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Risk Assessment of Road Tunnels using Bayesian Networks

Matthias Schubert[a*], Niels Peter Høj[b], Arild Ragnøy[c], Harald Buvik[c]

[a]*Matrisk GmbH, P.O. Box 469, CH-8049 Zürich, Switzerland*
[b]*HOJ Consulting GmbH, Ballyweg 33, CH-6440 Brunnen, Switzerland*
[c]*Norwegian Public Roads Administration, PO Box 8142 dep, NO-0033 Oslo, Norway*

Abstract

This paper introduces a methodology for the assessment of risks due to traffic in roadway tunnels. The proposed methodology utilizes Bayesian Probabilistic Networks for the risk assessment. The methodology is based on two hypotheses, i.e. that the roadway tunnel can be represented by a number of homogeneous segments and that the risks associated with a given segment can be represented through a set of Key Performance Indicators (KPI).
The KPIs are the observable characteristics of the tunnel and the traffic such as the annual average daily traffic, the number of lanes, possible traffic separation, width, curvature and gradients. The risk is calculated in terms of expected number of accidents, injuries, fatalities and tunnel fires over the entire tunnel length for both, normal traffic events and dangerous goods events. The dependencies and the conditional probabilities in the Bayesian Probabilistic Networks are based on three general pillars, i.e. data, models published in literature and expert opinion.
This new approach allows taking into account different specific characteristics of the tunnel and thus the risk of a complex tunnel system can easily be calculated. The Bayesian Probabilistic Networks are embedded into a Microsoft Excel Environment, so that the risk analysis can easily be performed. The methodology is generic, represents the best practice in the field of risk assessment and tunnel research, is realizable and easy to use, is transparent, supports the decision making process, and is modular so that it can be adopted to future findings.

Keywords: Bayesian Probabilistic Networks; Tunnel Risk Assessment; Decision Making; Accident Modelling

1. Introduction

Tunnels constitute nowadays an important component of an efficient infrastructure. Whereas the purpose of tunnels is to facilitate reliable and efficient 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 existing tunnels. When striving for safety in road tunnels, there is a need for a rational and consistent basis

[*]*Corresponding author. Tel.: +41 (0) 44 340 04 27; fax: +49 3213 141 89 34*
E-mail address: schubert@matrisk.com

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for decision making concerning safety and methods 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 the Channel Tunnel (1996), Mont Blanc Tunnel (1996), Tauern Tunnel (1999), Gleinalm Tunnel (2001) and Gotthard Tunnel (2001) among others. 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.

In order to coordinate and harmonize the developments, the Directive 2004/54/EC 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. A software tool was developed which takes basis in the proposed methodology. This tool is called TRANSIT. The present paper describes the methodology and presents briefly the application of the methodology.

1.1. State of the art in the tunnel risk assessment

The findings in the above-mentioned European research 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). The results of the JCSS 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 latter 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 harmonizing 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.

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) and ASTRA ADR (Switzerland).

All these methodologies have their advantages in specific fields. A review and analysis of these methodologies has shown 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, Hoj and Horn (2010).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.

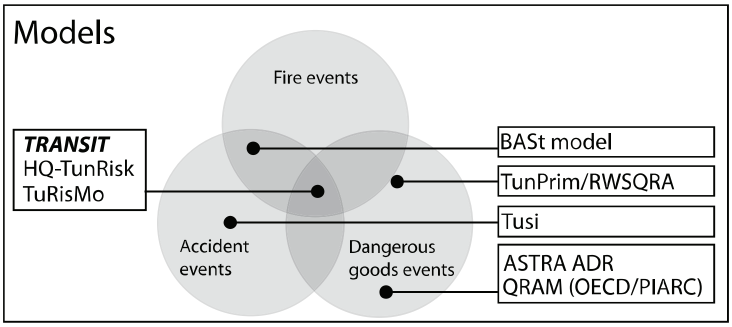


Fig. 1: Potential of different available models for the tunnel risk assessment.

The available models, however, are 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, Hoj and Horn (2010).

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 – and also to the model which is presented in this paper and will be described in the following sections.

