Review Article

Evaluating the role of risk assessment for road tunnel fire safety: A comparative review within the EU

Panagiotis Ntzeremes a, *, Konstantinos Kirytopoulos b

a School of Mechanical Engineering, National Technical University of Athens, Athens 15780, Greece
b School of Natural and Built Environments, University of South Australia, Adelaide, South Australia 5001, Australia

HIGHLIGHTS

• Fire is the foremost critical event for road tunnels’ safety.
• The role of risk assessment within the EU is evaluated.
• Questions about the level of the harmonisation of the framework are raised.
• The deficiencies and limitations of the methods are uncovered.
• Problems affecting the estimated level of safety are identified and discussed.

ARTICLE INFO

Article history:
Received 16 July 2018
Received in revised form 22 October 2018
Accepted 24 October 2018
Available online 3 April 2019

Keywords:
Road tunnel
Safety
Fire
Risk assessment

ABSTRACT

Fire is the foremost critical event for road tunnels’ safety. Therefore, the European Commission introduced the Directive 2004/54/EC for enhancing tunnels’ safety since they constitute a key element of the Trans-European Road Network. The Directive has established a common ground for tunnels’ safety evaluation providing certain minimum requirements while introducing officially the use of risk assessment. Despite the significant progress, this paper illustrates that further efforts are needed. Through a comparative review of the risk assessment methods, questions about the level of harmonisation of the framework are raised. Moreover, considerable problems are highlighted, like the incorporation of the new trends emerging from the literature or the deficiencies on addressing significant issues of the analysis, such as the risk acceptance criteria and the behaviour of trapped-users. These problems can affect the risk assessment process causing both significant discrepancies and deficiencies at the estimated level of tunnels’ safety. Uncovering, thus, the deficiencies and limitations of the methods, this paper contributes to i) the discourse for initiating relevant studies to enhance tunnels’ fire safety in Europe and worldwide, and ii) the harmonisation of risk assessment methods.

© 2019 Periodical Offices of Chang'an University. Publishing services by Elsevier B.V. on behalf of Owner. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
1. Introduction

Road transport is regarded as a fundamental factor in strengthening the European cohesion. Providing a high level of flexibility in linking all the regions of the European Union (EU), it can enable both the internal and the external market boosting EU’s economic growth. Meanwhile, road transport can enable the freedom for people to travel at 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 CO₂ emissions (EC, 2017c), the European Commission and the Council (EC) established the Trans-European Road Network (TERN) in the mid 90s (EC, 1993). TERN consists of all the member states’ motorways that connect Europe between West and East, North and South and it is estimated to encompass 90,000 km 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. In particular, the transport of goods was estimated 3524 billion ton per kilometer during 2016 while 49% of them were transported by road. Meanwhile, the transport of passengers was estimated 6591 billion people per kilometer with 72.38% of which were transported by road. Furthermore, the official reports project that road transport will continue to rise this share in the forthcoming future (EC, 2016). These numbers indicate that TERN should guarantee a high level of safety to the public. However, the goal for enhancing the overall level of TERN 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 amongst the member states.

The recent EU White Paper on transport has named infrastructure as the decisive factor that shapes mobility in TERN 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 TERNs infrastructure (Beard and Cope, 2008). However, their use emerges an endogenous problem that is the severity of potential accidents. Fire accidents especially can cause extremely adverse effects in regard to human losses and destruction of tunnel equipment and infrastructure (Caliendo et al., 2012). Therefore, EC reformed the legislation by issuing the Directive 2004/54/EC (EC, 2004). The Directive dictated that each TERN tunnel should provide the safety documentation at design, commissioning and operation stage. In addition, the tunnel manager and the emergency services have the obligation, in cooperation with the safety officer, to regularly renew safety documentation through organising joint periodic exercises for tunnel staff and the emergency services. Directive’s ultimate goal was to contribute to a higher standard level of safety for all the TERN tunnels longer than 500 m, by providing both a common context and framework. Responding to the Directive’s provisions, each member state has included in its regulation the risk assessment, along with the Directive’s minimum infrastructure and equipment requirements.

Despite the significant progress regarding the risk assessment frameworks and due to the tunnel system’s complexity, it is not sufficient whether just applying any risk assessment method is capable of ensuring preparedness against a fire accident. However, the better the planning and risk assessment methods, the better the preparedness level is going to be. Comparing the member states methods based on a critical review of the literature, potential problems are identified. These problems can affect the risk assessment process causing both significant discrepancies and deficiencies at the estimated level of safety of the TERN tunnels. Meanwhile, the level of harmonisation of the risk assessment frameworks also emerges. Uncovering, thus, the deficiencies and limitations of the methods, the aim of this paper is to contribute to i) the discourse for initiating relevant studies to enhance tunnels’ fire safety in Europe and worldwide, and ii) the harmonisation of risk assessment methods.

