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Sammendrag
I samarbeid med Sveitsiske vegmyndigheter er det utviklet et nytt kvantitativt risikoanalyseverktøy basert på såkalte Bayesiske nettverk. Modellen, som heter TRANSIT, beregner risiko for trafikkulykker og skadde og drepte, samt brannfrekvenser i tunneler basert på en lang rekke geometriske- og trafikale størrelser som beskriver tunnelen. Prinsippet ved beregningsmetoden går ut på å dele tunnellen/tunellsystemet inn i homogene delparseller og foreta separate beregninger for hver del og deretter addere resultatet til å gjelde hele tunnelen.

Summary

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Imprint

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This document can be downloaded at www.astra.admin.ch

The software ***TRANSIT*** is available on demand: contact@matrisk.com

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Summary

According to the Directive 2004/54/EC (European Parliament (2004)) of the European Parliament and of the Council, all Members States at the national level of 'detailed and well-defined methodology, corresponding to the best available practices' available for risk analysis in road tunnels and to inform the Commission about this practice. The methods should correspond to the best practice and may be merged into a single, Europe-wide methodology.

The aim of this research project is to develop and compile a 'best practice' methodology for the risk analysis of road tunnels. The 'best practice' method is applicable in principle for European road tunnel, but customized particular types of tunnels, which are relevant in Switzerland and Norway.

The 'best practice' method is developed to support decisions regarding the planning, operation and maintenance of road tunnels. The method has the following characteristics:

Focused: The method supports relevant decisions regarding the planning, operation and maintenance of road tunnels. These decisions aim at meeting the minimum safety requirements and at the same time using the available resources optimally for risk reduction, i.e. cost-efficient risk-reducing measures.

Innovative: The method represents the 'Best Practice' and combines the latest research and technology in traffic engineering and in the field of risk and safety research.

Consistent: Uncertainty and causal relationships in the risk modelling can be modelled using Bayesian networks. This allows a consistent account of new information, e.g. in the form of data or improved models.

Transparent: The methodology is documented in a transparent way and allows for continuous critical reflection and, if necessary, refinement and improvement of the models can be undertaken when new research results and experience are available. Evidence of lack of knowledge are clearly identified and reported.

Actionable: The method is implemented in an MS-Excel ® based software tool. The computer-based model can be used without any Particular knowledge about probabilistic modelling, however, it is strongly advised that the model is used only by qualified persons, who are familiar with tunnel safety and are able to acknowledge the limitations of the application of the program.

It should also be noted that the application of the model is subject to a fee to the user group managing the program. See contact details on the imprint page.

The results of this research project are summarized in this report. It contains a complete documentation of the method, an analysis of existing accident data, a user manual for the software tool and an outlook on further research and suggestions for future surveys. A main component of the project is to develop an MS-Excel ® based software tool for risk assessment available on request from the authors.

The project was carried out in close cooperation with the national road authorities of Norway and Switzerland. The project was supported by both parties, national road authorities of Norway and the FEDRO, jointly financed.

Zusammenfassung

Gemäss der Richtlinie 2004/54/EC (European Parliament (2004)) des Europäischen Parlaments sollen alle Mitgliederstaaten auf nationaler Ebene über ‘eine präzise, genau definierte und optimaler Praxis entsprechende Methodik‘ zur Risikoanalyse in Strassentunneln verfügen und die Kommission über diese Methoden informieren. Die Methoden sollen der verfügbaren ‚Besten Praxis‘ entsprechen und eventuell zu einer einheitlichen, europaweit gültigen Methodik zusammengeführt werden.

Das vorliegende Forschungsprojekt hat die Entwicklung und Zusammenstellung einer ‚Beste Praxis‘ Methode für die Risikoanalyse von Strassentunneln zum Ziel. Die ‚Beste Praxis‘ Methode ist prinzipiell anwendbar für europäische Strassentunnel, ist aber insbesondere auf Tunneltypen, welche in der Schweiz und in Norwegen von Bedeutung sind, zugeschnitten.

Die ‚Beste Praxis‘ Methode wird entwickelt, um Entscheidungen bezüglich der Planung, des Betriebes und des Unterhalts von Strassentunneln zu unterstützen. Die Methode hat folgende Eigenschaften:

Zielgerichtet: Die Methode unterstützt die relevanten Entscheidungen bezüglich der Planung, des Betriebes und des Unterhalts von Strassentunneln. Entscheidungen zielen darauf ab, die Mindestsicherheitsanforderungen einzuhalten und die verfügbaren Mittel optimal in risikoreduzierende Massnahmen einzusetzen, das heisst risikoreduzierende Massnahmen kosteneffizient einzusetzen.

Wegweisend: Die Methode manifestiert eine ‚Beste Praxis‘ und vereint den Stand der Forschung und Technik im Verkehrsingenieurwesen und im Bereich der Risiko und Sicherheitsforschung.

Konsistent: Unsicherheiten und kausale Zusammenhänge in der Risikomodellierung werden mit Hilfe von Bayes’schen Netzen modelliert. Dies erlaubt eine konsistente Berücksichtigung von neuer Information, z.B. von neuen Daten oder verbesserten Modellen.

Transparent: Die Methodik ist transparent dokumentiert und erlaubt eine kontinuierliche kritische Reflektion und ggfs. Verfeinerung und Verbesserung der verwendeten Modelle, wenn neue Forschungsergebnisse und Erfahrungen zur Verfügung stehen. Klare Hinweise auf fehlende Erkenntnisse werden identifiziert und angegeben.

Umsetzbar: Die Methode wird in ein MS-Excel® basiertes Software Tool implementiert. Das Computer-basierte Modell kann ohne besondere Kenntnisse probabilistischer Modellierungen verwendet werden. Es wird empfohlen, dass das Modell nur von qualifizierten Personen verwendet wird, die mit Tunnelsicherheit vertraut sind und in der Lage die Grenzen der Anwendung des Programms zu erkennen sind.

Es sollte auch darauf hingewiesen werden, dass für die kommerzielle Anwendung des Modells eine Gebühr für den User Group entfällt.

Die Ergebnisse dieses Forschungsprojektes sind in diesem Bericht zusammengestellt. Er enthält eine vollständige Dokumentation der Methode, eine Analyse von bestehenden Unfalldaten, eine Bedienungsanleitung für das Softwaretool und einen Ausblick auf weiteren Forschungsbedarf und Vorschläge für zukünftige Datenerhebungen. Hauptbestandteil des Projektes ist die Entwicklung eines MS-Excel® basiertes Softwaretool für die Risikoermittlung, welches auf Anfrage bei den Autoren erhältlich ist.

Das Projekt wurde in enger Zusammenarbeit mit den nationalen Strassenbehörden von Norwegen und der Schweiz durchgeführt. Das Projekt wurde von beiden Parteien, nationalen Strassenbehörden von Norwegen und dem ASTRA, gemeinschaftlich finanziert.

Résumé

Selon la Directive 2004/54/CE (Parlement européen (2004)) du Parlement européen et du Conseil, tous les États membres au niveau national d'une "méthodologie détaillée et bien définie, correspondant aux meilleures pratiques disponibles" pour l'analyse des risques dans les tunnels routiers et d'informer la Commission sur cette pratique. Les méthodes correspondant aux meilleures pratiques disponibles peuvent être fusionnées en une seule méthodologie à l'échelle européenne.

Le but de ce projet de recherche est le développement et compilation d'une méthode de «meilleures pratiques» pour l'analyse des risques dans les tunnels routiers. La méthode des «meilleures pratiques» est en principe applicable pour le tunnel routier européen, mais a être personnalisé des types particuliers de tunnels, qui sont pertinentes en Suisse et la Norvège.

La méthode de «meilleures pratiques» est conçue pour appuyer les décisions concernant la planification, l'exploitation et l'entretien des tunnels routiers. La méthode présente les caractéristiques suivantes:

Focalisée: Le procédé de l'aide à la décision pertinente concernant la planification, l'exploitation et l'entretien des tunnels routiers. Les décisions visent à répondre aux exigences minimales de sécurité et les ressources disponibles de façon optimale du risque de mesures de réduction, soit de réduction des risques des mesures visant à une utilisation rentable.

Innovante: La méthode représentant la "meilleure pratique" combine les dernières recherches et technologies dans la science du trafic et dans le domaine des risques et la recherche de sécurité.

Consistante: Les relations de cause à effet dans l'incertitude et la modélisation des risques peuvent être modélisés en utilisant les réseaux bayésiens. Ceci permet une description cohérente de nouvelles informations, par exemple sous la forme de données ou de modèles améliorés.

Transparente: La méthodologie est décrite d'une manière transparente et permet une réflexion critique continue et, si nécessaire, affiner et améliorer les modèles utilisés lorsque les résultats de nouvelles recherches et l'expérience sont disponibles. Des preuves d'un manque de connaissances sont identifiées et signalées.

Réalisable: Le procédé est mis en œuvre avec un logiciel basé sur MS-Excel ®. Le modèle informatique peut être utilisé sans aucune connaissance particulière sur la modélisation probabiliste, cependant, il est fortement conseillé que le modèle est utilisé uniquement par des personnes qualifiées, qui sont familiers avec la sécurité des tunnels et sont capables de reconnaître les limites de l'application du programme.

Il convient donc de noter que l'application du modèle est soumis à une redevance au User Group de gérer le programme. Voir les coordonnées sur la page "Imprint".

Les résultats de ce projet de recherche sont résumés dans le présent rapport. Il contient une documentation complète de la méthode, une analyse des données d'accidents existants, un mode d'emploi pour le logiciel et les perspectives pour de nouvelles recherches et des suggestions pour de futures enquêtes. Une composante principale du projet est le développement d'un outil logiciel programmé sur MS-Excel ® pour l'évaluation de risques. Le programme est disponible sur demande auprès des auteurs.

Le projet a été réalisé en étroite collaboration avec les autorités routières nationales de la Norvège et la Suisse. Le projet a été soutenu par les deux parties, les autorités routières nationales de la Norvège et l'OFROU, qui sont cofinancés.

0 Introduction

Tunnels constitute nowadays an important component of an efficient infrastructure. Whereas the purpose of tunnels is to facilitate reliable transport in respect of urban and natural environment, the tunnel safety remains an issue of major concern. Consequently the topic of tunnel safety constitutes an important decision criterion for the planning of new tunnels as well for the management of the operation tunnels. When striving for safety in road tunnels, there is a need for a rational and consistent basis for decision making concerning safety and methods and tools which facilitate that life safety risk can be assessed, documented and communicated transparently.

In the last decades, a significant development has taken place in the area of systematic risk assessment. New formulations have been developed and standardized by e.g. the Joint Committee on Structural Safety (JCSS). Modern risk assessment provides a consistent basis for supporting decisions on tunnel risk management. On this basis, it is possible to improve the understanding on which factors are dominating the risks and by which measures the risks may be efficiently reduced; this concerns both technical and organizational measures.

The safety of the tunnels in Europe was increasingly questioned in the late part of the 1990'ies on the background of the fatal tunnel catastrophes in among others the Channel Tunnel (1996), Mont Blanc Tunnel (1996), Tauern Tunnel (1999), Gleinalm Tunnel (2001) and Gotthard Tunnel (2001). These major accidents resulted in more than 70 fatalities and 120 serious injured and gave a signal within EU to initiate a number of common projects in order to survey the shortcomings and problem and upgrade existing tunnels in Europe. The projects were initiated in the period 1996-2003 and were concluded 2002-2007; also Norway and Switzerland participated actively in these projects (see an overview in Appel et al. (2009) and ERS2: OECD/ PIARC, DARTS, FIT, UPTUN. Virtual Fires, Safetunnel, Sirtaki, Safe-T etc.)

On the background of the public concern and the results of the research projects, the EU issued the 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 (European Parliament (2004)). Among a number of prescriptive minimum requirements, the directive also specifies risk analysis in order to validate and substantiate the tunnel design.

These requirements are in line with the efforts in leading public and industrial organizations to implement new formulations integrating risk considerations into their organizations in the daily management and decision making. This is e.g. the case concerning the AGB1[1] project recently completed by the Swiss federal road authorities FEDRO.

In order to coordinate and harmonize the developments, the Directive 2004/54/EC (European Parliament (2004)) invites the national road directories of all EU member states (and associated countries like Switzerland and Norway) to report on their methodologies for assessing risk in road tunnels. It is with this background that the cooperation between the federal road authorities of Switzerland (FEDRO) and Norway (NPRA) was initiated aiming at developing a joint “best practice” methodology and a corresponding tool for the risk assessment of tunnels. The present document describes the developed methodology and documents the tool resulting from this collaboration.

1 See http://www.aramis.admin.ch/Default.aspx?page=Grunddaten&projectid=19807 for further details (online accessed in August 2010)

0.1 Aim of the project

The main objective of this research project is the development of a 'best practice' method for road tunnel risk assessment under normal traffic situations. The method represents the current state of the art in the field of risk based decision making and in the field of traffic engineering, especially in the field of modeling of traffic accident frequencies and the consequences of accidents in road tunnels. The method is generally applicable to all road tunnels but it specifically takes into account the needs, regulatory requirements and tunnel layouts, which have been identified to be relevant for Switzerland and Norway. The method is easy to apply and supports typical life safety-related decisions during the planning, operation and maintenance of road tunnels.

0.2 Requirements of risk analyses in the EU directive

Based on this, the Directive 2004/54/EC of The European Parliament (2004) requires that risk assessments for tunnels are performed if specific conditions are prevailing, as it is summarised in the following.

Article 13: Risk analysis *(1) a) Risk analyses, where necessary, shall be carried out by a body which is functionally independent from the tunnel manager.* *b) The content and the results of the risk analysis shall be included in the safety documentation submitted to the Administrative Authority.* *c) A risk analysis is an analysis of risk for a given tunnel, taking into account all design factors and traffic conditions that affect safety, notably traffic characteristics, tunnel length, type of traffic and tunnel geometry, as well as the forecast number of heavy goods vehicles per day.* *(2) Member States shall ensure that a detailed and well-defined methodology, corresponding to the best available practices, is used uniformly at national level and shall inform the Commission of the methodology applied which will make this information available in electronic form to other Member States.*
Annex I *1. Basis for deciding on safety measures* *1.1.3 When a tunnel has a special characteristic as regards the aforementioned parameters, a risk analysis (…) shall be carried out to establish whether additional safety measures and/or supplementary equipment is necessary to ensure a high level of tunnel safety. This risk analysis shall take into consideration …* *Safety parameters* *- tunnel length,* *- number of tubes,* *- number of lanes,* *- cross-sectional geometry,* *- vertical and horizontal alignment,* *- type of construction,* *- uni-directional or bi-directional traffic,* *- traffic volume per tube (including its time distribution),* *- risk of congestion (daily or seasonal),* *- access time of the emergency services,* *- presence and percentage of heavy goods vehicles,* *- presence, percentage and type of dangerous goods traffic,* *- characteristics of the access roads,*

- lane width, *- speed considerations,* *- geographical and meteorological environment.*

Hence, the minimum requirement to the risk analysis is that it shall take into account the above-mentioned parameters.

Furthermore, risk analyses are required in order to support decisions on safety measures and deviations from the prescribed measures, which are mentioned under the section specifying the conditions for design and operation of the tunnel the directive.

1.2 Minimum requirements *1.2.1 (…) Limited deviations from these requirements may be allowed provided that the following procedure has been completed successfully: (…) the alternative risk reduction measures which are to be used or reinforced in order to ensure at least an equivalent level of safety, including proof therefore in the form of an analysis of relevant risks.*
2.2 Tunnel geometry *2.2.1 Safety shall be specially taken into consideration when designing the cross-sectional geometry and the horizontal and vertical alignment of a tunnel and its access roads, as these parameters have a large influence on the probability and severity of accidents.* *2.2.2 Longitudinal gradients above 5% shall not be permitted in new tunnels, unless no other solution is geographically possible.* *2.2.3 In tunnels with gradients higher than 3%, additional and/or reinforced measures shall be taken to enhance safety on the basis of a risk analysis.* *2.9.3 In tunnels with bi-directional and/or congested unidirectional traffic, longitudinal ventilation shall be allowed only if a risk analysis according to Article 13 shows it is acceptable and/or specific measures are taken, such as appropriate traffic management, shorter emergency exit distances, smoke exhausts at intervals.*
3.7 Transport of dangerous goods *The following measures shall be applied concerning access into tunnels of vehicles transporting dangerous goods, (…) perform a risk analysis in accordance with Article 13 before the regulations and requirements regarding dangerous goods through a tunnel are defined or modified; (…) consider specific operating measures designed to reduce the risks and related to all or parts of the vehicles transporting dangerous goods in tunnels (…), on a case by case basis further to the aforementioned risk analysis.*
3.8 Overtaking in tunnels *A risk analysis shall be carried out in order to decide whether heavy goods vehicles should be allowed to overtake in tunnels with more than one lane in each direction*

0.3 State of the art in risk assessment and tunnel safety

In the last decade, a number of European research projects have been conducted in the field of risk assessments for tunnels, among others, UPTUN (2006), DARTS (2004a) DARTS (2004b) DARTS (2004c), FIT (2007) and PIARC (1999) as well as ERS2: OECD/ PIARC, Virtual Fires, Safetunnel, Sirtaki and Safe-T.

The findings from these projects form the basis for the development of a uniform methodology which represents the best practice in field of tunnel risk assessments. As mentioned before, the results of these projects were also partly the basis for the EU directive.

The theoretical foundation used for the risk assessment for this project has been developed by the JCSS (2008) and Schubert and Faber (2009). The results of this project have been followed up in the project Faber et al. (2009) and a methodology for an uniform risk assessment for the Swiss road network was developed. The results of this project form the framework and precondition for an efficient, transparent and communicable treatment of risks and they facilitate that risks from different sources are treated in the same manner and assessed on the same basis so that they are comparable, may be aggregated and transparently documented and communicated.

PIARC has been one of the main initiators for promoting safety in tunnels and has among others initiated the ERS2 project in collaboration with OECD for harmonising the risk analysis and regulation of transport of dangerous goods. This topic has been ratified by UNECE and the ADR prescribes the risk analysis methodology for determining five predefined groups of restrictions for transport of dangerous goods through road tunnels.

In the report PIARC C3.3 Risk Analysis for Road Tunnels PIARC (2008), PIARC has followed up on the risk analysis methods used in Europe.

In the report is mentioned that the following countries have several years experience in application of risk analyses: Canada, France, United Kingdom, The Netherlands, Norway, Sweden and USA. Furthermore it is stated that the following countries are in the stage of developing and implementing new methodologies for risk analysis: Austria, Czech Republic, Denmark, Germany, Italy, Portugal and Switzerland.

For four countries, risk analysis methods are mentioned, namely for Austria (TuRisMo), the Netherlands (two models: a scenario analysis method and Tunprim), France (the Specific Hazard Investigation method), Italy (risk analysis approach, the Nowegian TUSI model also is mentioned and also the international model QRA developed by OECD/PIARC in the ERS2 project mentioned above.

The available models, however, present far from a uniform methodology to assess risks in road tunnels. Existing analysis methods vary in their approach, theoretical basis, their aim and in their level of detail.

When considering a quantitative systems-approach only the Austrian, to some degree the Italian, the Norwegian and the Dutch models apply. These models have been tested in a benchmark study in a workshop of ITACOSUF (International Tunneling Association Committee of Safety of Underground Facilities). The conclusion was that "the comparison shows that the aim and validity of each selected program hampers to do a proper benchmarking (because of different types of risk, specifically dedicated for different countries, etc)".

- RWSQRA version 1.1 and version 2.0 (1.1 also known as TunPrim), Netherlands; has focus on fire risks and dangerous goods but not on traffic accidents.

- TuRisMo, Austria; a simplified event tree analysis - only a few indicators can be taken into account in the analyses.

- TUSI, Norway; with a focus on accidents, incidents and fire

- QRAM (OECD – PIARC), International; with the aim to support decisions in regard to routing of dangerous goods only.

A proper validation of the methods can only be undertaken by comparing the predictions of risks with real observed consequences. This is a difficult task especially for rare events and in principle all models suffer from this fact. However, it can be checked if the assumptions which are made in the development of the model can represent the reality in a sufficient manner and if all relevant indicators are considered to support the decision making.

This also concerns implicit assumptions which are made by using event trees such as Markovian assumptions and the assumptions of independence of different events. These aspects apply to all models and approaches – to the model which is developed in this project and will be presented in the following sections.

1 Part I / Methodology

1.1 General Approach

The general approach utilized in the present project differs significantly from those mentioned in Chapter 0.2. The major difference is that the system is modelled and analyzed by using Bayesian Probabilistic Networks (BPN's) which results in a hierarchical indicator based risk model. Simplified, BPN's can be considered as an advancement of event trees. They provide the possibility to fully represent simple event trees but also dependencies between different indicators and consequences can be considered. They are also efficient in regard to the graphical representation of complex systems so that they facilitate to make plausibility checks in regard to causal relations between different indicators. Bayesian Networks represent the current state of the art in the risk assessment.

This report describes the status of the methodology implemented into the software tool ***TRANSIT*** version 1.0 in May 2011.

1.1.1 Definition of risk

Even though it may be understandable from the context of discussion what is meant by the different words it is necessary in the context of engineering decision making to be precise in the understanding of risk. Risk is to be understood as the expected consequences associated with a given activity, the activity being e.g. the operation of a road tunnel.

Considering an activity with only one event with potential consequences C the risk R is the probability that this event will occur P multiplied with the consequences given the event occurs i.e.:

$$R = P \cdot C \tag{1.1}$$

If e.g. n independent events with consequences C_i and occurrence probabilities P_i may result from the activity the total risk associated with the activity is simply assessed through the sum of the risks from the individual events, i.e.:

$$R = \sum_{i=1}^{n} P_i \cdot C_i \tag{1.2}$$

This definition of risk is consistent with the interpretation of risk used e.g. in the insurance industry and risk may e.g. be given in monetary terms or the number of accidents, injuries or fatalities. Even though most risk assessments have some focus on the possible negative consequences of events, the definitions in Equations (1.1) - (1.2) is also valid in the case where benefits are taken into account. In fact the definition in Equations (1.1) - (1.2) is more general and consistent with expected utility utilized as basis for decision analysis, see Faber (2009).

Equation (1.2) seems to be quite simple and in general it is simple. The remaining question is how to calculate P_i and C_i. Both should represent the real world with all possible influences and dependencies. Finding an appropriate representation of the real world in order to calculate these two figures can be regarded as the main challenge, consequently the intention of the following Sections is to illustrate how these figures are calculated in this project.

1.1.2 Generic system representation

The road tunnel users as well as the operators of road tunnels are exposed to various risks which have different causes. One major cause, however, is the traffic situation respectively the events of accidents. Fire events as consequence of accidents or due to technical problems with engine or brakes are also events which must be considered in road tunnel risk assessments.

In general, risks have to be considered in both the planning phase and the operational phase (including planning and management of maintenance) of tunnels since risks can efficiently be reduced by technical and organizational measures. Two different classes of measures can be differentiated: one class concerns the reduction of the exposure, i.e. the reduction of the accidents and fire frequency and the other class concerns the reduction of the consequences when a fire or an accident occurs. The main criterion in the planning phase of such measures is the cost efficiency of the measures. In order to judge the efficiency of measures, the influence of the measure on the risk has to be quantified.

In the project Faber et al. (2009), a risk informed decision support methodology was developed for the Swiss federal road authorities - FEDRO. A main focus in the project concerns the assessment of the efficiency of risk reducing measures for the planning, the operation and the maintenance of the infrastructure at road system level at object level as well as at portfolio level. A key feature of this methodology is that the uncertainties and the dependencies of the parameters, which are explicitly considered for the modelling of event frequencies and consequences, are quantified and accounted for. The system constituents are modelled using so called risk indicators which can represent the system in a generic manner, i.e. all possible configurations of the system can be represented by using an appropriate choice of the indicators.

From this definition, it is clear that the choice of the indicators plays a major role in the risk assessment and of course, any choice cannot be exhaustive. The European Parliament (2004) suggests a minimum list of indicators; these are design factors and traffic conditions that affect safety, notable traffic characteristics and type, tunnel length and tunnel geometry, as well as the forecasted number of heavy goods vehicles per day (see also Chapter 0.2). These indicators can be used to establish a generic system representation. In Figure 1.1 the general idea of such a generic system representation is shown. This representation is simplified and should be regarded as an illustrative example.

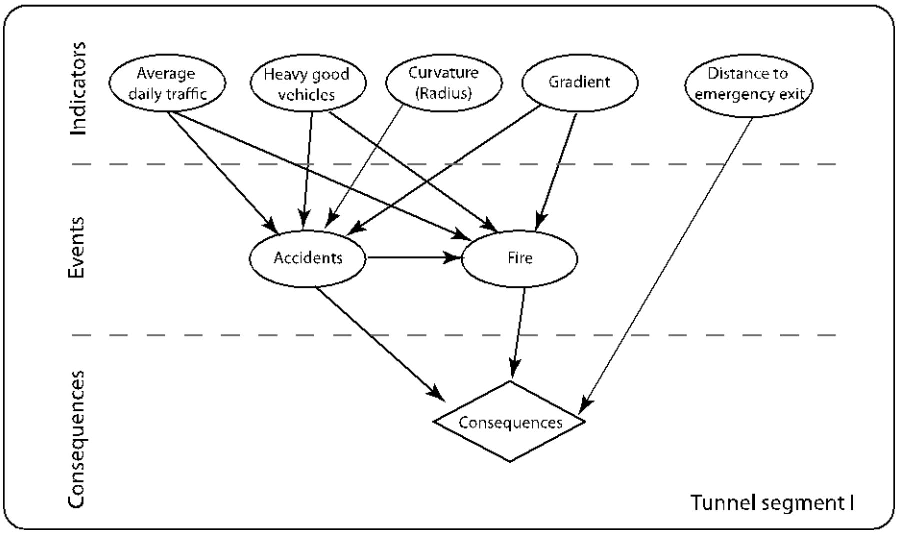


Figure 1.1: Simplified illustration of a generic system representation using a BPN.

In Figure 1.1 a tunnel segment is represented by several relevant risk indicators, i.e. the average annual daily traffic volume, the fraction of heavy goods vehicles (HGV), the curvature (i.e. the radius) of the segment and the maximum distance to the next emergency exit. These indicators are regarded as being causal influence factors on the risk, i.e. their specific values directly influence the risk. Qualitatively speaking, a high gradient in a tunnel segment leads to an increase in the accident rate and to an increase in the fire frequency. The links in Figure 1.1 indicate the causal relations between the risk indicators, the modelled events and the corresponding consequences. The dependencies in the model can be described by using empirical or physical models as well as available data. The formulation of the model, which is shown in Figure 1.1, provides a high degree of flexibility (see also Chapter 1.1.3). All available information can be considered and assembled in one model.

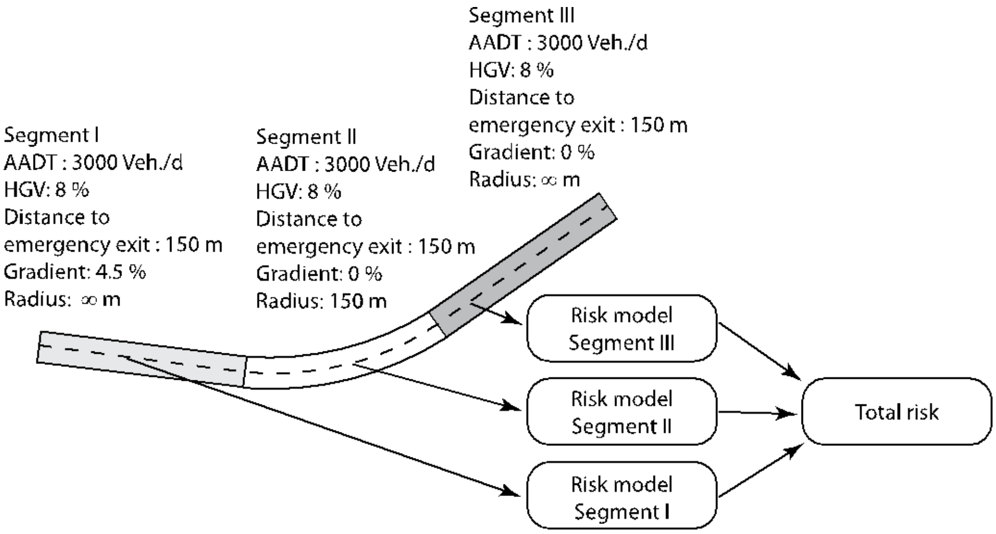


Figure 1.2: Combining single segment models to calculate the total risk.

The single segment model given in Figure 1.1 is then used to model the whole tunnel. Therefore, a hierarchical approach is employed. The entire tunnel is modelled by first defining homogeneous segments. Homogeneous means in this context that all considered indicators have the same value in a certain segment of the tunnel. This segment can then be regarded as one homogeneous segment. Since the length of the segments may significantly vary, here the risk is modelled by using rates. These rates are then transferred into an absolute value taking into account the traffic volume and the length of the section.

In Figure 1.2 the hierarchical model is shown. In this example the tunnel consists of three homogeneous segments in which the values of the risk indicators are constant. The information of the values for each segments are considered in the segment model, which is given in Figure 1.1. On a higher hierarchical level, the results of each segment are aggregated and the total risk is calculated (see Figure 1.2).

In the present version of the methodology, not all events in tunnels are explicitly addressed. The user of the model has to consider whether additional studies will have to be undertaken, e.g. studies on the structure, of the ventilation system, etc.

1.1.3 Introduction into Bayesian Networks

The general approach utilized in the present project differs significantly from those mentioned in Chapter 0.2. The major difference is that the system is modelled and analyzed using Bayesian Probabilistic Networks (BPN's) which results in a hierarchical indicator based risk model. Simplified, BPN's can be considered as an advancement of event trees. They provide the possibility to fully represent simple event trees but also dependencies between different indicators and consequences can be considered. They are also efficient with respect to the graphical representation of complex systems so that they facilitate making plausibility checks considering causal relations between different indicators. Bayesian Networks represent the current state of the art in risk assessment.

Bayesian Probabilistic Networks (BPN) have been developed in the mid of the 1980ies with the motivation to deal with information from different sources and interpret and establish coherent models (Pearl (1985)). Today, Bayesian Networks are widely used in systems with artificial intelligence, expert systems for diagnosing diseases (Kahn et al. (1997)) but also in the engineering sector (e.g. Faber et al. (2002)). They are used due to their flexibility and efficiency in regard to system representation. Also in spam filters and in search functions in the IT sector, Bayesian Networks are broadly utilized.

An introduction to Bayesian Probability Networks is given in detail in Annex I.

1.2 Structure of the Bayesian Network

In this Chapter, the structure of the developed Bayesian Networks for the risk assessment in road tunnels is presented. All calculations of tunnel risks are performed using Bayesian Networks. This network can be regarded as the core of the risk-analysis tool.

The total network can be divided into four logical parts, i.e. the:

- Hazard model for accidents,
- Hazard model for fires in tunnels,
- Consequence model for accidents and
- Consequence model for fires in tunnel
- Dangerous good incident model

Since many of the risk indicators are interrelated and in order to maximize the efficiency of the calculations, the different logical parts have been combined into one network. The network is given in Figure 1.3. The network is in principle the same for Norway and Switzerland; however, the prior probabilities for the risk indicators differ (see Chapter 1.4). The methodology and the underlying models are the same and if the information on the risk indicators would be the same, the model would give the same result for Switzerland and for Norway. Only if information on one or more of the indicators differs or is not available, the models yield different results for the two countries.

The BPN shown in Figure 1.3 contains 39 nodes and 58 links. Each node represents an indicator whereas some of the indicators are observable, some indicators are logical observable and some indicators are logical non observable.

The basic data, i.e. the accident rates, fatality rate per accident, fire rate etc. are incorporated in the nodes, as explained in the individual subsections of Chapter 1.3.

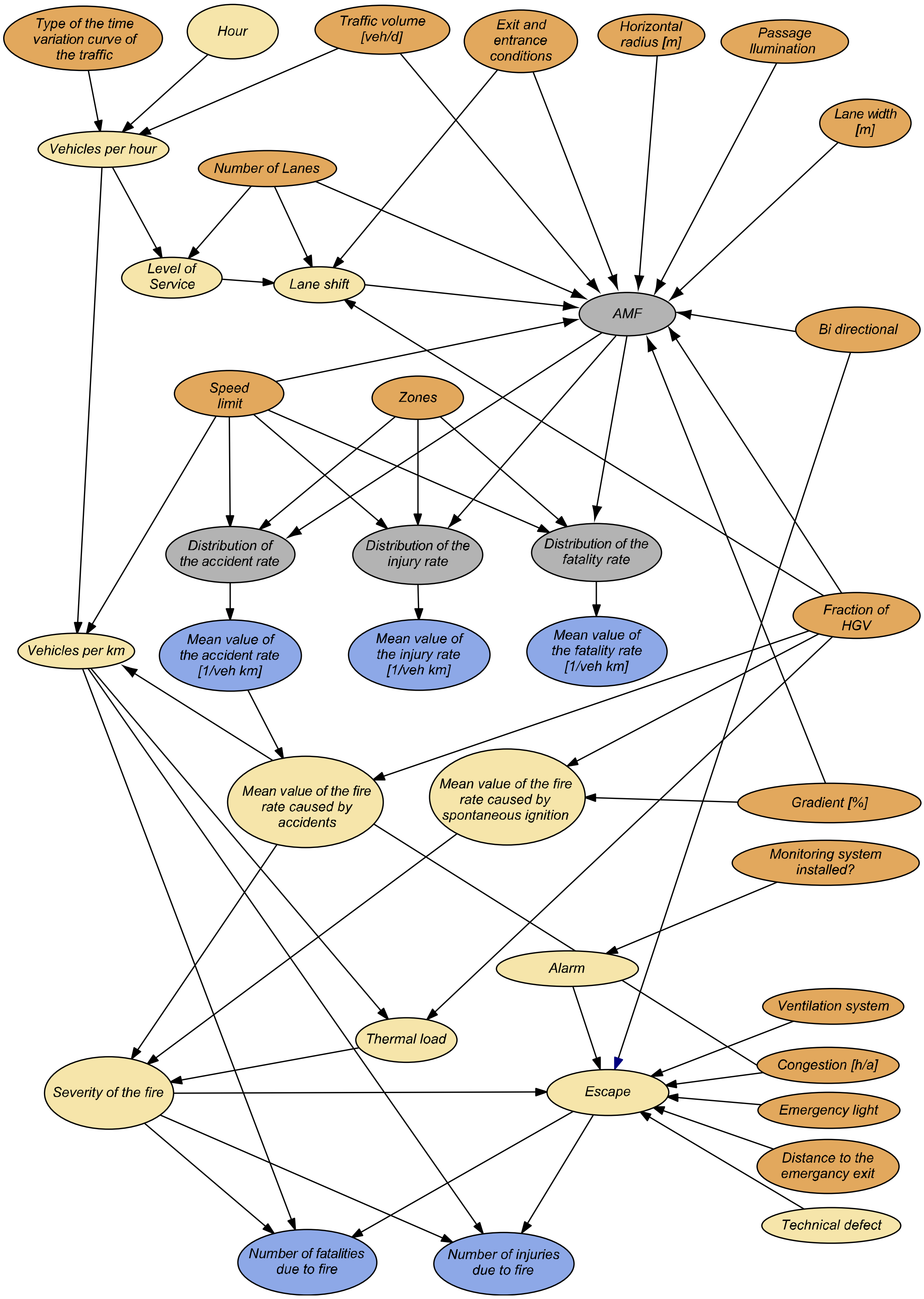


Figure 1.3: Bayesian Probabilistic Network of the hazard model for vehicle accidents in one tunnel segments.

The indicators are divided into the observable indicators and intermediate logical nodes.

Observable indicators

The observable indicators correspond to the indicators which are used to model the risk and they can be seen as input parameters for the analysis. Here, the following indicators have been considered (orange nodes in Figure 1.3)

- Time variation of the traffic during the hours of the day.(six different general types A-F are considered)
- Traffic volume [veh./d] (for one direction): average annual daily traffic pr direction.
- Exit and entrance conditions (for underground intersections).
- Bi directional traffic versus unidirectional traffic in each tunnel tube.
- Horizontal radius [m] of the alignment.
- Tunnel lighting.
- Lane width [m].
- Number of lanes per direction [#].
- Speed limit [km/h].
- Zones (depending on the segment location in the tunnel).
- Fraction of the HGV [%] (heavy good vehicles).
- Gradient [%].
- Monitoring system.
- Ventilation system.
- Congestion [h/a].
- Emergency light.
- Distance to the emergency exit [m].

An overview over of the nodes and the associated conditional probability tables are given in Table 1.1.

Intermediate nodes

The yellow nodes in Figure 1.3 are logical intermediate nodes. They contain information which is relevant to calculate the risk. They are calculated in dependency of the input of the user. These nodes are:

- Hour of the day
- Vehicles per hour depending on the AADT and the daily variation
- Level of service (the degree of free flow of the traffic)
- Lane shift (here a result depending on vehicles per hour and number of lanes. The indicator could also be have been defined as observable).
- Vehicles per kilometre (an intermediate node depending on vehicles per hour and speed limit)
- Severity of the fire (an intermediate node based on fire rate and thermal load, the node could also have been defined as open for direct input)
- Thermal load (an intermediate node based on vehicles per km and fraction of HGVs, the node could also have been defined as open for direct input)
- Alarm (an intermediate node with fixed input related to monitoring)
- Escape (an intermediate node based on distance to emergency exit, ventilation system, congestion rate, emergency light, alarm and technical defects in the equipment)
- Mean value of the fire rate caused by accidents (an intermediate node determining the fire rate based on the accident rate and the fraction of HGV)
- Mean value of the fire rate caused by spontaneous ignition. (an intermediate node determining the fire rate based on the gradient and the fraction of HGV)

- Technical defect (a fixed input node indicating the general reliability of technical systems).

With exception of the node *Level of service* the information on the marginal distribution of these nodes are not provided to the user. However, the information is contained in the Bayesian network and could also be given if it is decided at a later point of time.

Outcome

The following consequence indicators in the BPN for accidents are defined. These nodes contain information which is used to calculate the current risk in a specific tunnel segment. They represent the outcome of the hazard model and the consequence model for accidents (blue nodes in Figure 1.3).

- Accident rate (per vehicle km).
- Injury rate (per vehicle km).
- Fatality rate (per vehicle km).

The following consequence indicators for fire events in a tunnel segment have been considered:

- Number of fatalities due to tunnel fires.
- Number of injuries due to tunnel fires.
-

It is obvious that the number of fatalities and injuries due to a tunnel fire is not restricted to a single tunnel segment. The number of fatalities in the tunnel refers to the total number of fatalities and injuries in a tunnel given a fire in a specific tunnel segment. The assumption is made that the probability of two independent and simultaneous fire events in two different tunnel segments is negligible small. That does not imply that the fire cannot jump over to other tunnel segments. Thus, for fire events the consequences in the entire tunnel are taken into account.

Additionally, the observable indicators, these are the grey nodes in Figure 1.3 are not observable (or not directly observable) indicators, i.e.

- AMF, Accident Modification Factor.
- Distribution of the accident rate.
- Distribution of the injury rate.
- Distribution of the fatality rate.

The node denoted with AMF represents the so called Accident Modification Factors which are commonly used in accident prediction models (see also Chapter 1.3).

Table 1.1: Description of the nodes in BPN of the hazard model for accidents, see also Figure 1.3 and the further explanation in Chapter 1.2.

#	Node	Description	Size CPT [States x Conditions]	Label
1	Type of the time variation curve of the traffic	A: pronounced peak in the morning. B: peak in the morning combined with small peak in the afternoon. C: relative equally distributed traffic during the day. D: Pronounced peak in the morning and in the afternoon. E: pronounced peak in the afternoon, small peak in the morning. F: pronounced peak in the afternoon	6 x 1	Type A, Type B, Type C, Type D, Type E, Type F,
2	Traffic volume	Annual average daily traffic volume per direction	28 x 1	300, 600, 1000, …, 20000, 25000, …, 60000
3	Exit and Entrance conditions	Exit and entrance characteristics in the tunnel Label 1: No intersection Label 2- 41 Various combinations of exit, entrance and ramp lengths	41 x 1	1, 2, …, 41
4	Bi directional	Contra flow in the tunnel	2 x 1	Yes, No
5	Fraction of the heavy good vehicles	Fraction of the heavy good vehicles of the total annual average traffic volume in [%]	21 x 1	1, 2, …, 18, 20, 24, 26
6	Tunnel lighting	Lighting Yes: in accordance with guideline No: No lighting	2 x 1	Yes, No
7	Horizontal radius	Horizontal radius of the tunnel [m]	34 x 1	10, 15, 20, …, 50, 60, …, 200, 250, …, 700
8	Gradient	Longitudinal gradient in [%] Upwards / downwards	27 x 1	0,0.25,0.5,… , 3, 3.5, …, 10
9	Lane width	Width of the single lanes in the tunnel in [m]	9 x 1	3, 3.25, …,5
10	Number of Lanes	Number of lanes per direction	3 x 1	1, 2, 3
11	Speed limit	Speed limit in the tunnel	9 x 1	40, 50, …, 120

#	Node	Description	Size CPT [States x Conditions]	Label
12	Zones	Tunnel zone defined by the distance from the tunnel portal	4 x 1	Zone 1, Zone 2, Zone 3, Zone 4 Zone 5 Zone 6 Zone 7
13	Vehicles per hour	Vehicles per hour per direction	20 x 4'320	100, 200, 400, …, 5000, 6000
14	Hour	Hours per day	24 x 1	1 o'clock, …,24 o'clock
15	Level of Service	A: Free flow. B: Reasonably free flow. C: Stable flow. D: Approaching un-stable flow. E: Unstable flow. F: Forced or break-down flow.	6 x 81	Quality level A, Quality level B, Quality level C, Quality level D, Quality level E Quality level F
16	Lane shift	Describes the intensity of lane shifts in the tunnel section	4 x 6'765	No, Low, Medium, High
17	AMF	Accident modification factor	86'045'887'872 x 15'622	0, 0.05, …, 5, 5.2, …, 10, 10.5, …, 20, 22, …, 30, 35, …, 175
18	Distribution of the accident rate	Distribution of the accident rate	462 x 6'516	0, 0.005, …, 2, 2.05, …, 3, 3.1, …,7
19	Distribution of the injury rate	Distribution of the injury rate	462 x 6'516	0, 0.005, …, 2, 2.05, …, 3, 3.1, …,7
20	Distribution of the fatality rate	Distribution of the fatality rate	201 x 6'516	0, 0.004, …, 0.8
21	Mean value of the accident rate	Mean value of the accident rate	2 x 462	0, 1
22	Mean value of the injury rate	Mean value of the injury rate	2 x 462	0, 1
23	Mean value of the fatality rate	Mean value of the fatality rate	2 x 201	0, 1
24	Mean value of the fire rate caused by acci-dents	Represent fires result-ing from accidents	2 x 42	0, 1
25	Mean value of the fire rate caused by spon-taneous ignition	Represent fires result-ing from other causes such as electrical or mechanical defects	2 x 567	0, 1
26	Severity of the fire	Severity of the fire after ignition	4 x 16	0 MW 5 MW 30 MW 100 MW
27	Thermal load	Indicator for the pres-ence of the thermal load in the tunnel	4 x 210	Low Medium High Very high
28	Alarm	Will an alarm be trig-gered?	2 x 2	yes, no

#	Node	Description	Size CPT [States x Conditions]	Label
29	Escape	Probability for a single person to escape successfully from fire and smoke	2 x 173'952	Yes, no
30	Monitoring system installed	Is a monitoring system installed in the tunnel?	2 x 1	Monitoring system No monitoring system
31	Ventilation system	Considers different ventilation systems in the tunnel.	9 x 1	Natural ventilation Longitudinal ventilation Longitudinal ventilation with active control Longitudinal ventilation with extraction Longitudinal ventilation with extraction and active control Semi transverse ventilation Semi transverse ventilation with active control Full transverse ventilation Full transverse ventilation with active control
32	Congestion	Considers that the traffic in the tunnel is congested.	2 x 1	Congested Uncongested
33	Emergency light	Is Emergency light installed in the tunnel, coupled with an emergency power supply system?	2 x 1	yes, no
34	Distance to the emergency exit	Distance from the actual point to the next (nearest) Emergency exit in [m].	151 x 1	0,10,…,1500m
35	Vehicles per kilometre	Vehicles per kilometre present in the tunnel as a proxy for the persons in the tunnel and the thermal load	8 x 360	10, 20,…, 70, 100, 120, 180, 220, 250, 300
36	Technical defect	Represents the case where the technical equipment in the tunnel is not working.	2 x 1	Technical defect No technical defect
37	Number of fatalities due to fire	Expected number of fatalities due to fires in the tunnel	21 x 80	0, 1, …,10,20,…100, 150, 200
38	Number of injuries due to fire	Expected number of injuries due to fires in the tunnel	14 x 80	0,10,.., 100, 150, 200, 400

The BPN helps also to see and understand the causal relation in the entire network. Some indicators have an influence on the risk on different locations. Every node which has a link to one or more other nodes introduces a kind of dependency in the network. One example is the indicator Bi-directional. Bi-directional traffic conditions have an influence on the accident frequency and on the probability that a person can escape in the case of ventilation controlled fire in a tunnel. This introduces dependencies in the network and a purely multiplicative approach, such as event tree formulations are not appropriate to model such a complex system. As shown in Figure 1.3 the BPN can consider such dependencies of different indicators.