2. Bayesian Inference Model

The general approach utilized in TRANSIT differs significantly from the approach used in the other models mentioned above. The major difference is that the system is modeled 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 event trees but also dependencies between different indicators and consequences can be considered. They are 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 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 and in natural hazards management (Schubert et al. 2009). They are used due to their flexibility and efficiency in regard to system representation.

2.1. Generic risk representation

The road tunnel users are exposed to various risks which have different causes. The largest contributor to the risk is collisions and other types of "normal traffic 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. Finally rare events with potential large consequences, such as events with dangerous goods transports, must be considered as well.

In general, risk to users in the tunnel has to be considered in both the planning phase and during the operational phase 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. 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.

A key feature of this methodology is that the uncertainties and the dependencies of the parameters, which are explicitly considered for the modeling of event frequencies and consequences, are quantified and accounted for. The system constituents are modeled using so called Key Performance Indicators (KPI) 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. These Key Performance Indicators can be used to establish a generic system representation for a risk model for a generic tunnel segment.

The risk model for the segment is generic, that means that one risk model for all possible characteristics in a tunnel is used. The model becomes specific by introducing evidence on specific parameters, such as annual average daily traffic (AADT), the fraction of heavy goods vehicle, etc., in the model and by performing inference calculations.

For a specific tunnel segment some or all of the considered KPI's are known and this knowledge can be transferred in the model by introducing evidence in the generic model. In this sense the model becomes specific for this specific segment (see Fig. 2). The same generic model can be used to calculate the risk under different conditions. The risk can be calculated for each single segment as well as for the entire tunnel. Segments with higher risk in the tunnel can be identified and specific risk reducing measures for these segments can be identified.

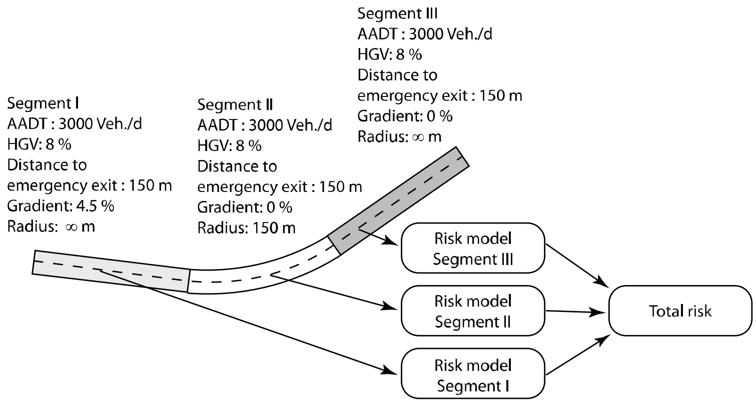


Fig. 2: Illustration of the generic system representation.

2.2. Bayesian Networks for accidents, fires and dangerous goods accidents

The risk model is established by employing Bayesian Probabilistic Networks. The BPN developed for accidents and fires in tunnel is shown in Fig. 3. It contains 39 nodes and 58 links. Each node represents an indicator whereas some of the indicators are observable (O), some indicators are logical observable (I) and some indicators are logical non observable (G). The nodes denoted with (R) are the outcome of the network. The links between the nodes represent the relation between the nodes. This relation can be a probabilistic or deterministic function or a function estimated by expert opinion. Each of the nodes contains a different number of so called *states*. These states represent the different possible characteristics of the node which can be observed in reality. The node *number of lanes* contain 3 states, i.e. one lane, two lanes and three lanes per direction.

One kernel node in the network shown in Fig. 3 is the node AMF. This node represents the accident modification factor (AMF). The hypothesis is made, that the average accident rate can be calculated over the entire tunnel network in one country. Under different circumstances this accident rate might be higher or smaller that the average rate. The AMF represents the difference of the accident rate in a specific segment from the mean value of all existing segments in the entire road network.

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. 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.

The Bayesian Network to model dangerous goods events in the tunnel is shown in Fig. 4. This network 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 "O" nodes, then the main node has the name *Dangerous Goods Incident*. This node contains all relevant and representative events and the rates per vehicle kilometer 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 and given the specific characteristics of the KPI's the expected number of fatalities and injuries can be calculated.

