Process Safety and Environmental Protection 9 2 (2 0 1 4) 329–337

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

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

Embedding the human factor in road tunnel risk analysis

Konstantinos Kirytopoulos[a], **Myrto Konstandinidou**[b,*], **Zoe Nivolianitou**[b], **Konstantinos Kazaras**[c]

[a] School of Natural and Built Environments, Barbara Hardy Institute, University of South Australia, City East Campus, Adelaide, SA, Australia
[b] Systems Reliability and Industrial Safety Laboratory, Institute of Nuclear & Radiology Sciences & Technology, Energy & Safety, National Center for Scientific Research "Dimokritos", Aghia Paraskevi 15310, Greece
[c] National Technical University of Athens, School of Mechanical Engineering, Heroon Polytechniou 9, Zografou campus 15780, Greece

A B S T R A C T

The paper is focusing on road tunnel safety and builds upon the Directive 2004/54/EC launched by the European Commission; the latter sets basic requirements and suggests the implementation of risk assessment in several tunnel cases apart from technical measures imposed on the basis of tunnel structural and operational characteristics. Since the EU Directive does not indicate the method for performing risk assessment, a wide range of methods have been proposed, most of them based on quantitative risk assessment (QRA). Although the majority of current road tunnel QRAs assess physical aspects of the tunnel system and consider several hazards concerning the transportation of dangerous goods through a tunnel, they do not take into account, sufficiently, several organizational and human-related factors that can greatly affect the overall safety level of these critical infrastructures. To cope with this limitation this paper proposes a fuzzy logic system based on CREAM method for human reliability analysis (Hollnagel, 1998) in order to provide more sophisticated estimations of the tunnel operator's performance in safety critical situations. It is deduced that a human reliability analysis component to analyze operator performance, like the fuzzy system proposed here, is important for risk analysts. Consideration of organizational and human factors will enhance risk analysts' studies and highlight the uncertainty related to human performance variability.

Keywords: Road tunnels; Directive 2004/54/EC; Fuzzy systems; CREAM; Risk analysis; Uncertainty representations; HRA

1. Introduction

A great increase has been noticed in the number of road tunnels both in Europe and worldwide over the last two decades. Furthermore, all the indications lead to the conclusion that this number will continue to increase in the coming years (Zhuang et al., 2009). This can be attributed to the improvement of tunnel construction technology which has rendered tunnels a cost effective solution to connect steep mountainous regions and traverse urban areas. However, the increasing

Abbreviations: ADR, European agreement concerning the international carriage of dangerous goods by road; ALARP, as low as reasonably practical; BLEVE, boiling liquid evaporating vapor explosion; CCTV, close circuit television; CPCs, common performance conditions; CREAM, cognitive reliability error analysis method; DG, dangerous goods; EU, European Union; EV, expected value; HGV, heavy goods vehicles; HRA, human reliability analysis; MMI, man–machine interface; QRA, quantitative risk assessment; PIARC, permanent international association of road congresses (World Road Association); PSFs, performance shaping factors; SCADA, supervisory control and data acquisition; VCE, vapour cloud explosions.

* *Corresponding author*. Tel.: +30 2106503723.
E-mail address: myrto@ipta.demokritos.gr (M. Konstandinidou).

Received 6 December 2013; Received in revised form 17 March 2014; Accepted 18 March 2014
http://dx.doi.org/10.1016/j.psep.2014.03.006
0957-5820/

number of these infrastructures is a double-edged sword raising upfront an endogenous problem too, which is the severity of accidents that may occur. Accidents in road tunnels may lead to heavily adverse consequences for the users, the infrastructure itself and the environment. Such accidents could be partly attributed to the difference in the driving conditions between tunnels and open road. Driving through a tunnel is stressful for a considerable number of drivers. These drivers are concerned because of the darkness, narrowness and noisiness of the tunnel. These conditions lead some of them even to be afraid while driving through tunnels (Ricard, 2005). Moreover, the poor sight conditions prohibit drivers from a sound estimation of distances, while the entrance and exit of tunnels (portals) favour reduced sight conditions, such as ocular blinding, black hole effect and need for eye adaptation. Additional psychological reactions have been also observed, like fear of being trapped into the tunnel and developing anxiety that has even lead drivers to a complete stop in front of long tunnels' portals (PIARC, 2008b).

