Tunnelling and Underground Space Technology 44 (2014) 88–96

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Effect of tunnel technological systems on evacuation time

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ARTICLE INFO

Article history:
Received 31 July 2013
Received in revised form 30 June 2014
Accepted 23 July 2014
Available online 17 August 2014

Keywords:
Tunnel safety
Tunnel technology
Evacuation time
Fuzzy system
Risk analysis

ABSTRACT

In this paper, the authors provide a discussion about technological systems in road tunnels and their effect on the overall time needed for people witnessing a fire to escape. Prompt identification of a fire, together with an optimal deployment of relevant information to the trapped people significantly increases their awareness and reduces the response time, thus speeding up the entire evacuation process. The fire identification and warning systems are in nature heterogeneous technological systems, composed of different sensors and actuators.

The major objective of this paper is to introduce a methodology of assessing awareness and response times in relation to such heterogeneous technological systems. The resulting estimated time does not only refine a scenario oriented risk analysis, but also optimizes the design as well as the price of the systems installed in a real particular tunnel. The theoretical foundations are also applied by the authors in a fuzzy evaluation system – CAPITA, which is also briefly described in this paper.

1. Introduction

Safety is one of the most important aspects when designing a road tunnel system. Many papers have been written concerning analysis of big fires (Fridolf et al., 2013). The tunnel designer faces the major task to provide a certain guaranteed degree of safety for tunnel users while keeping the price minimized. Such level of safety is a combination of construction layout of tunnel, technological systems and organizational processes. Generally the term "safety" is defined as the control of recognized hazards to achieve an acceptable level of risk. The level of risk is then often evaluated based on statistics demonstrating impacts of car accidents in tunnels (Fridolf et al., 2013).

1.1. Approaches to tunnel safety evaluation

Currently, there are two basic approaches to determine the required safety in road tunnels:

1. *Prescriptive-based approach*, which assumes that the tunnel is safe if it is designed in line with valid regulations. This approach does not however take into consideration the individual characteristic of each tunnel and instead only takes into account the general conditions valid in a given country.
2. *Risk-based approach*, which assumes that a tunnel is safe if it meets some predefined risk criteria. This approach assesses the risk for an individual tunnel and compares the different additional safety measures in term of risk reduction and/or cost effectiveness.

Prescriptive-based approach presents the traditional solution used in most countries. The construction and equipment of a tunnel is done according to given rules and requirements provided in tunnel design guidelines such as the German "Guidelines for the equipment and operation of road tunnels" (RABT, 2006), the US "Standard for Road Tunnels, Bridges, and Other Limited Access Highways" (NFPA 502, 2014), the Austrian standards "Tunnelausrüstung" (RVS 09.02.22, 2010) or the Czech guidelines Road Tunnel Equipment – Technical Specification" (TP98, 2003). The national requirements are often more strict than the specifications required by the European Directive 54/2004 (Directive, 2004).

These regulations and legislative guidelines are used to determine the minimum set of requirements; they have been developed during the past decades and are based on experiences with existing tunnels. Compiling such knowledge requires long term research including exceptional situations such as accidents or fires. Nevertheless, each tunnel is an individual construction with individual conditions. This is true not only for the physical characteristics of a tunnel, but even for its location. The driver's behaviour is determined by their level of knowledge, nationality, living conditions as well as their habits. This implies that using one common standard to implement tunnel safety systems for an arbitrary tunnel

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http://dx.doi.org/10.1016/j.tust.2014.07.014
0886-7798/

introduces certain shortcomings since it cannot reflect all differences in the conditions.

There is also another aspect limiting the prescriptive-based approach. The tunnel geometry, emergency lines, emergency bays as well as the placement and marking of the emergency exits are precisely described in the relevant national standards and guidelines, which are mandatory for design and building of new road tunnels. Nevertheless, there are many types of tunnel equipment which are not prescribed as mandatory but which are recommended for use according to safety categories of tunnels. For example, European directive 2004/54/ES defines five safety categories. Typically, this is the use of variable message signs and information displays, public address system or different firefighting equipment. However, these facilities are critical to the rescue of tunnel users in the case of fire. Early detection of fire combined with a warning system with a saving of a number of minutes or tenths of seconds may be critical to people trying to escape.

Since the prescriptive-based approach does not always provide a clear answer concerning the one particular tunnel, often an excessive level of tunnel safety technology is used just, to be on the safe side". This significantly influences the investment and is followed by high operational cost during the tunnel lifecycle.