It is assumed that in principle information on all indicators is available or can be obtained with a certain effort. If no information on a parameter is available, it is still possible to calculate the risk in the BPN. In this case, the prior distribution of the indicator is considered in the calculation. However, with little information about the actual tunnel, the risk analysis does not make much sense, and at least two indicators need to be known to calculate the risk, i.e. the length of the tunnel and the traffic volume per direction. Without the information about the configuration of the tunnel (number of tubes), the risk analysis should also not be carried out. The prior distribution and the models to calculate the risk are discussed and explained in the Chapter 1.4. The network is also dependent on the country for which it was developed. In the present version, two networks are available: one for Switzerland and one for Norway. The user specifies in the beginning of the analysis which BPN will be used in the analysis. The two BPNs differ presently only in the prior probabilities for the considered indicators. That implies that if information on all indicators is available, the result will be the same independent from the considered country. The structure of the network is the same for both countries.

1.3 Accident Modification Factor and accidents rates in tunnels

Accident Modification Factor

As it appears from Figure 1.3, the accident modification factor plays a central role in the combination of indicators and estimation of the risk for the actual tunnel.

The accident modification factor reflects the percentage reduction (or increase) in vehicle accidents rates that can be expected when one or more indicator deviates from the original state. A major question is what can be defined as the original state. Since accident statistics do normally not differentiate between different indicators, the mean accident rate in a highway network in one country can be regarded as the original state. This can be denoted with background accident rate (background injury rate and background fatality rates respectively) which corresponds to the mean value of the accident rate for the tunnels in the entire highway network.

The number of expected accidents in an arbitrary section in the highway network can then be calculated using the background accident rate in the case that no additional information is available. An AMF provides information on the expected proportional increase or reduction in the background accident rate on a highway section if more specific information becomes available.

The AMF is a normalized function of one or more indicators i, i.e. $AMF = f\left(i_1,..,i_n\right)$ with a definition range of [0, ∞]. The AMF are assessed with different methods and models for the different considered indicators. A detailed description is given in Chapter 1.4.

The size of the CPT of the node AMF in the Bayesian network (see Figure 3.13) contains 1’344’208’860’336’380 cells to account for all possible states of the parent nodes. The strength of BPN becomes at this stage obvious. An event tree formulation which would consider the same number of states of the indicators and the same number of indicators would have 1’344’208’860’336’380 branches at this stage of the calculation. This could be deemed as being complicated to be understandable at a glance while the BPN can still be printed on one page which helps to see and understand the dependencies between the considered indicators.

Background rates and tunnel zones

The background accident rate is the accident rate which can be observed on the entire tunnel network. It is the mean value of all accident rates. This rate is not dependent on the indicators and the Accident Modification Factor is used to decompose the background rate again to consider the different influencing factors. If it was possible to observe directly the different indicators in the data acquisition, the use of AMF would be obsolete. This would mean dedicated statistics for all combinations of traffic, tunnel lay-out, geometry, tunnel equipment etc. Since the tunnel designs are too diverse and the accidents, injuries and fatalities are too infrequent such statistics can hardly be established for all combinations. The concept of an accident modification factor (AMF) has the clear advantage that the models can be used and the results be extrapolated to conditions which are not directly observable. If statistics becomes available for some of the combinations, the existing prior distribution can be updated with this new information.

From statistics of tunnel accidents, it is observed that the accident rates show a variation over the tunnel length. Amundsen and Ranes (1997) have defined 4 different tunnel zones. It was observed that many accidents occurred in the approaching road just outside the entrance, also just inside the portal a concentration of accidents was observed whereas relatively few accidents occurred in the mid zone of the tunnel (Hovd (1981; Amundsen and Engebretsen (2009)). On the other hand, the investigations also revealed that the consequences are more severe at the tunnel interior.

In later studies, this observation was investigated in more detail and the concentration of accidents at the portals and the increased consequences at the interior were confirmed (See also the figures in Table 1.4). With these observations, it seems reasonable to discretize the tunnel in different zones for each traffic direction. Amundsen and Ranes (1997) proposed a reasonable discretization of the tunnel in four different zones in order to consider this phenomenon (Figure 1.4):

Zone 1: Last 50 m before the tunnel portal.
Zone 2: First 50 meters within the tunnel.
Zone 3: Next 100 meters into the tunnel.
Zone 4: 150 meters from the tunnel portal, mid-zone of the tunnel.

The same discretization is used in ***TRANSIT***. Conceptually the discretization is extended to the exit zones of the tunnel and three more zones are considered here (see Figure 1.4) i.e.

Zone 5: 150 meters to 50 meters before the exit portal.
Zone 6: 50 meters to 0 meters before the exit portal.
Zone 7: next 50 meters after the tunnel portal.

Due to the lack of data, the exit zones, i.e. zone 5, zone 6 and zone 7 are approximated by observations in the entrance zones. It is obvious that only tunnels with a length of more than 300 m contain all seven zones.

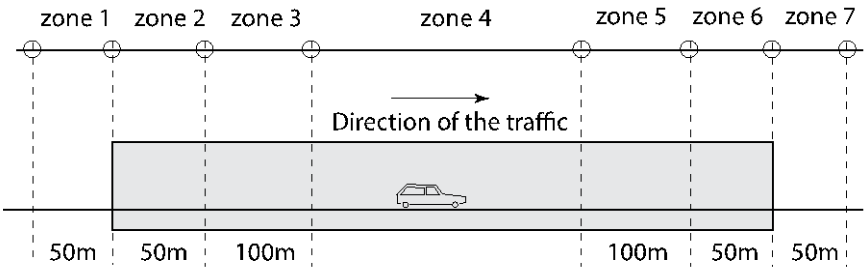


Figure 1.4: Illustration of the different tunnel zones in the tunnel.

In the node "zones" in ***TRANSIT***, it is specified in which particular zone the homogeneous segment lies.

The background accident rates calculated by using the data published in Amundsen and Engebretsen (2009) and in Amundsen and Melvær (1997) for the different tunnel zones are given in Table 1.2. Both studies on tunnel accidents contain the most comprehensive data on tunnel accidents available. Table 1.2 shows also the background injury rates and the background fatality rates in tunnels.

For ***TRANSIT***, data from both of the before mentioned studies is combined. It is assumed that the recently collected data has more explanative power and thus this information is given a higher weight in the model. The data from the early 1990th is weighted with 0.3 and the data from the early 2000'ies is weighted with 0.7.

Accidents are defined as injury accidents, implying that the injury rate is larger than the accident rate. The data given in Table 1.2 indicates that in average around 1.4 Persons are injured in an injury accident

The following definition for different types of injuries is given[2]:

- **Killed:** People who die within 30 days after the accident from injuries related to it.
- **Very seriously injured**: Life-threatening injuries or injuries of a permanent character.
- **Seriously injured:** Major, but not life-threatening injuries.
- **Slightly injured**: Minor fractures, scratches etc. Hospitalization is not required.
- **Severely injured**: A blanket term for “very seriously injured” and “seriously injured”.

Table 1.2: Background rates for the different zones in the tunnel.

		Background rate [mio. veh. km]		
		1992-1996	2001 - 2006	weighted mean
Accidents	Zone 1	0.2964	0.2700	0.2779
	Zone 2	0.2380	0.2400	0.2394
	Zone 3	0.1723	0.1900	0.1847
	Zone 4	0.0702	0.0800	0.0771
	Zone 5	-	-	0.11082
	Zone 6	-	-	0.17955
	Zone 7	-	-	0.22232
Injuries	Zone 1	0.4131	0.3927	0.3988
	Zone 2	0.3570	0.2930	0.3122
	Zone 3	0.2575	0.2784	0.2721
	Zone 4	0.0993	0.1097	0.1066
	Zone 5	-	-	0.16326
	Zone 6	-	-	0.23415
	Zone 7	-	-	0.31904
Fatalities	Zone 1	0.0140	0.0087	0.0103
	Zone 2	0.0025	0.0084	0.0066
	Zone 3	0.0036	0.0091	0.0075
	Zone 4	0.0066	0.0053	0.0057
	Zone 5	-	-	0.0045
	Zone 6	-	-	0.00495
	Zone 7	-	-	0.00824

The present dataset indicates that between 9% and 10% of all injuries are severe injuries. This differentiation is not implemented in the model but from the total number of injuries, the number of severe injuries can be estimated by multiplying the results of the software tool with the figures given in Table 1.3. The injury rate given in Table 1.2 contains all inju-

[2] Definitions from Statistics Norway, http://www.ssb.no/vtu_en/about.html, accessed December 2010

ries which have been registered by the police in Norway and stored the national road accident data base for the tunnel zones 1 to 4. The values for the zones 5, 6 and 7 are based on expert judgement due to the lack of observations.

For specific conditions, it may be meaningful to distinguish between the different types of injuries. For ***TRANSIT***, the term injury is used for slightly injury and severely injury.

From Table 1.2 it is seen that the accident rates are increased at the tunnel portal and the fatality rate is higher in the interior of the tunnel. It can also be noted that there is a slight increase of the fatality rate in zone 3 compared to zone 2. The reason might be statistical uncertainty but this was not investigated in this study.

Table 1.3: Ratio of severe injuries to light injuries.

	Ratio of severe Injuries to light injuries [%]		
	1992-1996	**2001 - 2006**	**weighted mean**
Zone 1	12.4	6.8	8.5
Zone 2	14.1	7.1	9.2
Zone 3	15.1	7.1	9.5
Zone 4	13.6	8.4	10.0

1.4 Prior Probabilities and used Models for the indicator nodes

1.4.1 Type of time variation curve of the traffic volume

The traffic is not uniformly distributed over the day. The Annual Average Daily Traffic (AADT) serves as an indicator to describe the traffic volume. However, the accidents in tunnel are more related to the density of the traffic which varies significantly over the day. To describe the daily variation of the traffic, collective and generalized type of time variation curves are employed in the risk analysis. Collective time variation curves of the traffic are used since the late 1970th mainly to describe the structure of the traffic on specific road sections.

Six different general types of collective time variation curves are identified by Pinkofsky (2005) and used employed in this project. Even though Pinkofsky analysed data from Germany the principal typification can still be used for other countries.

- Type A: pronounced peak in the morning.
- Type B: peak in the morning combined with small peak in the afternoon.
- Type C: relative equally distributed traffic during the day.
- Type D: Pronounced peak in the morning and in the afternoon.
- Type E: pronounced peak in the afternoon, small peak in the morning.
- Type F: pronounced peak in the afternoon.

In SN 640 005a (2001) a different classification is used. According to the dominating part of the traffic the following classes are used:

- Interregional traffic with commuters (refers to Type B)
- Commuters (refers to Type D)
- Local traffic (refers to Type E)
- Regional traffic (refers to Type F)
- Leisure Traffic (refers to Type C)

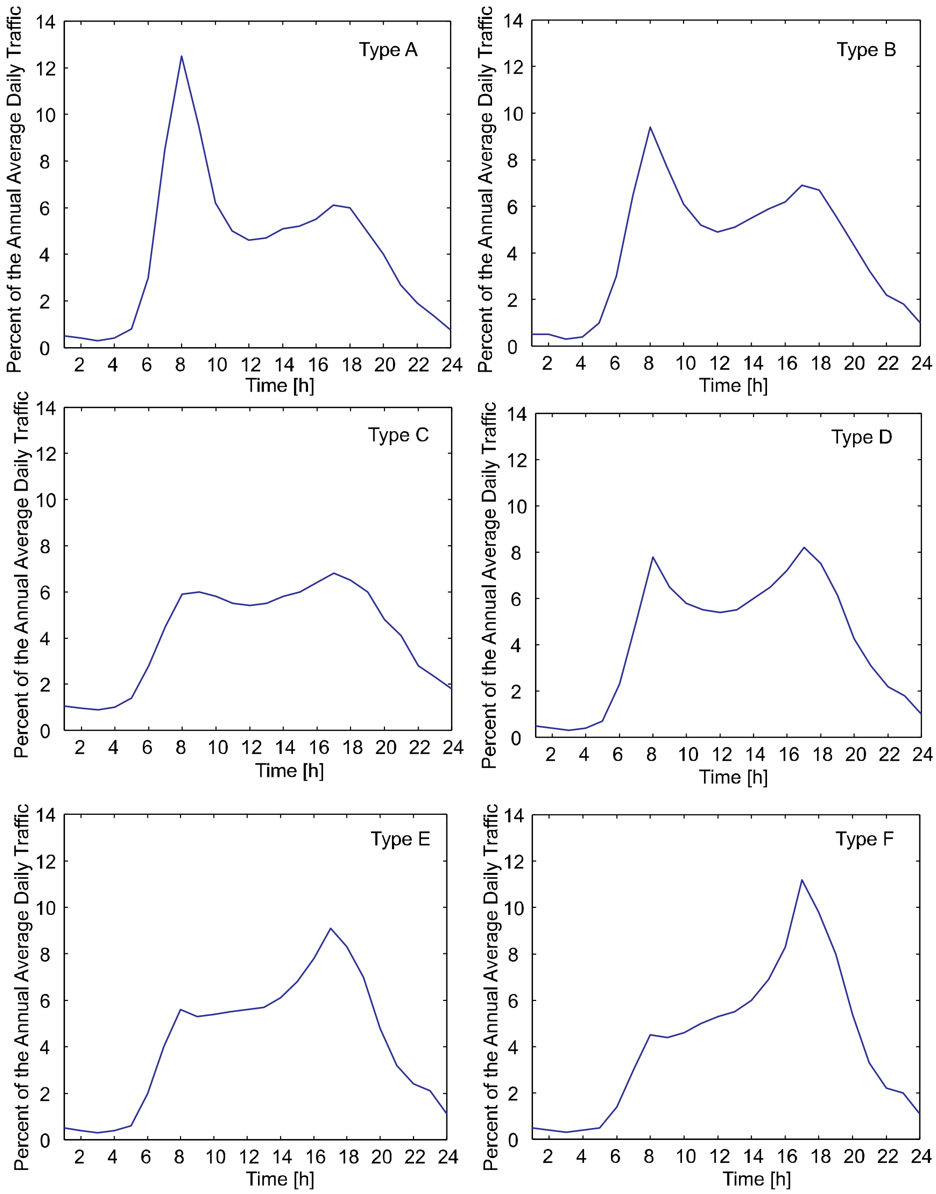


Figure 1.5: Illustration of the different types of time variation curves of the traffic.

A comparison shows that in principle the same types are used but the notation differs. Type A is not used in SN 640 005a (2001). In Figure 1.5 the general shapes of time variation curves are given. The six different types of time variation curves are sufficient for the risk analysis since the influence on the risk is not significant. The consideration of this indicator provides an additional interface for further developments of this model.

Using the statistics published in SN 640 005a (2001) the prior distribution for Switzerland and the assumption that is 5% of the roads in Switzerland fall into this category the prior probabilities for Switzerland given in Table 1.4 can be derived. The prior probabilities for the time variation curve published in Pinkofsky (2005) for Germany are also given in Table 1.4. The prior probabilities for Switzerland and Germany are quite similar and it is assumed that the prior probabilities for Norway have been be derived as mean value from the prior information of both countries.

In risk analysis where no information on the type of the time variation curve is available, the prior probabilities given in Table 1.4 will be used.

Table 1.4: Prior probabilities for the different type of time variation curves of the AADT.

	Prior distribution		
	Switzerland	**Germany**	**Norway**
Type A	0.05	0.08	0.07
Type B	0.16	0.15	0.16
Type C	0.12	0.15	0.14
Type D	0.32	0.24	0.28
Type E	0.26	0.25	0.26
Type F	0.10	0.12	0.11

1.4.2 Traffic volume [veh/d]

The traffic volume has an influence on the numbers of accidents, if the accident rates measured per million vehicle kilometre are applied without other modification, the relation will be linear. However, this may not always be the case.

The traffic volume has been studied in Amundsen and Ranes (1997). In that study a regression has been made between accident rates/fatality rates and traffic volume. It appeared thereby that an increase in traffic resulted in lower occurrence rates. Even though this is true, it should be taken into account that the tunnel design is also dependent on the traffic volume, so that tunnels with a high traffic have a high standard separated directions, etc.

Dense traffic may result in an increased risk of collisions with congested or slow traffic and by dense traffic the evasive manoeuvres may also have a higher risk of resulting in accidents and severe consequences. On the other hand when the traffic volume has reached a certain level then the speed limit is influenced so that the driving speed is generally lower and more homogeneous. Thereby the risk is reduced.

The following model is based on observations of accidents in the Elbe Tunnel in Hamburg, which has been chosen due to its 25 years of service and the very significant development in traffic in this period. The data has been received directly from the tunnel operator and cover the period 1975 – 2000 (i.e. before the extension with an additional tunnel tube) (Haack (1995) and Haack (2002)). A model for the traffic volume will naturally also have to take into account the number of lanes. The accident frequency seems to increase when the traffic volume is over a certain limit and until certain saturation is achieved (see Figure 1.6).

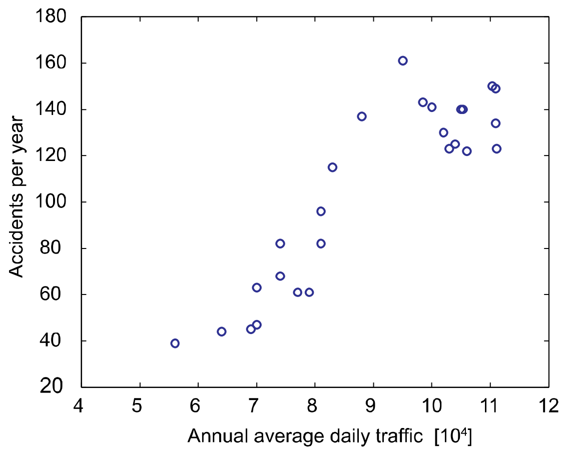


Figure 1.6: Annual number of accidents in the Elbe tunnel in the years from 1975-2000 in dependency from the annual average daily traffic.

By analysis of the Figure 1.6 a model is established as a function of the average annual daily traffic volume per direction and the number of lanes per direction. The joint influence of these two indicators on the AMF is modelled in the BPN by the relation given in Figure 1.7 and in Figure 1.8 the developed model is shown.

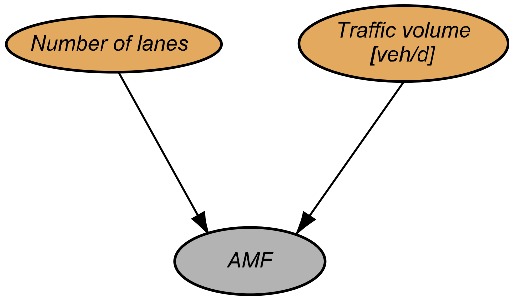


Figure 1.7: Part of the network for the consideration of the joint effect of traffic volume and number of lanes on the Accident Modification Factor AMF.

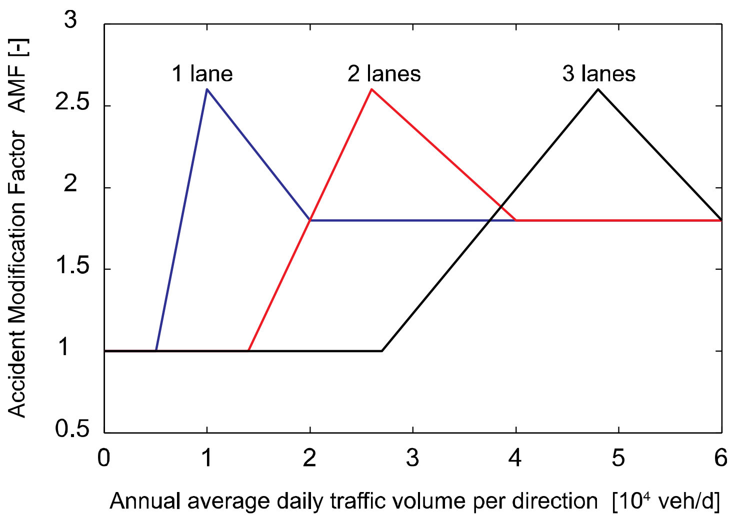


Figure 1.8: Relation between the AADT per direction and the AMF depend on the number of lanes.

The equations describe the relation given in Figure 1.8 between the number of lanes and annual average daily traffic volume $\rho \; [veh \,/\, d]$ per direction.

$$AMF_{1lane} = \begin{cases} 1 & 0 < \rho \leq 5'000 \\ 1 + \dfrac{1.6}{5000} \; \rho - 5000 & 5'000 < \rho \leq 10'000 \\ 2.6 - \dfrac{0.8}{10000} \; \rho - 10000 & 10'000 < \rho \leq 20'000 \\ 1.8 & 20'000 < \rho \leq 60'000 \end{cases} \qquad (1.3)$$

$$AMF_{2lane} = \begin{cases} 1 & 0 < \rho \leq 14'000 \\ 1 + \dfrac{1.6}{12000} \; \rho - 14000 & 14'000 < \rho \leq 26'000 \\ 2.6 - \dfrac{0.8}{14000} \; \rho - 26000 & 26'000 < \rho \leq 40'000 \\ 1.8 & 40'000 < \rho \leq 60'000 \end{cases} \qquad (1.4)$$

$$AMF_{3lane} = \begin{cases} 1 & 0 < \rho \leq 27'000 \\ 1 + \frac{1.6}{21000}\ \rho - 27000 & 27'000 < \rho \leq 48'000 \\ 2.6 - \frac{0.8}{12000}\ \rho - 48000 & 48'000 < \rho \leq 60'000 \end{cases} \quad (1.5)$$

The a-priori probabilities of the annual average daily traffic are given in Table 1.5. For Switzerland the values are based on the automatic road traffic counting 2007 published by the Federal Statistical Office (FSO)[3] . The mean value of the annual average traffic volume per direction is 16724 vehicles per day with a coefficient of variation of 0.82.

The prior probabilities for Norway are calculated by using the data published in Amundsen and Engebretsen (2009). The mean value of the annual average traffic volume per direction is 5500 vehicles per day and significant lower than in Switzerland. The coefficient of variation for Norway is 1.24 which reflects the large span between tunnels with little traffic and tunnels with dense traffic in the cities. These prior probabilities are not directly used in the analysis since the traffic volume needs to be known by the user in order to perform the analysis.

Table 1.5: Prior probabilities for the annual average daily traffic volume per direction.

AADT per direction	Prior distribution	
	Switzerland	Norway
0-300	1.10E-04	5.42E-02
300-600	1.71E-02	1.13E-01
600-1000	1.71E-02	7.88E-02
1000-2000	3.98E-02	1.72E-01
2000-3000	2.84E-02	7.88E-02
3000-4000	5.11E-02	6.90E-02
4000-5000	1.71E-02	6.40E-02
5000-6000	4.54E-02	4.93E-02
6000-7000	5.11E-02	4.93E-02
7000-8000	7.37E-02	2.46E-02
8000-9000	3.98E-02	4.93E-02
9000-1000	3.41E-02	5.42E-02
10000-11000	4.54E-02	4.93E-03
11000-12000	3.98E-02	4.93E-03
12000-13000	1.71E-02	1.97E-02
13000-14000	1.14E-02	2.46E-02
14000-15000	5.67E-02	9.85E-03
15000-16000	2.84E-02	9.85E-03
16000-17000	5.77E-03	4.93E-03
17000-18000	1.71E-02	4.93E-03
18000-19000	1.71E-02	9.85E-03
19000-20000	2.28E-02	9.85E-03
20000-25000	6.24E-02	1.48E-02
25000-30000	9.64E-02	4.93E-09
30000-35000	6.24E-02	9.85E-03

3 http://www.portal-stat.admin.ch/avz-2007/ , accessed July 2009

AADT per direction	Prior distribution	
	Switzerland	Norway
35000-40000	1.14E-02	9.85E-03
40000-45000	3.41E-02	4.93E-03
45000-50000	3.41E-02	4.93E-09
50000-55000	1.71E-02	4.93E-09
55000-60000	5.77E-03	4.93E-09

1.4.3 Exit and entrance conditions in the segment

Normally it is advices not to have exit / entrance ramps in the tunnel. For this reason the statistical basis is very weak. On the other hand, it does occur that tunnels are proposed with underground ramps, and it is necessary to have a model for evaluating this relative unusual feature.

The special risk at entrance and exit ramps in the tunnel are modelled by differentiating four different situations as shown in Figure 1.9. Hereby five types are established the four types of different ramps and the type “None”.

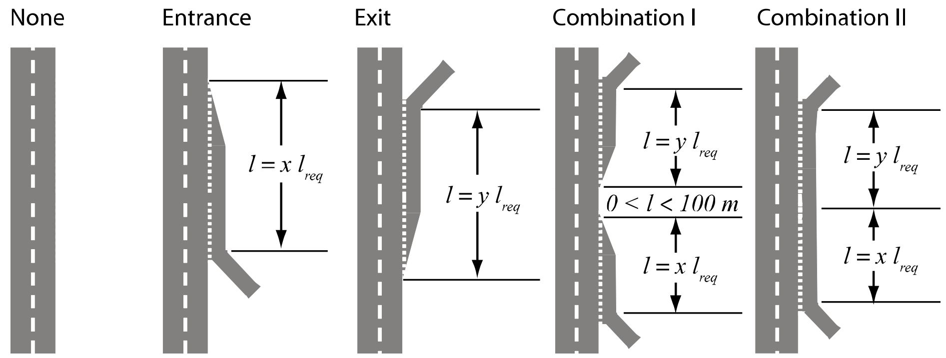


Figure 1.9: Five types of exit and entrance ramps in tunnels.

The model is based on experience and is an expert judgment model established in collaboration with experts at NPRA Region South / Statens Vegvesen Region Sör in 2008 (Hoj and Faber (2008)).

The expert judgments were consolidated to relative risks: the relative risk specific for the ramp at entrances is hereby estimated 3 times higher than at exits. At combined entrances and exits with less than 100 m between them the factor is 6 and with combined exit and entrance without any interruption the factor is 10.

Another aspect which influences the risk in tunnels is the length of the exit and entrance ramps in the tunnel. In general, the is regulated by the recent codes and standards, see e.g. SN 640 261 (2001) and Statens vegvesen (2010)). However, in existing tunnels these requirements are not always fulfilled. A crude approximation was made in order to cover all possible combinations of the length of the exit and entrance ramps: The present length l_{pres} of the ramp is expressed relative to the required length l_{req} in the code. The following states are considered: $l_{pres} = 0 \cdot l_{req},\ l_{pres} = 0.5 \cdot l_{req},\ l_{pres} = 1.0 \cdot l_{req},\ l_{pres} = 2.0 \cdot l_{req}$.

In total 41 combinations between the five types of exit and entrance and the length of the ramps are considered in the model.

The employed accident modification factors for the 41 states are given in Table 1.6

Table 1.6: Accident modification factors for the consideration of different exit and entrance conditions.

	Length of entrance ramp	Length of exit ramp	AMF
No ramp	-	-	1.0
Entrance ramp	$0 \cdot l_{req}$	-	2.80
	$0.5 \cdot l_{req}$		2.36
	$1.0 \cdot l_{req}$		1.91
	$2.0 \cdot l_{req}$		1.03
Exit ramp	-	$0 \cdot l_{req}$	1.86
		$0.5 \cdot l_{req}$	1.64
		$1.0 \cdot l_{req}$	1.42
		$2.0 \cdot l_{req}$	0.98
Combination I	$0 \cdot l_{req}$	$0 \cdot l_{req}$	4.68
	$0 \cdot l_{req}$	$0.5 \cdot l_{req}$	4.29
	$0 \cdot l_{req}$	$1.0 \cdot l_{req}$	3.90
	$0 \cdot l_{req}$	$2.0 \cdot l_{req}$	3.11
	$0.5 \cdot l_{req}$	$0 \cdot l_{req}$	4.06
	$0.5 \cdot l_{req}$	$0.5 \cdot l_{req}$	3.71
	$0.5 \cdot l_{req}$	$1.0 \cdot l_{req}$	3.35
	$0.5 \cdot l_{req}$	$2.0 \cdot l_{req}$	2.64
	$1.0 \cdot l_{req}$	$0 \cdot l_{req}$	3.44
	$1.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	3.13
	$1.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	2.81
	$1.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	2.18
	$2.0 \cdot l_{req}$	$0 \cdot l_{req}$	2.21
	$2.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	1.97
	$2.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	1.72
	$2.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	1.24
Combination II	$0 \cdot l_{req}$	$0 \cdot l_{req}$	4.07
	$0 \cdot l_{req}$	$0.5 \cdot l_{req}$	3.70
	$0 \cdot l_{req}$	$1.0 \cdot l_{req}$	3.33
	$0 \cdot l_{req}$	$2.0 \cdot l_{req}$	2.58
	$0.5 \cdot l_{req}$	$0 \cdot l_{req}$	3.36
	$0.5 \cdot l_{req}$	$0.5 \cdot l_{req}$	3.07
	$0.5 \cdot l_{req}$	$1.0 \cdot l_{req}$	2.78
	$0.5 \cdot l_{req}$	$2.0 \cdot l_{req}$	2.21
	$1.0 \cdot l_{req}$	$0 \cdot l_{req}$	2.65
	$1.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	2.45
	$1.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	2.24
	$1.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	1.84
	$2.0 \cdot l_{req}$	$0 \cdot l_{req}$	1.23
	$2.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	1.19
	$2.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	1.16
	$2.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	1.09

The factors given in Table 1.6 reflect the complex traffic situation at the entrance or exit in a tunnel. They do not reflect the elevated risk for accidents due to more lane shifts in this area. This effect is discussed 1.4.15.

1.4.4 Bidirectional or unidirectional traffic

Influence on accidents

By leading traffic through two tubes with unidirectional traffic, the frontal accidents are mitigated (except wrong-direction drivers) This reduces the accident rate and even more the fatality rate.

Furthermore, bidirectional traffic conditions may result in disturbance of the drivers by the head lights and the small distance to the oncoming vehicles.

In Table 1.7 the prior probabilities for the bidirectional traffic conditions in Switzerland and in Norway are given. They are based on Amundsen and Engebretsen (2009) for Norway and Salvisberg et al. (2004) for Switzerland, respectively. From the prior probabilities from Norway it is seen that more than 90% of the tunnels have bi directional traffic conditions. Since the accident statistics used in this project takes basis in the Norwegian accident studies, (Amundsen and Melvær (1997) and Amundsen and Engebretsen (2009)), it can assumed that the data mainly result from tunnels with bi directional traffic. Therefore, a positive effect on the accident rate is assumed for tunnel without bi directional traffic.

The following accident modification factors estimated based on the above data:

$$\begin{aligned} AMF_{unidirectional} &= 0.4 \\ AMF_{bidirectional} &= 1.0 \end{aligned} \qquad (1.6)$$

Table 1.7: Prior probabilities for tunnels with and without bi directional traffic.

	Prior distribution	
	Switzerland	**Norway**
bidirectional	0.71	0.09
unidirectional	0.29	0.91

Influence on tunnel fire

The traffic conditions also affect the probability for a successful escape of a person in a tunnel in the case of a tunnel fire which is controlled by the tunnel ventilation. The influence is rather complex and a complex numerical analysis which takes into account specific local conditions of the tunnel is needed to consider the different relevant effects on the probability that a person can escape from a tunnel fire. Here, a more heuristic approach is chosen which is presented in Chapter 1.4.27.

Overtaking in tunnels

Overtaking in tunnels with traffic in two directions is normally restricted outside Norway. The reason is the confined environment and the partly reduced line of sight and perception of distances.

A model for the increase of risk due to overtaking depends on a number of factors, such as lane width, line of sight, traffic composition, gradient, speed limit variance etc. An accurate mol for the risk involved shall be established in the further development of ***TRANSIT***.

In tunnels with divided directions it may also be considered to restrict overtaking, especially for HGVs. A model for the risk related to HGVs overtaking is also on the development plan.

Since the background accident rate includes accidents due to overtaking and in legel and illegal situations the risk of accidents due to overtaking in tunnels are thus implicitly considered in the model.

1.4.5 Fraction of the heavy good vehicles in the tunnel

It has been observed that HGVs have an increased frequency of accidents compared to personal vehicles. For reference see OECD (1997), similar observations are reported in OECD (2001) and PIARC (1999). It is assumed that the accident frequency is increased in the magnitude 40 – 50%, where the average percentage of HGVs is around 12%. By using these assumptions and by postulating a linear influence of the share of the heavy good vehicles the following function for the AMF can be derived:

$$AMF = 0.427 \cdot HGV[\%] + 0.949 \qquad (1.7)$$

Under the assumption that the fraction of the HGV in tunnel originate from the same population for normal national roads, the prior distribution is calculated by using the data published by the Swiss Federal Statistical Office (FSO)[4].

Table 1.8: Prior probabilities for tunnels the fraction of the HGV in tunnels.

Fraction of the HGV [%]	Prior distribution	
	Switzerland	Norway
0 - 2	0.02	0.02
2 - 4	0.06	0.06
4 - 6	0.07	0.07
6 - 8	0.07	0.07
8 - 10	0.09	0.09
10 - 12	0.18	0.18
12 - 14	0.13	0.13
14 - 16	0.16	0.16
16 - 18	0.11	0.11
18 - 20	0.03	0.03
20 - 26	0.08	0.08

Transport of dangerous goods

With respect to normal traffic accident it has been observed that HGVs transporting dangerous goods have a reduced frequency of accidents compared to other HGVs. The reason for this may be the special education of the drivers and the delicacy of the transports. For reference see OECD (2001) and OECD (1997). It is assumed that the accident frequency is reduced in the magnitude 20 % compared to other HGVs.

With respect to accident involving the dangerous material, particular severe consequences may result. However, this is dealt with separately, see chapter 0 and 1.2.

The transport of dangerous goods is generally regulated by the European Agreement concerning the International Carriage of Dangerous Goods by Road, commonly known as ADR (Accord européen relatif au transport international des marchandises dangereuses par route).

When placing restrictions on the carriage of dangerous goods the Tunnel Operator must determine, indicate and publish the restrictions in accordance with the system set out in ADR

A tunnel operator may apply one of five categories of restrictions (A to E) on the types of dangerous goods that may be carried. These range from no restrictions at all to a total ban on all dangerous goods (except where ADR specifies exemptions for small loads or limited quantities)

As basis for the ADR system reference is made to the rational approach of risks in tunnels, This approach must respect the EU Directive 2004/54/EC (see Chapter 0.2), where reference is made to risk analyses. Reference is also made to the OECD/PIARC/EU (2007)study and quantified risk assessment (QRA) and decision support model.

In Switzerland the transport of dangerous goods is regulated by BUWAL (1991) and a formalized risk assessment with given acceptance criteria is a legal requirement. This legal regulation has to be fulfilled.

TRANSIT does has a module for estimating accidents involving the dangerous materials. The analysis for dangerous goods is a first approximation of the risk. In some cases a more detailed analysis might be reasonable. In these cases separate analysis is necessary.

4 http://www.portal-stat.admin.ch/avz-2007/ , accessed July 2009

Accident of buses

Accidents with buses in tunnels can have severe problems because of the large number of persons involved. A specific model for accidents with buses and fires in buses is still pending. Here, busses are not explicitly addressed but the consequences are implicitly considered in the number of persons exposed to fire events in tunnels.

For tunnels in cities with a high percentage of buses, dedicated separate analyses are recommended.

1.4.6 Tunnel lighting

It is well known that the light conditions can have influence on the accident rates in tunnel. Tunnel lighting has several positive effects. The illumination increase the clarity in the entire tunnel but it diminishes also the differences in brightness between the other cars in the tunnel and the surrounding so that the dazzle effects can be reduced and adaptation of the eye to different light conditions is minimized. The tunnel lighting relaxes the eyes of the driver which has a positive effect on his concentration.

The tunnel lighting is described in terms of luminance (in the unit cd/m^2). The detailing of the influence of the light conditions distinguishes the driving direction in the entrance exit zones and describes the conditions in the tunnel interior and portal zones

The lighting level is specified in the guidelines and it the lighting is specified to be higher at the portals. In the portals the specifications are in most cases given in terms of adaption luminance (unit %).

The assumed prior probabilities for the presence of the passage illumination are given in Table 1.9. Due to the lack of data these prior probabilities are based on expert opinion and are basically only valid for Norway.

Table 1.9: Prior probabilities for passage illumination in tunnels (expert opinion, presently no data available).

Tunnel lighting Luminance [cd/m^2]	Prior distribution	
	Switzerland	Norway
< 0.5	0.1	0.20
0.5 - 1	0.9	0.40
1-2		0.15
2-3		0.10
3-4		0.05
4-5		0.05
6-8		0.03
> 8		0.02

Based on expert judgements, the following model for the accident modification factor for lighting can be established.

Tunnel interior

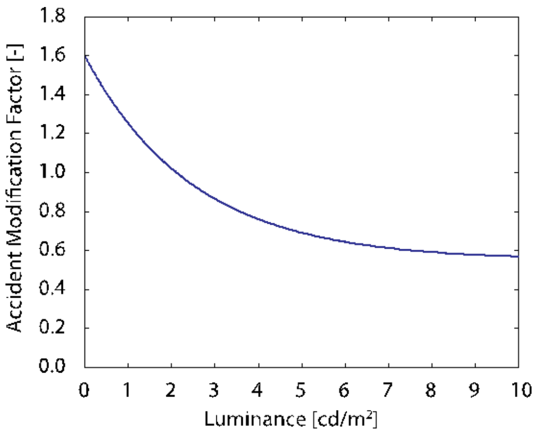


Figure 1.10: Relationship between AMF(light), accident modification factor for light and luminance in the tunnel interior.

The corresponding (simplified) formula for the importance of light can be formulated, where L is the luminance in cd/m^2.

$$AMF_{ligth} = 1.05 \cdot e^{-0.4 \cdot L} + 0.55 \qquad (1.8)$$

This relationship is shown in Figure 1.10.

Table 1.10: Accident modification factor for the tunnel lighting.

Tunnel lighting Luminance [cd/m^2]	Accident modification factor
< 0.5	1.60
0.5 - 1	1.41
1-2	1.25
2-3	1
3-4	0.87
4-5	0.76
6-8	0.69
> 8	0.59

The luminance to be used in the model is the luminance used at day-time. The model takes into account the variation of the light conditions outside the tunnel and the lower luminance, which is normal to use at night time.

It shall be taken into account that the values are relevant for lighting alone. When it is assumed that the speed level will increase, this effect will have to be considered separately.

As a rough guideline it is assumed that the speed is influenced as shown in Table 1.11, if no other measures are taken to control the actual speed.

Table 1.11: Influence on change of speed from luminance level unless other measures are taken.

Tunnel lighting Luminance [cd/m²]	Change in speed [km/h]
< 0.5	-10
0.5 - 1	-7.5
1-2	-5
2-3	0
3-4	+2.5
4-5	+5
6-8	+7.5
> 8	+10

Tunnel portals

At the tunnel portals the lighting conditions are particularly important. The portal areas have in general an increased risk of accidents, which is caused not least by the lighting conditions in these areas. The particular risk in the entrance zones are dealt with separately in Chapter 1.3.

The risk level in the entrance and exit zone of the tunnel is influences by the luminance level, which generally is regulated by means of the adaption luminance. The mean adaption luminance is specified to 1.5% - 5% in the entrance zone. The entrance zone is for simplicity in the present specified to 150 m corresponding to zone 2 and 3 in the tunnel zones.

The (increased) risk in the entrance zones is assumed to be based on a reference of 3% mean adaption luminance. Variations of the luminance level in the entrance zone takes starting point in this value.

The AMF factor goes asymptotic towards 0.5 for ambient light conditions, which will approximately overrule the increased accident risk in the portal are-as. It is, however, impossible to create daylight conditions in the tunnel.

The relationship between the $AMF_{lightEnt}$ for the entrance zones (zone 2 and 3) and the luminance is shown in Figure 1.11.

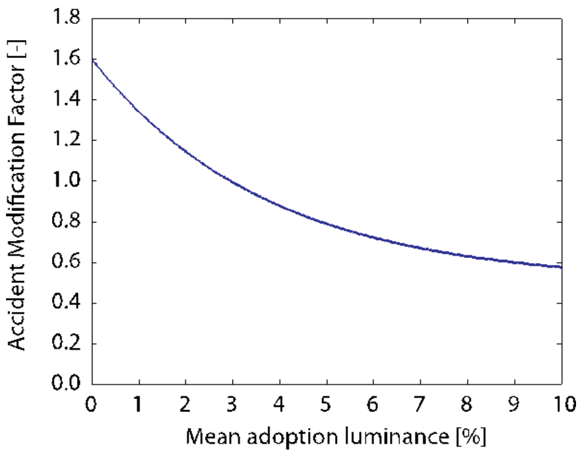


Figure 1.11: Relationship between $AMF_{lightEnt}$, accident modification factor for light and luminance for the entrance zone.

The corresponding (simplified) formula for the importance of light can be formulated where A is the adaption luminance.

$$AMF_{ligth\,Entr} = 1.10 \cdot e^{-26.66 \cdot A} + 0.50 \tag{1.9}$$

Also at the exit zones the lighting conditions are particularly important, at the transition between tunnel lighting condition and daylight a blinding effect can occur.

In the exit zones increased lighting is not always arranged. However, tunnels with bidirectional traffic benefit from the lighting arranged for the entrance zone in the other direction (see above).

An accident modification factor similar to the entrance zone is established below. The exit zone is for simplicity in the present specified to 150 m corresponding to zone 2 and 3 in the tunnel zones.

The corresponding (simplified) formula for the importance of light can be formulated where A is the adaption luminance.

$$AMF_{ligth\,Exit} = 0.46 \cdot e^{-26.66 \cdot A} + 0.75 \tag{1.10}$$

The relationship between the $AMF_{lightExit}$ for the exit zones (zone 5 and 6) and the luminance is shown in Figure 1.12.

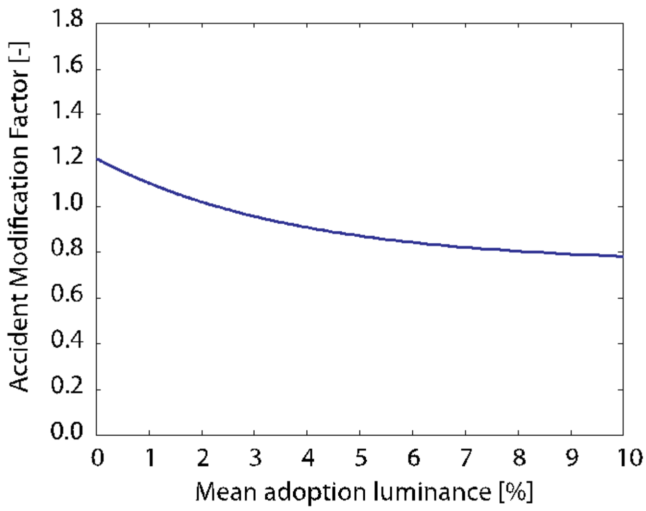


Figure 1.12: Relationship between $AMF_{lightExit}$, accident modification factor for light and luminance for the exit zone.

