National Technical University of Athens

School of Mechanical Engineering

Sector of Industrial Management and Operations Research

Doctoral Thesis

Developing a quantitative fire risk assessment method for critical infrastructures: The case of road tunnels

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Submitted by

Panagiotis N. Ntzeremes

Diploma in Mechanical Engineering, National Technical University of Athens

Supervisory Committee

Professor Ilias Tatsiopoulos

Professor Vrassidas Leopoulos

Associate Professor Stavros Ponis

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ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

Ανάπτυξη ποσοτικής μεθόδου αποτίμησης επικινδυνότητας πυρκαγιάς σε υποδομές κρίσιμης σημασίας: Η περίπτωση των οδικών σηράγγων

Υποβληθείσα από

Παναγιώτης Ν. Ντζερεμές

Διπλωματούχος Μηχανολόγος Μηχανικός ΕΜΠ

Συμβουλευτική επιτροπή

Καθηγητής Ηλίας Τατσιόπουλος

Καθηγητής Βρασίδας Λεώπουλος

Αναπληρωτής Καθηγητής Σταύρος Πόνης

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Dipl. Eng. Panagiotis Ntzeremes

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Table of Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

AADT	Annual Average Daily Traffic
AAT	Tunnel Administrative Authority
ADR	Agreement concerning the International Carriage of Dangerous Goods by Road
AHP	Analytic Hierarchy Process
ALARP	As Low As Reasonable Practicable
ANAS	Azienda Nazionale Autonoma delle Strade
ASET	Available Safe Egress Time
ASFiNAG	Autobahnen und Schnellstraßen Finanzierungs Aktiengesellschaft
BASt	Federal Highway Research Institute
BLEVE	Boiling Liquid Expanding Vapor Explosion
CAMATT	Calcul Monodimensionnel Anisotherme Transitoire en Tunnel
CETU	Centre d'études des tunnels
CFD	Computational Fluid Dynamics
CI	Consistency Index
CR	Consistency Ratio
CO	Carbon monoxide
DGs	Dangerous goods
DSA	Dutch scenario analysis method
EC	European Commission and the Council
ELECTRE	Elimination and Choice Expressing Reality
EU	European Union
EUR-Lex	European Legislation database
Euro 6	European emission standard 6
EUROTAP	European Tunnels Assessment Programme
EV	Expected Value
FDS+Evac	Fire Dynamics Simulator with Evacuation
FED	Fractional Effective Dose
FED_h	Fractional Effective Dose of radiant and convective heat
FED_{co}	Fractional Effective Dose of Carbon monoxide
F/N	Frequency/Number of fatalities

HGV	Heavy Goods Vehicles
HRR	Heat Release Rate
HRR_{max}	maximum Heat Release Rate
INERIS	Institut national de l'environnement industriel et des risques
IRA	Italian Risk Analysis method
ISO	International Organization for Standardisation
ITA	International Tunnelling Association
MATLAB	Matrix Laboratory
MCS	Monte Carlo Simulation
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NTUA	National Technical University of Athens
Ob	Research Objective
OECD	Organisation for Economic Co-operation and Development
OMOE	Road Construction Studies Guidelines
PIARC	Permanent International Association of Road Congresses or World Road Association
PROMETHE	Preference Ranking Organization Method for Enrichment of Evaluations
Q	Research Question
QRA	Quantitative Risk Analysis
RABT	Regulations for the equipment and operation of road tunnels
RI	Consistency index of a random-like matrix
RSET	Required Safe Egress Time
RWS	The Directorate-General of Public Works and Water Management
Safe-T	Safety in Tunnels Thematic Network
SAM	Scenario Analysis Method
SCADA	Supervisory Control and Data Acquisition
SFPE	Society of Fire Protection Engineers
SHI	Specific Hazard Investigation
SRA	Society of Risk Analysis
STEPS	Agent-based simulation software

TERN	Trans-European Road Network
TuRisMo	Austrian Tunnel Risk Model
UNECE	United Nations Economic Commission for Europe
UPTUN	Upgrading fire safety of existing tunnels
USA	United States of America

Abstract

Road transport is at the heart of critical development challenges for both modern economies and societies. Therefore, it should guarantee a high level of safety to the public. With a view to enhance road network’s safety, it is crucial to focus primarily on its critical infrastructures, one part of which is tunnels. Tunnels are the most sophisticated elements of the road infrastructure. Tunnels are regarded as complex socio-technical systems. Although tunnels benefit the operation of road networks, their use involves the risk that a potential dysfunction of a tunnel can cause serious dysfunction on the broader road network due to its interdependencies. This dysfunction can be particularly extensive in case of a fire accident. Fire is the foremost critical event for road tunnels’ safety. The severity of tunnel fires is related to some special attributes of these infrastructures. Fire safety of tunnels concerned intensely the public opinion after the disastrous trans-Alpine accidents in Europe in the late 90s. Therefore, risk assessment was officially introduced for ensuring tunnels’ level of safety. Despite the significant progress, it is disputable whether just applying any risk assessment method is capable of ensuring preparedness against a fire accident.

The review emerges the fact that important parameters for the safe operation of the tunnel system have significant uncertainty. Although these parameters play a key role in tunnel performance, current methods act on a deterministic approach ignoring thus their embedded uncertainties. Faced with these uncertainties, safety analysts make assumptions adopting a “mean” value or a “worst case” scenario. But, the variation to reality because of these assumptions can create serious fallacies regarding the estimated level of tunnel safety. Placed next to the potential risks due to the aforementioned deficiencies, the review indicates another important issue. Although the choice of additional to standard safety measures involves multiple criteria and a ranking of alternatives, current methods lack in dealing with and thus they pose challenges to risk assessment. Therefore, it is imperative to develop more robust risk assessment methods in order to deal with the impact of uncertainty on the tunnel fire safety, which current methods exhibit lack in dealing with.

This thesis presents a novel quantitative risk assessment method, named SIREN, aiming at enhancing road tunnels’ operational risk assessment regarding fire accidents. The stochastic-based approach of SIREN mitigates the fallacies arising from the traditional deterministic methods.

The structure of the method is as follows. Initially, examining tunnel system's parameters, the ones that should be treated as stochastic are identified. Subsequently, considering one-dimensional analysis for both estimating tunnel airflows and trapped-users' evacuation, the potential losses are estimated. Finally, by accumulating the results deriving from the Monte Carlo Simulation, the distribution of the trapped-users losses occurs, illustrating the system's level of safety. The SIREN method is illustrated through the case of an urban underground road tunnel during rush hour. The outcome highlights a significant proportion of scenarios that exceed the number of losses estimated by the traditional methods. Furthermore, the proposed method offers the possibility of examining the parameters' criticality, which assists safety analysts in choosing additional safety measures, if needed. In this way, the tunnel's level of safety is increased to as low as reasonable practicable.

Furthermore, this thesis proposes also the EVADE method in order to support the decision-making process towards the selection of fire safety measures for road tunnels. This method provides a systematic decision process through the use of particular and consistent decision criteria, together with considerations of alternative safety measures which are based on the stated subjective preferences of the decision-maker. It can be applied in addition to SIREN or independently. The method incorporates diverse stakeholders' views while it introduces a list of the most significant criteria that are valuable to judge the appropriateness of selected measures. The relative importance amongst the decision criteria is calculated through the Analytic Hierarchy Process, based on the expert opinion. Meanwhile, by applying the Monte Carlo simulation, the ranking of alternatives is considered reliable since it includes potential uncertainty related to the pairwise comparisons amongst all pairs of decision criteria as well as alternatives. Contrary to current approaches, the alternatives' ranking comes as a distribution instead of a single number providing the decision-maker richer information for selecting the most suitable measure(s) according to the specific tunnel's situation. The utilisation of the method is presented through an illustrative case of a typical European tunnel.

The results of this research provide a novel approach for enhancing the level of safety of road tunnels and the produced methods can be applied in all types of tunnels.

Abstract (in Greek)

Η παρούσα διδακτορική διατριβή αποσκοπεί να συνεισφέρει στη βελτίωση της ασφάλειας του οδικού δικτύου και συγκεκριμένα τις κρίσιμες υποδομές του, μια από τις οποίες είναι οι σήραγγες. Οι σήραγγες θεωρούνται σύνθετα κοινωνικό-τεχνικά συστήματα. Η φωτιά θεωρείται το σημαντικότερο κρίσιμο γεγονός για την ασφάλεια των οδικών σηράγγων. Έτσι και μετά από τα καταστροφικά ατυχήματα στις Άλπεις στα τέλη της δεκαετίας του '90, η συστηματική διαδικασία της αποτίμησης επικινδυνότητας εισήχθη για την εξασφάλιση ενός υψηλότερου επιπέδου ασφάλειας των σηράγγων. Παρά τη σημαντική πρόοδο που έχει συντελεστεί, υπάρχουν ακόμα περιθώρια βελτίωσης των μεθόδων αποτίμησης επικινδυνότητας ώστε να εξασφαλίζεται ακόμα καλύτερα η ετοιμότητα του συστήματος της σήραγγας έναντι ατυχήματος πυρκαγιάς.

Η ανασκόπηση της σχετικής βιβλιογραφίας που διεξήχθη στο πλαίσιο της παρούσας διατριβής, ανέδειξε το γεγονός ότι σημαντικές παράμετροι για την ασφαλή λειτουργία του συστήματος της σήραγγας εμπεριέχουν σημαντική αβεβαιότητα. Αν και αυτές οι παράμετροι διαδραματίζουν σημαντικό ρόλο στην απόδοση της σήραγγας σε ένα κρίσιμο γεγονός, οι τρέχουσες μέθοδοι δρουν σε μια ντετερμινιστική προσέγγιση, χωρίς να λαμβάνουν υπόψη τις αβεβαιότητες αυτές.

Για να αντιμετωπίσει αυτό το ζήτημα, η παρούσα διδακτορική διατριβή παρουσιάζει μια νέα μέθοδο ποσοτικής αποτίμησης επικινδυνότητας, που ονομάζεται SIREN, με στόχο την ενίσχυση της αποτίμησης της επικινδυνότητας των οδικών σηράγγων σχετικά με τα ατυχήματα πυρκαγιάς κατά τη λειτουργία τους. Η στοχαστική προσέγγιση της μεθόδου μετριάζει τους περιορισμούς που προκύπτουν από τις παραδοσιακές μεθόδους. Επιπλέον, προσφέρει τη δυνατότητα εξέτασης της κρισιμότητας των παραμέτρων, η οποία βοηθά τους αναλυτές να επιλέγουν πρόσθετα μέτρα ασφαλείας, αν αυτό χρειαστεί. Με τον τρόπο αυτό, η επικινδυνότητα της σήραγγας μειώνεται τόσο χαμηλά όσο λογικά είναι δυνατόν. Η μέθοδος SIREN παρουσιάζεται μέσω εφαρμογής σε υποθετική υπόγεια αστική οδική σήραγγα κατά την ώρα αιχμής.

Επιπλέον, η παρούσα διδακτορική διατριβή προτείνει τη συμπλήρωση της προτεινόμενης μεθόδου SIREN με τη μέθοδο EVADE για τη στήριξη της διαδικασίας λήψης αποφάσεων για την επιλογή μέτρων πυρασφάλειας στις οδικές σήραγγες. Η μέθοδος ενσωματώνει τις διαφορετικές απόψεις των ενδιαφερομένων μερών ενώ εισάγει έναν κατάλογο με τα σημαντικότερα κριτήρια που είναι πολύτιμα ώστε να κριθεί η καταλληλόλητα των επιλεγμένων μέτρων. Σε αντίθεση με τις τρέχουσες προσεγγίσεις, η κατάταξη των εναλλακτικών λύσεων έρχεται ως κατανομή αντί για μια απλή κατάταξη, παρέχοντας στον αναλυτή πλουσιότερες πληροφορίες για την επιλογή

του καταλληλότερου μέτρου ανάλογα με τα χαρακτηριστικά της εξεταζόμενης σήραγγας. Η χρήση της μεθόδου παρουσιάζεται μέσω εφαρμογής της σε μια τυπική ευρωπαϊκή σήραγγα. Διευκρινίζεται ότι η ανάλυση περιορίζεται σε αναλύσεις που δεν περιλαμβάνουν τη διέλευση επικίνδυνων εμπορευμάτων.

Τα αποτελέσματα αυτής της διδακτορικής έρευνας παρέχουν μια νέα προσέγγιση για τη βελτίωση του επιπέδου ασφάλειας των οδικών σηράγγων και οι παραγόμενες μέθοδοι μπορούν να εφαρμοστούν σε όλους τους τύπους σηράγγων.

Chapter 1

Introduction

1. Introduction

1.1 The importance of tunnels' fire safety for road transport

Road transport is at the heart of the critical challenges for both modern economies and societies. Enabling the exchange of goods, road transport promotes countries' internal and external markets while it empowers people to travel at regional, national and international level. Recent studies have indicated that road transport still keeps the lead in the transportation sector (EC, 2017b) whilst road network has been growing as well as modernising constantly worldwide over the last two decades (Ntzeremes and Kirytopoulos, 2019). The significance of road transport is highlighted through the World Bank's latest report, which projects that the number of vehicles on the road is expected to double and reach two billion by 2050 globally (World Bank, 2018).

In Europe particularly road transport is regarded as a fundamental factor in strengthening the European cohesion. Initially, providing a high level of flexibility in linking all the regions of the EU, it boosts EU's economic growth. Meanwhile, road transport enables the European citizens to travel freely in a national, regional and local level (EC, 2017b). In order to accomplish the aforementioned goals while confronting with resource and environmental constraints since the transport sector is responsible for 20% of EU27 CO_2 emissions (EC, 2017c), the EC established the TERN in the mid-90s (EC, 1993). TERN is consisted of all the EU member states' motorways that connect Europe between West and East, North and South. TERN is estimated to encompass 90,000km of motorways and high-quality roads by 2021 (EC, 2017a). The importance of TERN is highlighted as road transport possesses the highest share in the transportation of goods and passengers within the EU. The latest report of 2016 indicated that the transport of goods was estimated 3,524 billion tkm during 2016 with 49% of them were transported by road. Meanwhile, the transport of passengers was estimated 6,591 billion pkm with 72.38% of them were transported by road (EC, 2016). Provided that the economic growth and the increase in traffic volumes urge authorities for upgrading network's quality, road network should guarantee a high level of safety to the public since the quality level is strongly related to the safety level.

The goal for enhancing the overall level of road network's safety is related to the safety of its elements, namely: (a) the infrastructure, (b) the users, (c) the vehicles and last but not least (d) the different regulative requirements each country has adopted.

As far as infrastructure is concerned, the latest EU's White Paper on transport has named infrastructure as the decisive factor that shapes mobility in road network by supporting an adequate and intelligent network. Simultaneously, infrastructure is considered to render a positive impact on geographical accessibility, benefit economic growth, and empower mobility (EC, 2011). Tunnels particularly constitute a key element of road network's infrastructure (Beard and Cope, 2008).

Tunnels for road transport exist for centuries. In general, they are divided into urban and rural tunnels depending on their different operational and construction characteristics. Regarding urban areas, they are characterised by the high density of population as well as the high occupation on the surface and the extended perimeter of the city centres, all of which result in growing the demand for travel and mobility. Aiming to meet the requirements for efficient and less polluting urban road networks, authorities have put pressure on vehicles' technology by imposing tighter emission and noise standards (i.e. Euro 6 emission standard (EC, 2007)). Nevertheless, the steadily growing traffic volumes have caused urban road networks suffering by traffic congestion, which subsequently results in multiple adverse effects such as the excessive environmental pollution and noise deriving from vehicles' fumes and engines. Furthermore, traffic congestion is responsible for drivers' frustration while the cost of fuel as well as the significant loss of productive hours in every day movements increase the financial losses (Ernst et al., 2006; Menelaou et al., 2017).

Commonly formed as underground constructions, urban tunnels respond to the aforementioned needs by providing an efficient underground road corridor to move people and goods in urban areas preserving concurrently the land above for residential or public uses. Due to the growing land values in urban areas along with the advance of construction technology, underground infrastructures have become an economically viable solution compared to the classic ground network in the development of modern urban road networks (Ernst et al., 2006; Legacya et al., 2017). They meet specific environmental requirements by achieving accessibility and connecting remote urban areas, bypassing the difficulties arising from existing inner city build environment, and thus relieving environmental noise and pollution (Ntzeremes and Kirytopoulos, 2018b).

On the other hand, rural tunnels have been developed in order to enable crossing mountainous areas and creating shortcuts without changing the environment in the countryside (Kirytopoulos et al., 2017). Their importance is related to the fact that they minimise the environmental impact, the time and the transportation costs.

Due to the significant improvement of underground space technology in recent years (tunnelling cost decreases approximately 2% to 3% per year), tunnels have been rendered as a cost-effective engineering solution in developing new road networks (Maidl et al., 2014; Kaliampakos et al., 2016). As a consequence, their number is increasing as more and more tunnels are developing specifically in Asian countries, like China due to the economic growth (Ren et al., 2019) but also in Europe as part of the infrastructure enhancement (Ntzeremes and Kirytopoulos, 2019). Hence, the number of people and the volume of goods transported through them are increasing, too (ITA, 2019).

Despite the aforementioned advantages, the increasing use of tunnels emerges with emphasis an endogenous problem that is the severity of potential accidents. Although tunnel accidents have been reduced, tunnels are still considered risky environments (NTUA, 2013). The ground for such an assumption is the nature of accidents that might occurred, which could cause catastrophic consequences in terms of human loses, structural damage and unaffordable economic repairs (Voeltzel and Dix, 2004). Especially fire accidents, although they are very rare, when they occur, the peculiarity of the fire behaviour intensifies the disastrous consequences (Beard and Carvel, 2012; Ingason et al., 2015; Ntzeremes and Kirytopoulos, 2019). The experience from previous fire accidents in recent past as the fire in Mont Blanc in France (1999; 39 fatalities), the fire in Frejus in France (2005; 2 fatalities and 21 injuries) and the fire in Yanhou in China (2014; 40 fatalities) revealed such consequences. Hence, fire accidents are considered of major importance and they must be taken into account in order to design an adequate safety strategy during the operation phase of a tunnel.

To this respect, authorities have been forced to impose more rigorous fire requirements for road tunnels. The USA issued the NFPA 502 standard, which is revised regularly (NFPA, 2014). NFPA 502 standard includes the minimum requirements for road tunnels in both the construction and the operational phases. PIARC, which is a non-profit global organisation responsible for roads, issued relevant reports in which the state-of-the-art practices towards tunnel safety are included (PIARC, 1999; 2007; 2008). As far as the EU is concerned, fire safety of road tunnels was renewed due to the severe alpine tunnel fire accidents in the late 90s. As a result, the Directive 54/2004/EC on the 24th of April of 2004 was introduced. The Directive issued specific minimum infrastructure and equipment requirements, which all road tunnels longer than 500m that are part of TERN should comply with. Furthermore, the Directive includes the prevision that each member state has to adopt risk assessment in order to enhance tunnels' safety (EC, 2004, p.52).

In doing so, risk-based approach was introduced officially in the field of road tunnels. Nevertheless, the authorities together with safety analysts around the world, are constantly pursuing better and more reliable results with regard to tunnel safety. Thus, the development of efficient risk assessment methods that can help tunnel managers to achieve the safety objectives is definitely a challenge.

1.2 Description of the research problem

The rapid growth of tunnels implies that more fire accidents may occur in the future (ITA, 2019). The better the planning and risk assessment methods, the better the preparedness level is going to be. Various risk assessment methods have been developed over the last fifteen years (PIARC, 2008; Ntzeremes sand Kirytopoulos, 2019). Despite the significant progress, it is disputable whether just applying any risk assessment method is capable of ensuring preparedness against a fire accident.

The review of the relevant literature (see Chapter 3) emerges the fact that important parameters for the safe operation of the tunnel system have significant uncertainty. Although these parameters play a key role in tunnel performance, current methods act on a deterministic approach ignoring thus their embedded uncertainties. Faced with these uncertainties, safety analysts make assumptions adopting a "mean" value or a "worst case" scenario. But, the variation to reality because of these assumptions can create serious fallacies regarding the estimated level of tunnel safety.

Placed next to the potential risks due to the aforementioned deficiencies, Chapter 3 indicates another important issue. Although the choice of additional to standard safety measures involves multiple criteria and a ranking of alternatives, current methods lack in dealing with and thus they pose challenges to risk assessment.

Therefore, it is imperative to develop more robust risk assessment methods in order to deal with the impact of uncertainty on the tunnel fire safety, which current methods exhibit lack in dealing with. In addition, risk assessment methods should also provide safety analysts with adequate information enabling them to select the most suitable safety measure(s), when appropriate.

1.3 Aims, questions and objectives

Focusing on enhancing the level of fire safety of road tunnel systems, the aim of this thesis is to develop a method that can estimate the level of safety by integrating the stochastic behaviour of the system’s parameters that affect significantly the risk assessment process. The review of the relevant literature (see Chapter 3) showcases that current approaches keep treating deterministically tunnel system’s parameters such as the fire behaviour, the daily traffic volume or the behaviour of trapped-users during evacuation, and ignore their embedded uncertainty. Modelling deterministically these parameters affects the risk assessment process and so questions arise for the accuracy of the results. By doing so, the fallacies embedded in deterministic approaches are mitigated and the actual level of safety of the tunnel, is estimated more accurately. Meanwhile, this thesis aims also at providing the decision-maker with richer information for selecting the most suitable safety measure(s) through the use of a systematic decision process.

Based on the available literature on this topic (see Chapter 2), the optimal safety level of a road tunnel primarily depends on the reduction of human losses amongst tunnel users. This is the reason why this research endeavour focuses on estimating users’ evacuation and thus receiving valuable insights on the level of safety of the tunnel system.

The questions that guide solving the problem along with the objectives associated with are:

Q.1: Which are the vulnerable locations in tunnels with respect to fire accidents?

Ob.1.1: Investigate and evaluate relevant studies.

Ob.1.2: Simulate tunnel fire accidents.

Q.2: Which is the interrelation of the tunnel system with users during their evacuation process?

Ob.2.1: Investigate the structure and operation of current evacuation models.

Ob.2.2: Synthesise relevant data and develop an evacuation simulation model.

Q.3: How can current risk assessment methods be improved?

Ob.3.1: Investigate the current methods and identify potential deficiencies, problems and gaps.

Ob.3.2: Analyse the decision-making processes for selecting safety measures.

Ob.3.3: Develop a novel risk assessment method.

1.4 Contribution of the thesis

This thesis expands the knowledge body of the particular scientific area, mainly through:

- Identifying the limitations of the methods used for the quantitative assessment of road tunnel fire hazards,
- Developing a method of stochastic risk assessment, and
- Developing a supplementary decision-making method, can be used either in addition to the previous method or independently, for supporting the selection of fire safety measures for road tunnels.

1.4 Boundaries of the thesis

The presented thesis examines road tunnel systems. The definition of the tunnel system is provided in section 2.2. However, it is worth to define that only the “closed” part of the road is being examined in the following Chapters. Therefore, potential risks that may rise due to fire accidents in the “open” road sector near the tunnel portals, such as crashes or traffic jam that can affect the associated road network remain out of the scope of the presented analysis. Since the aim of the presented research endeavour is not an in-depth analysis of fire behaviour near the fire location but the response of the tunnel system, the analysis of the fire scenarios is carried-out through one-dimensional computation analysis. One-dimensional analysis provides adequate information about the backlayering, the operation of the ventilation system, and the stratification of both the smoke and air temperature. Another point that consists a boundary of this thesis is the selected fire scenarios. The developed methods deal with fires that give the time to users to evacuate themselves. Therefore, the examination of fires involving DGs or caused by explosion, such as BLEVEs, is excluded. At last, it must be stated that any criticism regarding the regulative requirements is out of the scope of the thesis.

1.5 Structure of the doctoral thesis

The rest of this thesis consists of eight Chapters. Chapter 2 introduces the state-of-the-art principles of fire safety management in road tunnels. At first, the criticality of tunnel fire accidents is explained through the examination of the fire behaviour and the consequences associated with. Defining the structure of the road tunnel system, the second section of this Chapter exhibits the rationale behind the change in fire safety approach and provides also the generic concept of the risk-based approach.

Since the EU is at the forefront regarding the risk assessment, in Chapter 3 a comparative analysis amongst the risk assessment methods within the EU is conducted. Despite the significant process in tunnel fire safety, important issues and key parameters of the fire safety management, highlighted either in the literature or in practice, can affect the risk assessment and, because of that, concern tunnel managers and practitioners. This review aims at assessing how current methods address all these as well as evaluates against the current literature. In the end, the research gaps are showcased.

Bearing in mind the users' role in tunnel fires, Chapter 4 critically examines the evacuation simulation models.

Chapter 5 provides in detail the research path that is followed in this thesis. The topics that are mentioned are: the research philosophy and approach, the research purpose, the research strategy and the methods used. Finally, the big picture of this thesis is depicted through a flowchart.

In order to explore the consequences of a fire accident in a tunnel, in Chapter 6, the simulation of fire scenarios in a typical Greek tunnel setting is conducted. By doing so, the knowledge from relevant studies is tested, the evolution of tunnel fire is examined and the evacuation of the trapped-users is estimate. In parallel, this Chapter investigates also the effect of national provisions on risk assessment through the use of two methods with a high degree of similarity, the Greek and the French one.

Chapter 7 issues the first contribution of this thesis. It presents the structure of the proposed SIREN method. SIREN is a novel quantitative risk assessment aiming at enhancing tunnel fire safety. The SIREN method is based on the unique characteristics of the tunnel system taking into account the variability and uncertainty of the system's stochastic parameters. Therefore, it can be applied to any type of road tunnel. The utilisation of the method is exhibited through a case study in a typical Greek tunnel. The validation confirms that the outcome is acceptable.

Chapter 8 introduces the second contribution of this thesis, the EVADE method. This method can be used either in addition to the SIREN method or independently. Through the EVADE, the gap regarding the absence of a systematic decision process for selecting safety measures is fulfilled. Initially, the structure of the method is provided and an implementation of the method is conducted in a typical Greek tunnel setting. By including multiple selection criteria and a ranking of alternatives, the stochastic-based EVADE method provides the decision-maker richer information for selecting the most suitable safety measure(s). The validation confirms that the outcome is acceptable.

Chapter 9 is the last Chapter of this thesis. It provides a coherent synthesis of the research findings on the top of the contribution on the body of knowledge. Furthermore, it suggests areas for further research while it presents the limitations of this research endeavour.

Chapter 2[1]

Fire safety management of road tunnels

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[1] Parts of this Chapter have been published in: (Ntzeremes et al., 2018; Ntzeremes and Kirytopoulos, 2018b; Ntzeremes and Kirytopoulos, 2019; Ntzeremes et al., Accepted; Kirytopoulos et al., Accepted)

2. Fire safety management of road tunnels

Fire is the foremost critical event for road tunnels' safety. Despite the existence of prescriptive requirements, there are significant deficiencies in managing tunnels since they are critical as well as complex socio-technical systems. Therefore, the use of risk assessment has been introduced after the disastrous fire accidents in Europe in the late 90s. The aim of this Chapter is twofold, at first, to present an overview of the particular characteristics of fires in road tunnels and secondly to describe the rationale behind the change in safety approach.

2.1 Fires in road tunnels

Tunnels are the most sophisticated elements of the road infrastructure (PIARC, 2016; 2017). The existence of complex surveillance systems for monitoring and detecting potential accidents (Chiu et al., 2014) along with advanced control systems for improving safety, such as the mechanical ventilation (Barbato et al., 2014) justify this description. Although the use of tunnels benefit the operation of road networks, their use involves the risk that a potential dysfunction of a tunnel can cause serious dysfunction on the broader road network due to its interdependencies (Zhuang et al., 2009). This dysfunction can be particularly extensive in case of a fire accident. Given the long period of dysfunction along with significant life loss criterion occurred in fire accidents, road tunnels are reasonably classified as critical infrastructures. Generally, a critical infrastructure can be defined as ''*... facilities of key importance to public interest whose failure or impairment could result in detrimental supply shortages, substantial disturbance to public order or similar dramatic impact*" (Gheorghe et al., 2006, p. 6). Disastrous fire accidents such as in Mont Blanc, in the boarders between France and Italy (1999; 39 fatalities), in Frejus in France (2005; 2 fatalities and 21 injuries) and in Yanhou in China (2014; 40 fatalities) have indicated the existing criticality. In addition to the heavy life loss criterion, the aforementioned catastrophes have also caused serious damages to the tunnels' infrastructure interrupting thus networks' operation for long (NTUA, 2013).

The severity of tunnel fires is related to some special attributes of these infrastructures (Ntzeremes et al., 2018). Tunnels exhibit: (a) arranged air movement due to the difference of pressure between tunnel portals, which can complicate ventilation's operation (Krol et al., 2017), (b) difficulties in approaching and rescuing users (Ronchi et al., 2013), and (c) irregularity of fire combustion (Ingason, 2008; Beard and Carvel, 2012).

Nevertheless, it is difficult to present the design of fire behaviour in a unique way since fire is affected significantly from the different behaviour of the burning materials (Hansen and Inganson, 2011). Furthermore, each tunnel is unique. It differs by type (uni- or bi-directional tunnel), length, width, method of construction, and type of traffic i.e. whether transportation of DGs is allowed. All these parameters influence on the evolution of fire affecting thus the required safety strategy (Caliendo and De Guglielmo, 2017; Ronchi et al., 2018). Methods for estimating fire behaviour in tunnels are in progress until today (Ingason, 2008; Hansen and Inganson, 2011; Caliendo et al., 2012; Ronchi et al., 2013; Vermesi et al., 2017; Wang et al., 2017). In general, tunnel fires are very complex phenomena due to the existence of complicated interactions between the fire and the tunnel environment. Li and Inganson (2018) have provided a summary of the some estimated HRRs from fire tests regarding passenger cars and busses (Figure 2.1 and 2.2).

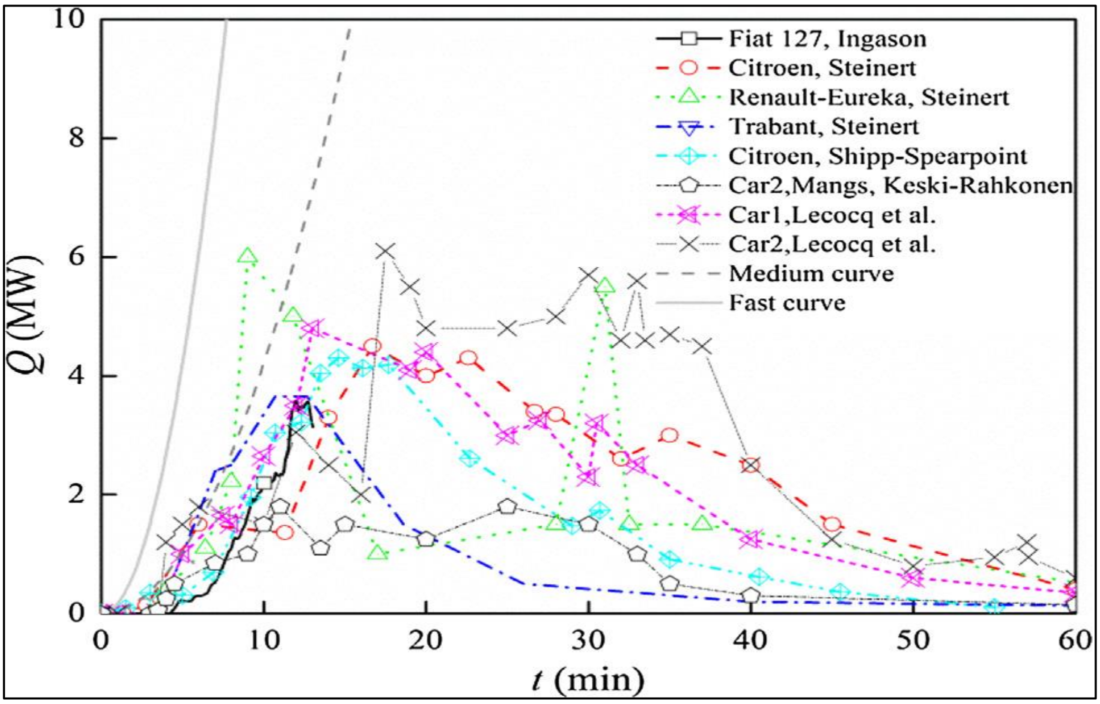

Figure 2.1: HRR for passenger cars (source: Li and Ingason, 2018, p. 570)

Conducted studies regarding fire combustion have observed that the heat feedback in tunnel fires tends to be more effective than in open fires (Beard and Carvel, 2012; Ingason et al., 2015). Consequently, vehicles that take part in a fire tend to burn more vigorously than in a fire in open road. Beard and Carvel (2012) have indicated that the HRR$_{max}$ of a tunnel fire could be up to four times higher compared to that of the same material burning in the open road. On the other hand, Li and Inganson (2018) have shown that this factor is one and a half. Regardless the exact number, both experiments confirm that tunnel fires are tend to be more vigorously.

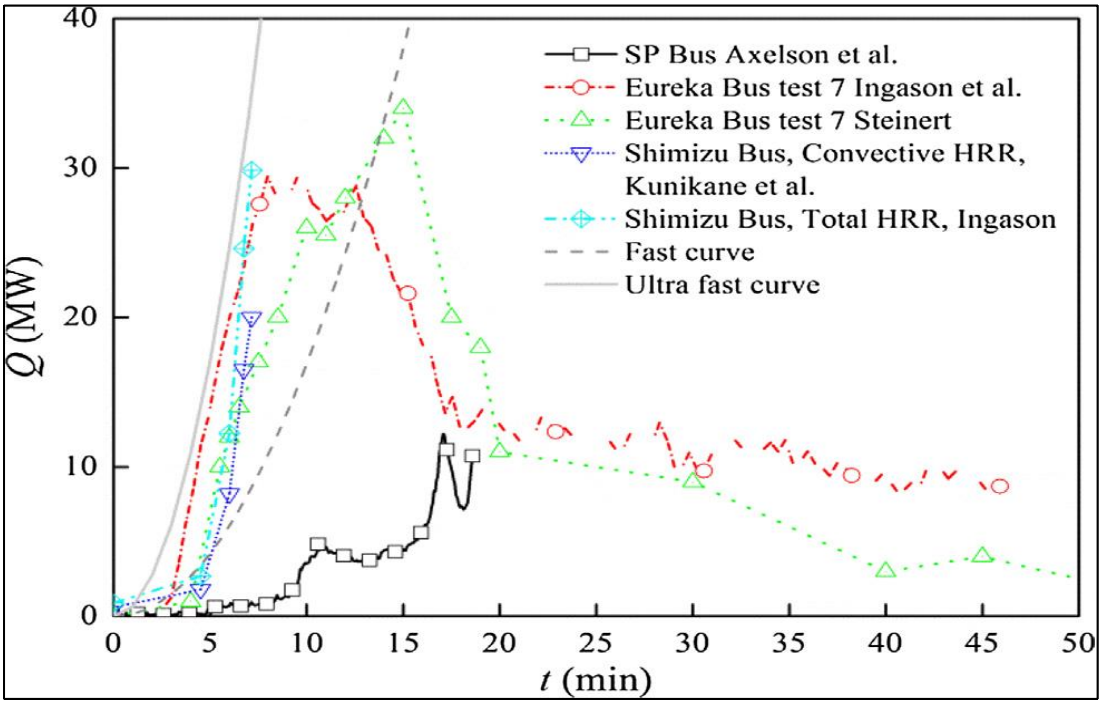

Figure 2.2: HRR for busses (source: Li and Ingason, 2018, p. 570)

Furthermore, heavy amount of heat is transferred to the vicinity of fire by radiation, approximately 33% of HRR, and to an extended tunnel area, approximately 67% of the HRR, by convection between hot air and various objects or tunnel ceilings. Additionally, tunnel fires can cause fatal hazards due to the availability of propagated toxic gases along with the limited availability of oxygen. The interaction between fire and ventilation airflow along with the aerodynamic disturbance of tunnel airflow can generate buoyancy effects that result in the development of the well-known backlayering phenomenon (refer to Figure 2.3).

Figure 2.3: Backlayering phenomenon in road tunnel fires (source: Ntzeremes et al., Accepted)

Backlayering expands the smoke environment upstream the fire location considerably enclosing thus the users trying to escape in toxic smoke (Caliendo et al., 2012). The visibility is impaired as the trapped-user is forced to pass through the backlayering irritant smoke (Boer, 2002; Papaioannou and Georgiou, 2003; Kinateder et al., 2014a, b; Ronchi et al., 2015; 2016; Ntzeremes et al., 2018). Recent studies have also mentioned the difficulties that members of rescue teams confront (Seike et al., 2016). Pain and breathing difficulties also arise as the trapped-users are exposed to toxic gases, which can lead them to confusion and loss of consciousness followed by death (Purser, 2009). Also, the heat from fire can impair trapped-users placed in the vicinity of fire due to radiation flux and can increase the temperature of the smoke and air, which can further cause problems in their respiratory system (Stec and Hull, 2010).

