CHEMICAL ENGINEERING TRANSACTIONS
VOL. 31, 2013
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
Guest Editors: Eddy De Rademaeker, Bruno Fabiano, Simberto Senni Buratti

ISBN 978-88-95608-22-8; **ISSN** 1974-9791
DOI: 10.3303/CET1331059

Enhancing Road Tunnel Risk Assessment with a Fuzzy System Based on the CREAM Methodology

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

[a]National Technical University of Athens, School of Mechanical Engineering, Heroon Polytechniou 9, Zografou campus, 15780, Greece.
[b]Systems Reliability and Industrial Safety Laboratory, Institute of Nuclear & Radiology Sciences & Tecnology, Energy & Safety, National Center for Scientific Research “Dimokritos”, Aghia Paraskevi 15310, Greece.
kkaz@central.ntua.gr

A great increase has been noticed in the number of road tunnels in Europe over the last decades. 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 number of these infrastructures is a double-edged sword raising upfront an endogenous problem too, which is the severity of accidents that may occur in them. Accidents in road tunnels may lead to heavy consequences for the users, the infrastructure itself and the environment. Within this context the European Commission launched the Directive 2004/54/EC that sets basic requirements and suggests the implementation of a risk assessment in several cases apart from the measures imposed based on tunnel length and traffic volume. Since the EU Directive does not indicate the method for performing the 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 (DGs) through a tunnel, they do not take into account several organizational and human 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 methodology in order to provide more sophisticated estimations of the tunnel operator’s performance in safety critical situations. This paper couples the results produced by the fuzzy logic system with the input parameters for a road tunnel QRA model (namely the OECD/PIARC DG-QRA Model). The results from the analysis reveal that the estimations of the tunnel operator’s performance produced by the fuzzy system significant affect the results of the road tunnel QRA. Therefore, it is deduced that the proposed fuzzy system can serve as a useful tool for the analyst to consider organizational and human factors so as to enhance the analysis and highlight the uncertainty related to human performance variability.

1. Introduction

Over the last two decades a great increase has been noticed in the number of road tunnels worldwide and all the indications are that this number will continue to increase in the coming years. However, the increasing number of these infrastructures is raising upfront an endogenous problem, which is the severity of accidents that may occur (Kirytopoulos et al., 2010). Especially when transportation of dangerous goods (DGs) is allowed through a road tunnel, the consequences of a possible accident take the form of a societal risk due to its potential extensive impact (Fabiano et al., 2005). Taking into account that the risk connected to dangerous goods (DGs) transport is comparable with the fixed plants one (Fabiano et al., 2002), tunnel authorities are requested to make risk-informed decisions as to whether such transport

Please cite this article as: Kazaras K., Konstandinidou M., Nivolianitou Z. and Kirytopoulos K., 2013, Enhancing road tunnel risk assessment with a fuzzy system based on the cream methodology, Chemical Engineering Transactions, 31, 349-354 DOI: 10.3303/CET1331059

should be permitted in road tunnels (EU-Directive, 2004). 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 subjected to many limitations (Kazaras et al., 2012). One of the most striking one is the fact that the performance variability of the tunnel operator is not taken into consideration by the analyst. Following this line of thought, this paper proposes a fuzzy logic system based on CREAM methodology in order to provide more sophisticated estimations of the tunnel operator's performance in safety critical situations. The developed fuzzy system takes into account factors that particularly affect operators' response time to activate safety critical systems and produces numerical values which can be further incorporated in 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. 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 some weaknesses of current road tunnel QRAs are mentioned. 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 concludes this work.

2. QRA in road tunnels

2.1 General concept and the OECD/PIARC DG-QRA Model

The increase in tunnel fires in Europe over the past decade, resulting in many human and financial losses, highlighted safety in tunnels as a matter of utmost importance. 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. An extended literature review of the QRA methods currently applied in the road tunnels field can be found in PIARC (2008a). The models 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. Other QRA methods that have been proposed in the road tunnels domain can be found in the relevant literature (Nyvlt et al., 2011).

