.039</td>
<td>0.221</td>
<td>4.5</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0.076</td>
<td>13.2</td>
<td>2933.80</td>
<td></td>
</tr>
<tr>
<td>Extra 5</td>
<td>0.026</td>
<td>0.076</td>
<td>2.2</td>
<td>11282.88</td>
</tr>
<tr>
<td>SUM</td>
<td>0.041</td>
<td>0.464</td>
<td>2.2</td>
<td>11282.88</td>
</tr>
</tbody>
</table>

### Div lengths

<table>
<thead>
<tr>
<th>Acc rate</th>
<th>0.123</th>
<th>0.100</th>
<th>0.065</th>
<th>0.043</th>
<th>0.027</th>
<th>0.024</th>
<th>0.042</th>
<th>0.042</th>
<th>0.040</th>
<th>0.055</th>
<th>0.075</th>
<th>0.092</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num/year</td>
<td>0.009</td>
<td>0.008</td>
<td>0.010</td>
<td>0.016</td>
<td>0.013</td>
<td>0.004</td>
<td>0.032</td>
<td>0.126</td>
<td>0.072</td>
<td>0.003</td>
<td>0.008</td>
<td>0.006</td>
</tr>
<tr>
<td>Year/acc</td>
<td>106.0</td>
<td>131.0</td>
<td>99.7</td>
<td>6.0</td>
<td>78.6</td>
<td>244.8</td>
<td>31.5</td>
<td>7.9</td>
<td>14.0</td>
<td>324.0</td>
<td>118.2</td>
<td>173.3</td>
</tr>
<tr>
<td>Length m</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>2543</td>
<td>367</td>
<td>100</td>
<td>863</td>
<td>1937</td>
<td>1100</td>
<td>50</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Slope%</td>
<td>-6.5</td>
<td>-7.1</td>
<td>-7.1</td>
<td>-7.1</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>7.0</td>
<td>7.0</td>
<td>6.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

### Summary different Zones

<table>
<thead>
<tr>
<th>Zone</th>
<th>Length (meters)</th>
<th>Travel X1000 vehkm</th>
<th>%</th>
<th>Accident rate pr mill vehkm</th>
<th>Accidents/year</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>100</td>
<td>100</td>
<td>153.30</td>
<td>153.30</td>
<td>1.36</td>
<td>0.108</td>
</tr>
<tr>
<td>Zone 2</td>
<td>100</td>
<td>200</td>
<td>153.30</td>
<td>153.30</td>
<td>1.36</td>
<td>0.087</td>
</tr>
<tr>
<td>Zone 3</td>
<td>200</td>
<td>7260</td>
<td>306.60</td>
<td>11129.58</td>
<td>98.64</td>
<td>0.060</td>
</tr>
<tr>
<td>Zone 4</td>
<td>6960</td>
<td>10669.68</td>
<td>10669.68</td>
<td>11129.58</td>
<td>98.64</td>
<td>0.039</td>
</tr>
<tr>
<td>SUM</td>
<td>7360</td>
<td>7360</td>
<td>11282.88</td>
<td>11282.88</td>
<td>100.00</td>
<td>0.041</td>
</tr>
</tbody>
</table>

**Figure 0-3 TUSI example**
1.5 NASA Probabilistic Risk Assessment method

1.5.1 Risk Analysis Comparison Scheme

<table>
<thead>
<tr>
<th></th>
<th>Type of risk assessment method</th>
<th>Probabilistic Risk Assessment Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Objective</td>
<td>Probabilistic Risk Assessment for the air and space industry. The method is developed for air and space safety, however is on a global/general level.</td>
</tr>
<tr>
<td>3</td>
<td>Type of accidents</td>
<td>N.A.</td>
</tr>
<tr>
<td>4</td>
<td>Methodology</td>
<td></td>
</tr>
</tbody>
</table>

4.1. Structure

The methodology consists of the following steps:
- Objectives definition
- System familiarisation
- Identification of initiating events
- Scenario modelling
- Failure modelling using e.g. Fault Trees
- Data collection, analysis and development
- Quantification and integration
- Uncertainty analysis
- Sensitivity analysis
- Importance ranking

4.2. Hazard Identification

Identification of initiating events, Master Logic Diagrams (MLD), Failure Mode and Effect Analysis (FMEA)

4.3. Frequency calculation

Fault Tree, data included are e.g.: component failure rate data, initiating event frequencies, structural failure probabilities, human error probabilities, process failure probabilities, and common cause failure probabilities. Uncertainty bounds and uncertainty distributions also represent each datum.

4.4. Consequence assessment

Event tree, data included are e.g.: repair time data. Uncertainty bounds and uncertainty distributions also represent each datum.

4.5. Risk calculation

The Fault Trees – or the results of an accident simulation – appearing in the path of each accident scenario are logically linked and quantified, usually using an integral probabilistic risk assessment computer program. Scenarios are grouped according to the end state of the scenario defining the consequences. All end states are then grouped, i.e., their frequencies are summed up into the frequency of a representative end state.

The risk data are further investigated using uncertainty analysis, sensitivity analysis and importance ranking techniques.

5. Risk monitoring & evaluation

5.1. Risk-informed decision making

N.A.

5.2. Risk acceptability criteria

N.A.

1.5.2 Methodology
In Figure 0.4 the tasks of a probabilistic risk analysis and their interrelationship are displayed. In the following sections individual tasks are outlined.