In order to reach the aforementioned aim, the rest of this paper is organised as follows. Section 2 seeks to outline the current fire safety approach within the EU. Therefore, at first, the criticality of road tunnels is illustrated through examining the potential severity of fire accidents in tunnels. Afterwards, the rationale that leads to the change in safety approach for tunnels and, as a result, to the introduction of risk assessment in the field of road tunnel is described. In particular, the risk assessment framework in use is presented, as well as its challenges for policy-makers, tunnel managers and safety analysts. Presenting the evolution of tunnel kilometres as well as the recorded accidents since the launch of the Directive 2004/54/EC, section 3 provides an overview of the selected EU risk assessment methods while a critical evaluation is performed. To do so, the selected methods are examined linked with the basic steps of the risk assessment. This approach facilitates the comparative review to reveal how each method addresses significant issues of the analysis enabling thus crucial themes, paradigms and research opportunities to emerge, based on the identified gaps. Finally, section 4 concludes a specific research agenda.

2. Tunnel fire safety within the EU

2.1. Fire in tunnels

Tunnels are the most sophisticated elements of the road infrastructure (PIARC, 2016a, 2017b). 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. Tunnels’ importance relates to the fact that they enable crossing mountainous areas and creating short traffic connections minimising simultaneously the environmental impact, the time and the transportation costs. Their underground utilisation improves transportation flow, as well as atmospheric and acoustic environment of densely populated urban areas by relieving them from the congestion and pollution that this entails (Maidi et al., 2014). Due to the improvement of underground space technology, tunnels have been rendered as a cost-effective engineering
solution in developing new road networks (Kaliampakos et al., 2016). Therefore, their number is increasing augmenting thus the number of people and the volume of goods passing through them (EC, 2016; Meng and Qu, 2012).

Potential dysfunction of a tunnel can cause serious dysfunction on the broader road network due to its interdependencies (Zhuang et al., 2009). Given the long period of dysfunction along with significant life loss criterion occurred in fire accidents, road tunnels are reasonable 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). Disastrous fire accidents such as the one happened in Mont Blanc, the one in the boarders between France and Italy (1999; 39 fatalities), the one in Frejus in France (2005; 2 fatalities and 21 injuries) and the one 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. Tunnels exhibit (a) no physical light passing through them, which makes difficult for drivers to adjust when passing through (Domenichini et al., 2017; Kirytopoulos et al., 2017; Yeung et al., 2013) (b) arranged air movement due to the pressure difference between tunnel portals, which can complicate ventilation’s operation (Krol et al., 2017) (c) difficulties in approaching and rescuing users (Ronchi et al., 2013), and (d) fire combustion irregularity (Beard and Carvel, 2012; Ingason, 2008). Nevertheless, it is difficult to present the design of fire behaviour in a unique way since it is affected by the different behaviour of the burning materials (Hansen and Inganson, 2011). Furthermore, each tunnel is unique. It differs by type (uni- or bi-directional), length, width, method of construction, and type of traffic, i.e., whether dangerous goods (DGs) transportation is allowed. All these parameters affect the evolution of fire and, thus, the required safety strategy (Caliendo and De Guglielmo, 2017; Ronchi et al., 2018). Methods for calculating fire behaviour in tunnels are in progress until today (Caliendo et al., 2012; Hansen and Inganson, 2011; Ingason, 2008; 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 fire and tunnel environment (Ntzeremes and Kirytopoulos, 2018b). Conducted studies that examined the fire combustion in tunnels have observed that the heat feedback in those 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 fires in tunnels could have its maximum heat release rate (HRRmax) up to four times higher compared to the same open road fires. In parallel, heavy amount of heat is transferred to the vicinity of fire and to an extended tunnel area. The released amount of heat results from both radiation by approximately 33% of HRR, and convection between hot air and various objects or tunnel ceilings by approximately 67% of the HRR. Furthermore, there is also the risk of explosion especially when DGs are involved (INERIS, 2005). As a result, 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, which result in the development of the well-known backlayering phenomenon. Backlayering expands the smoke environment upstream the fire location considerably enclosing thus the users trying to escape in smoke (Caliendo et al., 2012). Recent studies have examined the impact of smoke environment on users’ movement, in order to provide valuable information for designing an adequate safety strategy (Ntzeremes and Kirytopoulos, 2018a; Ronchi et al., 2018; Seike et al., 2016, 2017).