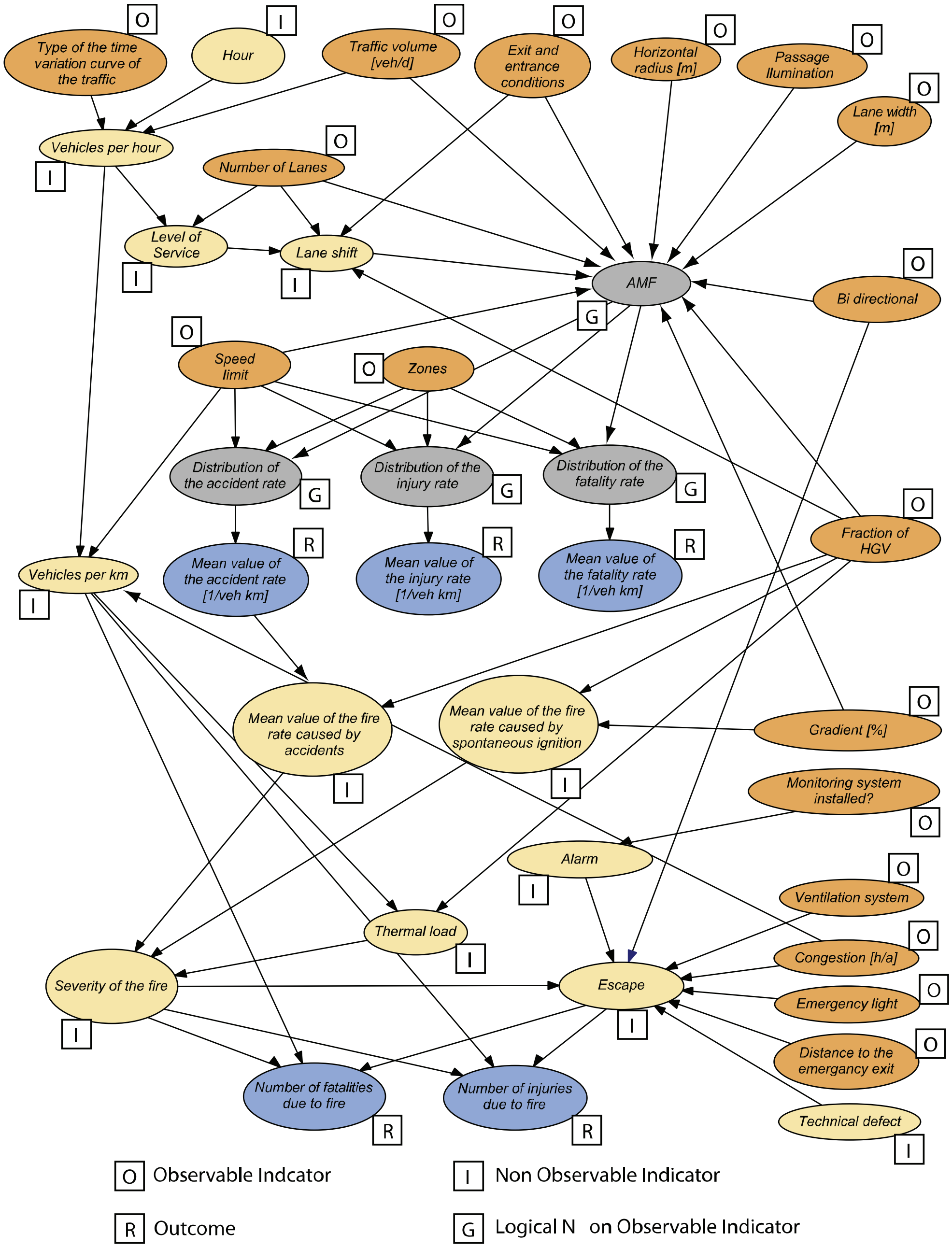


Fig. 3: Bayesian network for accidents and fire events due to general traffic conditions.