In order to have single unit for the lighting, the adaption luminance A is transformed into an “equivalent” luminance value for the exit zone $L_{equi,Exit}$ and the entrance zone $L_{equi,Entr}$, by the relationship:

$$L_{equi,Entr} = -\frac{1}{0.4}\log\left(\frac{1.1}{1.05}\mathrm{e}^{-26.66 \cdot A} - \frac{0.05}{1.05}\right) \tag{1.11}$$

$$L_{equi,Exit} = -\frac{1}{0.4}\ln\left(\frac{0.46}{1.05}\mathrm{e}^{-26.66 \cdot A} - \frac{0.2}{1.05}\right) \tag{1.12}$$

This relationship between the mean adoption luminance and the equivalent luminance for the exit zones (zone 5 and 6) and the entrance zones (zone 2 and 3) is shown in Figure 1.13.

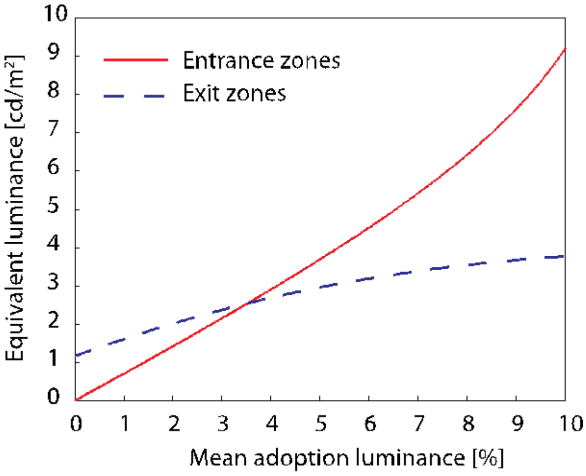


Figure 1.13: Relationship between the adaption luminance and the "equivalent" luminance value for the entrance and the exit zones.

1.4.7 Horizontal radius in the tunnel

It has been observed in selected tunnels that the number of accidents is larger in curves than on sections with more smooth alignments. This may partly be due to the reduced line of sight in curves. In codes and guidelines it is also normal to give requirements for minimum radii depending on the driving speed. However, completely straight tunnels are also not recommended, as it has been observed that this leads to monotony.

As a calculation model, the following relation has been established. The relationship it fitted and has the following equation which is dependent on the horizontal radius $z[m]$ and the speed limit $v\,[km\,/\,h]$:

$$AMF = \max \quad -\ln \quad z \quad \cdot 1.508 \cdot 10^{-4} + 1.119 \cdot 10^{-3} \quad v^2 - \quad \ln \quad z \quad \cdot 1.217 \cdot 10^{-4} + 1.237 \cdot 10^{-2} \quad v + 1\,;\, 0.95 \quad (1.13)$$

In Figure 1.14 the AMF for different speed limits is shown. It should be noted that the figure indicates combinations of speed limit and radius which would not be acceptable or allowed in accordance with the guidelines.

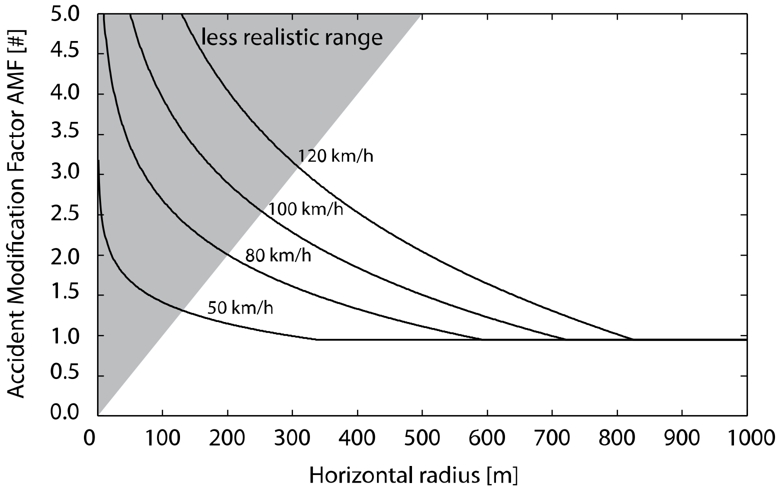


Figure 1.14: Accident modification factor depending on the curvature (radius) and the speed limit.

The joint influence of the speed limit and the horizontal radius is considered in the Bayesian network as shown in Figure 1.15.

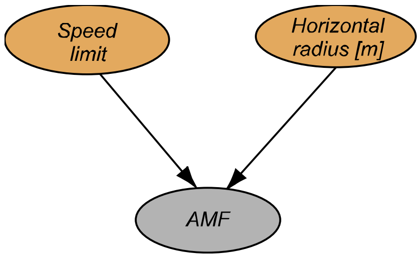


Figure 1.15: Part of the Bayesian Network for the consideration of the joint effect of the speed limit and the horizontal radius of the tunnel segment.

No information on the prior distribution of the radius of segments is presently available. A prior distribution of the horizontal radius is assumed. The assumption on the prior distribution is of little influence, since this indicator is normally known or can be measured for the actual tunnel.

Table 1.12: Prior probabilities for the horizontal radius in the tunnel

Radius [m]	Prior distribution	
	Switzerland	Norway
0 - 50	0.0011	0.0011
50 - 60	0.0002	0.0002
60 - 70	0.0003	0.0003
70 - 80	0.0003	0.0003
80 - 90	0.0004	0.0004
90 - 100	0.0004	0.0004
100 - 110	0.0005	0.0005
110 - 120	0.0006	0.0006
120 - 130	0.0007	0.0007
130 - 140	0.0008	0.0008
140 - 150	0.0009	0.0009
150 - 160	0.0010	0.0010
160 - 170	0.0012	0.0012
170 - 180	0.0014	0.0014
180 - 190	0.0016	0.0016
190 - 200	0.0018	0.0018
200 - 250	0.0128	0.0128
250 - 300	0.0219	0.0219
300 - 350	0.0346	0.0346
350 - 400	0.0508	0.0508
400 - 450	0.0691	0.0691
450 - 500	0.0869	0.0869
500 - 550	0.1013	0.1013
550 - 600	0.1094	0.1094
600 - 650	0.1094	0.1094
650 - 700	0.1013	0.1013
700 - 800	0.1560	0.1560
800 - 900	0.0855	0.0855
900 - ∞	0.0478	0.0478

1.4.8 Gradient of the tunnel

The longitudinal gradient of the tunnel influences the risk level negatively in several ways: Firstly the gradient upwards and downwards result in increasing accidents frequencies, secondly the gradient influence the frequency of stopped vehicles in the tunnels on the upwards branch of the tunnel (and reduce the frequency on the downwards branch), thirdly the frequency of fires is assumed to follow the same pattern as the accidents and stopped vehicles (for fires due to accidents and due to electrical/ mechanical problems respectively), finally large gradients may be a challenge for the ventilation equipment for longitudinal ventilation especially on the downwards branch. Thus, the node gradient has an influence on the accidents as well as on the ignition of tunnel fires.

Accidents on sloping roads

In the publication Hauer (2001) different causes for the increased accident frequency on road with gradients are mentioned. On the downwards branch it is mainly a higher speed that cause the increase of accidents. In the transition point between downwards and upwards branches and on the upwards branch itself it may be the difference in speed caused by the slowing down of heavy vehicles, which is the main reason for the increase.

A model has been proposed taking into account the overall development of accidents on the upwards and the downwards branches. An Accident Modification Factor $AMF_{gradient}$ is calculated as function of the change in gradient G in [%] :

$$AMF_{gradient} = e^{0.081 \quad G-2} \tag{1.14}$$

Since it must be assumed that most tunnels have a certain longitudinal slope. Here, it is assumed that the mean value of the gradient is 2% which is corresponds to the data for tunnels in Switzerland published in Salvisberg et al. (2004). Using equation (1.14) the relationship as presented in Figure 1.16 can be determined.

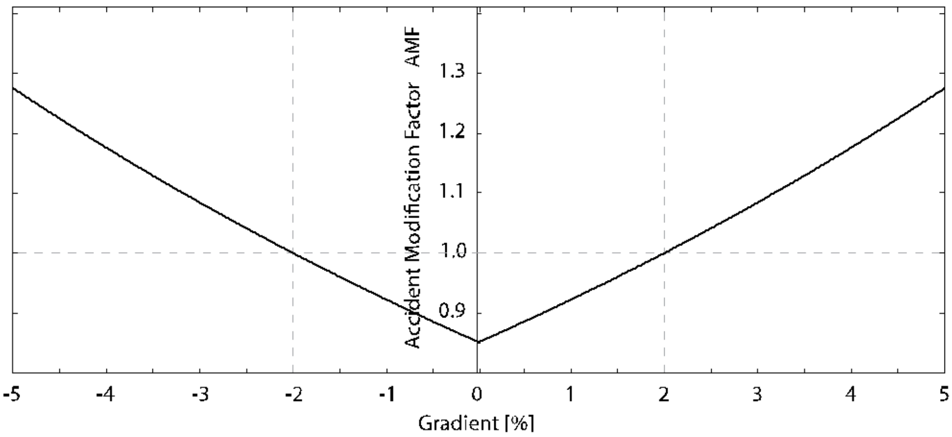


Figure 1.16: Accident modification factor depending on the longitudinal gradient in the tunnel.

It has been suggested that large gradients and small horizontal curvatures have an aggravating effect in addition to the combination of the two indicators. This seems plausible, but the basis for this needs to be further studied and has not been taken into account in the present initial version of ***TRANSIT***.

If no information on the gradient in the tunnel segment is available the prior distribution given in Table 1.13 will be used for the risk calculation. The prior distribution for Switzerland is calculated by using the dataset published in Salvisberg et al. (2004). It is assumed that the prior distribution of the gradients in tunnels is the same for Norway and for Switzerland.

Table 1.13: Prior probabilities for the gradient in the tunnel.

Gradient in the tunnel [%]	Prior distribution	
	Switzerland	**Norway**
0 - 2	0.05	0.05
2 - 4	0.52	0.52
4 - 6	0.24	0.24
6 - 8	0.17	0.17
8 - 10	0.02	0.02

Gradients in relation to motor stops and fires caused by electrical/mechanical problems

It has been observed that there is an increased occurrence of fires on tunnels with high gradients. However, no specific model seems presently available.

For the modeling of this indicator it is here assumed that the increased occurrence of stopped vehicles can also serve as indicator for the increase of fires due to technical defects. The risk of stopped vehicles has been reported as function of the gradient in PIARC (1999) and Lingelser (1998). The increase of the occurrence is on the upwards branch and the downwards branch gives a reduced frequency. Only gradients exceeding 2% are seen to result in an increase in frequency. According to the Accident Modification Factor a similar approach is employed also for the fire frequency. The fire frequency modification factor FMF has the same properties as discussed for the AMF in Chapter 1.2. The FMF is implicitly considered in the Bayesian Network.

The following function for the fire frequency modification factor FMF is assumed:

$$FMF_{gradient} = \begin{cases} 0.773 + 6.27 \cdot 10^{-2} \; G^{\;2} & G > 1\% \\ 0.8357 & G \leq 1\% \end{cases} \tag{1.15}$$

Wherein G is the gradient in [%]. In Figure 1.17 this relation is shown.

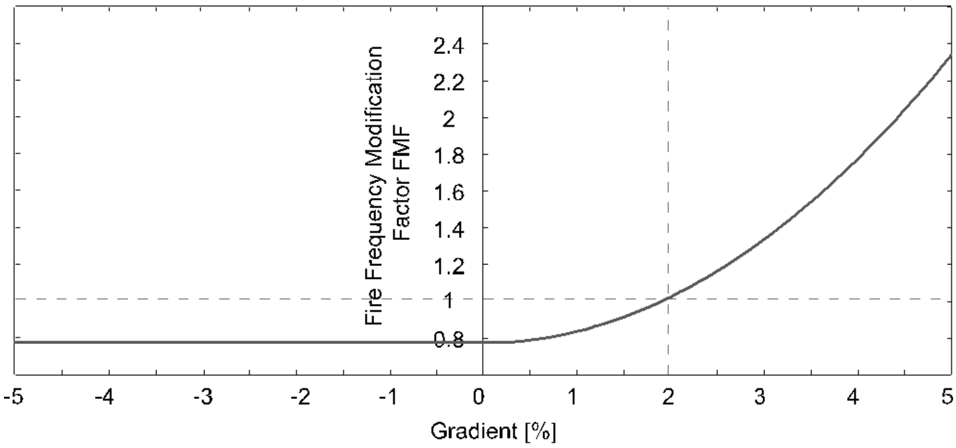


Figure 1.17: Modification factor for the fire frequency depending on the longitudinal gradient.

1.4.9 Lane width

The width of the tunnel cross section and the width of the road lanes have some influence on the risk. The influence is assumed to be rather small if normal regulations are respected. However, if the required width is not available the risk may be increased.

A tentative model for the influence of the lane width w [m] and the speed limit v [km/h] on the accident frequency has been established:

$$AMF = \; 67.78\ln(v)^{0.091} - 242\ln(v)^{-1} \;\; w^{-3.095} + \;\; -0.102\ln(v)^{0.091} + 1.15\ln(v)^{-1} \;\; w \qquad (1.16)$$

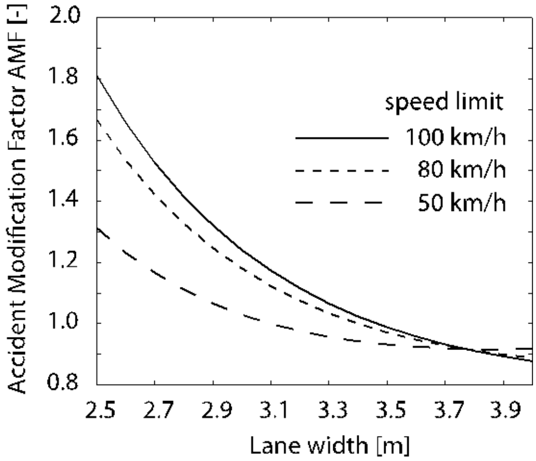


Figure 1.18: Accident Modification Factor in dependency of the velocity and the lane width.

From Figure 1.17 it can be seen that in general the lane width has a positive effect on the accident rate. Only in cases where the lane width is too large and the speed limit is low the accident rate tends to increase. This can be explained by the fact that on one hand guidance where to drive seems to be missing and on the other hand that some manoeuvres of the drivers such as overtaking might be done in dangerous situations.

The prior distribution for the lane width is given in Table 1.15. It is derived from data from Switzerland (Salvisberg et al. (2004)). It is assumed that the prior distribution for the width of the lanes in tunnels is the same in Norway.

Table 1.14: Prior probabilities for the width of the lanes.

Width of the lanes [m]	Prior distribution	
	Switzerland	Norway
0.00 - 3.00	0	0
3.00 - 3.25	0	0.04
3.25 - 3.50	0.03	0.10
3.50 - 3.75	0.51	0.51
3.75 - 4.00	0.40	0.30
4.00 - 4.25	0.02	0.02
4.25 - 4.50	0.04	0
4.50 - 4.75	0	0
4.75 - 5.00	0	0

1.4.10 Number of lanes per direction

From Figure 1.3 it can be observed that this indicator of the number of lanes has a central position in the net. One aspect is discussed in Chapter 1.4.2, namely the interaction with the traffic volume. Thereby, the number of lanes has an influence on the accident rate in dependency of the traffic volume. The influence on lane shifts is discussed in Chapter 1.4.14 and on level of service in 1.4.15.

The prior distribution for the number of lanes in Switzerland is derived from the data published in Salvisberg et al. (2004).

Table 1.15: Prior probabilities for number of lanes per direction in the tunnel.

Lanes per direction	Prior distribution	
	Switzerland	Norway
1	0.31	0.90
2	0.61	0.09
3	0.07	0.01

No information on the prior probabilities for the number of lanes is presently available for Norway. Here, it is assumed that the prior probabilities are the same in Switzerland and in Norway.

1.4.11 Speed limit in tunnels

The speed limit is one of the key indicators for traffic safety due to several reasons. The speed limit has a significant effect on the accident rate.

The influence of the speed limit on the accident modification factor (AMF) is discussed with respect to lane width in Chapter 1.4.9 and with respect to horizontal radius in Chapter 1.4.7.

The increase of the speed on accident rate, injury rate and fatality rate are well established and the models published by OECD based on work by Nilsson Nilsson (2004), show a strong relationship between increased speed an increased rates. The model is given in Table 1.16 and summarized in the following:

Frequency of accidents and consequences in terms of injuries and fatalities is dependent on the (average) speed of the traffic. This model is fully in compliance with a separate study carried out by Elvik “Potensmodel” which is reported in Elvik et al. (2004). The study by Elvik is specifically based on accidents in Norway. Elvik's formula is shown in Table 1.17. The models of Elvik and Nilsson very similar results.

For the practical application it is assumed that the reference speed in tunnels in Norway is 80 km/h. This reference speed is presumably also valid for Switzerland but not necessarily for all countries. The general indications of accidents frequency etc. are assumed to be valid for this reference speed. For speed limits resulting in lower speeds the frequency of accidents and the associated consequences are reduced and likewise increased for higher speeds.

Table 1.16: Relation between speed and traffic safety according to Nilsson.

Accidents (y)	**Causalities (z)**
Fatal accidents	Fatalities
$y_1 = \left(\frac{v_1}{v_{ref}}\right)^{x_1} y_0$	$z_1 = \left(\frac{v_1}{v_{ref}}\right)^{x_1} y_0 + \left(\frac{v_1}{v_{ref}}\right)^{2 \cdot x_1} z_0 - y_0$
Fatal and severe accidents	Fatalities and severy injured
$y_1 = \left(\frac{v_1}{v_{ref}}\right)^{x_2} y_0$	$z_1 = \left(\frac{v_1}{v_{ref}}\right)^{x_2} y_0 + \left(\frac{v_1}{v_{ref}}\right)^{2 \cdot x_2} z_0 - y_0$
All injury accidents	All injuried (fatalities included)
$y_1 = \left(\frac{v_1}{v_{ref}}\right)^{x_3} y_0$	$z_1 = \left(\frac{v_1}{v_{ref}}\right)^{x_3} y_0 + \left(\frac{v_1}{v_{ref}}\right)^{2 \cdot x_3} z_0 - y_0$

Where

v_{ref} reference speed [km/h].

v_1 driving speed [km/h].

y_0 expected number of fatal accidents/fatal.and severe accidents/ all injury accidents at v_{ref} .

y_1 expected number of accidents at v_1 .

z_0 expected number of fatalities/fatalities and severe injuries/all injuries at v_{ref} .

z_1 expected number of fatalities/fatalities and severe injuries/all injuries at v_1

x_1, x_2, x_3 model parameters,

where $x_1 = 4.0$, $x_2 = 3.0$ and $x_3 = 2.0$

Table 1.17: Relation between speed and traffic safety according to Elvik.

Fatalities: (S11/S01) = (v_1 / v_{ref}) x_1 *Injuries:* (S12/S02) = (v_1 / v_{ref}) x_2 *Injury accidents* (S13/S03) = (v_1 / v_{ref}) x_3 *Where* v_{ref} *reference speed [km/h].* v_1 *actual driving speed [km/h].* *S01 fatality rate at reference speed* *S11 fatality rate at actual driving speed* *S02 injury rate at reference speed* *S12 injury rate at actual driving speed* *S03 accident rate at reference speed* *S13 accident rate at actual driving speed*			
Model	**Model parameters**		
	Fatalities	**Injuries**	**Injury accidents**
	x_1	x_2	x_3
Elvik Type I (best estimate)	4.5	2.7	2.0

In the following Nilsson model is used. The implication of the choice of model is negligible since the two models give nearly identical results.

Driving speed, speed limit and speed distribution

It should be noted that the models by Nilsson and Elvik are referring to the actual average speed on the road section. For the decision on safety measures for a road section or a tunnel, one may decide on the speed limits indicated on the signs. For this reason the primary indicator for the tunnel is the signalised speed limit.

For the situation in Norway the average speed is assumed to be 80 km/h. The data in the accident database STRAKS has been studied and it has been found that the average speed for tunnels with two tubes (when the length and the traffic volume is taken into account) is 77 km/h Hoj (2008).

Consequently risk reduction respectively risk increase relative to the speed limits lower or higher than 80 km/h is assumed according to the Nilsson formula presented above.

Based on the data for tunnels from Salvisberg et al. (2004) it was found that the average speed limit in tunnels in Switzerland is 90 km/h. This average is based on the number of investigated tunnels, but not taking the traffic and the length into consideration. It is believed that the weighted average would be lower. The accident frequencies are primarily based on the on the Norwegian data (see Table 1.2); hence the data will be modified also based on the reference speed based on Norwegian conditions.

The speed limit may not be coinciding with the average speed. Erath and Fröhlich (2004) investigated the driving speed on national roads (open roads and tunnels) in Switzerland between 1990 and 2002. They observed that the coefficient of variation is 0.11.

Due to the non-linear influence of speed on the risk, the influence of vehicles driving faster than the average contribute more to the risk than the corresponding reduction of the risk by vehicles driving slower than the average. I.e. at a larger variance of the speed the risk will increase even though the average speed is the same. On the other hand the risk can be reduced by merely ensuring a more narrow range of speeds.

If the speed limit in a specific tunnel or road section is set very low, and the various problematic conditions in the structure, the equipment and the traffic hereby are compensated, then this tunnel (or road) is vulnerable towards drivers not keeping the low speed limit.

It should be noted that some tunnel designs and traffic compositions will influence the speed distribution: for example HGVs will be slowed down significantly on large (downwards and upwards) slopes, whereas light vehicles will tend to go faster on the downwards slope.

Erath and Fröhlich (2004) also observed that the ratio between the mean value of the driving speed and the speed limit is 0.96. This relationship is valid in the range from 60 km/h up to 120 km/h which can be seen from the data used in Lindenmann and Zuberbühler (1993).

It is the assumption that there is a certain relationship between the speed limit and the actual speed and that the difference between these two values is not high and the approximation of the driving speed with the speed limit is reasonable since the speed limit is easier to assess in a tunnel then the driving speed. However, for specific sections of road and for specific tunnels the deviation may be higher due to road-traffic conditions or other influencing factors.

Even though this close relationship between speed limit and the actual driving speed may be true for Norway and also for Switzerland, it is not necessarily the case for other countries. With other cultures of driving there may be less respect for the speed limits and a higher variance of the speed which implies that the speed limit as an approximation for the driving speed should not be used due to nonlinear effects.

In the case of no information on the speed limit in the tunnel the prior distribution is employed in the risk calculation. The prior distribution for Switzerland and Norway is given in Table 1.18.

Table 1.18: Prior probabilities for the speed limits in the tunnel.

Speed limits [km/h]	Prior distribution	
	Switzerland	Norway
40	0.01	0.00
50	0.00	0.01
60	0.01	0.06
70	0.00	0.31
80	0.50	0.44
90	0.00	0.16
100	0.46	0.02
110	0.00	0.00
120	0.02	0.00

1.4.12 Vehicles per hour

The indicator "vehicles per hour" is an intermediate logical indicator, which takes into account the different traffic characteristics during the day and the indicator can directly be calculated if the type of the time variation curve and the traffic volume are known (see Figure 1.19). The data for this node need not be inserted, as it is entirely a function of these two indicators. Since the numbers of vehicles change over the day the node "vehicles per hour" represent the probability distribution of the vehicles per hour over the day.

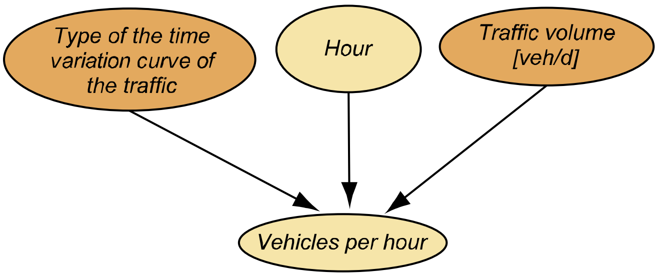


Figure 1.19: Part of the Bayesian Network for calculating the vehicles per hour.

This node has a direct influence on the ***TRANSIT*** node "vehicles per km" and the node "level of service" and has thus an influence on the consequences after a tunnel fire and on the number of accidents.

1.4.13 Hour

The node" hour" is a logical node in ***TRANSIT***. It is needed to calculate the vehicles per hour. This indicator is presently not considered as an indicator which can be changes by the user. If the distribution of the risk over the day is relevant for the decision making process it is in principle possible to use this node to display the results as function of the time of the day. This function is, however, not available in the initial version of ***TRANSIT***.

1.4.14 Level of Service

The level of service is an indicator of the quality of the traffic flow. This node is not directly a measure for the risk assessment and is thus an informative node. This indicator has been modelled with a direct influence on the lane shifts in a tunnel segment. The occurrence of lane shifts is in turn an indicator for the number of accidents in a tunnel segment. Here, the following definitions for the level of service have been used:

- Type A = Free flow.
- Type B = Reasonably free flow.
- Type C = Stable flow.
- Type D = Approaching unstable flow.
- Type E = Unstable flow.
- Type F= Forced or breakdown flow.

In order to calculate the probability for the different level of services the thresholds from Forschungsgesellschaft für Strassen- und Verkehrswesen (Deutschland) (2005) are used. These thresholds in dependency of the number of lanes are given in Table 1.19. The indicator level of service is directly dependent on the nodes number of lanes and the indicator vehicles per hour (see Figure 1.3).

Table 1.19: Threshold values for the vehicles per hour in dependency of the number of lanes for different quality levels.

TVC	Vehicles per hour		
	1 lane	2 lanes	3 lanes
Type A	<= 700	<= 1170	<= 1650
Type B	<= 1800	<= 2090	<= 3025
Type C	<= 2200	<= 2850	<= 4125
Type D	<= 2800	<= 3420	<= 4950
Type E	<= 3200	<= 3800	<= 5500
Type F	> 3200	> 3800	> 5500

1.4.15 Lane shifts

Traffic accidents may be caused by lane shifts. In a tunnel with dense traffic and high percentage of heavy vehicles, slow traffic, large gradient, ramps or in general in urban environment an increased frequency of lane shifts is expected.

As far as it has been investigated in the present study no dedicated models exist for the relationship between lane shifts and risk in tunnels. From general statistics on roads it can be seen that about 10%-15% of accidents are slanting accidents between vehicles in the same direction (Denmark Statistics, 2009).

The indicator lane shift is established in ***TRANSIT*** as a qualitative indicator. The indicator lane shift is represented by using four states, namely no lane shifts, small number of lane shifts, medium number of lane shifts and a high number of lane shifts.

The change of the probability of accidents is modelled by an Accident Modification Factor. Since no dedicated models for the indicator lane shifts exits, the following model is based on “expert judgment”.

Sections with many lane shifts are expected to have an increase occurrence of accidents. The relationship is shown in Table 1.20.

Table 1.20: AMF for the number of lane shifts.

Lane shifts	AMF
No	1.0
Low	1.0
Medium	1.1
High	1.4

The number of lane shifts in a specific section of a road is dependent on many different traffic and tunnel conditions. The most relevant indicators can be summarized as:

- The traffic conditions, represented by the level of service.
- The number of lanes.
- The fraction of heavy good vehicles.
- The entrance and exit conditions.

All these aspects interact and lead to the actual behaviour of the drivers of the vehicles. Here, an additive point rating scheme was developed to represent the number of lane shifts.
The points represent the tendency for an increase in the number of lane shifts. They are given in the following tables. It seems to be reasonable that the number of lane shifts is minimal if the traffic flows freely. The number of lane shifts reaches a maximum if an unstable flow is approaching. If the traffic is congested the number of lane shift is decreased again - or the lane shift occurs with a very low speed making the lane-shift-situation less critical than at normal operating speed. This is reflected by the rating points given in Table 1.21.

Table 1.21: Rating points for traffic conditions.

Level of service	Points
A	2
B	6
C	12
D	20
E	7
F	5

The number of lanes is a key indicator for the number of lane shift. It is obvious that in the case where only one lane is present in the tunnel segment without an exit or entrance ramp the number of lane shifts is also zero. This case is defined as a boundary condition in the point rating scheme. The probability of lane shifts in this case is zero since no lane shifts are possible. For all other cases the point scheme for the number of lanes is given in Table 1.22.

Table 1.22: Rating points for the number of lanes.

Lanes per direction	Points
1	0
2	4
3	2

The fraction of the heavy good vehicles in a section also contributes to the number of lane shifts. The number of lane shifts increases up to a fraction of 10-12%. In this range the passenger cars will still use the right lane intensively but they often have to overtake which goes along with lane shifts. If the fraction of heavy good vehicles increases normal passenger cars use more and more only the left lane so that the number of lane shifts decreases. This is reflected by the point scheme given in Table 1.23.

Table 1.23: Rating points for the fraction of the HGV

Fraction of the HGV [%]	Points
0 - 1	1
1 - 2	2
2 - 3	3
3 - 4	4
4 - 5	4
5 - 6	5
6 - 7	5
7 - 8	6
8 - 9	6
9 - 10	7
10 - 11	7
11 - 12	8
12 - 13	8
13 - 14	8
14 - 15	10

Fraction of the HGV [%]	Points
15 - 16	10
16 - 17	10
17 - 18	8
18 - 20	7
20 - 24	6
24 - 26	5

At merging areas lane shifts must necessarily occur, and this leads to an increase in the frequency of accidents. The risk is furthermore dependent on the length of the merging area. The point rating scheme for the different combinations of the entrance and exit conditions is given in Table 1.24.

Table 1.24: Rating points for the entrance and exit conditions.

	Length of entrance ramp	Length of exit ramp	Points
No ramp	-	-	0
Entrance ramp	$0 \cdot l_{req}$	-	10
	$0.5 \cdot l_{req}$		8.75
	$1.0 \cdot l_{req}$		7.5
	$2.0 \cdot l_{req}$		5
Exit ramp	-	$0 \cdot l_{req}$	10
		$0.5 \cdot l_{req}$	8.75
		$1.0 \cdot l_{req}$	7.5
		$2.0 \cdot l_{req}$	5
Combination I	$0 \cdot l_{req}$	$0 \cdot l_{req}$	10
	$0 \cdot l_{req}$	$0.5 \cdot l_{req}$	8.75
	$0 \cdot l_{req}$	$1.0 \cdot l_{req}$	7.5
	$0 \cdot l_{req}$	$2.0 \cdot l_{req}$	5
	$0.5 \cdot l_{req}$	$0 \cdot l_{req}$	8.75
	$0.5 \cdot l_{req}$	$0.5 \cdot l_{req}$	7.5
	$0.5 \cdot l_{req}$	$1.0 \cdot l_{req}$	6.25
	$0.5 \cdot l_{req}$	$2.0 \cdot l_{req}$	3.75
	$1.0 \cdot l_{req}$	$0 \cdot l_{req}$	7.5
	$1.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	6.25
	$1.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	5
	$1.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	2.5
	$2.0 \cdot l_{req}$	$0 \cdot l_{req}$	5
	$2.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	3.75
	$2.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	2.5
	$2.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	0
Combination II	$0 \cdot l_{req}$	$0 \cdot l_{req}$	10
	$0 \cdot l_{req}$	$0.5 \cdot l_{req}$	8.75
	$0 \cdot l_{req}$	$1.0 \cdot l_{req}$	7.5
	$0 \cdot l_{req}$	$2.0 \cdot l_{req}$	5
	$0.5 \cdot l_{req}$	$0 \cdot l_{req}$	8.75
	$0.5 \cdot l_{req}$	$0.5 \cdot l_{req}$	7.5
	$0.5 \cdot l_{req}$	$1.0 \cdot l_{req}$	6.25
	$0.5 \cdot l_{req}$	$2.0 \cdot l_{req}$	3.75
	$1.0 \cdot l_{req}$	$0 \cdot l_{req}$	7.5
	$1.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	6.25
	$1.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	5

	Length of entrance ramp	Length of exit ramp	Points
	$1.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	2.5
	$2.0 \cdot l_{req}$	$0 \cdot l_{req}$	5
	$2.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	3.75
	$2.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	2.5
	$2.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	0

The total number of points for the conditions in a special tunnel segment is calculated by the sum of the points given in Table 1.21 - Table 1.24. These points are used to determine the probability for the different intensity of lane shifts by using the following scheme:

$$P_{laneshift}[no] = \begin{cases} 1 & Exit\_Entrance = No \wedge Lane = 1 \\ 0 & else \end{cases} \quad (1.17)$$

$$P_{laneshift}[low] = \begin{cases} 1 - \frac{0.9}{20}\ \text{Points} - 4 & 4 < \text{Points} \leq 24 \\ 0 & \text{Points} > 24 \end{cases} \quad (1.18)$$

$$P_{laneshift}[medium] = \begin{cases} 1 - P[low] & 4 < \text{Points} < 24 \\ 0.8 & \text{Points} = 24 \\ 1 - P[high] & \text{Points} > 24 \end{cases} \quad (1.19)$$

$$P_{laneshift}[high] = \begin{cases} 0 & \text{Points} < 24 \\ 0.1 + \frac{0.9}{20}\ \text{Points} - 24 & \text{Points} \geq 24 \end{cases} \quad (1.20)$$

This heuristic model can be regarded as a module which might be exchanged in the future by using a more detailed analysis such as proposed in Helbing (1997).

1.4.16 Accident Modification factor, AMF

The node AMF represents the Accident Modification Factor. The general concept of AMF is given in Chapter 1.3. This node in the network is directly depending on 11 indicators. For all these nodes models the Accident Modification Factor has been established (see also Figure 1.20) :

- Lane shifts — Chapter 1.4.15
- Number of lanes — Chapter 1.4.10
- Traffic volume — Chapter 1.4.2
- Traffic speed — Chapter 1.7.11
- Exit and entrance conditions — Chapter 1.4.3
- Horizontal radius — Chapter 1.4.7
- Tunnel lighting — Chapter 1.4.6
- Lane width — Chapter 1.4.9
- Bi directional — Chapter 1.4.4
- Fraction of heavy good vehicles — Chapter 1.4.5
- Gradient — Chapter 1.4.8

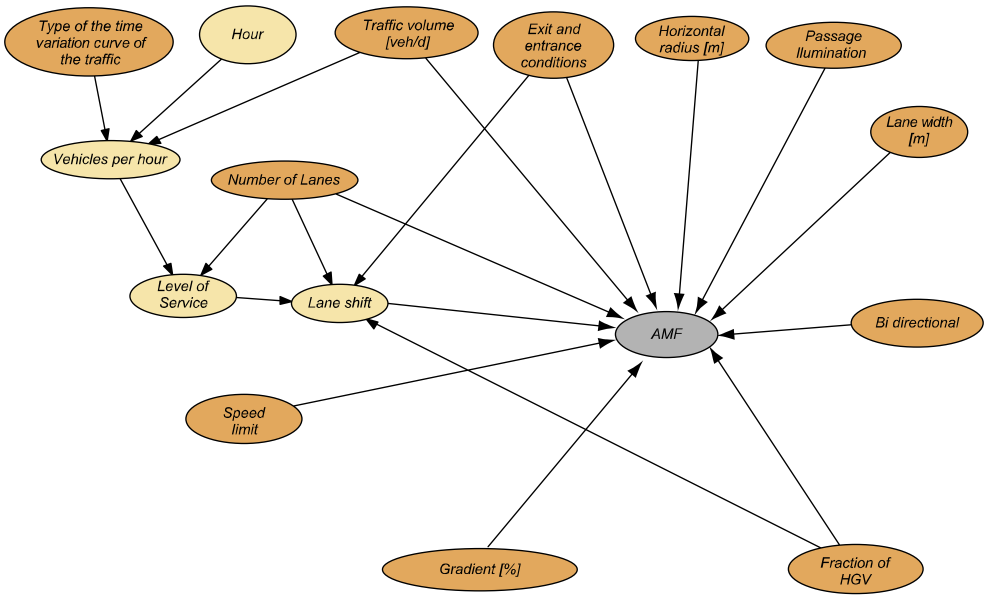


Figure 1.20: Indicators influencing the accident modification factor, AMF

By using these models the AMF is calculated as the product of all Accident Modification Factors described before. The node AMF contains the distribution of the AMF i.e. the result is not one single value for the tunnel segment but a distribution of the Accident Modification factor. The distribution reflects the uncertainty in the model as well as the epistemic uncertainty due to the lack of knowledge in regard to the state of certain indicators. The uncertainty is minimized in the case where the states of all indicators are known with certainty.

This is illustrated in Figure 1.19 and Figure 1.22. If no information is available the uncertainties in the model are quite high. The coefficient of variation of the AMF is 0.75. The mean value of the AMF is also elevated in this case. It can be observed that the distribution of the AMF has several modes. That is reasonable since different factors contribute to the distribution.

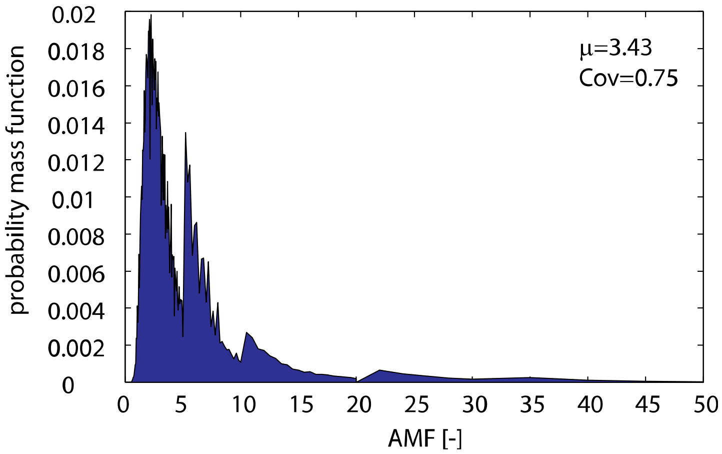


Figure 1.21: Distribution of the AMF in the case where no information on the indicators is available.

The distribution for an example where all indicators are known is given in Figure 1.22. It can be observed that the uncertainty is reduced significantly

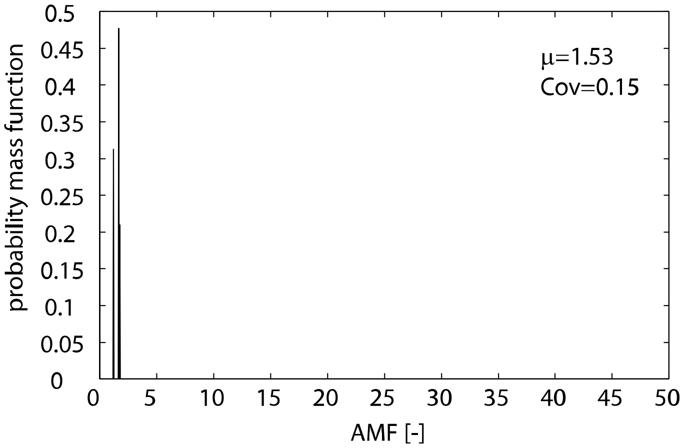


Figure 1.22: Example for one distribution of the AMF in the case where information on all indicators is available.

1.4.17 Distribution of the accident rate

The node "distribution of the accident rate" is dependent on the node AMF, zone and the speed limit. With the information contained in these nodes (see also Chapters 1.4.16 and 1.4.11) and the accident background rate (see Chapter 1.3) the distribution of the accident rate is calculated.

The distribution of the accident rate is not directly used for the decision making process.

1.4.18 Distribution of the injury rate

The node distribution of the injury rate is dependent on the node AMF, zone and the speed limit. With the information contained in these nodes (see also Chapters 1.4.16 and 1.4.11) and the injury background rate (see Chapter 1.3) the distribution of the injury rate is calculated.

1.4.19 Distribution of the fatality rate

The node distribution of the fatality rate is dependent on the node AMF, zone and the speed limit. With the information contained in these nodes (see also Chapters 1.4.16 and 1.4.11) and the injury background rate (see Chapter 1.3) the distribution of the injury rate is calculated.

1.4.20 Mean value of the accident rate

The only information of the distribution of the accident rate used in the results of ***TRANSIT*** is the mean value of the accident rate in a specific tunnel segment. Information on the distribution is not provided. The mean value of the accident rate is presently regarded as the information which is needed to characterize the risk and make rational decisions. However, the information on the uncertainties are already contained in the Bayesian Network and can be made available in if it is needed for the decision making process.

1.4.21 Mean value of the injury rate

Again, the mean value is presently the only measure of interest for the decision making process and thus the mean value of the injury rate is calculated in this node.

1.4.22 Mean value of the fatality rate

In this node the mean value of the fatality rate in a special tunnel segment is calculated. For the nodes described in the Chapters 1.4.20-1.4.22 in principle no Bayesian Network need to be employed. Here, it was done due to practical reasons and because the entire architecture of the Bayesian Network.

1.4.23 Mean value of the fire rate caused by accidents

Fire events can occur after accidents but also due to ignition resulting from technical defects etc on the vehicles. Both cases are modelled separately here.

The fire statistics in PIARC (1999) inform, that the frequency of fires is $4.6 \cdot 10^{-8} [1 / veh\ km]$ and that 20% of all fires in tunnels are caused by accidents. It follows that fires caused by accidents occur with a frequency of $0.9 \cdot 10^{-8} [1 / veh\ km]$. Similarly, the frequency of injury accidents is presently approximately $0.2 \cdot 10^{-6} [1 / veh\ km]$ in Switzerland and in Norway. With these figures, one can find that in approximately 4.6% of all injury accidents an ignition is expected.

However, it should be noted that also non-injury accidents, and given that the frequency of non-injury accidents is an order of magnitude higher than injury accidents, then it can be concluded that the probability of a fire given any accident is less than 0.5%.

This is well in accordance with Parsons (1990), where it was reported that in 0.3% of all accidents an ignition is expected.

The node "*mean value of the fire rate caused by accidents"* is dependent on the mean value of the accident rate (Chapter 1.4.20) and the fraction of heavy good vehicles.

The influence of the heavy good vehicles, which are assumed to have a 2 times higher fire rate than cars, is taken into account by a linear model:

$$P_{fire} \mid accident(HGV) = 4.11 \cdot 10^{-2} + 4.11 \cdot 10^{-4} \cdot HGV \quad 0 \leq HGV \leq 26 \tag{1.21}$$

Herein denotes $P_{fire} \mid accident(HGV)$ the probability for a fire in the tunnel given an injury accident as a function of the heavy goods vehicles $HGV[\%]$. With $HGV = 0\%$ one can calculate a probability for ignition after an injury accident of 4.1%. The before mentioned 4.6% are reached at a HGV of 12% and the probability increases up to 5.2% if the HGV is 26%.

1.4.24 Mean value of the fire rate caused by technical defects in the vehicles

The influence of technical defect or overheating of vehicles on the fire rate is modelled through the node "Technical defects". This fire rate according to PIARC (1999) is $3.6 \cdot 10^{-8} [1 / veh\ km]$. Furthermore it is specified that the risk of fires for HGV is 3 to 4 times the frequency for regular personal vehicles. With an average share of HGV of about 12% the resulting frequencies of fires are $2.8 \cdot 10^{-8} [1 / veh\ km]$ for regular personal vehicles and $1 \cdot 10^{-7} [1 / veh\ km]$ for heavy good vehicles. With these two figures the ignition rate in dependency of the fraction of heavy good vehicles is calculated.

The node is dependent on the fraction of heavy good vehicles and on the gradient. It has been observed that there is an increased occurrence of fires in tunnels with high Severity of fire

The severity of a fire is defined by 4 general classes, i.e. no fire, 5MW fire, 30MW fire and 100MW fire, which is regarded to represent sufficiently the total event space.

The node severity of the fire is dependent on the node thermal load (see Chapter 1.4.25), mean value of the fire rate caused by accidents (see Chapter 1.4.23) and the node mean value of the fire rate caused by technical defects (see Chapter 1.4.24). Since no model is available to quantify the conditional probability table of this node, this node is based on expert judgment. The conditional probability table is given in Table 1.24 - Table 1.28.