2.2. The rationale behind the change in safety approach

2.2.1. From established conditions to the trigger event

The trigger events that cause the policy-makers, the safety analysts and the European 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; Beard and Carvel, 2012; Voeltzel and Dix, 2004). 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; Kirytopoulos et al., 2017). These tragedies came just to remind that fire safety of tunnel systems has unavoidably become a complex issue (PIARC, 2016a).

Surely, the benefit of using prescriptive requirements lies in the simplicity of their use during the execution of the tunnel safety checks. The introduction of Directive (2004)/54/EC has established a common context by introducing a minimum body of infrastructure and equipment prescriptive requirements, which each TERN tunnel has to comply with.

However, the literature still indicates that even when the design is in accordance with the minimum 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. On the other hand,
Kirytopoulos et al. (2010), examined a TERN tunnel that is in line with Directive’s normative provisions regarding minimum requirements, however, their evaluation indicates that the level of safety can be below the specified limit and further measures should be adopted. Similar results have been reported in Bjelland and Aven (2013), where tunnel’s special features do not allow or do not guarantee an acceptable level of safety only by applying the Directive’s explicitly stated minimum requirements. This is why the Directive provision cases where additional risk analysis should be conducted.

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; EUROTOP, 2005–2007 projects investigated the operation of each tunnel system element, and predominantly in case of fire. A brief report of them is presented in PIARC (2007). Originally, these projects created the basis for the safety approach to start working based on the holistic notion of the tunnel system safety. In particular, the UPTUN and Safe-T projects reported a total number of 34 basic system parameters that affect tunnels’ safety. Grouping these parameters, results in a set of four basic elements, which form the safety ground of road tunnel system. These elements 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 users and (d) the facilities (PIARC, 2007). In particular, the first project, the tunnel system safe begins in the design process (Caputo 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 vehicles have different behaviours during their evacuation process (Kirytopoulos et al., 2017; Ntzzeremes 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 vehicules have different behaviours during their evacuation process (Kirytopoulos et al., 2017; Ntzzeremes and Kirytopoulos, 2018a; Ronchi et al., 2018).

Studies have shown that traffic plays a key role on the piston effect, which subsequently 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 process (Kirytopoulos et al., 2017; Ntzzeremes 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 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 generic concept of the risk-based approach

Without any doubt, the responsibility of making the road tunnel system safe begins in the design process (Caputo et al., 2013). However, tunnel system in the operation phase is subjected to uncertain changes (Ntzzeremes 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). 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), for nuclear installations (Garrick and Christie, 2002), offshore oil and gas platforms (Vinnem, 1998), as well as in the construction industry (Taroun, 2014). Given the deficiencies in prescriptive requirements, the use of risk assessment in road tunnels is recognised as the systematic approach to follow for facilitating the examination of specific accidents and the observation of possible residual risks while accounting for their intrinsic attributes (Beard and Carvel, 2012; Bjelland and Aven, 2013). 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 World Road Association formerly named PIARC (PIARC, 2007, 2008), as well as the terminology founded in existing risk assessment methods (Beard and Carvel, 2012; Kazaras and Krytopoulos, 2013; Ntzeremes and Krytopoulos, 2018b; Seike et al., 2017) 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 or trigger event. A critical or trigger event is a malicious event that can cause immediate or delayed harm to the tunnel system. 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”. Thus, risk is calculated as a product of probability of occurrence, referred as exhibition, and the severity of consequences. Following this terminology, the risk assessment framework for road tunnels in operation is shown in Fig. 2, which basically represents the PIARC approach (PIARC, 2008). Due to the fact that all the member states are also PIARCs members, this approach has unavoidably prevailed in the road tunnel field. Its basic steps are as following.

1. Risk analysis: this step performs the systematic approach in order to identify the hazards and subsequently calculate the risks. However, risk analysis in tunnels does not address opportunities. Risk analysis is divided into three discrete sub-steps following a top to bottom sequence. Initially, the system definition recognises the tunnel system and specifies the goals of risk assessment, together with the criteria. Subsequently, the hazard identification follows to identify potential hazards that can affect the proper operation of the system contributing to the critical event. Finally, the risk estimation follows in which cause and consequence analysis is carried-out.

2. Risk evaluation: this step aims at determining whether estimated risks are acceptable when compared to the predefined constraints, the so-called risk criteria. However, it cannot be chosen arbitrarily since it strongly relies upon the applied risk analysis method.

3. 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 the total 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. Finishing the risk treatment step, a new round of the process is conducted to re-evaluate the new situation.