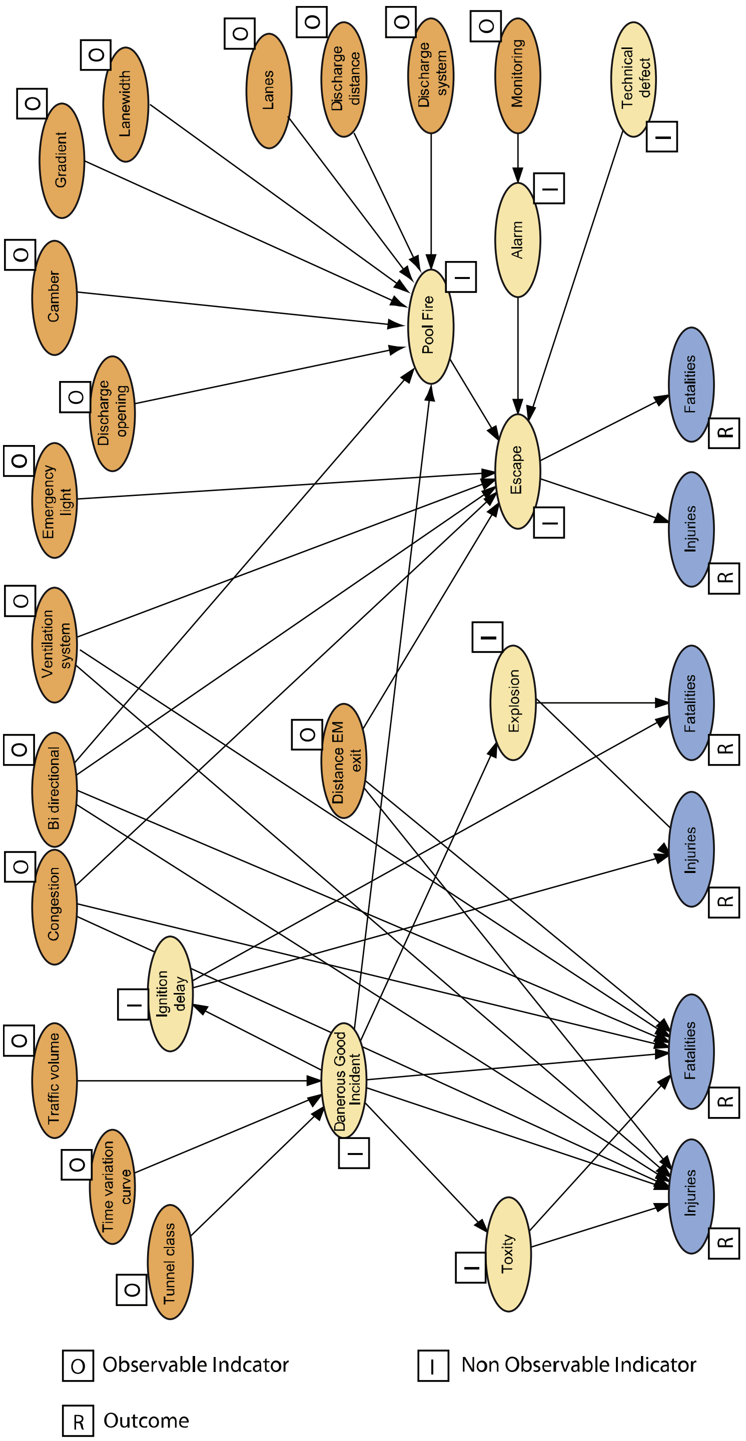


Fig. 4: Bayesian network for dangerous goods events.