Based on the official loss and injury indicators, recent studies have shown that road tunnels are as safe as the rest of the road network or safer than that (Beard and Cope, 2008; Nævestad and Meyer, 2014). They are safer because on the one hand their closed environment forces users to drive more carefully (Kirytopoulos, et al., 2017) and on the other hand the scarcity of junctions, pedestrians or advertising signs and bicyclists reduce the chances of causing accidents (Amundsen and Engebretsen, 2009). All the aforementioned factors are either sources for accidents or aggravating factors during accidents’ evolution. Furthermore, modern tunnels follow strict regulatory guidelines, like the Directive 54/200/EC in Europe (EC, 2004) and the NFPA standard 502 in the USA (NFPA, 2014). Therefore, the necessary equipment is installed and infrastructure requirements are adhered to in order to ensure tunnels’ safety in case of a fire accident.

In depth studies have revealed some general conclusions regarding accidents in tunnels (Amundsen and Engebretsen, 2009; Caliendo and De Guglielmo, 2012; NTUA, 2013; Nævestad and Meyer, 2014; Bassan, 2016; Ren et al., 2019):

- It is evident that bi-directional tunnels have higher accident rates than unidirectional ones. Moreover, the response to a fire in a bidirectional tunnel is much harder as usually vehicles are trapped both upstream and downstream the fire, thus the use of the ventilation systems is more complicated (pushing the smoke to either side will put some users in danger).

- The terminal zones are more prone to accidents than the central zones. This is related mostly to the changing conditions / geometry / environment, the black hole effect at the entry portal and the glaring at the exit portal.
- Higher accident rates are observed in sections that affect the traffic flow (e.g. speed changes, variations in alignment, etc.).
- Most of accidents are caused by rear-end collisions, poor maintenance of vehicles and disobedience of drivers in keeping a safe distance from vehicles in front.
- The most common causes for tunnel fires are the collisions between vehicles or between vehicles and the tunnel structure and the mechanical or electrical defects in vehicles such as the overheated bearings or brakes, etc.
- Users' behavior plays a crucial role before or right after the spark of a fire. Self-evacuation is regarded to be the most important factor in mitigating users' losses of an accident.

However, if an accident occurs, it might have greater severity than in the rest of the road network. Road tunnels are considered risky environments due to their closed environment since they feature: (a) no physical light passing through them, which makes difficult for drivers to adjust when passing through (Yeung et al., 2013; Wong et al, 2014; Domenichini et al., 2017), (b) difficulties in approaching and rescuing trapped-users in case of fire accidents, and (c) fire combustion irregularity (Calvi et al., 2012; Maschio et al., 2012; Mühlberger et al., 2012; Caroly et al., 2013). Additionally, tunnel managers must also handle the particular features of the around environment. Being usually part of cities' networks and main motorways, tunnels accommodate high traffic volumes. As a result, a potential accident can affect an extended part of the urban and rural road network causing significant casualties, as well. Urban tunnels particularly traverse densely populated urban areas and as a result they increase further the societal risk of potential accidents (Ntzeremes and Kirytopoulos, 2018b).

To this respect, a study from Italy showcases that severe accidents are more frequent in road tunnels. In particular, it is reported that between 2006 and 2009, road tunnels had a severe accident rate between 9.13 and 20.45 crashes/10^8veh.km, while on the associated motorways the rate was between 8.62 and 10.14 crashes/10^8veh.km (Caliendo and De Guglielmo, 2012). Another study in Norway, the country that already has over 1000 tunnels with 800km total length, shows that the average number of tunnel fires sparking from vehicles covering the period between 2008 and 2011 was 21.25 per year per 1000 tunnels (Nævestad and Meyer, 2014). Not all of them resulted in people getting harmed, but still the statistics indicate that there is a serious threat for tunnel users. Regarding China, Ren et al. (2019) indicate that a sum of 161 fire accidents has been recorded over the last fifteen years with over half of them were due to vehicles' technical problems.

Based on the aforementioned studies, the most common causes for tunnel fires are firstly the collisions between vehicles or between vehicles and the tunnel structure (e.g. the accident in Sierre; Switzerland, 2012) and secondly the mechanical or electrical defects in vehicles such as the overheated bearings or brakes, etc. Furthermore, they have indicated that drivers' behaviour plays a crucial role before or right after the spark of a fire (PIARC, 2008; Yeung et al., 2013; Nævestad and Meyer, 2014; Kirytopoulos et al., 2017).

2.2 Introduction to the risk-based approach

2.2.1 The rationale behind the change in fire safety policy

The trigger events that cause the policy-makers, the safety analysts and the public to doubt about road tunnel safety were the serious Alpine accidents that occurred in Mont Blanc – France, 1999; in Tauern – Austria, 1999; and in St. Gotthard – Switzerland, 2001 tunnels. These accidents resulted in a heavy life loss criterion since they cost the life of 39, 12 and 11 people, respectively, together with an extended destruction of their facilities and significant economic losses (AADT, 1999; Voeltzel and Dix, 2004; Beard and Carvel, 2012). Specifically, the Mont Blanc accident cost around 300 million euros for tunnel's rehabilitation while it remained closed for almost three years.

Before these events, tunnels' fire safety management was conducted based on the compliance of their infrastructure and facilities with the prescriptive requirements that each member state had imposed (PIARC, 1999). Prescriptive requirements have been developed over years reflecting the knowledge already gained from previous accidents. The disastrous consequences arose emphatically the shortcomings of theretofore approach. Typical examples were the necessity of tunnel surveillance only by a single control room or the necessity of connecting safety shelters with escape routes ending up to the external environment (Fridolph et al., 2013). These tragedies came just to remind that fire safety of tunnel systems has unavoidably become a complex issue (PIARC, 2016).

Surely, the benefit of using prescriptive requirements, such as the Directive 2004/54/EC minimum infrastructure and equipment prescriptive requirements for the TERN tunnels, lies in the simplicity of their use during the execution of the tunnel safety checks. However, the literature still indicates that even when the tunnel is designed in accordance with the imposed requirements, the level of safety is not always acceptable and vice versa. Borg et al. (2014) examining the safety of the Rogfast tunnel have showcased that while the deviation from these requirements is considered unacceptable, it can be counterbalanced without eventually creating vulnerability. Kirytopoulos et al. (2010) examine a TERN tunnel that is in line with Directive's normative provisions regarding the minimum requirements, however, their evaluation indicates that the level of safety can be below the specified safety limit and further measures should be adopted.

Apart from the choice of prescriptive requirements, there are two other reasons that necessitate the use of risk assessment in the road tunnel area. Road tunnels involve human, organisational and technical elements hence they can be understood as socio-technical systems (Kazaras et al., 2012). Moreover, they are also complex systems (see Figure 2.4).

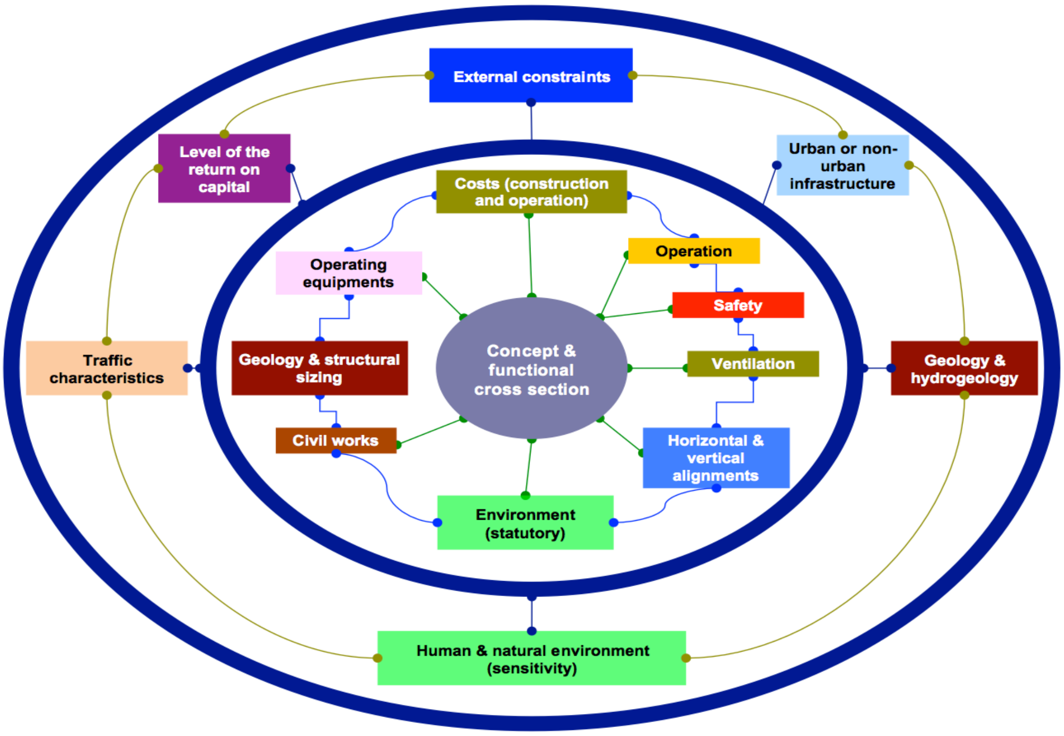

Figure 2.4: Tunnel as a complex system (source: PIARC, 2016, p. 12)

Therefore, they are regarded as complex socio-technical systems. The main issue with complex systems is that their overall safety is an emergent characteristic coming from the interaction of its components and not only the isolated safety level of the individual components. In road tunnels, it is the complexity of the non-linear interactions amongst the different elements of the system that characterise their overall safety. Research projects implementing in the years following the Alpine disasters have also contributed in forming the new safety approach. For instance, the UPTUN, 2002-2006; Safe-T, 2003-2006; EUROTAP, 2005-2007 projects investigated the operation of each tunnel system element, and predominantly in case of fire. A detailed report of them is presented in PIARC (2007). These projects created the basis for the safety approach to start working based on the holistic notion of the tunnel system safety.

In particular, a total number of 34 basic system parameters that affect tunnels' safety is reported. Grouping these parameters in relation to their characteristic, a set of four basic elements emerges. This set forms the safety ground of road tunnel system. The elements of this ground are: (a) the infrastructure, (b) the vehicles, (c) the users and (d) the facilities (PIARC, 2008). However, a fifth element, the traffic, although officially laying under vehicles can be a new element of the system (Figure 2.5). Modelling tunnel system by grouping the various system parameters in these five discrete elements can simplified its complexity (Ntzeremes and Kirytopoulos, 2019).

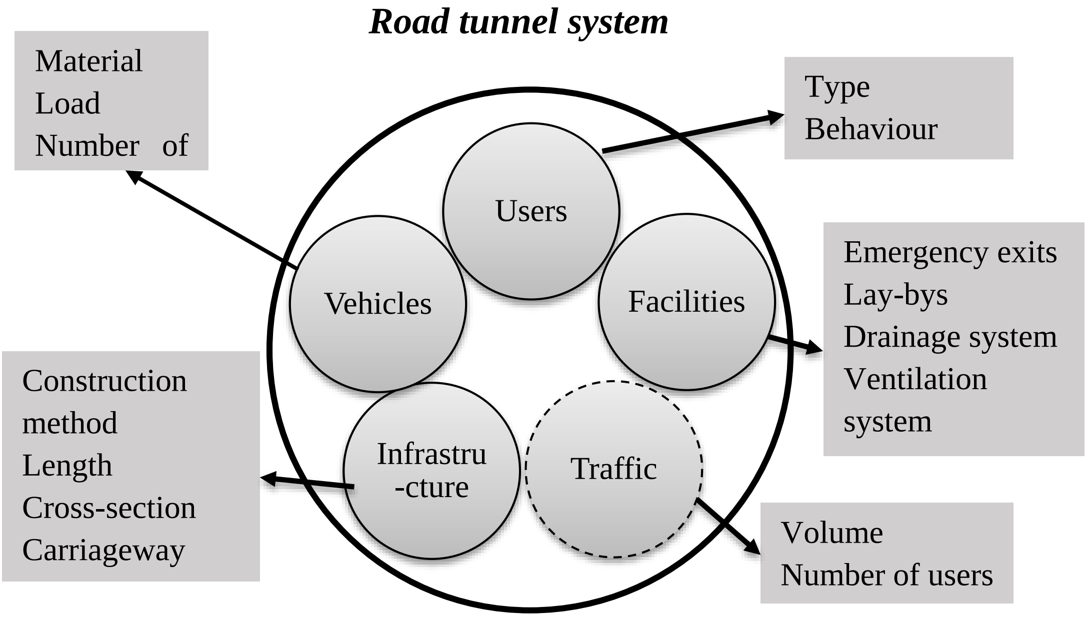

Figure 2.5: Basic elements of the tunnel safety ground (source: Ntzeremes and Kirytopoulos, 2019)

In brief, *infrastructure* refers to those parameters of the tunnel that influence its level of safety. Such parameters are the method of construction (i.e. cut-and-cover, mined/bored or immersed), the geometrical configuration, the ground conditions, and the environmental conditions (Maidl et al., 2014; Wang et al., 2014; PIARC, 2018). Subsequently, tunnel's type, length, width, cross-section geometry etc. have been also indicated as significant parameters (Bassan, 2015). Similarly, the resistance degree of tunnel materials is taken into account.

Facilities are divided into structural facilities and equipment. Regarding structural facilities, the emergency exits or the lay-bys and the cross-connections between tunnel tubes, along with the safety shelters as well as firefighting recesses are the most important (PIARC, 2007). In addition, the drainage system is taken into account when transportation of DGs is allowed. Regarding the equipment, it includes those sub-systems that their performance is crucial for the safe operation of the tunnel system. These facilities are: the SCADA, the surveillance, the lightning, the ventilation as well as the traffic interruption system (PIARC, 2018).

Users refers to the users' behaviour either in causing the accident or during their self-evacuation process since an efficient safety strategy should focus on both aspects (Fridolph et al., 2013). In addition, the performance of tunnel staff and the emergency services are also taken into account (PIARC, 2016).

Vehicles element considers the type of vehicles (i.e. HGV, busses, private cars or specific vehicles, e.g. ambulance) and in particular their load and their materials, which are crucial for the evolution of fire (Ingason, 2008).

Traffic plays a key role on the piston effect since piston effect impacts on the development of the backlayering (Caliendo et al., 2012). Additionally, traffic volume also specifies the amount, as well as the type of users (i.e. professional driver or bus passengers or disabled users) that can be trapped near to the fire location. The last point is important since different type of users have different behaviours during their evacuation (Kirytopoulos et al., 2017; Ntzeremes and Kirytopoulos, 2018a; Ronchi et al., 2018).

On the basis of the holistic approach, each of the above five elements has to adopt the necessary safety measures, considering not only its own requirements but also by taking into account potential interdependencies with the others. For instance, although the mission of emergency operation of mechanical ventilation is to definitely limit as soon as possible the evolution of fire, this should happen without putting trapped-users at risk. Considering all the elements of tunnel system, fire safety management has to be conducted now based on the synergy of the regulatory requirements and the risk assessment. By fulfilling these two parts, safety does not count only on "*learning from events*", since this is the primary source of prescriptive requirements, but also on "*assessing the system proactively*", which is the advisable approach followed for the safety of all the modern complex social-technical systems (Shirea et al., 2018).

2.2.2 The general framework of the risk-based approach

Without any doubt, tunnel systems in the operation phase are subjected to uncertain changes (Ntzeremes and Kirytopoulos, 2018b). Therefore, risk-based approach is regarded as a suitable tool for confronting these changes. Generally, the risk field includes two main tasks: (a) *At first, to use risk assessment to study and treat risk of specific activities and secondly (b) to perform generic risk research and development… to understand, assess, characterise, communicate and manage risk* (Aven, 2016, p. 1). Servicing these tasks, risk assessment has already been successfully used in many application areas (Goerlandt et al., 2017), like the chemical industry (Greenberg and Cramer, 1991) or the aerospace industry (NASA, 2011). Given the deficiencies in prescriptive requirements, the use of risk assessment in road tunnels is recognised as the systematic approach to follow for both illustrate tunnel's risk level extensively and facilitate the examination of specific accidents as well as the observation of possible residual risks while accounting for their intrinsic attributes (Beard, 2009; Beard and Carvel, 2012; Bjelland and Aven, 2013; Ntzeremes et al., 2018). By doing so, risk assessment supports fire safety management for estimating tunnel's level of safety and subsequently, selecting additional to standard safety measures, if needed.

Nowadays, risk assessment has been broadly accepted to form a robust scientific field (Aven, 2016). Therefore, it has to exhibit a well-defined and universally understood base of terminology. Taking into account the terminology cited in the official reports from the PIARC (PIARC, 2007; PIARC, 2008), as well as the terminology founded in existing risk assessment methods (Beard and Carvel, 2012; Kazaras and Kirytopoulos, 2014; Ntzeremes and Kirytopoulos, 2018b) a unified set of definitions results. Initially, *hazard* is considered as any ''potential source of harm'', which may lead either by itself or in combination with others to the spark of the critical event (i.e. fire). A *critical event* is "a malicious event that can cause immediate or delayed harm to the tunnel system elements (see Figure 2.5) and the road network in general". *Risk* is related to the ''expected loss or damage associated with the possibility of occurrence of the critical event or the subsequent chain of events''. Following this terminology, the risk assessment framework for road tunnels in operation is shown in Figure 2.6, which represents the PIARC approach (PIARC, 2008). Its basic steps are (Ntzeremes et al., 2018):

Figure 2.6: Risk assessment framework (source: Ntzeremes and Kirytopoulos, 2019)

- Risk analysis: This step performs the systematic approach in order to identify the hazards and subsequently calculate the risks. Risk analysis is divided into three discrete sub-steps following a top to bottom sequence. The first sub-step is to establish the context, which means to define the system and specify risk assessment goals and criteria. Presumably, this is the most important task, since the better the tunnel system is defined, the better the goals of the analysis would be achieved. In particular, the latter are the ones that they will strongly determine both the depth of the analysis and the system's boundaries (Ayyub and Klir, 2006). Subsequently, the hazard identification identifies potential hazards that may affect the proper operation of the system. Finally, the risk estimation follows in which cause and consequence analysis is carried-out.

- Risk evaluation: This step aims at determining whether estimated risks are acceptable when compared to the predefined constraints, the so-called risk criteria. However, the evaluation approach cannot be chosen arbitrarily since it strongly relies on the applied risk analysis method of the previous step.
- Risk treatment: This step aims at mitigating or eliminating, if possible, non-acceptable risks by imposing additional to standard fire safety measures and without re-designing totally the system. The objectives from the choice of additional measures are as follows: (a) protecting the users involved, (b) preventing the escalation of fire and limiting it, (c) limiting the damages to the tunnel structure, (d) restoring the normal functioning of the tunnel as soon as possible. In the end of the risk treatment step, a new round of the process is conducted to re-evaluate the new situation (Ntzeremes and Kirytopoulos, 2019).

However, the above framework is slightly differentiated from the general ISO standard (ISO, 2018) since the ISO risk assessment incorporates both risk analysis and risk evaluation but not risk treatment which is another process.

As far as the terminology of risk is concerned, there have been various definitions of risk until today. ISO (2018) latest report defines risk as "*effect of uncertainty on objectives*". A different definition is mentioned in Aven (2009), where risk is expressed as "*an event where the outcome is uncertain*". The relevant literature and the SRA (2018) glossary showcase other qualitative definitions, which express risk as the possibility of an unfortunate occurrence or the consequences of the activity and associated uncertainties or uncertainty about and severity of the consequences of an activity with respect to something that human's value or the deviation from a reference value and associated uncertainties. These definitions are followed by the respective metrics. Regarding road tunnel safety, the risk definition is probably closer to Kaplan and Garrick (1981), in which risk is defined as a set of scenarios (combination of hazards that lead in a critical event), each of which has a probability p_i and a consequence c_i (INERIS, 2005; PIARC, 2008).

Ideally, safety analysts select additional safety measures in order to mitigate the expected consequences while they also, and primarily attempt to mitigate the relevant probabilities of occurrence (PIARC, 2013). However, the rareness of fire accidents in tunnels and the scarcity of reliably informed statistical databases have unavoidably created a type of analysis that focusses specifically on the consequences part. This type of analysis is called scenario-based approach (PIARC, 2008). Following this approach, the road tunnel system is investigated under predetermined conditions (Ntzeremes et al., 2018). To do so, safety analysts rely on standardised fire scenarios commonly provided in each country's guidelines (PIARC, 2017). Although probabilities do play a role in determining the scenarios to be examined, the analysis itself of the scenarios considers only the impact. In this type of analysis, the risk is expressed as the considered expected losses associated with the occurrence of a possible critical event. Therefore, mitigating the fire risk is translated in mitigating primarily potential losses amongst tunnel users (Ntzeremes et al., Accepted).

Chapter 3[2]

Risk assessment methods within the EU: A comparative analysis

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[2] Parts of this Chapter have been published in: (Ntzeremes et al., 2018; Ntzeremes and Kirytopoulos, 2019; Ntzeremes and Kirytopoulos, Under review)

3. Risk assessment methods within the EU: A comparative analysis

The necessity for modern road network to develop more efficient, as well as longer infrastructure continues to bring forth the option for enhancing the level of safety of a complex infrastructure element of the road transportation system, such as tunnels. As far as risk assessment is concerned, the EU is at the forefront since the Directive 2004/54/EC introduced the risk assessment in the tunnel area worldwide. However, particular attention should be paid on important issues and key parameters of the fire safety management, highlighted either in the literature or in practice, that can affect the risk assessment and, because of that, concern tunnel managers and practitioners. This Chapter aims at assessing how each method addresses all these as well as evaluates them with the current literature.

3.1 Setting the scene

The database “EUR-Lex” (EUR-Lex, 2018) search indicates that apart from the Directive 54/2004/EC (EC, 2004) no further additions in the legislation have been made. Servicing the review aim, six risk assessment methods are selected and examined. These methods are: the Austrian (RVS, 2008; ASFiNAG, 2008), the French (CETU, 2003; 2005), the German (BASt/BMVBS, 2010), the Greek (AAT, 2011a; AAT, 2011b), the Dutch (RWS, 2006) and the Italian (ANAS, 2009) risk assessment method (PIARC, 2008; 2013; INERIS, 2005). These methods are selected either because they are related to member states which have a large number of tunnels longer than 500m and/or a considerable background in road infrastructure safety.

Figure 3.1 showcases the evolution of road tunnels in these member states (in tunnel meters) before the launch of Directive 54/2004/EC and after that until nowadays (NTUA, 2013; Lotsberg, 2016). It also depicts the projected increase of road tunnels for the coming years. A significant point of Figure 3.1 is the increasing trend of the use of road tunnels. As a result, Austria had 29.41% increase in the road tunnel meters from 2004 to 2010. During the same period, France had 4.10%, Germany had 44.24%, Greece had 213.24%, Italy had 31.59% and The Netherlands had 18.79%. Moreover, it is estimated that Italy will have 59.38% increase in tunnel meters during this decade reaching approximately 1.3 million and being in the first place within the EU while

Austria, Germany, Greece and France are estimated to have an increase of 39.91%, 72.18%, 92.87% and 42.50% respectively.

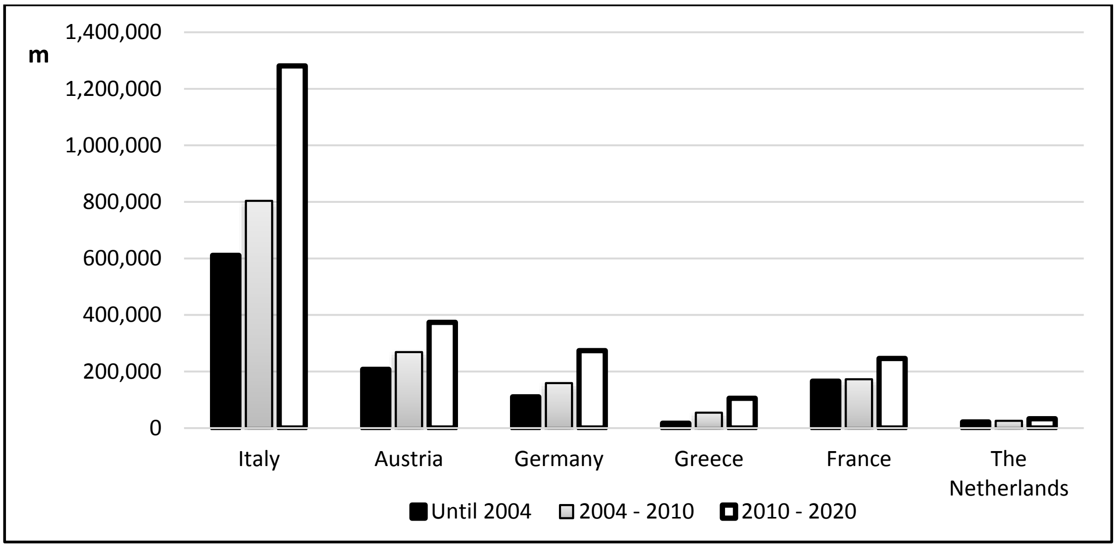

Figure 3.1: Evolution of tunnel meters per member state (source: Ntzeremes and Kirytopoulos, 2019)

Figure 3.2 indicates the tunnel accidents recorded in these member states until 2010 according to a study conducted by the department of mechanical engineering of the NTUA (NTUA, 2013). Although the Directive seems to aid member states to reduce the number of serious accidents, still further efforts should be done. Whilst accidents have been reduced, the EU has not reached its ambitious goal, which is a "zero vision" for all road deaths and injuries by 2050 (EC, 2017b).

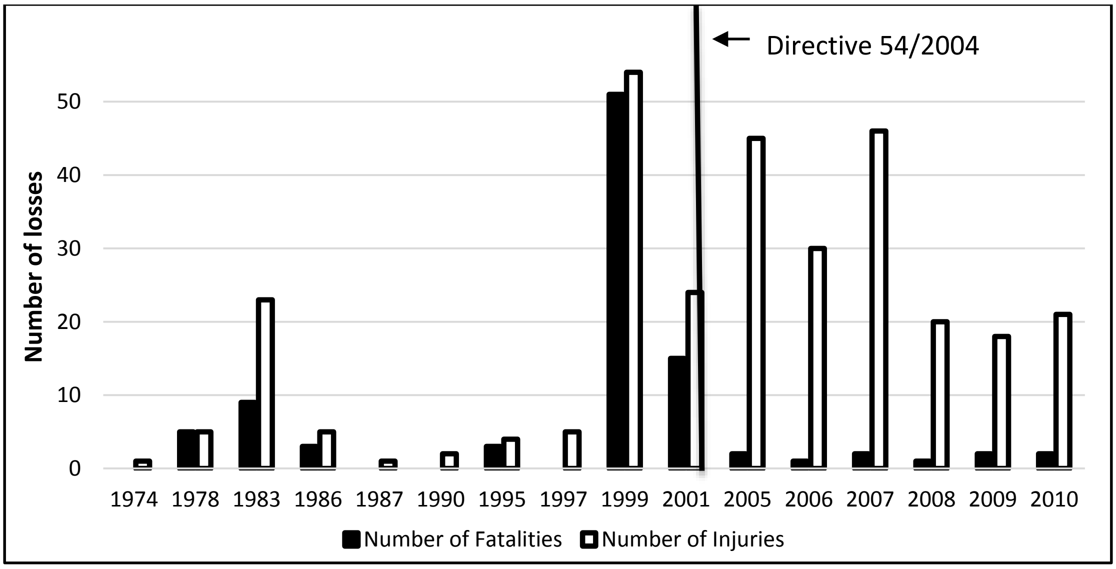

Figure 3.2: Overview of losses per member state (source: Ntzeremes and Kirytopoulos, 2019)

Another important aspect is that the rapid increase of the tunnels, should not allow complacency, especially, for member states like Greece (Benekos and Diamantidis, 2017), which quite recently have constructed tunnels in their national motorways, and they have not previous experience of major fire accidents. Besides, the scarcity of disastrous accidents, like in Mont Blanc, shows that tunnel managers and safety analysts must not be complacent at all about the level of fire safety of tunnels (Haack, 2002).

3.2 Overview of the risk assessment methods

Due to the adoption of the same risk assessment principles and function (see Figure 2.6), all the methods are considered equivalent at the higher level. Generally, all the methods dictate safety analysts to configure the tunnel system by taking into account the parameters forming the tunnel system elements (see Figure 2.5), since they affect the level of safety of the tunnel system, without providing further details on this issue. Officially, these parameters are governed by the standards and requirements given in the national provisions that each member state has imposed, such as the German RABT (RABT, 2006) or the Greek OMOE (OMOE, 2001) guidelines. An attempt to address potential differences arising from the national provisions have been made through the recommendations provided by both the EC (EC, 2004) and the PIARC (PIARC, 2008; 2013; 2018). However, each method has frequently a different orientation because of both the national particularities that unavoidably remain, and the inherent weakness of a unique risk assessment methods to act in a unidirectional way.

The analysis showcases that each method is formed by looking at three principal axes (Figure 3.3): (a) the type of risk approach, (b) the type of transported goods and (c) the type of method used (Ntzeremes et al., 2018). This categorisation affects the parameters that are used as inputs, the methods function and the type of presentation of the risk level.

Regarding the *type of risk approach*, methods that require a significant sum of fire scenarios in order to estimate the overall risk of the tunnel system rely on the system-based approach. For these methods, the risk estimation is performed on the basis of statistical analysis, i.e. Expected value, F/N curves etc., and determines thus the risk evaluation, accordingly. On the other hand, methods following the scenario-based approach, take into account only a subset of stand-alone relevant fire scenarios. This approach is used when there is need to investigate the operation of the tunnel system, under predetermined conditions, tackling potential lack of data. As a result, both the risk estimation and the risk evaluation are provided for each fire scenario by examining the number of potential losses or/and injuries without this being associated with the frequency of such scenarios.

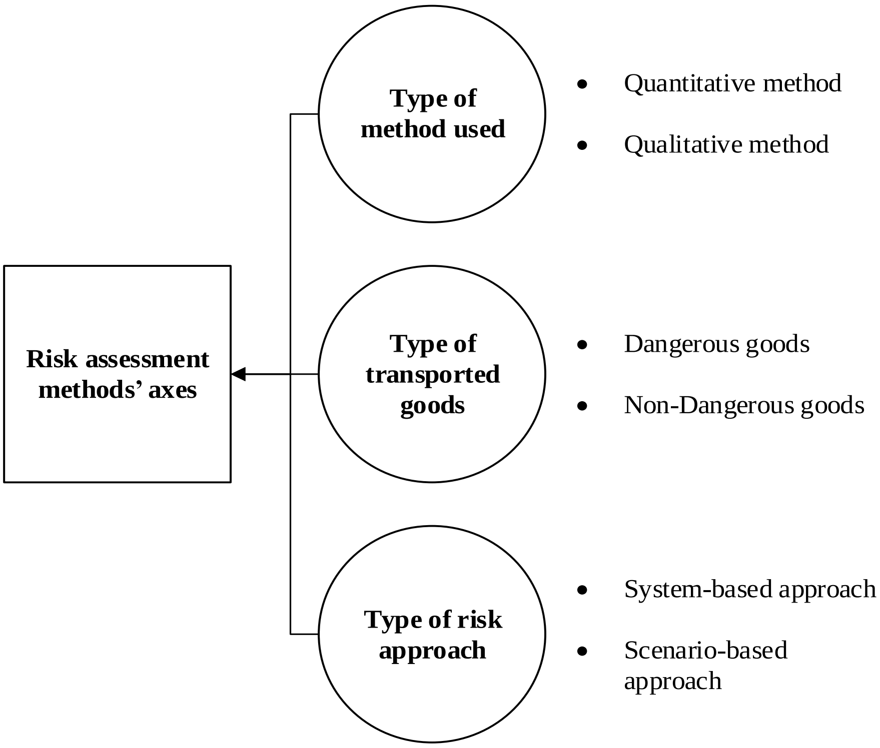

Figure 3.3: Overview of the axes that shape each method function (source: Ntzeremes et al., 2018).

A major division exists on how methods address the type of transported goods since they affect the design of fire, which is the most important parameter for describing its development and consequences (Li and Ingason, 2018). This difference steams from the nature of the arisen risks. According to the ADR agreement, transported goods are separated between DGs and non-DGs (UNECE, 2015). The consequences from accidents that involve DGs (i.e. air pollution, fire behaviour, number of users affected) are far more devastating when compared to those from accidents which do not involve DGs. Therefore, accidents involving DGs are recognised at a social-impact scale whereas accidents involving non-DGs at an individual-impact scale. Risk assessment methods are usually categorised according to the *type of transported goods* that they can handle. Generally, safety management in regard to DGs accidents primarily aims at reducing the frequency of the fire accident whereas in non-DGs safety management primarily aims at mitigating the consequences in regard to the trapped-users.

At last, methods are divided according to the *type of method used*. Therefore, quantitative methods are based on numerical data for identifying risk values (i.e. F/N curves, expected value) and often have a high degree of complexity. On the contrary, qualitative methods are based on expert judgment, risk matrix, checklists etc. and thus, they are more flexible and have lower complexity. Although most methods rely on numerical data, qualitative methods can enable the analysts to conceptualise better some parts of the risk picture than quantitative methods, such as for example modelling the organisational aspects of the system (Apostolakis, 2004). According to the aforementioned categorisation, the examined methods are depicted in Table 3.1.

Table 3.1: Overview of the methods (source: Ntzeremes and Kirytopoulos, 2019)

Member state	Name of the method	Type of risk approach	Type of transported goods	Type of method used	Year of publication
Austria	TuRisMo	System-based	Non-dangerous goods	Quantitative	2007
	OECD/PIARC QRA	System-based	Dangerous goods	Quantitative	2007
France	SHI	Scenario-based	Non-dangerous goods	Quantitative	2003
	OECD/PIARC QRA	System-based	Dangerous goods	Quantitative	2005
Germany	BASt	Scenario-based	Non-dangerous goods	Quantitative	2010
	OECD/PIARC QRA	System-based	Dangerous goods	Quantitative	2006
Greece	SAM	Scenario-based	Non-dangerous goods	Quantitative	2011
	OECD/PIARC QRA	System-based	Dangerous goods	Quantitative	2011
The Netherlands	DSA	Scenario-based	Both types of goods	Qualitative	2008
	RWS	System-based	Dangerous goods	Quantitative	2008
Italy	IRA	System-based	Both types of goods	Quantitative	2009

Table 3.1 shows that apart from Italy, which uses the same method for both types of goods, the rest of the member states employ different methods in relation to the type of transported goods. Regarding the type of risk approach, since the methods deal with DGs follow or rest on a system-based approach with OECD/PIARC QRA model, they use a system-based approach. On the contrary, methods dealing with non-DGs follow a scenario-based approach due to both the different fire strategy required and the lack of available databases. Finally, regarding the type of method used, a small exception is highlighted in the Dutch DSA method, which follows the qualitative type.

3.3 Critical evaluation of the methods

Subsequently, a deeper level of examination follows. This level aims at examining the methods linked with the basic steps of the risk assessment (see Figure 3.4).

3.3.1 Risk analysis

Having defined the required safe state of the tunnel system, both hazard identification and risk estimation steps focus on forming the examined fire scenarios (PIARC, 2010). Ideally, each method should select fire scenarios with a view to mobilise the whole tunnel system since risk assessment’s purpose is to investigate the performance on the system and, if needed, to propose potential additional to standard safety measures without a total redesign of the system (Hoj and Kröger, 2002). Through the bow-tie model, risk analysis is facilitated to identify potential hazards that can lead to the spark of the fire (PIARC, 2007). To this respect, various techniques are employed but the predominant method is the fault tree analysis (PIARC, 2008; Beard and Carvel, 2012). Subsequently, possible control measures are examined in order to mitigate the resulted consequences. In this step, CFD analysis combined with evacuation models or event tree analysis are predominately employed (Beard and Carvel, 2012; Kuligowski, 2013). However, examining the structure of the methods, it is shown that risk analysis quite often is limited mainly in examining only those fire scenarios that are imposed by the guidelines (see Chapter 6). By doing so, only possible control measures are examined. This trend exists for both types of goods. For instance, both the RWS and BASt methods define the fire scenario only from the spark of the fire, whereas the SAM method employs fault tree analysis or the SHI method focuses on the hazards prior to the spark of fire by providing standardised catalogue of potential hazards. In line with the bow-tie principles, conducted studies have also indicated that the equal importance should be given in both the preventive and mitigating measures. Indicatively, Chatzimichailidou and Dokas (2016) examining the safe design and maintenance of the tunnel system have identified that important elements of the system despite its compliance with regulations have to be re-designed in order to reduce tunnel despite its compliance with regulations have to be re-designed in order to reduce tunnel vulnerabilities and to prevent accidents and losses.