However, the above framework is slightly differentiated from the general ISO standard (ISO, 2015) since the ISO risk assessment incorporates both risk analysis and risk evaluation but not risk treatment which is another process.

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, the Directive suggested that the content and the results of the risk analysis shall be included in the safety documentation submitted to each member state’s Administrative Authority without proceeding further on this issue (EC, 2004). 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 paper aims at assessing how each method addresses all these as well as evaluates them with the current literature. As a result, a common body of principles can be formed, on which every risk assessment method should rely upon. Nevertheless, this common body should not limit each method’s flexibility to address each member state’s interests (PIARC, 2008). Certainly, each member state has to develop its own method according to its own interests (Fabbri and Contini, 2009). Subsequently, crucial themes, paradigms and research opportunities based on identified gaps can emerge, which can be used from policy-makers, tunnel managers and safety analysts in order to initiate relevant studies.
3. Comparative analysis and discussion

3.1. Concept and components

The database “EUR-Lex” (EUR-Lex, 2018) search indicates that apart from the Directive 54/2004/EC (EC, 2004) no further addition in the legislation has been made.

Servicing the review aim, six risk assessment methods are selected and examined. These methods are: the Austrian (ASFiNAG, 2008; RVS, 2008), the French (CETU, 2003, 2005), the German (BASt/BMVBS, 2010), the Greek (AAT, 2011a, b), the Dutch (RWS, 2006) and the Italian (ANAS, 2009) risk assessment method (INERIS, 2005; PIARC, 2008, 2013). These methods are selected either because they are related to member states which have a large number of tunnels longer than 500 m and/or a considerable background in road infrastructure safety.

Fig. 3 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 (Lotsberg, 2016; NTUA, 2013). It also depicts the projected increase of road tunnels for the coming years. A significant point of Fig. 3 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 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.

Fig. 4 indicates the tunnel accidents recorded in these member states until 2010 according to a study conducted by the department of mechanical engineering of the National Technical University of Athens (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). Another important aspect is that the rapid increase of the tunnels, should not allow complacency, especially, for member states like Greece, which quite recently have constructed tunnels in its national motorways (Benekos and Diamantidis, 2017), 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 (Fig. 2), 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 (Fig. 1), since they affect the level of safety of the tunnel system, without providing further details on this issue.

Fig. 3 – Evolution of tunnel meters per member state.

Fig. 4 – Overview of human losses in tunnel accidents per member state.
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.

According to the ADR agreement (UNECE, 2015), transported goods are separated between DGs and non-DGs. This division arises since each type requires different safety management. The consequences from accidents that involve DGs (i.e., fire behaviour, air pollution, number of users impacted) are far more serious when compared to those from accidents which do not involve DGs. Therefore, the consequences of accidents involving DGs are perceived at a social-impact scale whereas the consequences of 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 enabling thus the users’ evacuation process.

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. Contrary, qualitative methods involve qualitative or non-numeric data (i.e., expert judgment, risk matrix, checklists) and thus, they are more flexible and have lower complexity. Qualitative methods particularly can enable the analysts to better conceptualise 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 1.

Table 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.

The methods seem hitherto to frequently overlook the aspect of embedded uncertainty of the system parameters. Road tunnel system renders important for its safe operation parameters to exhibit significant uncertainty. Although these parameters play a key role in tunnel performance in case of fire accident, current methods act on a deterministic approach ignoring their embedded uncertainties (Ntzeremes and Kyrtoyopoulos, 2018a, b). The analysis comes up with parameters that their embedded uncertainty can manipulate the results of the risk assessment, manipulating, thus, the level of the tunnel safety. These parameters are: (a) the traffic (Caliendo and De Guglielmo, 2017), (b) the trapped-users behaviour during evacuation (Ntzeremes and Kyrtoyopoulos, 2018a, b), (c) the response of the tunnel personnel (Pribyl and Pribyl, 2017) in activating the mechanical ventilation or the traffic interruption (Kazaras et al., 2014), (d) the fire behaviour (Ntzeremes et al., 2016) and (e) the environmental conditions.

### 3.3. Critical evaluation and existing gaps

Subsequently, a deeper level of examination follows. This level aims at examining the methods linked with the basic steps of the risk assessment (Fig. 6). This approach facilitates the comparative review to reveal how each method addresses significant issues of the analysis.

