ON RISK ANALYSIS OF COMPLEX ROAD-TUNNEL SYSTEMS

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ABSTRACT

Quantified Risk Analysis (QRA) has become a cornerstone in the design and in particular in case of retrofit of road tunnels. Classical methods use event trees fault trees and similar for QRA. However due to the manifold of parameters and their mutual influencing, adequate event trees can only be developed for relatively simple cases. In the EU-directive 2004/54/EC (European Parliament, 2004),[1] 16 safety relevant parameters are defined. Assuming that each of these has 4 states, the resulting number of dependencies is more than one billion, which cannot be catered for employing event trees. Consequently, the here presented novel method is based on Bayesian Probabilistic Networks, which also permits to cater of the inter-dependency of the parameters.

The method was developed as a Best Praxis for Risk Analysis of road tunnels on behalf of the Norwegian and Swiss road authorities Schubert, Høj et al. (2011), [6]. Two separate Bayesian Probabilistic Networks are incorporated in the model: one for conventional traffic accidents with possible subsequent fires and another for transports of dangerous goods.

The tunnel of concern is divided into sections each with constant risk parameters e.g. invariant with respect to slope, traffic, lanes and all other relevant parameters. Portal zones as well as intersections are therefore always treated particularly.

The methodology has been implemented in a computer code TRANSIT.

As an example, a complex tunnel with several ramps connected by bifurcations has been considered and evaluated. Considering that this is an existing tunnel, the most cost efficient measure was to implement traffic speed control using cameras. Consequently, the speed limits were hardly exceeded and the fatality rate about halved.

Keywords: QRA, quantified risk analysis, tunnel, Bayesian probabilistic networks, upgrade, retrofit, cost efficiency, transports of dangerous goods, Transit.

1. INTRODUCTION

The demand for subsurface transport is increasing. This leads to complex underground systems with numerous stake holders with different expectations and requirements in terms of capacity, reliability availability, maintainability and safety.

Quantified Risk Analysis (QRA) is increasingly gaining importance in order to quantify the safety of road tunnels and hence to balance the requirements and expectation of various stake holders. Various reasons demand a QRA to be conducted. One reason may be that the tunnel has particular characteristics e.g. as defined in the EU-directive 2004/54/EC on the minimum requirements for the safety of road tunnels (European Parliament, 2004, [1]). Moreover, when upgrading existing tunnels, meeting current standards may be very costly or technically impossible. Finally, several new subsurface road systems display features beyond the current experience e.g. underground roundabout that cannot easily be assessed.

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 road tunnels Schubert, Høj et al. (2011), [6]. 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 the application of the methodology.

2. CONVENTIONAL APPLICATIONS OF ROAD-TUNNEL RISK ASSESSMENT

Building on the theoretical foundation developed by the JCSS in 2008, Faber et al. (2009), [2] developed a methodology for a uniform risk assessment for the Swiss road network. 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 harmonizing the risk analysis and regulation of transport of dangerous goods (Høj and Kroon, 2003, [10]). 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. Several methodologies and tools for the risk assessment in roadway tunnels exist already e.g: 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 (Høj and Horn (2010)) has showed that the requirements with regard to the modelling of specific events (e.g. accidents and fire) neither from the Directive 2004/54/EC of the European Parliament (2004) 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.

3. NEW APPROACH: BAYESIAN PROBALISTIC NETWORKS (BPN)

3.1. Introduction

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 modelled and analysed 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, see illustrative example Figure 1. 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.

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) [4]. Today, Bayesian Networks are widely used in the engineering sector and in natural hazards management. They are used due to their flexibility and efficiency in regard to system representation.