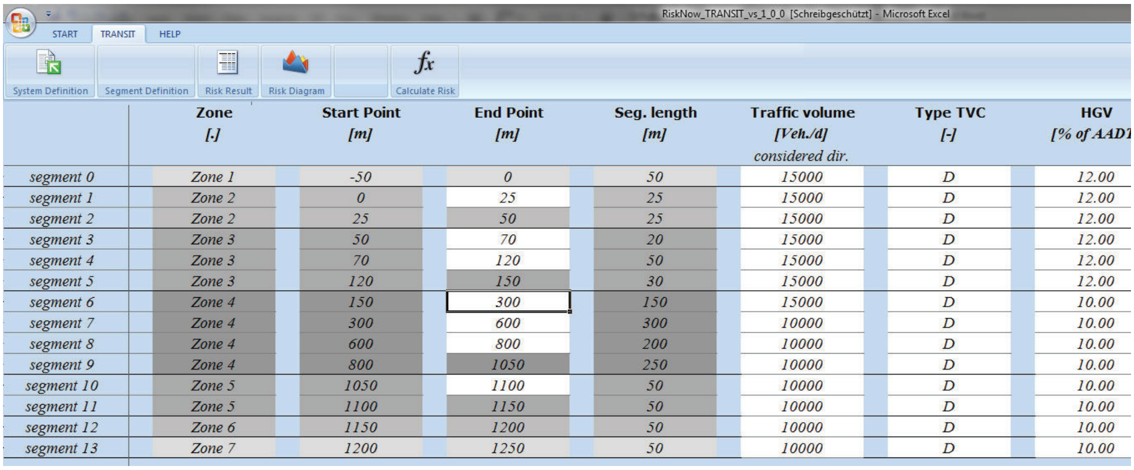
3. Software tool Transit

In the sections before, 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 Bayesian Networks are programmed in the software *GeNie/Smile* (see http://genie.sis.pitt.edu/).

The software tool for the user interface is developed in a Microsoft Excel 2007 environment and is programmed in Microsoft Visual Basic using the operating system (OS) Windows7. It can be used in Microsoft® Office Excel® 2007 and Microsoft® Office Excel® 2010.

The software is structured in a way which can be deemed as the current best practice in risk modelling (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 risk indicators for each segment of the tunnel.
- Establishment of the hazard model.
- Establishment of the consequence model.
- Risk assessment.
- Presentation of the results.



	Zone [-]	Start Point [m]	End Point [m]	Seg. length [m]	Traffic volume [Veh./d] considered dir.	Type TVC [-]	HGV [% of AADT
segment 0	Zone 1	-50	0	50	15000	D	12.00
segment 1	Zone 2	0	25	25	15000	D	12.00
segment 2	Zone 2	25	50	25	15000	D	12.00
segment 3	Zone 3	50	70	20	15000	D	12.00
segment 4	Zone 3	70	120	50	15000	D	12.00
segment 5	Zone 3	120	150	30	15000	D	12.00
segment 6	Zone 4	150	300	150	15000	D	10.00
segment 7	Zone 4	300	600	300	10000	D	10.00
segment 8	Zone 4	600	800	200	10000	D	10.00
segment 9	Zone 4	800	1050	250	10000	D	10.00
segment 10	Zone 5	1050	1100	50	10000	D	10.00
segment 11	Zone 5	1100	1150	50	10000	D	10.00
segment 12	Zone 6	1150	1200	50	10000	D	10.00
segment 13	Zone 7	1200	1250	50	10000	D	10.00

Fig. 5: Input sheet for the tunnel and traffic characteristics for each homogeneous section in the tunnel.

In the system definition merely project specific aspects can be defined, such as name of the tunnel, project name and year of construction. These aspects are relevant for documentation purposes. Also global characteristics are defined. These are the length of the tunnel, number of homogenous segments, ventilation system and if a monitoring system is present in the tunnel.

In the next spreadsheet the definition of the specific characteristics of each segment can be entered by the user (Fig. 5). If one or more information on indicators are missing, the user can also define that this information is not available. In this case the calculation is performed by employing the prior distribution for the specific KPI. A smaller part of the input spreadsheet is shown in Fig. 5. In total, 21 Key Perfomance Indicators are considered and information of these indicators should be collected for each tunnel analysis.

The information entered by the user is transferred to the Bayesian Network and the risk calculation in performed in the Bayesian Network. The result is afterwards transferred back to the Excel and displayed.

The software calculates the

- injury accident rate and the expected number of injury accidents, the
- injury rate and the expected number of injuries due to accidents, the
- fatality rate and the expected number of fatalities due to accidents,the
- fire rate and the expected number of tunnel fires as well as the expected number of injuries and fatalities due to fire,the
- expected number of fatalities due to dangerous goods events and the
- F-N Curve for the fatalities due to dangerous goods events in the tunnel.