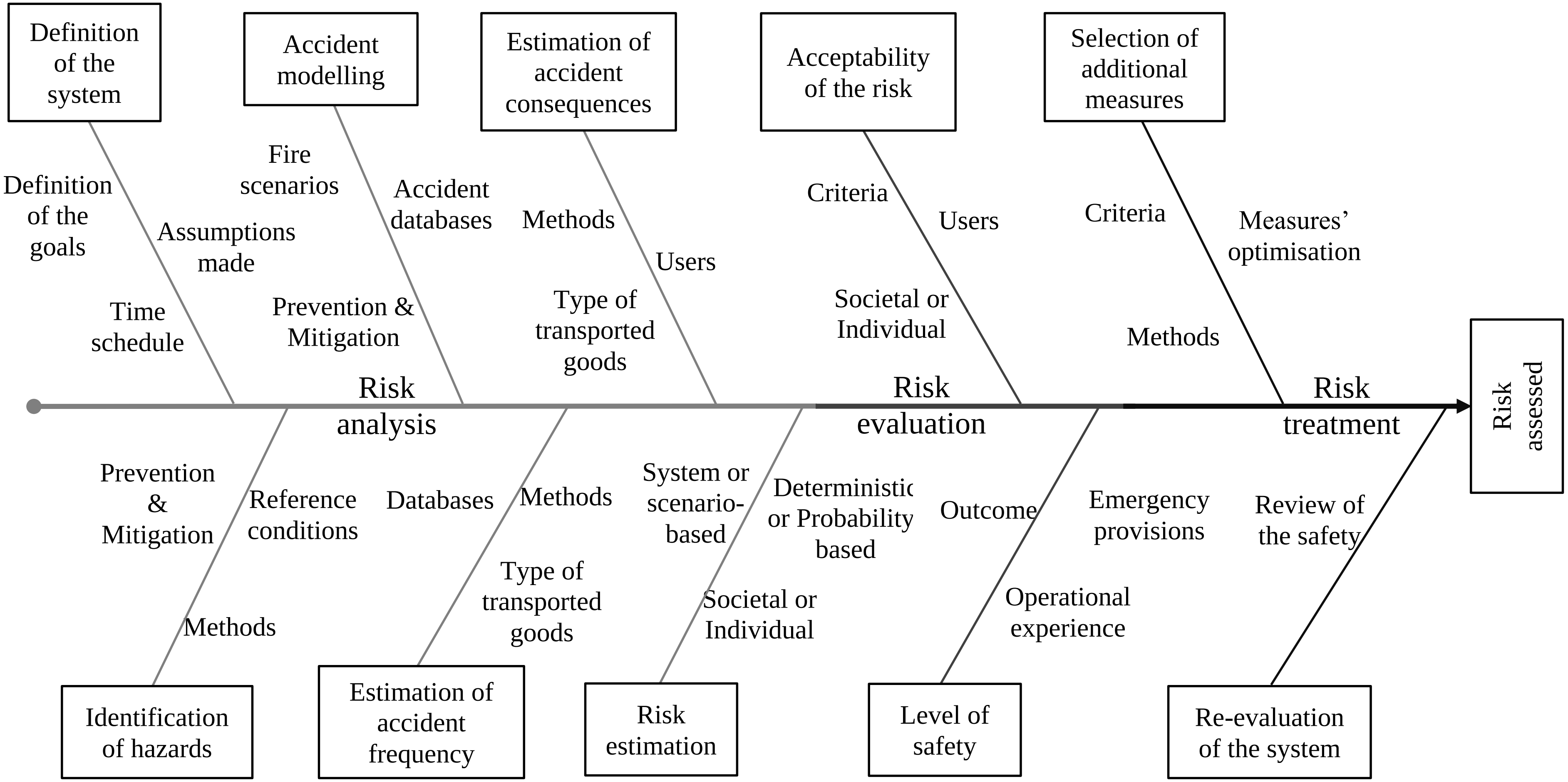

Figure 3.4: Main aspects of the risk assessment covered by the methods (source: Ntzeremes and Kirytopoulos, 2019)

Traditionally, tunnel managers and practitioners concern primarily on confronting risks derived from the transportation of DGs through tunnels. As far as risk analysis for fires involving DGs is concerned, there is a harmonised approach based on the methods used in Table 3.1. The most widely accepted risk assessment method for treating DGs in tunnels is the OECD/PIARC QRA model developed by INERIS, WS-Atkins and the Institute for Risk Research (INERIS, 2005). The model focuses on calculating the relevant probabilities of 13 reference scenarios (Benekos & Diamantidis, 2017; Ntzeremes and Kirytopoulos, 2018b). Surely, probability analysis and relevant statistical data enable the risk analysis to identify those hazards that contribute the most to the risk, guiding the analyst to make the decision on where to intervene to reduce the risk. Nevertheless, arguments for seeing beyond probabilities have been arisen. An essential condition to use probabilities is to exist background information about past accidents. However, not all the member states have the required data available in order to have a reliable outcome (e.g. Greece does not have any database). To overcome this issue, some countries provide analysts with standardised fire scenarios. For instance, the IRA method, which is based on probability analysis since it calculates the probability of fire accidents based on the Bayesian network, provides some standardised fire scenarios based on Italy’s database. By doing so, the legislation focuses on creating a minimum body of examined fire scenarios servicing the harmonasation goal. A similar approach is also followed by the OECD/PIARC QRA model by proposing 13 fire scenarios. Beyond the lack of databases, accidents’ history indicates emphatically that statistic data cannot always help in predicting future disasters due to the scarcity of disastrous accidents, like the Mont Blanc accident (Haack, 2002).

Despite the importance of DGs, it is not certain that fires without involving DGs are of lower importance or they should be underestimate when comparing with fires from DGs. In many cases, such as in the Gotthard fire accident, these fires can be equal to the fires that stem from DGs in terms of disastrous consequences, if the appropriate preparedness is lack (Beard, 2009; Mühlberger et al., 2012). However, fire scenarios related to non-DGs have been developed based either on national databases of accidents reports (for the unique tunnel or for the countries’ tunnels) as in the TuRisMo and IRA methods. PIARC (2016: p. 10) provides a detailed catalogue about the different fire scenarios examined predominantly in each member state based on their HRR_{max}. However, Ntzeremes et al. (2018) showcases the significant divergence of the estimated level of safety in a road tunnel due to a different standardisation of the fire behaviour (see Chapter 6).

Unavoidably, the selection of the examined scenarios may affect the results of the analysis since certain aspects may be overlooked. For instance, examining a fire of HRR_{max} 50MW required by the BASt method instead of HRR_{max} 100MW required by the SAM method cannot illustrate the potential deficiency of the mechanical ventilation estimated in the second fire scenario. Moreover, considering the beginning of the evacuation process of trapped-users in 30sec instead of 2min for the same fire scenario can also change drastically the risk outcome producing, thus, “manipulated” results (Ntzeremes and Kirytopoulos, 2018a). However, a potential solution could be the standardisation of certain fire scenarios along with their examination in certain locations in a tunnel. Such locations would indicate some valuable insights about the criticality of the fire incident and how this would affect the behavior of fire (e.g. the entrances and the centre of the tunnel). The problem is well-known (Amundsen, 1994; Nævestad and Meyer, 2014) but methods exhibit lack in dealing with.

3.3.2 Risk evaluation

Having estimated the risks of the tunnel system and through their evaluation, a decision should be made whether risk is accepted. This decision best meets the decision-maker’s values and priorities. These values and priorities are stem from the regulatory requirements and the view of the safety analyst himself. Therefore, during the decision-making process various constraints are introduced. These constraints are the so-called risk (acceptance) criteria.

In particular, the analysis for estimating risks deriving from DGs results in F/N diagram, which is the basis for the evaluation of risk. Subsequently, either the EV or the ALARP principle is employed. EV is the log-term average of statistically expected fatalities per year for the tunnel. Although expressing the risk in terms of the EV has the advantage that the risk level of the system is expressed as a single number, it is concurrently a drawback since it treats all F/N results as equally important. Therefore, this approach can cause serious deficiency at the safety level of the tunnel since from the safety perspective, disastrous accidents having a low possibility are obscured. Contrary, the ALARP principle arises from the fact that infinite time, effort and money could be spent in the attempt of reducing a risk to zero. It should not be understood as simply a quantitative measure of benefit against detriment (Ale et al., 2015). It is more a best common practice of judgement of the balance of risk and societal benefit. A detailed catalogue about the variety of ALARP lines and EV thresholds is included in PIARC (2013). As a result of the different ALARP limits each member state imposes, a tunnel that falls into the safe zone in one member state could be out of it in another member state arising serious questions about its “ultimate” level of safety.

Although the aforementioned drawbacks of the EV and ALARP, they create a minimum body of principles implemented for the evaluation of DGs fires. However, the evaluation step regarding non-DGs does not rely on either the EV or the ALARP principle. All the methods (Table 3.1) focus on estimating potential losses amongst trapped-users and taking into account the results, the level of safety of the tunnel is estimated. Ultimately, due to the absence of regulatory requirements, the view of the safety analyst himself plays the key role.

Users’ behaviour is in the centre of attention in order to assess and enhance road tunnels’ level of safety (Seike et al., 2017; Kirytopoulos et al., 2017). Although PIARC (1999) as well as post-accident reports (AADT, 1999) provide data about evacuation behaviour and movement along with the impact of fire in trapped-users behaviour, the methods exhibit lack in dealing with or implement oversimplified assumptions about the different stages of evacuation process and the behaviour of trapped-users (Ntzeremes and Kirytopoulos, 2018a). Apart from the SAM and the SHI method which provide specific walking speeds of the trapped-users, and in relation to the smoke environment (opacity), although in a qualitative correlation in between, rest of the methods do not give any information on this issue. By doing so, the effectiveness of both risk analysis and risk evaluation is reduced. Several studies can be used as valuable information sources for dealing with users’ behaviour. Indicatively, Kinateder et al. (2014a; 2014b; 2015) focus on the effect of the information on users’ behaviour as well as training, which are crucial factors during the evacuation process. Additionally, evacuation behaviours were shown in the experiments for calculating, one of the most important factor when assessing safety, the evacuation speed in a smoke-filled tunnel in Japan (Seike et al., 2016). Furthermore, Kirytopoulos et al. (2017) investigating the driving habits and safety critical behavioural intentions among road tunnel users in Greece have indicated the defficient level of uses’ education. Another questionnaire study from Singapore showed that drivers’ perspectives for open roads and tunnels are indeed different to some extent (Yeung et al., 2013). Besides, the methods exhibit also lack in establishing uniformly acceptable temperature and pollution thresholds that can enable the estimation of human performance. Most of the methods have not imposed any threshold, giving the analyst the choice. Finally, FED is an important tool for evaluating users' performance regarding both temperature and pollutant concentrations. PIARC (1999) as well as conducted studies can be valuable sources for this issue (Cha et al., 2012; Seike et al., 2016). However, only the SAM method employs FED, and only regarding temperature.

3.3.3 Risk treatment

Not only applying a prescriptive requirement but the optimisation of measures' effectiveness in regard to certain accident and fire circumstances is valuable for an adequate level of tunnel safety. Regarding the mechanical ventilation both PIARC's recommendations (PIARC, 2011) as well as recent studies (Krol et al., 2017; Sturm et al., 2017) have indicated that not only applying the system but its design of emergency operation is a crucial factor for mitigating effectively fire consequences. However, such kind of minimum provisions are missing. Literature provides useful remarks about various safety measures' effectiveness and deficiencies but methods do not provide risk treatment with relevant recommendations. Kirytopoulos et al. (2017) have tested the effectiveness of existing safety measures through the education of users in acting both in normal and critical situations. As a result, the study revealed that significant portion of users have several misconceptions concerning the recommended behaviour which partially relies on measures' effectiveness.

Generally, safety analysts after the evaluation of the estimated risks define a list of alternatives and make a decision that best meets the existing risk criteria. Risk criteria are constraints introduced to simplify the overall judgements providing concurrently a sufficient level of credibility. They are divided into two major groups: (a) the absolute and (b) the relative risk criteria (PIARC, 2013). Both groups need support from reliable and up-to-date accident databases, otherwise they can lead to misleading results.

The use of absolute risk criteria means that the evaluation strategy requires well-established thresholds or distinct risk targets being in line with the regulative requirements against which estimated risks should be below. Although the application of such criteria can be simple, the determination of thresholds in order to define the acceptability of risk has many difficulties. On the other hand, relative risk criteria need a standardised reference risk target complying with all guidelines and standards against which estimated risks are going to be compared with and should be below in every aspect. However, each risk assessment method and regulation includes different reference risk targets, which may lead to different deviations and thus to different alternatives.

In addition to predetermined thresholds and reference risk targets, the selection process has to adapt to the unique characteristics of the system. Exploring the relevant to road tunnel fire safety literature, four main selection criteria are identified as valuable to judge the appropriateness of a measure. These criteria are: the *effectiveness*, the *cost*, the *time* and the *uncertainty*. Each of these criteria consists of sub-criteria as depicted in Figure 3.5, which are of equal importance.

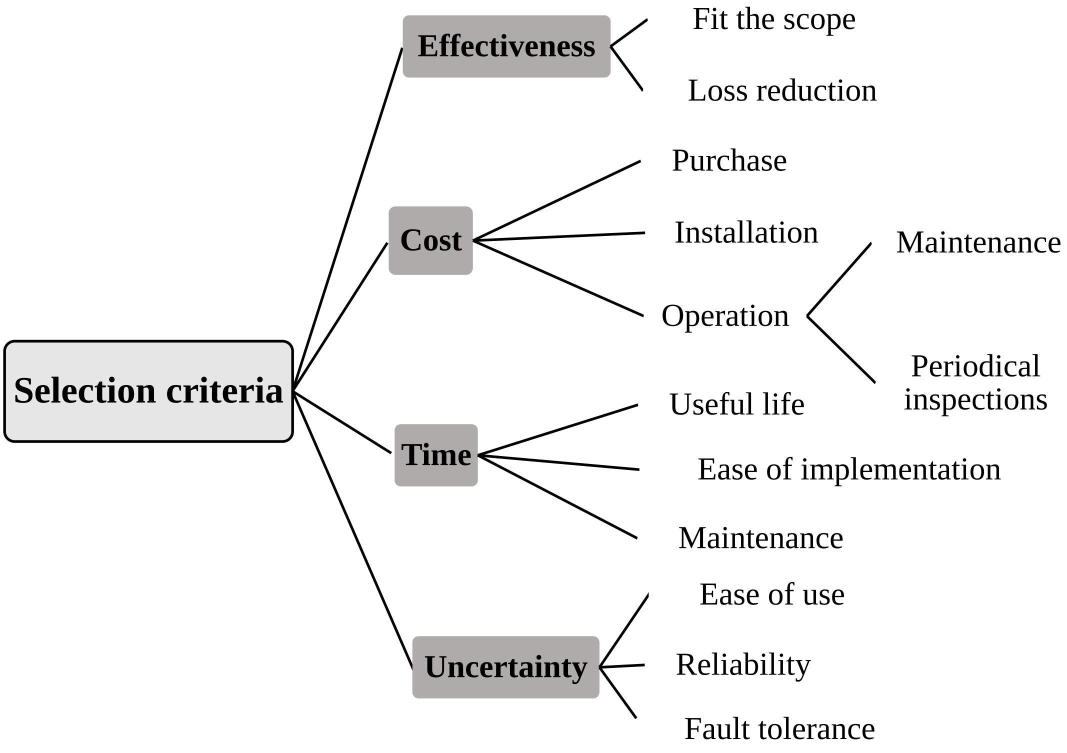

Figure 3.5: Key selection criteria for measures (source: Ntzeremes and Kirytopoulos, under review)

The *effectiveness* consists of two sub-criteria. Initially, the *fit the scope* shows the appropriateness of a measure to actually enhance the overall level of safety of the system conforming to the imposed requirements (Martón et al., 2016). Rated as yes or no, to satisfy this sub-criterion depends on measure’s compliance with existing risk criteria. Secondly, the *loss reduction* reflects the loss reduction achieved through the application of the safety measure estimated through the risk analysis.

Cost includes the *purchase* and *installation* cost of the safety measure as well as the *operation* cost, which consists of the *maintenance* cost and the cost of *periodical inspections*. Risk reduction bears costs due to the introduction of new measures. Therefore, the management of the trade-off between risk and costs is important (Abrahamsen et al., 2018).

Time is a crucial factor due to the importance of the timely application of additional measures. For example, when risk assessment is conducted for a tunnel in operation, it is impractical to close the tunnel for a very long time in order to redesign its system. Therefore, *the ease of implementation* is regarded as an important factor. For the same reasons, time required for *maintenance* consists another sub-criterion that should be taken into account. Another important issue related to this criterion is the *useful time,* which describes the expected durability of the safety measure (PIARC, 1999).

The last criterion is u*ncertainty*. First, this criterion estimates the ability of the measure to operate successfully, in other words its *reliability*. Furthermore, *uncertainty* also includes the *fault tolerance* sub-criterion. *Fault tolerance* refers to the capability of the safety measure to tolerate a sudden failure. For instance, a sensitive device of a safety measure such as for example a jet-fan-array of the mechanical ventilation system can be damaged by the high temperature near to the fire location and fail. However, the system still has to be effective in order to support trapped-users' evacuation (Barbato et al., 2014). Additionally, this criterion also includes the *ease of use*, which estimates the measure's capability of being used by the trapped-user and the operational staff in the appropriate manner. For instance, the operation of the emergency mechanical ventilation relies on both advanced detection systems and experienced operational staff of the control room. To this respect, mechanical ventilation is supposed to have a good score in this case. On the other hand, the way the trapped-users would respond to safety measures that assist their evacuation process such as the messages sent from the loudspeakers, the variable message signs or other notice equipment, is based on their education (Kirytopoulos et al., 2017) and their awareness (Kinateder et al., 2014a; 2015), which both of them include high variability. Therefore, these measures would probably have a lower score.

3.4 Existing gaps

The Directive 2004/54/EC was a necessary first step in order to enhance the level of fire safety of tunnels that belong to TERN but still, there is plenty of room for improvement. Although the EC has set as an aim to reach a “zero level” result towards road safety, the results of Figure 3.2 illustrate that the aim is yet to be reached. Despite the reduction of injuries and losses, these results can receive a significant degree of criticism since the scarcity of disastrous fire accidents shows that policy-makers and tunnel managers must not be complacent about the safety level in tunnels. Furthermore, some member states like Greece, which have increased rapidly their tunnel kilometres during the last decade (see Figure 3.1), they have not any experience from previous fire accidents in order to handle potential disasters.

This Chapter showcases that deterministic approach is predominately followed by risk assessment methods, especially regarding accidents without involving DGs. Nevertheless, faced with the uncertainties embedded in various parameters play a key role in tunnel performance (e.g. users’ behaviour, fire evolution), safety analysts make assumptions adopting a ‘mean’ value or a worst case scenario. But, the variation to reality because of these assumptions can create serious fallacies regarding the estimated level of tunnel safety. In addition, the evaluation process also raises questions.

Apart from the issues regarding the better performance of safety measures, another conclusion on risk treatment is the absence of a systematic decision process. Although the choice of additional to standard safety measures involves multiple criteria decision-making (see Figure 3.5), current risk assessment methods that support decision-making process lack such multiple criteria and a ranking of alternatives, as well.

Finally, users’ behaviour has the predominant role in tunnel safety. The analysis indicates that differences and deficiencies amongst methods exist in the use of certain standardised values and thresholds in order to assess the users’ self-evacuation process.

Chapter 4[3]

Evacuation simulation models

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[3] Parts of this Chapter have been published in: (Ntzeremes and Kirytopoulos, 2018a; Ntzeremes et al., Accepted)

4. Evacuation simulation models

Evacuation simulation models are reasonably considered valuable tools since they enable analysts to inspect thoroughly all the relevant to evacuation parameters. Evacuation simulation models have been consistently progressing until today. FDS+Evac (Korhonen, 2018) developed by NIST and STEPS (STEPS, 2018) developed by Mott MacDonald have been already used in studies (Ronchi et al., 2012). Meanwhile, Capote et al. (2012) have presented the EvacTunnel while Seike et al. (2017) have incorporated a simulation evacuation model in order to fulfill the proposed QRA approach. Predominantly partial behavioural, all the aforementioned models have been used for performance-based analysis either following the deterministic or the stochastic approach. Frequently, this approach depends on the countries requirements.

Additionally, different methodological solutions are employed in order to represent the evacuation process. Consequently, each model has its own particularities and often make for safety analysts difficult to understand how the required variables will affect the final result (Ronchi et al., 2012). In general, two main fields have to be defined in order to provide the models with adequate inputs. These are: the tunnel environment and the users' behaviour.

4.1 General characteristics of the tunnel environment

Estimating tunnel's airflows, almost always requires a CFD model. Through CFD analysis, the safety analyst is able to evaluate the effectiveness of different fire control and fighting strategies (Caliendo et al., 2012; Ntzeremes et al., 2018). Since trapped-users have to evacuate themselves under stratified smoke due to the backlayering phenomenon (see Figure 2.3), a reliable determination of smoke behaviour as well as radiation is important (Seike et al., 2016). Due to the fact that the smoke behaviour in tunnel fires is influenced by multiple factors, CFD analysis enables the safety analyst to integrate them in a rational model. The factors taken into account include (see Chapter 7:

- The environmental conditions of the tunnel. These are the natural ventilation's velocity, the ambient air temperature, the altitude of the tunnel location and the difference in pressure at tunnel portals, which either enables or impedes the airflow.

- The traffic conditions of the tunnel. Traffic conditions refer to the AADT, the percentage of HGV and each type of vehicle's permissible velocity.
- The system of mechanical ventilation. Mechanical ventilation is a crucial parameter regarding the safety of a tunnel (Barbato et al., 2014). Especially, the time the emergency ventilation is activated. Through CFD modelling, the mechanical ventilation is tested whether it meets in time the required critical velocity needed for addressing the backlayering (see Chapter 6).
- The traffic interruption system. The control of the traffic interruption system refers to either the time needed for activating traffic lights or the time needed for activating the traffic bars in the entrance of the tunnel.
- The development of fire, together with smoke propagation. A crucial parameter of the fire behaviour is the time the HRR_{max} is reached (see Chapter 6).

4.2 The role of users in fire safety

Indeed, tunnel users consist the most vulnerable factor of the tunnel system (Kirytopoulos et al., 2017). They are the first who confront with the consequences of the fire event in a tunnel and most of the cases without being adequately experienced in such circumstances. The process of evacuation is a complex phenomenon and embeds significant uncertainties. In order to estimate potential losses amongst trapped-users, the safety analyst should predict the performance of the evacuation process. With a view to predict human behaviour, the evacuation models must simulate two main things: the actions that people take and estimate how long it needs for these actions to be performed (Kuligowski, 2013). To this end, the theoretical framework can interpret how the evacuation process is going to be followed by the users. Therefore, four commonly used and accepted theories addressing the issue of user's behaviour in the event of fire are mentioned according to Fridolf et al.'s (2013) study. These theories are:

- The behaviour sequence model, which separates the human behaviour in four distinct areas (receive; interpret; prepare; act),
- The role – rule model, which considers that every person will behave according to the set of rules of his position,

- The affiliation model, which assumes that a person will head to places or follow people that are familiar to him and
- The social influence, which considers that a presence of other people can affect one's evacuation process.

Placed next to the theoretical framework, a valuable source about human behaviour in fire accidents is the post-accident reports (Ntzeremes and Kirytopoulos, 2018a). For instance, the report about the Mont Blanc accident recorded that 27 users died because they delayed the evacuation process or even started remaining in their vehicles (Fridolph et al., 2013). Various studies can also provide us with information about trapped-users' behaviour. Such as for example an evacuation experiment studying the human behaviour along with the technical installations of the tunnel indicates a range of values for users to start their evacuation (Nilsson et al., 2009). In Seike et al. (2016), an experiment of evacuation speed in a tunnel filled smoke has shown a strong interrelation between the extinction coefficient, which indicates how easily the air can be penetrated by a beam of light in m^{-1}, and the estimating walking speed in normal and emergency situations. Similar results are also provided from other previous experiments (see Figure 4.1). Moreover, Boer's (2002) study has described how trapped-users react based on the announcements by the tunnel operator.

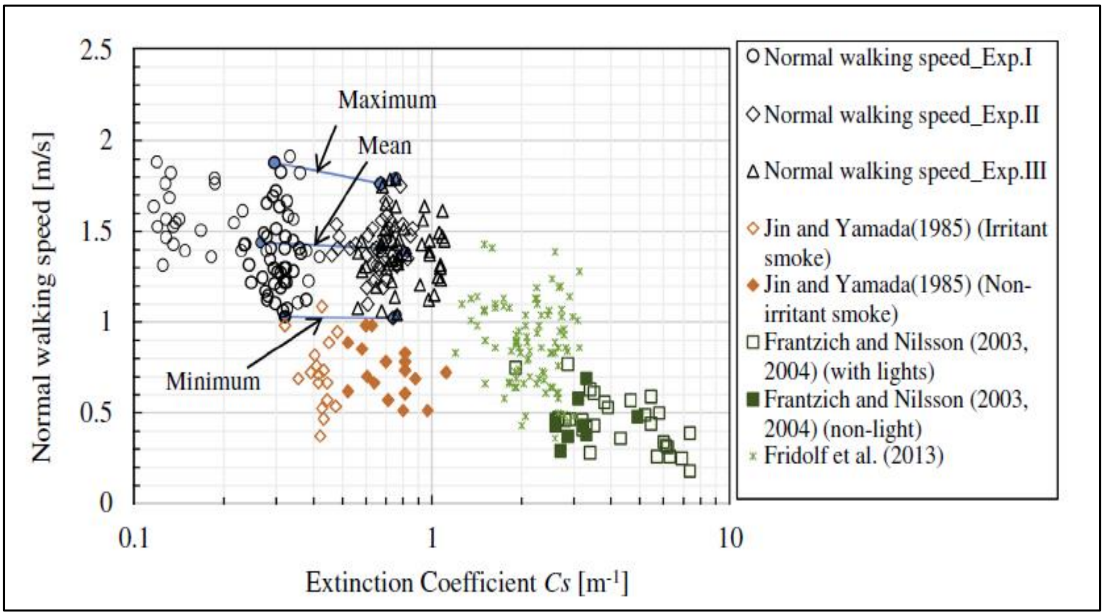

Figure 4.1: Walking speeds in smoke environment (source: Seike et al., 2016, p. 65)

As a result, human behaviour in fire evacuation process seems to depend on which phase of the evacuation process the user performs namely the pre-evacuation or the evacuation phase (Ronchi et al., 2012; Kuligowski, 2013). The pre-evacuation phase relates to the time elapsing between the ignition of the fire and the action of evacuation. Therefore, to simulate the evacuation process requires inputs of evacuation detection and reaction times. For instance, Italian regulations (ANAS, 2009) provide specific guidelines for pre-evacuation time since they impose the time users needed to abandon their vehicles (i.e. 300sec for vehicle users and 90sec for truck drives). On the other hand, Greek regulations (AAT, 2011a) provide specific emergency walking speeds in relation to the density of smoke environment.

Chapter 5

Research methodology

5. Research Methodology

This Chapter aims to describe in detail the research path that has been followed in this thesis. The topics that are mentioned herein are: the research philosophy and approach, the research purpose, the research strategy and the methods used, and at last, the big picture of this thesis is illustrated.

5.1 Philosophy and approach

Bearing in mind that the aims of this thesis (see section 1.3), the presented research endeavour reflects the philosophy of positivism. In general, positivism reflects the philosophy of both the natural scientists and engineers. According to positivism, a thorough observation and analysis of the examined engineering system, that is the road tunnel system in the case of this thesis, leads to the production of credible data that can be used to form more robust scientific principles (Sauders et al., 2009). The term “scientific principles” refers to the sum of rules that interpret both the composition and operation of the system, which form the basis for the development of the method.

In order to produce these date, the researcher needs the appropriate research strategy, which is explained in the following sections, together with existing knowledge and theories, which are provided in Chapters 2 to 4. All these form the basis for the development of a hypothesis that subsequently has to be tested and confirmed or refuted (Sauders et al., 2009). In this thesis, the developed hypothesis is as follows: “*The stochastic behaviour of tunnel system parameters that significantly affect the risk assessment process and thus the selection of safety measures can be taken into account by risk assessment in order to estimate the actual level of safety of the tunnel more accurately*”.

As far as the research approach is concerned, the inductive approach is employed. Induction is regarded as a data-driven research approach since from data the researcher builds his theory (Greenberg and Cramer, 1991). In this thesis, this is applied in the following way. Initially, the tunnel system is analysed, subsequently data are generated and analysed through the use of methods presented in section 5.4 and as a result the risk assessment method is developed (see Chapter 7 and 8).

5.2 Research purpose

The purpose of the research is directly related to the research questions and the associated objectives (Sauders et al., 2009). Therefore, it is defined as a combination of descriptive and exploratory research. The exploratory purpose is justified since the research questions Q1 to Q3 (see section 1.3) illustrate that the main emphasis of this research is to study the tunnel system in order to explore the causal relationships amongst the tunnel system's parameters (see Figure 2.4 and 2.5). Moreover, the description of important aspects regarding tunnel fire safety (such as fire scenarios, tunnel stystem's operation as well as human behaviour during evacuation process) is a precondition of the exploration stage (see Chapter 4 and 6).

5.3 Research strategy

In general, the definition and articulation of problems in engineering is a critical task in the processes of analysis and design, and can be systematically performed with the aid of system theory (Ayyub and Klir, 2006). Therefore, the research strategy of this thesis is based on the systemic approach.

With regard to the systemic approach, the well-formulation of the system is essential since it allows the researcher to develop a complete and comprehensive understanding of the nature of the examining problem, and underlying its processes and activities. Regarding the boundaries of the system, these are drawn strictly based on the research aim, goals, and objectives, as well as the class of performances (including failures) under consideration (see section 1.3).

However, first and before all a well-defined terminology is the first step in an overall methodology formulated for achieving a set of objectives (Ayyub and McCuen, 2011). At first, system definition can be based on observations of the different elements (or components) of the system, the interactions among these elements, and the expected behaviour of the system (see Figure 2.5 and 2.6). Each level of knowledge that is obtained about an engineering problem defines a system to represent the problem. As additional levels of knowledge are added to previous ones, higher epistemological levels of system definition and description are attained and all together form a hierarchy of the system descriptions (Hillier and Lieberman, 2001). It follows from these definitions that the term s*ystem* refers to a set of different elements associated with the relation amongst these elements. Section 2.2 introduces the tunnel system, which is categorised as a structured system, namely a set of smaller and clearly defined subsystems.

In addition to the systemic approach and servicing the aims of this research, the research strategy is based also on quantitative approach. Quantitative approach is predominantly used to highlight the use by research methods of data collection as well as data procedure that generates or uses numerical data (Vinnem, 1998).

Finally, the last attribute of the research strategy is the use of simulation. Commonly, the nature of engineering problems do not allow the researchers to estimate the operation of the system under the required circumstances (e.g. performance of the tunnel system in case of fire accidents) (Morgan, 2008). This task is far more complicated when researchers deal with complex socio-technical systems (Ayyub and McCuen, 2011).

In order to address this issue, a prototype model can be built and tested in actual operation in order to test the performance of the system under the required circumstances (i.e. fire accidents) and fine-tune the final design of the system, if needed (i.e. re-design the system by applying additional safety measures). Simulation enables an analyst to control any of the model parameters, variables, or initial conditions, something that is not possible with the real system. In doing so, the performance of the real system is imitated by using probability distributions to randomly generate various events that occur in the system (Ayyub and McCuen, 2011). In a few words, a simulation model synthesises the system by building it up component by component and event by event (see Figure 2.5). The uncertainty or randomness inherent in model elements (i.e. the stochastic parameters of the tunnel system) is incorporated into the model and the experiments are designed to account for this uncertainty. Then the model runs the simulated system to obtain statistical observations of the performance of the system that result from various randomly generated events. Commonly, because the simulation runs require generating and processing a vast amount of data, the simulated statistical experiments are inevitably performed on a computer-based environment (see Apendix).

At first, some preliminary analysis should be done with appropriate mathematical models to develop a rough design of the system by including its operating procedures. Then simulation is used to experiment with specific designs to estimate how well each will perform (Hillier and Lieberman, 2001). Afterwards, a detailed simulation model needs to be formulated to describe the operation of the system and how it is to be simulated. By the term model is defined herein as a representation of the tunnel system. The model can be either a physical model, such as those used in laboratories, or a mathematical model, such as the ones being examined in this research (Ayyub and McCuen, 2011). The model includes those system's components that reflect the examined processes and provides for interaction amongst them. In this way, the model can be used with simulation to assess the relative importance of the variables. Generally, each simulation model is consist of the following basic steps (Hillier and Lieberman, 2001):

- A definition of the state of the system (i.e. those conditions that correspond to the regular operation of the tunnel system).
- Identify the possible states of the system that can occur (i.e. the accident scenarios).
- Identify the possible events (i.e. potential fire scenarios) that would change the state of the system.
- A provision for a simulation clock, located at some address in the simulation program that will record the passage of the simulated time (i.e. 30 min in case of fire).
- A method for randomly generating the events of the various kinds (i.e. direct MCS based on pre-defined probability distributions).
- A formula for identifying state transitions that are generated by the various kinds of events (i.e. the estimation of losses amongst trapped-users (see Appendix 1)).

Simulation is a valuable tool because it enables the model to reflect conditions that have not occurred in the past but can be expected to occur in the future. Thus, the response of the tunnel system to future accidents can be evaluated and the effects of possible prevention measures can be evaluated (Hillier and Lieberman, 2001). Additionally, the effects of uncertainty in design inputs can be evaluated with simulation (Morgan, 2008).

Although simulation is extremely useful, it exhibits a few problems. Initially, the representation of the system can be possible through the development of several different though realistic models. These different models may lead to different decisions. Secondly, the data used to calibrate the model may be limited, so extrapolations beyond the range of the measured data may be especially inaccurate (Ayyub and McCuen, 2011).

5.4 Research tools

5.4.1 Monte Carlo Simulation

Uncertainty is an important dimension in the definition of risk and thus in the risk analysis. In general, *uncertainty* is defined as knowledge incompleteness due to inherent deficiencies in acquired knowledge. Furthermore, it can also characterise the state of a system as being unstable or in doubt. Therefore, uncertainty can be present in the definition of the hazards and fire scenarios, the tunnel system vulnerabilities and their magnitudes, evacuation models, underlying assumptions regarding human behaviour, effectiveness of safety measures, and appropriateness of the decision criteria. Traditionally, uncertainty in risk analysis processes is classified between two types (Ayyub and Klir, 2006).

The first type includes the inherent randomness or the so-called *aleatory uncertainty*. Some events and modeling variables are perceived to be inherently random and are treated to be nondeterministic in nature. The uncertainty in this case is attributed to the physical world because it cannot be reduced or eliminated by enhancing the underlying knowledge base. Although this type of uncertainty is addressed by representing it probabilistically through a random variable, alternative ways have been proposed beyond the use of probabilities in recent years.

The second type is the subjective or the so-called *epistemic uncertainty*. This is the most dominant type in risk analysis. In many situations, uncertainty is also present as a result of a lack of complete knowledge. In this case, the uncertainty could be reduced as a result of enhancing the state of knowledge by expending resources and time. Sometimes, this uncertainty cannot be reduced due to resource limitations, technological infeasibility, or sociopolitical constraints. However, with some additional efforts, it can be reduced. The path to do that is by using certain probability distributions to represent the random variables. By enhancing our knowledge with time, the aforementioned distributions can be more accurately updated.

The MCS, or simple random simulation, enables this research in order to deal with the uncertainty or randomness inherent in model elements (i.e. the stochastic parameters of the tunnel system). The principle behind the method is to develop a computer-based analytical model that can predict the behaviour of a system incorporating the appropriate parameters (see Chapter 7). When the model is evaluated using data measured from a system, it predicts the behaviour of the system, usually for many simulation runs. Each evaluation (or simulation cycle) is based on a certain randomly selected set of conditions for the input parameters of the system. Certain analytical tools are used to guarantee the random selection of the input parameters according to their respective probability distributions for each evaluation. As a result, several predictions of the behavior are obtained. Then statistical methods are used to evaluate the distribution type for the behavior of the system. The accuracy of the results of simulation is highly dependent on having an accurate definition for the system. The analytical and computational steps that are needed for performing MCS are (Hillier and Lieberman, 2001):

- Definition of the system,
- Generation of random numbers,
- Generation of random variables,
- Evaluation of the model,
- Statistical analysis of the resulting behaviour, and
- Study of simulation efficiency and convergence.

5.4.2 Computational Fluid Dynamics

CFD is a branch of fluid mechanics that uses numerical analysis and data structures to analyse and solve problems that involve fluid flows. In the case of this research the tunnel airflows is the examined fluid.