#### 3.3.1. Risk analysis: theoretic approach and challenges

Prior to proceeding to the hazard identification step, it is essential to define the reference conditions of the tunnel system. Reference conditions specify the first goal of the risk assessment since they form the desired safe state that the tunnel system should adopt, being in line with the prescriptive requirements. Therefore, if potential deviations are identified, risk assessment should be carried forward. However, the analysis indicates that there are different approaches regarding the definition of reference conditions amongst methods. Although some methods (e.g., SAM/Greece and RWS/The Netherlands) determine as reference conditions, those for which the tunnel system simply complies with the prerequisites of the Directive 2004/54/EC, the reference conditions in other methods (e.g., SHI/France and BASt/Germany) are determined based on the compliance of the tunnel system with both the Directive’s and, additionally, the national provisions, which of course do not include the same specifications. Discrepancies of reference conditions can lead to different deviations. As a result, different additional measures would be proposed, which would lead to either potentially unnecessary increased expenses for the tunnel or a safety gap since the desired safe state for the tunnel system would not always be the same for all the TERN tunnels.

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
The 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 (Høj and Kröger, 2002). To do so, risk analysis bases on the bow-tie model. Through the bow-tie model, risk analysis focuses primarily on identifying potential hazards that 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. To do so, computational fluid dynamics (CFD) analysis along with evacuation models or event tree analysis are predominately employed (Beard and Carvel, 2012; Kuligowski, 2013). However, examining the methods structure, it is shown that risk analysis in many methods is limited mainly in examining only those fire scenarios that are imposed by each member state. 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 addition to 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’s (2016) study 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 vulnerabilities and to prevent accidents and losses.

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 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). OECD/PIARC QRA model consists of spreadsheet-based tools which examines 13 standardised fire scenarios or more if needed, concerning potential DG and accident categories by providing evaluation of their consequences. The model focuses on calculating the relevant probabilities of those scenarios (Benekos and 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. Although probability analysis is the most common tool especially in DGs, 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 analysis.

### Table 1 – Overview of the methods.

<table>
<thead>
<tr>
<th>Member state</th>
<th>Name of the method</th>
<th>Type of risk approach</th>
<th>Type of transported goods</th>
<th>Type of method used</th>
<th>Year of publication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>TuRiMo</td>
<td>System-based</td>
<td>Non-dangerous goods</td>
<td>Quantitative</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>OECD/PIARC QRA</td>
<td>System-based</td>
<td>Dangerous goods</td>
<td>Quantitative</td>
<td>2007</td>
</tr>
<tr>
<td>France</td>
<td>SHI</td>
<td>Scenario-based</td>
<td>Non-dangerous goods</td>
<td>Quantitative</td>
<td>2003</td>
</tr>
<tr>
<td></td>
<td>OECD/PIARC QRA</td>
<td>System-based</td>
<td>Dangerous goods</td>
<td>Quantitative</td>
<td>2005</td>
</tr>
<tr>
<td>Germany</td>
<td>BASt</td>
<td>Scenario-based</td>
<td>Non-dangerous goods</td>
<td>Quantitative</td>
<td>2006</td>
</tr>
<tr>
<td></td>
<td>OECD/PIARC QRA</td>
<td>System-based</td>
<td>Dangerous goods</td>
<td>Quantitative</td>
<td>2010</td>
</tr>
<tr>
<td>Greece</td>
<td>SAM</td>
<td>Scenario-based</td>
<td>Non-dangerous goods</td>
<td>Quantitative</td>
<td>2011</td>
</tr>
<tr>
<td></td>
<td>OECD/PIARC QRA</td>
<td>System-based</td>
<td>Dangerous goods</td>
<td>Quantitative</td>
<td>2011</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>DSA</td>
<td>Scenario-based</td>
<td>Both types of goods</td>
<td>Qualitative</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>RWS</td>
<td>System-based</td>
<td>Dangerous goods</td>
<td>Quantitative</td>
<td>2008</td>
</tr>
<tr>
<td>Italy</td>
<td>IRA</td>
<td>System-based</td>
<td>Both types of goods</td>
<td>Quantitative</td>
<td>2009</td>
</tr>
</tbody>
</table>
concerns. But, since the road network has been unified tunnel hazards and the attached risks according to its centre). The problem is well-known (Amundsen, 1994; would affect the behaviour of fire (e.g., entrances and insights about the criticality of the fire incident and how this solution could be the standardisation of certain fire (Ntzeremes and Kirytopoulos, 2018b). However, a potential risk outcome producing, thus, for the same fire scenario can also change drastically the evacuation process of trapped-users in 30 s instead of 2 min mechanical ventilation estimated in the second fire BASt method instead of HRRmax 100 MW required by the

