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Introducing the STAMP method in road tunnel safety assessment

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ABSTRACT

After the tremendous accidents in European road tunnels over the past decade, many risk assessment methods have been proposed worldwide, most of them based on Quantitative Risk Assessment (QRA). Although QRAs are helpful to address physical aspects and facilities of tunnels, current approaches in the road tunnel field have limitations to model organizational aspects, software behavior and the adaptation of the tunnel system over time. This paper reviews the aforementioned limitations and highlights the need to enhance the safety assessment process of these critical infrastructures with a complementary approach that links the organizational factors to the operational and technical issues, analyze software behavior and models the dynamics of the tunnel system. To achieve this objective, this paper examines the scope for introducing a safety assessment method which is based on the systems thinking paradigm and draws upon the STAMP model. The method proposed is demonstrated through a case study of a tunnel ventilation system and the results show that it has the potential to identify scenarios that encompass both the technical system and the organizational structure. However, since the method does not provide quantitative estimations of risk, it is recommended to be used as a complementary approach to the traditional risk assessments rather than as an alternative.

1. Introduction

Over the last two decades there has been a great increase in the number of road tunnels worldwide and all the indications are that this number will continue to increase in the coming years. The improvement of tunnel construction technology has rendered tunnels as a cost-effective solution to connect steep mountainous regions and traverse urban areas (Zhuang et al., 2009). However, the increasing number of these infrastructures is a double-edged sword also raising upfront an endogenous problem, which is the severity of accidents that may occur. Although accident rates appear to be slightly lower in tunnels than on open road, an accident in a tunnel may have much greater impact (Beard and Cope, 2008), especially in the event of fire, where the enclosed space hinders the dissipation of smoke and poses difficulty in ensuring safe escape route of the tunnel users. Apart from human losses and injuries, accidents in road tunnels can also result in considerable financial losses and prejudicial consequences for the Tunnel Manager, so it is only natural that tunnel safety is now considered as being one of the key elements in tunnel design, development and operation.

Indeed, it was the spate of tunnel fires in Europe over the past decade, resulting in many human and financial losses that highlighted safety in these infrastructures as a matter of utmost importance. Accidents in Mont Blanc, Tauren and St. Gottard resulted in 58 fatalities over a period of just two years, and forced the European Commission to embark upon a major review of road tunnel safety (Beard and Cope, 2008). In this context, the European Commission launched the Directive 2004/54/EC that sets minimum safety requirements and suggests, apart from the measures imposed based on tunnel characteristics, the implementation of a risk assessment in several cases. The aim of the risk assessment, as indicated by the Directive, is to form a basis for decision-making and to demonstrate and document a sufficient safety level to authorities (EU, 2004). However, even if the objectives are clearly defined, the EU Directive does not indicate either the method for performing the risk assessment or the criteria for risk acceptance. Therefore, a wide range of methods have been proposed, most of them based on Quantitative Risk Assessment (PIARC, 2008a).

Although QRA contribution to manage safety has been great in many fields (Kontogiannis et al., 2000), such as the nuclear power industry (where it is called Probabilistic Risk Assessment—PRA) and chemical processing industry (Nivolianitou et al., 2004), it has been argued that QRA results should not form the sole basis for safety-related decision making, since there are several items that might not be handled well by the QRA modeling (Apostolakis, 2004). Briefly, the main challenges to the acceptance of QRA concern: (a) the treatment of human performance, including not only human error per se but also management and organizational

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factors, (b) understanding the kinds of failure modes that may be introduced when using software to control safety critical systems and (c) capturing the adaptation of the system (i.e. the slow, incremental migration of the system to the boundaries of its safety envelope). It seems that with the arrival of the socio-technical approach and the recognition of multiple non-technical aspects in accidents' occurrence, the challenges to the acceptance of QRAs have been significantly stressed, particularly when trying to capture the overall risk picture of complex socio-technical systems (Leveson, 2011b).

As a result, many efforts have been made to cope with these challenges, and in some industries QRA models have become sophisticated enough to incorporate organizational factors (e.g. Mohaghegh and Mosleh, 2009; Pate-Cornell and Murphy, 1996) or to cope with the context dependence of software behavior (e.g. Garret and Apostolakis, 1999). In parallel, new safety approaches have emerged, deviating from the QRA paradigm. For example, safety approaches which are based on the systems-theoretical assumptions are now considering a promising way to understand and manage safety (Larsson et al., 2009; Leveson, 2004,2011a; Woods et al., 2010). Rather than adopting a "normative view" that decomposes systems into separate processes that are likely to fail, the systems theoretic perspective regards safety as a control problem (i.e. inadequacy to enforce safety constraints) and accidents are viewed as the result of performance variability of human behaviors and organizational processes whose complex interactions and coincidences are not adequately handled (Hollnagel, 2004; Leveson, 2004; Rasmussen, 1997). Some notable systemic accident models that have been proposed are the Functional Resonance Accident Model (FRAM; Hollnagel, 2004), Accimaps (Svedung and Rasmussen, 2002) and Leveson's (2004) Systems-Theoretic Accident Model and Processes (STAMP). It must be mentioned that although some of these models have been introduced as accident analysis techniques, STAMP can also drive a safety assessment process (Leveson, 2011b).

Taking into account that road tunnels are not merely technical, engineering systems but also have intrinsic organizational, social and managerial dimensions that impact or contribute to their safety (PIARC, 2007), this article's objective is twofold. The first objective is to highlight the fact that the challenges of QRAs, as they have been pinpointed in the literature, have not been addressed adequately in the road tunnels field. Therefore, even if QRA methods are essential to assess physical aspects and facilities of tunnels, they neglect an important part of non-technical factors and they do not transfer results into identification of safety–critical systems and actions, for which performance criteria (and subsequent management responsibility) need to be established. To cope with these limitations, the second objective of this work is to propose an innovative method that has the ability to provide decision-makers with scenarios that even though they have not been considered by the traditional road tunnel QRAs they have the potential to lead to accidents. The method introduced in this paper draws upon the STAMP accident model; hence, it has the potential to consider organizational factors, software behavior and the dynamics of the tunnel system integrally. By using the proposed method the analyst (i.e. tunnel safety officer or tunnel safety engineer) can identify a notable number of scenarios that have the potential to lead to accidents, assess (in a qualitative manner) the current safety level of the tunnel and propose additional measures, if the safeguards in place are not adequate. The scope for using a STAMP-based road tunnel safety assessment method is thoroughly explored through a case study.

The remainder of this paper is organized as follows. In Section 2, the concept of QRA in the road tunnels field is briefly presented and the weaknesses of current road tunnel QRAs are mentioned. Section 3 pinpoints the need to enhance the safety assessment process of road tunnels with a complementary method based on the systems theory paradigm, whereas Section 4 introduces and demonstrates the proposed STAMP-based road tunnel safety assessment method through a case study example of a tunnel ventilation system. Section 5 discusses the method and finally, Section 6 concludes this work.

2. QRA in the road tunnels field

2.1. The concept of current road tunnel QRAs

QRA methods have been adapted to the road tunnels field in order to cope with the limitations of prescriptive standards and regulations that traditionally and globally have controlled the safety issue of these critical infrastructures (Beard and Cope, 2008; Dix, 2004; PIARC, 2008a). Such regulations and standards, even if they manage to ensure a minimum level of safety, are implemented more or less without taking into account the special characteristics of a tunnel, or the interactions among different parts of the tunnel system (PIARC, 2008a). As a result, a risk-based approach is also needed to provide a structured and transparent assessment of risks for each particular tunnel. In this perspective, the ultimate purpose of a QRA is to calculate and evaluate the risk level of a tunnel and then determine whether the desired safety level has been accomplished. In order to evaluate the risk level two criteria are mainly used. The first criterion is the personal (i.e. individual risk) which indicates the risk of the most exposed average individual, using fatality rate per year or per tunnel km. The second is the societal risk (or group risk) which expresses the probability of large accidents with multiple fatalities and addresses society's perception of large accidents (i.e. risk aversion). Societal risk is usually presented by the popular *F–N* curve that is a cumulative presentation of accident frequencies as function of the severity of accidents.

An extended literature review of the QRA methods currently applied in the road tunnels field can be found in PIARC (2008a). The models that are presented in this report are the Austrian tunnel risk model TuRisMo, the Dutch TUNPRIM model, the French specific hazard investigation, the Italian risk analysis model and the OECD/PIARC DG-QRA model which is the most widely used decision aiding tool for the transportation of hazardous materials through a road tunnel. A detailed risk assessment with the OECD/PIARC DG-QRA method can also be found in Kirytopoulos et al. (2010). Other QRA methods that have been proposed in the road tunnels domain can be found in the relevant literature (Holicky, 2009; Nývlt et al., 2011; Weger et al., 2001; Xiaobo et al., 2011).

All the aforementioned QRA methods consider different accident scenarios since they have been developed for different types of routes and tunnels (i.e. unidirectional or bidirectional tunnels, longitudinally or transverse ventilated tunnels, etc.). The considerable number of parameters used in the QRA model also differs. However, the great majority of current road tunnel QRA methods consist of the same following modeling steps (Hoj and Kröger, 2002; Xiaobo et al., 2011):

1. Identification of all possible accidents such as fire, explosions, leaks and flood as critical events.
2. Fault tree and event tree analysis for each defined critical event. Event tree consists of a number of particular scenarios triggered by the critical event and fault tree analysis is used to estimate the probability of the critical event. Then, consequence estimation models can be applied to calculate the expected number of fatalities for the various scenarios involved in the event tree.
3. After obtaining probability and fatality of each scenario, the societal risk and the expected value is estimated. Smoke dispersion calculations are particularly used for fire scenarios in order