Tunnelling and Underground Space Technology 43 (2014) 300–314

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Reflections on Bayesian Network models for road tunnel safety design: A case study from Norway

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ARTICLE INFO

Article history:
Received 7 July 2013
Received in revised form 5 May 2014
Accepted 12 May 2014

Keywords:
Bayesian Network model
Road tunnels
Risk assessment
Case study
Rogfast

ABSTRACT

Directive 2004/54/EC from the European Parliament states that all EU member states should have well defined methodologies for risk analysis. This means that decisions regarding the design of road tunnels must be supported by risk information. TRANSIT, a Bayesian Network (BN) model for conducting quantitative road tunnel risk assessments has been developed to comply with the requirements. The developers of TRANSIT claim that their model represents best practice for risk assessments of road tunnels. This article explores the foundation for this claim. Furthermore, we assess TRANSIT as a tool for decision support regarding the design of new and novel road tunnel designs. The interactions between TRANSIT and the engineering environment and between risk analysts and responsible decision makers are studied by analyzing the engineering process of the 25 km Rogfast subsea road tunnel project in Norway.

Our analysis shows that TRANSIT could be a useful tool in combination with other risk assessment activities. We also find that the model has severe limitations, especially when used for novel tunnel design projects such as Rogfast. First, the model applies a definition of risk that in most cases fails to provide an adequate risk picture, and hence fails to communicate risk to important stakeholders. Second, both data and models are rigid and presented to the users as a "black box". This poses challenges with regard to the ownership of the analysis results and the responsibility for decisions made on the basis of the model, i.e., the relationship between the developer/owner and the analysts. Third, a standardized model will lead to standardized problems and solutions, which means that the results obtained from TRANSIT will be predictable when some experience with the model is gathered. In this way the model will preserve existing design and not promote innovation with regards to traffic safety designs. Fourth, the model emphasizes key performance indicators such as average annual daily traffic (AADT), tunnel length and curvature, while causes found in accident reports such as driving behavior, latent conditions and organizational and managerial factors may be neglected in the design process.

1. Introduction

1.1. Requirements for risk analyses in road tunnels

The European directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network (TERN) has had a major influence on work to improve tunnel safety in Europe during the past decade. The directive specifies minimum requirements for European road tunnels longer than 500 m. It is a traditional prescriptive legislation regime. However, the directive allows for exceptions from the requirements, for instance when it is not technically feasible to adhere to the requirements, or where it is only possible to fulfill the requirements at a disproportionate cost (EU, 2004:46). In such cases, the prescribed safety measures may be substituted for alternative safety arrangements if it can be shown that the alternative solution provides a safety level that is at least equal to or higher than the demands in the TERN requirements. In order to evaluate the safety level in such cases, the directive uses the concept of risk. According to the directive, a "*risk analysis is an analysis of risks for a given tunnel, taking into account all design factors and traffic conditions that affect safety*, ..." (EU, 2004:54). Furthermore, the directive states that risk analyses shall be conducted for tunnels showing special characteristics with respect to design parameters. Examples of such parameters are: tunnel length, vertical and horizontal alignment, access time for emergency services, and proportion of heavy goods vehicles (EU, 2004:59).

Since 2004, a large number of risk analyses have been conducted as part of Norwegian road tunnel projects. The Norwegian Public Road Administration (NPRA) has adopted risk assessment techniques for road tunnel design problems and experiences have

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http://dx.doi.org/10.1016/j.tust.2014.05.004
0886-7798/

been gathered and evaluated (Njå et al., 2013). Most of the risk assessments have been based on qualitative or semi-quantitative techniques.

1.2. Developing a new quantitative Bayesian Network model

In 2009 the Federal Road Office (FEDRO) in Switzerland and the NPRA initiated "ASTRA 2009/001" an international research project in cooperation with Matrisk GmbH and HOJ Consulting GmbH. The project resulted in the development of a risk assessment software tool, TRANSIT, which is based on Bayesian Network (BN) methodology (Schubert et al., 2011, 2012; Brandt et al., 2012). TRANSIT developers claim that the model can be adapted to all road tunnel systems, providing accurate and reliable risk results.

TRANSIT is based on a BN structure with a Microsoft Excel-based interface. A BN is a directed acyclic graph that consists of variables, depicted by nodes and directed arcs (links) that reflect the probabilistic dependencies between the nodes (Jensen, 2001). The structure of nodes and arcs provides qualitative information by illustrating the variables in the system and how the different variables interact. Quantitative information is obtained through the system structure and conditional probability tables. A major advantage of the Bayesian Network methodology is its ability to make "direct representations of the world, not of reasoning processes" (Pearl and Russel, 2001). This has led to the BN methodology being used for a wide range of risk assessment problems (Chen and Pollino, 2012; Wang and Mosleh, 2010), including transportation sectors such as air (e.g., Luxhøj and Coit, 2006; Call and Gonsalves, 2006), maritime (e.g., Antão et al., 2009) and road tunnels (e.g., Holický and Šajtar, 2005; Cárdenas et al., 2012).