Despite the importance of DGs, it is disputable if fires without involving DGs should be of lower importance or they should be underestimate when comparing with fires derive from DGs. In many cases, such as in the Gotthard fire accident, this fires without involving DGs can be equal to the fires that come from DGs in terms of disastrous consequences, if the appropriate preparedness is lack (Beard, 2009; Mühlberger et al., 2012). Although there is a level of harmonisation regarding DGs, different approaches are followed amongst member states regarding fires involving non-DGs, since there is not any provision regarding the examination of fire scenarios related to non-DGs. Therefore, each member state imposes different standardised fire scenarios. These fire scenarios 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 (2017a) provides a detailed catalogue about the different fire scenarios examined predominantly in each member state based on their maximum heat release rates. However, Ntzeremes et al.'s (2018) study showcases the significant divergence of the estimated level of safety in a road tunnel due to a different standardisation of the fire behaviour. Even if the same fire accident with the same HRRmax of 100 MW but with 5 min difference in reaching it, renders the tunnel inadequate from the safety perspective. Therefore, 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 HRRmax 50 MW required by the BAST method instead of HRRmax 100 MW 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 30 s instead of 2 min for the same fire scenario can also change drastically the risk outcome producing, thus, “manipulated” results (Ntzeremes and Krytopoulos, 2018b). 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 behaviour of fire (e.g., entrances and centre). The problem is well-known (Amundsen, 1994; Navestad and Meyer, 2014) but methods exhibit lack in dealing with. Definitely, every member state has to prioritise tunnel hazards and the attached risks according to its concerns. But, since the road network has been unified through TERN and concurrently, since various research projects (PIARC, 2007) (e.g., Safe-T) have shown that tunnel fires are significantly important for tunnel safety, and risk analysis should be based on even more harmonised basic principles.

Table 1 illustrates that quantitative risk analysis is predominantly employed as preferred type of method. Although quantitative risk analysis models have facilitated analysts to manage safety in many fields (Kontogiannis et al., 2000), it has been argued that their results should not form the sole basis for a rational risk-based decision making, since there are many items as well as aspects of the system that might not be well managed (Apostolakis, 2004). Concisely, the main challenges to the acceptance of quantitative risk analysis are the handle of human performance or the comprehension of potential failure modes that may be raised when software is employed to control safety critical systems. Therefore, the aid of the socio-technical approach and the recognition of multiple non-technical aspects in accidents’ occurrence seems inevitable to deal with the challenges arise form quantitative risk analysis models, particularly when the overall risk of complex socio-technical systems is required (Leveson, 2011). However, only the Dutch RWS method examines hazards (like organisational hazards) in a qualitative way. Due to potential disadvantages of the quantitative risk analysis models, the use of supplementary qualitative methods has also been proposed for road tunnels, such as the system theoretic model (Kazaras et al., 2012, 2014).

Another important factor that seems to be omitted in the process of risk analysis by the methods is the tunnel design. However, the geometry parameters of tunnel have a significant influence on the probability of accidents. To this respect, Directive 2004/54/EC simply mentions that risk analysis should always be carried-out if the slope of tunnel is above ±5%. Important findings have been reported in Bassan’s (2016) study, regarding the traffic safety aspects and design in road tunnels. He has indicated that not only gradient but also both the curvature and the tunnel length affect the potential crashes in tunnels (Bassan, 2015). The average number for crashes involving fire, although less frequent than other crashes, are significant due to their catastrophe potential. Indicatively, Bassan (2016) has reported that the average fire crash rate was found to be 32% of the total severe crash rate while another study from Norway has showcased that 21% of average vehicle fires derive from vehicle crashes (Navestad and Meyer, 2014). Other studies have particularly highlighted that the tunnel design affects accidents rates due to the inadequate lighting and signing conditions in tunnel portals or the lack of tunnel walls and ceilings in the interior zone to mitigate monotonous driving (Amundsen, 1994; Amundsen et al., 2001).

Apart from the influence of tunnel design on the probability of accidents, tunnel design is a crucial parameter for the severity of fire accidents, too. Tunnel design can strongly affect the fire development. Therefore, critical velocity and smoke development are affected. For instance, Wang et al. (2017) have studied how critical velocity and smoke movement are affected in curved tunnels by comparing numerical results from curved tunnels with straight tunnel fires. How tunnel geometry affects the HGV fire in curved hi-
directional tunnel was also investigated in the study of Caliendo et al. (2012). Since tunnel geometry affects fire development, tunnel facilities have to be designed accordingly, in order to ensure an adequate environment for tunnel users. In particular, tunnel geometry interacts with the required ventilation strategy (Barbato et al., 2014).