Table 1.25: Conditional probability table of the node severity of fire for a low thermal load.

Thermal load	**Low**			
Fire accidents	**no fire**		**fire**	
Technical defects	**no fire**	**fire**	**no fire**	**fire**
No fire	1	0	0	0
5MW fire	0	0.99	0.98	0.98
30 MW fire	0	0.01	0.18	0.18
100 MW fire	0	0	0.002	0.02

Table 1.26: Conditional probability table of the node severity of fire for a medium thermal load.

Thermal load	**medium**			
Fire accidents	**no fire**		**fire**	
Technical defects	**no fire**	**fire**	**no fire**	**fire**
No fire	1	0	0	0
5MW fire	0	0.98	0.9	0.9
30 MW fire	0	0.02	0.08	0.08
100 MW fire	0	0	0.02	0.02

Table 1.27: Conditional probability table of the node severity of fire for a high thermal load.

Thermal load	**high**			
Fire accidents	**no fire**		**fire**	
Technical defects	**no fire**	**fire**	**no fire**	**fire**
No fire	1	0	0	0
5MW fire	0	0.85	0.77	0.77
30 MW fire	0	0.13	0.2	0.2
100 MW fire	0	0.02	0.03	0.03

Table 1.28: Conditional probability table of the node severity of fire for a high thermal load.

Thermal load	**very high**			
Fire accidents	**no fire**		**fire**	
Technical defects	**no fire**	**fire**	**no fire**	**fire**
No fire	1	0	0	0
5MW fire	0	0.8	0.72	0.72
30 MW fire	0	0.17	0.23	0.23
100 MW fire	0	0.03	0.05	0.05

1.4.25 Thermal load

The thermal load in the tunnel can serve as an indicator for the severity of a tunnel fire. According to other approaches in modeling of fires (Köhler et al. (2006)) the thermal load inside the tunnel is estimated is estimated based on the number of vehicles at the time of fire and the individual fire load of each vehicle.

With reference to PIARC (1999) the mean value of the thermal load of a passenger car is assumed 3000 - 7000 MJ and the mean value of the thermal load of an heavy good vehicle is 88000 MJ, whereas a $50m^3$ tanker is assumed 1500000 MJ. Based on these values the thermal load inside the tunnel can be estimated in in dependency of the vehicles per kilometre and the fraction of the heavy good vehicles.

Five states are considered here, low, medium, high and very high. Low corresponds to a thermal load of 150000 MJ/km, medium to a thermal load of 1200000 MJ/km, high to a thermal load of 2500000 MJ/km and very high to a thermal load larger than 2500000 MJ/km.

1.4.26 Alarm

In several studies (e.g. UPTUN (2006)) it is reported that the passengers prefer to stay in their cars as long as they can. Clear instructions through a visible or audible alarm or by communication via radio or other communication systems can be an effective measure to increase the probability that a self-rescue is successful. The trigger of an alarm requires that a monitoring system such as video surveillance, visibility monitors and fire detectors are installed in the tunnel. Therefore, the node *Alarm* is dependent on the node *Monitoring*. In Table 1.29 the conditional probability table for the node alarm is given. It is assumed that the probability that an alarm is triggered in an emergency case given a monitoring system is installed is 0.95. Here, no differentiation is made between Switzerland and Norway.

Table 1.29: Conditional probability table for the node Alarm.

	Monitoring	**No Monitoring**
No Alarm	0.05	1
Alarm	0.95	0

1.4.27 Escape

In Figure 1.23 the influencing factors for a successful escape in the case of a fire event are illustrated. Indicators which have an influence are the traffic conditions, these are the congestion hours and the type of the traffic routing (unidirectional or bidirectional) are considered as well as indicators which describe the tunnel characteristics, these are the ventilation system, the presence of emergency light and the distance to the emergency exit and if a monitoring system is present. The latter one is indirectly represented by the node *Alarm* (see also Chapter 1.4.28). Since all the technical installations in the tunnel are not fail safe, there is a certain probability that either the fire program of the ventilation or the emergency lights are not working properly. This modelled by the node *Technical defect.* The probability for a successful escape depends also on the event itself. In severe events the probability for a successful escape is significant lower than in small fire events.

Basic escape rates have been established based on the evaluation of the response surface and representing the case where no risk reducing measures are present in the tunnel. These basic rates are given in Table 1.30. It should be noted that they represent the probability that one single person can or cannot escape from the fire event.

Different risk reducing measures can increase the probability that a person can escape from the fire. Here, third-party rescue as well as self-rescue is considered whereas the latter one is more relevant for tunnel fires.

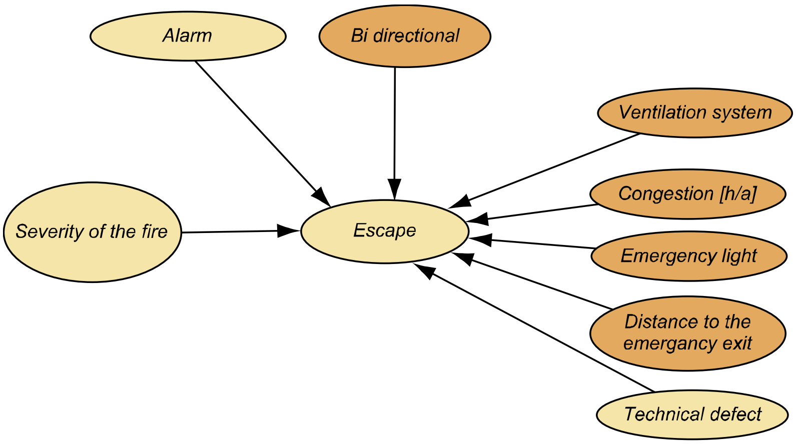


Figure 1.23: Part of the Bayesian Network showing the direct causal relations to the node Escape.

Table 1.30: Basic escape rates in dependency of the severity of the fire.

Escape	no fire	5MW	30MW	100MW
No escape	0	0.1	0.3	0.6
Escape	1	0.9	0.7	0.4

Different measures have a positive influence on the basic escape rates. The influence is modelled by using influence factors. These factors are multiplied with the basic escape rates.

The presence of emergency light has a slight influence on the probability of a successful escape. The corresponding factor is given in Table 1.31. The slight increase lies in the fact that emergency lights are especially necessary in cases where heavy smoke is in the tunnel. However, regarding the time line of the event it can be reasonably being assumed that a person has already left the site before heavy smoke is in at the location. However, since this measure is comparable cheap it might be efficient to perform this measure.

Table 1.31: Influence of the distance of the emergency lights on the probability to escape.

Emergency light	Factor	
	No defect	**defect**
yes	0.9	1.0
no	1.0	1.0

The distance of the emergency exits has a larger influence on the probability that a person can escape. The factor is given in Table 1.32. A small distance between the emergency exits has in general a high influence on the probability that a person can escape. The larger the distance between the emergency exists are the less the influence is. One can observe from Table 1.32 that a distance of more than 650 m has no influence on the escape probability.

Table 1.32: Influence of the distance of the emergency distance on the probability to escape.

Distance to the emergency exit	Factor
0-150 [m]	0.1
150 - 350 [m]	0.4
350 - 650 [m]	0.7
> 650 [m]	1.0

An Alarm can help the tunnel users to make the right decisions at the right time and thus help to increase the escape probability of a person in the tunnel. The effect of an alarm system on the escape probability is given in Table 1.33 as a multiplicator for the basic escape rates.

Table 1.33 Influence of the alarm on the probability to escape.

Alarm	Factor
yes	0.7
no	1.0

The ventilation system plays a major role in increasing the escape probability. The effectiveness of the ventilation system depends on several factors. One factor is the severity of the fire. The smaller a tunnel fire is, the more efficiently the ventilation system can increase the probability of escape. The type of traffic, i.e. unidirectional or bi-directional traffic plays a role in particular for longitudinal ventilation system without smoke extraction. In cases with traffic congestion, longitudinal ventilation systems have hardly a positive effect on the escape probability.

Here, 9 different types of ventilation systems are considered. A detailed description of these systems is given in Chapter 1.4.29.

In Table 1.34 and Table 1.35 the effect on the probability of escape depending on the ventilation system is given.

Table 1.34: Influence of the ventilation system on the probability for a successful escape in the case where the traffic is not congested.

Congestion	No congestion							
Bi - directional	**Uni directional traffic**				**Bi directional traffic**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
Ventilation Type 1	1	1	1	1	1	1	1	1
Ventilation Type 2	1	0.2	0.2	0.5	1	1	1	1
Ventilation Type 3	1	0.2	0.2	0.5	1	0.5	0.5	0.7
Ventilation Type 4	1	0.4	0.4	0.8	1	0.4	0.4	0.8
Ventilation Type 5	1	0.2	0.2	0.5	1	0.2	0.2	0.5
Ventilation Type 6	1	0.4	0.4	0.8	1	0.4	0.4	0.8
Ventilation Type 7	1	0.2	0.2	0.5	1	0.2	0.2	0.5
Ventilation Type 8	1	0.4	0.4	0.8	1	0.4	0.4	0.8
Ventilation Type 9	1	0.2	0.2	0.5	1	0.2	0.2	0.5

Table 1.35: Influence of the ventilation system on the probability for a successful escape in the case where the traffic is congested.

Congestion	congestion							
Bi - directional	**Uni directional traffic**				**Bi directional traffic**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
Ventilation Type 1	1	1	1	1	1	1	1	1
Ventilation Type 2	1	1	1	1	1	1	1	1
Ventilation Type 3	1	0.5	0.5	0.7	1	0.5	0.5	0.7
Ventilation Type 4	1	0.4	0.4	0.8	1	0.4	0.4	0.8
Ventilation Type 5	1	0.2	0.2	0.5	1	0.2	0.2	0.5
Ventilation Type 6	1	0.4	0.4	0.8	1	0.4	0.4	0.8
Ventilation Type 7	1	0.2	0.2	0.5	1	0.2	0.2	0.5
Ventilation Type 8	1	0.4	0.4	0.8	1	0.4	0.4	0.8
Ventilation Type 9	1	0.2	0.2	0.5	1	0.2	0.2	0.5

1.4.28 Monitoring system

Manifold different monitoring systems for fire detection in tunnel are available.

These monitoring systems can help to trigger an alarm so that the probability of self-rescue of persons is increased and gives input to starting and controlling the fire mode of the ventilation system. In the initial version of ***TRANSIT*** it is only considered if a monitoring system is installed or not. The various systems are not differentiated. The main reason for this is that the models for the influence on the consequences of a tunnel fire for different monitoring systems have to be established first. ***TRANSIT*** can be upgraded when such a model becomes available.

It is assumed that presently a monitoring system is installed in 50% of all tunnels.

1.4.29 Ventilation system

Fires generally result in a complex toxic environment and it is recognized that the smoke leads to more fatalities and injuries than due to thermal injuries. In fire events, numerous toxic gases such as carbon monoxide and cyanide are released but also oxygen depletes.

The main function of the fire-ventilation is to manage the smoke and thereby establish favorable conditions for escape and rescue.

The effectiveness of a ventilation system dependents on many factors such as the type of ventilation system, tunnel geometry, differences in altitude between the two portals, the design of the tunnel (bi-directional or unidirectional traffic), the probability of congestion, the natural stack effect, external wind pressure and the size of the design fire.

The tunnel ventilation can be considered in a formalized manner with some generalizations and simplifications.

The approach followed here is based on expert opinion. The expert panel was composed of Dr. Rune Brandt and Dr. Ingo Riess both from HBI Haerter[5] , Niels Peter Høj, Prof. Dr. Michael Faber, Dr. Matthias Schubert and Dr. Jochen Köhler. Different scenarios have been identified and the effect on the probability that a person can escape successfully was estimated and plausibility checks of the results were conducted (see Chapter 1.4.27 and Table 1.34

Table 1.35). This approach is a strong simplification, but it is believed that the model is sufficient to give an estimate of the risk taking the ventilation into account. It should be noted, however, that t. However, the approach is comparable to the approach used in Zulauf et al. (2007) and presently be regarded as best practice even though more sophisticated methods are available and could be used. This could not be done in this project but the methodology allows including this as soon as the probabilities are calculated by using e.g. CFD (Computational Fluid Dynamics) simulations and egress modeling. The employed approach cannot substitute a detailed investigation of the ventilation system nor computerised smoke dispersion models, e.g. CFD (Computational Fluid Dynamics) analysis combined with egress modeling.

Factors influencing the efficiency of the ventilation system are also the total gradient of the tunnel (Δ height between the two tunnel portals) combined with the difference between the internal and ambient temperature. Moreover, external climate: air pressure, wind conditions etc. can influence the efficiency of the ventilation system. These factors could be included in future developments of the program.system. These factors could be included in future developments of the program.

[5] With more than 600 successful reference objects HBI is an internationally leading consultant specialized in tunnel ventilation (see also www.hbi.ch; online accessed in December 2010).

The approach for calculation the probability for a successful escape in the case of a tunnel fire is described in Chapter 1.4.29.

The following ventilation systems are considered in ***TRANSIT***:

- Natural ventilation (Ventilation Type 1)
- Longitudinal ventilation (Ventilation Type 2)
- Longitudinal ventilation with active control (Ventilation Type 3)
- Longitudinal ventilation with smoke extraction (Ventilation Type 4)
- Longitudinal ventilation with smoke extraction and active control (Ventilation Type 5)
- Semi transverse ventilation (Ventilation Type 6)
- Semi transverse ventilation with active control (Ventilation Type 7)
- Transverse ventilation (Ventilation Type 8)
- Transverse ventilation with active control (Ventilation Type 9)

These systems are consistent with those reported in ASTRA (2008). Combinations of these systems can presently not be considered. An illustration of the ventilation systems is given in Figure 1.24 - Figure 1.27.

The active control refers to a system that during the smoke management automatically and permanently optimizes the longitudinal flow in order to obtain the best possible smoke management.

It is currently assumed that all systems encompassing a smoke extraction (types 4 to 9) have an adequate smoke-extraction capacity and that the smoke is extracted over a short distance at the vicinity of the fire.

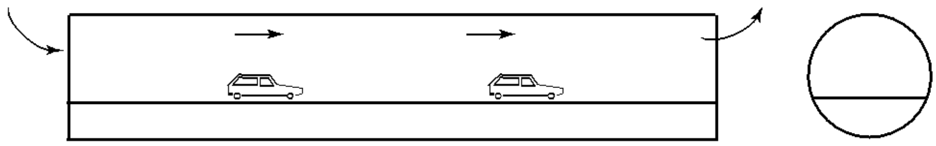


Figure 1.24: Type 1: Natural ventilation.

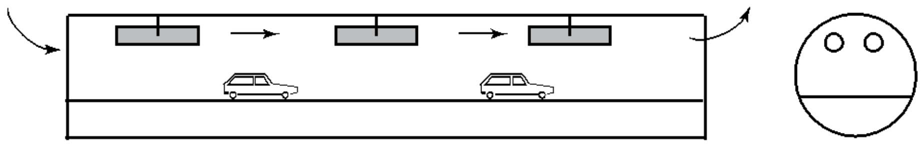


Figure 1.25: Type 2 and 3: Longitudinal ventilation with or without active control.

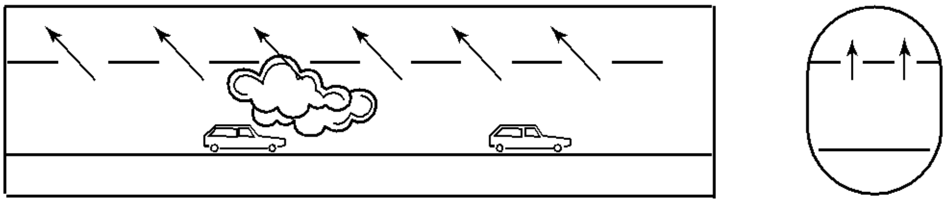


Figure 1.26: Types 4 and 5 longitudinal ventilation with smoke extraction with or without active control. This is also the principle for Types 6 and 7: Semi-transverse ventilation with or without active control.

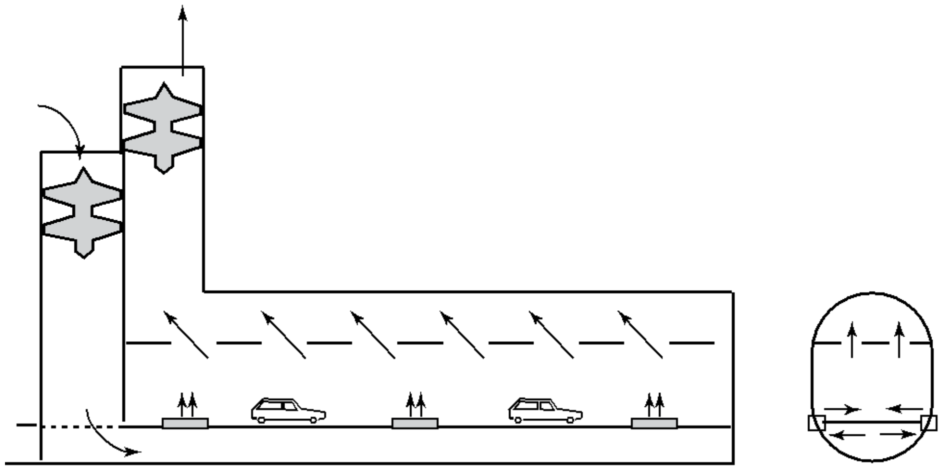


Figure 1.27: Types 8 and 9: Transverse ventilation with or without active control.

If no information on the ventilation system in the tunnel is available the program employs a representative prior distribution for the calculation. The prior distribution is given in Table 1.36.

Table 1.36: Prior probabilities for the presence of different ventilation systems.

Ventilation systems	Prior distribution	
	Switzerland	Norway
Type 1: Natural ventilation	0.08	0.70
Type 2: Longitudinal ventilation	0.12	0.20
Type 3: Longitudinal ventilation with active control	0.16	0.10
Type 4. Longitudinal ventilation with smoke extraction	0.08	0.00
Type 5: Longitudinal ventilation with smoke extraction and active	0.04	0.00
Type 6: Semi transverse ventilation	0.245	0.00
Type 7: Semi transverse ventilation with active control	0.105	0.00
Type 8: Full transverse ventilation	0.119	0.00
Type 9: Full transverse ventilation with active control	0.051	0.00

1.4.30 Congestion

The ability of the tunnel ventilation system to create safe conditions for escape in case of fire depends on whether congestion occurs in the tunnel, in which case many users will be in the tunnel, possibly also down-stream of the fire for tunnels with unidirectional traffic. This effect is described in Chapter 1.4.27.

In cases where no information on the number annual congestion hours is available, the prior probabilities are used. The prior probabilities are given in Table 1.37. The prior probability of congestion for Switzerland corresponds to 100 hours/year, the prior probability for Norway corresponds to 10 hours/year.

Table 1.37: Prior probabilities for the congestion in the tunnel.

Congestion	Prior distribution	
	Switzerland	Norway
Congestion	0.0114	0.00114
No Congestion	0.9886	0.99886

It should be noted that a reduction in the congestion hours in the tunnel can be considered as a risk reducing measure in itself. Such a measure is for example utilized in the Gotthard tunnel in Switzerland.

1.4.31 Emergency lights

Emergency lighting is intended to indicate the shortest distance to the next (emergency) exit and to increase the speed of getting to this exit (see Aizlewood and Webber (1995)). The system shall be able to fulfil it function also under conditions of the fire, smoke and by loss of the normal power supply. It is a requirement for the system that unbreakable power supply and/or an independent power supply is available. The different emergency light systems are not discussed in the present report.

Presently, the effects of emergency lights are described qualitatively in the literature. It is known that these lights can help but no model has yet been developed to take this effect quantitatively into account. Therefore this effect was estimated by expert opinion. The effect on the probability of escape is described in Chapter 1.4.27.

1.4.32 Distance to the emergency exit

To model the effect of the distances of the emergency a modification of the approach used in TUNprim (Weger et al. (2001)) and Vrouwenfelder et al. (2001) is employed. Close to the emergency exits, it is assumed that the probability of dying or being injures is (close to) zero.

It is assumed that the probability of dying and the probability of getting injured is fully correlated with the probability of a successful escape. Near to the exit the probability of dying increases linearly from zero to the probability of dying. Thus, the modification factor increases linearly from zero to one. Some distance away from the emergency exit the probability of dying is constant. The general scheme of this approach and the distances are given in Figure 1.28. From this scheme the modification factor is calculated as follows:

$$MF = \begin{cases} 0.03 & L_{tot} \leq 50\,m \\ \dfrac{L_{tot} \cdot 0.03 + \dfrac{0.97\left(L_{tot}-50\right)^2}{150}}{L_{tot}} & 50\,m < L_{tot} \leq 200\,m \\ 1 - \dfrac{48.5}{L_{tot}} & 200\,m < L_{tot} \end{cases} \qquad (1.22)$$

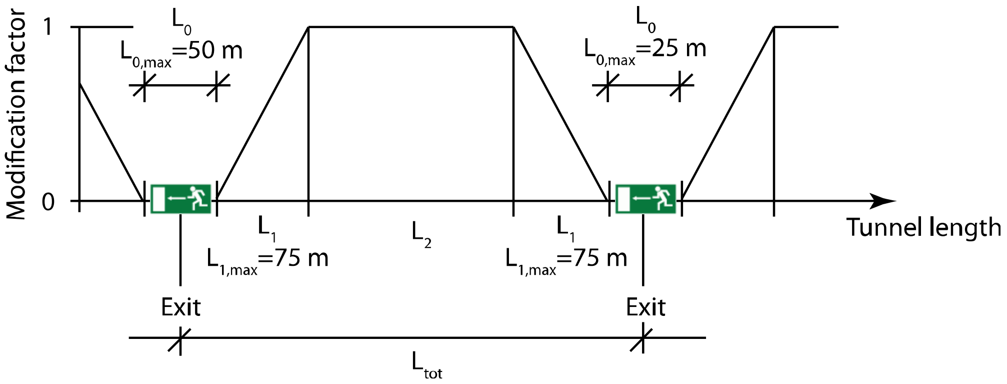


Figure 1.28: Modification factor on the escape probability near and some distance away from the emergency exists.

In the BPN of ***TRANSIT*** discrete states are used. For these states, the modification factor can be calculated according to Equation (1.22). The effect on the probability of escape is described in Chapter 1.4.27.

1.4.33 Vehicles per km

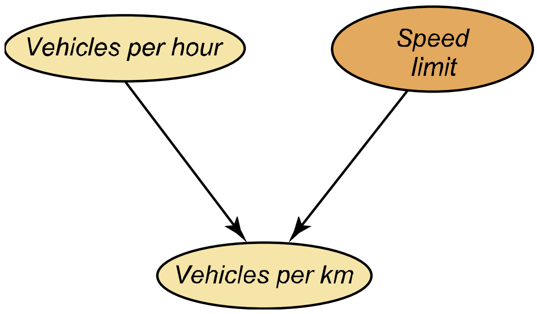


Figure 1.29: Part of the Bayesian Network showing the direct causal relations to the node Vehicles per km.

The node "vehicles per kilometre" is a logical node and calculated by the division of the vehicles per hour by the speed limit. This is an approximation under the assumption that the traffic is in free flow conditions and under the assumption that the road user can drive with the speed limit. The node vehicles per kilometre serves as an indicator for the thermal load in the tunnel and an indicator for the number of injuries and the number of fatalities in case of a tunnel fire.

1.4.34 Technical defect

Alarm systems and ventilation systems can help to decrease significantly the consequences of tunnel fires. Technical equipment in the tunnel like automatic warning systems but also the ventilation system might not work in the case of an incident. Every system has its specific defect probability distribution and data on the defect frequency is not studied in detail. Additionally, a detailed model will hardly influence the risk significantly since the probability of defect on demand can be assumed to be low. The defect probability of 0.01 proposed by Zulauf et al. (2007) for the technical equipment in the tunnel is also adopted for ***TRANSIT***.

1.4.35 Number of fatalities and number of injuries due to tunnel fire

The number of fatalities and injuries after a tunnel fire can hardly be based on real observation because of the relative few events of fatal fires. The conditional probability of the number of fatalities can be assessed by expert opinion based on the few existing observations. In the present report the severity of the fire with respect to fatalities and injuries is modelled by expert opinion. The fatalities and injuries are assumed to be related to the indicator "fire severity" and the indicator "chances of escape". Also the potential number of road users in the tunnel has to be considered. The smaller the number of vehicles per kilometre is the smaller is the expected number of fatalities.

In Table 1.38 - Table 1.42 the conditional probability mass function for the number of fatalities in dependency of the fire severity, the number of vehicles per kilometre and for the event that the road user could not escape is given. The state "no fire" is not shown as it in all cases gives the result "severity of fire" = 0.

In Table 1.43 - Table 1.47 the conditional probability mass function for the number of injuries in dependency of the fire severity, the number of vehicles per kilometre and for the event that the road user could not escape is given. The state "no fire" is not shown as it in all cases gives the result "severity of fire" = 0.

Table 1.38: Conditional probability table for the indicator 'Number of fatalities due to tunnel fire' for 10 and 30 vehicles per km.

Vehicles per km	**10**				**30**			
Escape	**No escape**				**No escape**			
Severity of the fire	no fire	5MW	30MW	100MW	no fire	5MW	30MW	100MW
0	1	0.9	0	0	1	0.8	0	0
1	0	0.1	1	2.11e-4	0	0.2	2.61e-1	0
2	0	0	0	9.99e-1	0	0	7.39e-1	0
3	0	0	0	3.10e-4	0	0	0	2.11e-4
4	0	0	0	0	0	0	0	2.60e-1
5	0	0	0	0	0	0	0	6.84e-1
6	0	0	0	0	0	0	0	5.50e-2
7	0	0	0	0	0	0	0	3.09e-4
8	0	0	0	0	0	0	0	3.38e-7
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0

Table 1.39: Conditional probability table for the indicator 'Number of fatalities due to tunnel fire' for 50 and 70 vehicles per km.

Vehicles per km	**50**				**70**			
Escape	**No escape**				**No escape**			
Severity of the fire	no fire	5MW	30MW	100MW	no fire	5MW	30MW	100MW
0	1	0.5	0	0	1	0.3	0	0
1	0	0.5	4.14e-9	0	0	0.7	0	0
2	0	0	8.82e-1	0	0	0	1.44e-2	0
3	0	0	1.18e-1	0	0	0	9.55e-1	0
4	0	0	7.57e-8	4.14e-9	0	0	3.02e-2	0
5	0	0	0	2.11e-4	0	0	9.6e-7	0
6	0	0	0	4.45e-2	0	0	0	1.98e-7
7	0	0	0	3.95e-1	0	0	0	2.11e-4
8	0	0	0	4.43e-1	0	0	0	1.42e-2
9	0	0	0	1.09e-1	0	0	0	1.43e-1
10	0	0	0	8.66e-3	0	0	0	3.63e-1
20	0	0	0	3.1e-4	0	0	0	4.8e-1
30	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0

Table 1.40: Conditional probability table for the indicator 'Number of fatalities due to tunnel fire' for 100 and 120 vehicles per km.

Vehicles per km	**100**				**120**			
Escape	**No escape**				**No escape**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
0	1	0	0	0	1	0	0	0
1	0	1	0	0	0	1	0	0
2	0	0	4.14e-9	0	0	0	0	0
3	0	0	4.48e-2	0	0	0	2.11e-4	0
4	0	0	8.37e-1	0	0	0	2.60e-1	0
5	0	0	1.18e-1	0	0	0	6.84e-1	0
6	0	0	3.10e-4	0	0	0	5.5e-2	0
7	0	0	7.57e-8	0	0	0	3.09e-4	0
8	0	0	0	4.14e-9	0	0	3.38e-7	0
9	0	0	0	2.30e-6	0	0	0	0
10	0	0	0	2.09e-4	0	0	0	4.31e-8
20	0	0	0	9.99e-1	0	0	0	9.45e-1
30	0	0	0	3.10e-4	0	0	0	5.53e-2
50	0	0	0	0	0	0	0	7.57e-9
60	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0

Table 1.41: Conditional probability table for the indicator 'Number of fatalities due to tunnel fire' for 180 and 220 vehicles per km.

Vehicles per km	**180**				**220**			
Escape	**No escape**				**No escape**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
0	1	0	0	0	1	0	0	0
1	0	2.61e-1	0	0	0	3.98e-3	0	0
2	0	7.39e-1	0	0	0	9.96e-1	0	0
3	0	0	0	0	0	8.72e-6	0	0
4	0	0	1.26e-6	0	0	0	0	0
5	0	0	6.76e-3	0	0	0	3.71e-6	0
6	0	0	2.54e-1	0	0	0	9.98e-3	0
7	0	0	5.56e-1	0	0	0	1.30e-1	0
8	0	0	1.71e-1	0	0	0	4.57e-1	0
9	0	0	1.22e-2	0	0	0	3.30e-1	0
10	0	0	3.06e-4	0	0	0	7.23e-2	0
20	0	0	3.75e-6	6.76e-3	0	0	6.80e-3	3.71e-6
30	0	0	0	9.38e-1	0	0	0	3.39e-1
50	0	0	0	5.53e-2	0	0	0	6.61e-1
60	0	0	0	0	0	0	0	1.27e-6
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0

Table 1.42: Conditional probability table for the indicator 'Number of fatalities due to tunnel fire' for 250 and 300 vehicles per km.

Vehicles per km	**250**				**300**			
Escape	**No escape**				**No escape**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
0	1	0	0	0	1	0	0	0
1	0	4.16e-5	0	0	0	4.14e-9	0	0
2	0	9.99e-1	0	0	0	8.82e-1	0	0
3	0	1.29e-3	0	0	0	1.18e-1	0	0
4	0	0	0	0	0	7.57e-8	0	0
5	0	0	4.14e-9	0	0	0	0	0
6	0	0	4.16e-5	0	0	0	4.14e-9	0
7	0	0	8.39e-3	0	0	0	1.24e-5	0
8	0	0	1.38e-1	0	0	0	1.98e-3	0
9	0	0	4.05e-1	0	0	0	4.28e-2	0
10	0	0	3.31e-1	0	0	0	2.16e-1	0
20	0	0	1.18e-1	4.14e-9	0	0	7.37e-1	0
30	0	0	0	4.48e-2	0	0	0	2.11e-4
50	0	0	0	9.55e-1	0	0	0	9.44e-1
60	0	0	0	3.10e-4	0	0	0	5.50e-2
70	0	0	0	7.57e-8	0	0	0	3.09e-4
80	0	0	0	0	0	0	0	3.38e-7
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0

Table 1.43: Conditional probability table for the indicator 'Number of injuries due to tunnel fire' for 10 and 30 vehicles per km.

Vehicles per km	10				30			
Escape	**No escape**				**No escape**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
0	1	8.18e-1	0	0	1	6.67e-1	0	0
10	0	1.82e-1	1	1	0	3.33e-1	1	1
20	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0

Table 1.44: Conditional probability table for the indicator 'Number of injuries due to tunnel fire' for 50 and 70 vehicles per km.

Vehicles per km	50				70			
Escape	**No escape**				**No escape**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
0	1	3.33e-1	0	0	1	1.76e-1	0	0
10	0	6.67e-1	1	2.61e-1	0	8.24e-1	1	2.97e-5
20	0	0	0	7.39e-1	0	0	0	9.98e-1
30	0	0	0	0	0	0	0	1.67e-3
40	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0

Table 1.45: Conditional probability table for the indicator 'Number of injuries due to tunnel fire' for 100 and 120 vehicles per km.

Vehicles per km	**100**				**120**			
Escape	**No escape**				**No escape**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
0	1	0	0	0	1	0	0	0
10	0	1	1	0	0	1	1	0
20	0	0	0	2.61e-1	0	0	0	6.76e-3
30	0	0	0	7.39e-1	0	0	0	9.38e-1
40	0	0	0	3.1e-4	0	0	0	5.53e-2
50	0	0	0	0	0	0	0	3.75e-2
60	0	0	0	0	0	0	0	3.75e-6
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0

Table 1.46: Conditional probability table for the indicator 'Number of injuries due to tunnel fire' for 180 and 220 vehicles per km.

Vehicles per km	**180**				**220**			
Escape	**No escape**				**No escape**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
0	1	0	0	0	1	0	0	0
10	0	1	6.61e-1	0	0	1	5.51e-2	0
20	0	0	3.39e-1	0	0	0	9.45e-1	0
30	0	0	0	6.76e-3	0	0	4.36e-8	3.71e-6
40	0	0	0	6.54e-1	0	0	0	5.51e-2
50	0	0	0	3.35e-1	0	0	0	6.84e-1
60	0	0	0	4.00e-3	0	0	0	2.54e-1
70	0	0	0	3.75e-6	0	0	0	6.77e-3
80	0	0	0	0	0	0	0	3.00e-5
90	0	0	0	0	0	0	0	4.36e-8
100	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0

Table 1.47: Conditional probability table for the indicator 'Number of injuries due to tunnel fire' for 250 and 300 vehicles per km.

Vehicles per km	**250**				**300**			
Escape	**No escape**				**No escape**			
Severity of the fire	**no fire**	**5MW**	**30MW**	**100MW**	**no fire**	**5MW**	**30MW**	**100MW**
0	1	0	0	0	1	0	0	0
10	0	1	2.00e-3	0	0	1	1.26e-6	0
20	0	0	9.98e-1	0	0	0	9.88e-1	0
30	0	0	2.35e-5	4.14e-9	0	0	1.25e-2	0
40	0	0	0	2.00e-3	0	0	0	1.26e-6
50	0	0	0	2.59e-1	0	0	0	6.76e-3
60	0	0	0	6.22e-1	0	0	0	2.54e-1
70	0	0	0	1.15e-1	0	0	0	5.56e-1
80	0	0	0	3.13e-3	0	0	0	1.71e-1
90	0	0	0	2.34e-5	0	0	0	1.22e-2
100	0	0	0	7.56e-8	0	0	0	3.06e-4
150	0	0	0	0	0	0	0	3.75e-6
200	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0

2 Part II / Dangerous goods incidents

2.1 Structure of the Bayesian Network

In this Chapter, the structure of the developed Bayesian Networks for the risk assessment in road tunnels is presented with regard to dangerous goods.
The Bayesian Network to model dangerous goods events in the tunnel is shown in Figure 2.1.

The network shown in Figure 2.1 can easily be simplified for the purpose of illustration. If one neglects all risk indicators describing the site and object specific characteristics, i.e. all orange nodes, then the main node has the name *Dangerous Goods Incident*. This node contains all relevant and representative events and the rates per vehicle kilometre specified by PIARC. From this node three general links go to the three principle hazards, i.e. *pool fire*, *explosion* and *toxic events*. Given a specific principle event fatalities and injuries can occur. In this sense the BPN is simple.

However, in order to describe these principle events a lot of risk indicators are used. The used assumptions and the specific models considered in the network are explained in the following.

Observable indicators

The observable indicators correspond to the indicators which are used to model the risk and they can be seen as input parameters for the analysis. These indicators are merely the same as for events due to the normal traffic situation. Here, the following indicators have been considered (orange nodes in Figure 1.2.)

- Time variation of the traffic during the hours of the day.(six different general types A-F are considered)
- Traffic volume [veh./d] (for one direction): average annual daily traffic pr direction.
- Bi directional traffic versus unidirectional traffic in each tunnel tube.
- Lane width [m].
- Number of lanes per direction [#].
- Gradient [%].
- Monitoring system.
- Ventilation system.
- Congestion [h/a].
- Emergency light.
- Distance to the emergency exit [m].
- Tunnel class according to ADR
- Discharge system (none, continuous or discrete gutters)
- Discharge opening in the case that the discharge system is continuous [cm]
- Discharge distance in the case that the discharge system is discrete [m]
- Camber [%]

An overview over of the nodes and the associated conditional probability tables are given in Table 2.1. Some of these indicators are already described in detail in Chapter 1.4.

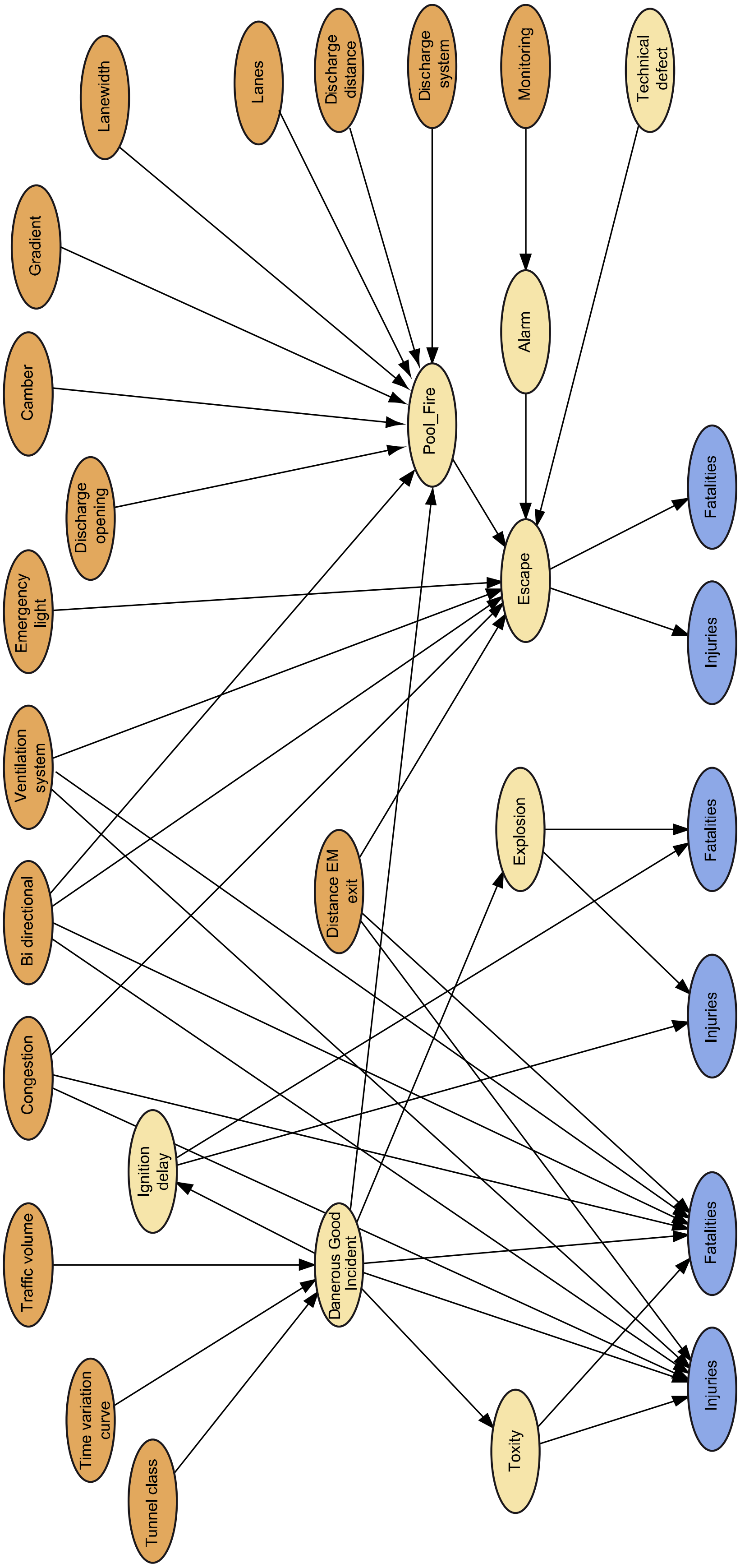


Figure 2.1: Bayesian Probabilistic Network for the calculation of dangerous goods incidents.

The indicators are divided into the observable indicators and intermediate logical nodes.

Intermediate nodes

The yellow nodes in Figure 1.2 are logical intermediate nodes. They contain information which is relevant to calculate the risk. They are calculated in dependency of the input of the user. These nodes are:

- Dangerous Goods Incidents
- Ignition delay
- Toxicity
- Pool fire
- Explosion
- Alarm (an intermediate node with fixed input related to monitoring)
- Escape (an intermediate node based on distance to emergency exit, ventilation system, congestion rate, emergency light, alarm and technical defects in the equipment)
- Technical defect (a fixed input node indicating the general reliability of technical systems)

Outcome

The following consequence indicators in the BPN for dangerous good incidents are defined. These nodes contain information which is used to calculate the current risk in a specific tunnel segment. They represent the outcome of the BPN model and the consequence model for dangerous goods incidents (blue nodes in Figure 1.2).

- Fatalities (pool fire) – probability of dying due to an event
- Injuries (pool fire) – probability of being injured due to an event
- Fatalities (explosion) – probability of dying due to an event
- Injuries (explosion) – probability of being injured due to an event
- Fatalities (toxicity) – probability of dying due to an event
- Injuries (toxicity) – probability of being injured due to an event

By using the probability that a person in the tunnel is injured or dies, the number of fatalities is calculated by taking into account the

Table 2.1: Description of the nodes in BPN of the hazard model for accidents, see also and the further explanation in Chapter 1.2.

#	Node	Description	Size CPT [States x Conditions]	Label
1	Type of the time variation curve of the traffic	A: pronounced peak in the morning. B: peak in the morning combined with small peak in the afternoon. C: relative equally distributed traffic during the day. D: Pronounced peak in the morning and in the afternoon. E: pronounced peak in the afternoon, small peak in the morning. F: pronounced peak in the afternoon	6 x 1	Type A, Type B, Type C, Type D, Type E, Type F,
2	Traffic volume	Annual average daily traffic volume per direction	28 x 1	300, 600, 1000, …, 20000, 25000, …, 60000
4	Bi directional	Contra flow in the tunnel	2 x 1	Yes, No
8	Gradient	Longitudinal gradient in [%] Upwards / downwards	27 x 1	0,0.25,0.5,… , 3, 3.5, …, 10
9	Lane width	Width of the single lanes in the tunnel in [m]	9 x 1	3, 3.25, …,5
10	Number of Lanes	Number of lanes per direction	3 x 1	1, 2, 3
39	Tunnel class	Considers different restrictions of tunnel	5 x 1	Type A, Type B, Type C, Type D, Type E,
40	Discharge opening	Considers the size of the of a continuous gutter in the tunnel in [cm]	11 x 1	3cm, 4cm, 5cm, 6cm, 7cm, 8cm, 9cm, 10cm, 12cm, 14cm, 16cm
41	Camber	Camber of the road in [%]	17 x 1	0, 0.5, 1, ..., 8
42	Discharge distance	Considers the distance of discrete gutters in the tunnel in [m]	11 x 1	10m, 15m,...60m
43	Discharge system	Considers if and which system is installed	3 x 1	no system, continuous system, discrete system
28	Alarm	Will an alarm be triggered?	2 x 2	yes, no

#	Node	Description	Size CPT [States x Conditions]	Label
29	Escape	Probability for a single person to escape successfully from fire and smoke	2 x 260'928	Yes, no
30	Monitoring system installed	Is a monitoring system installed in the tunnel?	2 x 1	Monitoring system No monitoring system
31	Ventilation system	Considers different ventilation systems in the tunnel.	9 x 1	Natural ventilation Longitudinal ventilation Longitudinal ventilation with active control Longitudinal ventilation with extraction Longitudinal ventilation with extraction and active control Semi transverse ventilation Semi transverse ventilation with active control Full transverse ventilation Full transverse ventilation with active control
32	Congestion	Considers that the traffic in the tunnel is congested.	2 x 1	Congested Uncongested
33	Emergency light	Is Emergency light installed in the tunnel, coupled with an emer-gency power supply system?	2 x 1	yes, no
34	Distance to the emergency exit	Distance from the actual point to the next (nearest) Emergency exit in [m].	151 x 1	0,10,…,1500m
36	Technical defect	Represents the case where the technical equipment in the tunnel is not working.	2 x 1	Technical defect No technical defect
44	Pool fire	Specifies the severity of a fire event	6 x 107'967'816	0 MW, 50 MW, 100 MW, 150 MW, 200 MW, 300 MW

#	Node	Description	Size CPT [States x Conditions]	Label
45	Dangerous good incidents	Specifies the rate of an dangerous good event according to PIARC	12 x 840	No event, BLEVE Propgas Zylinder 50kg, Pool fire fuel Explosion fuel vapours, Chlor Discharge 20t tank, BLEVE Propangas 18t tank, Gascloud fire Propanga 18t tank, Gasflare fire Propangas 18t tank, Amoniak discharge 18t tank, Acrolein discharge 25t tank, Acrolein discharge 100l zylinder, BLEVE Co2 liquid 20t tank
46	Toxicity	Specifies the severity of a toxic event	4 x 12	No toxicity Small toxicity Medium toxicity High toxicity
47	Explosion	Specifies the severity of an explosion event	4 x 12	No explosion Small explosion Medium explosion Large explosion
48	Fatalities (Toxity)	Represents the probability that one person will die after an event	2 x 260'928	yes, no
49	Injuries (Toxity)	Represents the probability that one person will be injured after an event	2 x 260'928	yes, no
50	Fatalities (Explosion)	Represents the probability that one person will die after an event	2 x 48	yes, no
51	Injuries (Explosion)	Represents the probability that one person will be injured after an event	2 x 48	yes, no
52	Fatalities (Pool fire)	Represents the probability that one person will die after an event	2 x 2	yes, no
53	Injuries (Pool fire)	Represents the probability that one person will be injured after an event	2 x 2	yes, no

2.2 Prior Probabilities and models for the indicator nodes for the dangerous goods model

2.2.1 Dangerous goods incidents

In the model for the dangerous goods incidents the same scenarios as specified in the OECD/PIARC model are used.Table 2.2 summarizes the considered scenarios.