All results are displayed graphically and shown numerically in a spreadsheet (see Fig. 6 for an example). It can be seen that the accident rate varies quite significant over the tunnel length in this example. This is due to the different characteristics in the tunnel. In the portal zones the accident rate is in general higher than in the mid zone of the tunnel. In this example an exit ramp is present in the tunnel and thus the traffic volume is reduced in the second part of the tunnel (see also Fig. 5). It can be seen that is represented by the methodology. Of course, different gradients, horizontal radius and light conditions over the tunnel length have also an influence on the accident rate and on the fatality rate (see Fig. 6). The representation of the result over the tunnel length can help to identify black spots in the tunnel and to implement risk reducing measures at specific locations, such as a decrease of the signalized velocity in parts of the tunnel.

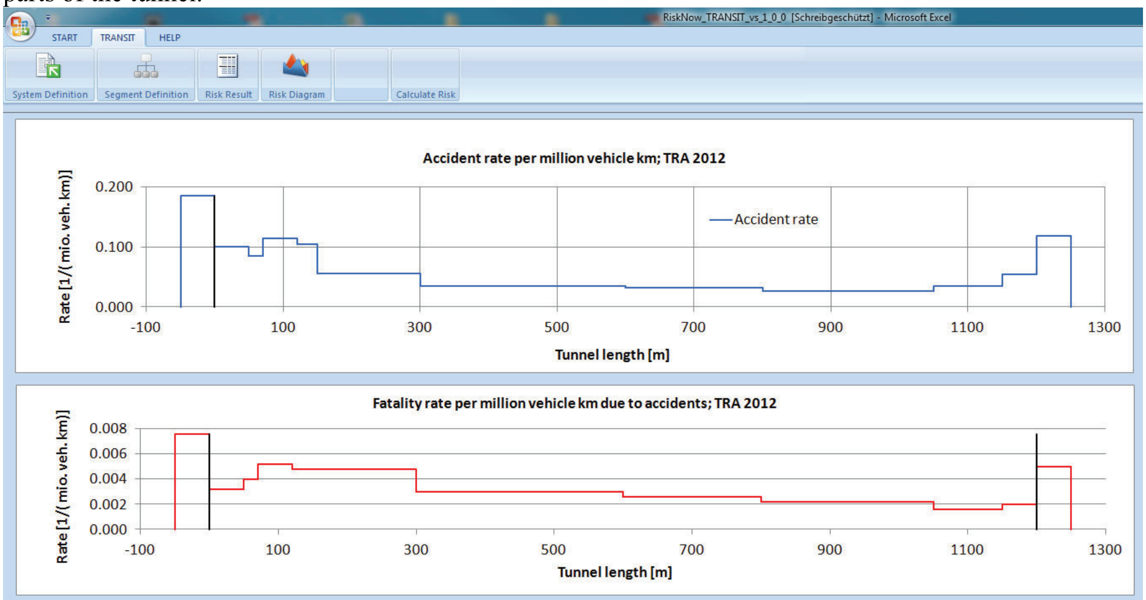


Fig. 6: Graphical representation of the results in the excel tool TRANSIT.

4. Conclusions

A sound methodology is developed and presented in this paper representing the best practice in the field of traffic safety assessment of road tunnels in accordance with the best practice in the field of risk assessment. The methodology facilitate the risk based decision making in regard to risk reducing measured during the planning and during the operation of the tunnel. The methodology gives comparable and reproducible results and that the results are independent on the person performing the analysis.

The general approach in this project differs significantly from other methodologies for the risk assessment in roadway tunnels. Bayesian Probabilistic Networks 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. 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.

TRANSIT has already reached a level of detail of the analyses and degree of maturity where it can model most of the aspects required for normal practice for risk analyses of tunnel risk.

The data used to calculate the basic risk are, however, in the majority Norwegian data supplemented with international data used to model Norwegian conditions. The general methodology itself is on the other hand not restricted to a specific country and can be adapted to all countries. 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.

Due to the modular characteristics of TRANSIT it is foreseen that the model will be refined and adapted in case that better models become available or the practice shown a need for adaption. This large flexibility is one of the major strength of TRANSIT.

Acknowledgement

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