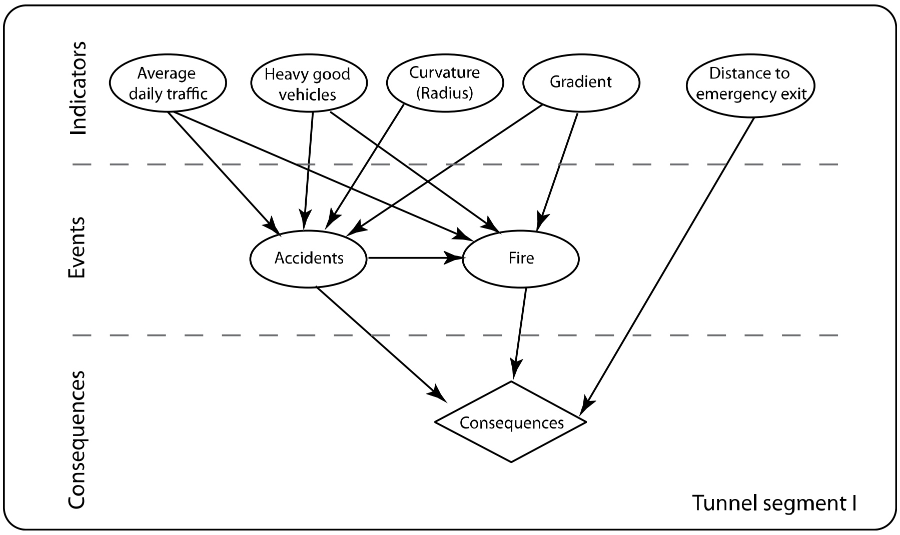

Figure 1: Simplified illustration of a generic system representation using a BPN.

3.2. 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. 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.

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. These Key Performance Indicators (KPI) 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 the 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 Figure 2). The same generic model can be used to calculate the risk under specific 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.

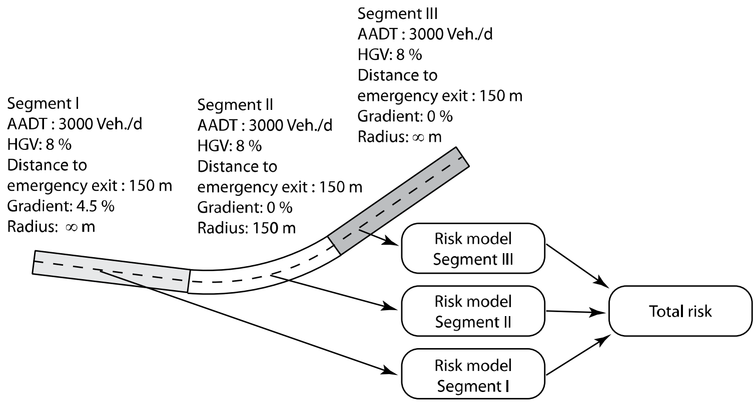

Figure 2: Illustration of the generic system representation, examples of parameters..

3.3. 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. 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" contains 3 states, i.e. one lane, two lanes and three lanes per direction. By knowing the number of lanes and the number of vehicles per hour, the level of service can be calculated. One kernel node in the network is the node AMF. This node represents the "Accident Modification Factor" (AMF). The hypothesis is made that one basis or mean accident rate for the tunnel can be calculated over the entire network. Under different circumstances, this accident rate might be higher or smaller than 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. When statistics becomes available for some of the combinations, the existing prior distribution can be updated with this new information. The AMF is a normalized function of one or more indicators i, i.e. $AMF = f(i_1,\ldots,i_n)$ with a definition range of $[0, \infty]$. The AMF are assessed with different methods and models for the different considered indicators.

An additional Bayesian Network to model dangerous goods events in the tunnel is also contained in the methodology.

4. EXAMPLE OF APPLICATION

4.1. Analysed tunnel system

The risk profile of an existing road tunnel was analysed and mitigation measured proposed in order to reach the desired risk level. Cost efficient safety measures should be introduced in accordance with the ALARP principle, in addition the risk level was compared to the average risk on the motorways. As risk indicator, the main parameter was the rate of fatalities per billion vehicle kilometres.

The tunnel is composed of two dual-lane unidirectional traffic main tubes that near each end connect to ramps, see **Figure *3***. The ramps are operated with unidirectional traffic at the intersections with the main tunnel but merges to become bidirectional near the portals. The tunnel is hence composed of 10 sections. The curvatures of some the ramps are very narrow.

Further main tunnel characteristics are:

- Length: 785 m of main tunnel tubes and 2553 m long ramps.
- Slope on most sections of main tunnel below 1.2% but up to 6% at one portal; the ramps have slopes of up to 5 %.
- Main tunnel with two traffic lanes throughout and additional lanes at bifurcations connecting to ramps.
- Max traffic of 46’000 vehicles per 24h (AADT). Heavy goods vehicles (HGV): 10% main tunnel and varies between 5%, 6% and 10% on the ramps. 3 % of HGV is dangerous goods; ADR class A.