In Table 2.2 the event rates per vehicle kilometre for the specific transports of hazardous materials are also given. It can be observed that the event rates in Switzerland differ from rates in the standard model. This adoption was made by the Swiss Federal Road Authorities because it was observed that the rates of the PIARC standard model give a conservative result, which means they overestimate the risk of dangerous good incidents.

Table 2.2: Considered scenarios and event rate per vehicle km of the standard PIARC model and the adoption for the Swiss model.

[#]	Scenario	OECD/PIARC Standard model(veh.km)		OECD/PIARC CH model (veh.km)	
		Urban	Rural	Urban	Rural
3	BLEVE of LPG in cylinder (50 kg)	1.50E-09	4.30E-09	1.20E-12	1.50E-12
4	Motor spirit pool fire (28t)	2.40E-09	1.70E-08	1.90E-09	1.50E-09
5	VCE of motor spirit (28t)	2.40E-10	1.70E-09	2.40E-10	3.10E-10
6	Chlorine release (20 t)	2.60E-10	4.60E-10	4.80E-10	6.00E-10
7	BLEVE of LPG in bulk (18 t)	2.40E-10	1.70E-09	1.20E-12	1.50E-12
8	VCE of LPG in bulk (18 t)	2.40E-10	1.70E-09	3.90E-11	4.90E-11
9	Torch fire of LPG in bulk (18 t)	2.40E-09	1.70E-08	1.10E-10	1.40E-10
10	Ammonia release (18 t)	2.60E-08	4.60E-08	4.80E-10	6.00E-10
11	Acrolein in bulk release (25 t)	2.20E-08	4.10E-08	4.80E-09	6.00E-09
12	Acrolein in cylinder release (100 l)	5.60E-09	1.10E-08	4.80E-09	6.00E-09
13	BLEVE of liquefied refrigerated air (20 t)	2.30E-10	1.60E-09	1.20E-12	1.50E-12

The OECD PIARC model differentiates in principle between urban and rural tunnels. In Transit this differentiation is not made because of two principle reasons. The first reason is that the differentiation between urban and rural tunnels is not always definite and thus it can in certain cases be dependent on the appraisal of the person performing the risk analysis. The second reason is that the different event rates in urban and rural tunnels are caused by specific traffic conditions such as the annual daily traffic or the distribution of the traffic over the day. Thus, here the rates given in Table 2.2 are assigned to specific characteristics. These conditions are summarized in Table 2.3.

Table 2.3: Definition of the conditions for the use of the rural and urban accident rates in Transit.

Conditions	Urban rate	Rural rate
AADT <=3500		X
Type TVC A , AADT > 3500	X	
Type TVC B , AADT > 3500	X	
Type TVC C , AADT > 3500		X
Type TVC D , AADT > 3500		X
Type TVC E , AADT > 3500	X	
Type TVC F , AADT > 3500	X	

The distribution of the transported dangerous goods for Switzerland and for Norway which can cause the related scenarios is given in Table 2.4. This distribution represents the standard distribution according to the ASTRA documentation ASTRA 84 002. For Switzerland it is considered that almost no chlorine is transported on the roadway. Thus, the fraction for chlorine given in Table 2.4 is almost zero.

Table 2.4: Distribution of the transported dangerous goods which can cause the related scenarios.

[#]	Szenario	Fraction DG Norway	Fraction DG Switzerland
	No relevant szenario	5.21E-01	5.38E-01
3	BLEVE of LPG in cylinder (50 kg)	4.66E-02	4.66E-02
4	Motor spirit pool fire (28t)	2.31E-01	2.31E-01
5	VCE of motor spirit (28t)	1.19E-01	1.19E-01
6	Chlorine release (20 t)	1.75E-02	1.19E-04
7	BLEVE of LPG in bulk (18 t)	4.66E-03	4.66E-03
8	VCE of LPG in bulk (18 t)	4.66E-03	4.66E-03
9	Torch fire of LPG in bulk (18 t)	4.66E-03	4.66E-03
10	Ammonia release (18 t)	8.75E-03	8.75E-03
11	Acrolein in bulk release (25 t)	1.75E-02	1.75E-02
12	Acrolein in cylinder release (100 l)	1.75E-02	1.75E-02
13	BLEVE of liquefied refrigerated air (20 t)	7.62E-03	7.62E-03

2.2.2 Tunnel Class

The European Agreement concerning the International Carriage of Dangerous Goods by Road, known as ADR, regulates the transport of dangerous or hazardous goods. The ADR differentiate 9 different classes. These classes are given in Table 1.42

Table 2.5: Classes of the hazardous goods according to ADR.

Class	Description
1	Explosive substances and articles
2	Gases
3	Flammable liquids
4.1	Flammable solids, self-reactive substances and solid desensitized explosives
4.2	Substances liable to spontaneous combustion
4.3	Substances which, in contact with water, emit flammable gases
5.1	Oxidizing substances
5.2	Organic peroxides
6.1	Toxic substances
6.2	Infectious substances
7	Radioactive material
8	Corrosive substances
9	Miscellaneous dangerous substances and articles

Bases on these goods a harmonized regulation with regard to restrictions of the transport for several hazardous materials in the tunnel are made in the recent ADR document from 2007 (UNECE (2007)). The regulation differentiates five categories (A-E).

Table 2.6: Tunnel categories according to ADR 2007

Categorie	Description
A	No restriction
B	Restrictions for goods which can cause major explosion events
C	Restrictions for goods which can cause major explosion events, large explosion events or a large release of toxic substances
D	Restrictions for goods which can cause major explosion events, large explosion events, a large release of toxic substances or cause a major fire event.
E	Restriction for all dangerous goods except goods with the UN-Number 2919, 3291, 3331, 3359 und 3373

With this regulation several hazardous accident scenarios can be avoided or at least the probability of occurrence can significantly be reduced. The categories given in Table 2.6 are considered in Transit a can be chosen. Thereby it is considered that in case of restriction the tunnel is still used also by transporters which are not allowed to use this tunnel. It is anticipated that 5% do not respect the restriction. This is summarized in Table 2.7.

Table 2.7: Probability that a transport vehicle with a specific dangerous good will use a tunnel with a certain restriction.

		Probability that a specific dangerous good transport will use a restricted tunnel				
[#]	Scenario	**Cat. A**	**Cat. B**	**Cat. C**	**Cat. D**	**Cat. E**
3	BLEVE of LPG in cylinder (50 kg)	1	1	1	0.05	0.05
4	Motor spirit pool fire (28t)	1	1	1	0.05	0.05
5	VCE of motor spirit (28t)	1	1	1	0.05	0.05
6	Chlorine release (20 t)	1	1	0.05	0.05	0.05
7	BLEVE of LPG in bulk (18 t)	1	0.05	0.05	0.05	0.05
8	VCE of LPG in bulk (18 t)	1	0.05	0.05	0.05	0.05
9	Torch fire of LPG in bulk (18 t)	1	0.05	0.05	0.05	0.05
10	Ammonia release (18 t)	1	1	0.05	0.05	0.05
11	Acrolein in bulk release (25 t)	1	1	0.05	0.05	0.05
12	Acrolein in cylinder release (100 l)	1	1	1	0.05	0.05
13	BLEVE of liquefied refrigerated air (20 t)	1	1	0.05	0.05	0.05

In Switzerland almost all tunnel are presently in the tunnel category A. Only 5% of the tunnels are in category E. No tunnels have presently one of the other categorizations.

By using the information given in Table 2.2, Table 2.3, Table 2.4 and Table 2.6 the CPT of the node Dangerous Goods Incidents is filled. This node represents the event rates for a specific dangerous good scenario. From all the scenarios specified in this node, three principle scenarios are defined, i.e. toxic events, explosions and pool fires.

The prior distributions for the tunnel classes for Switzerland and Norway are given in Table 2.8. For Switzerland data is available to estimate the prior distribution. The prior distribution for Norway is presently based on expert opinion.

Table 2.8: Prior probabilities for the ADR tunnel class.

Discharge System	Prior distribution	
	Switzerland	Norway
A	0.95	0.8
B	0.00	0.05
C	0.00	0.05
D	0.00	0.05
E	0.05	0.05

2.2.3 Toxicity

The node toxicity contains information on how severe several toxic accidents are. In this model four different states are considered, that is no toxicity, low toxicity, medium toxicity and high toxicity. The description of the states is more qualitatively; however, the connection to the probability of a fatality and injuries is made in the node fatalities and in the node injuries (see Chapter 2.2.13). The probabilities for the severity of different toxic events contained in this node are given in Table 2.9. The numbering of the scenarios is given in Table 2.7.

Table 2.9: Probabilities for the severity of different toxic events.

	Scenario Nr.			
Toxicity	6	10	11	12
No	0	0	0	0.05
Low	0	0	0	0.9
Medium	0.3	0.6	0.1	0.05
High	0.7	0.4	0.9	0

2.2.4 Camber

The node camber is an indicator used for the calculation for the pool area in case of spirit spill after a dangerous good incident (see Chapter 2.2.5). The user can specify the camber in the tunnel section. In case where no information on the camber is available the prior distribution is employed in the calculation. The prior probabilities are given in Table 2.10. The mean value of the prior distribution is 2%.

Table 2.10: Prior probabilities for the camber of the tunnel road.

Camber [%]	Prior distribution	
	Switzerland	Norway
0.00 - 0.50	0.01	0.01
0.50 - 1.00	0.05	0.05
1.00 - 1.50	0.1	0.1
1.50 - 2.00	0.1	0.1
2.00 - 2.50	0.4997	0.4997
2.50 - 3.00	0.1	0.1
3.00 - 3.50	0.065	0.065
3.50 - 4.00	0.05	0.05
4.00 - 4.50	0.01	0.01
4.50 - 5.00	0.005	0.005
5.00 - 5.50	0.004	0.004
5.50 - 6.00	0.003	0.003
6.00 - 6.50	0.002	0.002
6.50 – 7.00	0.001	0.001
7.00 – 7.50	0.0001	0.0001
7.50 – 8.00	0.0001	0.0001

2.2.5 Pool fire

The event rate for a pool fire per vehicle km is defined by the OECD/PIARC model. The severity of a pool fire is determined by the wetted area i.e. the pool.

A significantly influenced on the size of the pool has the discharge system which is installed in the tunnel and its drainage capacity. In principle two different systems can be differentiated, i.e. continuous systems with slot openings and discrete systems with gutters in a certain distance.

Of course, the pool size is also influenced by the camber and the longitudinal gradient g in the tunnel and the size of the tunnel. This can be represented by the lane width, the number of lanes and type of traffic routing (uni-directional or bi-directional). Here, the absolute value of the camber is considered. That implies that for a two lane unidirectional tunnel with two lanes the mean value of distance between the event location and the gutter is equal to the lane width (see Figure 2.2)

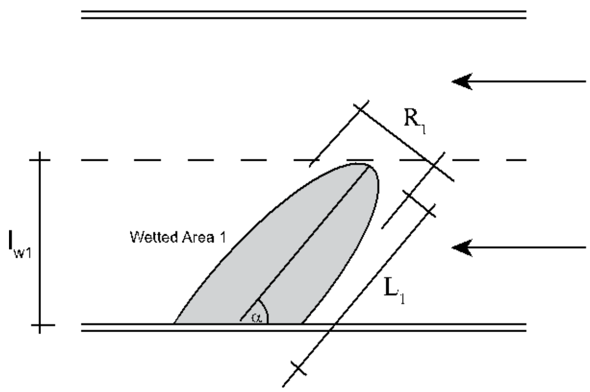


Figure 2.2: Part of the wetted area after a release of spirit of a dangerous good transport.

The length of the first wetted area (Wetted Area 1 in Figure 2.2) L_1 is calculated as follows. The angle α is calculated by

$$\alpha = a\sin\left(\frac{\sqrt{1+\frac{1}{c^2}}}{\sqrt{2+\frac{1}{c^2}+\frac{1}{g^2}}}\right)[rad] \qquad (2.1)$$

Herein denotes c the camber at the specific tunnel location and g is the longitudinal gradient. With the known length l_w which is dependent on the lane width, the number of lanes and the traffic routing, the length L_1 can be calculated, whereas the release location is assumed to be at the midpoint of the road in one direction:

$$L_1 = \frac{l_{w1}}{\cos\ \alpha}\ [m] \qquad (2.2)$$

According to the OECD/PIARC document, a modification of Ingason's expression for pool width is used:

$$R_1 = 2.4 \cdot V^{0.46}\ [m] \qquad (2.3)$$

With R_1 the width of the pool area is denoted and V is the liquid flow rate in (litres/s) according to the considered scenario. The wetted area in the tunnel A_1 due to a spill is calculated by:

$$A_1 \approx L_1 \cdot R_1\ [m^2] \qquad (2.4)$$

The second area is the area of spirit at the border of the lane. This area is strongly dependent on the drainage system which is used in the tunnel.

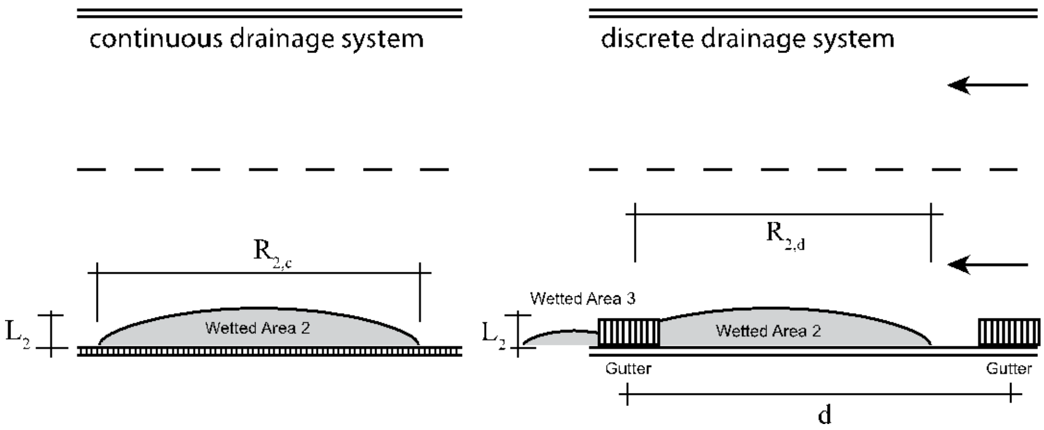


Figure 2.3: Wetted area at the drainage system.

The second area develops in dependency of the drainage system. For the continuous drainage systems the wetted area 2 can be calculated by:

$$R_{2,c} = \frac{V}{0.5 \cdot x\ [cm]}\ [m]$$

Whereas V is the liquid flow rate in litres/s and x is the slot opening in cm. According to the PIARC report it is assumed that the drainage capacity is 50 l/s/m^2 opening. The average width of the gutter flow L_2 is taken to be proportional to V$^{0.5}$/camber. Thus, the second Part of the pool area is calculated by:

$$A_{2,c} \approx L_2 \cdot R_{2,c}\ [m^2]$$

In case of a discrete drainage system the second part of the area is calculated by:

$$R_{2,d} = \frac{d}{2}$$

$$A_{2,d} \approx L_2 \cdot R_{2,d} + 20\ [m^2]$$

Herein denotes d the distance between the discrete gutters. It is assumed that in the case of discrete gutters a part of the spirit spills over the gutter. As an approximation this part is assumed to be 20 m^2.

The total heat output, Q (MW), is given by:

$$Q = m'' \cdot A \cdot H \qquad (2.5)$$

With m'' is the burning rate of motor spirit, A is the pool area and H is the heat combustion of motor spirit. It can be assumed that:

$$m'' = 0.055 \left[\frac{kg}{s \cdot m^2}\right] \qquad (2.6)$$

$$H = 48 \left[\frac{MJ}{kg}\right] = 48'000'000 \left[\frac{m^2}{s^2}\right] \qquad (2.7)$$

So that the total heat output is:

$$Q \approx A \cdot 2.64\,[MW] \tag{2.8}$$

In order to take into account the uncertainties of the pool size, burning rate and heat combustion, the heat output is modelled by using a lognormal distribution with a mean value Q according to Equation (2.8) and a coefficient of variation of 1.1.

2.2.6 Discharge systems

Two different principle discharge systems are considered in Transit, continuous discharge systems and those with discrete drainage points. The discharge system has an influence on the pool size of spill of motor spirit from a tanker and thus has an influence on the severity of a fire event. The systems are briefly described in Chapter 2.2.7 for continuous systems and in Chapter 2.2.8 for discrete systems.
If the discharge system is unknown, the prior distribution is used in the calculation. The prior probabilities are given in Table 2.11.

Table 2.11: Prior probabilities for the discharge system.

Discharge System	**Prior distribution**	
	Switzerland	**Norway**
No system	0.01	0.30
Continuous	0.30	0.20
Discrete	0.69	0.50

2.2.7 Discharge opening

In the case a continuous drainage system is present in the tunnel, the drainage capacity is represented by the slot opening in the drainage system. In Figure 2.4 two possible cross sections for continuous systems are shown. The slot opening is denoted with x .

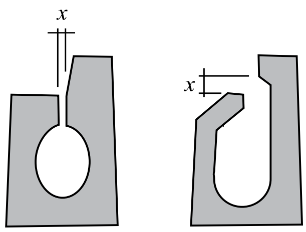


Figure 2.4: Examples of different continuous drainage systems.

The influence of this indicator on the severity of a pool fire is given in Chapter 2.2.5.

If the size of the discharge opening is unknown, the prior distribution is used in the calculation. The prior probabilities are given in Table 2.12. The mean value of the prior distribution is assumed to be 7.3 cm.

Table 2.12: Prior probabilities for the discharge opening.

Discharge opening [cm]	Prior distribution	
	Switzerland	Norway
3	0.01	0.01
4	0.01	0.01
5	0.1	0.1
6	0.2	0.2
7	0.3	0.3
8	0.2	0.2
9	0.1	0.1
10	0.05	0.05
12	0.01	0.01
14	0.01	0.01
16	0.01	0.01

2.2.8 Discharge distance

In the case that a discrete drainage system is present in the tunnel, the drainage capacity is represented by the distance of the gutter points. The discretization for the considered distances of the gutter points is given in Table 2.1.

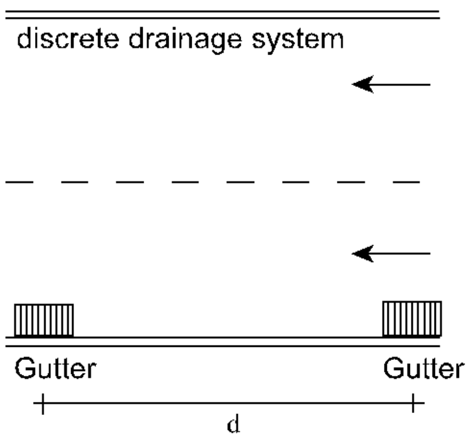


Figure 2.5: Discrete drainage system.

If the discharge distance is unknown, the prior distribution is used in the calculation. The prior probabilities are given in Table 2.13. The mean value of the prior distribution is assumed to be around 30 m.

Table 2.13: Prior probabilities for the discharge opening.

Discharge distance [m]	Prior distribution	
	Switzerland	Norway
10	0.01	0.01
15	0.01	0.01
20	0.1	0.1
25	0.2	0.2
30	0.3	0.3
35	0.2	0.2
40	0.1	0.1
45	0.05	0.05
50	0.01	0.01
55	0.01	0.01
60	0.01	0.01

2.2.9 Escape

The node escape describes the probability of a successful escape in case of a fire event. It is modelled according to the description given in Chapter 1.4.27. Only derivations from this model are described in this section. The derivations from this model are mainly determined by the larger fire size which is considered in the Dangerous goods model. Here, events up to 300 MW are taken into account in the analysis.

The basic escape rates for the fire events for dangerous good fire events are given Table 2.14.

Table 2.14: Basic escape rates in dependency of the severity of the fire.

Escape	no fire	50MW	100MW	150MW	200MW	300MW
No escape	0	0.40	0.60	0.65	0.80	0.9
Escape	1	0.60	0.40	0.35	0.2	0.1

The influence of the ventilation system on the escape probability is given in Table 2.15 - Table 2.18. It can be observed that the influence of the ventilation system is not significant for severe fire events in the tunnel. For events of 200 MW and larger the ventilation has no effect on the escape probability.

Table 2.15: Influence of the ventilation system on the probability for a successful escape in the case where the traffic is not congested for unidirectional traffic.

	No congestion					
	Unidirectional traffic					
Severity of the fire	**No fire**	**50MW**	**100MW**	**150MW**	**200MW**	**300MW**
Ventilation Type 1	1.00	1.00	1.00	1.00	1.00	1.00
Ventilation Type 2	1.00	0.15	0.30	0.60	1.00	1.00
Ventilation Type 3	1.00	0.15	0.30	0.60	1.00	1.00
Ventilation Type 4	1.00	0.25	0.60	1.00	1.00	1.00
Ventilation Type 5	1.00	0.15	0.30	0.60	1.00	1.00
Ventilation Type 6	1.00	0.25	0.60	1.00	1.00	1.00
Ventilation Type 7	1.00	0.15	0.30	0.60	1.00	1.00
Ventilation Type 8	1.00	0.25	0.60	1.00	1.00	1.00
Ventilation Type 9	1.00	0.15	0.30	0.60	1.00	1.00

Table 2.16: Influence of the ventilation system on the probability for a successful escape in the case where the traffic is congested for unidirectional traffic.

	congestion					
	Unidirectional traffic					
Severity of the fire	**No fire**	**50MW**	**100MW**	**150MW**	**200MW**	**300MW**
Ventilation Type 1	1.00	1.00	1.00	1.00	1.00	1.00
Ventilation Type 2	1.00	1.00	1.00	1.00	1.00	1.00
Ventilation Type 3	1.00	0.50	0.60	1.00	1.00	1.00
Ventilation Type 4	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 5	1.00	0.15	0.30	0.60	1.00	1.00
Ventilation Type 6	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 7	1.00	0.20	0.30	0.60	1.00	1.00
Ventilation Type 8	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 9	1.00	0.20	0.30	0.60	1.00	1.00

Table 2.17: Influence of the ventilation system on the probability for a successful escape in the case where the traffic is not congested for bi-directional traffic.

	No congestion					
	Bi - directional traffic					
Severity of the fire	**No fire**	**50MW**	**100MW**	**150MW**	**200MW**	**300MW**
Ventilation Type 1	1.00	1.00	1.00	1.00	1.00	1.00
Ventilation Type 2	1.00	1.00	1.00	1.00	1.00	1.00
Ventilation Type 3	1.00	0.50	0.60	1.00	1.00	1.00
Ventilation Type 4	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 5	1.00	0.15	0.30	0.60	1.00	1.00
Ventilation Type 6	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 7	1.00	0.20	0.30	0.60	1.00	1.00
Ventilation Type 8	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 9	1.00	0.20	0.30	0.60	1.00	1.00

Table 2.18: Influence of the ventilation system on the probability for a successful escape in the case where the traffic is congested for bi-directional traffic.

	congestion					
	Bi - directional traffic					
Severity of the fire	**No fire**	**50MW**	**100MW**	**150MW**	**200MW**	**300MW**
Ventilation Type 1	1.00	1.00	1.00	1.00	1.00	1.00
Ventilation Type 2	1.00	1.00	1.00	1.00	1.00	1.00
Ventilation Type 3	1.00	0.50	0.60	1.00	1.00	1.00
Ventilation Type 4	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 5	1.00	0.15	0.30	0.60	1.00	1.00
Ventilation Type 6	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 7	1.00	0.20	0.30	0.60	1.00	1.00
Ventilation Type 8	1.00	0.30	0.40	0.80	1.00	1.00
Ventilation Type 9	1.00	0.20	0.30	0.60	1.00	1.00

2.2.10 Fatalities and injuries due to fire events

In the node Escape the probability of a successful escape is modelled. Given the escape is successful it is assumed that the person remains unaffected of the event. In cases where the escape is not successful it is assumed that the probability of dying is around 30% and the probability of being injured is around 70%. Here it assumed that the ratio between injuries and fatalities remains constant and is not dependent of the severity. It can be argued that this assumption is crude but it should be noted that the severity of the event and the probability for a successful escape is considered in the node Escape.

2.2.11 Explosion

The scenario explosion represents several scenarios according to the specification given in Table 2.2. This includes vapour cloud explosions (VCEs) and boiling liquid expanding vapour explosions (BLEVEs) and a torch fire event.

An event where a cloud of flammable gas is mixed with air in an open atmosphere is ignited, is called vapour cloud explosion (VCE).

A BLEVE is a boiler or vessel explosion and occurs when the pressure inside the vessel containing a liquid is larger than the resistance against pressure of the vessel. The high pressure in the vessel can occur due to several reasons, mainly as a result of a fire event. According to the Piarc report the torch fire is caused by an early ignition of the release to the atmosphere of a liquefied flammable gas, initially contained in a tank which has been punctured.

The probabilities for the different severity of the considered scenarios are given in Table 2.19. The numbering of the scenarios is given in Table 2.7.

Table 2.19: Probabilities for the severity of different explosive events.

	Scenario Nr.					
Explosion	**3**	**5**	**7**	**8**	**9**	**13**
No	0	0	0	0	0	0
Small	0.9	0.05	0	0.05	0.05	0.05
Medium	0.1	0.9	0.1	0.9	0.9	0.05
High	0	0.05	0.9	0.05	0.05	0.9

2.2.12 Fatalities and injuries due to explosion events

The probability to die after an explosion event is estimated by taking into account the ignition delay of the event into account. The ignition delay between the accident and the explosion can help to leave the section in danger. The probability of dying is given in dependency of the ignition delay of the event in Table 2.20. It should be noted that the probability of survival includes the probability that is a person is not affected and the probability that a person in injured.

Table 2.20: Probability of dying in an explosion event in the tunnel. (S= small, M= medium, L=large).

Explosion	**Ignition Delay = 0 s**			**Ignition Delay = 60 s**			**Ignition Delay = 90 s**		
	S	M	L	S	M	L	S	M	L
Survive	0.95	0.80	0.20	0.95	0.81	0.23	0.95	0.81	0.25
Die	0.05	0.20	0.80	0.05	0.19	0.77	0.05	0.19	0.75
Explosion	**Ignition Delay = 120 s**			**Ignition Delay = 180 s**			**Ignition Delay = 300 s**		
	S	M	L	S	M	L	S	M	L
Survive	0.96	0.82	0.27	0.96	0.82	0.30	0.8	0.84	0.37
Die	0.04	0.18	0.73	0.04	0.18	0.70	0.2	0.16	0.63
Explosion	**Ignition Delay = 600 s**			**Ignition Delay = 900 s**					
	S	M	L	S	M	L			
Survive	0.98	0.88	0.53	0.99	0.92	0.7			
Die	0.02	0.12	0.47	0.01	0.08	0.3			

The probability of being injured after an explosion event is modelled analogously. The estimation is given in Table 2.21. In this estimation it is taken in to account that the events “injury” and “dying” are mutually exclusive events. A person in the tunnel can either die, being injured or being not affected by the event. Thus, the probability of no injury means that the person is not affected by the event.

Table 2.21: Probability of being injured in an explosion event in the tunnel (S= small, M= medium, L=large).

	Ignition Delay = 0 s			**Ignition Delay = 60 s**			**Ignition Delay = 90 s**		
Explosion	S	M	L	S	M	L	S	M	L
No injury	0.85	0.70	0.90	0.86	0.71	0.89	0.86	0.72	0.89
Injury	0.15	0.30	0.10	0.14	0.29	0.11	0.14	0.28	0.11
	Ignition Delay = 120 s			Ignition Delay = 180 s			Ignition Delay = 300 s		
Explosion	S	M	L	S	M	L	S	M	L
No injury	0.86	0.72	0.89	0.87	0.73	0.88	0.88	0.75	0.87
Injury	0.14	0.28	0.11	0.13	0.27	0.12	0.12	0.25	0.13
	Ignition Delay = 600 s			Ignition Delay = 900 s					
Explosion	S	M	L	S	M	L			
No injury	0.92	0.80	0.83	0.95	0.85	0.80			
Injury	0.08	0.20	0.17	0.05	0.15	0.20			

2.2.13 Fatalities and injuries due to toxic events

The node fatalities due to toxic events represent the probability that a person dies due to a toxic event in the tunnel. In the following a description is given on how this probability is calculated. In the PIARC model the probability for a fatality is modelled by using Probit functions. This Probit function provides a relation between the probability for a fatality and specific concentrations of toxic substances in the tunnel. The Probit functions for chlorines, ammonium and acrolein are defined by:

$$\mathrm{Probit}_{chlorine,fat} = -5 + 0.5\ln\ C^{2.75}t \tag{2.9}$$

$$\mathrm{Probit}_{ammonium,fat} = -35.95 + 1.85\ln\ C^{2}t \tag{2.10}$$

$$\mathrm{Probit}_{acrolein,fat} = -3.18 + \ln\ Ct \tag{2.11}$$

Similar functions are also available for injuries due to accidents with toxic substances:

$$\mathrm{Probit}_{chlorine,inj} = -10.085 + \ln\ C^{2.75}t \tag{2.12}$$

$$\mathrm{Probit}_{ammonium,inj} = -21.43 + \ln\ C^{3.33}t \tag{2.13}$$

$$\mathrm{Probit}_{acrolein,inj} = -2.34 + \ln\ Ct \tag{2.14}$$

Herein denotes C the concentration of the toxic substance and t is the time after the release.

Assuming that a low toxicity would lead to probability for a fatality Pr_{fat} of 5%, a Medium toxicity would lead to a probability for a fatality Pr_{fat} of 35% and a high toxicity would lead to a probability for a fatality Pr_{fat} of 80%, the corresponding Probit value can be calculated for these three scenarios by using the following equation

$$\mathrm{Probit} = \Phi^{-1}\ \mathrm{Pr}_{fat}\ + 5 \tag{2.15}$$

Herein denotes Φ^{-1} the inverse of the standard normal distribution. The Probit values for the different states of considered toxicities in the tunnel are summarized in Table 2.22.

Table 2.22: Probit values for the different considered states of toxicity in the tunnel.

Toxicity	Probit	Probability Fatality
No	-infinity	
Low	3.36	0.05
Medium	4.61	0.35
High	5.84	0.80

Assuming further that the Probit functions given in the OECD/PIARC methodology are calibrated for the different events, the basic concentrations for the specific events can be calculated. These concentrations are given in Table 2.23. A time of 2 minutes is considered to calculate the basic concentrations.

Table 2.23: Basic concentrations of toxic substances after toxic events in a tunnel.

		Basic Concentrations ppm		
	Scenario	Low	Medium	High
6	Chlorine release (20 t)	338	846	2065
10	Ammonia release (18 t)	29040	40817	56866
11	Acrolein in bulk release (25 t)	344	1214	4140
12	Acrolein in cylinder release (100 l)	344	1214	4140

The different scenarios defined in the PIARC report can be deemed to have different toxicities. A chlorine release of a 20t transport would lead to a high toxicity in the tunnel, an Ammonium release of 18t would lead to a medium to high toxicity, an acrolein bulk release would also result in high toxicity whereas a release of acrolein from 100l containments would lead to a low toxicity.

These concentrations can be influences by a ventilation system in the tunnel. An efficient ventilation system can significantly reduce the concentrations in the tunnel. Reduction factors in dependency of the presence of different ventilation systems are estimated and summarized in Table 2.24.

Table 2.24: Influence of the ventilation system on the concentration of toxic substances in a tunnel.

Ventilation System	Reduction factor
Natural ventilation	1.00
Longitudinal ventilation	0.80
Longitudinal with active control	0.70
Longitudinal with smoke extraction	0.60
Longitudinal with smoke extraction and active control	0.50
Semi-transverse ventilation	0.60
Semi-transverse with active control	0.50
Transverse ventilation	0.60
Transverse with active control	0.50

By using Table 2.24, the basic concentration rates given in Table 2.23 and the concentration of toxic substances and subsequently also the probabilities for fatalities and injuries respectively can be calculated, depending on the ventilation system installed in the tunnel.

2.2.14 Calculation of the number of fatalities and injuries

The calculation of the number of fatalities is calculated outside of the Bayesian Networks. The Bayesian network is used to calculate the event rates for the different scenarios in vehicle km and the probability that a person will die given that specific event.

By taking into account the daily variation of the traffic, the speed limit, the daily traffic volume, the fraction of dangerous goods vehicles and the average number of persons in a car, the number of exposed persons in an affected section is calculated. It is taken into account that the number of exposed persons will differ in unidirectional and bidirectional tunnels.

The length of the affected area for the specific events is determined by the values given in Table 2.25. These values represent the maximum affected length. For a tunnel length smaller than the values given in Table 2.25 the tunnel length is taken for the calculation.

Table 2.25: Basic concentrations of toxic substances after toxic events in a tunnel.

Fire	**50MW**	**100MW**	**150MW**	**200MW**	**300MW**
Length [m]	150	350	450	500	800
Toxicity	**Small**	**Medium**	**High**		
Length [m]	100	300	600		
Explosion	**Small**	**Medium**	**High**		
Length [m]	100	300	600		

The present version of transit does not calculate the expected number of injuries. As described in the sections above it is principally possible to calculate also the number of injuries. Presently, decisions in regard to investments into safety measures are made only on the bases of expected fatalities and the risk reduction in regard to fatalities.

3 Part III / User Manual

3.1 Introduction

In Chapter 1 a general methodology for the risk assessment in tunnel is described. This methodology is quite complex and calculation by hand can hardly been performed even though it would be theoretically possible. The methodology was therefore implemented in a software tool. The requirements in regard to hardware and software as well as some some detail information on the use, the installing process and features is given in the following sections. The use of the software tool is subject to a fee to the user group. It can be downloaded on demand (contact@matrisk.com).

3.2 General requirements

The software tool is developed in a Microsoft Excel 2007 environment (Microsoft® Office Excel® 2007 (12.0.6331.5000) SP1 MSO (12.0.6320.5000)) and is programmed in Microsoft Visual Basic (VBA Retail 6.5.1024) using the operating system (OS) Windows Vista SP 1. This results in the following system requirements:

- OS Windows XP, OS Windows Vista or OS Windows 7
- 32 bit-system or 64 bit-system
- 2 GB random access memory (RAM)
- 2 GB space on the hard disk
- Minimum 2.0 GHZ CPU
- Complete installation of Microsoft® Office Excel® 2007
- Complete installation of Microsoft® Office Word® 2007
- The software is optimized for a screen resolution of 1600 x 1200 pixel
- Acrobat Reader (available on http://www.adobe.com/)

The software is designed for Office 2007 and its functionality can only be ensured if the before mentioned requirements are fulfilled.

The present software is installed directly to the PC. For the installation administrator rights are necessary. To install the program the file Setup RiskNow-TRANSIT 1.0.exe has to be started the install files of the program are shown in Figure 3.1.

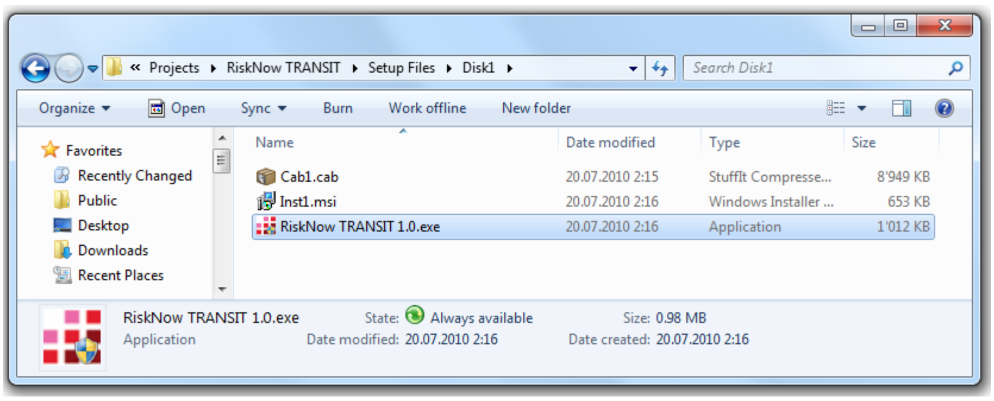


Figure 3.1: Setup files for Transit.

During the installation process the ActiveX component *Safe_Tunnels.ocx* is registered in the operating system. Additionally, a key is written in the registry of the operating system in order to activate macros and the ActiveX component in MS Excel. The software requires the registration of an ActiveX component in the operating system. This registry key facilitates to control the security settings of MS Excel so that the user does not need to make any changes during the usage of the software. During the installation process the software is also digitally signed so that the process of enabling the macros in MS Excel is not necessary. The user has to accept this digital signature from Matrisk GmbH and Hoj Consulting GmbH.

During the installation process the program prompts the user to specify the location on the PC where the software is to be installed (see Figure 3.2). Please note that now the program ***TRANSIT*** is completely installed to the PC.

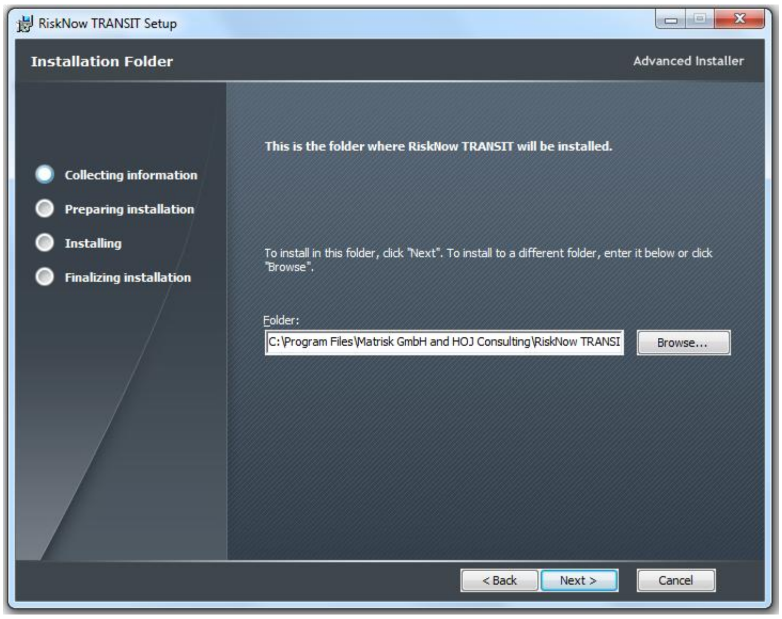


Figure 3.2: Selection of location for installation of the software.

After the successful installation of the software ***TRANSIT*** a shortcut appears on the desktop and in the start menu. The installation routine is only executed when the software is used the first time on a specific PC. The program should only be started by executing the shortcuts in the start menu, the shortcut on the desktop or directly by executing the file RiskNow TRANSIT.exe.

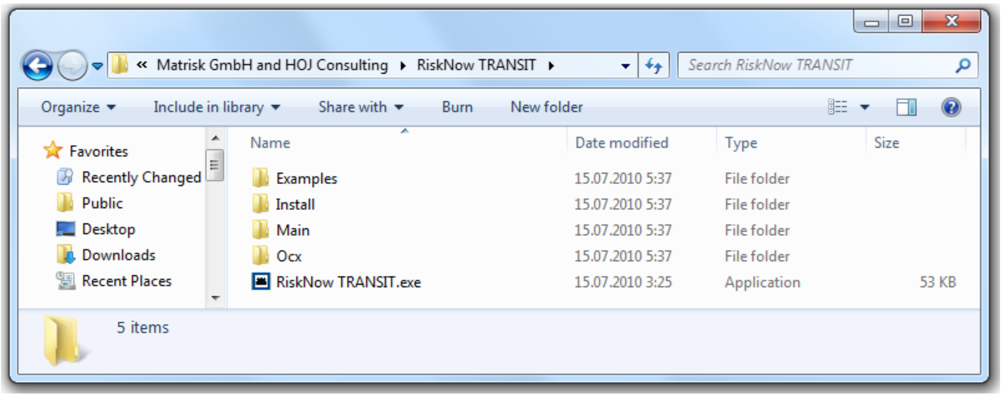


*Figure 3.3: Files and Folders of the program RiskNow **TRANSIT**.*

After the successful installation the program files and folders should not be moved to another location on the PC. The program can be uninstalled by selecting Uninstall RiskNow ***TRANSIT*** from the windows start menu under “All Programs” (see Figure 3.4).

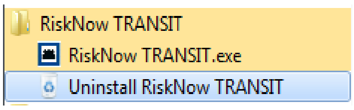


Figure 3.4: Uninstaller in the windows start menu.

In the present version it is also possible to use the program under different user profiles on one PC because the program uses advertised shortcuts. When an advertised shortcut is launched it validates the checks associated with the key resources. If any is missing it will fix it by running the installation package and installing again all information from the .msi file.

3.3 Structure, layout and use of the software

The software is structured in a way which can be deemed as the current best practice in risk modeling (see e.g. Faber et al. (2009)). The risk analysis conducted by using the software includes the following steps:

- Definition of the system.
- Definition of the global exposure.
- Definition of risk indicators for each segment of the tunnel.
- Establishment of the hazard model.
- Establishment of the consequence model.
- Risk assessment.
- Presentation of the results.

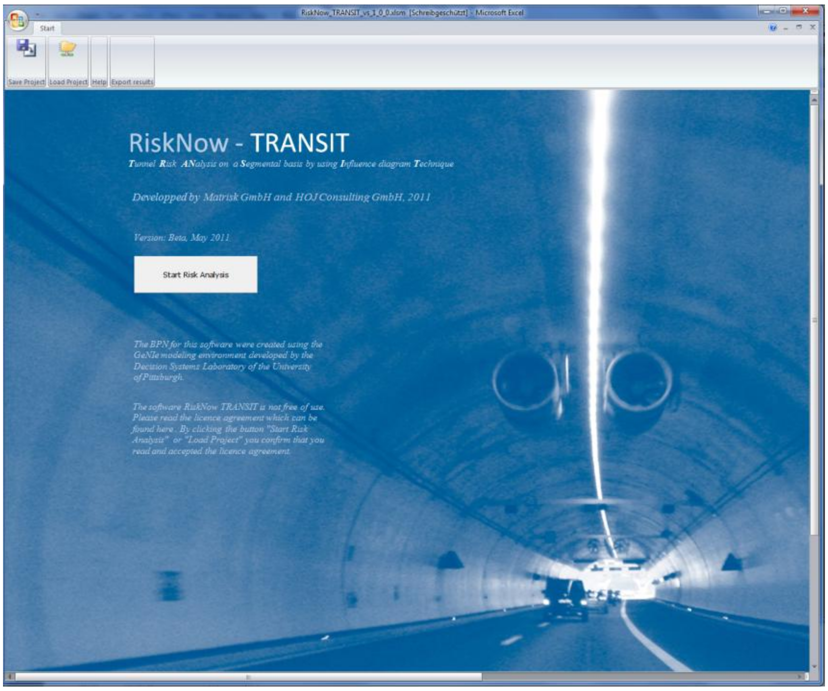


Figure 3.5: Start screen of the software RiskNow - TRANSIT.