Tunnel fires produce high temperatures, heat radiation, and low concentration of oxygen, visibility, and toxic gases. These physical phenomena can be dangerous to tunnel users, infrastructure and equipment. To assist the evaluation of these conditions, the simulation performs one-dimensional analysis of tunnel airflows, describing the changes in ambient conditions of air temperature, air opacity and air pollution in the tunnel from the outbreak of the fire until the 30th minute, as this time interval is considered to be critical for the resulting consequences.

CFD simulations of tunnel fires require a solution of the Navier–Stokes equations associated with the appropriate boundary conditions. The advantage of the CFD approach is that the complex physical interactions that occur in a tunnel fire can be modelled simultaneously, and hence their relative influence on the total behaviour of the system is understood. Furthermore, One-dimensional approach is suitable for applications requiring the computation of a large number of scenarios, such as during the assessment of safety strategies for complex tunnels (Beard and Carvel, 2012).

Estimating tunnel's airflows, almost always requires a CFD analysis. Current literature indicates that several models have been applied for estimating fire behaviour and tunnel's airflows. Each CFD model entails slightly different approaches to represent the same process exhibiting each one different strengths and limitations. Indicatively, FDS was developed by the NIST of the United States Department of Commerce, in cooperation with VTT Technical Research Centre of Finland. FDS solves numerically a large eddy simulation form of the Navier–Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires, to describe the evolution of fire (NIST, 2018). ANSYS FLUENT uses also the Navier–Stokes equations to describe the fundamental processes of momentum, heat, and mass transfer. Along with the Navier–Stokes equations, ANSYS FLUENT incorporates further mathematical models in order to describe the processes of turbulence, combustion and radiation (ANSYS, 2018). In this research, the one-dimensional analysis is conducted with the aid of CAMATT 2.0 software is a CFD modeling tool developed and supported by the French Tunnel Study Center in order to estimate particularly road tunnel airflows in the event of fire (Vincent et al., 2005).

The CAMATT 2.20 software solves the following physical equations that govern the tunnel's airflows along with the thermodynamic equations, namely the equation of state and the specific enthalpy:

The equation expressing the conservation of mass: $\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = S_m$

The term source (or sink) S_m of the mass represents the mass flow blown into or extracted from the tunnel per unit of volume. The mass sources calculated by the software are based on:

- Ambient air density,
- Distributed blowing flow rate imposed on a section, and
- Flow rate imposed for blowing ventilations and injectors.

In addition the mass sinks calculated by the software are based on:

- Ambient air density for the distributed extractions and extraction dampers,

- Air density in the tunnel for massive extractions,
- Distributed extraction flow rate imposed on a section, and
- Flow rate imposed for extraction dampers and massive extractions.

The equation expressing the conservation of the momentum in the main direction of flow: $\frac{\partial \rho u}{\partial t}+\frac{\partial (\rho u^2)}{\partial x}=\frac{\partial P_s}{\partial x}+S_{mvt}$

The momentum source term (or sink) S_{mvt} represents the variation over time of the momentum of air per unit of volume due to the action of:

- Buoyancy forces due to the buoyancy acting on hot smoke,
- Air friction forces acting on tunnel walls,
- Vehicle forces acting on the air,
- Driving forces communicated to the air by jet fan arrays,
- Driving forces communicated to the air by injectors, and
- Forces due to air friction in turbulence zones that created by opposite singularities (e.g. change of section, obstacles, etc.)

The equation expressing the conservation of enthalpy: $\frac{\partial \rho h}{\partial t}+\frac{\partial (\rho u h)}{\partial x}=S_{enth}$

The enthalpy source term S_{enth} represents the variation over time of the enthalpy of air per unit of volume due to the:

- Amount of heat emitted by the seat of the fire,
- Convective heat transfers between air and walls,
- Radiant heat transfers between smoke and walls, and
- Transfers of heat during the blowing or extraction of air

Along with these equations, the equations that govern the transport of a passive scalar in the flow can be added in order to identify a pollutant concentration along the tunnel at any time. The analysis of passive scalar transportation enables to simulate the transport of a scalar quantity within an incompressible fluid flow, such as the tunnel air. According to this analysis, the quantities that are transported within the flow do not affect the fluid flow. Therefore are named as passive. In the CAMATT software two types of passive scalar are used, the one type is the concentrations of gaseous pollutants and the other type is the air opacity.

Despite the advantages of the one-dimensional analysis, some limitations exist due to the fact that the flow quantities are assumed to be homogeneous in each cross-section, and thus they are identified with a unique value for each of the variables pressure, velocity, temperature, smoke concentration, etc. This assumption makes one-dimensional modelling unsuitable for simulating the tunnel airflows behaviour in regions characterised by high temperature or velocity gradients (Beard and Carvel, 2012; Ingason et al., 2015).

A fire scenario corresponds to a tunnel with its ramps, if any, and its equipment modelled in a drawing sheet and linked to a set of time, environment and traffic parameters that make it possible to run the simulation (see Figure 7.2).

5.4.3 Description of the evacuation process

Users' losses is the representative parameter that provides the preparedness of the tunnel system in confronting fire accidents. Thus, each of the risk assessment methods focuses primarily on estimating the possible losses amongst trapped-users and is concerned about how to reduce them (PIARC, 2013).

Indeed, tunnel users consist the most vulnerable factor of the system. They are the first who confront with the fire consequences in a tunnel and in most of the cases without being adequately experienced in such circumstances. Moreover, they do not have appropriate equipment with them and often they do not have the education of other groups, like the members of the rescue teams, on how to react in critical situations (Kirytopoulos et al., 2017).

Furthermore, fire in tunnel has much different behaviour than fire in the open road. In particular, it has rapid development, remains in maximum Heat Release Rate (HRR_{max}) longer and releases much more fumes (Beard and Carvel, 2012; PIARC, 2017). As a result, trapped-users have to evacuate themselves in a strictly limited time interval, which does not allow for any delay in the beginning of the self-evacuation process for the anticipation of external rescue teams.

Time is the basic engineering measure of trapped-users' evacuation for refuge finding. A basic representation of the fire emergency timeline that depicts the critical human responses or behaviours that impact and contribute to the evacuation process is illustrated below in Figure 5.1.

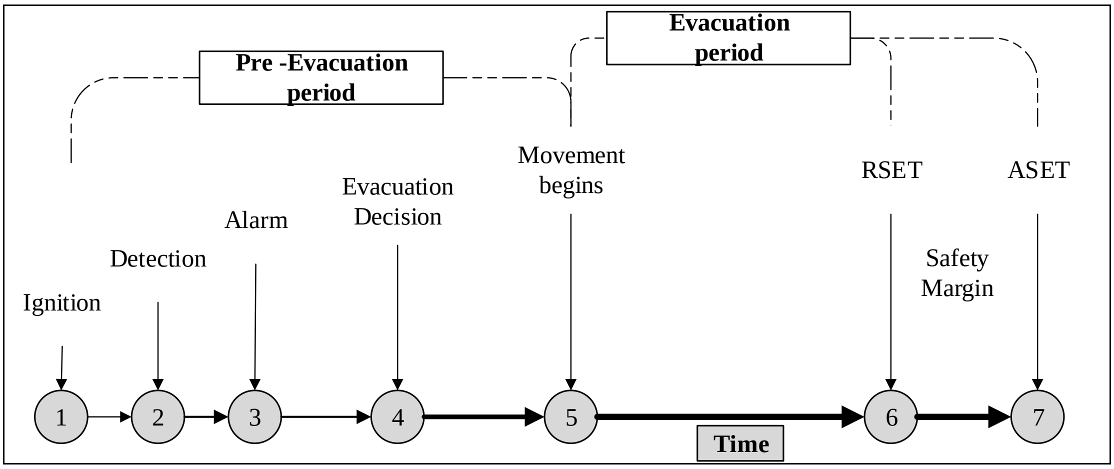

Figure 5.1: Timeline of the evacuation process (adapted from SFPE, 2019)

The majority of the evacuation models, like engineering hand calculations and computer tools, are used in order to calculate the time it takes for trapped users to evacuate the tunnel walking away from the fire environment and heading towards a safe place as the emergency exit doors or the tunnel portals (it depends from the fire location) as soon as possible. An important prerequisite in this direction is the establishment of two basic time parameters, the ASET and the RSET. ASET is defined as the time which is actually available for trapped users from fire sparking and the time point at which conditions become inadequate for human life, because of the high rates of pollutant concentration and radiation. On the other hand, RSET refers to the time that trapped users actually need for a successful outcome of their self-evacuation. The aim of the safety analysts is to achieve the ASET to be greater than RSET (Kinateder et al., 2015). To do so, they have to forecast two main things of the evacuation process: the actions that people take and the time it needs for these actions to be performed.

However, most of the risk assessment methods as well as evacuation models implement oversimplified assumptions about the different stages of evacuation process and the behaviour of trapped-users. Furthermore, they have to follow the country-specific regulatory requirements. These approaches might increase the uncertainty of evacuation models that subsequently lead to a considerable uncertainty of the whole safety approach. Hence, it is important to design models taking into account potential information or clues from both real accidents and studies about human behaviour in fire evacuation and adapting them to the models, accordingly. If so, the uncertainties regarding the overall level of tunnel safety could be diminished.

During the evacuation, users are subject to receiving, recognising and interpreting cues that may impact their decisions before and during their movement towards a safe location. Once movement begins, relevant cues such as the smoke or potential communications amongst users along with the exposure to heat/smoke/toxic gases may be encountered that may influence occupant responses and in turn movement time. Therefore, these factors should be appropriately considered.

In order to make some estimate of the likely toxic hazard in a particular fire, it is necessary to determine at what point the user will have inhaled a toxic dose. A practical method for making this calculation is the concept of FED based on specific toxicity analysis techniques (see section 7.5).

5.4.4 Analytic Hierarch Process

Multi-criteria decision methods have been applied in various engineering problems in order to evaluate alternative solutions due to their clarity and robustness. The successful selection of the most appropriate method is based on the research objectives and the considered inter-connections amongst the different criteria. Such methods are: the family of multi-criteria decision analysis ELECTRE methods, the family of multi-criteria decision analysis PROMETHEE methods and the AHP. ELECTRE and PROMETHE methods are characterised by the use of veto, preference and indifference thresholds (Kolios et al., 2016). However, decision-making regarding fire safety measures involves commonly a small group of four or five alternatives. These group of alternatives has been resulted from the conducted risk assessment. Trough risk assessment, potential measures’ applicability as well as appropriateness has been scrutinised since risk assessment excludes those measures that do not meet the imposed risk criteria (e.g. ALARP curves or EV threshold) (Ale et al., 2015). As a result, veto and indifference thresholds have no use in tunnel area.

In order to support the decision-making process towards the selection of fire safety measures for road tunnels, the AHP is employed (see Chapter 8). Following a top to bottom sequence, the implementation of the AHP method requires the next steps (Saaty, 1990):

- Analyse the decision process into a hierarchy of goals, criteria, and alternatives.
- Estimate priorities. To do so, criteria are compared pairwise with respect to the desired goal to derive their weights.

- Estimate local priorities following a similar process regarding the consistency of the judgments as in the previous step.
- Estimate the overall priorities. The alternative with the highest overall priority constitutes the best choice.

However, it is impossible to avoid some inconsistencies in the final matrix of judgments. The question that arises is how much inconsistency is acceptable. For this purpose, AHP calculates a CR comparing the CI of the matrix in question versus the CI of a RI (Caputo et al., 2013). More specifically, RI is the average CI of 500 randomly filled in matrices. Saaty (2012) provides the calculated RI value for matrices of different sizes. In AHP, the consistency ratio is defined as CR where CR = CI/RI. Saaty (2012) suggests that CR of 0.10 or less is acceptable. If the consistency ratio is greater than 0.10, it is necessary to revise the judgments in order to locate the cause of the inconsistency.

5.5 Research design

The aforementioned research tools are employed in order to reach the research objectives (see section 1.3). The flowchart in Figure 5.2 illustrates the overview of the research development. As shown by the flowchart, the research comprises of four distinct phases each of which follows a sequence of particular steps. The completion of each step is a prerequisite for embarking on the next step. The steps in the end of which each objective is fulfilled are highlighted in the flowchart.

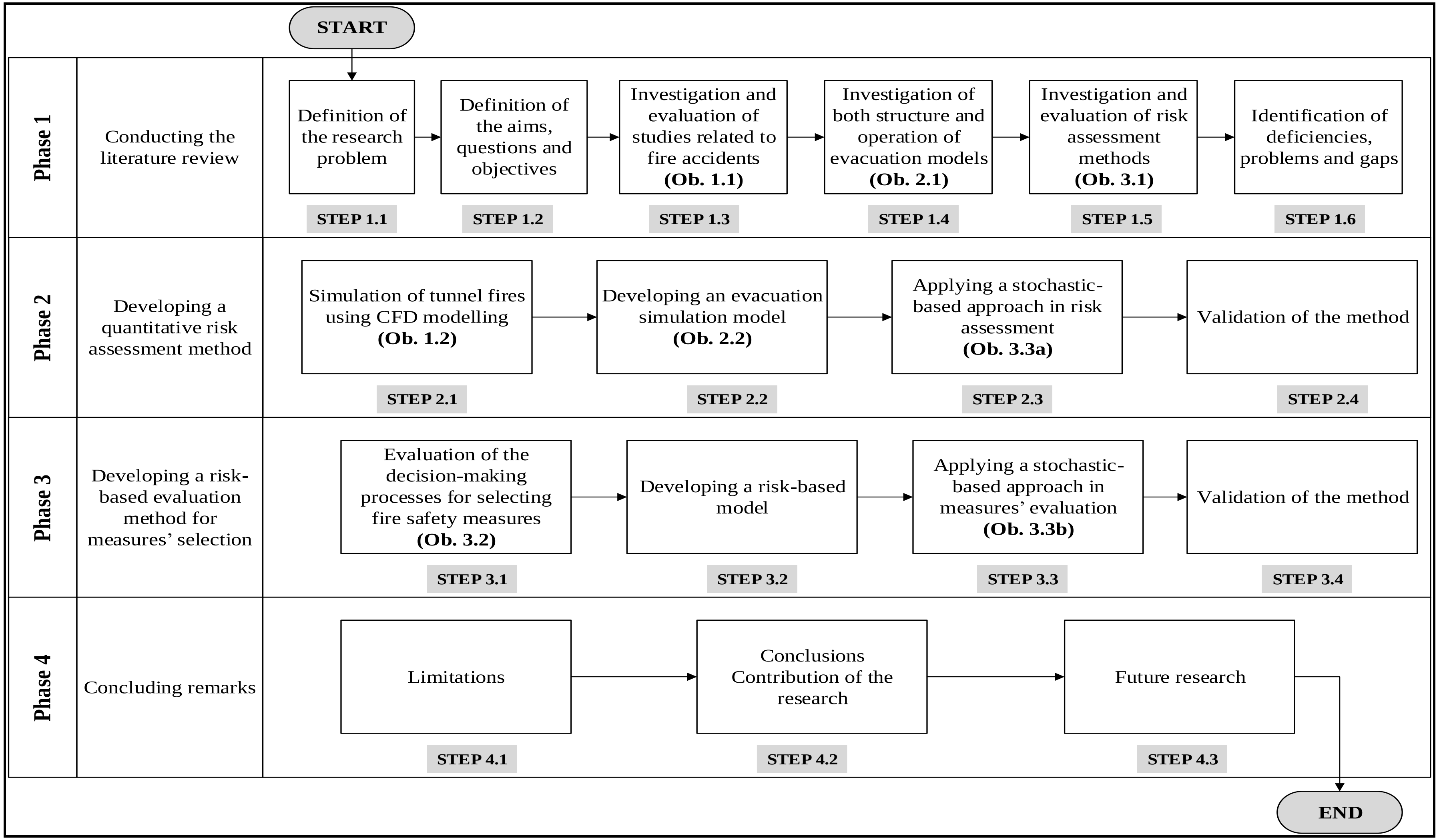

Figure 5.2: Flowchart of the research development

Chapter 6[4]

Exploring the effect of national policies on risk assessment through the examination of fire scenarios

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[4] Parts of this Chapter have been published in: (Ntzeremes et al., 2016; Ntzeremes et al, 2018)

6. Exploring the effect of national policies on risk assessment through the examination of fire scenarios.

The primary aim of this Chapter is to simulate a tunnel fire in order to explore the consequences of a fire accident in a tunnel. By doing so, the evolution of fire is examined, the vulnerable locations of the tunnel are identified and the performance of the users' evacuation is assessed. Furthermore, in order to explore the impact of the variations of the regulatory guidelines (see Chapter 3) to the level of tunnel safety, the examination of the fire scenarios is performed through the French SHI (CETU, 2003) and the Greek SAM (AAT, 2011a) tunnel risk assessment methods. The choice is not arbitrary as these methods share a high degree of similarity in their inherent approaches and assumptions (see Figure 3.3 and Table 3.1), while at the same time it results that their discrepancies on parameters that should not be country-specific are significant enough to change the estimated level of safety of the same tunnel. The concept behind the selection is that if two very similar methods can lead to considerable discrepancies, these discrepancies would further increase if the methods used were more dissimilar.

6.1 Background comparison of the two approaches

Both countries comply with the provisions of the European legislative framework for increasing the level of safety in road tunnels either by imposing new regulations (Greece) or aligning with it (France). Especially in the part of risk assessment, France was amongst the first member states that designed, before the Directive was in force, a comprehensive risk assessment method and included it in its safety documentation guidelines for all road tunnels longer than 300m, in 2003 (CETU, 2003). Greece imposed an equivalent method for all road tunnels longer than 500m, in 2011 (AAT, 2011a). The main purpose of both methods is to test the tunnels' level of safety and contribute to the design of emergency response plans and provision of supplementary safety measures if required.

By comparing the two methods towards EU requirements at a high level, it can be inferred that their approaches are, in general, extremely similar. Specifically, both methods state in their introduction that road tunnel safety must be approached with a systematic view encompassing all the elements of the tunnel system (see Figure 2.5) and by examining interactions amongst the elements. Moreover, both methods refer to the need of using quantitative risk assessment as an efficient estimator of tunnel accidents' results.

In regard to the axes that shape each method function (see Figure 3.3), both methods are scenario-based because they suggest that a number of two or three crucial accident scenarios should be examined. Also, both methods do not consider the transport of dangerous goods. In both countries, the study of DGs by HGVs through road tunnels is subject to separate regulatory framework that foresees detailed quantitative risk assessments using the OECD/PIARC QRA software (see section 3.3). However, both methods use standardised fire scenarios, which could specifically account for HGVs carrying DGs (i.e. fire scenarios with HRRmax of 200MW).

Despite the aforementioned similarities at a higher level, a deeper examination can exhibit some important differences. Firstly, the definition of the reference conditions for a tunnel differs. Specifically, in the Greek method the reference conditions are those for which the tunnel would comply with all infrastructure and safety equipment prerequisites of Directive 2004/54/EC. In the French method, the reference conditions come mainly from the national legislative provisions.

Secondly, a difference exists in the way of introducing accident scenarios. Both methods state that accident scenarios that are to be chosen should mobilise the whole system, thus, any vulnerability and "black boxes" would be enlightened. The purpose is, if needed, to propose potential corrective measures without a total redesign of the system and to contribute in the design of emergency response plans. To this purpose, the French method defines the accident scenario from the triggering of the crucial event, usually by connecting it to precedent events that lead to accident-causing states, thus, focusing its analysis in primarily diminishing the consequences from the appearance of the crucial event. In contrast, the Greek method also examines potential hazards that lead to the triggering event and possible control measures for these, based on the bow-tie model.

Thirdly, there is a different approach in risk identification. The French method uses a guide to distinguish the risks amongst accident-causing situations, critical events and aggravating factors, in which recorded risks are also separated amongst users, personal staff, internal and external space. In contrast, the Greek method provides a guide for some main critical events and in a subsequent step challenges the experts to determine and document the sequence of Hazards → Critical Event → Consequences.

Last but probably the most important, differences pertain to the parameters' default values used in the two methods. Especially in cases of accident scenarios involving fire, these differences refer to the formation of the developing smoke and fire environment inside the tunnel in which users are presented and to the attitudes of users during the development of the fire. Thereby, both methods provide a number of standardised fire scenarios as well as standardised parameters' values and thresholds in order to assess the users' self-evacuation process (users' perception and moving velocities, temperature and pollution thresholds) and the infrastructure and facilities durability and resistance (i.e. temperature thresholds for mechanical ventilation and against spalling). Also, different approaches exist in estimating the effects of the fire environment among trapped users. For instance, the use of FED, which estimates the radiative and the convective heat of trapped users, is not mandatory, in both methods.

A schematic representation of the aforementioned points is shown in Figure 6.1.

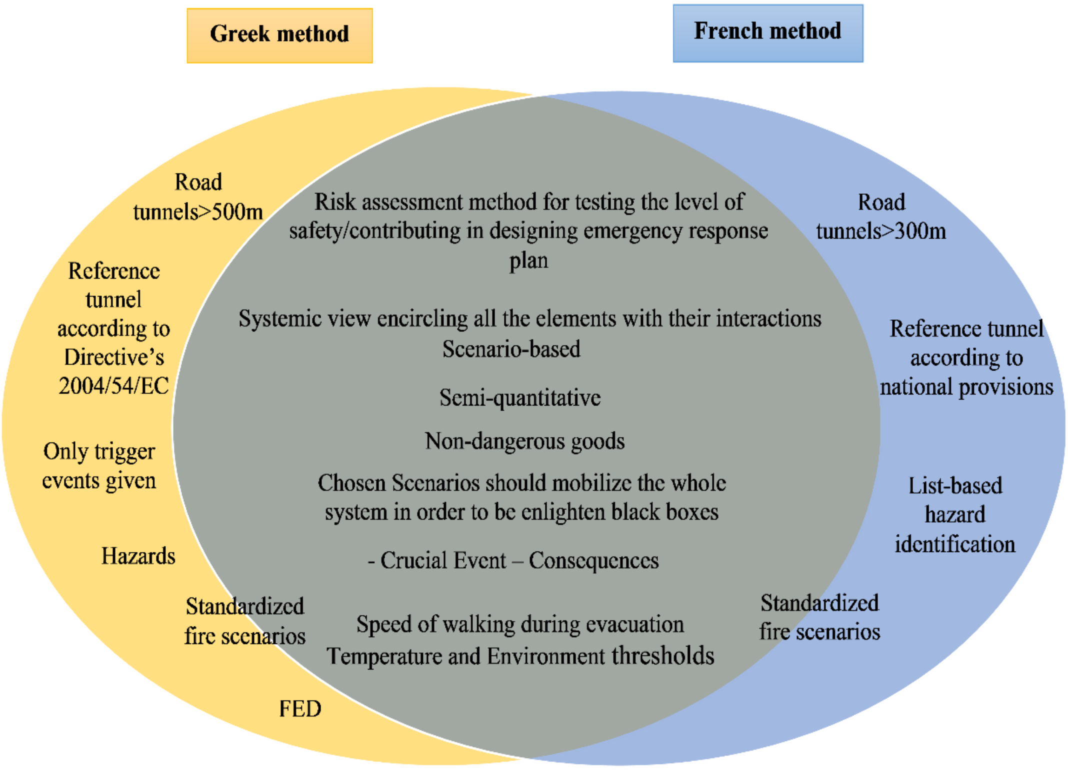


Figure 6.1: French and Greek methods' characteristics (source: Ntzeremes et al., 2018, p. 48)

6.2 Case study description

A typical road tunnel in Greece, meeting the infrastructure and equipment requirements as specified by of Directive 2004/54/EC for tunnels belonging to the TERN, is selected. Table 6.1 reports the main attributes of the tunnel.

Table 6.1: Tunnel attributes (source: Ntzeremes et al., 2018, p. 49)

Designing features	One bore – single sector	
	Total length	2.700m
	Slope	-1,5%
	Number of emergency exits	6
	Number of traffic interruptions	7
	Launch of traffic lights after fire ignition	5min
Mechanical ventilation	Number of jet-fan-array	8+1(backup)
	Number of jet fans making up the array	2
	Progressive function	
	Launch of the system after fire ignition	2min
Pressure difference	95% of max velocity based on local estimations regardless direction	28Pa
Environmental conditions	Temperature	12°C
	Altitude	600m
Traffic conditions	Vehicle flux (quiet part, 0:00–8:00)	55 veh./hr.
	Vehicle flux (regular part, 8:00-0:00)	255 veh./hr.
	Proportion of HGVs	30%

The examination of risk assessment is performed for three accident scenarios each one involving a fire event from HGV at distances of 350m, 1,500m and 2,350m from the entrance of the tunnel for regular and quiet traffic conditions. According to previous studies, the selected locations are considered to be the most crucial from a risk-level perspective as these are the most vulnerable tunnel locations while also exhibiting different behaviour of fire (Amundsen, 1994).

The fire scenario that is implemented in each location is a standardised fire scenario including in the Greek and French method. It has the following description: Fire involving a HGV with a standardised source term of 100MW at peak (HRRmax = 100MW). This case was selected because it is one of the most frequently used scenarios in the EU. It has a considerable high HRR and refers to HGVs, which are more often involved in fire accidents than other vehicles (Beard and Cope, 2008). The main difference between the Greek and French standardised scenarios is that the assumption for the time needed for the fire to reach its HRRmax, is 5 and 10 minutes respectively. Fire produces high temperatures, heat radiation, low concentration of oxygen, low visibility, and toxic gases. These physical phenomena can be dangerous to users, infrastructure and equipment. To assist the evaluation of these conditions, the simulation performs one-dimensional analysis of tunnel airflows, describing the changes in ambient conditions of air temperature, air opacity and air pollution in the tunnel from the outbreak of the fire until the 30th minute, as this time interval is considered to be critical for the resulting consequences. The one-dimensional analysis is conducted with the aid of Camatt 2.0 software.

6.3 Outcomes and discussion

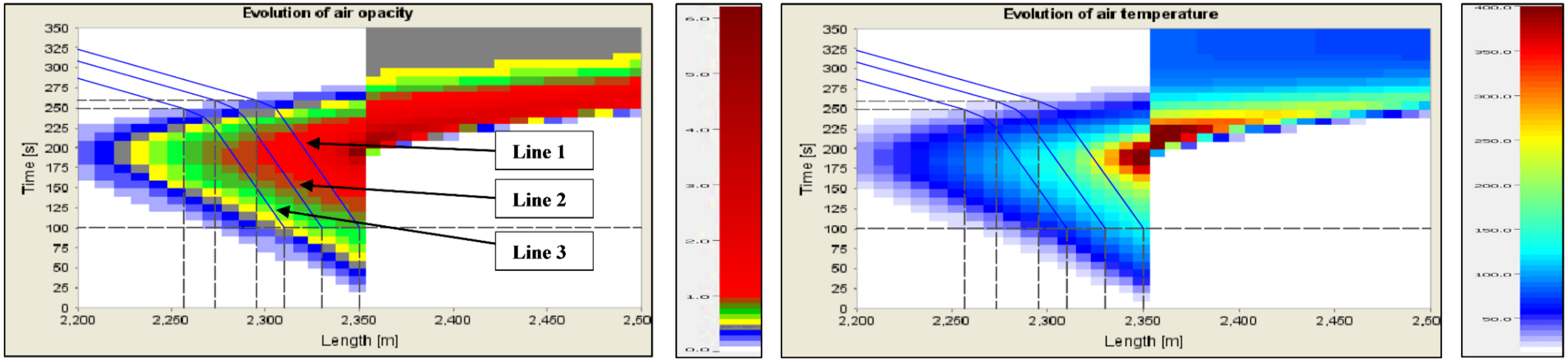
The accident results in five vehicles, including one bus and the HGV that caused the accident, being trapped in the tunnel. Other vehicles remain outside of the tunnel as traffic lights stop the traffic at the entrance of the tunnel and those that are past the fire location are supposed to continue towards the exit portal. It is further assumed that 100s elapse from the start of the fire for all trapped users before they realise the criticality of the event and start the self-evacuation process moving towards the nearest emergency exit. The emergency exits are located at 1,200m and 2,000m from the entrance of the tunnel for the accident scenarios occurring at 1,500m and 2,350m from the tunnel’s entrance respectively or directly at the entrance for the accident scenario occurring at 350m from the tunnel’s entrance.

The Camatt 2.0 software was used to simulate the evolution of air opacity and air temperature for all accident locations. As smoke backlayering effects do not occur in the regular traffic conditions due to the presence of strong piston effect, Figure 6.2 – 6.4 present only the evolution of the air opacity and the air temperature for the quiet traffic case.

The aim of the mechanical ventilation system is to diminish the length of backlayering achieving as soon as possible the critical velocity. The critical velocity is the minimum steady-state velocity of the ventilation airflow moving toward the fire within a tunnel that is required to prevent backlayering upstream of the fire location.

The disruption of traffic rotates the flux of air from the exit to the entrance of the tunnel due to the pressure difference at the tunnel portals. From that point and until the mechanical ventilation reaches the critical velocity, backlayering may occur. The analysis shows that initially the existing pressure differences between the tunnel portals, influence the “sharpening” of the smoke layer at the different fire locations. Consequently, the further the fire location from the tunnel’s entrance is, the less extended the backlayering of smoke. In turn, this also decreases the time needed to reach peak temperature at fire locations closer to the tunnel’s entrance.

Fire scenario according to the French method:



Fire scenario according to the Greek method:

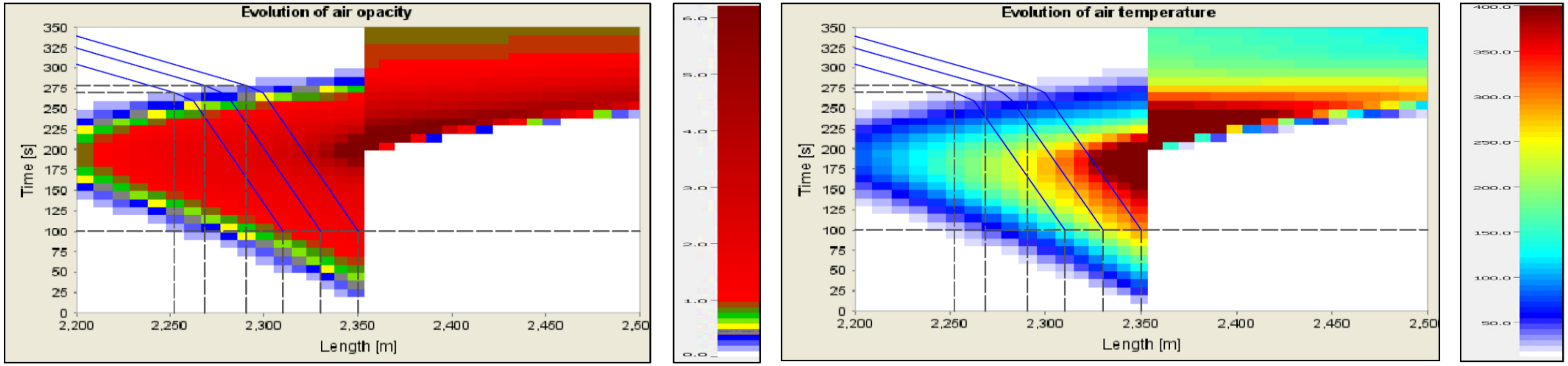
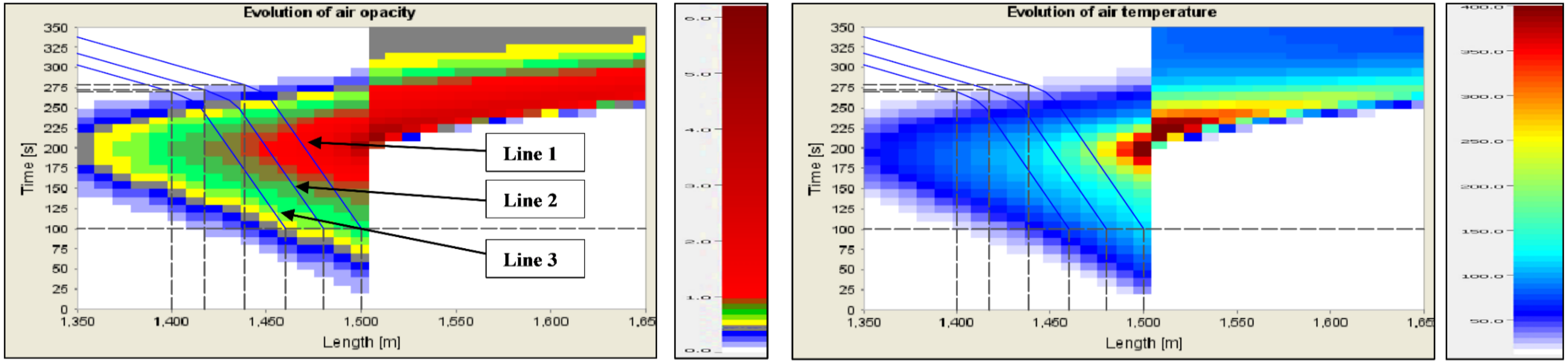


Figure 6.2: Air Temperature (^{0}C) and Opacity (m^{-1}) along with Escaping lines of trapped users, x=2,350m (source: Ntzeremes et al., 2018, p. 51)

Fire scenario according to the French method:



Fire scenario according to the Greek method:

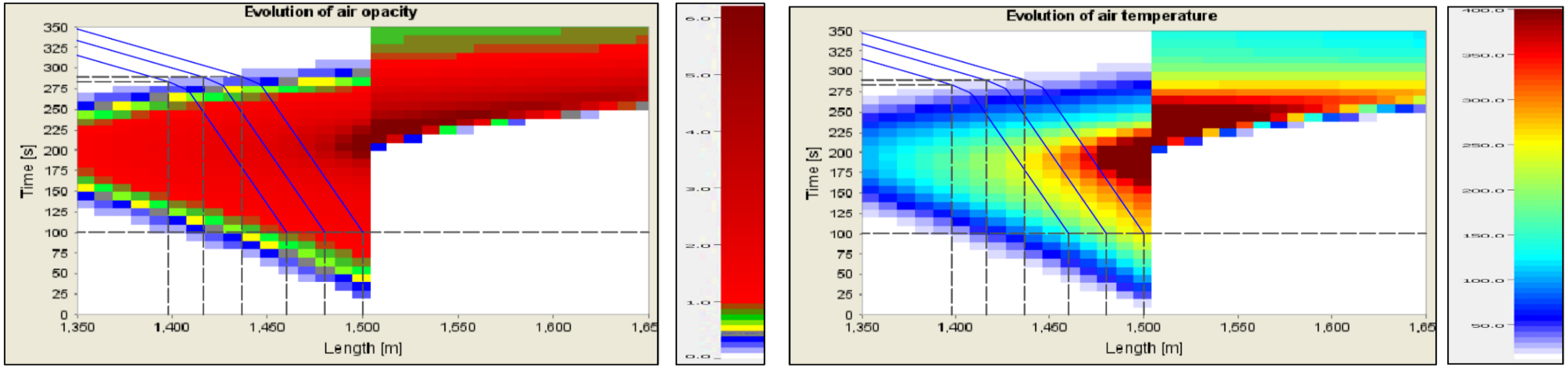
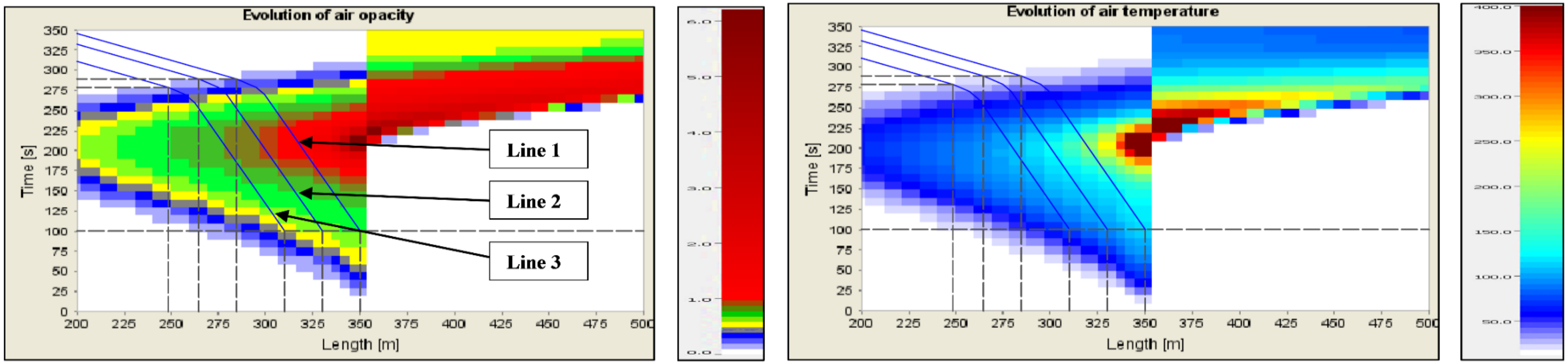


Figure 6.3: Air Temperature (^{0}C) and Opacity (m^{-1}) along with Escaping lines of trapped users, x=1,500m, (source: Ntzeremes et al., 2018, p. 51)

Fire scenario according to the French method:



Fire scenario according to the Greek method:

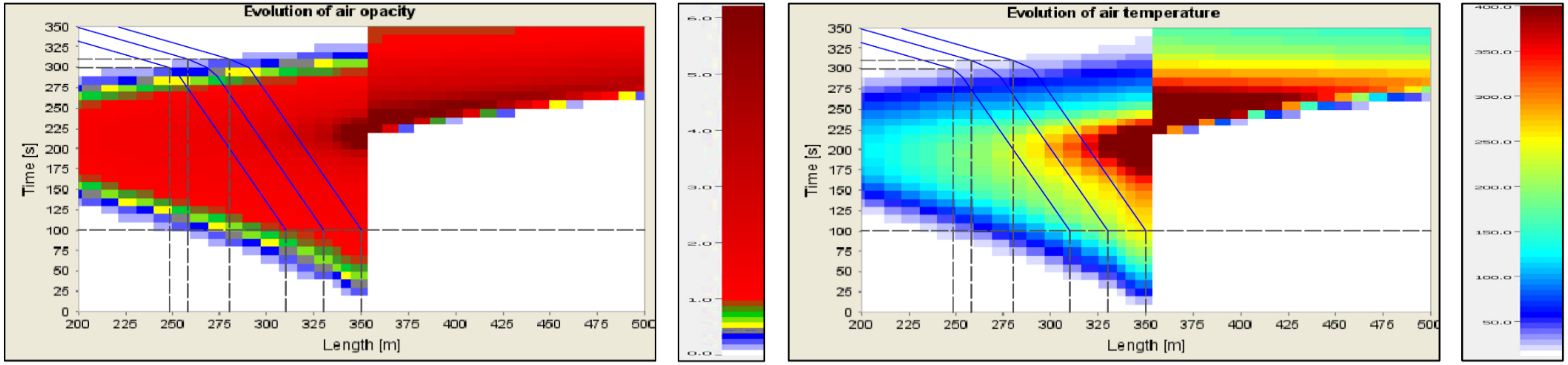


Figure 6.4: Air Temperature (^{0}C) and Opacity (m^{-1}) along with Escaping lines of trapped users, x=350m, (source: Ntzeremes et al., 2018, p. 52)

The evolution of fire and the respective effectiveness of the mechanical ventilation are presented in Figure 6.5, for the three fire locations and the two methods considered. The Greek method results in a significant increase of the air opacity and the air temperature in comparison to those of the French method for every location, (Figure 6.2 – 6.4). This is due to the difference in fire standardisation between the two methods. Even though both methods assume a fire of maximum HRR equal to 100MW, this value is reached in ten minutes according to the French standardisation but only in five minutes according to the Greek standardisation.