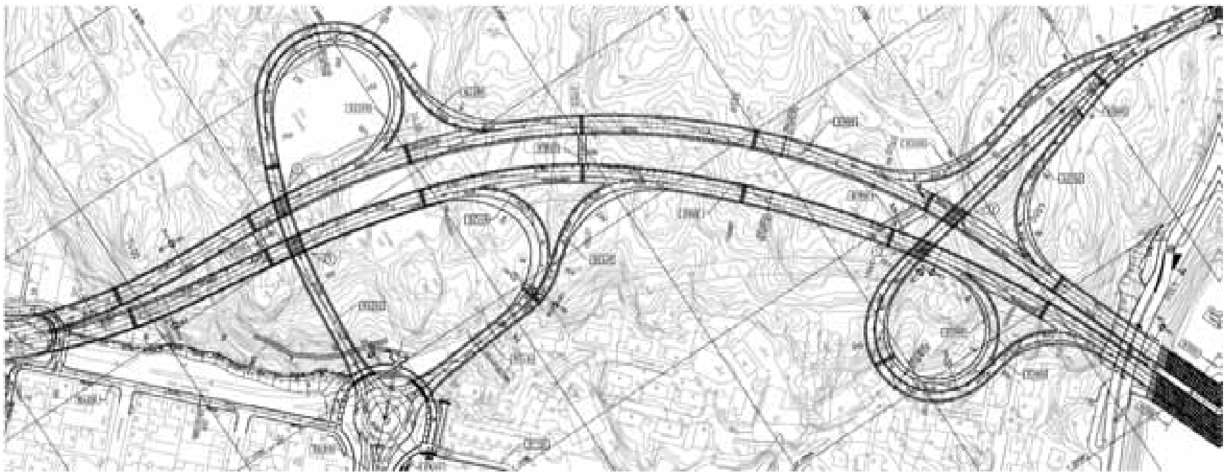

Figure 3: Tunnel with several bifurcations to and from ramps, unidirectional traffic in main tunnel but uni- and bi-directional traffic on ramps.

4.2. Methodology

Using the described methodology that is incorporated in the computer code TRANSIT, the risk on all tunnel sections was calculated for following distinct situations:

- Accidents (collisions and similar excluding fires and dangerous goods events)
- Fires (excluding fires in dangerous goods)
- Event involving dangerous goods

4.3. Risk level in original situation prior to 2007

In spite of the speed limit of 60 km/h, the typical speed in the main tunnel was 70 to 75 km/h. Using Transit, the theoretical fatalities, injuries and accidents were computed, see **Table *1***. The computed 2.125 accidents per year agreed well with past experience.

As the estimated rate of fatalities was much higher than the average on the national roads and about double of that on national 4-lane motorways, the situation was deemed unacceptable.

Table 1: Computation of the risk in the original situation up to 2007

	Fatalities / year	**Injuries / year**	**Incidents / year**
Accidents	0.1037	3.184	2.125
Fires	0.0165	0.036	0.579
Dangerous goods	0.0013	0.004	0.000
Total	**0.1215**	**3.225**	**2.704**
Rates			
Traffic	16.24		10^6 vehicle-km/year
Accident rate	0.131		Per 10^6 vehicle-km
Fire rate	0.036		Per 10^6 vehicle-km
Fatality rate	7.48		Per 10^9 vehicle-km

4.4. Analysis of the original situation

Compared to a standard tunnel some aspects lead to reduced risk level:

- Lower traffic speed, (reference for all tunnels is 80 km/h, for motorways 100 km/t)
- Lower fraction of heavy goods vehicles; (reference 12 to 15%)
- Better light at 4 cd/m^2; (reference for all tunnels is 2 cd/m^2, for motorways 4 cd/m^2)

Other aspects lead to higher risk levels:

- Slopes up to 6% in main tunnel (causes increase in risk by 38%) and up to 5% on ramps (result in risk increase by 25%); here reference value is 2%
- Narrow curves on ramps
- Bifurcations.

The influence of the bifurcations are clearly visible e.g. in the eastern part of the eastbound main tunnel, see **Figure *4***.