After starting the software a start screen appears (see Figure 3.5). The typical ribbon of Office 2007 is invisible. Some of the well known functions in MS Excel are disabled (e.g. save and print). However, the user input can be saved as a RiskNow - TRANSIT file *(*.rsk* file) by clicking the icon *Save project* in the MS Excel Ribbon bar. By choosing the icon *Load Project* the user can import the user input from previous projects. Only the input is saved in the **.rsk*-files. The results have to be recalculated after tan existing project is loaded.

All results of the risk analysis can be exported either to MS Word as a formatted **.doc* file or to MS Excel.

By using the button *Start Risk Analysis* the user enters the project description and the global system definition, which is shown in Figure 3.6. By clicking the button the user also confirm that he read and agreed to the license agreement.

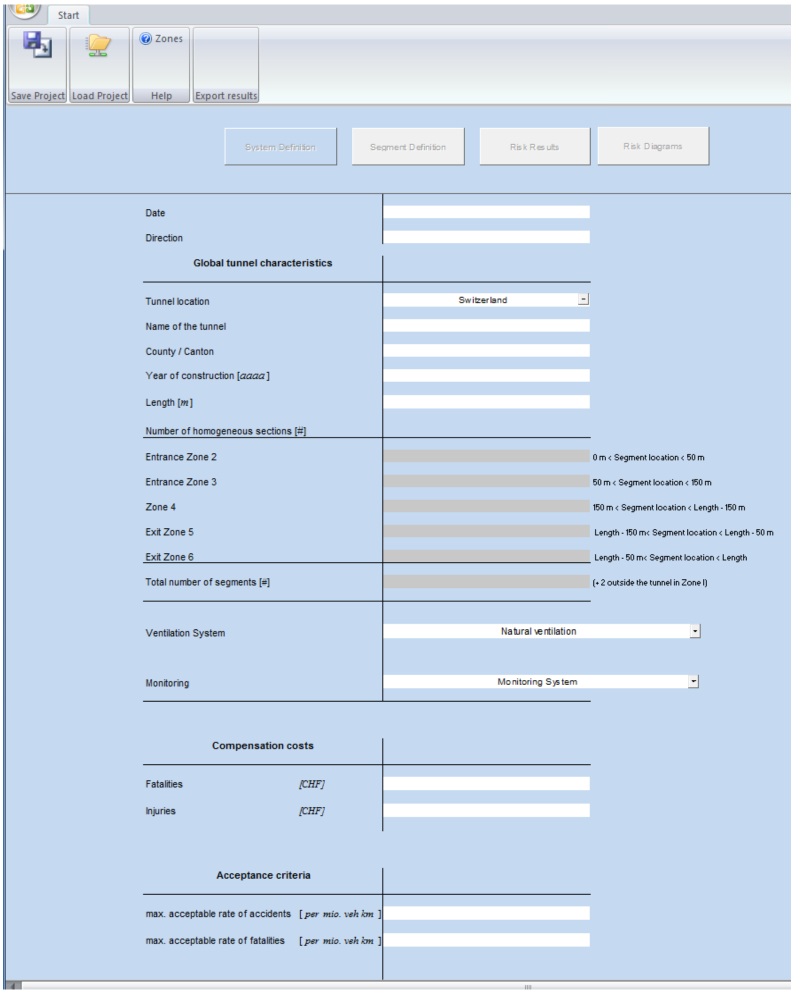


Figure 3.6: Input sheet for the definition of the project and the global system.

In the upper part of the display (see Figure 3.6) the navigation buttons are visible. They are inactive as long as not all necessary input is made by the use in the current sheet. If the input is complete and valid the next selectable navigation button becomes active.

The navigation button for the currently active sheet is inactive and the background is set transparent. As can be seen in Figure 3.6, the navigation button *System Definition* has this property. In the help segment of the ribbon bar, the help file Zones become available. By clicking the help button a window according to Figure 3.7 will open.

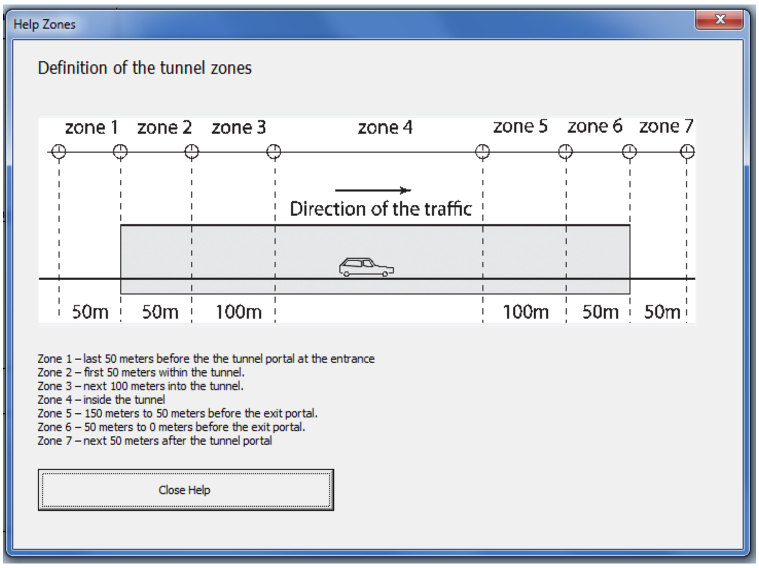


Figure 3.7: Help sheet for the tunnel zones.

The intention of the help sheets is to provide a fast overview on the relevant aspect. A detailed description is not in the focus of the help sheets. For more information the user the present report can be used.

3.3.1 System definition

The domain of all objects, events, consequences, assumptions and boundary conditions which are necessary for a certain risk analysis are the building stones for the considered system. In the system definition the system is established and described. All relevant input are collected in the system definition, i.e. data, expert knowledge, models or any other information.

In the system definition general settings and assumptions have to be defined. The general system definition for the project requires more than the information that has to be inserted in the software. The documentation of the system definition contains at least:

- The identification of the decision maker and stakeholders.
- The identification of the relevant problem and decision that should be supported.
- The representation of the system.
- The boundaries, restrictions and limitations of the considered system.
- The assessment of the relevant hazards and scenarios that are considered in the analysis.
- The source of any used information (i.e. data, expert judgment, etc).

The identification of the decision maker and the identification of the relevant problem ensure that the risk analysis is consistent with the context of the risk assessment. The problem setting is in general closely coupled to the decision situation so that a clear documentation of the before mentioned aspects for the system definition is of utmost importance.

A software tool, which assists the decision maker in the risk assessment can only party support a complete system definition. In order to avoid misinterpretation of results the system definition should be regarded as the general frame for the whole risk assessment.

The system definition should be well documented and should be beyond the pure collection of the necessary information that are required for using the software tool.

Project

All specifications which are related to the project have only informative character. They serve only for the documentation of the results of the risk analysis. The user is free to insert any arbitrary text in these fields. No consistency check is performed on these fields.

In Figure 3.8 the input sheet for the project description is shown.

Project	
Project	Test Application
Name of the author	Matthias Schubert
Project ID	14102019
Project name	Test project
Client	ASTRA/NPRA
Date	09.06.2010
Direction	1.01

Figure 3.8: Input sheet for the project description.

Global tunnel characteristics

In the section 'global tunnel characteristics' the general tunnel characteristics are specified. Under the input field *Tunnel location* the user can either choose Switzerland or Norway in the present version of the software. The choice of the tunnel location can influence the result of the risk assessment in specific cases.

More details are given in Chapter 1.2 and 1.4.

The input field *Name of the tunnel*, *Place / Canton* and *Year of construction* have only informative character. This information is not considered in the risk analysis.

The input field *Length [m]* has a direct influence on the analysis. By entering the total length of the tunnel the software determines the types of zones which are present in the tunnel. According to the studies published in Amundsen and Ranes (1997), the accident rates in tunnels are a function of the longitudinal position in the tunnel which lead to a division of the tunnel into four different zones with the following definition:

Zone 1: Last 50 m before the tunnel portal.
Zone 2: First 50 meters within the tunnel.
Zone 3: Next 100 meters into the tunnel.
Zone 4: 150 meters from the tunnel portal, mid-zone of the tunnel.
Zone 5: 150 meters to 50 meters before the exit portal.
Zone 6: 50 meters to 0 meters before the exit portal.
Zone 7: next 50 meters after the tunnel portal.

For each of the present zones in the tunnel the user can specify the number of homogeneous segments that are considered. Homogenous refers here to the risk indicators considered in the analysis. These indicators are given and discussed in the Chapter 3.3.2. Homogeneity can be assumed if none of the values of the indicators change over the section in the tunnel. In Figure 3.9 an example for the definition of homogeneous segments is given. In many cases, i.e. if the conditions do not change in the tunnel, only one homogeneous segment per zone needs to be considered. However, a change in one indicator might lead to a significant alteration of the risk in tunnels at specific locations. The differentiation into homogeneous segments allows to identify hot spots in the tunnel and also to find appropriate measures for the risk reduction.

Global tunnel characteristics	
Tunnel location	Switzerland
Name of the tunnel	Testtunnel
County / Canton	Zürich
Year of construction [*aaaa*]	1974
Length [*m*]	400.00
Number of homogeneous sections [#]	
Entrance Zone 2	1
Entrance Zone 3	2
Zone 4	5
Exit Zone 5	2
Exit Zone 6	1
Total number of segments [#]	11

Figure 3.9: Input sheet for the definition of global tunnel characteristics.

The input fields for the definition of the number of segments are inactive in the beginning. Depending on the inserted length of the tunnel (category *Length [m]*) the software activates the types of zones that are present in the tunnel. For a tunnel with a length of only 100 m only the category *Entrance Zone 2* is active, i.e. there background color changes to white and numbers can be entered. In Figure 3.9 all fields are active since in a tunnel with a length of 400 m all four considered tunnel zones are present (see also Chapter 3.3.2).

Ventilation system

Depending on the tunnel characteristics and on the construction year different ventilation systems may be present in tunnels. The ventilation can have a significant influence on the self evacuation of persons during a tunnel fire. Depending on the conditions the influence of a ventilation system can be either positive or negative. In this risk analysis the following ventilation systems are considered and can be chosen by the user:

- Natural ventilation.
- Longitudinal ventilation.
- Longitudinal ventilation with active control.
- Longitudinal exhaust ventilation.
- Longitudinal exhaust ventilation with active control.
- Semi transverse ventilation.
- Semi transverse ventilation with active control.
- Transverse ventilation.
- Transverse ventilation with active control.
- N/A.

In the present version of the software no detailed analysis was made to in regard to the efficiency of different ventilation systems in tunnels. The risk analysis represents, however, in qualitative terms the best available expert knowledge in the field of tunnel ventilation. Of course, a combination of expert knowledge and refined smoke propagation models (e.g. CFD-FMA) would be preferable but due to a lack of reliable smoke propagation models this seems to be unfeasible at the present time.

A challenge for the future is to develop a probabilistic model taking into account different effects such as changes in the stability of the flow and upstream as well as downstream effects by using different models and to combine these with the experience from experts and from full scale tunnel fire experiments. Such a model could be straightforwardly implemented into this software tool.

Monitoring

The indicator *Monitoring* considers whether a monitoring system is installed in the tunnel. The user can enter *Yes* if a monitoring system is installed, *No* if no monitoring system is present and *N/A* if no information is available (see Chapter 1.4.28 for more details).

Compensation costs

Consequences are only partly considered in the software tool. The compensation costs for fatalities and for injuries can be defined by the user. These costs might vary strongly in dependency of the legal system of the country and the common practice. The costs assigned in Figure 3.10 are arbitrary numbers and cannot be considered recommendations. Which values should be assigned here has to be discussed jointly with the decision maker.

It should be noted that the costs assigned here are average costs for compensation, i.e. every fatality is compensated by the decision maker with the assigned number. It should not be confused with the marginal cost principle used for developing acceptance criteria (see e.g. Rackwitz (2002)).

Here the role of the decision maker becomes more pronounced. It has to be defined in the system definition who carries the consequences and who pays for risk reducing measures in order to make a consistent decision based on the assessment of the real benefits and disbenefits for the decision maker. In some cases this might be the society in other cases a private owner. The resulting consequences might be different in the two cases and thus, the decision might differ. A careful assessment of the consequences is thus quite important.

Compensation costs		
Fatalities	[CHF]	3 800 000
Injuries	[CHF]	2 000 000

Figure 3.10: Considered compensation costs.

Other consequences such as property damages in the tunnel or on private vehicles are not considered here. The latter can be directly calculated using the results of risk analysis. Also not considered are societal costs such as user costs. They arise in cases where a tunnel has to be closed after events and the user has to take detours.

Acceptance criteria

In the software so called hard acceptance criteria's can be considered. Hard acceptance criteria's are fixed numbers which are independent from the costs associated with a reduction of the risk. They can be used for a fast overview and the valuation of the results in a tunnel. It is not recommended to base any decision making process on these values. The authors recommend that decisions in this regard should take basis in the marginal cost principles (see e.g. Rackwitz (2002), Faber and Maes (2009) and Schubert (2009) for an overview).

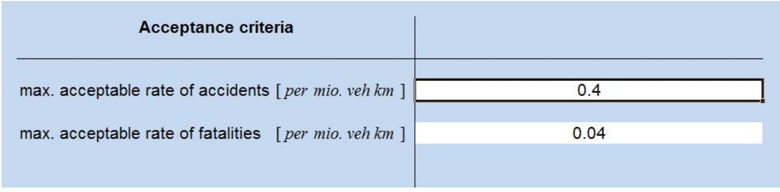
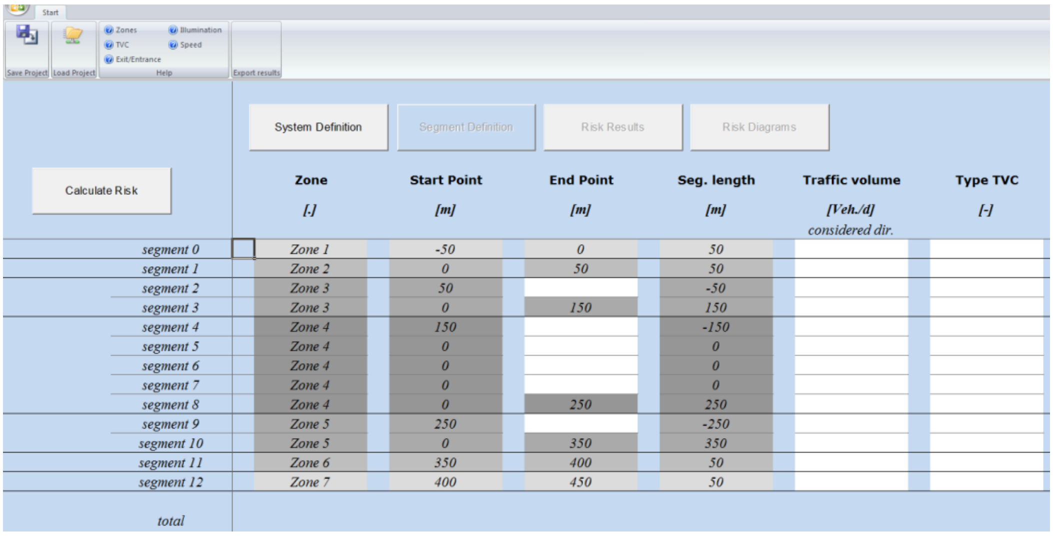


Figure 3.11: Input sheet for the definition of hard acceptance criteria.

In Figure 3.12 the input sheet for the hard acceptance criteria's is shown. The user can specify these values. However, these values are not obligatory and if the input fields remain empty no acceptance criteria's are considered in the analysis.

After specifying all necessary information in the sheet given in Figure 3.6, the button 'Segment Definition' becomes active, i.e. the color of the font becomes black. By pressing this button the input sheet for the segment definition becomes active.



	Zone [-]	Start Point [m]	End Point [m]	Seg. length [m]	Traffic volume [Veh./d] considered dir.	Type TVC [-]
segment 0	Zone 1	-50	0	50		
segment 1	Zone 2	0	50	50		
segment 2	Zone 3	50		-50		
segment 3	Zone 3	0	150	150		
segment 4	Zone 4	150		-150		
segment 5	Zone 4	0		0		
segment 6	Zone 4	0		0		
segment 7	Zone 4	0		0		
segment 8	Zone 4	0	250	250		
segment 9	Zone 5	250		-250		
segment 10	Zone 5	0	350	350		
segment 11	Zone 6	350	400	50		
segment 12	Zone 7	400	450	50		
total						

Figure 3.12: Details of the input sheet for the segment definition.

In this sheet also more help sheet become available. Presently help sheets for the time variation curves TVC, the Exit and entrance conditions, the signalized speed and the Illumination conditions are included. For the illumination conditions the help sheet contains the graph to calculate the equivalent luminance according to Figure 1.13.

3.3.2 Segment Definition

According to the specification by the user with regard to the length of the tunnel and the number of homogeneous sections of each tunnel zone the input field for the risk indicators is automatically generated. For the conditions given in Figure 3.9 the input sheet for the segment definition is shown in Figure 3.12.

Each of the homogeneous segments has a specific number and according to the distance of the section from the tunnel portal the type of zone is assigned. The grey tone of the input fields indicates which zone the segment belongs to. Light grey indicates a smaller distance from the tunnel portal and a dark grey indicates the mid-zone of the tunnel.

In all fields with a white background colour a user input is required. The user input is directly used in the risk assessment. Each of the white fields in the segment definition requires an input value. If fields are empty during the calculation process the user is informed by the software that empty input fields are not valid for the calculation.

If no information is available the input N/A can be given. This will make use of the prior values as default. (See Chapter 1.4 for more details on the priors) However, the model shall be used with extreme care if sufficient data is not available.

In the following sections a description of the considered indicators and the required user input is given.

Zones

The zones of the tunnel are assigned according to the specifications the user made in the system definition (see Chapter 3.3.1). This assignment cannot be changed in the sheet *Segment Definition* and thus the according fields are not selectable.

Start points

The start point of each of the homogeneous section is calculated automatically by the software according to the end point user input (see below). These values cannot be changed in the input sheet *Segment Definition* and thus the according fields are not selectable.

End points

The user has to specify the end point for each of the homogeneous sections. The endpoint is defined by the longitudinal distance from the tunnel portal.

The end points of the borders of the zones, i.e. the transition between one zone type to another, are predefined by the software and cannot be changed (see Figure 3.12).

The software checks the consistency of the user input and will show an error message in case the inserted numbers are inconsistent.

Segment length

The segment length is calculated automatically by the software according to the user input. These values cannot be changed in the sheet *Segment Definition* and thus the according fields are not selectable.

Traffic volume

The user can specify the annual average traffic volume as vehicles per day for each homogeneous segment. Since the risk calculation is performed for only one direction of the tunnel the traffic volume which should be used here is the annual average daily traffic volume in the considered direction. This is one of the indicators which have to be known for running the analysis. Here, the user cannot use N/A if this information is not available. Information for Switzerland on the traffic volume separately for each direction for most of the existing tunnels can be found in Bundesamt für Statistik (BFS) (2007).

In Chapter 1.4.2 the user can get some hints on the distribution of the annual average daily traffic which might help to find an appropriate value if no other information is available.

Type TVC

The indicator 'TVC' is used to consider the daily Time Variation Curve (TVC) of the traffic. Here six different types of time variation curves are considered following the studies of Pinkofsky (2005) and the standard SN 640 005a (2001), whereas in the latter one does not consider the type A. The different time variation curves are illustrated in Figure 1.5.

- A: pronounced peak in the morning.
- B: peak in the morning combined with small peak in the afternoon.

- C: relative equally distributed traffic during the day.
- D: pronounced peak in the morning and in the afternoon.
- E: pronounced peak in the afternoon, small peak in the morning.
- F: pronounced peak in the afternoon.

The user can choose one of the six different types of the time variation curves in order to describe the daily variation of the traffic. As an input either *A*, *B*, *C*, *D*, *E*, *F* or *N/A* is required; the latter in cases where no information on the type of TVC is available. In this cases a representative (prior) distribution of the types of TVC is used in the analysis (see Chapter 1.4.1 for more details).

HGV

Under the input field *HGV* the user can specify the percentage of heavy goods vehicles (HGV) of the annual average traffic volume for the considered direction. For Switzerland information on the HGV separately for each direction for most of the existing tunnels can be found in Bundesamt für Statistik (BFS) (2007).

Speed limit

The speed limit in [*km/h*] in each of the homogeneous segments can be specified under this input field.

Lanes

This risk indicator considers the number of lanes per direction for each homogeneous section. Here the user can choose *1*, *2*, *3* or *N/A*. More than 4 lanes per direction in a tunnel are not considered in the risk analysis. Please note that an exit or an entrance ramp is not considered as an additional lane in the segment. The aspects of entrance and exit conditions are considered by the indicator *Exit-Entrance*.

Lane width

The indicator *Lane Width* considers the lane width of the single lanes in the tunnel in meter. If the single lanes have a different lane width it is recommended to use the smallest lane width of all present lanes.

Gradient

The indicator *Gradient* considers the longitudinal gradient of the road segment in the tunnel and should be entered in [*%*].

H-Radius

The indicator *H-Radius* considers the horizontal radius in [*m*] of the tunnel in the segment. It is an indicator for the curviness of the tunnel. For clothoids the homogeneous sections has to be defined a way that the horizontal radius can reasonable be assumed be constant. For segments with no curvature the value has to be set to a value larger than 1000 m. Please note that radius 0 is an invalid input.

Bi directional

This indicator considers if the considered tunnel segment is used for traffic in both directions. The user can enter *Yes*, *No* or *N/A*. Information on the representative prior distribution can be found in Chapter 1.4.4.

Exit - Entrance

The entrance and exit conditions in a tunnel have a major impact on the accident rate in a tunnel and thus also on the risk. The conditions can be quite different depending on the year of construction and the location of the tunnel. To reflect this fact in total 41 different cases for entrance ramps, exit ramps and their combinations are considered. Especially in existing tunnels the length entrance and exit ramps might be shorter (or longer) than the the required regulated length in the national tunnel guidelines L_{req} .

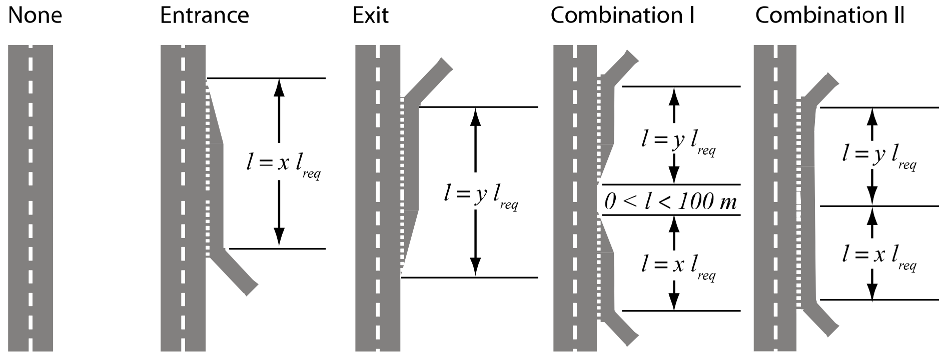


Figure 3.13: Considered exit and entrance condition in the tunnel.

Table 3.1: Notation for the different considered exit and entrance conditions.

	Length of entrance ramp	Length of exit ramp	Nr
No ramp	-	-	1
Entrance ramp	$0 \cdot l_{req}$	-	2
	$0.5 \cdot l_{req}$		3
	$1.0 \cdot l_{req}$		4
	$2.0 \cdot l_{req}$		5
Exit ramp	-	$0 \cdot l_{req}$	6
		$0.5 \cdot l_{req}$	7
		$1.0 \cdot l_{req}$	8
		$2.0 \cdot l_{req}$	9
Combination I	$0 \cdot l_{req}$	$0 \cdot l_{req}$	10
	$0 \cdot l_{req}$	$0.5 \cdot l_{req}$	11
	$0 \cdot l_{req}$	$1.0 \cdot l_{req}$	12
	$0 \cdot l_{req}$	$2.0 \cdot l_{req}$	13
	$0.5 \cdot l_{req}$	$0 \cdot l_{req}$	14
	$0.5 \cdot l_{req}$	$0.5 \cdot l_{req}$	15
	$0.5 \cdot l_{req}$	$1.0 \cdot l_{req}$	16
	$0.5 \cdot l_{req}$	$2.0 \cdot l_{req}$	17
	$1.0 \cdot l_{req}$	$0 \cdot l_{req}$	18
	$1.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	19
	$1.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	20
	$1.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	21
	$2.0 \cdot l_{req}$	$0 \cdot l_{req}$	22
	$2.0 \cdot l_{req}$	$0.5 \cdot l_{req}$	23
	$2.0 \cdot l_{req}$	$1.0 \cdot l_{req}$	24
	$2.0 \cdot l_{req}$	$2.0 \cdot l_{req}$	25
Combination II	$0 \cdot l_{req}$	$0 \cdot l_{req}$	26
	$0 \cdot l_{req}$	$0.5 \cdot l_{req}$	27
	$0 \cdot l_{req}$	$1.0 \cdot l_{req}$	28
	$0 \cdot l_{req}$	$2.0 \cdot l_{req}$	29
	$0.5 \cdot l_{req}$	$0 \cdot l_{req}$	30

	Length of entrance ramp	Length of exit ramp	Nr
	$0.5 \cdot l_{rea}$	$0.5 \cdot l_{rea}$	31
	$0.5 \cdot l_{rea}$	$1.0 \cdot l_{rea}$	32
	$0.5 \cdot l_{rea}$	$2.0 \cdot l_{rea}$	33
	$1.0 \cdot l_{rea}$	$0 \cdot l_{rea}$	34
	$1.0 \cdot l_{rea}$	$0.5 \cdot l_{rea}$	35
	$1.0 \cdot l_{rea}$	$1.0 \cdot l_{rea}$	36
	$1.0 \cdot l_{rea}$	$2.0 \cdot l_{rea}$	37
	$2.0 \cdot l_{rea}$	$0 \cdot l_{rea}$	38
	$2.0 \cdot l_{rea}$	$0.5 \cdot l_{rea}$	39
	$2.0 \cdot l_{rea}$	$1.0 \cdot l_{rea}$	40
	$2.0 \cdot l_{rea}$	$2.0 \cdot l_{rea}$	41

In Figure 3.13 the considered exit and entrance conditions in the tunnel are given. In Figure 3.13 the variables x and y are scaling factors which in principle can take any value larger than or equal to zero. As an approximation of the real world the following values for x and y are considered: *0.0*, *0.5*, *1.0*, *2.0*. The consideration of these values lead to a total number of 41 different combinations for the entrance and exit conditions. The user has to decide by which category the present situation is appropriately reflected. In Table 3.1 the possible combinations are given. The software requires as an input either a number between *1* and *41*.

The values 1, 4, 8, 20, 36 corresponds to the situation required in the tunnel guideline for the five entrance / exit combinations.

In most cases the input shall be "1", representing a section without any intersection.

Tunnel lighting

The illumination of the tunnel is another indicator for the risk. Presently, a wide range of light systems are available such as adaptive systems with high pressure lamps or adaptive systems with light emission diodes. The conditions light is here represented by candela per square meter and can change from segment to segment. So it is possible to consider different light conditions also in the exit and the entrance zones.

Emergency light

The indicator *Emergency Light* considers the presence of an emergency light system. The user can enter *Yes* if an emergency light system is installed, *No* if no emergency light system is present. The software is case insensitive in regard to the upper and lower case of the input.

Emergency exit distance

The indicator *Emergency exit distance* considers the distance to the next emergency exit in [*m*]. The distance is defined as the maximum distance to the next emergency exit in the tunnel. In cases where no emergency exit is present in the investigated tunnel, the distance to the emergency exit is equivalent to the distance to the tunnel portal.

If no information on emergency exit distances is available the user can enter *N/A* in the input field for the segment definition. It should be noted that the case where no emergency exit is present in the tunnel is not equivalent to the case where no information is available.

Congestion hours

The indicator congestion hours *[h/a]* has a direct influence on the consequences in the case of fire. If no information on the annual congestion hours in the tunnel is available, the user can enter N/A in the input field and a representative (prior) distribution for the annual average congestion hours in a tunnel is considered in the analysis.

ADR Tunnel Class

The indicator ADR tunnel class considers that the tunnel is restricted for the transport of dangerous goods. The classification is according to the classes defined by ADR (*Accord européen relatif au transport international des marchandises Dangereuses par Route).* The class A refers to no restriction in the tunnel (see also Chapter 2.2.2).

Fraction dangerous goods

In the input field *Fraction dan. goods* the user can specify the percentage of dangerous goods vehicles of the heavy goods vehicles for the considered direction.

Discharge system

This indicator considers the general type of discharge system which is present in the specific section. The user can specify if a discrete system with point gutters is present by entering *dis* (for discrete) in the program. If a continuous discharge system is present the user can enter *cont* in the program or he can choose *no* in case that the tunnel has no discharge system.

Discharge opening

In the case that in the tunnel a continuous discharge system is present the user can specify the slot opening in the discharge system in [cm]. This input field is disabled in the case where the tunnel has either no discharge system or a discrete discharge system.

Discharge distance

In the case that the tunnel segment has a discrete discharge system the user can specify in this input field the distance between the gutter points in [m].]. This input field is disabled in the case where the tunnel has either no discharge system or a continuous discharge system.

Camber

This indicator considers the specific camber of the road in the tunnel segment. The user can enter absolute values of the camber between 0 and 8%. Values larger than 8% are not considered.

3.3.3 Risk Analysis

After the input sheet for the segment definition has been completed with all available information the risk analysis can be performed; an example for the completed input sheet is given in Figure 3.14. Please note that all white input fields in the sheet have to be filled out before the risk assessment can be started.

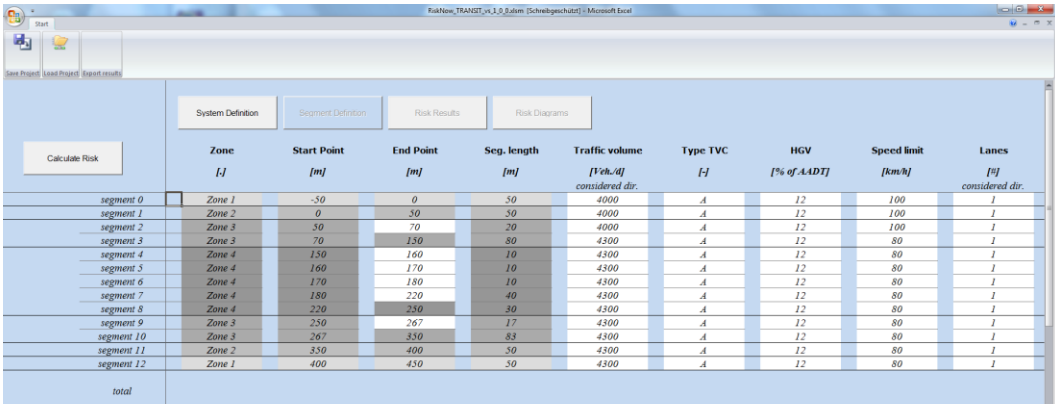


Figure 3.14: Detail of the filled input sheet.

The risk analysis is started by pressing the button *Calculate Risk* which is located on the left side of the input sheet (see Figure 3.14).

The risk is calculated by using Bayesian Probabilistic Networks (BPN). An introduction into BPN's is given in Annex I. During the calculation process MS Excel is inactivated and the user is asked to wait during this process.

Depending on the software and hardware configuration the calculation process might take several minutes.

3.3.4 Risk Results

The results of the analysis are presented in several ways. To get a first overview a summary of the results is given in the input sheet for the segment definition. This facilitates to check which indicators contribute significantly to the risk and to get a first impression which measures might decrease the risk.

It also facilitates to change values of indicators and see the impact on the risk.

More results of the risk analysis are given by pressing the button *Risk Results*. The results are given directly in this spreadsheet. The conditional formatting of the input fields in the MS Excel sheet helps to get a quick overview.

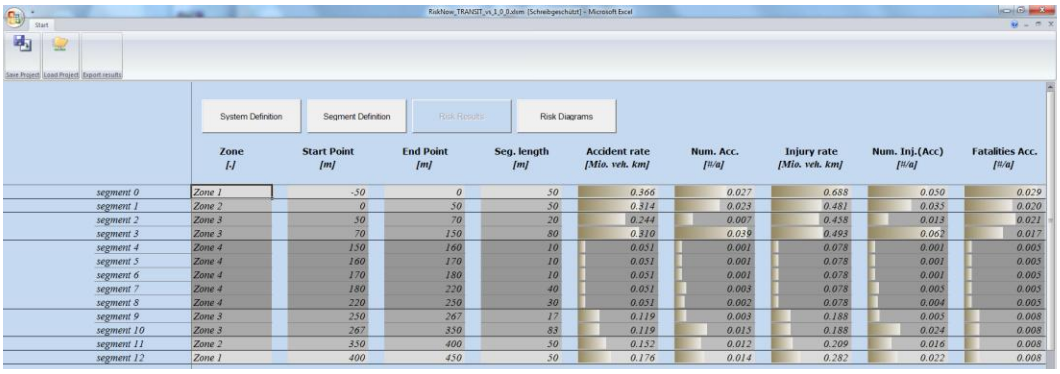


Figure 3.15: Illustration of the tabulated results of the risk analysis in MS Excel 2007.

Additionally to the tabulated results are provided in diagrams. By pressing the button *Risk Diagrams*, the graphs similar as shown in Figure 3.16 will be displayed.

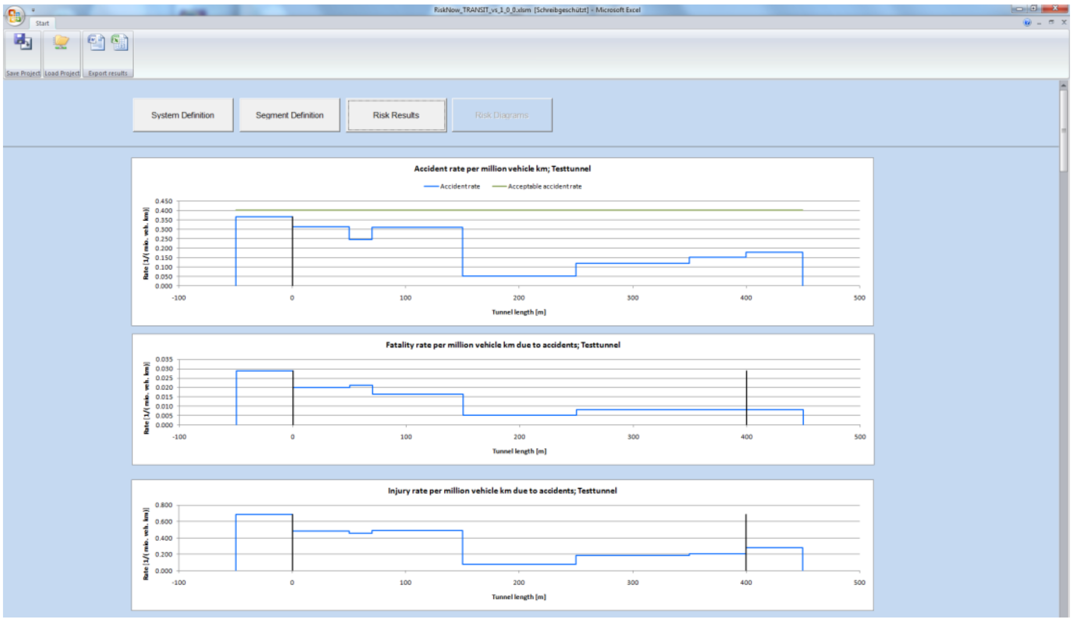


Figure 3.16: Results of the risk analysis in MS Excel diagrams.

The following diagrams are provided by the software:

- Accident rate per segment in million vehicle km.
- Fatality rate per segment in million vehicle km.
- Casualty rate per segment in million vehicle km.
- Fire rate per segment in million vehicle km.
- Annual expected number of accidents per tunnel segment.
- Annual expected number of fatalities per tunnel segment.
- Annual expected number of casualties per tunnel segment.
- Annual expected number of fires per tunnel segment.
- Annual expected number of fatalities due to fires per tunnel segment.
- Annual expected number of casualties due to fires per tunnel segment.
- Annual expected number of fatalities per tunnel segment due to fires and accidents.
- Annual expected number of casualties per tunnel segment due to fires and accidents.
- Accident rate per million vehicle km in the different zones in the tunnel.
- Annual exceedance frequency of fatalities due to dangerous goods events.

3.3.5 Export results

Two different export options are provided by the software. The first option is to export the results to Microsoft Word by clicking the *MS Word* icon in the MS Excel Ribbon bar. (see Figure 3.17).

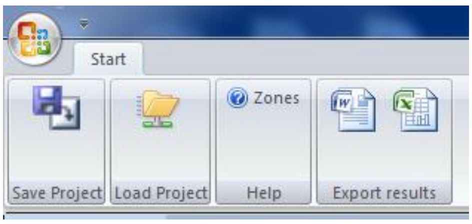


Figure 3.17: MS Excel Ribbon with the buttons for the export of the results.

A word document is generated automatically. This document includes all figures shown in the software as well the input which was created by the user. In total the export document contains 14 figures, 3 tables and a summary of the main results on 7 pages (see Figure 3.18).

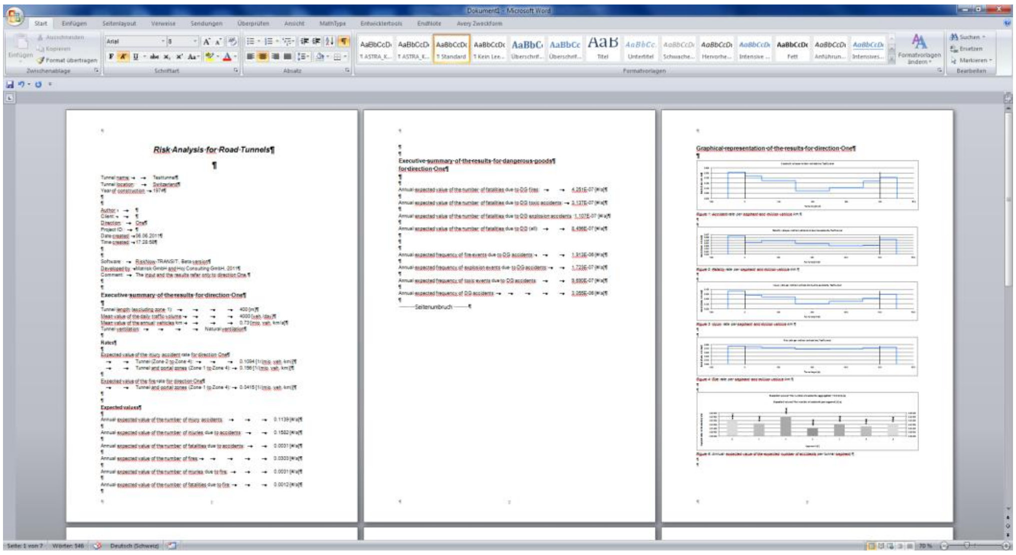


Figure 3.18: Export of the results to a Word document.

The word document can be regarded as a complete documentation of the results of the risk analysis since it contains all information required to reproduce the results by using Transit. Of course, it cannot be regarded as a full documentation of the risk analysis because the system definition and references to the values used in the analysis are missing (see also Chapter 3.3.1).

The second option is to export the results into a MS Excel file by clicking the *MS-Excel* icon in the MS Excel ribbon bar. An MS Excel file is then created containing all user defined input as well as all results that a required to produce the figures. The MS Excel file is completely unformatted (see Figure 3.19).

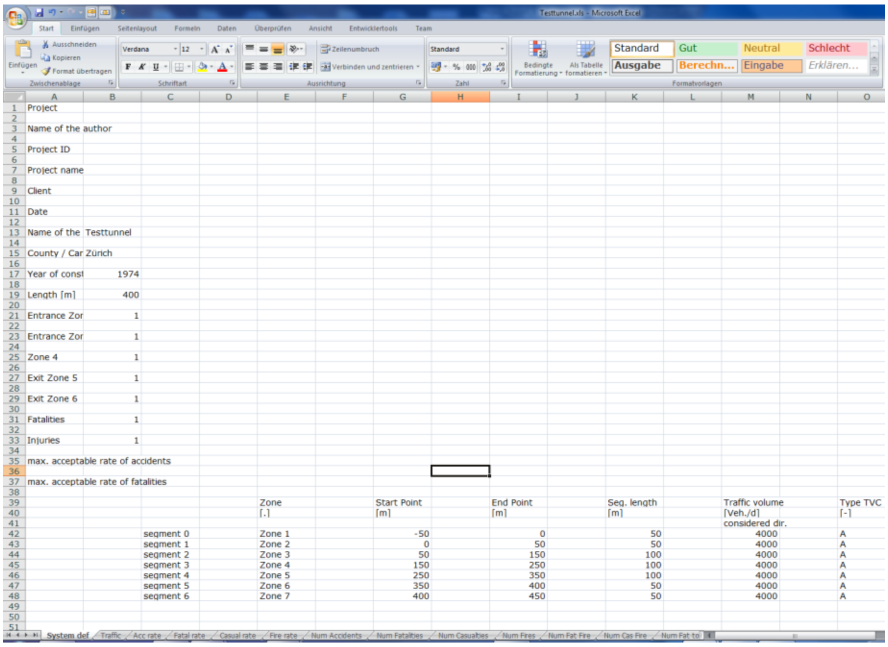


Figure 3.19: Export of the results to an unformatted MS Excel file.

In the start spreadsheet of the MSExcel file all input information is summarized. In the subsequent 17 spreadsheets (see tabs in the lower part of Figure 3.19) the results of the analysis are given. These results can be directly used to calculate the change in the risk ΔR for a set of risk reducing measures. The decision making process is supported and the acceptance of measures can be assessed.

4 Conclusions and Outlook

4.1 Conclusions

The aim of this project was to develop a sound methodology which reflects the best practice in the field of traffic safety assessment and reflects the best practice in the field of risk assessment. The methodology should facilitate the risk based decision making in regard to risk reducing measured during the planning and during the operation of the tunnel.

Another aim was that the methodology should give comparable and reproducible results and that the results should not be dependent on the person performing the analysis. These principal aims together with the typical problem setting in the decision making process have defined the general requirements for this project. On the operational level the methodology should facilitate the assessment of the current safety level of a tunnel. Furthermore, on the strategic level the methodology should facilitate a prioritization among different risk reducing measures and should also facilitate the assessment of the efficiency of different measures.

Several methodologies and tools for the risk assessment in roadway tunnels exist already. The most common are

- TuRisMo (Austria)
- TuSi (Norway)
- BASt model (Germany)
- HQ-TunRisk
- TunPrim/RWSQRA (Netherland)
- QRAM (OECD – PIARC)
- ASTRA ADR (Switzerland)

All these methodologies have their advantages in specific fields. A review and analysis of these methodologies has showed that the requirements with regard to the modeling of specific events (e.g. accidents and fire) neither from the Directive 2004/54/EC of the European Parliament nor from FEDRO and NPRA are fully met. The methodologies fail to model all events or relevant indicators are not considered. Another aspect is that in some methodologies the level of detail is not sufficient for the ranking of different decision alternatives to reduce the risk.