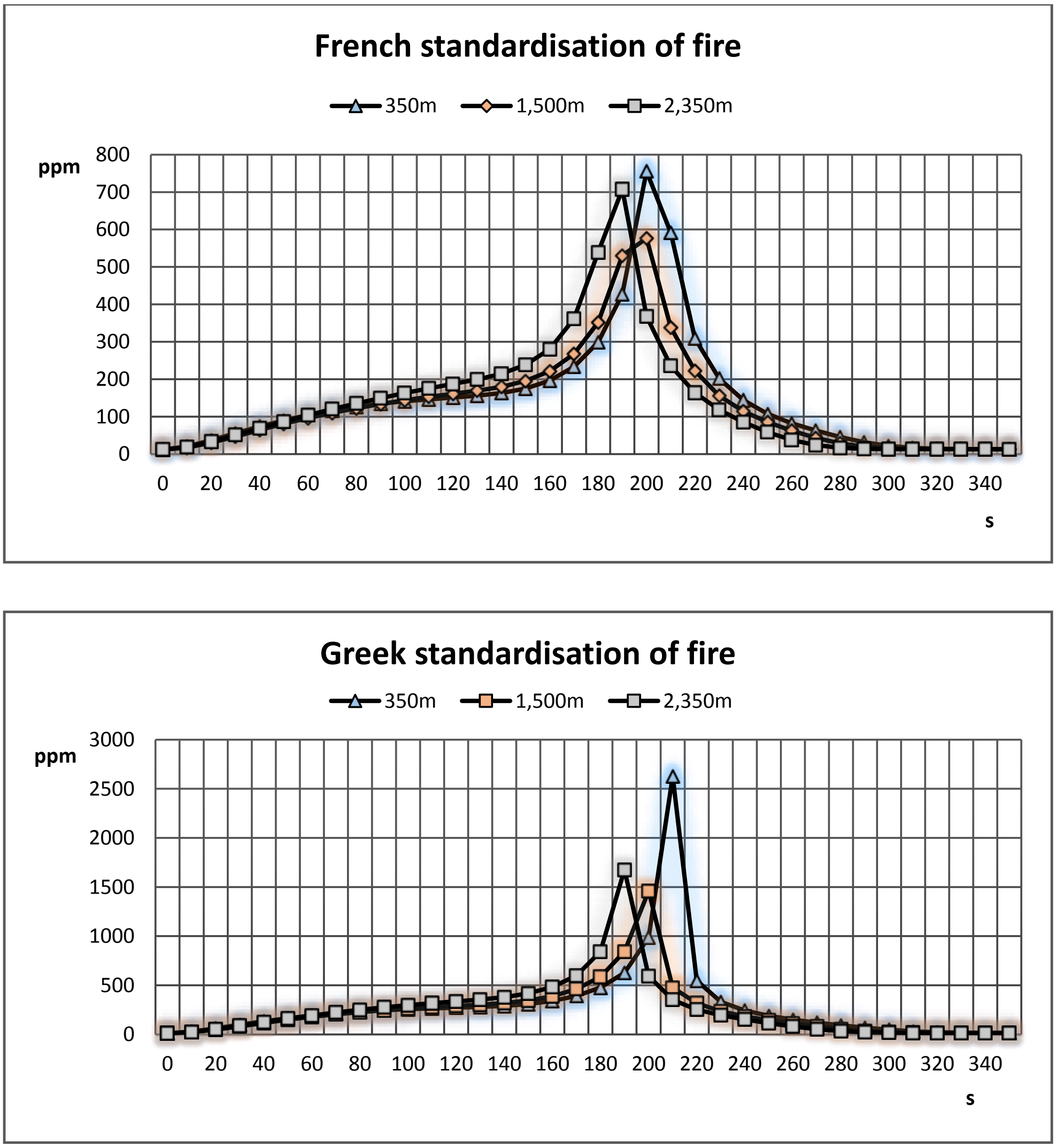


Figure 6.5: Evolution of the pollutant concentration at fire locations for Greek and French scenarios (source: Ntzeremes et al., 2018, p. 53)

The earlier time needed for the fire to reach its maximum HRR in the Greek standardisation translates into an accelerating evolution of the fire which results to faster and further expansion of the smoke and the temperature layer upstream of the fire location. However, both methods assume that the system of mechanical ventilation starts operating at the same time, i.e. two minutes after the outbreak of the fire. This results in fire scenarios under the Greek method to release more heat but the respective top temperatures to be reached at approximately the same time.

Another major consequence due to the difference in fire standardisation occurs with respect to the longitudinal ventilation system. For fire accidents located at 350m, only one jet fan array is destroyed at 180s in the French method as opposed to two jet fan arrays destroyed at 110s and 280s respectively in the Greek method. A similar situation occurs for the fire accidents located at 2,350m from the tunnel’s entrance: in the French method, no jet fan array is destroyed, whereas, two jet fan arrays are destroyed at 110s and 260s respectively in the Greek method resulting in significant deterioration of the air environment. Thus, for the Greek method mechanical longitudinal ventilation is evaluated as insufficient for this fire scenario standardisation.

However, the different provisions have serious effects in the 48 trapped users. Figure 6.2 – 6.4 also illustrate the crucial part of the evacuation lines of trapped users, specifically during the first 350s. Table 6.2 below presents the movement of users in a fire environment, which is used for these calculations (PIARC, 1999; CETU, 2003; AAT, 2011a).

Table 6.2: Trapped users’ movement (source: Ntzeremes et al., 2018, p. 52)

Velocity (m/s)	1.50	1.00	0.50	0.30
Opacity (m^{-1})	[0]	(0, 0.30)	[0.30, 0.50]	[0.50, 10)

Users are trapped at 0m, 10m, 20m, 30m and 40m upstream the fire locations, according to the distribution of the vehicles after the outbreak of the fire. Thus, assuming two passengers per vehicle and 40 passengers per bus 48 users are trapped. Total duration needed by users to escape from the smoke environment are depicted in Figure 6.6.

Smoke propagation in the Greek method develops considerably faster than when compared to the French method due to the lesser time needed as per the default assumption of the two models for the fire to reach its HRRmax. Consequently, reduced user velocities are assumed during the self-evacuation process for all Greek accident scenarios, which in turn result in increased exposure to the smoke environment, as depicted in the opacity diagrams (Figure 6.2 – 6.4). The increase in exposure time to the smoke environment for users of the Greek fire scenarios as compared to the users of the French fire scenarios range between +10s and +22s for the three distance scenarios examined.

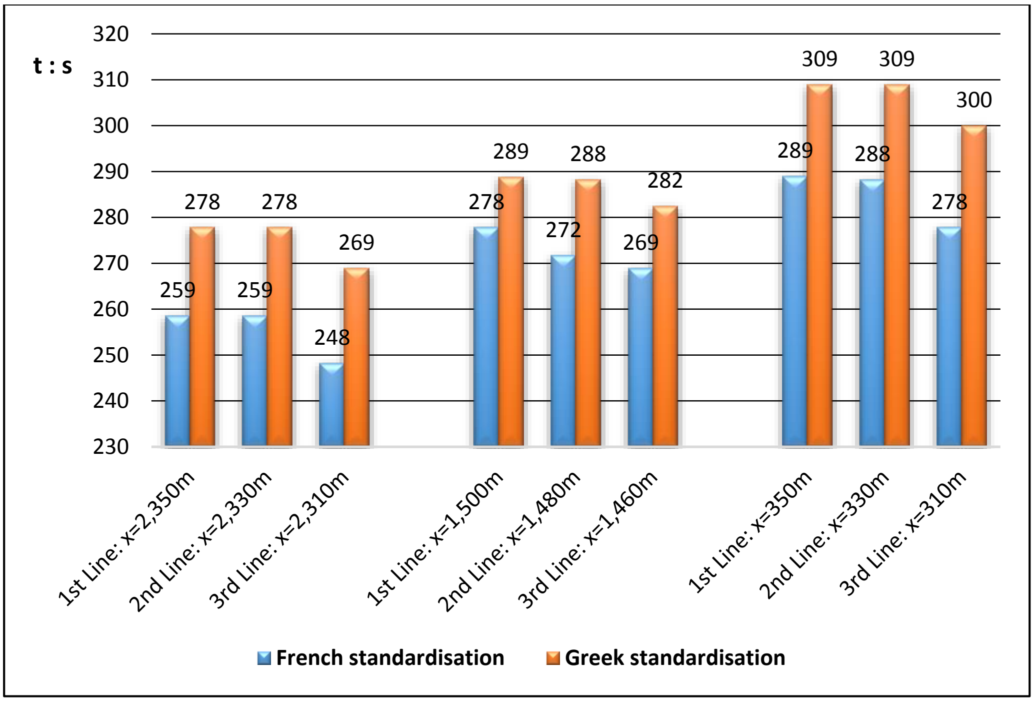


Figure 6.6: Total time needed for users to find themselves out of the smoke cloud (source: Ntzeremes et al., 2018, p. 53)

It is important to note that for air opacities above 0.7m-1 both methods state that 50% of users might direct to the opposite direction rather than the correct. As the air opacity increases the aforementioned percentage may worsen. In the Greek method, trapped users are confronted with such deteriorated conditions for each fire location scenario. In contrast, trapped users under the French method do not confront such conditions in the exception of those located at the location of the fire which might be threatened by the direct exposure to fire (Figure 6.2 – 6.4).

Another consequence of the increased propagation of smoke in the Greek method is that users absorb higher heat which occurs as a consequence of higher air temperatures from both their longer exposure to the smoke layer and the higher heat release from the fire itself. Radiation is created by temperature. The level of radiation that a user collects depends on the temperature and the emissivity of the smoke. In order to provide a level of magnitude for the effect of the radiation on trapped users, the FED is used. FED consists of calculations for radiant and convective heat (Ntzeremes et al., 2016).

FED_h is calculated as:

$$FED_{h.} = \Sigma(1/t_{iconv.}+1/t_{irad})*\Delta t \qquad (1)$$

where t_{iconv} is the time duration for convective heat, which is calculated as:

$$t_{iconv} = (5*107)*T-3.4 : \text{for light clothing} \qquad (2)$$

where {t} the time in minutes and {T} the temperature in °C,
and where tirad is the time duration for burning of skin, which is calculated as:

$$t_{irad} = 4*q-1.36 \qquad (3)$$

where {t} the time in minutes and {q} the radiant heat flux in kW/m2 (for q>2.5kW/m2; for q<2.5kW/m2 this time is equal to 30min).

For example, as it can be inferred from Figure 6.2 for the accident scenario located at 2,350m, in the Greek method all users are exposed to temperatures of at least 200°C. The Greek guidelines assume that users are neutralised for FED_h values greater than 0.3. Based on this assumption, it is estimated that a user could tolerate approximately 13.50s in an environment of 200°C until becoming neutralised. Hence, in this case all trapped users are to be neutralised. By contrast, for the same scenario using the results from the French method in conjunction with the calculation of the FED_h, it can be shown that users located at 2,330m and at 2,310m experience air-temperatures of approximately 150°C which allows them to hold for approximately 54s before being neutralised. This difference in neutralisation time significantly increases the chances for self-rescue. Similar conclusions can be derived for the other two fire locations at 1,500m and 350m.

6.4 Conclusions

As a conclusion for all accident locations, by using Greek method trapped users located 20m and 40m before the fire location are affected more as a result of an increase of the air temperature. These users under the French method could have better chances to be self-evacuated. Trapped users of the 1st line are located in front of the fire positions so they confront in both methods high air temperatures and absorb convective heat along with radiant heat too.

To summarise, the underlying differences in default parameter values of standardised fire scenarios and the possibility of using different exposure assumptions (i.e. FED_h), can lead to significant differences in tunnel environment simulation (i.e. air and opacity temperature), which affects the results on self-evacuation process of trapped users. Furthermore, the safety equipment of the road tunnel is also affected. Longitudinal mechanical ventilation is evaluated as being insufficient when the analysis is done with the Greek method and needs to be re-designed whereas according to the French method it is deemed acceptable.

Although these methods share a high degree of similarity in their inherent approaches and assumptions (see Figure 3.3 and Table 3.1), the consequences of the aforementioned differences may significantly impact the overall estimated level of safety as model results combined with FED_h calculations have shown that these may lead to estimates of additional losses amongst trapped users. Even if self-evacuation is not considered, the resulting differences in air temperature and opacity model estimates clearly indicate increased potential for damages to the ventilation system in the Greek method which in turn will result in a significant degradation of the air environment inside the tunnel as compared to the French method. So, in Greek method tunnel becomes unable to respond to the requirements of safety.

At last, methods do not account for parameter variability and/or uncertainty and instead use standard normative provisions. A possible direction is to demonstrate by the use of probabilistic methods the effect the of parameters' values variability and uncertainty in the aimed harmonisation of safety level for road tunnels.

Chapter 7[5]

Applying a stochastic-based approach for developing a quantitative risk assessment method on the fire safety of road tunnels

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[5] This Chapter has been published in: (Ntzeremes and Kirytopoulos, 2018b; Ntzeremes et al., Accepted)

7. Applying a stochastic-based approach for developing a quantitative risk assessment method on the fire safety of road tunnels.

7.1 Role of risk assessment in tunnel fire safety

QRAs have been consistently progressing until today (Charter et al., 1994; Kohl and Forster, 2012; Neumann and Sistenich, 2011; Ronchi et al., 2012; Seike et al., 2017). The general framework of QRAs deals with fire accidents based predominantly on scenario-based approaches with a view to estimate the resulting consequences amongst tunnel users (see section 2.2). With this respect, the employment of CFD models from QRAs has been proved essential (Caliendo et al., 2012). CFD models employ computer simulation for showing fire behaviour and its impact in the tunnel system (see section 5.4.2). To this respect, the model evaluates the fire efficiently and quickly since all the relevant tunnel characteristics, like its geometry, traffic, environmental conditions, etc. are taken into account. Therefore, the smoke and temperature environment is interpreted in much detail assisting, thus, the estimation of the evacuation process of trapped-users. The potential losses amongst tunnel users provide the safety analyst with information about the tunnel’s level of safety and, thus, constitutes the ultimate goal of each QRA method.

A significant differentiation exists towards the approach of tunnel fires depending on the type of transporting goods (see section 3.3). Although most QRA methods follow the deterministic paradigm, risk assessment regarding DGs is based on a stochastic approach having as central point the aversion of the potential fire causes (usually through DGs access restrictions) (Kirytopoulos, et al., 2010; Caliendo & De Guglielmo, 2017). This strategy is followed as the nature of accidents involving DGs makes it difficult to effectively intervene after the accident’s outbreak to reduce their consequences.

Contrary to the DGs approach, the risk assessment methods for non-DGs related fires follow a deterministic approach. However, the main drawback of such an approach is that it gives accurate results if the exact values of the system parameters are known (Morgan, 2008). Existing data about such fires though, especially data related to the human factor, are often deficient and this is why fire scenarios are stipulated by the methods (PIARC, 2013) or by the national requirements (Ntzeremes et al., 2018).

The tunnel system includes many parameters that relate to human behaviour like the time needed by the user to start the evacuation or the time required from the control room supervising the tunnel to react in case of fire accident and activate the traffic interruption as well as the mechanical ventilation. The uncertainty related to the traffic conditions or the environmental conditions has also a significant impact on the evolution of fire affecting the backlayering and, thus, the evacuation process. Faced with these uncertainties, safety analysts make assumptions adopting a ‘mean’ value or a worst case scenario. But, the variation to reality because of these assumptions can create serious fallacies regarding the estimated level of tunnel safety. This is highlighted by a series of reviews on existing risk assessment methods showing that the uncertainties related to important parameters of tunnel systems are often ignored (Beard and Cope, 2008; PIARC, 2008; 2013; Caliendo et al., 2012; Seike et al., 2017). To this respect, the presented research endeavour proposes a novel QRA method which is based on a stochastic approach. The proposed method takes into account the parameters of the tunnel system that present considerable uncertainties, and thus, estimates the level of the tunnel safety more accurately. By doing so, it mitigates the fallacies arising from the traditional deterministic methods.

7.2 Proposed SIREN method

In this section a new method, named SIREN, is proposed. Following a scenario-based approach, the aim of the proposed method is to develop a quantitative approach for assessing fire safety of road tunnels. Contrary to the prevailing deterministic approaches used by the existing risk assessment methods, the proposed method employs a stochastic-based approach. Therefore, the embedded uncertainty of important parameters of the tunnel system, which plays a crucial role during the risk assessment process, is taken into account. As a result, the level of safety of the tunnel system is estimated more accurately. Furthermore, by mitigating potential fallacies, which are embedded in the deterministic approaches, the proposed method supports the forthcoming decision-making process to enhance tunnel’s level of safety not only to choose but also to test and rank potential additional measures. It should be stated that in this research it is acknowledged that road tunnel systems are complex socio-technical systems (see Chapter 2). As such, it is not always possible to obtain absolute safety because of (a) the technological constrains (b) the cost-benefit ratio that may become grossly disproportionate in achieving absolute safety or (c) due to the unpredictable human behavior under emergency situations. To this respect, safety analysts and tunnel engineers usually operate within the ALARP principle (HSE, 2001; Jones-Lee and Aven, 2011). The term "reasonable practicable" means that "*the risk must be insignificant in relation to the sacrifice (in terms of money, time or trouble) required to avert it*" or else "*risks must be averted unless there is a "gross disproportion" between the costs and the benefits of doing so*" (Ale et al., 2015, p. 91). The SIREN method assists the safety analyst to act on the ALARP principle by providing a more realistic depiction of the effect (benefit) of potential safety measures.

7.3 Process application

7.3.1 Stochastic analysis of the tunnel system (Layer 1)

The framework of the SIREN's process, given in Figure 7.1, consists of four main layers following a top to bottom decision sequence. Each layer consists of a certain number of steps.

Layer 1 is the stochastic analysis of the system. Every tunnel system has its unique characteristics (Bjelland and Aven, 2013). Thus, the first step (**Step 1.1**) is to examine thoroughly the system in order to identify the system's parameters that are involved in the risk assessment process. On this basis, the parameters that should be treated stochastically (from now on referred to as 'stochastic parameters') and take part in the scenarios to be examined are also identified (**Step 1.2**). Often, these parameters appear explicitly in the CFD software used for estimating tunnel airflows and also in the parameters used for estimating trapped-users during the evacuation process. Reviewing the existing literature on evacuation processes and CFDs software, these parameters can be clustered into five main sectors: (a) the traffic sector, (b) the environmental sector, (c) the infrastructure sector, (d) the facility sector and (e) the user sector. Exploiting existing data from small- and full-scale experiments (Ronchi et al., 2012; Seike et al., 2016), data from post-accident reports (Voeltzel and Dix, 2004) as well as regulatory requirements (CETU, 2003; AAT, 2011a; PIARC, 2013), probability distributions for these parameters are synthesised. Although relevant information for the distributions are provided in this Chapter depicting the current level of knowledge, safety analysts that will use this method need to update the relevant information as necessary. This information requires a continuous update with new data from new accidents or findings that may change the probability distributions.

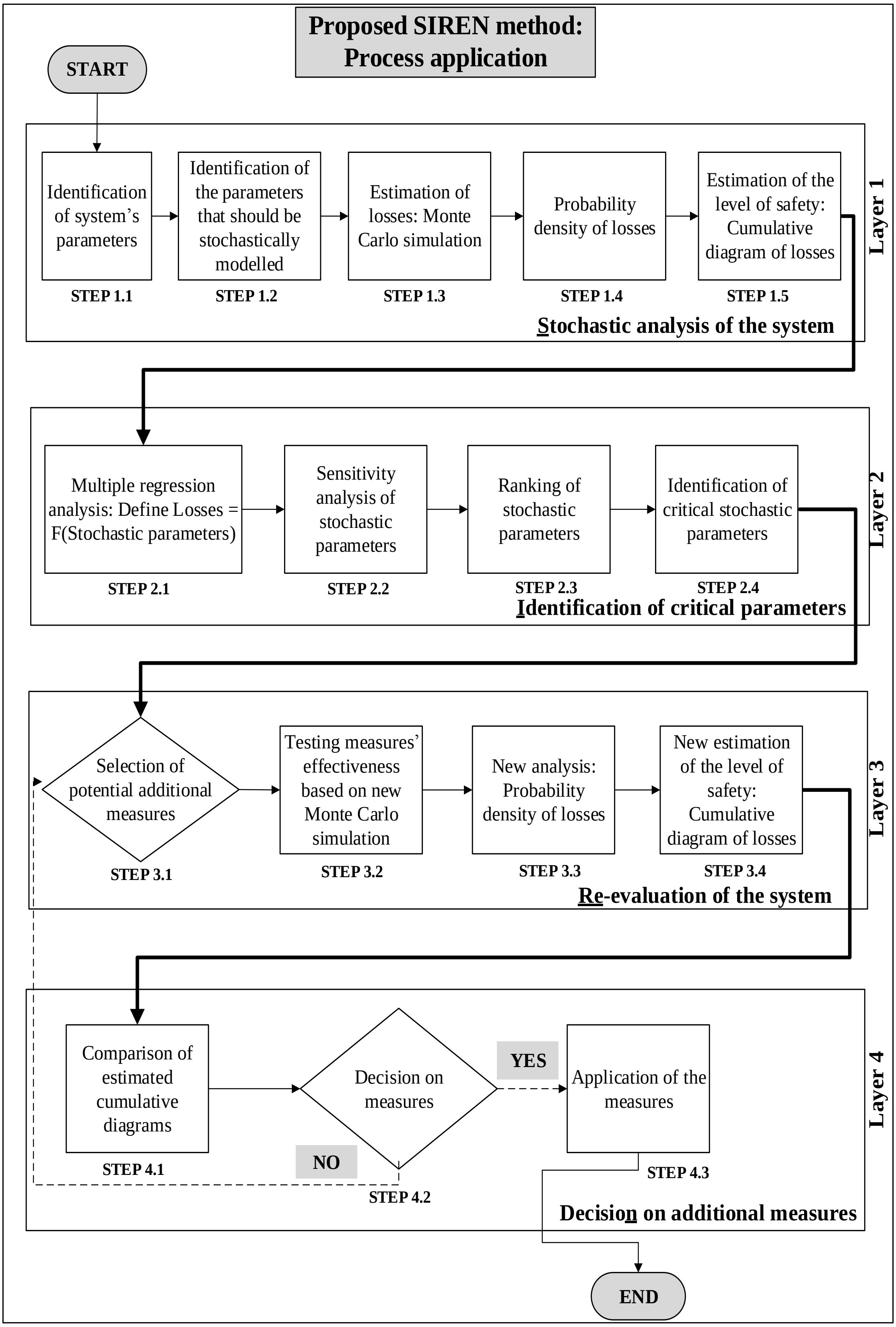


Figure 7.1: Proposed SIREN method (source: Ntzeremes and Kirytopoulos, 2018b, p. 620)

Step 1.3 comprises the estimation of trapped-users' losses. In order to achieve this, a MCS is employed to handle the computational complexity. Initially, the MCS is used to define the tunnel environment by changing the CFD's stochastic parameters. This calculation is carried-out in order to estimate the detailed tunnel airflows, namely the smoke and temperature environment. Subsequently, the outcome of this simulation is used as an input in order to perform a second round of MCS for estimating the outcome of the self-evacuation process of trapped-users. With regard to this step, a one-dimensional evacuation simulation is conducted, as trapped-users' evacuation route is predominantly limited to one dimension because of the large length to width ratio of the tunnel area (Seike et al., 2017).

Afterwards, **Step 1.4** of the process consists in the analysis of the results. In this respect, the probability density function of losses for the scenarios conducted is estimated. Meanwhile, the reference scenario, namely the scenario that uses the mean values of the stochastic variables is also calculated. The reference scenario corresponds to the examined scenario that a deterministic-approach of traditional methods uses. Subsequently, a comparison between the two outcomes, the stochastic and the deterministic, is conducted. This step illustrates the dispersion of stochastic results with regard to the reference scenario.

In the end, at the last step of the first layer (**Step 1.5**), the level of tunnel safety is estimated. To this respect the cumulative diagram of losses is presented in order to demonstrate the percentage of scenarios that outnumber the reference scenario.

7.3.2 Identification of critical factors (Layer 2)

If the tunnel's level of safety, as estimated in **Layer 1** is considered inappropriate, the second layer of the process (**Layer 2**), which is the identification of the critical factors, is conducted. During **Step 2.1**) of this layer a multiple regression analysis is carried-out. The aim of this step is to discover the correlation between losses and stochastic parameters. If the correlation is considered strong, namely $R^2>0.8$ (Field, 2009; Afraei et al., 2018), the characteristic curve of the losses in the tunnel system is created based on the coefficients that the multiple regression estimates. If not, further simulations must be conducted in order to achieve a higher correlation. Using the estimated characteristic curve, the second step of the sensitivity analysis is conducted (**Step 2.2**). The objective of this step is to aid ranking the stochastic parameters (**Step 2.3**) in order to find out their criticality, specifically their effect of variation on losses fluctuation. Each parameter varies with regard to its mean value between -50% and +50%. Finally, the critical analysis continues by selecting the critical parameters that should be changed in order to enhance level of safety (**Step 2.4**).

7.3.3 Re-evaluation of the tunnel system (Layer 3)

Having selected the critical parameters that can be changed, **Layer 3** comprises the re-evaluation of the tunnel system. For this purpose, the possible additional measures are selected (**Step 3.1**). These measures interact implicitly or explicitly with the critical parameters, which have been selected in **Layer 2**. Consequently, a new round of MCS is being conducted (**Step 3.2** similar to **Step 1.2**) in order to test the effectiveness of the new measures. The test is accomplished by applying the measure or measures needed for changing the examined stochastic parameter. Thus, a new probability density function (**Step 3.3**) and a new cumulative diagram are estimated (**Step 3.4**). These new results, practically, depict the effectiveness of the measures that were introduced.

7.3.4 Decision on additional measures (Layer 4)

At the last layer of the process (**Layer 4)**, a comparison of the estimated cumulative diagrams before and after additional measures introduction is carried-out. As a result, the outcome on the tunnel’s level of safety after the implementation of the additional measures is highlighted (**Step 4.1**). If the outcome is considered satisfactory (**Step 4.2**), the measure(s) are applied (**Step 4.3**). Otherwise, the process turns back to the first step of the third layer so that different measures are explored. The ALARP principle plays an important role during the decision in **Step 4.2**. The safety analyst can determine which combination of parameters would zeroed the losses of all scenarios. Subsequently, they can check whether this is feasible from a technological and/or economical point of view, always in relation to the actual benefit provided (reduction of losses). The method cannot provide this information automatically, but it allows the analyst to act on ALARP principle based on his judgment and existing regulative requirements.

7.4 Case study description

A typical urban underground road tunnel is selected that meets the infrastructure and equipment requirements as specified by both the Directive 54/2004/EC for road tunnels belonging to TERN and the Greek regulatory requirements on critical road infrastructures safety (EU, 2004; AAT, 2011a). The tunnel case is illustrative; however, its characteristics are based on existing tunnels and their relevant studies. Table 7.1 reports the tunnel's main characteristics.

The proposed method is performed for a fire scenario involving a HGV with a standardised source term of HRR_{max} equal to 100MW. The selected scenario includes the typical designed fire examined in Greece (AAT, 2011a; PIARC, 2017). Furthermore, it has a considerably high HRR and refers to HGVs, which are more often involved in fire accidents than other vehicles (Beard and Cope, 2008). Amongst the various cases investigated, in this case only the results relevant to the worst case scenario are discussed. According to risk analysis, the burning HGV is located in the middle of the tunnel (500m) during rush hour. Relevant studies have shown that the selected location is considered to be one of the most crucial locations of the tunnel (Amundsen, 1994; Ntzeremes et al., 2016; PIARC, 2017).

Table 7.1: Tunnel attributes (source: Ntzeremes and Kirytopoulos, 2018b, p. 623)

Designing features of the tunnel	One direction – single bore	
	Total length	1.000m
	Slope	-1,5%
	Number of emergency exits	2 (every 350m)
	Number of traffic interruptions	3 (every 350m)
	Time for traffic lights to turn red after fire ignition	3min
System of mechanical ventilation	Number of jet-fan-array	4 (every 170m)
	Number of jet fans making-up the array	2
	Progressive function	
	Starting time of the system after fire ignition	3min
Pressure difference between entrance - exit	95% of max velocity based on local estimations regardless direction	15Pa
Environmental conditions	Ambient temperature	12°C
	Altitude	600m
Traffic conditions	Vehicle flux (8:00–10:00 & 17:00-19:00)	1,500 veh./hr.
	Proportion of HGVs	30%

To assist the evaluation of the tunnel environmental conditions in the vicinity of fire, the examined case study performs one-dimensional analysis of tunnel airflows, describing the changes in ambient conditions of air temperature, air opacity and air pollution in the tunnel from the outbreak of the fire until the 30th minute, as this time interval is considered to be critical for the resulting consequences. The one-dimensional analysis is imposed by the Greek authorities (AAT, 2011a). It is also the preferred method of approach in a large number of existing risk assessment methods (PIARC, 2013). The one-dimensional analysis is conducted with the aid of Camatt 2.0 software. With respect to trapped-users' evacuation, apart from the Greek requirements, the evacuation direction is regarded predominately limited to one dimension because of the large length-to-width ratio of tunnel geometry (AAT, 2011; Seike et al., 2017).

The underground tunnel system along with its equipment positions referred in Table 7.1 and the fire location is presented in one-dimensional view in the following Figure 7. 2. It is assumed that after the ignition of the fire, trapped-users move towards the nearest safe location, which is the emergency exit door 350m from the entrance of the tunnel placed next to the second traffic interruption. It is also assumed that the users upstream the emergency exit location move towards the tunnel entrance and the vehicles downstream the fire accident continue to move out of the tunnel without any delay.

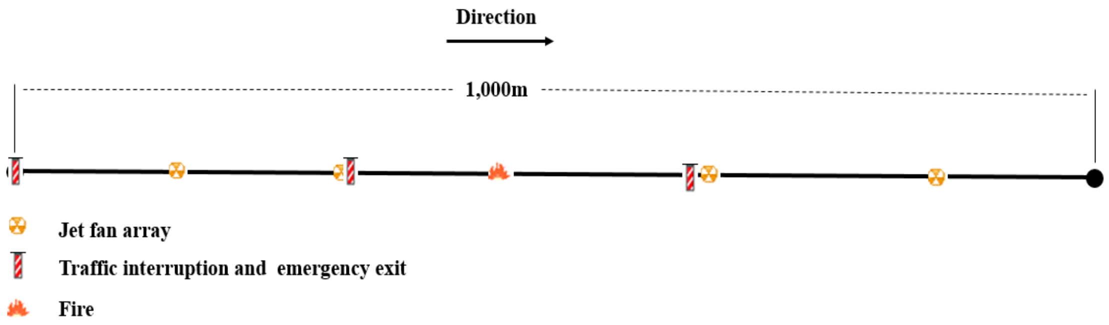


Figure 7.2: Tunnel exhibition in one dimensional view (source: Ntzeremes and Kirytopoulos, 2018b, p. 624)

7.5 Implementation of the method

Having defined the tunnel system's characteristics, the proposed QRA method requires the determination of both the scenarios to be examined and also the stochastic parameters amongst them (Step 1.1 and 1.2). Examining thoroughly the tunnel system, the system's parameters that are taken into account in the risk assessment process are presented in Figure 7.3.

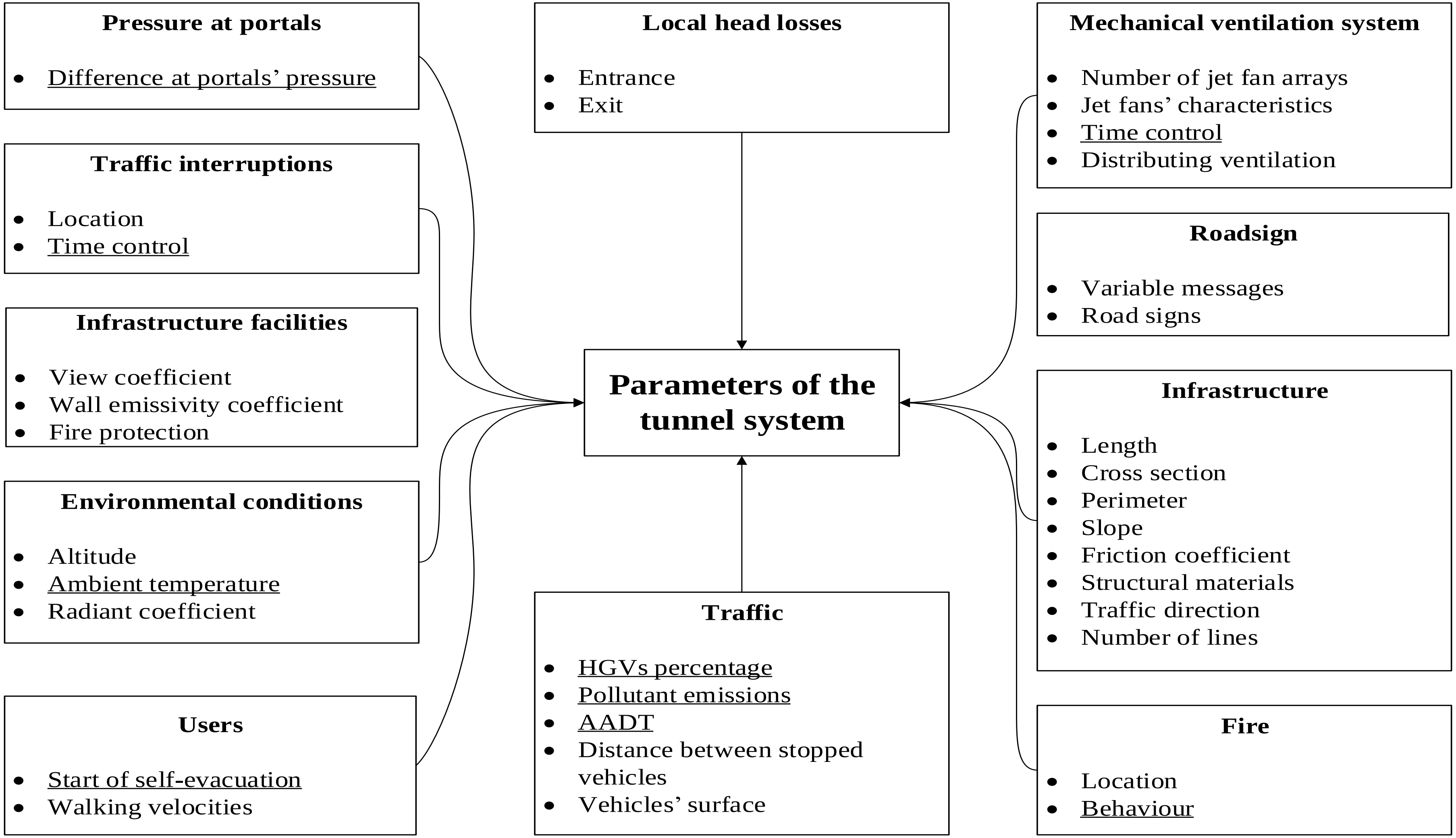


Figure 7.3: Parameters of the analysis –Stochastic parameters are underlined (source: Ntzeremes and Kirytopoulos, 2018b, p. 625)

In the same figure, the stochastic parameters are denoted with underlined text. For the stochastic parameters, the concept of probability distribution is put forward. With regard to the five main sectors that affect the tunnel system safety (refer to Section 2.2.2), the analysis showcases that, firstly, the traffic sector includes two parameters that develop stochastic behaviour, the AADT)and the percentage of HGVs. Exploiting available reports form the tunnel managers along with the experience of the analyst both parameters are considered to follow a normal distribution. Subsequently, the analysis regarding the environmental sector showcases that two stochastic parameters, the ambient temperature and portals' pressure should be included. Based on the local measurements of the relevant authorities, the distributions of the aforementioned parameters are normal, too. Regarding the facilities sector, two facilities are regarded to have stochastic behaviour. These are the activation of the mechanical ventilation as well as the traffic interruptions. Based on existing data from past exercises and/or post-accidents reports, their distributions are considered to follow the beta distribution. Table 7.3 summarises the characteristics of all the relevant stochastic variable.

With regard to fire, studies have indicated (Ingason et al., 2015) that fire evolution has variability, depending especially on its standardisation (e.g. triangular form, trapezoidal form, etc.). Our case study, adhering to the Greek regulations regards fire behaviour as having a trapezoidal form. The stochastic parameter is considered to be the time that the HRR_{max} is reached (NCHRP, 2011). The variation of this time has been studied from other researchers and institutes (Ingason et al., 2015; PIARC, 2017). The infrastructure sector does not include any parameters with a stochastic behaviour. Lastly, in respect to users' behaviour, the parameter that is stochastically approached is the time referred to the pre-evacuation stage. The pre-evacuation time accounts for the time lapse between the decision to evacuate and the action. This time was investigated in previous studies (Reneke, 2013; Lovreglio et al., 2016). The pre-evacuation time setting is significant in evaluating the evacuation with high reliability. There are various theories related to pre-evacuation time, and in this case study it is assumed that the trapped-users consist of a mix of well-educated by management agencies users that will evacuate after recognising dangerous factors, those that have partial relevant education and others with no education at all (Nilsson et al., 2009). As a result, the pre-evacuation time randomly varied for each trapped-user in the range of 60–120s uniformly (Table 7.3). The walking speed of the users corresponding to each extinction coefficient are imposed by Greek regulations and, thus, remain as deterministic parameters (AAT, 2011a).

In the third step of the first Layer of the process (refer to Figure 7.1), a stochastic-based approach is carried-out. This approach uses the MCS in order to conduct a number of simulations with the aid of the CFD software which estimates the tunnel airflows. Regarding the input data for executing the process, these correspond to: (a) the necessary geometric characteristics of the tunnel for its one-dimensional depiction (i.e. length, slope etc.), (b) the tunnel equipment, namely, the system of mechanical ventilation (time function, jet-fan arrays’ position, thrust, jet-fan’s heat resistance, etc.) and the time function of traffic interruption system, (c) the environmental conditions (i.e. altitude, ambient temperature, pressure at tunnel’s portals etc.), (d) the traffic conditions (i.e. vehicle flux, percentage of HGVs, etc.), and (e) the fire behaviour (Vincent et al., 2005). Afterwards, the one-dimensional software solves the fundamental equations governing flow at any length of the tunnel as well as any moment of time along with the thermodynamic equations and the equations expressing the opacity.

The results from CFD calculations provided in excel files are further used in order to predict the one-dimensional trapped-users evacuation process. The one-dimensional analysis of trapped-users’ evacuation is conducted with the aid of MATLAB 2017b software. To this respect, road tunnels are considered to have generally simple and straight geometries in which the relative distance of the users from the fire source, the fire characteristics and the time spent inside the tunnel are the main factors affecting life safety. Trapped-users’ evacuation is illustrated as a trajectory, depicted as line segments depending on the walking speed, with regard to tunnel length and time. Figure 7.4 provides an example of the evacuation process.

The structure of the proposed simulation-based evacuation model in order to support quantitative risk assessment on road tunnel fire safety is presented in Appendix 1. The model is developed with the aid of MATLAB software (see Appendix 1). Combining the results of CFD analysis with the human behavior of trapped-users through MATLAB, the proposed tool enables the safety analyst to create many scenarios rapidly and with accuracy. Therefore, this model can be included as a MATLAB add-in to the traditional CFD models in order to help safety analysts get a better understanding of the evacuation process of the trapped-users for the purpose of prediction of potential losses amongst them and relevant decision-making. By predicting potential losses, the tool illustrates also the effectiveness of critical system parameters regarding the fire safety as well as the performance of existing or additional safety measures. As a result, it enables the safety analyst to decide the appropriate fire safety strategy for the tunnel.

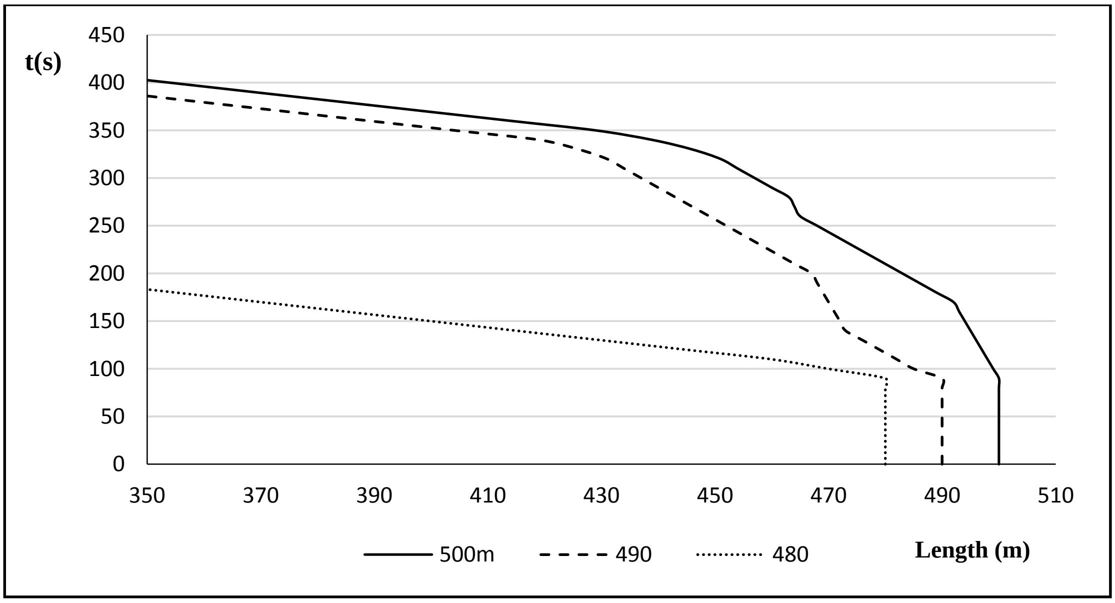


Figure 7.4: Evacuation process with fire location at 500m (source: Ntzeremes and Kirytopoulos, 2018b, p. 626)

Since the aim of the model is to predict the potential losses amongst trapped-users in the event of fire, determining the tunnel environment is the first point. Because in tunnel fires the evacuation direction is predominately limited to one dimension due to the large length-to-width ratio of tunnel geometry, a one-dimensional evacuation simulation is conducted.

With a view to estimate the potential losses amongst trapped-users, the tool is designed to separate the two phases of users' evacuation process. Therefore, the pre-evacuation phase is related through a specific time lag between the ignition of the fire and the action of evacuation. This time lag is provided to the tool by the safety analyst. Furthermore, the tool is supplied with the data of the fire scenario deriving from the CFD analysis in order to run the simulations in MATLAB. These data are the temperature and the opacity values of the tunnel environment. Afterwards, it is constructed to link the smoke environment of the tunnel (opacity value) with the evacuation movement of the trapped-user. For doing that, at each point of the tunnel, the trapped-user receives certain moving speed depending on the opacity level within which they pass each moment. The moving speed can be defined either deterministic, if certain guidelines exist or stochastic. Meanwhile, the accumulating heat of radiation and convection along with the accumulating smoke throughout the evacuation process is estimated.

In this case, fire sparks at the scene of the accident located 500m from the entrance of the tunnel. Considering that stopped vehicles keep constant space in between, here approximately 10m, trapped-users located at the position of the fire, 10m and 20m before, initiate their self-evacuation 90s after the fire ignition. The three lines, black, dashed and dotted, depict the movement of the trapped-users from the three locations until they reach the emergency exit located 150m before the position of the fire.

In order to estimate the users' movement, the Greek regulations are used which provide specific walking speeds with regard to opacity (Table 7.2). However, the time in which the evacuation process begins is a stochastic parameter.

Table 7.2: Trapped users' emergency walking speed adapted from (source: Ntzeremes and Kirytopoulos, 2018b, p. 624)

Speed (m/s)	1.50	1.00	0.50	0.30
Extinction coefficient (m^{-1})	Cs=0	0≤Cs≤0.50	0.50≤Cs≤ 0.70	Cs≥0.70

These regulations are similar to the regulations of other countries (PIARC, 2013), to PIARC's suggestions (PIARC, 1999) and also to a number of full-scale experiments (Seike et al., 2016). In order to provide a level of magnitude for the effect of the radiation on trapped-users, the FED_h is calculated through the MATLAB model (see Appendix 1). FED_h consists of calculations for radiant and convective heat (see section 6.3).

Furthermore, Carbon monoxide (CO) is the toxic gas on which toxicity is raised, based on the national standards. The estimation of the FED_{co} in every time step and location is estimated as follows:

$$FED_{co}= \Sigma(0.00083*CO^{-1.036}*\Delta t)/D$$

where {Δt} is the exposure time in minutes, {CO} is the CO concentration in ppm and {D} is the concentration at incapacitation. If the total FED equals or exceeds the value of 0.3, the trapped-user is neutralised and the evacuation process is interrupted. In the example of Figure 7.4 this did not occur and the users, following the trajectories shown, successfully reached the emergency exit.

Table 7.3: Stochastic parameters' probability distributions (source: Ntzeremes and Kirytopoulos, 2018b, p. 625)

Stochastic Parameters	**Mechanical Ventilation (min)**	**Interruption (min)**	**Difference at portals' pressures (Pa)**	**Fire HRRmax (min)**	**AADT (V/h)**	**HGV (%)**	**Environmental Temp.(^{0}C)**	**Evacuations' Starting time (s)**
Probability distribution	Triangular distribution	Triangular distribution	Normal distribution	Uniform distribution	Normal distribution	Normal distribution	Normal distribution	Normal distribution
min	4.00	2.00	13.00∗	5.00	1,200	0.20	8.00	60.00
max	7.00	7.00	20.00	15.00	1,500	0.40	16.00	120.00
mode	5.00	4.00	-	-	-	-	-	-
mean	5.33	4.33	16.00	10.00	1,350	0.30	12.00	90.00

∗min and max in normal distribution refer to m±3σ respectively

Table 7.4: Simulations results (source: Ntzeremes and Kirytopoulos, 2018b, p. 625)

A/A	**Vent. (min)**	**Inter. (min)**	**ΔP (Pa)**	**Fire (min)**	**AADT (V/h)**	**HGV (%)**	**T (^{0}C)**	**Evac. (s)**	**Losses**
1	4.8	2.6	15.14	5.1	1482	0.32	13.95	90.16	8
2	4.9	3.4	16.82	11.4	1361	0.31	11.48	102.00	12
3	4.9	5.0	14.20	7.7	1283	0.27	12.58	90.82	16
4	5.4	5.4	16.63	13.8	1334	0.31	13.79	113.37	20
5	6.8	4.3	13.91	6.6	1360	0.31	13.12	98.07	12
6	5.2	6.2	16.05	11.0	1335	0.26	16.74	84.17	12
…	…	…	…	…	…	…	…	…	…
499	4.9	5.1	17.14	13.1	1307	0.35	11.99	88.22	36
500	5.1	5.1	14.40	12.4	1353	0.24	13.20	109.18	8

7.6 Results and discussion

In order to estimate the potential losses resulted from the unsuccessful evacuation procees of the trapped-users, some assumptions need to be made. Initially, the traffic is considered normal and also it is assumed that the vehicles upstream the accident location will stop keeping constant space in between, approximately 4m. Furthermore, the locations of stopped vehicles are the locations from where the trapped-users begin their evacuation. Additionally, every vehicle, private or HGV is considered to have two passengers. Thus, during the one-dimensional estimation, if the evacuation from a specific location or trajectory proved to be fatal, it corresponds to 4 losses due to the existence of two lanes in the tunnel.

Initially, the analysis estimates the losses resulted from the reference scenario. The reference scenario is defined as the scenario that applies the mean values of the parameters' distributions, which is what is commonly used for the deterministic analysis. Following the analysis, 16 losses are estimated for the reference scenario (deterministic point). The estimation of losses from the reference scenario is followed by a MCS that allows for the depiction of the effect of stochasticity in the result. In this stage, other scenarios are created by changing the stochastic parameters of the system (e.g. the starting time of mechanical ventilation), according to their distributions. This will aid the decision analyst to get a depiction of the actual level of safety of the tunnel. The results of the stochastic analysis of Layer 2 are presented in Figure 7.5 (based on Table 7.3 - stochastic parameters).

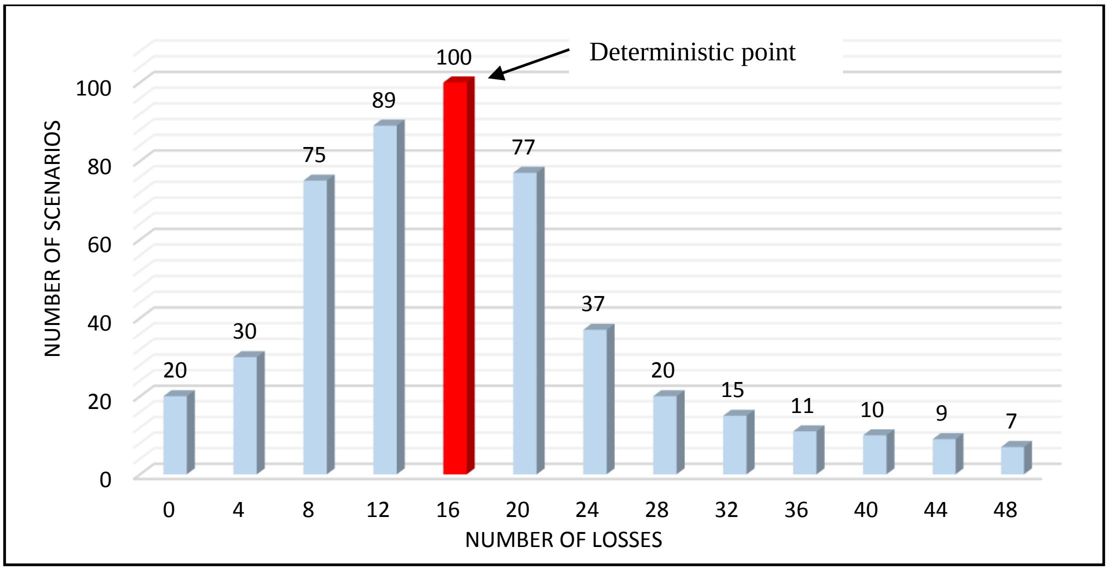


Figure 7.5: Losses distribution (source: Ntzeremes & Kirytopoulos, 2018b, p. 627)

Although the reference scenario estimates 16 losses amongst trapped users, the resulting distribution of losses illustrates that 186 scenarios of the 500 or 37.2% of the set result in higher number of losses comparing to the losses of the reference scenario. Furthermore, approximately 10% of the scenarios has two-fold or more increase in total losses, which can be extended up to 48 losses for 1.5% of the scenarios.

On the other hand, 214 scenarios or 42.8% result in lower number of losses than the reference scenario. Even though this result can counterbalance the previous result, still 32.8% of the scenarios results in 8 or 12 losses (75 scenarios give 8 losses and 89 scenarios 12), which accounts for the fact that even under favorable conditions the possibility of avoiding serious number of losses amongst trapped-users is limited. Furthermore, the fact that only 50 scenarios have no or less than 4 losses (losses occur in the fire location might be acceptable) confirms further the aforementioned conclusion. Only the 20% of sets results in the exact same number of losses as the reference scenario. Subsequently, the cumulative diagram (Figure 7.6) illustrates that the level of safety of the tunnel is below the required level of safety. Even if we overlook the 8 losses that correspond to a distance of four meters before the fire due to high radiation released, the 75% of the scenarios has more than 8 losses.

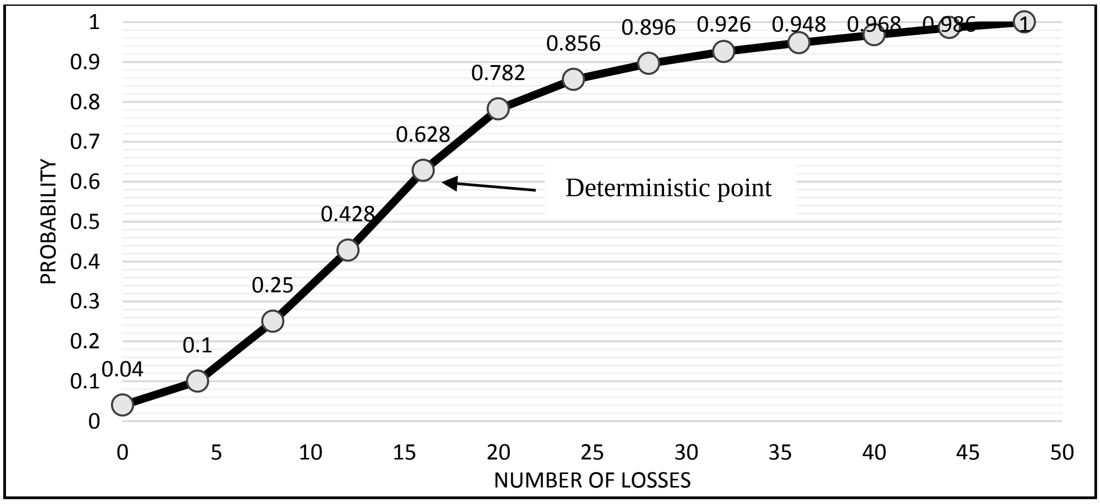


Figure 7.6: Cumulative diagram (source: Ntzeremes & Kirytopoulos, 2018b, p. 627)

The next step of Layer 2 is the estimation and the classification based on the parameters criticality. To this respect, the results from the regression analysis are illustrated in Table 7.5.

Table 7.5: Regression's results (source: Ntzeremes & Kirytopoulos, 2018b, p. 627)

Regression Statistics	
Multiple R	0.910
R Square	0.856
Adjusted R Square	0.826
Standard Error	0.477
Observations	500
Significance F	4.318E-21

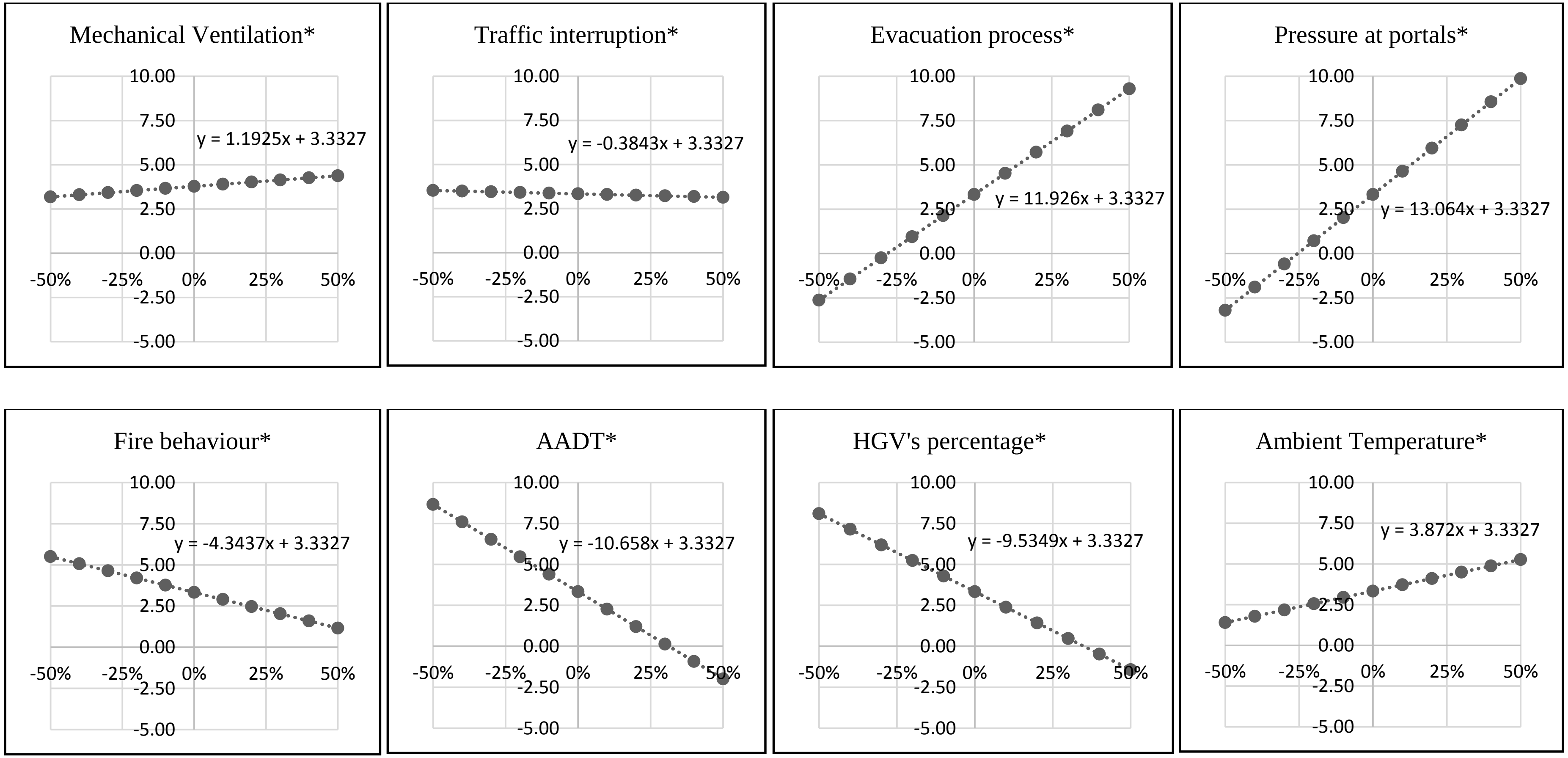
Consequently, the R Square is estimated to 0.856, which shows a good correlation between losses and the selected stochastic parameters (Field, 2009). Based on the results derived from the regression analysis, Table 7.6 illustrates the coefficients of the characteristic curve for the tunnel system operation derived from the regression analysis.

Table 7.6: Characteristic Curve (source: Ntzeremes & Kirytopoulos, 2018b, p. 627)

Variables	*Coefficients*
Intercept	-0.350274792
Vent. (min)	0.224994823
Inter. (min)	-0.089372623
ΔP (Pa)	0.816496491
Fire (min)	-0.434372126
AADT (V/h)	-0.007894987
HGV (%)	-31.783134010
T (^{0}C)	0.322665488
Evac. (s)	0.132507900

The characteristic curve illustrates the level of tunnel safety through estimating the losses amongst trapped-users (expressed in fatal trajectories), which result from the change of the stochastic parameters of the tunnel system. In particular, each trajectory corresponds to four trapped-users. The characteristic curve will be thereupon employed in order to examine the sensitivity of overall safety (potential losses) to the stochastic parameters. Therefore, a sensitivity analysis of the stochastic parameters varying between -50% to +50%, is conducted. The outcome of the sensitivity analysis is depicted in Figure 7.7.

Considering the constant term for each parameter of the resulted sensitivity lines, a classification of the parameters' criticality can be concluded. The results show that the difference of pressure between tunnel portals has the greatest impact on the estimated losses. This parameter affects the shape of backlayering as the increase of pressure difference sharpens its shape. As a result, greater tunnel length upstream the fire location is covered by smoke and trapped-users might fall into the adverse effects of the tunnel's fire environment.



***Y** axis signifies the number of fatal trajectories (each trajectory corresponds to four trapped-users), and

X axis signifies percentage variation from the nominal value of the relevant stochastic parameter

Negative losses can be explained by the fact that variable has values that do not fall in its domain (see Table 7.3)

Figure 7.7: Sensitivity analysis (source: Ntzeremes & Kirytopoulos, 2018b, p. 628)

The second crucial parameter is the pre-evacuation time. This result is also confirmed by existing studies which refer to the significance of educating users in confronting fire accidents (Kirytopoulos et al., 2017). Subsequently, regarding the fire behaviour, when the time needed to reach peak temperature decreases, the fire releases higher heat in the time space when the evacuation process has, possibly, not started yet. Consequently, trapped-users' evacuation is hindered due to the higher volume of smoke and toxic gases along with the higher temperatures which increase the convective and radiative heat. As a result, potential losses increase.

With regard to the traffic parameters, a fallacy regarding CFDs arises. AADT and percentage of HGVs seem to help in lowering casualties. This is possible because the increase of these parameters assist the increase of piston effect, thus reduce the length of the backlayering significant or eliminating it at all. However, from the safety perspective, it is not acceptable to send more vehicles, meaning more users, towards the fire location or do not interrupt the traffic in case of accident.

In addition, the analysis indicates that mechanical ventilation has a weak impact on preventing losses. Even though the system would get the 100% efficiency in 3min instead of 5 (50% reduction), estimated losses would fall from 16 (4 fatal trajectories) to 13 (approximately 3.83 fatal trajectories), which is a weak reduction.

As a result, the system has to improve its efficiency in order to increase the level of safety. The safety analyst has as a priority to highlight the parameters that can be both easily and effectively modified. Therefore, because human behaviour takes time to be changed through education and while both fire and traffic conditions cannot be easily changed, other interventions were explored. Taking into account the previous sensitivity analysis and after carrying-out a number of test simulations, it was decided that a proper additional measure would be that the ventilation system constantly works at 5% of its capacity during rush hours. Furthermore, the time in which it catches-up the 100% capacity (full on) has to be in 1.25min instead of 2min.

In order to test the new additional measure related to the mechanical ventilation system, a new MCS is conducted based on Table's 7.7 new parameters' distributions.

Table 7.7: New stochastic parameters’ probability distributions (source: Ntzeremes and Kirytopoulos, 2018b, p. 628)

Stochastic Parameters	**Mechanical Ventilation (min)**	**Interruption (min)**	**Difference at portals' pressures (Pa)**	**Fire HRRmax (min)**	**Traffic (V/h)**	**Traffic % HGV**	**Environmental Temp.(^{0}C)**	**Evacuations’ Starting time (s)**
Probability distribution	Triangular distribution	Triangular distribution	Normal distribution	Uniform distribution	Normal distribution	Normal distribution	Normal distribution	Normal distribution
min	3.10	2.00	13.00	5.00	1,200	0.20	8.00	60.00
max	6.10	7.00	20.00	15.00	1,500	0.40	16.00	120.00
mode	4.10	4.00	-	-	-	-	-	-
mean	4.43	4.33	16.00	10.00	1,350	0.30	12.00	90.00

Table 7.8: New simulations results (source: Ntzeremes and Kirytopoulos, 2018b, p. 629)

A/A	**Vent. (min)**	**Inter. (min)**	**ΔP (Pa)**	**Fire (min)**	**Traffic (V/h)**	**HGV (%)**	**T (^{0}C)**	**Evac. (s)**	**Losses**
1	4.0	2.6	15.14	5.1	1482	0.32	13.95	90.16	0
2	4.9	3.4	16.82	11.4	1361	0.31	11.48	102.00	0
3	4.6	5.0	14.20	7.7	1283	0.27	12.58	90.82	12
4	5.1	5.4	16.63	13.8	1334	0.31	13.79	113.37	0
5	4.1	4.3	13.91	6.6	1360	0.31	13.12	98.07	0
6	3.4	6.2	16.05	11.0	1335	0.26	16.74	84.17	0
…	…	…	…	…	…	…	…	…	…
499	4.3	5.1	17.14	13.1	1307	0.35	11.99	88.22	0
500	4.7	5.1	14.40	12.4	1353	0.24	13.20	109.18	0

In particular, the mechanical ventilation distribution illustrated in underlined text has been changed as a result of the measures to be taken. The distributions of the other stochastic parameters remained unchanged. The new results in comparison to the results before any measures taken are illustrated in Figure 7.8. A truncated beta distribution was used as there is no meaning in negative losses. The result now indicates that after the new measures related to the mechanical ventilation system 415 scenarios or 90% appear no losses. The new cumulative diagram (see Figure 9) illustrates this major change on the tunnel safety level.

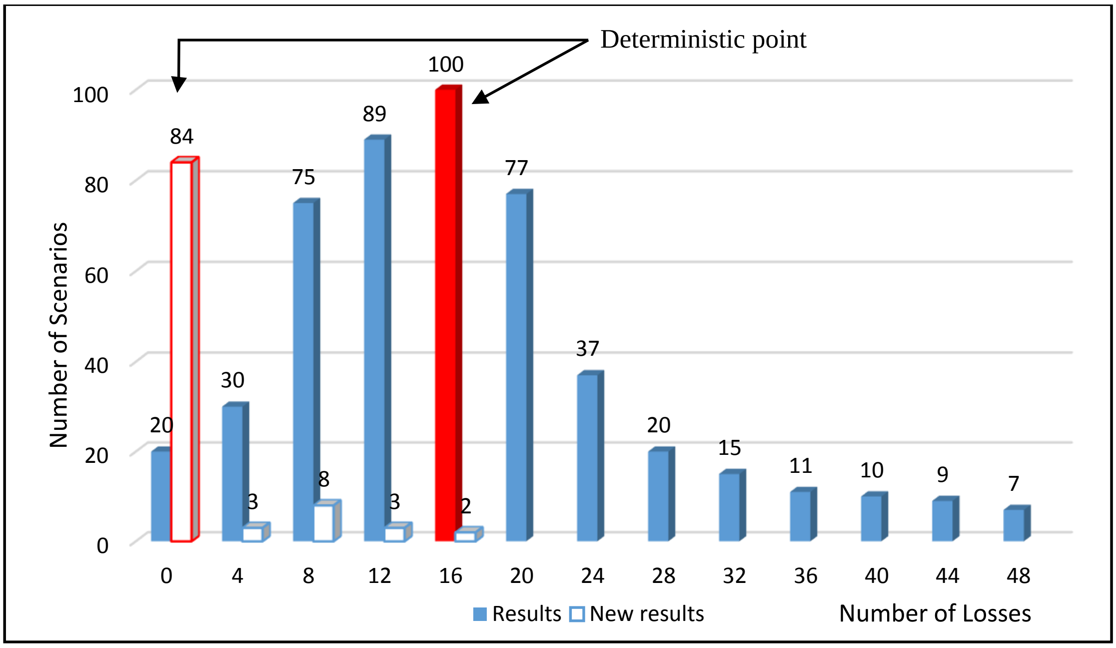


Figure 7.8: New losses distribution (source: Ntzeremes and Kirytopoulos, 2018b, p. 629)

However, there are also scenarios that include losses. Further actions might require a decision at the highest level as the analysis indicates that in order to reduce further the potential casualties, the efficiency of normal operation of the ventilation must further increase. Such an action may probably increase extremely the cost of tunnel operation in a disproportional to the benefit way (PIARC, 2011; Barbato et al., 2014; Ingason et al., 2015). Apart from the discrepancy in the evaluation itself, one should consider the relevant consequences, as well. Although the goal is always to provide a safe environment for the users, safety levels should be based on an “as low as reasonable practicable” risk principle. That is, when we make decisions we also need to take into account the cost of measures taken in relation to the benefit gained. That is, it should be examined whether the remaining 17% of scenarios that still include losses correspond to an “acceptable” risk. However, there are no official regulative provisions that define this risk and so the decision comes back to the analyst.

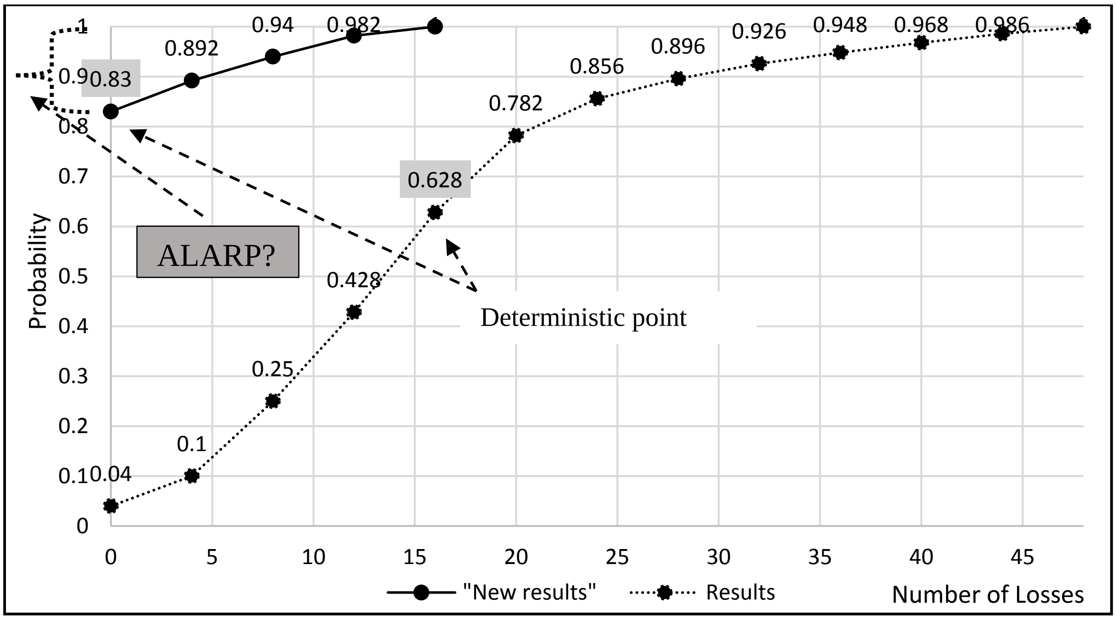


Figure 7.9: New Cumulative diagram (source: Ntzeremes and Kirytopoulos, 2018b, p. 627)

7.7 Validation of the method

In this section, the validation of the proposed SIREN method is presented. Validation is an essential process since it determines the degree to which the proposed method appears to be an accurate representation of the real world from the perspective of the intended uses of the method (Hillier and Lieberman, 2001). In case of this thesis, the aim of the SIREN method is to develop a quantitative approach for assessing fire safety of road tunnel systems by taking into account the embedded uncertainty of important parameters of the system, which plays a crucial role during the risk assessment process.

In general, the process to establish the validity of a method is not a simple test (Ayyub and Klir, 2006). In particular, three main areas have to be validated that is: *the inputs*, *the assumptions* and *the outputs*. There are three approaches in order to conduct a validation. The first approach is based on the use of *real measurements techniques*. According to this technique, if the comparison between the real data with those from the method shows no discrepancy, the model is regarded to have validity However, in many cases the nature of the problem does not allow the analyst to compare the proposed method to that actual system to see how it corresponds, such as to test real fire accident in a tunnel. The second approach is based on the *experts' opinion*. The evaluation of the developed method by a group of experts can better guarantee that the considered assumptions and the inputs/outputs are valid. The last approach is the use of *theoretical analysis* and *results* from previous studies. If these sources exist, this approach can prove as the most efficient since it can overcome the drawbacks of the previous approaches, the weakness of conducting a real experiment and identifying a representative group of available experts. Regarding tunnel fire accidents, which is the focus of this thesis, the reports from previous fire accidents together with the available data from virtual, full- and small-scale experiments form a valuable source of real data. To this respect, they appertain simultaneously to both the first and the third approach. In addition, the compliance with the international, national guidelines, such as the PIARC's or the EU's reports, can further guarantee the validity of the adopted assumptions of the method.

Therefore, the approach followed in this thesis belongs to the third approach since it provides the analyst with the available data to establish the validity of the method. To do so, the following framework is employed based on the best-practice followed in computer and engineering systems.

The first step is the validation process is the *front-end* validation. In this step, the validation relates to the audit of the data of the input parameters as well as the reconciliation consistency of the inputs. Regarding the input data of the tunnel system that referred either to the tunnel attributes (see Table 7.1) or the traffic and environmental conditions are originated from typical road tunnels in Greece, and therefore, they are valid. In addition, the inputs that referred to the stochastic parameters have been also provided from the same source. As far as the users' behaviour during evacuation process, the data have been resulted from previous tunnel accidents and conducted small and full scale experiments (see section 4.2). These sources are also in line with the PIARC (1999) and the SFPE (2019). Finally, the use of fire scenarios as well as the evolution of fire are provided in the Greek national guidelines (AAT, 2011a), the PIARC (2017) and in relevant fire bibliography (see section 2.1).

The second step of the validation process is the *review of the method setup* and of the associated models used. In this step, the structure of the both method and the models has to be configured for the purpose of conducting appropriately the modelled activities. As far as the risk assessment structure is concerned, the SIREN method applies the framework that is already included in both the PIARC (2008) and in each national provision of the EU member states (see Chapter 3). The parameters that should be treated stochastically have been identified after an extensive review of the literature and the use of CFD and evacuation models (see section 7.3.1). Regarding the validation of both the CFD software and the MATLAB evacuation model, the first one has been performed by the CETU (Vincent, et al., 2005), which is the developer of the model, while the second one follows the conceptual principles that have been provided in the SFPE guideline (see section 5.4.3) as well as in various post-accident reports, e.g. (Voeltzel and Dix, 2004). Furthermore, the mathematical model has been also solved by the Ecxel software (see Appendix 1).

The third step refers to the *back-end* validation of the outputs. In the absence of other methods that follow a stochastic-based approach against which the results could be validated, the validation of the outputs is conducted through the comparison of the results with the existing deterministic approach. The outcome shows that outputs are valid (see Figure 7.9).

Back-testing is usually used to confirm the ability of a method to predict the actual outcome base on real historical data. However, this step could not be conducted in this thesis since the case study used relates to the Greek context in which only few fire accidents occurred in the past and thus no reliable historical data are available. Furthermore, this step could not be performed in any other tunnel due to the unavailability of the required information (see section 7.4).

The absence of other stochastic-based methods is also the reason why the *benchmark* of the method is performed (see Figure 7.9) through the comparison of the results to the existing best-practice (AAT, 2011a), which follows the deterministic approach (PIARC, 2008).

7.8 Conclusions

This study proposed a novel quantitative risk assessment method, named SIREN, aiming at enhancing underground tunnel fire safety. However, the SIREN method can be applied to any type of road tunnel. The SIREN method is based on the unique characteristics of the tunnel system taking into account the variability and uncertainty of the system’s stochastic parameters. Because urban road tunnels bear daily high traffic volumes, they are regarded as one of the most critical and complex infrastructure systems for the daily operation of modern urban networks. To this respect, the proposed method is implemented in a typical urban underground road tunnel conforming to both the European and Greek requirements.

The stochastic approach is conducted after identifying the stochastic parameters of the system. Subsequently, a MCS is employed based on the specified probability distributions of these parameters. One-dimensional simulations are conducted for the estimation of tunnel airflows and the trapped-users' evacuation process. The one-dimensional analysis is employed since the evacuation direction in tunnel fires is predominately limited to one dimension because of the large length-to-width ratio of tunnel geometry. The worst case scenario is examined, which includes a fire involving from a HGV in the middle of the tunnel during rush hour carrying-out. Having conducted 500 simulations, the outcome highlights a significant proportion of scenarios that exceeds the losses estimated by the traditional deterministic methods. The resulting distribution of losses illustrates that 186 scenarios of the 500 or 37.2% of the set result in higher number of losses comparing to the losses of the reference scenario. Furthermore, approximately 10% of the scenarios have two-fold or more increase in total losses, which can be extended up to 48 losses for the 1.5% of the scenarios. Furthermore, the conducted sensitivity analysis, which examines parameters' criticality, reveals that amongst stochastic parameters that the analyst can change to increase safety, the operation of mechanical ventilation appears to have the most potential in preventing losses. Thus, by re-designing ventilation's operation both in normal and emergency situation, and carrying-out a new set of simulations, a significant reduction of potential losses occurs with approximately 83% of new scenarios to be estimated without any losses. However, further actions might require a decision at the highest level as safety levels should be based on an "as low as reasonable practical" risk principle. That is, when we make decisions we also need to take into account the cost of measures taken in relation to the benefit gained.

It should be noted that the aforementioned analysis could also include busses amongst the trapped-vehicles. This depends on the statistical analysis of the traffic volume. This means that if a bus is trapped in a fatal path this would dramatically increase the total number of fatalities due to the larger capacity of the bus, approximately 40 passengers. Nevertheless, despite of the difference in the total number of fatalities in the case of the bus involvement the model still contributes to the increase of the level of safety since it primarily focuses on the reduction of the number of the fatal scenarios. In addition, it should also be stressed that the ALARP principle (see Figure 9) plays a central role in defining the exact level of safety for the tunnel in this case.

Chapter 8[6]

Developing a risk-based decision support method for selecting fire safety measures for road tunnels

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[6] This Chapter has been published in: (Ntzeremes and Kirytopoulos, Under review)

8. Developing a risk-based decision support method for selecting fire safety measures for road tunnels

8.1 Concept and components

In this section a new method in order to support the decision-making process towards the selection of fire safety measures for road tunnels is presented. The method aims to enable analysts to both evaluate and prioritise additional to standard fire safety measures, when appropriate. This method can be used either in addition to the SIREN method or independently.

The selection of additional to standard measures relies mainly on risk assessment results and is accomplished based on strictly determined regulations requirements (see section 3.3). Thus, risk analysis results are associated with certain solution sets avoiding to weight alternative solutions. As a result, the selection process can lead to either serious fallacies or might not meet the required level of safety of the individual tunnel system (Kirytopoulos et al., 2010; Borg et al., 2014).

Initially, the proposed method focuses on integrating the requirements of all the system's stakeholders (Figure 8.1), namely the tunnel manager, the users, the regulatory requirements, and the possible safety solutions, along with the risk analysis results.

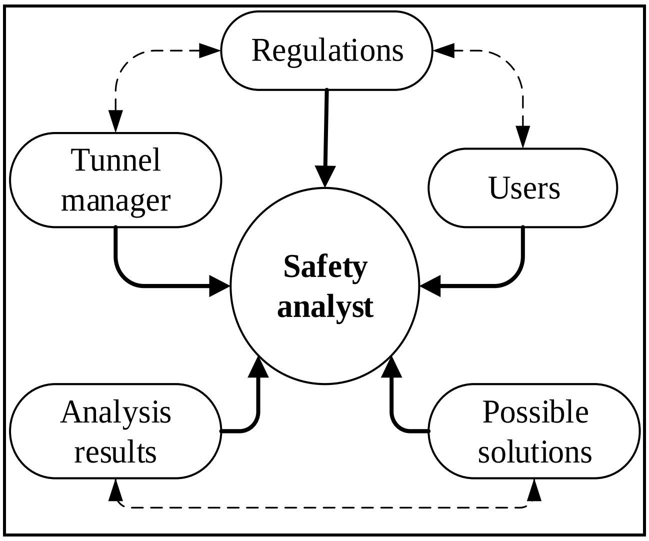

Figure 8.1: Stakeholders of the tunnel system (source: Ntzeremes and Kirytopoulos, Under review)

A brief summary of these requirements showcases their differentiations amongst them. Formulated by authorities, regulations are sets of rules and trends.

Predominantly stem from knowledge gained from previous accidents (AADT, 1999) and experiments (PIARC, 1999; Seike et al., 2016), they are imposed to tunnels in order to fulfill specific and generally accepted requirements. Tunnel managers are primarily responsible to check for their application otherwise risk analysis has to advocate for potential deviations, if allowed. Risk analysis is the systematic way to estimate the level of safety of the tunnel system. Given that risk analysis in tunnels follows the scenario-based approach, tunnel system is examined under predetermined conditions and unavoidably various assumptions have to be taken into account regarding for example the users' behaviour, the traffic, environmental conditions, etc. (INERIS, 2005). As a consequence, the estimated level is embedded with subjective (or epistemic) uncertainty that decision on safety measures should account for.

Furthermore, cost and time criteria are also valuable for both tunnel managers and analysts, although with different weights, to judge the appropriateness of a safety measure. Additionally, tunnel managers and analysts may perceive specific hazards and critical events differently due to their different experience or orientation. Consequently, they can result in different decisions regarding the suggested measures. Moreover, since users' behaviour constitutes a key factor during risk analysis (Ntzeremes and Kirytopoulos, 2018a), the selection process should also take into account the users' knowledge and potential behavioural intentions as several experiments have indicated that these factors can determine significantly the performance of safety measures (Kinateder et al., 2015; Ronchi et al., 2016). Finally, the selected measures should also be applicable. The term applicable implies both compliance with regulation and the ability of the measure to achieve the required functionality (Přibyl and Přibyl, 2014).

To synthesise the aforementioned views, a combination of two well-known methods the AHP and the MCS is employed. The AHP requires from decision-makers to make pairwise comparisons amongst all pairs of decision criteria as well as alternatives in a ratio scale (Saaty, 1990; Caputo et al., 2013). Therefore, it creates the ground for a consistent assessment of the alternatives ensuring concurrently that the ratio scale is self-consistent. However, each decision-maker may interpret the requirements of each stakeholder in a different way. Besides, the amount of the available information as well as the way of understanding the problem are also factors that can affect the comparisons. To address these issues, MCS is used (Aslett et al., 2017). By applying the MCS, the ranking of alternatives is considered reliable since it includes potential uncertainty related to the pairwise comparisons amongst all pairs of decision criteria as well as alternatives (Levary and Wan, 1998). Hence, the proposed method supports the analyst(s) to estimate the level of safety of each measure, and select the appropriate measure(s) that indeed enhance(s) the level of safety of the tunnel system.

8.2 Description of the EVADE method

The proposed method is depicted in Figure 4 and consists of three main layers following a top to bottom decision sequence. The name of the method results from the first letters of the layers' titles (refer to Figure 8.2).

8.2.1 Evaluation of the tunnel system

Initially, the method evaluates the current level of safety of the examined tunnel system (**Layer 1**). Thus, the necessity of additional to standard safety measures, if needed, arises. At the beginning, the lifecycle phase of the tunnel should be defined (**Step 1.1**) because it strongly determines the entire decision-making process. For instance, conducting risk assessment just before giving the tunnel in operation (commissioning phase) accounts for different priorities, regarding especially the cost and the time, than conducting the same analysis in the designing phase. Because each tunnel has its unique characteristics and also each method has its specific requirements, the system parameters that are taken into account during risk assessment have to be identified (**Step 1.2**). Due to different types of transported goods, fire accidents do not result in the same consequences and thus do not require the same approach. Therefore, the determination of the examined fire accident scenarios is essential (**Step 1.3**).

Having defined the general context, the analyst has to estimate potential losses since they denote the level of safety of the examined tunnel (**Step 1.4**). In order to estimate the impact of fire on users, the tunnel's airflows (the air temperature and the air opacity) are estimated commonly with the aid of a CFD software. The outcome provides two sources of data, the air temperature and the air opacity with regard to the tunnel length and time. These data are used for the estimation of the effect of the heat and pollution on the users' evacuation process. Therefore, estimated losses test the performance of current measures, determine the existing level of the safety and illustrate whether additional measures are required (**Step 1.5**).

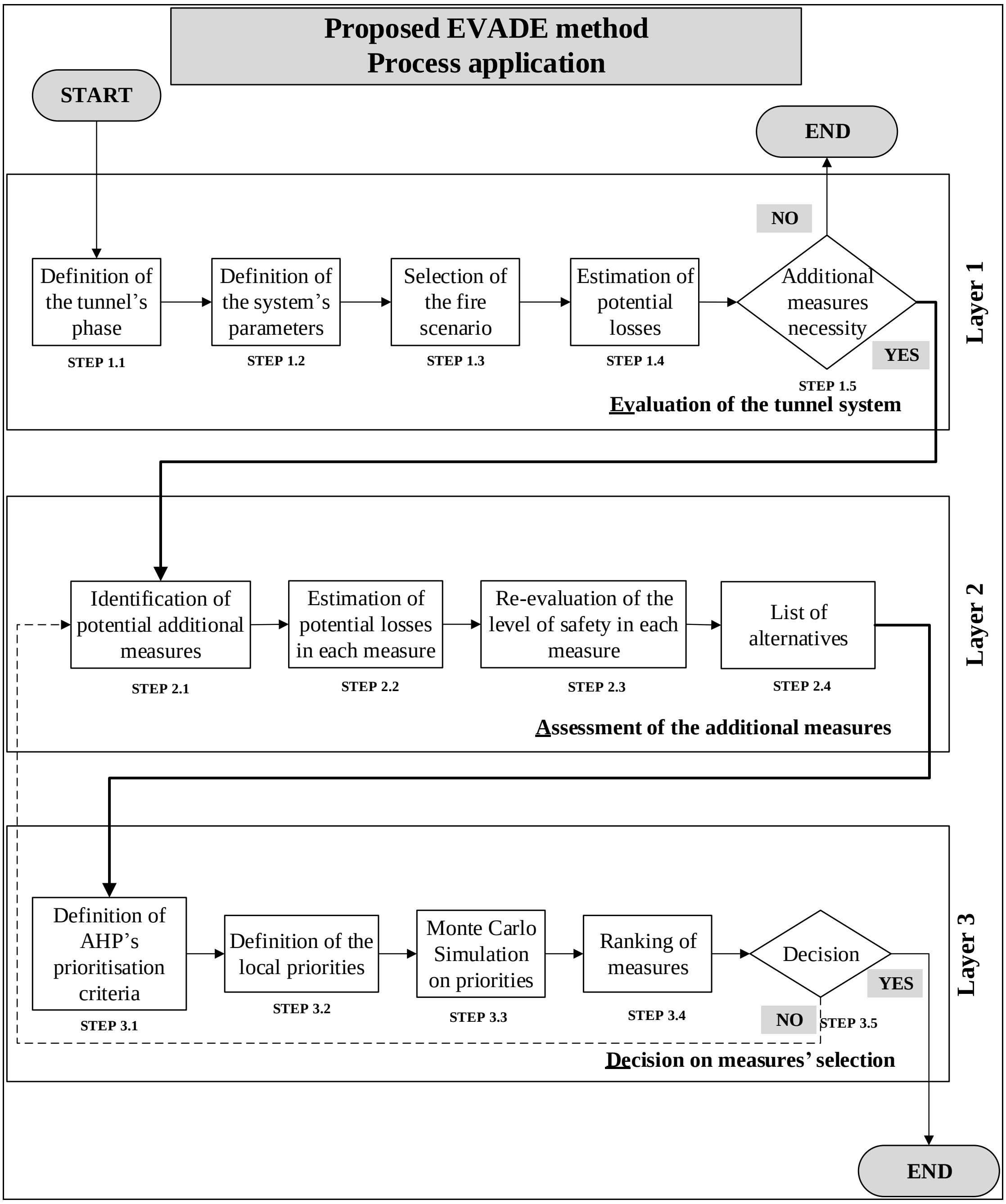

Figure 8.2: Proposed EVADE method (source: Ntzeremes and Kirytopoulos, Under review)

8.2.2 Assessment of the additional measures

After estimating the losses amongst trapped-users, the forthcoming analysis focuses on assessing potential additional measures that required in order to enhance the tunnel level of fire safety (**Layer 2**). To this respect, the analyst examines which are the appropriate additional measures needed in order to mitigate the estimated losses (**Step 2.1**). In this step, the decision criteria as mentioned in section 3.3 that define the suitability of each measure considering all the stakeholders' views (Figure 8.1) are reported. Afterwards, a second round of calculation is conducted in order to estimate potential losses amongst users by implementing each measure (or set of measures) separately (**Step 2.2**). Therefore, the level of safety of the tunnel system is re-evaluated (**Step 2.3**). At last, a final list of alternatives is recorded (**Step 2.4**).

8.2.3 Decision on measures' selection

At the last layer of the method, a decision on which measure(s) to be selected has to be made (**Layer 3**). This method is applied in order to evaluate the alternatives, prioritise them regarding the cost, the time, the resulted effectiveness and the uncertainty of their application (refer to Figure 3.5). Before proceeding to the pairwise comparison of the listed alternatives, the relative importance amongst the decision criteria is calculated through the AHP, based on expert opinion (**Step 3.1**). While comparing the criteria amongst themselves to come up with their importance, it is important to acknowledge the lifecycle phase of the tunnel system since for each phase the criteria may have different weights. Subsequently, pairwise comparisons of alternatives against the criteria are made and the local priorities for the alternatives are estimated (**Step 3.2**). Afterwards, in the sense of sensitivity analysis, the MCS is employed in re-estimating the ranking of alternatives by carrying-out a number of iterations (**Step 3.3**). By doing so, the ranking of alternative safety measures is illustrated. However, it is also important to estimate the consistency of the judgments (Levary and Wan, 1998). As a result, the alternatives' ranking comes as a distribution instead of a single number, which is used in current approaches, providing the decision-maker with better information for selecting the most suitable measure(s) according to the tunnel's situation (**Step 3.4**). Finally, consulting the total results, the decision-maker proposes the appropriate measure(s) (**Step 3.5**).

8.3 Method implementation and results

A typical TERN tunnel that belongs to the Greek national motorway is selected, which meets all the Directive 54/2004/EC's requirements. In the beginning, the method requires the tunnel phase. The significance of the tunnel's lifecycle phase has already been pointed-out since it determines both the potential applicable measures and the weights of the decision criteria. In the presented illustrative case, a tunnel in the commissioning phase is examined. As a result, the available time as well as the available budget for additional measures are rather limited.

The selection of fire scenarios follows reporting the tunnel system parameters (Table 8.1). The case of fire accident without involvement of dangerous goods is examined. The examined scenario comprises a fire accident sparking from a heavy goods vehicle without dangerous goods involvement having a standardised source term of HRR_{max} equal to 100MW. Amongst the various cases that are investigated, in this case, only the results relevant to the worst case scenario are discussed. Thus, the burning heavy goods vehicle is located in the last section of the tunnel, 150m before the tunnel exit. Relevant studies have indicated that the selected location is considered to be one of the most vulnerable locations of the tunnel (see Chapter 6). Subsequently, the estimation of potential losses amongst trapped-users is taking place.

Table 8.1: Tunnel attributes (source: Ntzeremes and Kirytopoulos, Under review)

Designing features of the tunnel	Single bore	
	Length	2.500m
	Slope	-1,5%
	Emergency Exits	4
	Traffic interruption	4
	Launch of traffic lights after the ignition	3min
System of longitudinal mechanical ventilation	Jet-fan-arrays	4
	Number of jet fans making up the array	2
	Progressive function	
	Launch of the ventilation after the ignition	3min
Pressure	Difference between tunnel portals	28 Pa
Environmental conditions	Temperature	12°C
	Altitude	600m
Traffic conditions	Vehicle flux	60 veh/hr
	Uniform vehicle flux	
	Proportion of heavy goods vehicles	30%

Trapped-users’ self-evacuation is illustrated as a trajectory, depicted as line segments depending on the walking speed, with regard to tunnel length and time (Figure 8.3). During their movement, users’ safety is affected by accumulating heat of both radiation and convection (AAT, 2011a; Purser, 2009). The estimation of both the FED_h and the FED_{co} in every time step are estimated (see section 6.3 and 7.5).

The accident results in six trapped vehicles in the tunnel, including the heavy goods vehicle that caused the fire, which have 10m interval in between. Due to the assumed uniform distribution of the vehicles, the estimated evacuation trajectories correspond to three tunnel locations. It is further assumed that 100s elapse from the ignition of the fire to the point where all trapped-users realise the criticality of the event and begin their self-evacuation moving, directly, to the nearest emergency exit located at 2,000m from the entrance of the tunnel. The analysis shows that eight trapped-users corresponding to the first two trajectories are neutrilised (Figure 8.3).

Since the fire accident disrupts the traffic in the tunnel, the impact of the piston effect is gradually diminishing causing a rotation of the air flux from the exit to the entrance of the tunnel due to the presence of pressure difference at the tunnel portals. As a result, the well-known phenomenon of backlayering occurs and impedes the evacuation process of the trapped-users (refer to Figure 8.3). The aim of the mechanical ventilation system is to diminish the length of backlayering achieving as soon as possible the critical velocity. This condition is not achieved in this case. Furthermore, trapped-users begin their self-evacuation process is 100sec. The pre-evacuation time is significant in estimating potential losses with high reliability. Greek requirements have not any provision regarding the pre-evacuation time. Post-accidents reports along with other countries' regulations (Fridolph et al., 2013), have provided safety analysts some information on this issue. Furthermore, there are various theories related to this aspect of user's behaviour (Kuligowski, 2013). Although the education of users plays a crucial role, the establishment of safety measures that can inform and move trapped-users to action is also important (Kirytopoulos et al., 2017). Finally, the hypothesis that vehicles moving towards the tunnel entrance obey to the red traffic light can be under criticism.

Thus, further safety measures should be adopted. Synthesing legislation and tunnel managers' requirements along with users' necessities and combining them with risk analysis results four possible safety measures are qualified.

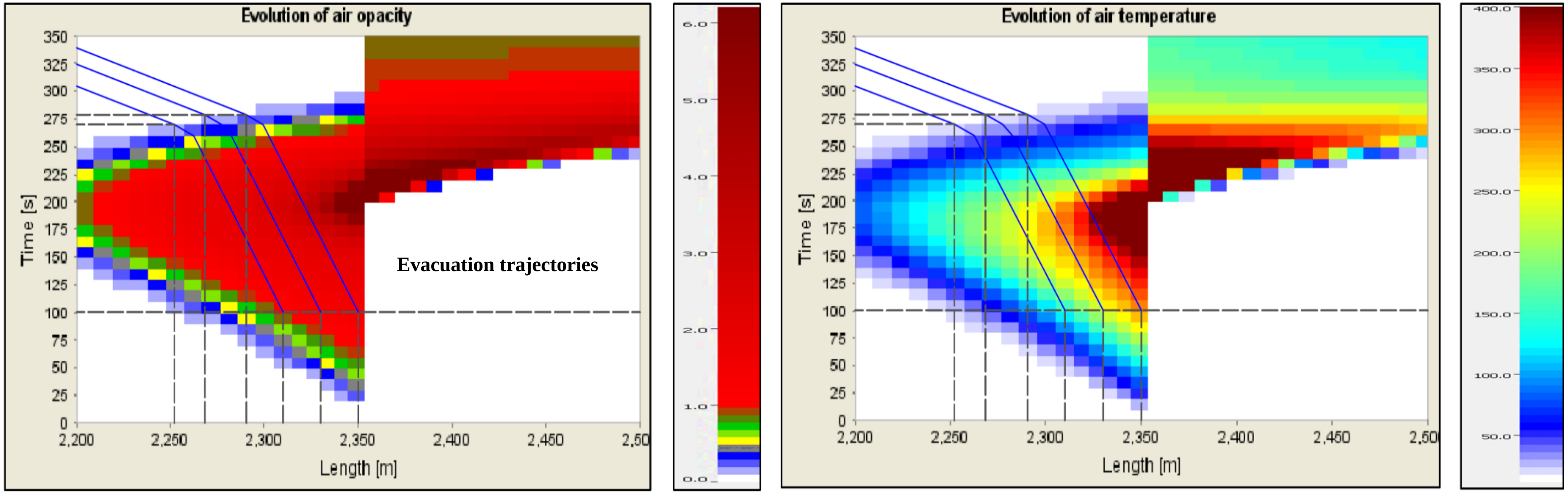

Figure 8.3: Fire and Smoke environment of the reference scenario (source: Ntzeremes and Kirytopoulos, Under review)

The four resulting alternatives along with the four decision criteria as described in section 3.2 are depicted in Figure 8.4.

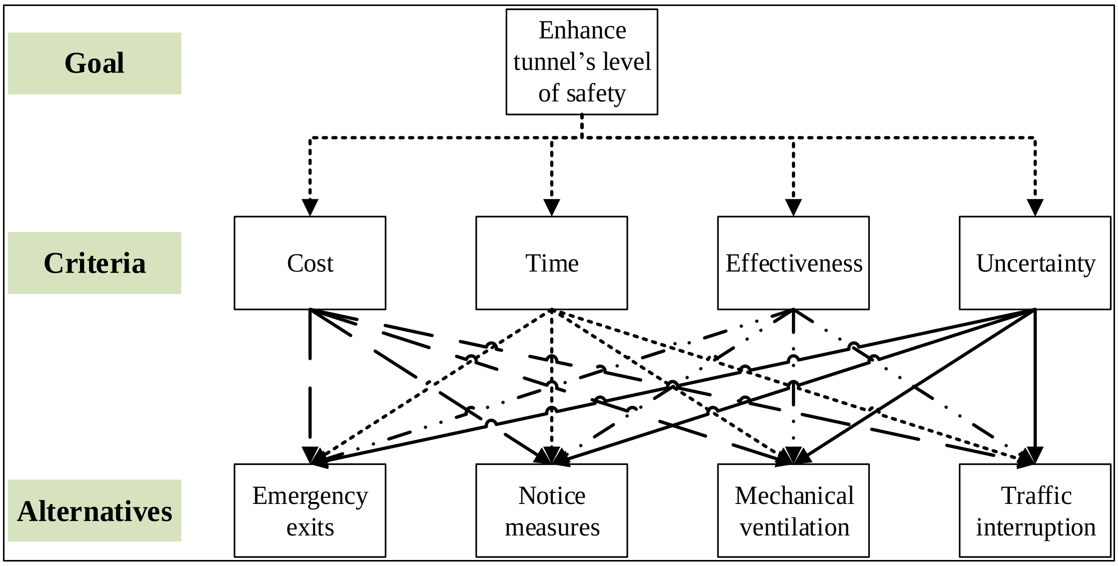

Figure 8.4: Decision hierarchy for selecting additional safety measures (source: Ntzeremes and Kirytopoulos, Under review)

According to Figure 8.4, the decision is broken down in a hierarchy of goal, criteria and alternatives. Afterwards, the evaluation of each measure effectiveness in reducing trapped-users losses is carried-out according to the aforementioned calculation process. The final outcome, combined with the rest of the values of the rest criteria that are going to be used in the decision stage, is illustrated in Table 8.2.

The AHP is employed to select one alternative from the given set of alternatives (refer to Table 8.2). During the pairwise comparisons it is difficult to come up with a single value in terms of superiority of one solution over another against a specific criterion.

Table 8.2: Features of the alternative safety measures (source: Ntzeremes and Kirytopoulos, Under review)

Criteria **Alternatives**	*Time* *(mth)*	*Cost* *(MM)*	*Effectiveness** *(losses)*	*Uncertainty*
Emergency exit	18	2	4	Medium
Notice measures	3	0.5	2	High
Mechanical ventilation	9	1.2	4	Low
Traffic interruption	6	0.8	4	Low

*In case the **SIREN method** is performed, the effectiveness column will include the relevant cumulative diagrams, such as the **Figure 7.10** in **section 7.7**.

Apart from the difficulty in providing a single value for the superiority (preference in terms of AHP), the problem is aggravated by the existence of different stakeholders that may have different judgments. To alleviate that, a distribution is given instead of a single value for the comparison amongst different criteria or alternatives. Using this approach, pairwise evaluations are steamed from predefined probability distributions (Levary & Wan, 1998). These probabilities are given by the decision-maker (discrete uniform distributions) who synthesises the different opinions amongst stakeholders or amongst safety analysts regarding the preference for each of the comparisons. These uniform distributions are based on a scale of 1 to 9. This approach differs from the traditional AHP since pairwise comparisons follow a stochastic approach. The MCS is employed so that the ranking of the alternatives (potential measures) takes into account the uncertainty related to the decision-making judgment regarding the pairwise comparisons.

Carrying-out 1,000 iterations, the outcome is depicted in Figure 8.5. The results that appeared a CI above 12% were excluded. Saaty proposes that CI should be up to 10% (Saaty, 1990). However, the embedded uncertainty of the ratio scale probably allows the analyst to include a little higher inconsistency. So, the final results sample comprises 631 iterations. Figure 8.5 depicts the ranking of each measure in the total of 631 iterations. That is, how many times the measure was ranked first, second, third or fourth within the 631 iterations.

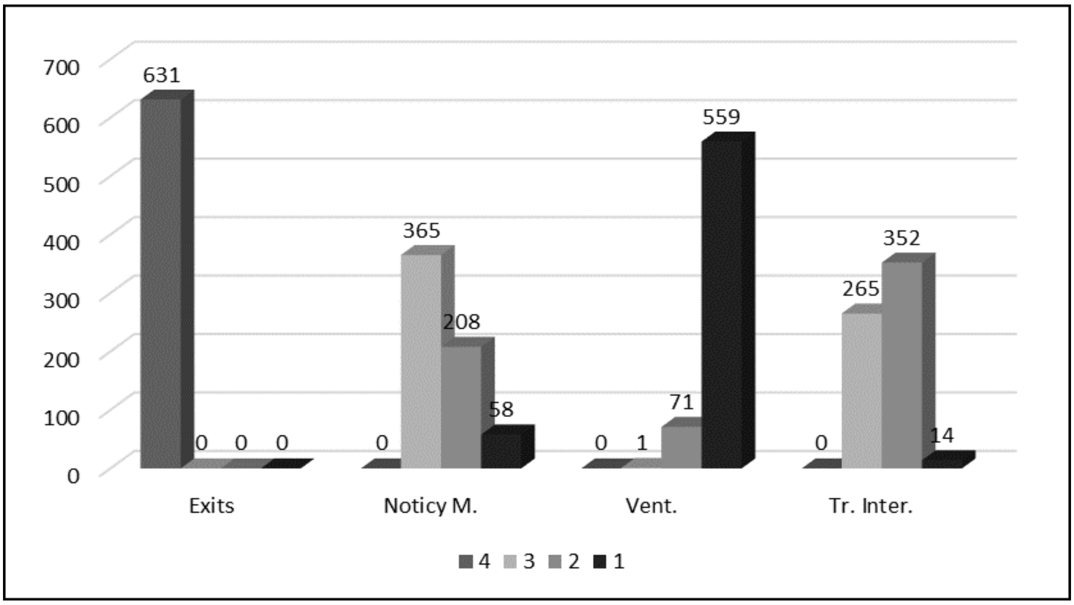

Figure 8.5: Ranking of the alternative safety measures (source: Ntzeremes and Kirytopoulos, Under review)

Figure 8.5 can give to the decision-makers an overall picture of the preference for each measure (not just a point value) and, thus, enable them to take an informed decision that will take into account the whole spectrum of risk criteria and judgment uncertainty. In this case, for instance, based on the outcome depicted in Figure 8.5, the emergency exits are ranked as 4th appropriate alternative and the mechanical ventilation as the 1st in most of the times. This gives to the decision-maker an increased confidence that mechanical ventilation should be the first measure to consider and emergency exits the last. In addition, the same outcome results from the estimation of the average (AVG) priority that each measure has (Table 8.3).

Table 8.3: Average priority score of each safety measure (source: Ntzeremes and Kirytopoulos, Under review)

Alternatives	*Exits*	*Notice M.*	*Ventilation*	*Interruption*
Priority (%)	11.29	27.71	33.50	28.50

On the other hand, between the traffic interruption and the notice measures the distinction is not that clear and needs interpretation. The first seems to rank above the second, although notice measures are in the first position more times than the traffic interruption. However, even in this case, the method proposed here gives to the decision-maker a broader and more accurate of the reality picture that will help them rank properly the safety measures.

In order to assist the decision-maker to overcome the short distance between the average scores of the measures, a subsequent step is to estimate the probability density function of each measure priorities. Figure 8.6 illustrates the probability density of the measures' priorities, which except for the emergency exits, they seem to reach the probability density of a normal distribution.

Figure 8.6 supports the decision-maker to understand further the superiority relationship amongst alternative measures as the differences between the average scores of the measures, approximately 5% amongst the first three, and the overlapping of priorities interval are depicted. By doing so, the outcome is better visualised as the probability density of the alternative measures illustrate the different potential ranking scenarios. Nevertheless, the decision on the appropriateness between the two measures (traffic interruption and notice measures) is not obvious.

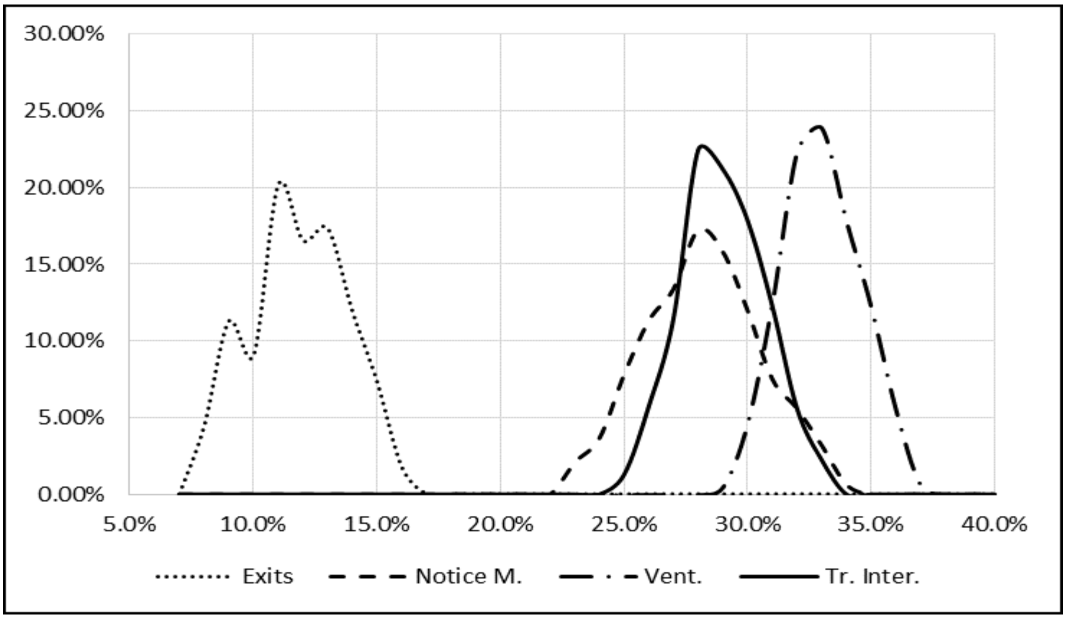

Figure 8.6: Probability density of safety measures' priorities (source: Ntzeremes and Kirytopoulos, Under review)

To this respect, the proposed method estimates the variability or the spread of data around their average score. By doing so, the decision-maker clarifies how the sum of each measure's priorities is clustered in regard to the average score. In case the variability of a measure is larger than other, measure's priorities are wider spread. Thus, it is possible for some extreme scores to give a distorted view about measure's adequacy. Figure 8.7 shows the variability of each measure priorities.

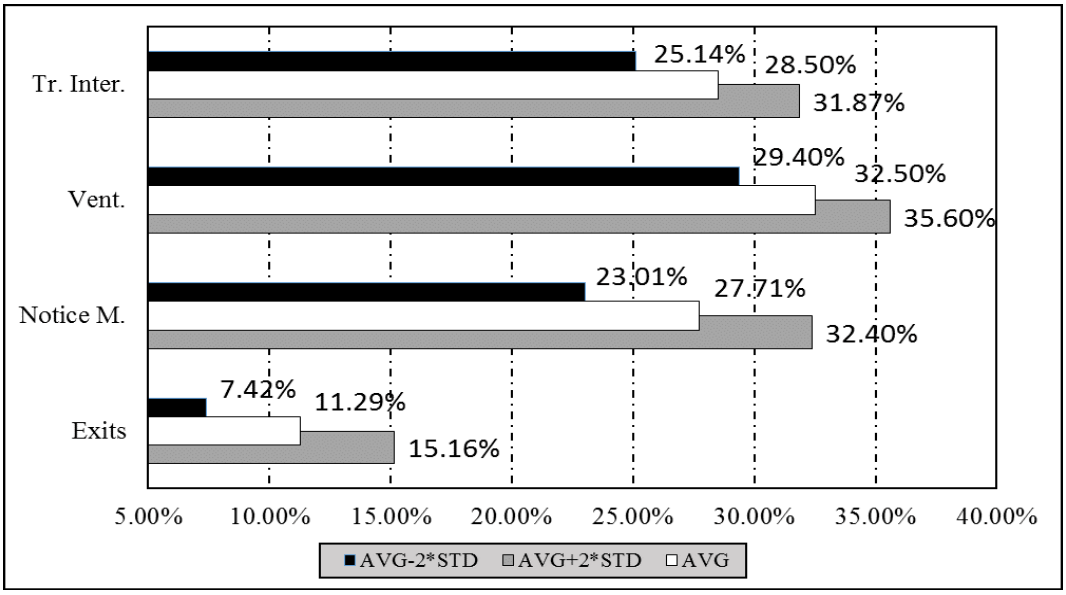

Figure 8.7: Spread of safety measures' priorities around average (source: Ntzeremes and Kirytopoulos, Under review)

This variability is represented by the spread of each sum of priorities around the average score within the specified interval of two standard deviations (STD). Such a representation can help the decision maker clarify better the proper ranking of measures. In the illustrative case, traffic interruption has higher average (28.50%) than notice measures (27.71%) and smaller variability, as traffic interruption's priorities spreads within 6.73% interval comparing to notice measures which spreads within 9.39%. Hence, despite the partial overlapping of the intervals, traffic interruption overweighs notice measures. Due to Figure 8.6 and Figure 8.7 results, mechanical ventilation is prioritised first since it has the highest average along with the lowest variability.