3.3.2. Risk evaluation: acceptance criteria and users’ role
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.

Risk criteria are divided into relative and absolute criteria (PIARC, 2013). Relative criteria are related with both the reference conditions and the different statistical databases, i.e., French, the Netherlands and Italy’s risk criteria rely on different databases. Although TERN is considered to have the same safety standards in all its parts, each region evaluates its part by using different criteria. And this is the case for both the relative and absolute criteria (DNV, 2014).

Initially, the transport of DGs throughout TERN is governed predominantly by the Directive 2008/68/EC (EC, 2008) and the ADR agreement (UNECE, 2015). Although these regulations should form an acceptable level of safety, each member state is able to apply additional safety requirements with respect to its own particularities. Therefore, potential inconsistencies can be produced, which can result in competitive disadvantages through the increases in cost for industries and operators or unequal protection against risk amongst member states (DNV, 2014).

In particular, the analysis for estimating risks deriving from DGs is based on the OECD/PIARC QRA model. The model results in F/N diagram, which is the basis for the evaluation of risk. Subsequently, either the expected value (EV) or the as low as reasonable practicable (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. Hence, the ALARP emerges since most of the times infinite time, effort and money can be spent in order to minimise or eliminate, if possible, the arisen risk. Therefore, it should not be understood only as a quantitative measure of benefit gained against harm/damage caused (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 report of 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 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 (Kirytopoulos et al., 2017; Seike et al., 2017). Knowledge about users’ behaviour enables the analysts to achieve the available safe egress time (ASET) to be greater than required safe egress time (RSET) (Kinateder et al., 2015; Kuligowski, 2013). 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 (Mühlberger et al., 2012). 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, b).

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 for managing their evacuation process with success. Additionally, evacuation behaviours were examined via the calculation, of, the users speed in a smoke-filled tunnel in Japan. Users’ speed is the primary factor for assessing measures’ performance (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 deficient level of users’ 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, fractional effective dose (FED) is an important tool for evaluating users’ performance regarding both temperature and pollutant concentrations. PIARC (1999) as well as conducted studies (Cha et al., 2012; Seike et al., 2016) can be valuable sources for this issue. However, only the SAM method employs FED, and only regarding temperature.
3.3.3. Risk treatment: selection process and measures’ optimisation

All the methods accomplish risk treatment through strictly determined regulative requirements and experts’ judgment, based on the evaluation results. However, the analysis reveals that apart from the effectiveness or loss reduction criterion, there are further criteria that should be taken into account. These criteria are the ease of implementation of the measure, its construction and operational cost and its embedded uncertainty (Borg et al., 2014). Uncertainty is related to two important issues. Initially, this criterion measures the ability of the measure to operate successfully. For instance, a sensitive device of a safety measure such as for example a jet-fan-array can be damaged by the high temperature near to the fire location and fail. As a result, this measure is considered to some degree unreliable. Secondly, this criterion also includes the capability of being used by the trapped-user or/and operational staff in the proper manner. For instance, the way the trapped-users would respond to the messages sent from loudspeakers, variable message signs or other notice equipment that assist their evacuation process (Wong et al., 2014).

Each method follows primarily the Directive’s provisions for defining the desired minimum body of measures the tunnel should adopt. However, a lack about the use of fixed fire fighting systems (FFFS) is observed. This measure is considered important for fire safety in countries outside the EU that have regularly used FFFS for decades, like Australia and Japan (PIARC, 2016b). Their use is not widespread because it is still recognised that FFFS may not be the most appropriate measure to adopt in all circumstances or in all locations. However, it has been indicated that where FFFS have been installed, they manage to minimise fire growth and to provide the desired effectiveness only if they have been activated in the early stages of a fire.

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. Although OECD PIARC QRA model checks whether drainage system exists, Klein et al. (2018) experiment proposes how this system can be designed to limit the size of the pool of liquid fuel.

Emergency exits are considered from methods as a potential, additional measure. Ronchi et al. (2016) performing a fire experiment examined particularly, how the different designs of emergency exits were evaluated in the smoke-filled section of the tunnel. The outcome indicated that their design regarding way-finding and exit choice was appropriate for the intended use. However, in order to increase their performance, they suggested that the emergency exits can be accompanied with both “information signs on the wall opposite to the exit, and a loudspeaker installation that can inform evacuees about the location of available exits”. In addition, Ronchi et al. (2016) investigated also the performance of variable message signs (VMS) as a way-finding aid for road tunnel emergency evacuations. The results demonstrate that VMS features enable emergency evacuation of users by providing the use of larger signs, the use of flashing lights and the combination of emergency exit pictorial symbol in green in one panel and text in amber in the other panel of the sign.