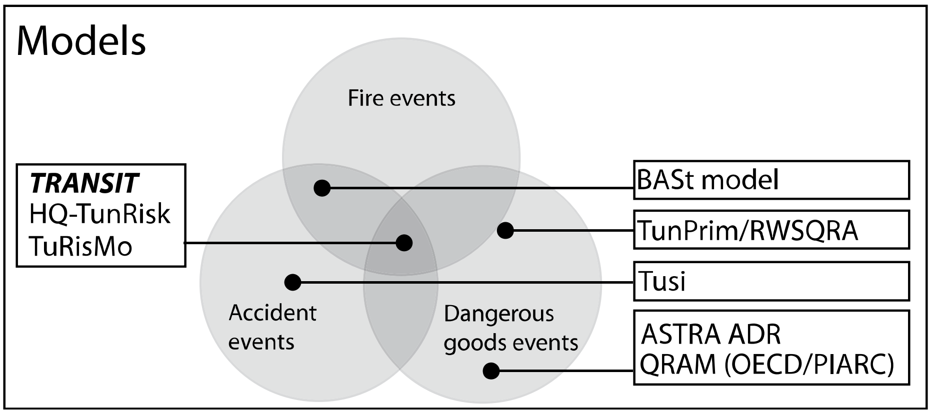


Figure 4.1: Potential of different available models for the tunnel risk assessment.

In this project all relevant “best-practice” models for the interaction between the configuration, design and equipment of the tunnel and the traffic on one side and the resulting risk on the other side have been identified and further developed. Furthermore, a “best-practice” modeling tool for the risk calculations has been applied: namely Bayesian Probabilistic Nets. Hereby the methodology and tool ***TRANSIT*** has been developed to close the gap between the before mentioned requirements and the abilities of a generic methodology.

The general approach in this project differs significantly from other methodologies for the risk assessment in roadway tunnels. Bayesian Probabilistic Nets BPN, which are used to model the events, are a best practice methodology in the field of risk assessment and they facilitate the assessment according to recent scientific standards. BPNs have the potential to substitute fully conventional fault tree or event tree formulations. A major advantage of Bayesian Probabilistic Nets is their ability to take into account uncertainties and dependencies of different risk indicators. Hereby causal relations between indicators and events in the model can be explored and validated by experts. Even complex interrelations in a system can be illustrated transparently.

TRANSIT represents the tunnel system in a generic manner, i.e. risks are assessed in segments, which are defined as a function of tunnel and traffic characteristics. ***TRANSIT*** facilitates the risk assessment on different levels of detail. If only a few details on the tunnel and traffic characteristics are known, the analysis can still be performed. Missing information on risk indicators is replaced by a priori distributions. If more specific information is available, the level of detail of the analysis can be increased.

The causal relations in the BPN are modeled by using physical and phenomenological models based on scientific findings and on expert judgment. Thus, the model reflects the current best practice in accident and event prediction modeling. This formulation has a large potential especially because these models can be updated with new information or exchanged if new or better models becomes available.

A major benefit of the developed methodology is the implementation into a software tool. With this tool the risk analysis can be performed efficiently, i.e. the time needed for the calculation is negligible and thus a large portfolio of tunnels can be assessed.

It can be concluded that all project aims have been reached and the risk assessment in tunnels made a step to a new generation of risk analysis tools. The methodology and tool is Focused, Innovative, Consistent, Transparent, Actionable. It is foreseen that the model will be further developed. For the purpose of the further development: continuing improvement, calibration and maintenance of ***TRANSIT*** a steering board and a user group will be established. Periodically new versions of ***TRANSIT*** may be issued. Hereby the methodology will provide high quality risk assessments – also with new requirements and new knowledge in the future.

4.2 Outlook

TRANSIT has been established as part of a research project with the aim of a best practice methodology. As part of the project a tool was developed to a status where it can be used for practical analyses.

4.2.1 Use of Transit in Norway

At the time of issuing the present report (April 2011) the ***TRANSIT*** tool has al-ready been used in Norway for a number of practical risk analyses.

The practical application of the program has given feed-back for the program development and contributed to the validation and control of the program.

It is the goal that the ***TRANSIT*** tool is used in Norway for all risk analyses of road tunnels. The program gives the possibility to achieve results both in cases with few input data and with a comprehensive set of input data. Hence, the programme can be used both for quick simple checks – for a first estimate of the risk and for detailed risk analyses with a more accurate estimate of the risk.

With the easy use of ***TRANSIT*** there is no reason to carry out risk analyses which are purely qualitative – a quantitative estimate can be made with ***TRANSIT*** and the results can – if necessary – be supported by qualitative considerations and identifications of additional hazards.

To ensure that the wide spread use of ***TRANSIT*** will become reality in Norway; it is the intention to carry out workshops with decision makers, professionals and stake holders within NPRA. The aim of the workshops is to explain the background of the program and the “best practice”, give an understanding of the nature of the modelling of indicators in ***TRANSIT*** and discuss the boundaries and limitation of ***TRANSIT***. Finally it shall be demonstrated how the programme works.

In order to facilitate the general use of ***TRANSIT*** for all road tunnel risk analyses in Norway, it may also be helpful to modify the Norwegian “Guideline for Risk Analyses of road tunnels” (Veileder for risikoanalyser av vegtunneler (Revidert) Rapport nr: TS 2007:11 Vegdirektoratet, Veg- og trafikkavdelingen, Trafikksikkerhetsseksjonen, Dato: 2007-10-31) in order to establish ***TRANSIT*** as the preferred tool for simple and detailed risk analyses.

4.2.2 Use of Transit in Switzerland

At the time of issuing the present report (April 2011) the ***TRANSIT*** tool has been used in Switzerland for pilot studies, and tests.

A project has been started to establish a Swiss federal guideline for carrying out risk analyses of road tunnels: A project “Methodology for the risk analysis of tunnel on the national roads”. (Methodik für die Risikoanalyse von Tunnels der Nationalstrasse) has been tendered by FEDRO (Federal Road Office) in two phases. The first phase has been completed primo April and the second phase will be completed in July 2013.

At the end of the project, an approved guideline with recommended, validated methods for risk analyses of road tunnel in Switzerland will have been established.
The “best practice of methodology for risk assessment in road tunnels” has been part of the basis for the development of a methodology in Switzerland. A draft version of the present report has been available for the first phase of the project and for the second phase the present final report is available.

4.2.3 User group and Steering Board

The project of the development of the best practice methodology for risk as-sessment of road tunnels and the ***TRANSIT*** tool has been coordinated by a “user group” consisting of the Norwegian and the Swiss Road Authorities and the consultants HOJ Consulting and Matrisk.

It is the intention that this “user group” is transformed into a Steering Board which shall coordinate further development of the best practice and of the software tool.
It is the goal that the methodology is concurrently developed with respect to models, methods and data (see the chapter “Further developments”). Some initiatives have already been taken to add supplementing models and expand the use of the model.
It is also the goal of the Steering Board that the ***TRANSIT*** too shall be used in other countries than Norway and Switzerland. Initiatives have been taken to include further countries in the user group.

It is also planned to form a user group with the parties (national authorities and their consultants) which are using the tool in practice. By means of the user group feed-back from the use and ideas for the further development can be collected.

It will also be discussed how a technical support function can be arranged. It is the intention that support can be required over a web page. This web page can also contain a FAQ list (frequent answers and questions) and similar on-line guidance.

The organisation of the support will still have to be discussed in detail and put into practice at a later point of time.

5 Future Developments

TRANSIT has already reached a level of detail of the analyses and degree of maturity where it can be used in practice for risk analyses of the most tunnel risk analyses occurring in practice.

The data used to calculate the basic risk are, however, in the majority Norwegian data supplemented with international data. For Switzerland some specific data have been incorporated.

For the use in Switzerland, it may be necessary to collect further data, and in-corporate these data in the part of the model valid for Switzerland.

Also in connection with the development of a Swiss guideline "Methodology for the risk analysis of tunnel on the national roads" (Methodik für die Risikoanalyse von Tunnels der Nationalstrasse) by FEDRO further need of development may be identified.

Presently the ***TRANSIT*** tool is specifically intended for the use in Norway and Switzerland, and only these two countries can be selected in the model. When the application of the tool is extended to other countries it will be necessary to include the relevant data for these countries.

The tailor-made adaption for additional countries may be more or less extensive depending on the available data in the respective countries. For countries with little experience (e.g. few tunnels) an adaption of international data may be pursued. For countries with extensive statistical data, the basic data in ***TRANSIT*** can be replaced by the national data.

As described in chapter 4 it is the intention that the methodology is concurrently developed with respect to models, methods and data – based on feed-back from the users and based on ideas discussed in the steering board.

Based on these ideas and plans, new projects for extension of field of application, refinement of the modelling, incorporation of additional models and aspects will be launched. It is the intention to launch a new version of ***TRANSIT*** every year (depending on the funds and the needs).

At present the following activities are planned. In part the execution of the modelling and implementation has been commenced, and will be included in the next version of ***TRANSIT*** (provisional name "***TRANSIT 2011***") to be issued at the end of 2011:

- Additional collection and implementation of Swiss data
- Validation of the model for use in Switzerland
- Incorporation of additional models for:
- Risk analyses of dangerous goods transports
- Models for complex tunnel systems consisting of two or more components
- Tunnel systems with weekly or annual variation of the traffic
- Incorporation of actual tunnel speed (in addition to the signalised speed limits)
- Influence of observed or assumed speed distribution
- Refined models for light conditions depending on cd/m^2 and similar
- Distinction of the particular conditions at the exit zones of a tunnel
- Detailing of the influence of the gradient, distinguishing up- and down-grades
- Influence of camber on the risk (dangerous goods accidents)
- Influence of the drainage system, slot gutters or discrete gutters (dangerous goods accidents).

Further ideas, which have previously been discussed for development and incorporation in the ***TRANSIT*** model, are given below. These modules or extensions may be included in future versions of ***TRANSIT***. However, other (more urgent) ideas for development might be identified and initiated before the below ideas:

- Smaller steps in the discretisation of the indicators
- Influence of variable speed limits
- Distance between SOS cabinets
- Estimation of the consequences in terms of monetary costs
- Estimation of the consequences in terms of traffic disruption
- Estimation of frequency of break-downs
- Influence of width and design of shoulders
- Influence of emergency lanes and lay-byes
- Influence of height of tunnel
- Influence of SOS stations, telephones and hydrants
- Influence of intervention time from rescue services
- Lane control signs and variable information signs
- Optical guidance
- Rough tunnel surfaces
- Influence of the slopes and traffic conditions of the access roads
- Adaption of the model for use by one lane tunnels with two-way traffic

Furthermore it is generally foreseen that the data base shall be regularly up-dated- taking new available data into account. This is assumed to take place every approximately 5 years or less.

Finally it may be pursued to develop a similar model for open roads.

The users of ***TRANSIT*** and the readers of the present research report are welcome to contact the developers (Matrisk – HOJ), the User Group / Steering Board if they have ideas for further developments and comments concerning the future development.

6 Formular 3

7 Annex 1: Bayesian Networks

7.1 Introduction into Bayesian Networks

Bayesian Probabilistic Networks (BPN) have been developed in the mid of the 1980th with the motivation to deal with information from different sources and interpret and establish coherent models (Pearl (1985)). Today, Bayesian Networks are widely used in systems with artificial intelligence, expert systems for diagnosing diseases (Kahn et al. (1997)) but also in the engineering sector (e.g. Faber et al. (2002)) they are used due to their flexibility and efficiency in regard to system representation. Also in spam filters and in search functions in the IT sector Bayesian Networks are broadly utilized.

The following sections are intended to serve as a small introduction into Bayesian Probabilistic Networks and they are based on Jensen (2001), Kjaerulff and Madsen (2006), Rammelt (1998) and Faber (2008).

Components of Bayesian Networks

Bayesian Probabilistic Networks (BPN’s) are directed acyclic graphs (DAG). The DAG contains chance nodes which represent random variables. The representation of the random variables can either be continuous or consists of finite set of discrete states. The chance nodes in the BPN are connected through links representing the dependencies between the random variables. The links in the BPN's have a direction. The direction represents the direct causal relation between two (or more) random variables.

Causal relations between random variables are not always obvious and causality is sometimes dependent on options and decisions alternatives which are available to change the state on the random variables. Sometimes it is necessary to set the direction according to the problem setting because the direction of the links is not obvious from the beginning. The more important is a careful system definition as the basis for the establishment of a consistent model.

In Figure 7.1 different symbols are shown which can be used to establish a BPN. In general the distinction between discrete and continuous nodes can be made in BPN's. In continuous nodes the random variables are represented through (conditional) probability density functions whereas in discrete nodes random variables are represented by (conditional) probability tables. These tables contain the (conditional) probabilities for each considered state.

Additional to the chance nodes also utility nodes can be used in a network. Such nets can be used to calculate directly the expected value of the consequences, i.e. the risk. In this case the nets are called influence diagrams. Also utility nodes can contain continuous functions or discrete states.

Bayesian networks can also directly support the decision making process. For this purpose decision nodes are introduced in the network (see Figure 7.1). In these nodes different decision alternatives are defined.

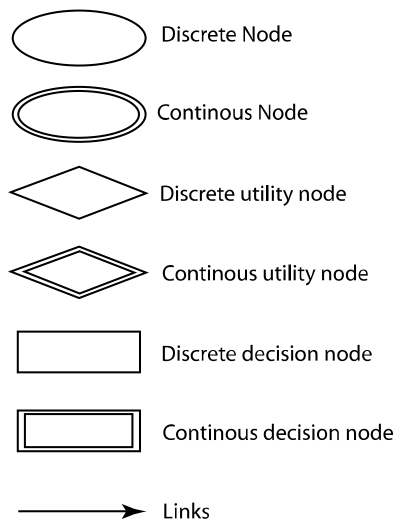


Figure 7.1: Symbols in Bayesian Networks.

In practical applications merely discrete nodes are used. The reason lies in the fact that algorithms used in commercial software such as Hugin (2008) or GeNIe&Smile (2006) are presently optimized to calculate the probabilities for discrete nodes. However, this is not really a disadvantage since every continuous density function can be represented by discrete states. The challenge here is to find an appropriate discretization which leads to a minimum loss of information. A general constraint with regard to the number of states is given by the present hardware and software environment in which the software is used. The cost for a higher degree of detail in the discretization is a significantly higher computational time.

The structure of the net is described by using family relations. Is a node A directly linked to a node B then the node A is denoted as the parent node of the child B. Every network consists at least of one parent node. In general it consists of

- all relevant risk indicators which are relevant to model the system and to describe the problem.
- the conditional probability distributions to describe the indicators.
- a net structure in form of a acyclic directed graph.

Dependencies in Networks

Bayesian Networks can be categorized by their configuration. A so called serial connected BPN is shown in Figure 7.2.

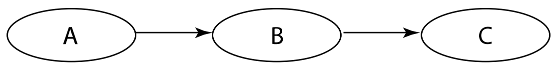


Figure 7.2: Serially connected BPN.

In this network the parent node A influences the chance node B which has a direct influence on the chance node C. Each of the nodes contains information on the indicator they represent. This information is uncertain and thus they are represented by using random variables. The underlying distribution of each node is conditioned on the parent node. In Figure 7.2 only the node A is unconditional. If a state of a node with known with certainty this information can be considered in the network. So called hard evidence can be introduced in the network. If e.g. evidence is introduced in the node A in Figure 7.2 this information has an direct influence on the nodes B and C because the nodes are dependent. Evidence can also lead to independence between nodes. If e.g. evidence on the node B is introduced in the Network the flow of information between the nodes A and C is interrupted. The nodes A and C are *d-separated* which means they are conditional independent.

In Figure 7.3 a different Network configuration is shown. Here, the nodes B, C and D are conditional independent if evidence on the node A is introduced. This configuration is called diverging.

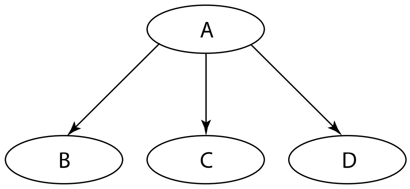


Figure 7.3: Diverging Bayesian Probabilistic Network.

Figure 7.4 shows a converging BPN. Here, the nodes B, C and D are independent as long as no evidence on one of the nodes is available. If evidence is introduced in one of the nodes in Figure 7.4 all parent nodes become dependent. This is denoted as conditional dependency.

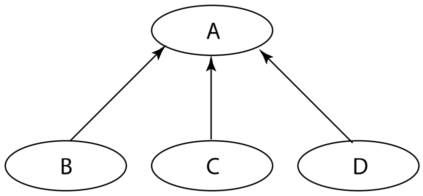


Figure 7.4: Converging Bayesian Probabilistic Network.

Evidence can be introduced either as hard or as soft evidence. Hard evidence is information which is not subjected to any inherent uncertainty. Soft evidence is information which is subjected to uncertainty. A *d-separation* in serial or converging networks can only be achieved by hard evidence. Dependencies in converging networks emerge from hard and soft evidence in networks.

Probabilities in Bayesian Networks and inference calculation

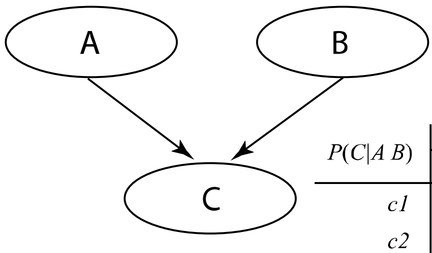
Different types of nodes have been introduced in **Fehler! Verweisquelle konnte nicht gefunden werden.**. Due to the practical relevance the following sections focus on discrete nodes in BPN's. The information on the indicators is described in the nodes by using multidimensional conditional probability tables. The dimension *dim(Y)* of these probability tables of a node can be calculated by using the following equation:

$$\dim\ Y\ = 1 + \sum_{i=1}^{n} X_i \qquad (7.1)$$

Herein X_i denotes the i parent nodes of the node Y .For the diverging network given in Figure 7.3 the dimension of the node A is one since this node has no parent nodes. The node A in Figure 7.4 has four dimensions since it has three parent nodes. The number of dimensions increases with the number of parent nodes. The probability tables in the nodes are used to describe this multidimensionality.

$P(A)$	
$a1$	0.4
$a2$	0.6

$P(B)$	
$b1$	0.2
$b2$	0.8



$P(C\|A\ B)$	$b1$		$b2$	
	$a1$	$a2$	$a1$	$a2$
$c1$	0.6	0.3	0.2	0.1
$c2$	0.4	0.7	0.8	0.9

$P(C, A, B)$	$b1$		$b2$		
	$a1$	$a2$	$a1$	$a2$	$P(C)$
$c1$	0.016	0.023	0.063	0.094	0.196
$c2$	0.064	0.096	0.257	0.386	0.804
$P(B)$	0.2		0.8		
$P(A)$	0.4	0.6			

Figure 7.5: Converging Bayesian Probabilistic Network and the corresponding probability tables.

In Figure 7.5 a converging BPN and the probability tables which are contained in the nodes is shown. The indicators A, B and C are represented by random variables with two states each. In general, considerably more states are necessary to represent the indicators in a meaningful manner.

The use of the conditional probability tables in BPN's is a particular advantage. This also eases the expert judgment and estimation of a-priori distribution of the random variables and facilitates plausibility checks for models since the assessment can be performed conditional on a specific state of a system. A certain degree of lucidity (especially in multidimensional problems) is reached through the use of probability tables.

By using the conditional probability tables the joint probability distribution of all nodes in the net $P(\mathbf{X})$ can be calculated by:

$$P(\mathbf{X}) = \prod_{i=1}^{n} P(x_i \mid pa_i, S^h) \tag{7.2}$$

In Equation (7.2) $\mathbf{X}$ represents all nodes in the network and $P(x_i \mid pa_i, S^h)$ is the probability distribution of the nodes x_i conditional on the parents of each node pa_i and the structure of the network S^h. In this section it is assumed that the network structure is known and this condition is dropped in the following.

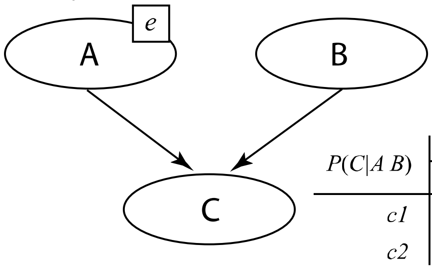
The joint probability distribution for the network given in Figure 7.6 is calculated according to Equation (7.2) by:

$$P(A,B,C) = P(C \mid A,B)\, P(A)\, P(B) \tag{7.3}$$

The corresponding probability tables are given in Figure 7.5. By using the probability tables the marginal distribution of the nodes can be calculated by integrating respectively by summing up over all other nodes.

$P(A)$	
$a1$	1.0
$a2$	0.0

$P(B)$	
$b1$	0.2
$b2$	0.8



$P(C\|A\ B)$	$b1$		$b2$	
	$a1$	$a2$	$a1$	$a2$
$c1$	0.6	0.3	0.2	0.1
$c2$	0.4	0.7	0.8	0.9

$P(C, B\| A=a_1)$	$b1$		$b2$		$P(C)$
	$a1$	$a2$	$a1$	$a2$	
$c1$	0.12	0.0	0.16	0.0	0.28
$c2$	0.08	0.0	0.64	0.0	0.72
$P(B)$	0.2		0.8		
$P(A)$	1.0	0.0			

Figure 7.6: Converging Bayesian Network and the corresponding probability tables.

For the example given in Figure 7.6 the marginal distribution for the node C is calculated by:

$$P(C) = \sum_A \sum_B P(A,B,C) \quad (7.4)$$

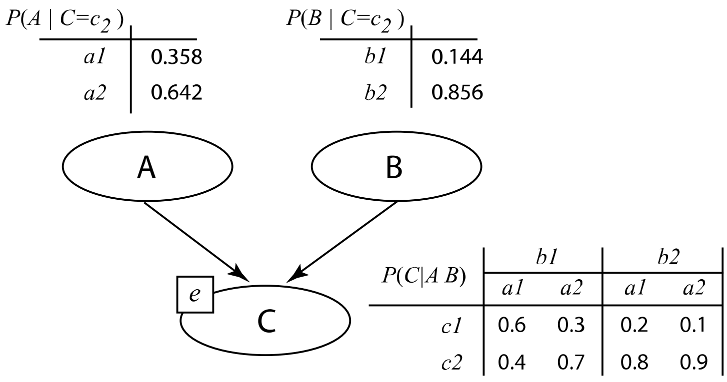
The inference calculation in BPN serves for propagating information through the network. The inference calculation uses the structure, the family relations in the network and the conditional probability tables in order to propagate information through the network by using efficient algorithms. More details in regard to the algorithms can be found in the abovementioned literature.

Simple examples can be calculated without such algorithms. Some small examples are shown in the following to illustrate the idea and the concept of BPN's. The first example is shown in Figure 7.6.

Here, the state of the node A is known with certainty (hard evidence). Does this information have an influence on the other nodes in the network? The joint probability distribution of the nodes B and C, $P(C,B \mid A = a_1)$ is calculated by:

$$P(\mathbf{X}_j \mid \boldsymbol{\varepsilon}) = \frac{P(\boldsymbol{\varepsilon} \mid \mathbf{X}_j)\, P(\mathbf{X}_j)}{P(\boldsymbol{\varepsilon})} \quad (7.5)$$

In Equation (7.5) $\boldsymbol{\varepsilon} = \{e_1, e_2, ..., e_n\}$ denotes the set of evidence of the variables $\mathbf{X}(\boldsymbol{\varepsilon})$ in the network. $\mathbf{X}_j$ denotes all variables on which no observations (and thus evidence) is available. The aim of the calculation is to obtain the joint probability distribution of the network under the consideration of all available observations. The result of this example is given in Figure 7.6. It should be noted that the knowledge of the state of the node A has an influence on the marginal distribution of the node C but not on the node B. In this case the nodes A and B are independent.



$P(A, B \mid C=c_2)$	$b1$		$b2$		$P(C)$
	$a1$	$a2$	$a1$	$a2$	
$c1$	0.0	0.0	0.0	0.0	0.00
$c2$	0.05	0.09	0.31	0.55	1.00
$P(B)$	0.14		0.86		
$P(A)$	0.36	0.64			

Figure 7.7: Converging Bayesian Network with evidence in node A.

In cases where evidence is introduced on nodes which have parents the parent nodes become dependent. An example for such a case is given in Figure 7.7. Hard evidence is introduced in the node C. The marginal probability distributions of the parent nodes A and B change according to Equation (7.5). The probability of state $a1$ in node A is calculated by:

$$P\left(A = a_1 \mid C = c_2\right) = \frac{\sum_{i=1}^{2} P\left(C = c_2 \mid A = a_1, B = b_i\right) P\left(B = b_i\right)}{\sum_{j=1}^{2}\sum_{i=1}^{2} P\left(C = c_2 \mid A = a_j, B = b_i\right) P\left(B = b_i\right)} \tag{7.6}$$

The result of the calculation is given in Figure 7.7.

Consideration of datasets in Bayesian Networks

The probability distribution which are contained in each of the chance nodes in the BPN's can be calculated by using probabilistic models or they can be calculated by using datasets. In the first case the input quantities of the model are considered as uncertain and the probability distribution is calculated for a specific state of the model. Probabilistic models are normally used in cases where the general phenomenon is known but no data is available.

If enough data is available the probability distribution of the nodes can directly be assessed. This estimation is subjected to statistical uncertainty which can be reduced if the number of data is large enough. The word enough is used here to illustrate that the number of data which can be assumed to be sufficient is dependent on the problem settings and the model itself. The more dependencies in a network are considered and the more states each node has the more data is necessary to estimate the probability distribution.

Available datasets can be preprocessed and arranged in so called contingency tables. The type of observations can be differently for different indicators. In Table 7.1 a general contingency table is given. There, thy type of information for the indicator X_1 is Boolean and for indicator X_2 is labeled. In most cases the type of information on indicators are real numbers $\mathbb{R}$, natural numbers $\mathbb{N}$ or integers $\mathbb{Z}$.

It is quite frequent that information in datasets is missing. This is the case for the indicator X_2 and the second observation. Accordingly N/A (for not available) is assigned in Table 7.1 for this case. Also incomplete datasets can be considered in BPN's. In the next section it is shown how datasets can be used to update the BPN's and how incomplete datasets can be considered.

Table 7.1: Contingency table for different types of indicators.

	Indicators				
	X_1	X_2	X_3	X_i	X_n
1. observation	Boolean	Label	$\mathbb{R}$	$\mathbb{Z}$	$\mathbb{N}$
2. observation	Boolean	N/A	$\mathbb{R}$	$\mathbb{Z}$	$\mathbb{N}$
i. observation					
n. observation					

Updating of Bayesian networks under consideration of datasets

Available datasets can directly be used in BPN's to estimate the distribution of the considered Indicators or to update them. The contingency tables can be used to *learn* the network. This option is of utmost importance for all fields where new data becomes available. In tunnels, new data on accidents and fires are collected regularly and can thus be used to improve the model. The contingency table can also assist to set up a scheme which information should (at least) be collected to improve the model.

In general it is of interest how the probability distribution changes if observations are considered in the model. In the following it is illustrated how learning in a Bayesian Network can be performed. The first example considers a *non-informative a priori distribution* in the node (Box and Tiao (1992)). The a priori distribution is updated with the available information and the posterior distribution can directly be calculated by using the maximum likelihood estimator (MLE). The MLE $P\left(X_2 = x \mid X_1 = y\right)$ of the conditional probability given that $X_1 = y$ is can be calculated by:

$$P\left(X_2 = x \mid X_1 = y\right) = \frac{P\left(X_2 = x, X_1 = y\right)}{P\left(X_1 = y\right)} = \frac{\frac{n\left(X_2 = x, X_1 = y\right)}{N}}{\frac{n\left(X_1 = y\right)}{N}} = \frac{n\left(X_2 = x, X_1 = y\right)}{n\left(X_1 = y\right)} \qquad (7.7)$$

Herein $n\left(X_2 = x, X_1 = y\right)$ denotes the number of observations in the dataset where the indicator X_2 is equal to x and X_1 is equal to y at the same time. The divisor $n\left(X_1 = y\right)$ in Equation (7.7) is the total number of observation in which the indicator X_1 is equal to y. Equation (7.7) can be formulated more general by considering all parent nodes in the Network:

$$\boldsymbol{\theta} = P\left(X_i \mid pa_i\right) = \frac{n\left(X_i, pa_i\right)}{n\left(pa_i\right)} \qquad (7.8)$$

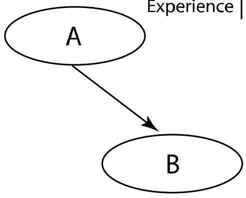
In Equation (7.8) $\boldsymbol{\theta}$ can be interpreted as the vector of all parameters of the distribution. The updating process is illustrated by using a simple example which is shown in Figure 7.8. The structure of the net is known but no information on the a-priori distribution is available. The lack of information is represented by a uniform distribution in the node, i.e. each state of the node has the same probability (see Figure 7.8). The a priori distribution is in general denoted by $P'\left(\cdot\right)$. A set of nine observations is available and should be used for updating the probability distribution in the nodes. The corresponding contingency table is also shown in Figure 7.8. From the contingency table it is seen that the state a_1 of the node A is observed five times. According to equation (7.8) the posterior probability $P''(A = a_1) = 5/9 = 0.566$. The posterior distribution is in general denoted by $P''(\cdot)$. The other results are given in Figure 7.8.

Contingency table

Observations	A	B
1	a1	b1
2	a1	b2
3	a2	b1
4	a2	b2
5	a1	b2
6	a1	b3
7	a2	b2
8	a1	b1
9	a2	b1

P'(A)	
a1	0.5
a2	0.5

P''(A)	
a1	0.556
a2	0.444
Experience	9



P'(B | A)	a1	a2
b1	0.333	0.333
b2	0.333	0.333
b3	0.333	0.333

P''(B | A)	a1	a2
b1	0.400	0.500
b2	0.400	0.500
b3	0.200	0.000
Experience	5	4

Figure 7.8: Updating of the probability tables in a BPN by using observations.

In the posterior conditional probability table of the node B one cell is equal to zero. That implies that this state was not present in the dataset. It should be noted that such a case should be avoided in practical applications because such states cannot be updated in the future even though in new dataset this state is observed. It is obvious that in large networks not all states can be observed which does not imply that the probability for this state is equal to zero.

One way to avoid such zero states is to introduce experience in the model. As seen from Figure 7.8 the experience corresponds to the number of observations which are available. This experience is used to weight the information. Existing (and old) information can be weighted in order to reflect the value of the information. If e.g. an old dataset and a new dataset can be deemed to be equivalent in terms of the value of information each of the observations in the dataset counts with one *experience point*. In cases where new dataset (or information) is deemed to be more valuable then old one the observations in the old dataset can be weighted with less experience. In that sense the experience can reflect the degree of belief. A high value of experience indicated that an expert is quite sure that the a priori distribution reflects the real world. The possibility to introduce this expert knowledge in the network is a major advantage since it facilitates to use real data and expert experience. If the expert knowledge is considered Equation (7.8) can be extended to (dirichlet prior):

$$\boldsymbol{\theta} = \frac{\alpha(X_i \mid pa_i) + n(X_i \mid pa_i)}{\alpha(pa_i) + n(pa_i)} \quad (7.9)$$

The additional term $\alpha(X_i \mid pa_i)$ considerers the equivalent sample size κ of the a priori distribution for the state of the parent node pa_i and is calculated by:

$$\alpha(X_i \mid pa_i) = \kappa P'(X_i \mid pa_i) \quad (7.10)$$

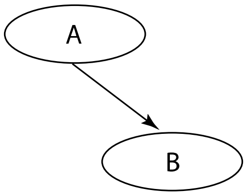
In cases where the probability tables are calculated by using probabilistic models they also can be updated. In this case the expert has to judge upon the validity of the used probabilistic model. The higher the validity of a model is ranked, the less the influence of a dataset is. In cases where a model shall be updated with observations the expert has to judge upon the validity of the model by using an equivalent sample size.

Contingency table

Observations	A	B
1	*a1*	*b1*
2	*a1*	*b2*
3	*a2*	*b1*
4	*a2*	*b2*
5	*a1*	*b2*
6	*a1*	*b3*
7	*a2*	*b2*
8	*a1*	*b1*
9	*a2*	*b1*

$P'(A)$	
a1	0.8
a2	0.2
Experience	4

$P''(A)$	
a1	0.631
a2	0.369
Experience	13



$P'(B \mid A)$	*a1*	*a2*
b1	0.500	0.200
b2	0.300	0.600
b3	0.200	0.200
Experience	4	4

$P''(B \mid A)$	*a1*	*a2*
b1	0.444	0.350
b2	0.356	0.550
b3	0.200	0.100
Experience	9	8

Figure 7.9: Updating of the probability tables in a BPN by using observations and expert knowledge.

An example for a weighted a priori distribution is given in Figure 7.9. Here, the a priori distribution of the node A is assumed to correspond to an equivalent sample size of four. The posterior distribution for the state a_1 of the node A is calculated by:

$$P''(A = a_1 \mid pa_i) = \frac{\alpha(A = a_1 \mid pa_i) + n(A = a_1 \mid pa_i)}{\alpha(pa_i) + n(pa_i)} = \frac{4 \cdot 0.8 + 5}{4 + 9} = 0.631 \quad (7.11)$$

It is quite frequent that a dataset is incomplete. There are several reasons for the incompleteness. One reason is that the data comes from different surveys with a different focus. As a result some information is just not collected in one survey. Sometimes it was just forgotten to assess data or the data was not assessable. In general two different cases should be differentiated. In the first case the data is missing without a certain reason (randomly missing) in the second case the reason for the missing data is dependent on the state of the indicator (not randomly missing) (see Heckman (1995)). In both cases the information can be considered in the updating process. For the application in tunnels the first one is of more relevance and an example is given in the following.

If the data is missing randomly, the missing data can be approximated by using probabilistic methods. The most common method is the *Markov-Chain-Monte-Carlo-Method* which is also known as *Gibbs-Sampling* (Geman and Geman (1984), Clark (2006)) and the *Expectation-Maximation-Algorithm* (EM) (Dempster et al. (1977), Lauritzen (1995)). The EM algorithm is very efficient and simple. It is widely used (Hugin (2008), GeNIe&Smile (2006)). The application of this algorithm is shown by using the example shown in Figure 7.10.

The EM algorithm consists of two steps:

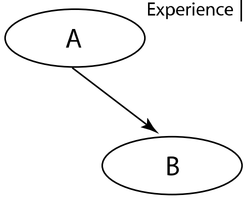
- Calculating the expected value for a specific realization (E-Step).
- Maximizing the likelihood (M-Step).

Contingency table

Observations	A	B
1	*a1*	*N/A*
2	*a1*	*b2*
3	*a2*	*b1*
4	*a2*	*b2*
5	*a1*	*b2*
6	*a1*	*b3*
7	*a2*	*b2*
8	*a1*	*b1*
9	*a2*	*b1*

$P'(A)$	
a1	0.5
a2	0.5

$P''(A)$	
a1	0.556
a2	0.444
Experience	9



$P'(B \mid A)$	*a1*	*a2*
b1	0.333	0.333
b2	0.333	0.333
b3	0.333	0.333

$P''(B \mid A)$	*a1*	*a2*
b1	0.250	0.500
b2	0.500	0.500
b3	0.200	0.000
Experience	5	4

Figure 7.10: Updating of the probability tables in a BPN by using an incomplete dataset of observations.

In BPN's the E-Steps serves to calculate the expected number of a specific realization.

The number of not observed states given the states of the parent nodes pa_i is given and denoted by $u\ pa_i$. In the first step the expected number of realizations for each state of the node is calculated by:

$$E\left[n\ X_i \mid pa_i\ \right] = n\ X_i \mid pa_i\ + u\ pa_i\ P'\ X_i \mid pa_i \qquad (7.12)$$

By using the expected value the MLE is calculated by using Equation (7.8) which corresponds to the M-Step in the EM algorithm. This estimator is used in the next iteration step as the a priori distribution $P'\ X_i \mid pa_i$ and the expected value is again calculated. This iteration is performed until the convergence criterion is reached. In general the convergence criterion is defined in a way that difference in the logarithm of the likelihood $l\ \cdot$ between two iteration steps i and $i+1$ is smaller than a predefined value δ:

$$l\ \boldsymbol{\theta}_i\ - l\ \boldsymbol{\theta}_{i+1}\ \leq \delta \qquad (7.13)$$

In Figure 7.10 an example for the learning algorithm by using an incomplete dataset is given. There, a non-informative prior distribution for the indicators is chosen. An incomplete dataset is provided in the contingency table. No data is missing for the indicator A. *N/A* (not available) is used in the contingency table to denote the case where the data is missing.

The iteration scheme of the *EM* algorithm for this example is given in Table 7.1. In the first step the expected number of observations for $B = b_1$, $B = b_2$ and $B = b_3$ given that $A = a_1$ is calculated under the assumption of the specified prior distribution. By using this result the posterior distribution for the indicator B is calculated. The iteration steps of the EM algorithm are given in Table 7.1. The convergence criterion is set to $\delta = 0.001$ is reached after five iteration steps.

In case that experience was introduced in the model Equation (7.11) is used to calculate the posterior distribution in the M-Step of the EM algorithm.

A disadvantage of the EM algorithm is that the algorithm converges to a local minimum of the likelihood. If the nodes contain multimodal distributions it should be noted that different start values of the algorithm (i.e. different prior distributions) might lead to different posterior distributions. Due to Jensen's inequality (Jensen (1906)) the likelihood increases at each iteration step. This increase is especially large in the first steps so that this algorithm converges faster than others (Lange (1999)). Thus, this algorithm is very efficient if the convergence criterion is not set too small.

Table 7.2: Iteration steps for the EM algorithm for the example given in Figure 7.10.

	iteration steps of the EM algorithm				
	1	2	3	4	5
$E\left[n\ \ B = b_1 \mid A = a_1\ \right]$	1.333	1.267	1.253	1.251	1.250
$E\left[n\ \ B = b_2 \mid A = a_1\ \right]$	2.333	2.467	2.493	2.499	2.500
$E\left[n\ \ B = b_3 \mid A = a_1\ \right]$	1.333	1.267	1.253	1.251	1.250
$P"\ \ B = b_1 \mid A = a_1$	0.267	0.253	0.251	0.250	0.250
$P"\ \ B = b_2 \mid A = a_1$	0.467	0.493	0.499	0.500	0.500
$P"\ \ B = b_3 \mid A = a_1$	0.267	0.253	0.251	0.250	0.250
l	-5.303	-5.221	-5.203	-5.200	-5.199
δ	-	0.082	0.018	0.004	0.001

These techniques can help to improve the here developed software tool. Over time the influence of all models and assumptions considered will disappear if the networks are learned with real data. This is a large potential for the improvement of the model. The use of models and data to improve the software over time is unique and a real advantage of this approach.

8 Annex 2: Tunnel system considerations

8.1 Introduction

The TRANSIT model operates by calculating the risks in tunnels in one direction. For establishing the total risk in a tunnel it is in most cases necessary to add the two directions. Furthermore for tunnel systems with ramps or multiple tunnels it may be necessary to add a number of individual directions in order to establish the total risk in the tunnel system. In the present note it is presented how this can be done.

8.2 Tunnel Systems

8.2.1 Introduction

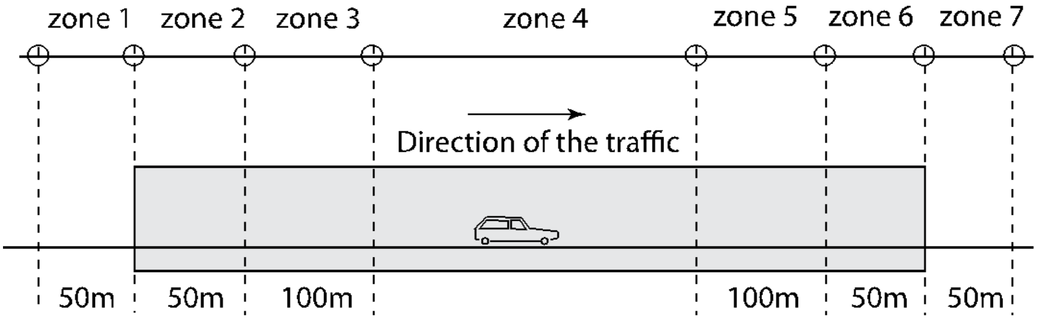


Figure 8.1 Illustration of the different tunnel zones in the tunnel.

Transit calculates the risk in one direction of a bi-directional or unidirectional tunnel. In reality most tunnel systems consist of two directions (in one or more tunnel tubes) or consist of several tunnel tubes (main tunnels and ramps) in a tunnel network, as shown below.

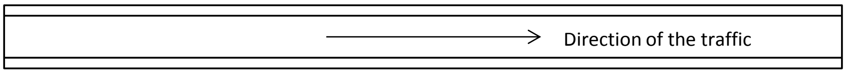


Figure 8.2 Tunnel system with only one direction and one lane is calculated by TRANSIT directly

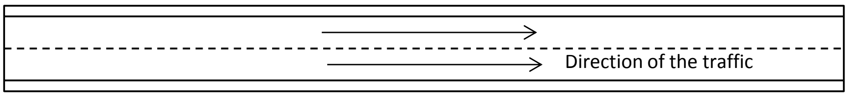


Figure 8.3 Tunnel system with one direction and 2 - 3 lanes is calculated by TRANSIT directly.

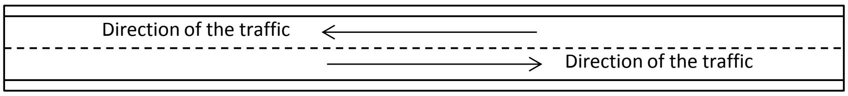


Figure 8.4 Tunnel system with two directions in a single tube in bi-directional traffic. The configuration allows up to 3 lanes in each direction. Each direction is calculated by TRANSIT separately and compiled.

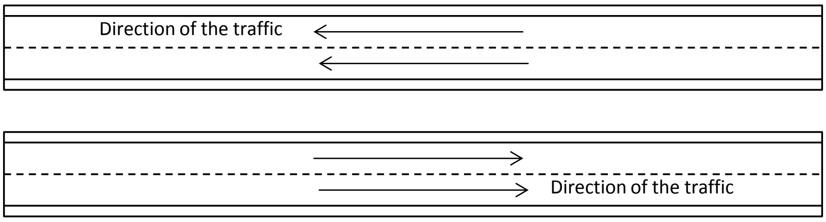


Figure 8.5 Tunnel system with two directions in two unidirectional tubes (with up to 3 lanes in each direction). Each direction is calculated by TRANSIT separately and compiled.

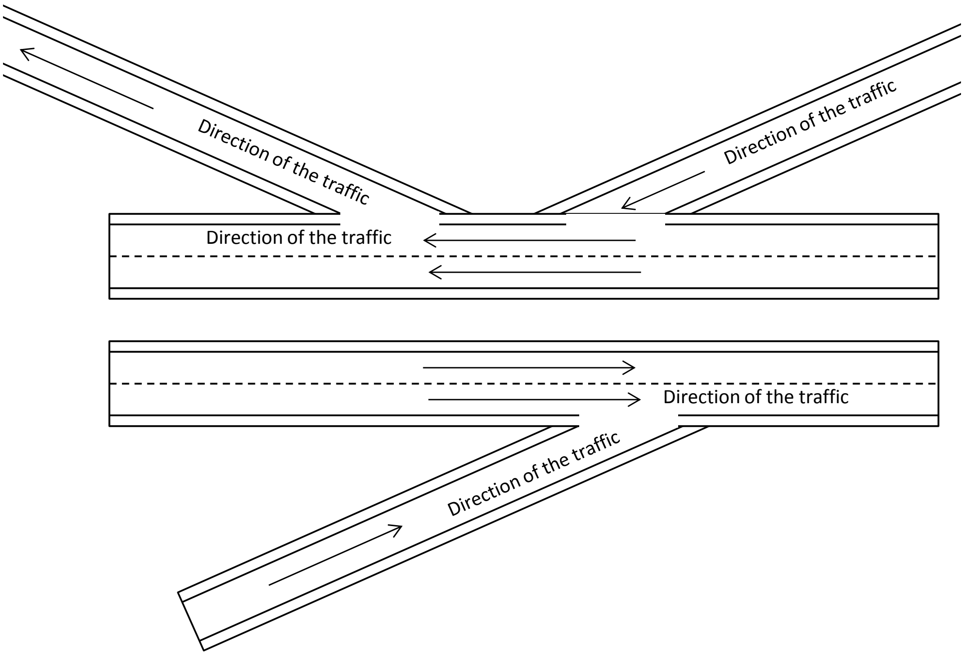


Figure 8.6 Tunnel system with ramps (here one ramp in one direction and two ramps in the other direction). Each main-tunnel-direction and each ramp will have to be calculated separately in TRANSIT and compiled. The intersection areas are modelled directly by TRANSIT.