The main objective of the TRANSIT project was to provide a "best practice" methodology for risk assessments, constructed by reviewing historical data, expert judgment and scientific studies. It is claimed that the approach is so promising that it should be established as the "preferred tool for simple and detailed risk analyses" (Schubert et al., 2011:119). Furthermore, it is argued that the method represents the current state of the art in the fields of risk-based decision making and traffic engineering, especially in modeling traffic accident frequencies and the consequences of accidents in road tunnels. The method is applicable to all road tunnels, but the current version specifically takes into account the needs, regulatory requirements and tunnel layouts that have been identified as relevant for Switzerland and Norway. How the developers validate this assumption is not clear. Furthermore it is claimed that the TRANSIT project can "*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*" (Schubert et al., 2011:17).

To adapt the generic model to a specific project, the user specifies key characteristics of the tunnel (evidence in the BN-model) in a set of pre-determined input nodes/variables. The entire TRANSIT model is included in Appendix A. Below we present the accident modification factor (AMF). It consists of 11 indicators assumed to represent all factors influencing the relevant rates (accident, injury and fatality). According to Brandt et al. (2012:44), "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" and may take on values in the interval $[0, \infty]$.

TRANSIT builds on research studies whose results show that accidents are not uniformly distributed over the whole length of tunnels, but that certain zones, e.g., the tunnel entrance, are overexposed compared to the average national background accident rate (Amundsen and Ranes, 2000). TRANSIT requires the user to specify tunnel characteristics in terms of a set of homogeneous segments that are located in the predefined tunnel zones (zone 1: outside, zone 2 and 3: entrance/exit and zone 4: mid zone). TRANSIT calculates a modification factor for the background accident rate for each segment. Other inputs, such as horizontal and vertical gradient, AADT, speed limit are also important in the model. The TRANSIT methodology also consists of the following premises and assumptions:

- Prior distributions are embedded in the model, which makes risk assessments possible also when limited information is available.
- It is possible to specify "hard acceptance criteria" for risk-based decision making. However, the developers recommend managerial review and decision making based on a broader foundation than TRANSIT calculations alone (Schubert et al., 2011:106).
- The background rates are given for each of the seven zones in the tunnel (see Appendix B). The basis for the background rates are statistics from 1992 to 2006 (Amundsen and Engebretsen, 2008; Amundsen and Melvær, 1997).
- The major aims of the methodology are to (Schubert et al., 2011:11–17):
- Support decisions regarding the planning, operation and maintenance of road tunnels.
  - o Meet minimum safety requirements (EU directive).
  - o Optimize available resources.
  - o Provide transparent documentation of the assessments of risk.
  - o Predict observable consequences.

1.3. Introducing the Rogfast tunnel project

Subsea road tunnels are a solution to the problem of how to build roads that must cross numerous fjords along the western coast of Norway. However, the Norwegian topography and traditional way of designing subsea road tunnels often do not comply with requirements in the EU directive 2004/54/EC and national regulation regimes. Subsea tunnels usually have a distinct V-form because of the steep fjords. According to the directive, no new tunnels with a longitudinal gradient of more than 5% shall be built, "*unless no other solution is geographically possible*" (EU, 2004:63). Most Norwegian subsea tunnels fail to comply with the longitudinal gradient requirement, and Norway has been granted a "general" derogation from this requirement (NPRA, 2012a:25). Safety for tunnel users has become a political issue as a result of several severe incidents, for example the fire in the Oslofjord tunnel in 2011 (AIBN, 2012) and the rock blocks that fell from the tunnel roof of the Hanekleiv tunnel in 2006 (Bollingmo et al., 2007).

To improve cargo and passenger transportation on the coastal highway (E 39) along the west coast of Norway, the NPRA is working towards realizing a permanent ferry-free road from Kristiansand in the south to Trondheim in the north (see NPRA, 2012b). The Rogfast subsea road tunnel project north of Stavanger, is one milestone in the work towards this goal. The tunnel will provide a solid link across the Bokn-fjord, connecting Harestad and Arsvågen, see Fig. 2. The design incorporates a branch to the island of Kvitsøy, which means the tunnel system will include a subsea traffic junction (see Fig. 3).

By replacing the existing ferry connection the Rogfast tunnel will reduce travel time significantly, and ensure a continuous traffic flow that will be especially beneficial to the commercial heavy goods road transport sector. When completed, the Rogfast road tunnel will be the longest and deepest underwater road tunnel in the world. The main tubes are currently designed to be 25.5 km long.