As proven in practice (Beard and Carvel, 2005; TRB, 2011; Vianello et al., 2012), the most important and dangerous outcome of accidents inside road tunnels are those involving the occurrence of fire. Despite the fact that the probability of such an event is usually extremely low, the consequences are considerably high. There are several factors that aggravate such consequences like the limited area of the tunnel, which favours fast smoke propagation, the very fast development of fire curves, the development of extremely high temperature (sometimes higher than 1000 °C) and the spreading from one vehicle to another even when they are detained in distances of 200 m from one another. All these adverse factors are coupled with the fact that road tunnel users normally fail to quickly realize the danger to which they are exposed, or fail to apply the safety measures and processes. The latter comes as a result to the fact that they are in general uneducated (TRB, 2011). Another aggravating factor in case of fire is the existence of heavy goods vehicles carrying dangerous goods. Transportation of dangerous goods has been a topic of interest for societies but also a spark for scientific research. As an example, a risk analysis system was recently proposed to cover external safety of people for the different modalities of dangerous goods transport: roads, railways, inland watering and pipelines (Bogaert et al., 2013). In road tunnels where the transportation of dangerous goods is allowed, the consequences of a possible accident take the form of a big societal hazard due to the potential extensive impact of the hazardous substance (Fabiano et al., 2002, 2005; Kirytopoulos et al., 2010a). Since the risk connected to dangerous goods transportation is comparable with that of fixed plants (Fabiano et al., 2002), the European Commission launched the Directive, 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network (EC, 2004), that sets basic requirements and suggests the implementation of a risk assessment in several tunnel cases apart from technical measures imposed on the basis of tunnel length and traffic volume. Indeed, tunnel authorities are now requested to make risk-informed decisions as to whether the transport of dangerous goods should be permitted through road tunnels.

In this perspective, quantitative risk assessment (QRA) models, such as the OECD/PIARC DG-QRA Model (INERIS, 2005), have been developed to assist decision making by providing objective estimates of risks. Nevertheless, current road tunnel QRAs are also subject to many limitations, as mentioned in Bjelland and Aven (2013), Kazaras et al. (2012) and Kazaras and Kirytopoulos (2013). One of the most striking limitations is the fact that the performance variability of the tunnel operator is not taken into consideration by the analyst, despite the fact that it plays an extremely important role on the development of the accident. The term performance variability refers mainly to the time elapsing between the occurrence of an emergency situation (e.g., fire in tunnel) and the completion of the relevant corrective actions by the operator. Such actions may include time to close the tunnel, time to activate emergency ventilation, time to call the emergency services, etc. The research problem raised here is to explore how the human factor can be incorporated in the analysis (Kazaras et al., 2013). If this is done, the next question is whether there would be a significant difference in the risk analysis outcome or not. This paper aims at addressing the problem by exploring the utilization of a fuzzy logic system based on CREAM method for human reliability analysis in order to provide more sophisticated estimations of the tunnel operator's performance in safety critical situations. In order to achieve this goal, the research focuses on a particular compound human factor that influences the development of a road tunnel accident, namely the performance variability of the tunnel control centres' operators. The developed fuzzy system takes into account factors such as the adequacy of systems' interface in the control centre, the availability of procedures and operators training and experience that particularly affect operators' response time to activate safety critical systems. The fuzzy system produces numerical values which can be further incorporated into a traditional road tunnel QRA. In this way the analyst has the potential to consider some basic organizational and human aspects that greatly affect the overall risk picture of the infrastructure. Despite that this research is focusing on risk analysis involving dangerous goods, the outcomes may be beneficial and find application in any kind of road tunnel risk analysis including non-dangerous goods transportation as well as typical users (private car drivers and passengers). The remainder of this paper is organized as follows: in Section 2 the concept of QRA in the road tunnels field is briefly presented together with the highlighting of weaknesses in current road tunnel QRAs. Section 3 presents the fuzzy system that enhances the road tunnel risk assessment process and demonstrates how the results produced by the fuzzy system can be incorporated in a QRA model, i.e., the OECD/PIARC DG-QRA Model. Section 4 presents the results from the analysis and Section 5 concludes this work.

2. QRA in road tunnels

2.1. *General concept and the OECD/PIARC DG-QRA model*

Tunnel fires in Europe over the past two decades, resulting in many human and financial losses, have render safety in tunnels a matter of utmost importance (Dix, 2004). In this context, the European Commission launched the Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network. The directive aims at all the road tunnels belonging to the trans-European road network having a length that exceeds 500 m; the former can be in operation, under construction or at the design stage. The directive sets minimum safety requirements and suggests in several tunnel cases the implementation of a risk assessment,