**Objectives definition**
The objectives of the risk assessment must be well defined, and the undesirable consequences of interest (end states) must be identified and selected. These may include items like extent of harm to humans or environment (e.g., injuries or deaths) or economic losses.

**System familiarisation**
System familiarisation covers all relevant design and operational information including engineering and process drawings as well as operating and emergency procedures. If the probabilistic risk assessment is performed on an existing system that has been operated for some time, the engineering information must be on the as-built rather than on the as-designed system. Visual inspection of the system at this point is recommended if possible.

If the risk influence of modifications to the existing system is to be evaluated, familiarisation has to include detailed information on the planned modifications.

**Identification of Initiating Events**
The complete set of Initiating Events that serve as trigger events in sequences of events (accident scenarios) leading to end states must be identified and retained in the analysis. In more complex cases it is recommended to accomplish this task with special types of top-level hierarchies, like master logic diagrams (MLDs), or with techniques like Failure Mode and Effect Analysis (FMEA). Independent Initiating Events that lead to similar scenarios are grouped and their frequencies are summed up to evaluate the group initiator frequency.

**Scenario modelling**
The modelling of each accident scenario proceeds with an inductive logic and probabilistic tool called event tree (ET). An event tree starts with the initiating event and progresses through the scenario, a series of successes or failures of intermediate events called pivotal events, until an end state is reached.

A graphical tool called event sequence diagram (ESD) can first be used to describe an accident scenario because it lends itself better to engineering thinking than does an event tree. The event sequence diagram must then be converted into an event tree for quantification.
Failure modelling

Each failure (or its complement, success) of a pivotal event in an accident scenario is usually modelled with a deductive logic and probabilistic tool called fault tree (FT). A fault tree consists of three parts. The top part is the top event of the fault tree and is the given pivotal event defined in an accident scenario. The middle part of the fault tree consists of intermediate events (failures) causing the top event. These events are linked through logic gates (e.g., AND gates and OR gates) to the basic events, whose failures ultimately causes the top event to occur. The fault trees are then linked and simplified (using Boolean reduction rules) to support quantification of accident scenarios.

If the pivotal event is not determined by failure or success of a system (or a component), but by certain criteria of a physical process (e.g., exceedance of a temperature), than – instead of a fault tree - a simulation of the process of interest can be used for quantification of this element.

Data collection, analysis, and development

Various types of data must be collected and processed for use throughout the probabilistic risk assessment process. This activity proceeds in parallel, or in conjunction, with some of the steps described above. Data are assembled to quantify the frequency of accident scenarios and accident contributors. Data include component failure rate data, repair time data, initiating event frequencies, structural failure probabilities, human error probabilities (HEPs, see SafeT workpackage 5), process failure probabilities, and common cause failure (CCF) probabilities (see SafeT workpackage 5). Uncertainty bounds and uncertainty distributions also represent each datum.

Quantification and integration

The fault trees – or the results of an accident simulation – appearing in the path of each accident scenario are logically linked and quantified, usually using an integral probabilistic risk assessment computer program. The frequency of occurrence of each end state in the event tree is the product of the initiating event frequency and the (conditional) probabilities of the pivotal events along the scenario linking the initiating event to the end state. Dependencies between several fault trees (e.g. from the systems supplying electrical power), used for the quantification of an event tree, have to be taken into account. Scenarios are grouped according to the end state of the scenario defining the consequences. All end states are then grouped, i.e., their frequencies are summed up into the frequency of a representative end state.

Uncertainty analysis

As part of the quantification, uncertainty analyses are performed to evaluate the degree of knowledge or confidence in the calculated numerical risk results (see also section 3.3.3). Monte Carlo simulation models are generally used to perform uncertainty analysis, although other methods exist.

Sensitivity analysis

Sensitivity analyses are also frequently performed in a probabilistic risk assessment to indicate analysis inputs or elements whose value changes cause the greatest changes in partial or final risk results. They are also performed to identify components in the analysis to whose quality of data the analysis results are or are not sensitive.

Importance ranking

In some probabilistic risk assessment applications, special techniques are used to identify the lead, or dominant, contributors to risk in accident sequences or scenarios. The identification of lead contributors in decreasing order of importance is called importance ranking. The steps, outlined in sections 3.3.1 to 3.3.10, including illustrations of the models and data used, are described in detail in [10].

Limited-scope and Simplified probabilistic risk assessment
Besides the full-scale probabilistic risk analysis method described above, NASA [10] also describes a “limited-scope” and a “simplified” probabilistic risk analysis method.

A “limited-scope” probabilistic risk assessment is one that applies the steps outlined above with the same general rigor as a full-scale probabilistic risk assessment but focuses on IEs, scenarios or end-states of specific decision making interest, instead of all applicable elements of a probabilistic risk assessment. The scope should be defined on a case-by-case basis, so that its results can provide specific answers to pre-identified questions, rather than assess all relevant risks. Uncertainty analysis should be performed for a limited scope probabilistic risk assessment.

A “simplified” probabilistic risk assessment is one that applies essentially the same process outlined above, but identifies and quantifies major (rather than all) risk contributors (to all end states of interest) and generally applies to systems of lesser technological complexity or systems having less available design data than those requiring a full-scope probabilistic risk assessment. Thus, a simplified probabilistic risk assessment may contain a reduced set of scenarios or simplified scenarios designed to capture only essential risk contributors.

References


References from [4]:


