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# On risk assessment and risk acceptance of dangerous goods transportation through road tunnels in Greece

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ABSTRACT

Prescriptive and risk-based methods including qualitative, semi-quantitative and quantitative approaches exist for the risk assessment of road tunnels. This paper provides an overview and a brief discussion of these methods and uses representative traffic and accident data in Greece in a typical tunnel conforming with the minimum infrastructure requirements of the European Directive 2004/54/EC to compare and discuss the resulting risk for each of these methods. Conclusions regarding the implementation of risk analysis methods and the use of the associated existing national guideline are drawn and recommendations for further developments in standards are provided. An integrated framework for the optimal selection of safety measures based on risk reduction and socio-economic considerations is proposed and its applicability in risk analysis of road tunnels is discussed.



## 1. Introduction

The road network worldwide has grown steadily over the last three decades due to the considerable increase in traffic volumes. The development of the network is frequently obstructed by mountainous regions, which require the construction of underground infrastructure. In urban areas tunnel projects are realized in order to relieve congestion in heavily developed areas and remove visible traffic from sensitive environment. In semi-urban areas tunnel projects are constructed in order to reduce travel times. The longest road tunnels are located in mountainous countries such as Norway, Italy, Austria, Japan and China. There are more than twenty tunnels worldwide with a length greater than 10 km. In Greece, the national road network has expanded basically through the construction of the West-East axis EGNATIA and the associated access roads as well as the upgrade of the South-North axis PATHE and its new access roads. A considerable number of road tunnels have been realized or are under design or construction reaching lengths up to 5 km.

Road tunnels are complex infrastructure systems that may be exposed to hazard situations leading to events involving accidents with serious consequences. This has been experienced in significant tunnel accidents which occurred in the last two decades, such as the fire in the Mont-Blanc tunnel in France (1999; 39 deaths), the accident in the Tauern tunnel in Austria (1999; 12 deaths), the fire in the Gotthard tunnel in Switzerland (2001; 11 deaths) and the crash flowed by fire accident in the Viamala tunnel in Switzerland (2006; 9 deaths). The economic and human consequences and implications of those accidents have reached catastrophic dimensions.

Accident events become therefore a major issue for safety concerns in the design of road tunnels in particular when the transportation of dangerous goods (DGs) through the tunnel is not prohibited. The combination of mixed traffic and extreme tunnel length (up to 25 km) has namely in such cases a significant impact on the inherent risk of the tunnel system. Consequently, potential risk has a significant influence on the specification of design parameters of a tunnel such as the tunnel's configuration and cross section and on the selection of prevention and mitigation safety measures.

A summary of related literature and the state-of practice in standards are briefly discussed first. The applied risk assessment procedures such as the semi-quantitative risk matrix approach and the quantitative risk analysis model based on the recommendations of the World Road Association (PIARC) are presented. The risk assessment of road tunnels in Greece is analyzed by considering representative traffic and accident data from Greek motorways in a typical tunnel conforming with the minimum infrastructure

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requirements of the European Directive 2004/54/EC (EU, 2004) using both the aforementioned semi-quantitative and quantitative World Road Association's (PIARC) Quantitative Risk Assessment Model (QRAM) software for transport of dangerous goods approaches. The experience of the authors relevant to risk analysis of several road tunnels in Greece is reflected. Important practical aspects such as data collection and data analysis, implementation of risk criteria, and definition of risk acceptance are illustrated. A risk-cost-benefit optimization framework approach is proposed for evaluating potential safety measures and different safety measures are appraised using a simple semi-quantitative approach. Conclusions regarding the use of risk analysis methods are drawn and recommendations for further research and developments in standards are provided.

## 2. Literature review and state-of-practice

### 2.1. Indicative literature review

Risk-based approaches to the design and evaluation of structures have been developed for the military industry after World War II and already in the 70's for the nuclear and offshore industry. Since the planning of the large tunnel projects such as the Eurotunnel, the Gotthard tunnel or the Brenner tunnel in the 90's, they have been implemented to assess the risk of several tunnels (see for example Diamantidis, 2005; Kohl and Zibert, 2010; Neumann and Sistenich, 2011). The societal risk criterion is used in the risk assessment studies. To society as a whole or to a company or institution responsible for a specific activity, the total damage due to a hazard is of prime interest (see for example CIB, 2001). To comprehend this point of view the notion of societal risk R is:

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

where $n$ is the number of all independent and mutually exclusive accident scenarios $i$, $p_i$ is the probability of occurrence (per year) of scenario $i$, and $C_i$ are the consequences of scenario $i$ for example in terms of fatalities. The probabilities of occurrence for various scenarios are obtained based on available data; for fire in road tunnels see for example Hoj (2004) for release of dangerous goods Knoflacher (2001). The consequences may include human, economical and environmental consequences and can be therefore measured in terms other than fatalities per year, for instance in, monetary units or emission of a given substance. An important aspect thereby, is the combination of the various types of consequences under a common metric since different types of impact cannot be directly compared. This can be performed by assigning a monetary value to all types of consequences or by introducing a set of compatible categories that embrace the different impacts.

Consequence scenarios in case of road tunnel accidents especially involving fire have been investigated extensively in the literature; see Beard and Carvel (2011). A computer model that simulates fire growth movement in tunnels is described by Charters et al. (1994) including methods for predicting mass flows, velocities, smoke concentrations, and heat transfer. Using different techniques from the decision support tools, such as the analytic hierarchy process, and fire dynamics simulation, the priority in the classification of the fire-fighting systems in tunnels is analyzed by Fera and Macchiaroli (2010). A semi-empirical model for the determination of the physical characteristics of fire in tunnels focusing on heptane pool fires has been developed by Megrèt and Vauquelin (2000). With respect to the release of dangerous goods the related consequence scenarios are critically reviewed in state-of-the-art publications of the World Road Association PIARC (2008, 2013). Modeling of trapped users evacuation in tunnel accidents has been provided by Noren and Winer (2001), while the human behavior in tunnel fires is analyzed by Frazer-Mitchel and Charters (2005).

The calculated societal risk must fulfil the risk acceptance criteria, i.e. must be less than a specified minimum and acceptable value (threshold). The tunnel is consequently considered safe if it meets predefined risk acceptance criteria as presented in case studies, for example Diamantidis, 2005; Botschek et al., 2007; Kohl and Zibert, 2010. Application of a risk analysis requires appropriate methods and tools and input data on accident frequencies and consequences. The analysis provides a powerful decision tool since it allows a structured, harmonised and transparent risk assessment. It can be used for the comparison of alternative tunnel or route configuration solutions and for the cost-effective selection of safety measures. Consequently, it can also be used to demonstrate the safety of a tunnel in case of deviations from the prescriptive regulations. A quantitative risk analysis for road tunnels complying with EU regulations has been presented by Kirytopoulos et al. (2010).

The aforementioned literature is only indicative, yet representative, as the scope of the present contribution is aimed to provide a comparison of the different conceptual approaches, i.e. prescriptive versus the risk-based approaches, as outlined below, and not to focus on specific hazards or trigger events.

### 2.2. Implementation in standards

The implementation of tunnel safety in standards is conceived in analogy to the approach followed in structural safety (see for example a review performed by Diamantidis, 2008), which builds on two different methods: the prescriptive and the risk- (or performance-) based approach.

#### 2.2.1. Prescriptive approach

The traditional approach to the design of structures and infrastructure is based on prescriptive regulations. These are usually developed over many years and reflect a considerable state of knowledge. In a prescriptive approach, the tunnel is safe if it is designed in line with valid regulations, which means the tunnel and its safety devices fulfil the minimum requirements given in the standards. The standards specify particular safety features, actions, etc. to be implemented. Such minimum requirements are provided in: the European Directive 2004/54/EC (EU, 2004) and its transportation into Greek law by the Greek Presidential Decree no 230 of 2007 (P.D., 230/2007), the recommendations given by the World Road Association PIARC (PIARC, 2008, 2013), the German Standard (RABT, 2006), the Czech standard (CSN 73 7507, 2007) or the Japanese recommendations (Mashimo, 2002). The requirements are of comparable characteristics in those standards; however, the German RABT (RABT, 2006) is providing more details regarding the design of the safety measures, such as fire resistance of tunnel equipment and structural components, geometry of evacuation routes, etc.

Safety checks in such a prescriptive approach can be performed based on code requirements. Thereby, tunnels are classified in categories on the basis of their traffic volume, tunnel configuration and tunnel length. For each category, a set of safety measures is recommended. In some standards, technical specifications for the safety measures are also provided. Consequently, the use of such an approach is simple but not transparent since the risk of the tunnel is not known. Based on the classification scheme described above, different safety measures are proposed as minimum satisfactory requirements according to tunnel class. The proposed measures can, be categorized into prevention measures that reduce the probabilities for an accident and mitigation measures that reduce the consequences from an accident.