The OECD / PIARC QRA Model, which is the most widely used model for the risk assessment of DGs transport through road tunnels (PIARC, 2008a) considers 13 accident scenarios. These accident scenarios (namely: HGV fire 20 MW, HGV fire 100 MW, BLEVE of LPG in cylinder, motor spirit pool fire, VCE of motor spirit, chlorine release, BLEVE of LPG in bulk, VCE of LPG in bulk, torch fire of LPG in bulk, ammonia release, acrolein in bulk release, acrolein in cylinders release, BLEVE of carbon dioxide in bulk) are representative of the groupings of DGs by ADR and have been chosen to examine different severe effects such as overpressure, thermal effect and toxicity. The most important inputs of the Model include the technical characteristics of the tunnel and the traffic data. The outcome of the Model is the average annual number of fatalities caused by accidents involving DGs which is called expected value (EV), as well as the relevant F/N curves which present graphically the frequency (F) of accidents with N or more victims. The safety evaluation of the tunnel based on the outcomes produced by the Model is made either on a comparative basis (comparison to alternative routes) or according to the positioning of the F/N curves compared to ALAPR limits (INERIS, 2005). A detailed risk assessment with the OECD/PIARC DG-QRA model can also be found in Kirytopoulos et al. (2010).

2.2 Challenges to cope with human and organizational aspects

Although QRA contribution to manage tunnels safety has been great (PIARC, 2008a), current risk assessment methods are also subjected to many limitations. Kazaras et al. (2012) have mentioned several aspects that might not be handled well by current road tunnel QRAs, with the tunnel operator's performance variability forming a major challenge that the analyst must overcome. Tunnel operators play a significant role in the safety and operation of the tunnels (PIARC, 2007), particularly in the detection and mitigation of critical events. In order to improve tunnel operators' performance, possible solutions can be found in terms of: recruitment (by imposing the proper selection criteria), training and exercise, task support (such as procedures and guidelines), control room and interface design (PIARC, 2008b). However, such aspects even though they greatly affect the operators' performance are usually omitted from the analysis. This paper aspires to fill this research gap by proposing a fuzzy logic system for estimating the tunnel operator's response time reaction, a variable which can be further incorporated in a QRA model.

3. A Fuzzy model for tunnel operator's response time reaction

3.1 The fuzzy logic as a modeling tool

Fuzzy logic theory has emerged over the last years as a useful tool for modeling processes which are too complex for conventional quantitative techniques or when the available information from the process is qualitative, inexact or uncertain. The reason for this rapid development of fuzzy systems is simple. Fuzzy logic addresses qualitative information perfectly as it resembles the way humans make inferences and take decisions. Fuzzy logic starts with the concept of a fuzzy set. A fuzzy set is a set without a crisp, clearly defined boundary. The fundamental difference of fuzzy logic compared to conventional modeling techniques is on the definition of sets. Traditional set theory is based on bivalent logic where a number or object is either a member of a set or it is not. Contrary to that, fuzzy logic allows a number or object to be a member of more than one set and most importantly it introduces the notion of partial membership. A degree of membership in a set is based on a scale from 0 to 1 with 1 corresponding to complete membership and 0 meaning no membership. Several fuzzy logic systems have been proposed for human reliability analysis to calculate not only the probability of erroneous actions (Konstandinidou et al., 2006) but also the dependence between human actions (Zio et al. 2009) as well as the estimation for the response time of the operator in the performance of a critical task (Konstandinidou et al. 2010). In this paper authors are presenting the development of a fuzzy system for the estimation of tunnel's operator response time in critical situations.

3.2 Development of a fuzzy logic system based on CREAM methodology

3.2.1 Selection of the input parameters

In order to develop the fuzzy system for the estimation of the tunnel operator's response time to activate safety critical systems, CREAM methodology (Hollnagel, 1998) has been selected among the most known and used methods for Human Reliability Analysis. Taking into account that the tunnel operator's performance is a function of many factors, the selection of the input parameters has been made so that the most important influencing factors have been considered, while maintaining the system at a reasonable size. Based on the aforementioned criteria, three out of nine –normally used- input parameters that are used in the CREAM have been selected. These parameters are: the adequacy of man-machine interface (MMI), the availability of procedures and the adequacy of training and experience. The aforementioned criteria have been also mentioned as major performance shaping factors in the road tunnels safety related literature (PIARC, 2008b). Finally, a unique output parameter has been defined and that is the 'Tunnel Operator's Response Time', meaning the response time of the tunnel operator to activate the emergency equipment of the tunnel (i.e. emergency ventilation and systems to close safely the tunnel).