4. Conclusions and future research agenda

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 Fig. 4 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 policymakers and tunnel managers must not be complacent about the safety level in tunnels. Furthermore, some member states such as Greece, which have increased rapidly their tunnel kilometres during the last decade (Fig. 3), they have not any experience from previous fire accidents in order to handle potential disasters.

Through the Directive 2004/54/EC, risk assessment has been incorporated in the field of road tunnel safety on top of the minimum requirements regarding tunnel facilities and infrastructure. The outcome shows that risk assessment has already provided important contributions in supporting the enhancement of the level of tunnel fire safety in practice. Although tunnel kilometres have increased (Fig. 3), losses and injuries from accidents have declined (Fig. 4).

However, there are concerns whether the existing framework necessarily guarantees the required minimum level of fire safety for the TERN tunnels. The search in the EU-Lex database indicates that besides the Directive 2004/54/EC no further additions have been made. Thereby, the new advances in the field that would enhance tunnels’ level of safety (e.g., Fixed Fire Fighting Systems) are missing. Furthermore, it is not sufficient whether just applying any risk assessment method is capable of ensuring the required minimum level of fire safety for the TERN tunnels, uniformly, along all member states.

This review showcases primarily the significance of the different definition of the reference conditions. However, different reference conditions can lead to different deviations and, thus, a different level of safety would be estimated. As a result, different additional measures would be proposed, which could lead to either potentially unnecessary increased expenses for the tunnel or a safety gap since the desired safe state for the tunnel system will not always be the same for all the TERN tunnels.
Due to the tunnels’ complexity, 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.

Although quantitative risk analysis contribution to manage safety has been great, main challenges of the tunnel safety, like the treatment of human performance or the understanding of failure modes are often underestimated. It seems that potential supplementary aid of a socio-technical approach and the recognition of multiple non-technical aspects in accidents’ occurrence, may support safety analyst to capture the overall risk picture of complex socio-technical systems such as tunnels.

Experts make decisions based on risk acceptance criteria. However, they also need to take into account the cost of measures taken in relation to the benefit gained. There are cases in which very strict methods, in an attempt to secure absolute safety, employ a greater number of safety measures. These results in sometimes unnecessary increased expenses, with a minimal overall benefit to the safety of the tunnel or in safety gaps amongst the TERN tunnels. Further harmonisation on both the risk acceptance criteria and the selection of some common fire scenarios has to be carried out, so as to prevent these phenomena.

Another conclusion on risk treatment 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 that support decision-making process lack such multiple criteria and rankings of alternatives.

Users’ behaviour has the predominant role in tunnel safety. Although there are relevant studies, the examined methods include significant deficiencies. 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. Furthermore, a common body of principles is also needed regarding users’ perception as well as moving velocities. Because these are important aspects of human performance, the aforementioned problems can affect the risk assessment process causing both significant discrepancies and deficiencies at the estimated level of tunnels’ safety.

In conclusion, the necessity for the 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. Uncovering the deficiencies and limitations of the risk assessment methods within the EU, this paper provides policy-makers, tunnel managers and safety analysts with information for initiating relevant studies in order to enhance tunnels’ fire safety both in Europe and worldwide, and contributes to the harmonisation of risk assessment methods without limiting their flexibility.

**Conflict of interest**

The authors do not have any conflict of interest with other entities or researchers.

**Acknowledgments**

The authors would like to express their gratitude to the reviewers and the editors for both their time and the valuable comments provided that did improve the readability and contribution of the paper.

**References**


Leveson, N.G., 2011. Applying systems thinking to analyze and learn from events. Safety Science 49, 55–64.


Panagiotis Ntzeremes is a PhD candidate at the School of Mechanical Engineering, National Technical University of Athens (NTUA). He holds a diploma in mechanical engineering from NTUA with a specialisation in energy engineering. He is preparing his doctoral thesis in the field of risk management in the operation of road tunnels. He has experience in the development of mechanical technical projects and in particular has participated in the development of tunnels' hazard studies. He has also published work with papers in peer reviewed international conferences and journals in the field of tunnel risk management.

Konstantinos Kirytopoulos holds a diploma in mechanical engineering from the National Technical University of Athens (NTUA) and a PhD on risk management from NTUA. He is an associate professor at the School of Natural and Built Environments, University of South Australia, where he works on project and risk management. He has many years of experience in the field of risk management in road tunnels and has coordinated research programs on this area. He has participated in major risk management research and industry projects and has already published a significant amount of papers in peer reviewed journals and international conferences.