Figure 8.8 illustrates one iteration of the method. Comparing the EVADE method's outcome with the outcome of the first iteration of the process in Figure 8.8, the advantage of employing MCS is illustrated. If a single-point prioritisation was made as in the one instance presented in Figure 8.8, the notice measure would come over both the mechanical ventilation and the traffic interruption. On the contrary, the proposed method shows that this is not the case. After 1,000 iterations, the decision-maker finds the opposite based on the results presented in Figure 8.5 and Figure 8.6. Figure 8.8 shows that the notice measure is ranked above but the distance between the first three alternatives is very small, approximately .01 between the first and the second alternative and .035 between the second and third alternative. This short distance makes the judgment considerable unsafe.

The overall conclusion from the analysis shows that while notice measure is more effective regarding loss reduction as well as cost and time, it involves considerable uncertainty since it is directly related to tunnel users' perception and education. The same feature is contained also in emergency exit. However, the possibility of reducing distance amongst emergency exits by inserting further emergency exits in the tunnel system is excluded due to the commissioning phase of the tunnel, which does not allow such intervention. Thus, ventilation and traffic interruption measures, although they fail to achieve the most in effectiveness having lower uncertainty (they are activated by the tunnel operator who is regarded to be trained enough), they ranked above the previous measures.

AHP - MCS

	Critiria matrix				Normilised critiria matrix				PRIORITY	Criteria Consistency matrix					
	Time	Cost	Effectiveness	Uncertainty	Time	Cost	Effectiveness	Uncertainty		Time	Cost	Effectiveness	Uncertainty	SUM	SUM / PRIOR.
Time	1.000	1.000	0.333	0.333	0.125	0.125	0.071	0.167	0.122	0.122	0.122	0.094	0.158	0.496	4.065
Cost	1.000	1.000	0.333	0.333	0.125	0.125	0.071	0.167	0.122	0.122	0.122	0.094	0.158	0.496	4.065
Effectiveness	3.000	3.000	1.000	0.333	0.375	0.375	0.214	0.167	0.283	0.366	0.366	0.283	0.158	1.173	4.147
Uncertainty	3.000	3.000	3.000	1.000	0.375	0.375	0.643	0.500	0.473	0.366	0.366	0.848	0.473	2.054	4.340
SUM	8.000	8.000	4.667	2.000	1.000	1.000	1.000	1.000	1.000	CI	0.051	RI	0.900	λ max	4.154
														CR	0.057

	Time matrix				Normilised Time matrix				PRIORITY	Time Consistency matrix					
	Exits	Notice M.	Vent.	Tr. Inter.	Exits	Notice M.	Vent.	Tr. Inter.		Exits	Notice M.	Vent.	Tr. Inter.	SUM	SUM/PRIOR.
Exits	1.000	0.143	0.333	0.333	0.071	0.079	0.063	0.063	0.069	0.069	0.078	0.064	0.064	0.276	4.002
Notice M.	7.000	1.000	3.000	3.000	0.500	0.553	0.563	0.563	0.544	0.482	0.544	0.580	0.580	2.187	4.016
Vent.	3.000	0.333	1.000	1.000	0.214	0.184	0.188	0.188	0.193	0.207	0.181	0.193	0.193	0.775	4.006
Tr. Inter.	3.000	0.333	1.000	1.000	0.214	0.184	0.188	0.188	0.193	0.207	0.181	0.193	0.193	0.775	4.006
SUM	14.000	1.810	5.333	5.333	1.000	1.000	1.000	1.000	1.000	CI	0.003	RI	0.900	λ max	4.008
														CR	0.003

	Cost matrix				Normilised Cost matrix				PRIORITY	Cost Consistency matrix					
	Exits	Notice M.	Vent.	Tr. Inter.	Exits	Notice M.	Vent.	Tr. Inter.		Exits	Notice M.	Vent.	Tr. Inter.	SUM	SUM/PRIOR.
Exits	1.000	0.143	0.333	0.333	0.071	0.093	0.045	0.045	0.064	0.064	0.090	0.051	0.051	0.256	4.020
Notice M.	7.000	1.000	5.000	5.000	0.500	0.648	0.682	0.682	0.628	0.446	0.628	0.771	0.771	2.616	4.165
Vent.	3.000	0.200	1.000	1.000	0.214	0.130	0.136	0.136	0.154	0.191	0.126	0.154	0.154	0.625	4.055
Tr. Inter.	3.000	0.200	1.000	1.000	0.214	0.130	0.136	0.136	0.154	0.191	0.126	0.154	0.154	0.625	4.055
SUM	14.000	1.543	7.333	7.333	1.000	1.000	1.000	1.000	1.000	CI	0.025	RI	0.900	λ max	4.074
														CR	0.027

	Effectiveness matrix				Normilised Effectiveness matrix				PRIORITY	Effectiveness Consistency matrix					
	Exits	Notice M.	Vent.	Tr. Inter.	Exits	Notice M.	Vent.	Tr. Inter.		Exits	Notice M.	Vent.	Tr. Inter.	SUM	SUM/PRIOR.
Exits	1.000	0.333	0.333	0.333	0.100	0.167	0.063	0.063	0.098	0.098	0.160	0.070	0.070	0.399	4.071
Notice M.	3.000	1.000	3.000	3.000	0.300	0.500	0.563	0.563	0.481	0.294	0.481	0.631	0.631	2.038	4.234
Vent.	3.000	0.333	1.000	1.000	0.300	0.167	0.188	0.188	0.210	0.294	0.160	0.210	0.210	0.875	4.158
Tr. Inter.	3.000	0.333	1.000	1.000	0.300	0.167	0.188	0.188	0.210	0.294	0.160	0.210	0.210	0.875	4.158
SUM	10.000	2.000	5.333	5.333	1.000	1.000	1.000	1.000	1.000	CI	0.052	RI	0.900	λ max	4.155
														CR	0.058

	Uncertainty matrix				Normilised Uncertainty matrix				PRIORITY	Uncertainty Consistency matrix					
	Exits	Notice M.	Vent.	Tr. Inter.	Exits	Notice M.	Vent.	Tr. Inter.		Exits	Notice M.	Vent.	Tr. Inter.	SUM	SUM/PRIOR.
Exits	1.000	3.000	0.200	0.333	0.107	0.250	0.083	0.125	0.141	0.141	0.246	0.087	0.114	0.588	4.157
Notice M.	0.333	1.000	0.200	0.333	0.036	0.083	0.083	0.125	0.082	0.047	0.082	0.087	0.114	0.330	4.029
Vent.	5.000	5.000	1.000	1.000	0.536	0.417	0.417	0.375	0.436	0.707	0.409	0.436	0.341	1.893	4.341
Tr. Inter.	3.000	3.000	1.000	1.000	0.321	0.250	0.417	0.375	0.341	0.424	0.246	0.436	0.341	1.446	4.245
SUM	9.333	12.000	2.400	2.667	1.000	1.000	1.000	1.000	1.000	CI	0.064	RI	0.900	λ max	4.193
														CR	0.071

	Overall matrix					Normilised Overall matrix					
	Time	Cost	Effectiveness	Uncertainty	Cr. Prior.	Time	Cost	Effectiveness	Uncertainty	F. Priority	Ranking
Exits	0.069	0.064	0.098	0.141	0.122	0.008	0.008	0.028	0.067	0.111	4
Notice M.	0.544	0.628	0.481	0.082	0.122	0.066	0.077	0.136	0.039	0.318	1
Vent.	0.193	0.154	0.210	0.436	0.283	0.024	0.019	0.059	0.206	0.308	2
Tr. Inter.	0.193	0.154	0.210	0.341	0.473	0.024	0.019	0.059	0.161	0.263	3

Figure 8.8: One of the 1,000 iterations of the method (source: Ntzeremes and Kirytopoulos, Under review)

The comparison between them shows that despite the lower score of mechanical ventilation in cost and time criteria, re-design of the ventilation system is more preferred than traffic interruption since risk analysis illustrates an unacceptable backlayering length for trapped-users (Figure 8.4).

8.4 Validation of the method

In this section, the validation of the proposed EVADE method is presented. Both the framework and the approach followed are the same as these were described in section 7.7.

However, further description has to be added regarding the identification of the decision criteria. The validation of these criteria has been performed through the review of the relevant literature regarding the selection of safety measures (see section 3.3.3) along with the national guidelines of each EU member state (see section 3.1).

Furthermore, as far as the predefined probability distributions (Levary & Wan, 1998) is concerned, these probabilities are given by the decision-maker (discrete uniform distributions) who synthesises the different opinions amongst stakeholders or amongst safety analysts regarding the preference for each of the comparisons as the relevant literature has indicated (see section 3.3.3).

8.5 Conclusions

Despite the significant progress in developing robust risk analysis techniques and models, current methods exhibit limited progress regarding the link of risk assessment with the selection of additional to standard safety measures, when indicated by risk analysis. Commonly, measures’ selection relies mainly on strict regulatory requirements. However, it should be noted that the selection of additional measures requires that the safety analyst should include the views of different stakeholders of the tunnel system while it should be also based on many different decision criteria as well as a ranking of alternatives.

Therefore, the main advantage of the EVADE method is that it provides a systematic decision process through the use of particular and consistent decision criteria, together with considerations of alternative safety measures which are based on the stated subjective preferences of the decision-maker. Thus, the proposed method protects the safety analyst from the adoption of arbitrary decisions.

An illustrative case is examined to present the utilisation of the EVADE method. Comparing alternative measures' effectiveness depicted in Table 8.2, which traditional deterministic approaches take into account, Figure's 8.4 results, which presents a single iteration of the process, and the results of Figure 8.5, which accounts for the EVADE approach, a significant difference regarding the ranking of the measures arise. This difference can affect the level of safety of the tunnel. Furthermore, it should be mentioned that the proposed method is especially valuable when no clearly dominant alternative exists as shown in Figure 8.6 and 8.7 of the presented illustrative case.

Chapter 9[7]

Conclusions, recommendations and areas for further research

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[7] Parts of this Chapter has been published in: (Ntzeremes et al. 2018; Ntzeremes and Kirytopoulos, 2018b, Ntzeremes and Kirytopoulos, 2019, Ntzeremes et al., Accepted); Ntzeremes and Kirytopoulos, Under review)

9. Conclusions, limitations and areas for further research

9.1 Synthesis of findings

The progress of findings is associated with the first three discrete phases of the research design as these depicted in Figure 5.2.

9.1.1 Phase 1

The various benefits for both the economies and societies from the use of road tunnels along with the improvement of underground space technology in recent decades has led to the rapid increase of road tunnels worldwide rising thus the number of people and the volume of goods passing through them. Although the accident rates confirm that accidents are lower in tunnels than on the open roads, if an accident occurs, it might have greater severity than in the rest of the road network. However, Chapter 2 showcases that their use involves the risk that a potential dysfunction of a tunnel can cause serious dysfunction on the broader road network due to its interdependencies. This dysfunction can be particularly extensive in case of a fire accident. Thus, they are considered as critical infrastructures. Furthermore, tunnels are the most sophisticated elements of the road infrastructure. Figures 2.4 & 2.5 indicate not only the complexity of tunnel systems but they also justify their socio-technical attribute.

Indeed, fire is the foremost critical event for road tunnels' safety. The devastating consequences of previous accidents, i.e. Monte Blanc, 1999 or Yanhou, 2014 demonstrate this criticality. Section 2.1 provides the reasons why road tunnels are considered risky environments. In brief, their closed environment causes: (a) no physical light passing through them, which makes difficult for drivers to adjust when passing through, (b) arranged air movement, (c) difficulties in approaching and rescuing trapped-users in case of accidents, particularly in case of fire accidents and (d) fire combustion irregularity. In addition, by providing an overview of the particular characteristics of fires in tunnels, section 2.1 indicates the complexity of this critical event. Key points of this overview are: (a) the combustion irregularity that increases the HRR_{max} of tunnel fires up to four times higher in contrast to open fires, (b) the availability of propagated toxic gases along with the limited availability of oxygen, and

(c) the development of the backlayering that poses a serious threat for the trapped-users (see Figure 2.4).

Therefore, the Directive 2004/54/EC was a necessary first step in order to enhance the level of fire safety of road tunnels. Section 2.2 illustrates that through the Directive, the fire safety approach in road tunnels has changed. Safety management has to be conducted now based on the synergy of the regulatory requirements and the risk assessment. Therefore, safety does not count only on "*learning from events*", since this is the primary source of prescriptive requirements, but also on "*assessing the system proactively*", which is the advisable approach followed for the safety of all the modern complex social-technical systems.

Although the use of risk assessment by safety analysts and tunnel managers, the results of Figure 3.2 illustrate that the aim of reaching the "vision zero" goal has not accomplished yet. Another important aspect is that the scarcity of disastrous fire accidents shows that tunnel managers and safety analysts must not be complacent at all about the level of fire safety of tunnels. To this respect, there is plenty of room for improvement and the development of more robust risk assessment methods possesses the first and most important role, especially when fire accidents are involved.

Prior to do so, particular attention should be paid on important issues and key parameters of the fire safety management, highlighted either in the literature or in practice, that can affect the risk assessment and, because of that, concern tunnel managers and practitioners. The critical review of Chapter 3 aims at assessing how current risk assessment methods address all these. These methods are selected either because they are related to member states which have a large number of tunnels longer than 500m and/or a considerable background in road infrastructure safety. Furthermore, section 3.3 aims at examining the methods linked with the basic steps of the risk assessment (see Figure 3.4).

The outcome showcases that important parameters for the safe operation of tunnel systems have significant uncertainty. These parameters include: (a) the traffic, (b) the trapped-users behaviour during evacuation, (c) the response of the tunnel personnel in activating the mechanical ventilation or the traffic interruption, (d) the fire behaviour and (e) the environmental conditions. Although these parameters play a key role in tunnel performance, current methods act on a deterministic approach ignoring thus their embedded uncertainties. Faced with these uncertainties, safety analysts make assumptions adopting a 'mean' value or a worst case scenario. But, the variation to reality because of these assumptions can create serious fallacies regarding the estimated level of tunnel safety.

Another conclusion is that, although the choice of additional to standard safety measures involves multiple criteria decision-making and a ranking of alternatives, current risk assessment methods lack such multiple criteria and a ranking of alternatives.

The final conclusion of section 3.3 refers to the users' behaviour, which has the predominant role in tunnel safety. The analysis indicates that differences and deficiencies amongst methods exist in the use of certain standardised values and thresholds in order to assess the users' self-evacuation process. Further analysis on this issue exists in Chapter 4 that describes the approach of modern evacuation simulation models in represent more accurate the evacuation process.

In this point, the thesis meets its first three objectives, namely, the ***Ob.1.1:*** Investigate and evaluate relevant studies, the ***Ob.2.1:*** Investigate the structure and operation of current evacuation models and the ***Ob.3.1:*** Investigate the current methods and identify potential deficiencies, problems and gaps (see sections 1.3 and 5.5).

9.1.2 Phase 2

The primary aim of Chapter 6 is to simulate a tunnel fire in order to explore the consequences of a fire accident in a tunnel. By doing so, the evolution of fire is examined (see Figure 6.5), the vulnerable locations of the tunnel are identified (see Figures 6.2, 6.3 & 6.4) and the performance of the users' evacuation is assessed (see Figure 6.6). Furthermore, in order to explore the impact of the variations of the regulatory guidelines (see Chapter 3) to the level of tunnel safety, the examination of the fire scenarios is performed through the French SHI (CETU, 2003) and the Greek SAM (AAT, 2011a) tunnel risk assessment methods. The choice is not arbitrary as these methods share a high degree of similarity in their inherent approaches and assumptions (see Figure 3.3 and Table 3.1), while it results that their discrepancies on parameters that should not be country-specific are significant enough to change the estimated level of safety of the same tunnel (i.e. the time that fire catches the HRR_{max}). The concept behind the selection is that if two very similar methods can lead to considerable discrepancies, these discrepancies would further increase if the methods used were more dissimilar.

Having performed an overview on the existing risk methods of member states, a relevant categorisation is proposed by looking at three principal axes: (a) the type of risk approach, (b) the type of transported goods and (c) the type of method used. Moreover, a deeper level of examination unearths the variations in key parameters and assumptions that each member state has imposed. The impact of these national policies is explored in the indicative case study, which compares the simulated self-evacuation and the overall level of tunnel safety arising from the use of the Greek and the French assessment methods.

As demonstrated, the differences in national policies in the selection of parameters' values and in the standardised fire scenarios may significantly affect both the results of the self-evacuation process as well as the performance of the system of mechanical ventilation. Design that may be deemed acceptable by the French Standards in regard to the achieved level of safety, clearly underperforms when it is examined under the relevant Greek provisions. Therefore, it can be inferred that based on the underlying assumptions of the fire standardisation scenarios considered, the Greek method is stricter from a safety point of view. Apart from the discrepancy in the evaluation itself, one should consider the relevant consequences, as well. Although the goal is always to provide a safe environment for the users, safety levels should be based on an "as low as reasonable practical" risk principle. That is, when we make decisions we also need to take into account the cost of measures taken in relation to the benefit gained. Furthermore, the case study demonstrates that methods do not account for parameter variability and/or uncertainty and instead use standard normative provisions.

In the end of Chapter 6, the ***Ob.1.2:*** Simulate tunnel fire accidents, is fulfilled.

Initially, the role of risk assessment in tunnel fire safety is indicated (see section 7.1). Although most QRA methods follow the deterministic paradigm, risk assessment regarding DGs is based on a stochastic approach having as central point the aversion of the potential fire causes (usually through DGs access restrictions). This strategy is followed as the nature of accidents involving DGs makes it difficult to effectively intervene after the accident's outbreak to reduce their consequences. Therefore, the methods' outputs dealing with DGs, i.e. the OECD/PIARC QRA model, which is the most widely accepted risk assessment method for treating DGs in tunnels, consider probabilities to select which DGs access should be excluded.

Contrary to the DGs approach, the risk assessment methods for non-DGs related fires follow a deterministic approach. However, the main drawback of such an approach is that it gives accurate results if the exact values of the system parameters are known. Existing data about such fires though, especially data related to the human factor, are often deficient and this is why fire scenarios are stipulated by the methods (see Chapter 3) and by the national requirements (see Chapter 6).

However, the tunnel system includes many parameters that relate to human behaviour like the time needed by the user to start the evacuation or the time required from the control room supervising the tunnel to react in case of fire accident and activate the traffic interruption as well as the mechanical ventilation. The uncertainty related to the traffic conditions or the environmental conditions has also a significant impact on the evolution of fire affecting the backlayering and, thus, the evacuation process. Faced with these uncertainties, safety analysts make assumptions adopting a ‘mean’ value or a worst case scenario. But, the variation to reality because of these assumptions can create serious fallacies regarding the estimated level of tunnel safety. To this respect, the presented research endeavour proposes a novel QRA method, named SIREN (see Figure 7.1), which is based on a stochastic approach. The proposed method takes into account the parameters of the tunnel system that present considerable uncertainties (see Figure 7.3), and thus, estimates the level of the tunnel safety more accurately. By doing so, it mitigates the fallacies arising from the traditional deterministic methods.

In brief, the proposed method is implemented in a typical urban underground road tunnel conforming to both the European and Greek requirements (see sections 7.5 & 7.6). The stochastic approach is conducted after identifying the stochastic parameters of the system. Subsequently, a MCS is employed based on the specified probability distributions of these parameters. One-dimensional simulations are conducted for the estimation of tunnel airflows and the trapped-users’ evacuation process. The one-dimensional analysis is employed since the evacuation direction in tunnel fires is predominately limited to one dimension because of the large length-to-width ratio of tunnel geometry. The worst case scenario is examined, which includes a fire involving from a HGV in the middle of the tunnel during rush hour carrying-out.

Having conducted 500 simulations, the outcome highlights a significant proportion of scenarios that exceeds the losses estimated by the traditional deterministic methods (see Figure 7.10). The resulting distribution of losses illustrates that 186 scenarios of the 500 or 37.2% of the set result in higher number of losses comparing to the losses of the reference scenario. Furthermore, approximately 10% of the scenarios have two-fold or more increase in total losses, which can be extended up to 48 losses for the 1.5% of the scenarios. Furthermore, the conducted sensitivity analysis, which examines parameters' criticality, reveals that amongst stochastic parameters that the analyst can change to increase safety, the operation of mechanical ventilation appears to have the most potential in preventing losses. Thus, by re-designing ventilation's operation both in normal and emergency situation, and carrying-out a new set of simulations, a significant reduction of potential losses occurs with approximately 83% of new scenarios to be estimated without any losses (see Figure 7.10). However, further actions might require a decision at the highest level as safety levels should be based on an "as low as reasonable practical" risk principle. The validation of the method (see section 7.7) justifies its accuracy.

In the end of Chapter 7, the ***Ob.2.2:*** Synthesise relevant data and develop an evacuation simulation model and the ***Ob.3.3a:*** Develop a novel risk assessment method are fulfilled.

9.1.3 Phase 3

In Chapter 8 a new method, named EVADE, in order to support the decision-making process towards the selection of fire safety measures for road tunnels is presented (see Figure 8.2). The method aims to enable analysts to both evaluate and prioritise additional to standard fire safety measures, when appropriate. This method can be used either in addition to the SIREN method or independently. In general, the selection of additional to standard measures relies mainly on risk assessment results and is accomplished based on strictly determined regulations requirements. Thus, risk analysis results are associated with certain solution sets avoiding to weight alternative solutions (see section 3.3). As a result, the selection process can lead to either serious fallacies or might not meet the required level of safety of the individual tunnel system.

Initially, the proposed method focuses on integrating the requirements of all the system's stakeholders (Figure 8.1), namely the tunnel manager, the users, the regulatory requirements, and the possible safety solutions, along with the risk analysis results (see section 8.1). To synthesise the aforementioned views, a combination of two well-known methods the AHP and the MCS is employed. The AHP requires from decision-makers to make pairwise comparisons amongst all pairs of decision criteria as well as alternatives in a ratio scale. Therefore, it creates the ground for a consistent assessment of the alternatives ensuring concurrently that the ratio scale is self-consistent. However, each decision-maker may interpret the requirements of each stakeholder in a different way. Besides, the amount of the available information as well as the way of understanding the problem are also factors that can affect the comparisons. To address these issues, MCS is used. By applying the MCS, the ranking of alternatives is considered reliable since it includes potential uncertainty related to the pairwise comparisons amongst all pairs of decision criteria as well as alternatives. Hence, the proposed method supports the analyst(s) to estimate the level of safety of each measure, and select the appropriate measure(s) that indeed enhance(s) the level of safety of the tunnel system.

An illustrative case is examined to present the utilisation of the EVADE method. A typical TERN tunnel that belongs to the Greek national motorway is selected, which meets all the Directive 54/2004/EC’s requirements. The case of fire accident without involvement of dangerous goods is examined. The examined scenario comprises a fire accident sparking from a heavy goods vehicle without dangerous goods involvement having a standardised source term of maximum heat release rate equal to 100MW. Comparing alternative measures’ effectiveness depicted in Table 8.2, which traditional deterministic approaches take into account, Figure’s 8.4 results, which presents a single iteration of the process, and the results of Figure 8.5, which accounts for the EVADE approach, a significant difference regarding the ranking of the measures arise. This difference can affect the level of safety of the tunnel. Furthermore, it should be mentioned that the proposed method is especially valuable when no clearly dominant alternative exists as shown in Figure 8.6 and 8.7 of the presented illustrative case. The validation of the method (see sections 7.7 & 8.4) justifies its accuracy.

In the end of Chapter 8, the ***Ob.3.2:*** Analyse the decision-making processes for selecting safety measures and the ***Ob.3.3b:*** Develop a novel risk assessment method are fulfilled.

9.2 Contribution to the body of knowledge

The review of the literature indicates that important parameters for the safe operation of road tunnel systems have significant uncertainty. These parameters include: (a) the traffic, (b) the trapped-users behaviour during evacuation, (c) the response of the tunnel personnel in activating the mechanical ventilation or the traffic interruption, (d) the fire behaviour and (e) the environmental conditions. Although these parameters play a key role in tunnel performance, current methods act on a deterministic approach ignoring thus their embedded uncertainties.

This thesis proposes a novel quantitative risk assessment method, named SIREN, aiming at enhancing road tunnel fire safety. The proposed SIREN method by applying a stochastic-based approach addresses this weakness. As a result, it reveals the actual level of safety of the underground system, assisting, thus, decision-making process in choosing additional measures focused exactly on the systems' vulnerabilities and increases the tunnel's level of safety to as low as reasonable practicable.

Furthermore, the SIREN method is based on the unique characteristics of the tunnel system taking into account the variability and uncertainty of the system's stochastic parameters. Therefore, it can be applied to any type of road tunnel.

The method is illustrated through the case of an urban underground road tunnel during rush hour. Because underground road tunnels bear daily high traffic volumes, they are regarded as one of the most critical and complex infrastructure systems for the daily operation of modern urban networks. To this respect, the proposed method is implemented in a typical urban underground road tunnel conforming to both the European and Greek requirements. The outcome highlights a significant proportion of scenarios that exceed the number of losses estimated by the traditional methods. Furthermore, the proposed method offers the possibility of examining the parameters' criticality, which assists safety analysts in choosing additional safety measures, if needed. In this way, the tunnel's level of safety is increased to as low as reasonable practicable.

This thesis proposes also the EVADE method. As mentioned in section 3.3, despite the significant progress in developing robust risk analysis techniques and models, current methods exhibit limited progress regarding the link of risk assessment with the selection of additional to standard safety measures, when indicated by risk analysis. Commonly, measures' selection relies mainly on strict regulatory requirements. However, the choice of specific measures should also be based on many different criteria and ranking of alternatives should take place.

With this respect, measures' selection can be misled. Potential problems that can emerge during measures' selection could be that:

(1) The safety analyst may not include all the relevant decision criteria resulting, thus, in arbitrary decisions.

(2) Despite the unique characteristics each road tunnel exhibits, the safety analyst may give more than expected preference on the minimum requirements imposed by legislation, and selecting, thus, “standardised” safety measures.

(3) The safety analyst may not evaluate alternative measures on a stated subjective preference.

Therefore, the main advantage of the EVADE method is that it provides a systematic decision process through the use of particular and consistent decision criteria, together with considerations of alternative safety measures which are based on the stated subjective preferences of the decision-maker. Thus, the proposed method protects the safety analyst from the adoption of arbitrary decisions.

Meanwhile, by applying the Monte Carlo simulation, the ranking of alternatives is considered reliable since it includes potential uncertainty related to the pairwise comparisons amongst all pairs of decision criteria as well as alternatives. Contrary to current approaches, the alternatives’ ranking comes as a distribution instead of a single number providing the decision-maker richer information for selecting the most suitable measure(s) according to the specific tunnel’s situation. The utilisation of the proposed EVADE method is presented through an illustrative case of a typical European tunnel.

9.3 Practical implications

Traditional risk assessment methods often apply QRA models using only deterministic values even though these are mean values of stochastic parameters imposed by regulations. Therefore, the uncertainty embedded in significant parameters for the safety of each tunnel system, is not taken into account during the analysis. Often, a sensitivity analysis fills this gap by examining a limited number of scenarios based on either expert judgment, common best practice or imposed requirements.

As a result, significant problems arise when tunnel managers and safety analysts try to find the combination of the right measures to achieve the required safety level of the system. However, taking into account the stochastic-based approach presented in the proposed SIREN method, a more representative view of the variability of the safety level of the tunnel occurs, which is evident through the density and cumulative diagrams of losses. Having estimated this distribution, the criticality of parameters is tested. Thus, targeted measure(s) are taken in order to fix the situation reducing the parameters' variability and their uncertainty in safety-acceptable levels.

Furthermore, a general discussion arises regarding the resulting risk reduction when additional measures are applied. Risk evaluation is the very next step of risk analysis in the framework of risk assessment process according to both the ISO 31000 and PIARC (2013). During the risk evaluation step and in order to assess the acceptability of the risk estimated in the previous risk analysis step, some definite risk criteria must be determined against which the comparison can be made. These risk criteria could be classified in two major groups: (a) the absolute criteria and (b) the relevant criteria. The evaluation strategy against absolute risk criteria requires well-established thresholds or distinct risk targets which will determine the maximum estimated risks. On the other hand, relevant criteria need a standardised reference risk target to comply with all guidelines and standards. The kind of criteria to be used should not be arbitrarily selected but should rather stem from the selected risk evaluation strategy, which strongly depends on the selected risk analysis framework.

All the aforementioned approaches have many endogenous problems such as the uncertainty and the lack of sufficient accident databases which could lead to misleading results. Also, in cases of scenario-based approaches usually only prescriptive-based criteria are implemented.

This gap is fulfilled through the EVADE method, which incorporates diverse stakeholders' views while it introduces a list of the most significant criteria that are valuable to judge the appropriateness of selected measures. The main advantage of the EVADE method is that it provides a systematic decision process through the use of particular and consistent decision criteria, together with considerations of alternative safety measures which are based on the stated subjective preferences of the decision-maker. As a result, the outcome of the EVADE method illustrates the ranking of the potential fire safety measures, which comes as a distribution instead of a single number (which is used in current approaches), providing the decision-maker better information for selecting the most suitable measure(s) according to the specific tunnel's situation.

9.4 Limitations

With respect to existing limitations, SIREN and EVADE methods are based on the knowledge of the stochastic behaviour of tunnel system parameters, the one and on the knowledge of the experts opinion the other. However, determining the parameters' attributes is not always an easy task as often there is a lack of data (e.g. for new tunnels). Moreover, there are also limitations regarding the CFD models (see section 5.4.2). To this respect, the analysis shows that either increasing the AADT or increasing the percentage of HGVs or diminishing the time when traffic interruptions close the traffic, ameliorates the results. However, even though this could be acceptable in order to enhance the piston effect and as a result reduce backlayering length, from a system safety perspective, it would be unacceptable to leave the tunnel in operation since more users would be trapped near to the fire location. The studies on users' behavior have already illustrated that this can be disastrous. Furthermore, due to the potential technological constrains or because the cost-benefit ratio becomes gross disproportionate or due to the unpredictable human behavior under emergency situations, the safety analyst should act on the ALARP principle. Both methods method help the analyst to act on this principle. The proposed methods do not provide a decision for the safety analyst rather they supports him to come up with one.

The EVADE method includes some limitations. Initially, it does not provide the decision-maker with the potential set of alternative safety measures to be compared. This choice is allowed to the judgment of the decision-maker formed based on the risk assessment results, the regulative requirements and his previous experience. Another limitation of the proposed method is the parameter of the subjectivity of the decision-maker regarding the development of the priority scale. Unavoidably, since decision-makers are allowed to interpret the stakeholders' different views, they express their opinion. Furthermore, they have to deal with the unique particularities each tunnel system includes, and which the regulatory requirements cannot always make provision for.

9.5 Areas for further research

Apart from the direct implication to practitioners (these being the safety analysts) this research is also contributing to academic research in the sense that it opens the way of a different paradigm in road tunnel risk analysis that improves the realistic modelling of safety critical situations. It also puts forward a research agenda towards the same direction. Potential forthcoming research agenda includes the trapped-users' pre-evacuation behaviour and the estimation of walking speeds. For the first part, the contribution of academia by conducting experiments and the authorities by conducting information campaigns is valuable. Also, special population groups such as disabled users must be examined further. Regarding the CFD models, the fallacies created from the piston effect is another area to be further examined. On top of those suggestions, priority also exists in the development of relevant software to handle SIREN and EVADE or relevant methods' calculations. The MCS can be a tedious work and bridge software that will automatically take the results of CFD software to feed the evacuation modelling software should be built.

Another important issue is the detailed listing of suitable ALARP criteria that can be an important field for further research.

Finally, the proposed SIREN and EVADE method comes to confirm that further effort is needed by policymakers and practitioners for a cohesive risk analysis without limiting the flexibility of the selected approaches and methods. Chapter 6 showcases the potential difficulties that exist due to the lack of harmonised principles.

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Appendix 1: Evacuation simulation model

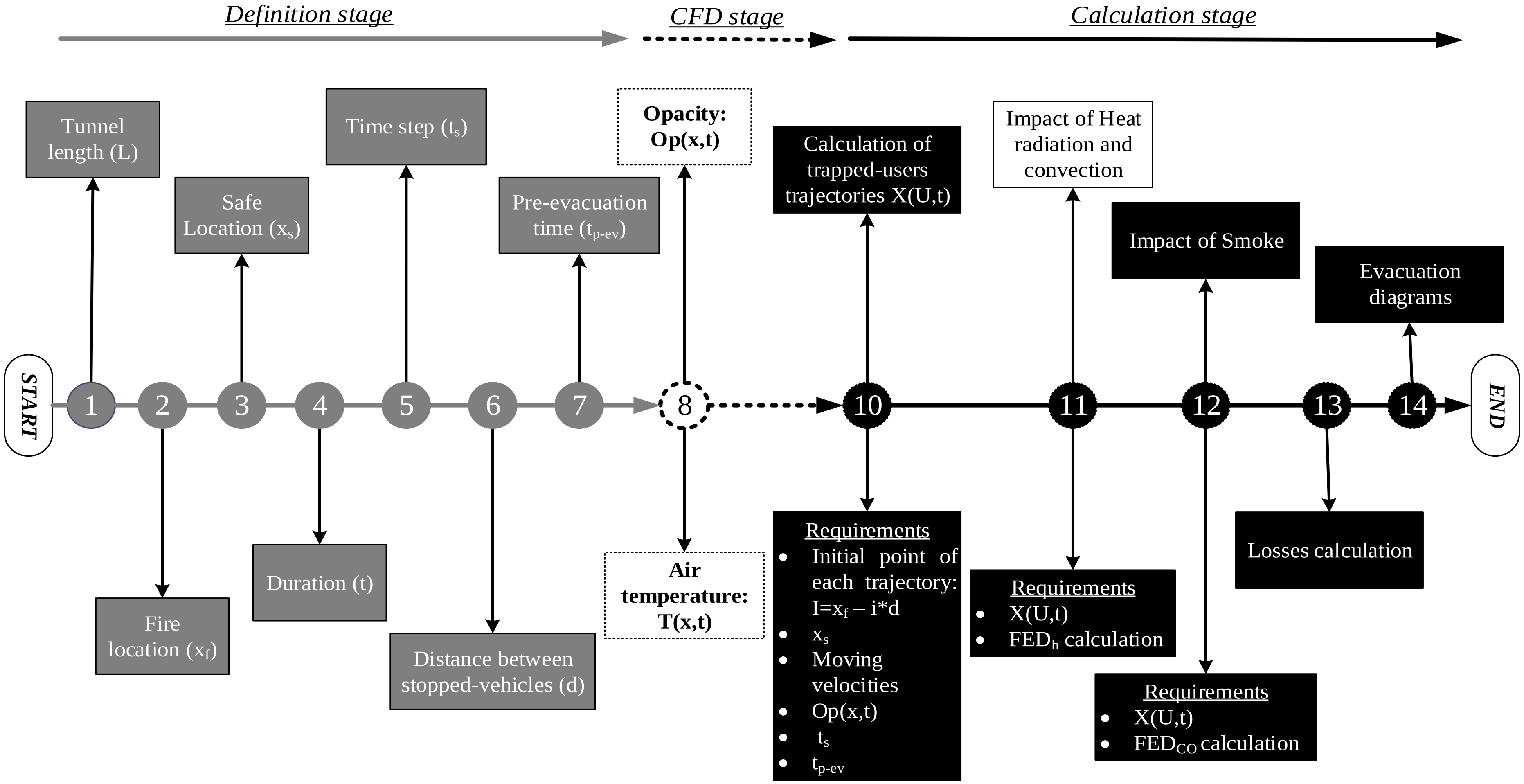

Figure A1: Flowchart of the evacuation simulation model