3.2.2 Development of the fuzzy sets

At this step in order to better depict the impact of each input parameter, the risk analyst should associate two or more fuzzy sets for the description of the parameter. For the development of the particular fuzzy sets it has been considered that design options and procedures may significantly differ from tunnel to tunnel. However, based on the relative literature (PIARC, 2008b) it can be deduced that typical characteristics of fuzzy sets for the input and the output parameter can be the following:

Adequacy of MMI: Three fuzzy sets, namely 'Inappropriate', 'Adequate' and 'Supportive' have been defined on the input space of this variable. The MMI is characterized as 'Inappropriate' if the system does not produce any visual signs. It is characterized as 'Adequate' if the system produces alarms and visual signs when there is smoke in the tunnel and finally it is characterized as 'Supportive' if the system produces alarms (visual and sound signals) and also the tunnel is supervised by a Close Circuit Television (CCTV) that enables the visual location of the smoke point.

Availability of procedures: Two fuzzy sets have been defined for this variable, namely 'Inappropriate' and 'Appropriate'. The procedures are characterized as 'Appropriate' if emergency plans are in paper in the control room -or electronically available within the Supervisory Control and Data Acquisition (SCADA) system- AND emergency plans are revised after emergency exercises and real accidents. On the contrary, the procedures are characterized as 'Inappropriate' if emergency plans are not found in the control room (or not electronically available within the SCADA) OR emergency plans are not revised after emergency exercises and real accidents.

Adequacy of training and experience: As in the previous input parameter, two fuzzy sets have been defined named respectively, 'Inadequate' and 'Adequate'. The training and experience are characterized as 'Appropriate' if there are specific recruitment criteria in the tunnel organization concerning tunnel operators' selection AND if training sessions are periodically provided. If the aforementioned criteria are not fulfilled then the training and experience are characterized as 'Inappropriate'.

The output parameter '*Tunnel Operator's Response Time'* has to cover the time interval between 0 and 10 minutes. After this time it is very difficult to control a fire in the tunnel (PIARC, 2007) so the fuzzy sets and their time intervals are presented in Table 1.

Table 1: Output fuzzy sets for the Tunnel Operator's Response Time

Fuzzy Set	**Time Interval (s)**
Very Good	0 < t < 120
Good	60 < t < 180
Normal	90 < t < 300
Critical	240 < t < 600

3.2.3 Development of the fuzzy rules

Literature review (PIARC, 2008b) and expert judgment were the knowledge base for the development of the fuzzy rules. It should be noticed that the development of fuzzy rules in every application is based on the knowledge and on the experience of the analyst regarding the specific application. The rules are constructed in simple linguistic terms and can be understood at a common sense level. These rules result in specific and reproducible results (same inputs give same output).The first rule of the system is: "if the MMI is inappropriate, the availability of procedures is inappropriate and the adequacy of training is inadequate then the tunnel operator's response time is critical". The other rules have been defined accordingly as presented in Table 2.

Table 2: The fuzzy rules of the system

MMI	**Procedures**	**Training and Experience**	**Output**
Inappropriate	Inappropriate	Inadequate	Critical
Inappropriate	Appropriate	Adequate	Critical
Inappropriate	Inappropriate	Adequate	Critical
Inappropriate	Appropriate	Inadequate	Critical
Adequate	Inappropriate	Inadequate	Normal
Adequate	Inappropriate	Adequate	Normal
Adequate	Appropriate	Inadequate	Good
Adequate	Appropriate	Adequate	Very Good
Supportive	Inappropriate	Inadequate	Normal
Supportive	Inappropriate	Adequate	Good
Supportive	Appropriate	Inadequate	Good
Supportive	Appropriate	Adequate	Very Good

3.3 Application of the fuzzy system in conjunction with the OECD /PIARC DG-QRA Model

Since the final output of the fuzzy system should be a crisp number for the tunnel operator's response time, the fuzzy output needs to be 'defuzzified'. This is done through the centroid defuzzication method and is based on the analytical calculation of the "gravity" centre of the produced area for the combined membership function produced from the fuzzy inference. After the estimation of operators' response time with the developed fuzzy system, the estimated response times can be used as input parameters for a conventional road tunnel QRA model, such as the OECD/PIARC DG-QRA Model. As far as the OECD/PIARC DG-QRA Model is concerned, the tunnel operator's response time affect two particular input variables of the model. The first one is the ‘time taken to activate the emergency ventilation’ and the other is the ‘time delay for stopping approaching traffic’. Current road tunnel risk analysis methods, such as the OECD/PIARC DG-QRA Model, only requests the operator’s response time as an input parameter without considering the conditions that may affect this variable. Therefore, the proposed fuzzy logic system can be used in this step of the analysis so as to consider some basic human and organizational aspects. In order to examine the influence of the variance of the tunnel operator’s response time on the overall risk level a sensitivity analysis with the OECD/PIARC DG-QRA Model has been made. The examined case study that has been used for the analysis is a Greek road tunnel with the following characteristics:

Table 3: Tunnel Characteristics

Tunnel Characteristics	
Type	Twin-Bore
Length	1500 m
Emergency Ventilation (longitudinal)	330 $m^{3/}s$
Average spacing between emergency exits	350 m
Traffic volume (both directions)	7500 vehicles/d
Percentage of DGs- Heavy Goods Vehicles	12 %

According to the estimates of the fuzzy system a tunnel operator with adequate training, appropriate procedures and adequate MMI will react in 60 s, whereas a tunnel operator with inappropriate MMI, appropriate procedures and inadequate training will react in 420 s. These response times are introduced as an input in the OECD/PIARC DG-QRA Model and the results are presented in the following section.

4. Results and conclusions

The outcome of the OECD/PIARC DG-QRA Model is the expected number of fatalities (EV) per year caused by accidents involving DGs in the tunnel. The EV has been estimated $2.44*10^{-3}$ for operator’s response time 60 s whereas it has been estimated $4.13*10^{-3}$ for operator’s response time 420 s keeping all other input parameters in the QRA model stable. Thus, the estimated risk for tunnel operator’s response time in 420 s is almost two times higher than the one for tunnel operator’s response time in 60 s. Moreover, there is difference in the F/N curves related to the two different response times, as depicted in Figure 1, in which the vertical axis corresponds to the cumulated frequency whereas the horizontal axis corresponds to the expected number of fatalities.