For this reason, in addition to the prescriptive method, so-called ***risk-based approach*** is often used. This is supported also by PIARC (World Road Association), the Technical committee C3.3 "Road Tunnel Operation" where especially WG2 is focusing on this issue. The risk-based approach is a systematic method to analyse the causes of accidents. It consists of three components: Risk Analysis, Risk Evaluation and Risk Management (PIARC, 2008). Such a process enables identification of the system's weak points together with their impact on safety. Based on the consequences and their probability, tangible improvements shall be proposed in order to minimise probability of serious risks. Nevertheless, risk assessment is not a universal cure. Like any other toolbox, sometimes it may be inappropriate for a given task or to be used in the wrong way.

When speaking about risk analysis, it is necessary to distinguish ***qualitative*** and ***quantitative methods*** (Radu, 2009).

Qualitative methods are suitable for a preliminary rough risks assessment. Typically, they involve a group of experts using different methods such as expert judgment, brainstorming, what-if-analysis, statistically adjusted failure mode and effect analysis (SAFMEA) or others (Beard, 2010). These approaches are relatively straightforward and can be easily adopted for almost any problem field. However, they have a significant disadvantage, since they provide only approximate answers – estimation of expected results.

The ***quantitative methods*** additionally are composed of two categories:

– *Non-deterministic risk assessment* presented by probabilistic models, e.g. fault trees, Bayesian models and stochastic models.
– *Scenario based analysis* (SBA) which uses a deterministic physical model for heat and smoke dispersion and simulation models for modelling the evacuation process of trapped people in tunnels to evaluate different scenarios and their effect on safety.

Probabilistic fault tree analysis (FTA), or Event Tree Analysis (ETA), is widely used in tunnel risk assessment; see for example (Xu, 2011; Fouladgar et al., 2012; or Qu et al., 2011). The national methods of risk analysis are described in annex of PIARC (World Road Association) document (PIARC, 2012). It refers to the Dutch event tree analysis (RWS, 2013), French (CETA, 2003), German (RABT, 2006) and Italian (IRAM, 2009) risk analysis methods. A stochastic method using tree analysis has been applied also in the Austrian Tunnel Risk Model TuRisMo (FSV, 2008). Some countries prefer a stochastic approach combined with deterministic scenario oriented models.

The scenario based analysis focuses on particular tunnels and takes into account any specific conditions – concrete tunnel layout and equipment as well as real traffic and environmental conditions. The scenario takes into consideration the power and other parameters of the fire (e.g. its development in time) as well as the process of ventilation. The physical model calculates values of temperature and concentration of toxic gases in the 3D or 2D dimension. A simulation program then estimates the escape time for people trapped under the same conditions. A merging of both models provides an estimate of potential fatalities under given scenario.

There is one limitation concerning both categories of risk-based approaches highlighted in (Beard, 2010). It is not possible to reason that a model has been validated and proven correct because:

1. Probabilistic models cannot be directly compared with any experiment and also validation of such a model is rather problematic. There is only one possibility to validate this model according to historical statistical data and that is historical data which can be used to calculate the probability of events in the actual model.
2. Results from the scenario-based models can be verified by an experiment. However, the way how the experiment is carried out is very important and determines its usability. Even experiments which are intended to replicate earlier experiments may not produce consistent results.

Additionally, these models introduce another significant limitation which has not been discussed in literature before. None of these methods includes in the calculations the quality of tunnel equipment, which directly affects the pre-movement time. This time is a more important element of the required escape time than that which is needed to move to a safe place (Bryan, 2002). Incident analyses have shown that there is a connection between a delayed evacuation and a high number of fire deaths. The shortening of pre-movement time has crucial importance on how many people will use self-evacuation. The assessment of time response of automated fire identification and efficiency of warning information is a key topic of this article.

This paper aims to demonstrate that tunnel technological systems and their effect on safety must be part of the risk analysis. Secondly, it aims to propose a solution and to show how these heterogeneous tunnel systems can be evaluated using artificial intelligence. A methodology improving the deterministic risk analysis by modelling the effect of tunnel technology on the pre-movement time is provided. The resulting system is able to support the decision makers in the process of selecting the right level of safety technologies prior to the building of a road tunnel, as well as to evaluate an existing tunnel from the same point of view.

1.2. Evacuation process in road tunnels

Disastrous fires in road tunnels have clearly shown the importance of effective and prompt evacuation. Before we start evaluating the technological systems in terms of pre-movement time, the general evacuation process must be introduced. The evacuation process covers all steps from the time that a fire starts until the trapped people reach a safe area. According to Persson (2002), it can be divided into three phases, each taking a certain amount of time:

1. Awareness phase (t_a – awareness time).
2. Response phase (t_r – response time).
3. Movement phase (t_m – movement time).