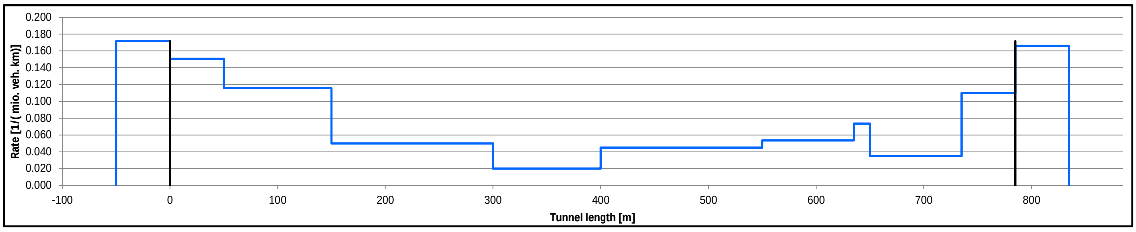

Figure 4: Accident frequency in eastbound main tunnel

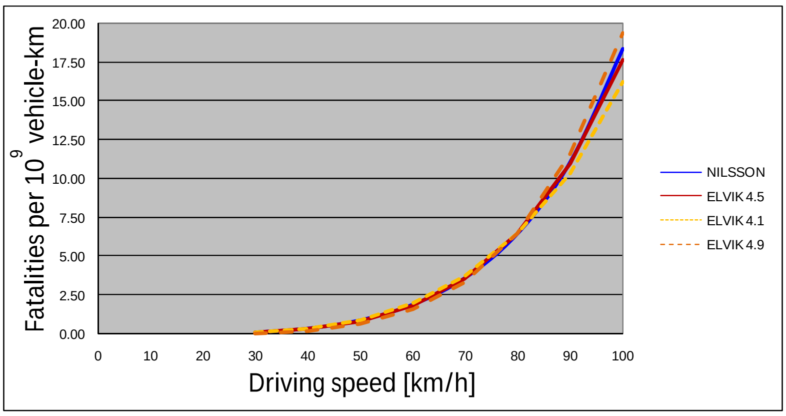

Figure 5: Relationship between driving speed and fatalities

Considering that the tunnel is already constructed and that the speed limits are not respected, it is interesting to examine further the influence of traffic speed.

The frequency and the consequences in terms of injuries and fatalities depend on the average travel speed. Elvik (2004), [8] et al. has developed such a model which agrees with the earlier model established by Nilsson (1997), [7]. By reducing the drive speed form about 75 km/h to 60 km/h, it is anticipated that the fatality rate is about halved, see **Figure *5***. Similar models have been established for the injury rate.

4.5. Result of mitigation measures

Based on the analysis of the original situation, the cost efficient mitigation measure was to ensure that the speed limits were respected. Therefore in 2007, an automatic traffic control with speed cameras was installed. After this the drivers respected the relatively low speed limit of 50 to 60 km/h i.e. reducing the driving speed by 10 to 15 km/h. In the main tunnel with a speed limit of 60 km/h, typical traffic speeds of 63 to 64 km/h were measured.

The computed risks are shown in **Table *2***. The predicted 1.179 incidents per year agree well with the experience for the period 2007 to 2011 that had 4 incidents with injuries.

As the computed fatality rate is below that for national roads and close to the one for national motorways, the introduced mitigation measures were judged successful.

Table 2: Computation of the risk in the new situation after 2007

	Fatalities / year	Injuries / year	Incidents / year
Accidents	0.0336	1.592	1.179
Fires	0.0161	0.036	0.536
Dangerous goods	0.0016	0.005	0.000
Total	**0.0513**	**1.633**	**1.715**
Rates			
Traffic	16.24		10^6 vehicle-km/year
Accident rate	0.073		Per 10^6 vehicle-km
Fire rate	0.033		Per 10^6 vehicle-km
Fatality rate	3.16		Per 10^9 vehicle-km

5. 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 state of the art in the field of risk assessment. The methodology facilitates the risk-based decision making with respect to risk-reducing measures during the planning and during the operation of the tunnel. The methodology gives comparable and reproducible use-independent results.

The general approach in this project differs significantly from other methodologies for the risk assessment in road 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 the 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. When more specific information is available, the level of detail of the analysis can be improved.

The example of application has demonstrated that even complex tunnel networks can be analysed using this methodology and the tool Transit. The risk level of the tunnel, which has been in operation since 2002, was well estimated. Moreover, the situation for the period 2007 to 2011 subsequent to the implementation of the mitigation measure was also well estimated. For this existing tunnel, the efficiency of the implementation of traffic speed control using speed cameras was verified. As a consequence, the speed limits were hardly exceeded and the fatality rates about halved. The example should be regarded as a successful application of TRANSIT, the success of the application of speed control cameras, on the other hand, may be related to local conditions.

6. ACKNOWLEDGEMENT

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