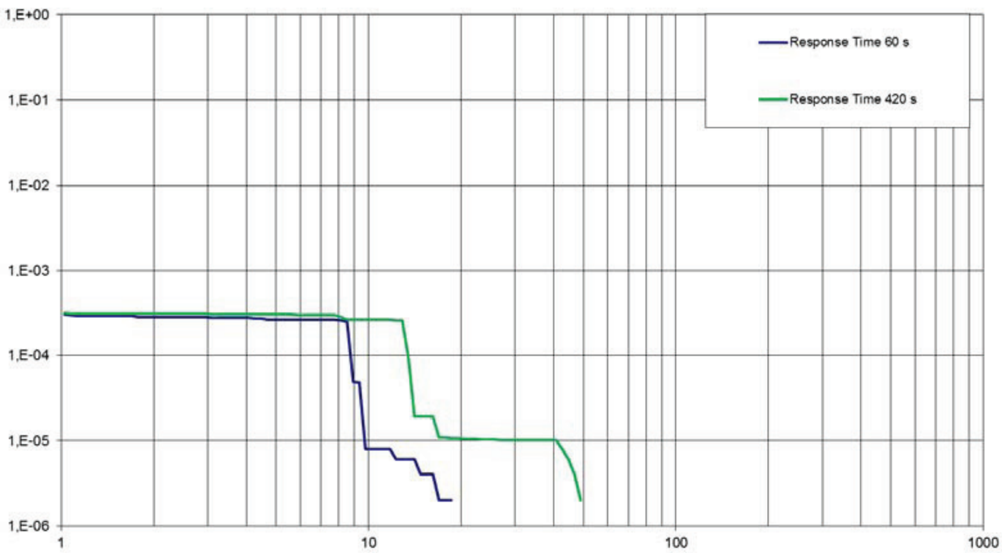

Figure 1: The results of the analysis

Concerning the F/N curve, the first observation to note is that response time in 420 s has the potential to lead to much more fatalities in the road tunnel than response time in 60 s. Therefore, the curves are not very distinct for a low number of fatalities (up to 9 fatalities) whereas they are significantly different for high lethality. Concluding, it can be deduced that the proposed fuzzy system has succeeded in providing more sophisticated estimations of the tunnel operator's performance in safety critical situations which significant affect the results of road tunnel QRAs. Following this line of thought, the proposed fuzzy system can serve as a useful tool for the analyst to consider organizational and human factors so as to enhance the road tunnel risk assessment and highlight the uncertainty related to humans' performance variability. This is of utmost importance especially when DGs are transported via the tunnel. In such cases the consequences of accidents may have tremendous effects (Giacone et al., 2012). By running different scenarios with the fuzzy system the importance of different human and organizational factors on the overall risk can be depicted. The proposed fuzzy system can be also expanded to incorporate other Common Performance Conditions (CPCs) mentioned in the CREAM methodology (Hollnagel, 1998), such as: the adequacy of the organization, the number of simultaneous goals for the tunnel operator and the time of day (related to the circadian rhythm and the shift changes). In this way more human and organizational aspects can be taken into consideration. Moreover, in order to identify the majority of organizational aspects and systemic factors that affect road tunnels safety, the analysis can be enhanced by sophisticated accidents models, such as the STAMP approach (Hardy et al., 2011). Nevertheless, in order to check the results produced by the fuzzy system, future work should concentrate on evaluating the results with data from real tunnel operations in safety critical situations, as well as from emergency exercises.

References

EU Directive 2004/54/EC, 2004, Directive 2004/54/EC of the European Parliament and of the Council on minimum safety requirements for tunnels in the Trans-European Road Network, European Commission, Directorate-General for Energy and Transport, Brussels, Belgium.

Fabiano B., Curro F., Pallazzi E.,Pastorino R., 2002, A framework for risk assessment and decision-making strategies in dangerous good transportation, Journal of Hazardous Materials, 93, 1-15.

Fabiano B., Curro F., Reverberi A.P., Pastorino R., 2005, Dangerous good transportation by road: from risk analysis to emergency planning, Journal of Loss Prevention in the Process Industries, 18, 403-413.

Giacone M., Bratta F., Gandini P., Studer L., 2012, Dangerous goods transportation by road: a risk analysis model and a global integrated information system to monitor hazardous materials land transportation in order to protect territory, Chemical Engineering Transactions, 26, 579-584.

Hardy K., Guarnieri F., 2011. Modelling and hazard analysis for contaminated sediments using STAMP model, Chemical Engineering Transactions, 25, 737-742.

Hollnagel E., 1998, Cognitive reliability and error analysis method (CREAM) Elsevier Science Ltd, Amsterdam, the Netherlands

INERIS, 2005, Transport of Dangerous goods through road tunnels, Quantitative Risk Assessment Model (v. 3.60 and v. 3.61) Reference Manual, Verneuil-en-Halatte, France.

Kazaras K., Kirytopoulos K., Rentizelas A., 2012, Introducing the STAMP method in road tunnel safety assessment, Safety Science, 50, 1806-1817.

Kirytopoulos K., Rentizelas A., Kazaras K., Tatsiopoulos I., 2010, Quantitative operational risk analysis for dangerous goods transportation through cut and over road tunnels. In Ale, B. Papazoglou, I. & Zio, E. (eds.), Back to the future. Proceedings of European Safety and Reliability Conference 2010 (ESREL 2010), Rhodes, Greece,.

Konstandinidou M., Nivolianitou Z., Kiranoudis C., Markatos N., 2006, A fuzzy modeling application of CREAM methodology for human reliability analysis, Reliability Engineering and System Safety, 91, 706-716.

Konstandinidou M., Nivolianitou Z., Kiranoudis C., Markatos N., 2010, Fuzzy systems for the estimation of operators response time in critical situations, 13th International Symposium on Loss Prevention, 6-9 June 2010, Bruges, Belgium.

Nývlt O., Prívara S., Ferkl L., 2011, Probabilistic risk assessment of highway tunnels, Tunneling and Underground Space Technology 26, 71-82.

PIARC, 2007, Integrated Approach to Road Tunnel Safety, World Road Association (PIARC), France.

PIARC, 2008a, Risk analysis for road tunnels, World Road Association (PIARC), France.

PIARC, 2008b, Human factors and road tunnel safety regarding users, World Road Association (PIARC), France.

Zadeh L.,1965, Fuzzy Sets, Information and Control, 8, 338-353.

Zio E.,Baraldi P., Librizzi M., Podofillini L., Dang V.N., 2009, A fuzzy set-based approach for modeling dependence among human errors, Fuzzy Sets and Systems, 160 (13), 1947-1964.