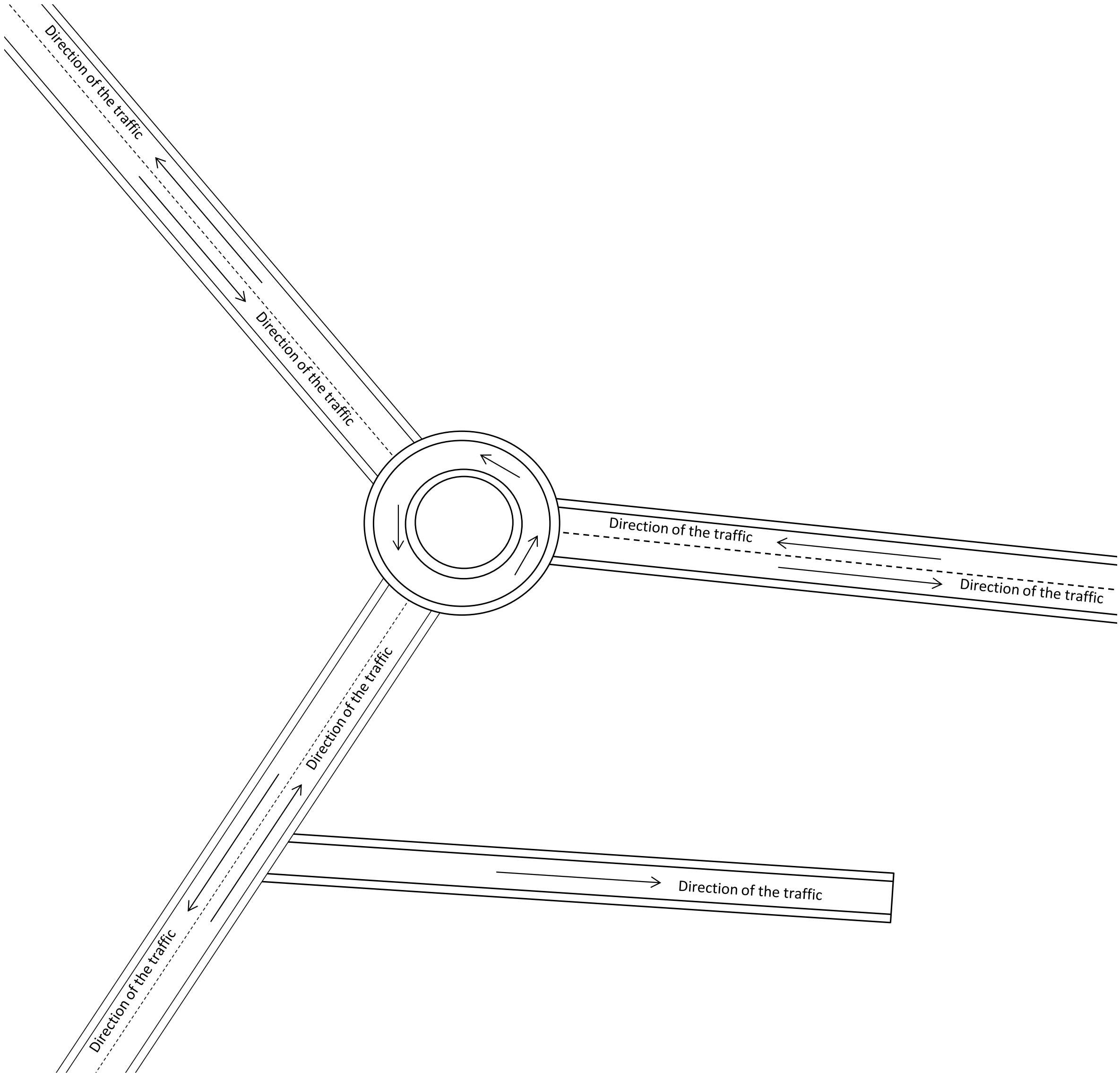


Figure 8.7 Tunnel system (network) of unidirectional and bidirectional tunnels. Each tunnel direction will have to be calculated separately and compiled. In the above example this involves 7 tunnel directions. In the example three tunnels are connected with an underground roundabout. The roundabout cannot be modelled directly in TRANSIT. A separate calculation can be carried out and added as the eighth element in the system compilation.

8.2.2 Systems compilation

8.2.2.1 Definition of tunnel system components

As explained in the introduction the tunnel will have to be calculated in one direction In order to make it possible to compile and add together the results, the tunnel system shall be divided into mutually exclusive parts.

One Component

For the tunnel with only one direction, as shown in Figure 8.2 and Figure 8.3 the tunnel system consist of one component. A systems compilation is not strictly necessary – the results can be taken directly from a single run of TRANSIT. A system with one component can also be defined.

Two components

For at tunnel with two directions as shown in Figure 8.4 and Figure 8.5 in the introduction the tunnel system consists of two components: one for each direction. For the individual direction the TRANSIT calculation will have to be carried out with the specific tunnel characteristics for this direction (incl. the traffic in this direction).

Three and more components

For a tunnel with ramps or a tunnel network as illustrated in Figure 8.6 and Figure 8.7 the tunnel system will have to be divided into mutually exclusive components.

For the tunnel with ramps as shown in Figure 8.6 the tunnel is conveniently divided into in total five components: the two main tunnels in their full lengths and the three ramps from the portals to the intersection. It should be noted that the traffic (in average annual daily traffic per direction) in the main tunnel by this configuration will have a discontinuity at the intersection.

Fur the tunnel network shown in Figure 8.7, the tunnel system will have to be divided into 7 tunnel directions with each its individual length and average annual daily traffic per direction. In addition the risk associated with the roundabout will have to be modelled separately and added.

For the tunnel components which are not ending and/or beginning in a portal, the zone characterisation shall be adapted to this situation. This means that the zones 1-3 and/or 5-7 may be have to be omitted. If the start/end of the components has particular risk conditions, which are not characterised by junction models, then this will have to be considered separately. This may relate for example to the junction between a tunnel component and a roundabout or an X- or T- cross in the tunnel.

8.2.2.2 TRANSIT calculations

For each of the components of the tunnel system a calculation with TRANSIT will have to be carried out (in the above examples this involves 1 – 7 TRANSIT calculations).

For each TRANSIT calculation the results are exported to an excel file, which is given an easily identifiable name. The export facility of TRANSIT is used. For the usual configuration in Figure 8.4 and Figure 8.5 this can for example be TunnelName_1_N.xlsx and TunnelName_1_S.xlsx (where 1 stands for a version or alternative and N and S stand for North and South direction) or what is found suitable for the actual case.

For the tunnel systems with ramps or networks the TRANSIT export files are similarly given easily identifiable names.

8.2.2.3 Compiled results

Given that the tunnel system is divided into mutually exclusive parts, the results of the risk estimates of each component can be summarised to form the risk of the entire system.

Only the risk in absolute numbers per year can be added: the rates per million vehicle–km cannot be added. Hence in order to estimate the accident-, injury-, fire- and fatality rates, the total annual risk will have to be determined and divided by the total traffic.

The individual user is free to use whatever method he/she want to carry out the compilation. As an example an excel-workbook with a framework for the compilation is presented in the following.

8.3 Compilation and Presentation of Tunnel System Risks

8.3.1 Introduction

In the following an example of an excel-workbook with a framework for the compilation is presented.

The present description relates to the version of TRANSIT available May 2011.

The excel work book consists of 1 sheet. In the following the sheet is explained. In the worksheet comment cells are included for additional help.

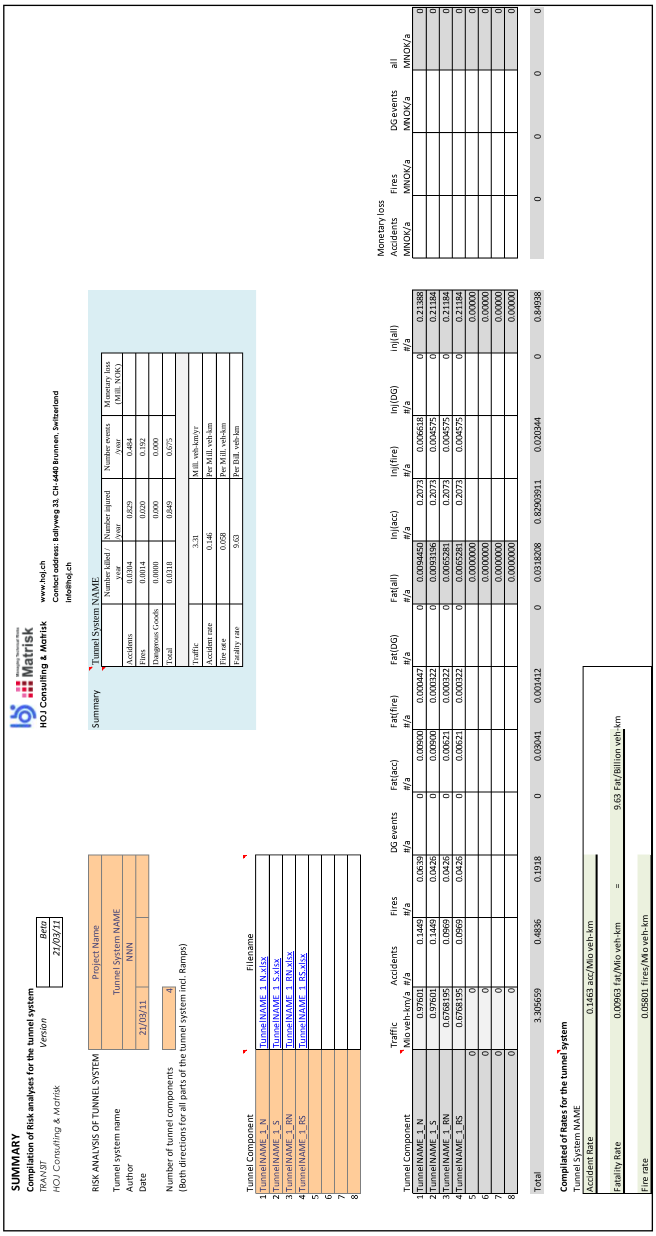


Figure 8.8 TRANSIT Tunnel system compilation sheet

8.3.2 Explanation of sheet

8.3.2.1 Identification

In the upper left of the sheet, the system to which the calculation relates is identified.

SUMMARY			
Compilation of Risk analyses for the tunnel system			
TRANSIT	*Version*	*Beta*	
Matrisk & HOJ Consulting		*21/03/11*	
RISK ANALYSIS OF TUNNEL SYSTEM	Project Name		
Tunnel system name	Tunnel System NAME		
Author	NNN		
Date	21/03/11		
Number of tunnel components	4		
(Both directions for all parts of the tunnel system incl. Ramps)			

Figure 8.9 Identification of TRANSIT system

The heading indicates the version of TRANSIT to which this summary sheet is related. This part cannot be changed.

The user has to insert the name of the project and the name of the tunnel system and his name or initials and the date. This serves only as identification.

In addition the user will have to identify how many components the system consists of, in the example above; this is defined as 4 for two main tunnels and two ramps.

8.3.2.2 Components

	Tunnel Component	Filename
1	TunnelNAME_1_N	TunnelNAME_1_N.xlsx
2	TunnelNAME_1_S	TunnelNAME_1_S.xlsx
3	TunnelNAME_1_RN	TunnelNAME_1_RN.xlsx
4	TunnelNAME_1_RS	TunnelNAME_1_RS.xlsx
5		
6		
7		
8		

Figure 8.10 Identification of components

Each of the identified components (here 4) must be given an unambiguous and easy name: here TunnelNAME_1_N.xlsx etc. for indication of version and direction of the main tunnel. The ramps are identified with an R in the name. For each component a TRANSIT calculation will have to be carried out and in the cell “File name” a hyper link to the excel work book is inserted.

If more than 8 components have been identified, additional lines will have to be inserted.

The hyperlinks can be managed by the “Data / Edit Links” function, as shown in Figure 8.11.

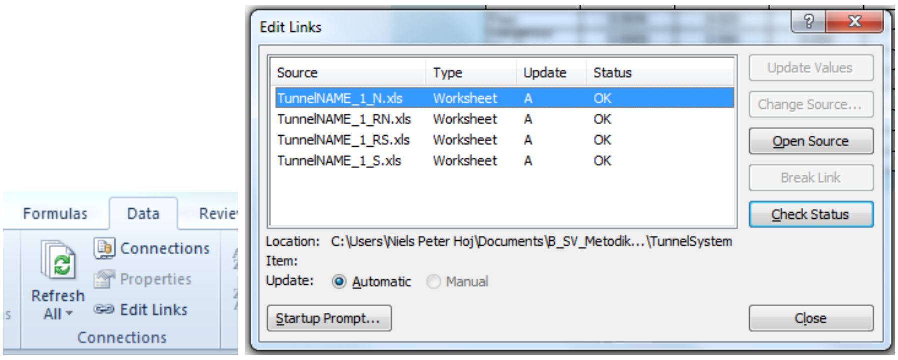


Figure 8.11 Management of hyper links

8.3.2.3 Transfer of results

For each of the components the results of the TRANSIT calculations are transferred with hyperlinks. A number of lines corresponding to the number of components is used.

Traffic

	Tunnel Component	Traffic Mio veh-km/a
1	TunnelNAME_1_N	0.97601
2	TunnelNAME_1_S	0.97601
3	TunnelNAME_1_RN	0.6768195
4	TunnelNAME_1_RS	0.6768195
5	0	0
6	0	0
7	0	0
8	0	0

Figure 8.12 Transfer of traffic (volume per year) for each component.

The values of traffic in million vehicle-km per year for each tunnel system component are transferred from the exported TRANSIT excel sheet with reference to the sheets “Traffic”. A hyper link is inserted in the cells for each component with a format “=SUM('[TunnelNAME_1_N.xls]Traffic!$C$3:$C$999)” respectively “=SUM('[TunnelNAME_1 _N.xls]Traffic!$C$3:$C$999)”.

Accidents, Fires and DG events

Accidents #/a	Fires #/a	DG events #/a
0.1297	0.0616	0
0.1297	0.0409	0
0.0969	0.0409	0
0.0969	0.0409	0

Figure 8.13 Transfer of number of accidents, fire and DG events per year for each component.

The number of accidents and fires are transferred from the exported TRANSIT excel sheet with reference to the sheets “Num Accidents” and “Num Fires”. A hyper link is inserted in the cells for each component with a format “=SUM('[TunnelNAME_1_N.xls]Num Accidents '!$C$3:$C$999)” respectively “=SUM('[TunnelNAME_1_N.xls]Num Fires'!$C$3:$C$999)”.

Results of DG calculations are transferred in a similar way. In addition it is possible to link with results available from other sources, for example from the QRA model of OECD/PIARC.

Fatalities

Fat(acc) #/a	Fat(fire) #/a	Fat(DG) #/a	Fat(all) #/a
0.00852	0.000436	0	0.0089610
0.00852	0.000312	0	0.0088372
0.00621	0.000312	0	0.0065189
0.00621	0.000312	0	0.0065189

Figure 8.14 Transfer of number of fatalities per year for each component.

The number of fatalities are transferred from the exported TRANSIT excel sheet with reference to the sheets "Num fatalities" and "Num Fat Fire". A hyper link is inserted in the cells for each component with a format "=SUM('[TunnelNAME_1_N.xls]Num Fatalities'!$C$3:$C$999)" respectively =SUM('[TunnelNAME_1_N.xls]Num Fat Fire'!$C$3:$C$999)".

At present the DG calculations have not been fully integrated in TRANSIT, so the results will have to be inserted manually in the cells

In the right column the fatalities are calculated as a sum of the three types of events.

Injuries

Inj(acc) #/a	Inj(fire) #/a	Inj(DG) #/a	inj(all) #/a
0.1952	0.006349	0	0.20150
0.1952	0.004360	0	0.19951
0.1952	0.004360	0	0.19951
0.1952	0.004360	0	0.19951

Figure 8.15 Transfer of number of injuries per year for each component.

The number of injuries are transferred from the exported TRANSIT excel sheet with reference to the sheets "Num Accidents" and "Num Fires". A hyper link is inserted in the cells for each component with a format "=SUM('[TunnelNAME_1_S.xls]Num Casualties'!$C$3:$C$999)" respectively "=SUM('[TunnelNAME_1_S.xls]Num Cas Fire'!$C$3 :$C$999))".

At present the DG calculations have not been fully integrated in TRANSIT, so the results will have to be inserted manually in the cells

In the right column the injuries are calculated as a sum of the three types of events.

Monetary Loss

The tunnel system compilation sheet is prepared also for monetary loss. This part is presently not determined by TRANSIT, but the results of separate calculations can be inserted for each tunnel component.

Compilation

The annual risk results and the traffic for the defined components are calculated as the sum in the row "Total".

	Tunnel Component	Traffic Mio veh-km/a	Accidents #/a	Fires #/a	DG events #/a	Fat(acc) #/a	Fat(fire) #/a	Fat(DG) #/a	Fat(all) #/a	Inj(acc) #/a	Inj(fire) #/a	Inj(DG) #/a	inj(all) #/a
1	TunnelNAME_1_N	0.97601	0.1297	0.0616	0	0.00852	0.000436	0	0.0089610	0.1952	0.006349	0	0.20150
2	TunnelNAME_1_S	0.97601	0.1297	0.0409	0	0.00852	0.000312	0	0.0088372	0.1952	0.004360	0	0.19951
3	TunnelNAME_1_RN	0.6768195	0.0969	0.0409	0	0.00621	0.000312	0	0.0065189	0.1952	0.004360	0	0.19951
4	TunnelNAME_1_RS	0.6768195	0.0969	0.0409	0	0.00621	0.000312	0	0.0065189	0.1952	0.004360	0	0.19951
5	0	0							0.0000000				0.00000
6	0	0							0.0000000				0.00000
7	0	0							0.0000000				0.00000
8	0	0							0.0000000				0.00000
	Total	3.305659	0.4531	0.1844	0	0.02946	0.001373	0	0.0308361	0.780604655	0.019429	0	0.80003

Figure 8.16 Compilation of annual risk and traffic.

The rates of accidents, fires and fatalities for the entire system can be calculated by dividing the annual risks with the annual traffic.

Compilated of Rates for the tunnel system
Tunnel System NAME

Accident Rate	0.1371 acc/Mio veh-km		
Fatality Rate	0.00933 fat/Mio veh-km	=	9.33 Fat/Billion veh-km
Fire rate	0.05577 fires/Mio veh-km		

Figure 8.17 Rates of accidents, fatalities and fires for the tunnel system

8.3.3 Summary

In addition to the above numbers, the sheet establishes a table with the key results of the analysis of the system in a format which can be used directly in the relevant reporting of the risk analysis. The table is automatically established based on the data available on the sheet.

Tunnel System NAME

	Number killed / year	Number injured /year	Number events /year	Monetary loss (Mill. NOK)
Accidents	0.0304	0.829	0.484	
Fires	0.0014	0.020	0.192	
Dangerous Goods	0.0000	0.000	0.000	
Total	0.0318	0.849	0.675	

Traffic	3.31	Mill. veh-km/yr
Accident rate	0.146	Per Mill. veh-km
Fire rate	0.058	Per Mill. veh-km
Fatality rate	9.63	Per Bill. veh-km

Figure 8.18 Summary of the risk analyses provided by the Tunnel System Sheet.

9 Annex 3: Seasonal variations

9.1 Introduction

As an additional application of the tunnel system approach (see Annex 2) it is illustrated how seasonal variation in the traffic can be taken into account in the systems approach

The seasonal variation of traffic in summer and winter may in some cases be very significant. This may in some cases be 2-10 higher in the high season than in the low season. Also the daily variation of the traffic may be different in these seasons.

In these cases an annual average may not be suitable for estimating the risk, and the following sections describe how the situation can be handled.

A similar approach can be used for weekly variations and other variations longer than one day.

9.2 System

As described in the chapter on the tunnel system the tunnel can be divided into mutually exclusive components. This can be done for the physical system as well as for a division in periods.

Hence, the tunnel system can be divided into a “high season” and the rest of the year, or multiple seasons, which add up to the entire year.

Say, the tunnel system has four physical components and two seasons will have to be considered: a high season and the rest of the year.

For each season and each physical component a TRANSIT calculation is carried out, i.e. 8 TRANSIT runs in the given example. TRANSIT generally calculated annual risks, so the compilation of the four component-calculations (

Figure 8.19 and Figure 8.20) returns the annual risk as if the traffic was valid for the entire year.

	Tunnel Component	Traffic Mio veh-km/a	Accidents #/a	Fires #/a	DG events #/a	Fat(acc) #/a	Fat(fire) #/a	Fat(DG) #/a	Fat(all) #/a	Inj(acc) #/a	Inj(fire) #/a	Inj(DG) #/a	inj(all) #/a
1	TunnelNAME_1_N	0.97601	0.1297	0.0616	0	0.00852	0.000436	0	0.0089610	0.1952	0.006349	0	0.20150
2	TunnelNAME_1_S	0.97601	0.1297	0.0409	0	0.00852	0.000312	0	0.0088372	0.1952	0.004360	0	0.19951
3	TunnelNAME_1_RN	0.6768195	0.0969	0.0409	0	0.00621	0.000312	0	0.0065189	0.1952	0.004360	0	0.19951
4	TunnelNAME_1_RS	0.6768195	0.0969	0.0409	0	0.00621	0.000312	0	0.0065189	0.1952	0.004360	0	0.19951
5	0	0							0.0000000				0.00000
6	0	0							0.0000000				0.00000
7	0	0							0.0000000				0.00000
8	0	0							0.0000000				0.00000
	Total	3.305659	0.4531	0.1844	0	0.02946	0.001373	0	0.0308361	0.780604655	0.019429	0	0.80003

Figure 8.19 Compilation of annual risk and traffic (Conditions as Season 1)

	Tunnel Component	Traffic Mio veh-km/a	Accidents #/a	Fires #/a	DG events #/a	Fat(acc) #/a	Fat(fire) #/a	Fat(DG) #/a	Fat(all) #/a	Inj(acc) #/a	Inj(fire) #/a	Inj(DG) #/a	inj(all) #/a
1	TunnelNAME_1_N	1.95202	0.2899	0.1278	0	0.01800	0.000894	0	0.0188900	0.4145	0.013236	0	0.42776
2	TunnelNAME_1_S	1.95202	0.2899	0.0852	0	0.01800	0.000643	0	0.0186391	0.4145	0.009151	0	0.42367
3	TunnelNAME_1_RN	1.353639	0.0969	0.0426	0	0.00621	0.000322	0	0.0065281	0.2073	0.004575	0	0.21184
4	TunnelNAME_1_RS	1.353639	0.0969	0.0426	0	0.00621	0.000322	0	0.0065281	0.2073	0.004575	0	0.21184
5	0	0							0.0000000				0.00000
6	0	0							0.0000000				0.00000
7	0	0							0.0000000				0.00000
8	0	0							0.0000000				0.00000
	Total	6.611318	0.7735	0.2983	0	0.04840	0.002181	0	0.0505854	1.243558665	0.031537	0	1.27510

Figure 8.20 Compilation of annual risk and traffic (Conditions as Season 2)

In order to have the annual risk with the seasonal variation, the results of the two compilations of the physical components will have to be added with a weight factor. If, for example, the Season 1 corresponds to 3 months, the compiled results for Season 1 are multiplied with 3/12 and added to the 9/12 multiplied with the compiled results of Season 2. This is illustrated in Figure 8.21.

Season	Weight		Traffic	Accidents	Fires	DG events	Fat(acc)	Fat(fire)	Fat(DG)	Fat(all)	Inj(acc)	Inj(fire)	Inj(DG)	inj(all)
			Mio veh-km/	#/a	#/a	#/a	#/a	#/a	#/a	#/a	#/a	#/a	#/a	#/a
1	0.25	Total	6.6113	0.7735	0.2983	0	0.0484	0.0022	0	0.05059	1.24356	0.03154	0	1.2751
2	0.75	Total	3.3057	0.3867	0.1491	0	0.0242	0.0011	0	0.02529	0.62178	0.01577	0	0.6375
Year weighted			4.1321	0.4834	0.1864	0.0000	0.0303	0.0014	0.0000	0.0316	0.7772	0.0197	0.0000	0.7969

Figure 8.21 Weighting of two seasons.

For three and more season the same procedure can be applied.

Variation of traffic conditions etc. on weekdays

For a distinction of weekdays the same procedures can be applied as well. The calculation can be split up into workdays and weekend days or every single days can be distinguished. The daily distributions differ normally in weekends from work days. This can be defined in the normal TRANSIT input set.

Variations within one day cannot be considered in this way. Instead the indicator “Type A – F” of time variation curve of the traffic volume should be used.

Comments

It is the experience that the conditions will have to differ significantly in the different “seasons”, before the traffic conditions have an influence on the annual weighted average. The reason for this is quasi-linearly dependent on the traffic volume and the risk.

By performing separate risk calculations it is also possible to take out the rates from the high season and the low season separately and compare them.

10 Annex 5: Actual speed

10.1 Introduction

The speed has proven to be a significant influencing factor for the risk in road tunnels as well as on roads in general. In TRANSIT the relation between accident-, injury and fatality risk and speed has be incorporated by means of the formulas suggested by Nilsson (in accordance with the relationship suggested by Elvik).

The influencing factor is in fact the actual speed of the vehicles, whereas the possible actions for a tunnel are speed influencing measures. An important speed influencing factor is of course the speed limit for the given tunnel. This speed limit may be shown on speed limit signs in the tunnel or corresponding to the same speed limit outside the tunnel. Other influencing factors are speed control and – enforcement measures and the general design, lay-out and equipment of the tunnel. It is assumed that these measures have a causable effect on the actual speed.

In some cases for existing tunnels, the actual speed (average and distribution) can be observed. In these cases it may be possible to use the observed speed directly. However, it should be noted that a change in the influencing measures also in this case may influence the speed. This may be the case in tunnels with substandard lighting, where the speed may be lower than for comparable tunnels. If the lighting (or other measures) is improved, the speed may increase.

10.2 Speed

10.2.1 Speed limit

The design speed and the speed limits for a tunnel under design is normally one of the most important speed influencing factors in the design phase.

In TRANSIT the risk is modified in relation to the reference data. The reference accident-, injury- and fatality rate is assumed to relate to a reference speed limit of 80 km/h. This assumption is based on studies of the data in the database STRAKS. The speed limits are generally assumed to 80 km/h for tunnels with bi-directional traffic. For motorway tunnels the speed limit may be 100 km/h and for tunnels with low standard or with particular conditions the speed limit may be 60 km/h. In some extraordinary cases the speed limit may be down to 40 km/h.

Based on the data for tunnels from Salvisberg et al. (2004) it was found that the average speed limit in tunnels in Switzerland is 90 km/h. This average is based on the number of investigated tunnels, but not taking the traffic and the length into consideration. It is believed that the weighted average would be lower. The accident frequencies are primarily based on the on the Norwegian data (see **Table 1.2**); hence the data will be modified also based on the reference speed based on Norwegian conditions.

10.2.2 Actual speed

The speed limit may not be coinciding with the average speed. Erath and Fröhlich (2004) investigated the driving speed on national roads (open roads and tunnels) in Switzerland between 1990 and 2002. They observed that the coefficient of variation is 0.11.

Due to the non-linear influence of speed on the risk, the influence of vehicles driving faster than the average contribute more to the risk than the corresponding reduction of the risk by vehicles driving slower than the average. I.e. at a larger variance of the speed the risk will increase even though the average speed is the same. On the other hand the risk can be reduced by merely ensuring a more narrow range of speeds.

If the speed limit in a specific tunnel is set very low, and the various problematic conditions in the structure, the equipment and the traffic hereby are compensated, then this tunnel is vulnerable towards drivers not keeping the low speed limit.

It should be noted that some tunnel designs and traffic compositions will influence the speed distribution: for example HGVs will be slowed down significantly on large (downwards and upwards) slopes, whereas light vehicles will tend to go faster on the downwards slope.

Erath and Fröhlich (2004) also observed that the ratio between the mean value of the driving speed and the speed limit is 0.96. This relationship is valid in the range from 60 km/h up to 120 km/h which can be seen from the data used in Lindenmann and Zuberbühler (1993). For lower speed limits the ratio between mean speed and driving speed as well as the variation may be larger. Also for large speed limits (i.e. over the general speed limits for lorries) the variation may be larger.

Based on these observations the general relation between actual speed and speed limit is based on rounded figures as follows. The reference distribution assumes no particular speed control measures.

Table 8.1 Assumed reference distribution of speed

	Percentile of speed higher than v				
	98%	85%	50%	15%	2%
Speed limit (km/h)	**Speed, v**				
40	27	33	38	44	50
50	34	41	48	55	62
60	40	49	58	66	75
70	47	57	67	77	87
80	54	65	77	88	100
90	60	73	86	99	112
100	67	82	96	110	125
110	74	90	106	121	137
120	81	98	115	132	150

10.2.3 Risk at speed distribution

In the following the accident-, injury- and fatality rate are estimated for the assumed reference speed distributions. The relative factor is given to a situation where all vehicles drive 80 km/h.

Table 8.2 Influence of speed limit on fatality and accident risk relative to the situation where all vehicles drive uniformly 80 km/h.

	Fatalities	**Accidents**
Speed limit (km/h)	**Speed distribution**	**Speed distribution**
40	6%	24%
50	14%	37%
60	29%	53%
70	56%	72%
80	101%	94%
90	175%	120%
100	296%	148%
110	516%	184%
120	970%	243%

It appears from Table 8.2 that the fatality risk is slightly increased and the accident risk is slightly reduced at 80 km/h and distribution of speed, compared with the situation of uniform 80 km/h speed. In order to compare with the reference situation (speed limit 80 km/h) the influencing factors will have to be normalised with rates at 80 km/h with distributed speeds. This is illustrated in Table 8.3. In Table 8.3 the relative factor for uniform is also shown. This uses the speed limits directly corresponding to a uniform speed characterised by the speed limit. The comparison of the figures demonstrates a modest difference.

Table 8.3 Influence of speed limit on fatality and accident risk relative to the situation at speed limit 80 km/h (speed distribution and uniform speed).

	Fatalities		**Accidents**	
Speed limit (km/h)	**Speed distribution**	**Uniform speed**	**Speed distribution**	**Uniform speed**
40	6%	6%	26%	25%
50	14%	14%	39%	39%
60	29%	29%	56%	56%
70	56%	56%	77%	71%
80	100%	100%	100%	100%
90	173%	171%	128%	127%
100	293%	283%	157%	156%
110	511%	459%	196%	189%
120	960%	733%	259%	225%

10.3 Influence of measures on actual speed

There are various conditions which influence the actual speed. As mentioned in the previous section, the speed limits signed in the tunnel or outside the tunnel is the main influencing factor. However other factors may influence the actual speed as well. In the following some aspects are discussed:

Curves / alignment:	A tunnel with a straight alignment may give rise to increased speed and a curved tunnel may reduce the speed.
Tunnel width:	Tunnel which are very narrow may give an unsafe impression, which lead to a lower speed. This may particularly be the case for tunnels where the distance to the tunnel walls or to the approaching traffic is very low – for example for substandard tunnels.
Slopes:	Downslopes are known to result in higher speeds whereas slopes upwards give a larger variance in the speed. This aspect is partly taken into account in the modelling of the slope but an additional factor may be applicable for very slow vehicles in the tunnel. In some cases heavy vehicles also drive slow at steep downwards slopes.
Distracting objects	Distracting objects in the tunnel may reduce the speed but at the same time increase the risk.
Roundabouts or X or T crossing	Roundabouts or X or T crossing will reduce the speed. However, if just a small minority of the tunnel users do not realise the crossing and hereby not reduce the speed accordingly – it may result in an increase of the risk.
Road surface	A poor road surface will tend to reduce the speed, whereas a new smooth road surface with proper lines and good optical guidance may tend to increase the speed. In any case it is not recommendable to build tunnels with poor road surfaces.
Lighting:	Poor lighting may reduce the speed whereas very bright lighting in the tunnel may increase the speed. It is assumed in the model of tunnel lighting that a tunnel without lighting will result in an approximately 10 km/h reduced speed, whereas the speed increase goes towards 10 km/h for very bright (over-standard) lighting. The speed influencing factors of the various measures cannot be additively or multiplicatively combined. It is in the present context assumed that a tunnel which is subjective felt as unsafe will make the user reduce the speed by approximately 10 – 15 km/h, whereas an extremely over-standard tunnel may result in a speed increase of 10 – 15 km/h.
Control measures	At information measures like "Your speed XX km/h" signs, the speed may be reduced – it is assumed that the speed hereby is reduced to the normal mean value and variance for the given speed limit
Police control radars (Auto-matic Traffic Controls)	For police control radars (Automatic Traffic Controls) the speed is assumed to be reduced to less than the normal mean value and variance for the given speed limit. An average speed of 0.90 of the speed limit and a coefficient of variation of 10% is assumed. This corresponds to a reduction of the speed of approximately 4 km/h at a speed limit of 80 km/h, 5 km/h at a speed limit of 100 km/h and 3 km/h at a speed limit of 60 km/h. The factors for speed difference "No slow vehicles" can be used to model this effect. Control measures are assumed to govern over the speed increasing measures mentioned above, but are assumed not to have any effect if the speed is observed to be lower than normally expected for the given speed limit.

10.4 Observed speed distribution

10.4.1 Introduction

In some cases, the actual speed (average and distribution) can be observed. In these cases it may be possible to use the observed speed directly.

If for example in a tunnel with a speed limit of 80 km/h it is observed that the mean speed is 67 km/h and the coefficient of variation is 20%, then these data may be used for estimating the risk in the tunnel.

The average speed in this example corresponds to the average speed for a speed limit of 70 km/h, but the coefficient of variation is larger than normal.

In this case, due to the larger variation, the fatality risk is 62% of the reference risk at 80 km/h instead of 55% which would be the modification at 70 km/h in distributions of the speed, which is expected normally (COV = 15%). It can be calculated that the observed speed distribution would correspond to a (hypothetical) speed limit of 82 km/h.

10.4.2 Estimated risk at observed speed distributions

Table 8.4 and

Table 8.5 illustrate the modifications of the fatality risk and accident risk as function of the average speed and the coefficient of variation.

Table 8.4 Modifications of the fatality risk in function of the average speed and the coefficient of variation.

Average Speed (km/h)[6]	Coefficient of variation of the speed distribution				
	5%	**10%**	**15%**	**20%**	**25%**
	Modification factor				
38.0	4%	5%	6%	6%	7%
47.5	11%	13%	14%	15%	17%
57.0	25%	27%	29%	32%	37%
66.5	48%	50%	55%	62%	71%
76.0	84%	90%	100%	114%	135%
85.5	144%	154%	173%	203%	256%
95.0	237%	256%	293%	369%	517%
104.5	381%	419%	511%	717%	1054%
114.0	606%	695%	960%	1414%	2017%

Table 8.5 Modifications of the accident risk in function of the average speed and the coefficient of variation.

Average Speed (km/h)[1]	Coefficient of variation of the speed distribution				
	5%	**10%**	15%	20%	25%
	Modification factor				
38.0	23%	24%	26%	26%	27%
47.5	37%	38%	39%	40%	40%
57.0	54%	55%	56%	57%	59%
66.5	74%	76%	77%	79%	80%
76.0	98%	99%	100%	102%	104%
85.5	124%	126%	127%	130%	135%
95.0	153%	155%	157%	164%	179%
104.5	186%	187%	196%	217%	251%
114.0	221%	228%	259%	306%	362%

The modification factors for the distribution of the speed can be formulated in terms of the corresponding speed limit. These speed limits are hypothetical only; the speed limits are presented in steps of 1 km/h.

[6] Reference speed limit 80 km/h = average speed 76 km/h)

Table 8.6 Conversion of the observed mean speed and variation into hypothetical speed limits. Speeds based on fatality rates and in parenthesis speeds based on accident rates, when deviating.

Average Speed (km/h)	Coefficient of variation of the speed distribution				
	5%	10%	15%	20%	25%
	Hypothetical speed limit				
38.0	38	39	40	41	42
47.5	48	49	50	51	52 (51)
57.0	58 (59)	59	60	61	63 (62)
66.5	67 (69)	68 (70)	70	72 (71)	74 (72)
76.0	77 (79)	78 (80)	80	82 (81)	85 (82)
85.5	87 (89)	88 (90)	90	93 (91)	98 (93)
95.0	96 (99)	98 (100)	100	105 (102)	112 (107)
104.5	106 (110)	108 (110)	112	120 (118)	128 (127)
114.0	116(119)	119 (120)	126	135 (140)	142

It can be observed that most observations can be reasonably associated with the average speed. Only for combinations of high average speed and high coefficients of variations the speed cannot be modelled by the average speed. In these cases the speed can be modelled by a higher speed level. For example: by an observed average speed of 104 km/h and a coefficient of variation of 20% the speed limit is formally inserted as 120 km/h.

10.5 Practical guidance

The speed limits can only be specified in steps of 10 km/h in TRANSIT. The following guide is proposed to be used for specifying the speed limits based on observed speed distribution. In addition to this modelling it should be noted that high coefficients of variation of the speeds may give an up to 30% increase of the risk. High coefficient of variations of the speed (particularly in connection with high speed limits) is a particular point of concern which should be dealt with and suitable measures taken.

Table 8.7 Proposed speed limits for use in TRANSIT at observed speed distributions.

Average Speed (km/h)	Coefficient of variation of the speed distribution				
	5%	10%	15%	20%	25%
	Speed limit to be inserted in TRANSIT				
38.0	40	40	40	40	40
47.5	50	50	50	50	50
57.0	60	60	60	60	60
66.5	70	70	70	70	70
76.0	80	80	80	80	80
85.5	90	90	90	90	100
95.0	100	100	100	100	110
104.5	110	110	110	120	130
114.0	120	120	120	130	140

The difference in speed (for example very slow HGV traffic in a tunnel with otherwise high speed) may result in increased risk of front-end collisions and increase the risk of legal or illegal overtaking manoeuvres. This risk is not taken into account in the factors above.

The increased risk may partly be included in the risk modification factor for steep gradients. A risk increasing factor for this aspect is proposed in function of speed difference, share of slow vehicles and bi-directional / unidirectional traffic. This factor can be used both for existing tunnels with observed speed distribution and for projects where this effect is expected. The factor is estimated in the order of magnitude 1.2 to 1.5.

This factor can also be used to model a large variation of the speed distribution within the speed limits proposed in Table 8.7.

Table 8.8 Modification factor for speed difference – slow vehicles.

Conditions	Modification factor	
	Uni-directional	Bi-directional
No slow vehicles	0.95	0.95
Normal conditions	1.00	1.00
Moderate occurrence of slow vehicles	1.10	1.15
Frequent occurrence of slow vehicles	1.20	1.30
Frequent occurrence of slow vehicles and large speed difference	1.40	1.50

10.6 Discussion

If the observed speed deviates from the expectation with the given speed limit, then the annual risk will be characterised by the observed speed.

Low observed speed

Say, the speed limit is 80 km/h and the observed speed is in average 66.5 km/h with a coefficient of variation of 15%, then the risk corresponds to a speed limit of 70 km/h and the annual risk is reduced with a factor 0.55 compared to the reference situation with a speed limit of 80 km/h. Hence, the fatality rate (fatalities per billion vehicle-km) will be determined based on these figures. This fatality rate will be used for the evaluation of the acceptability.

However, the individual user driving exactly 80 km/h according to the signed speed limit will experience a risk which is nearly the double of the risk used for the risk assessment. – This may not be a reasonable situation.

If the observed average speed is significantly lower than it would be expected for the given speed limit, it is an indicator of problems with the tunnel, which will have to be addressed.

It may for this reason be considered either: to establish speed limit signs in accordance with the actual speed, or to use the signed speed as reference for the risk evaluation.

Upgrade / change of other conditions

If the observed speed has been taken as basis for the risk estimate, it should be noted that a change in the influencing measures in this case may influence the speed. This may be the case in tunnels with substandard lighting, where the speed may be lower than for comparable tunnels. If the lighting (or other measures) is improved, the speed may increase.

This combination is not unusual, because the reason for the low observed speed may be a low standard of the tunnel. If the standard is improved, the effect may be partly lost in the higher speed level, or measures should be taken to remain the speed at the original low level (for example by introducing speed limit in accordance with the actual speed before upgrade).

In addition it should be noted that even though the risk reducing effect of an upgrade may be partly lost by an increased speed, this does not imply that the upgrade is useless. The benefits of higher speed and comfort in the tunnel are a value of itself.

High observed speed

If on the other hand the average speed is significantly higher than the speed expected for the given speed limit, then the observed speed shall be used for the risk estimate.

If the risk of the tunnel system is found to be acceptable based on the observed speed, it may be considered to adjust the speed limit (and control that the speed is not further increased).

If the risk of the tunnel system is found to be unacceptable, measures should be taken to control the speed: this could be warning signs, information signs, or police controls.

11 References

11.1 Overview over recent EU financed Tunnel safety projects

ERS2: OECD/ PIARC Transport of dangerous goods through tunnels

DARTS: Durable And Reliable Tunnel Structures

Virtual Fires: Virtual Real Time Emergency Simulator

Safetunnel: Innovative systems and frameworks for enhancing of traffic safety in road tunnels

Sirtaki: Safety Improvement in Road & rail Tunnels using Advanced ICT and Knowledge Intensive DSS

FIT: European thematic network on fire in tunnels

Safe-T: Thematic Network on development of European guidelines for upgrading tunnel safety

Uptun: cost-effective, sustainable and innovative upgrading methods for fire safety in existing tunnels

STOA: Assessment of the Safety of Tunnels

11.2 Standards and guidelines

Statens vegvesen HB 021 Håndbok 021 Normal Vegtunneler, Statens Vegvesen desember 2006. Revision af HB021, mars 2010.

Statens vegvesen HB 017 Håndbok 017 Normaler Veg- og gateutformning, Statens vegvesen, mai 2008.

NS 5814 Norsk Standard. Krav till risikoanalyser

Statens vegvesen HB271 Håndbok 271 Risikovurderinger i vegtrafikken, februar. 2007

Statens vegvesen HB 140 Håndbok 140. Konsekvensanalyser, Statens Vegvesen juni 2006

Statens vegvesen Håndbok: HB269 Håndbok 269 Sikkerhetsforvaltning av vegtunneler

Veileder for Risikoanalyser av Vegtunneler Rapport, nr. TS 2007:11. Vegdirektoratet, Veg- og trafikkavdelingen, Trafikksikkerhetsseksjonen, Revisjons dato: 2007-10-31
Forskrift av 1. Desember 2006 nr 1331 om transport av farlig gods på veg og jernbane med veiledning

Tunnelsikkerhedsforskriften, 15. Maj 2007
Norsk Standard NS 3901 Risikoanalyse av brann i byggverk, 1. Udg. Mai 1998 samt Risikoanalyse av brann i vegtunneler, Veiledning til NS 3901, NBR Norges byggstandardiseringsråd, januar 2000.

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Directive 2004/54/EC of the European Parliament and of the Council on “Minimum Safety Requirements for Tunnels in the Trans-European Road Network”, Brussels 29 April 2004.

ADR 2009 European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR), http://www.unece.org/trans/danger/publi/adr/adr2009/09ContentsE.html

ASTRA 13 001: Bundesamt für Strassen, Swiss Design Code - Richtlinie Lüftung der Strassentunnel, June 2008 V2.00 (Swiss design guide for tunnel ventilation) Systemwahl, Dimensionierung und Ausstattung.

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