Exploring the effect of national policies on the safety level of tunnels that belong to the trans-European road network: a comparative analysis

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Abstract: The trans-European road network (TERN) was defined to improve EU road network guarantee users a high and uniform level of safety. TERNs tunnels must be designed to serve these purposes. To this respect, the EU introduced the Directive 2004/54/EC. The Directive imposed minimum infrastructure and equipment requirements for all TERNs tunnels attributing high importance to risk assessment method. This paper illustrates that the variety of the methods adopted by each member state do not guarantee the same level of safety for all TERNs tunnels. Presenting the general principles of EU methods, two methods, which share a high degree of similarity, are used to study the same fire accident at the same tunnel. The differences occurred in the estimated level of safety raises skepticism, as the tunnel has different safety level depending on the method and national policies used. The outcome illustrates the need to improve policy formulation on this matter.

Keywords: road network; transportation; road tunnel; Directive 54/2004/EC; risk assessment; infrastructure safety.


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1 Introduction

Road transport is a fundamental factor for the society and the economy as it provides people the freedom to travel and enables the exchange of goods (EC, 2011). According to the latest reports, road transport in the European Union (EU) contributes to the transportation of goods and passengers more than all the other means of transport combined (EDT, 2012; EC, 2014). Hence, the safety of the network’s infrastructure plays a determinant role upon the overall safety of the road network (EC, 2011; Hémond and Robert, 2014; Hanssen and Jorgensen, 2015). Despite the rapid development of infrastructure technology during the last decades, member states and authorities do not always succeed in implementing the appropriate strategies and techniques that could
prevent a significant number of tunnel accidents. Often, it is only after an accident happens that policymakers and practitioners begin to deal with the problem. This is the type of approach that was previously implemented with respect to road tunnels, even though they may have significant consequences on the safety of the road network. The tremendous accidents that occurred in the Mont Blanc – France, 1999; Tauern – Austria, 1999; and St. Gotthard – Switzerland, 2001, tunnels not only cost the life of 39, 12 and 11 people, respectively, but also caused an extended destruction of their facilities and significant economic losses that by far exceeded the rehabilitation of the infrastructure (Harrald, 2012). Subsequently, post-accident reports (ABBH, 1999; Voeltzel and Dix, 2004; Beard and Carvel, 2012) discussed several issues of tunnels’ vulnerability. As a result, a legislative reform took place for enhancing road tunnel safety at a European level with the introduction of the Directive 2004/54/EC (EC, 2004). Meanwhile, an outbreak of several research programs addressing this issue, occurred, e.g., Safe-T (Kraussmann and Mushtaq, 2005).

The Directive’s main goal was to contribute to a higher standard level of safety for all road tunnels belonging to the trans-European road network (TERN) by providing both a common context and framework (EC, 2004). Within this framework, the specific risk assessment method to be followed was left at the discretion of each member state. Responding to Directive 2004/54/EC’s provisions, all member states included in their regulations the systematic consideration of tunnel safety with the aid of risk assessment methods, on top of the minimum infrastructure and equipment requirements (EC, 2004; Article 13; PIARC, 2007).

Despite the provision of common principles in the general risk assessment framework, a wide variety of risk assessment methods and related software tools were proposed and implemented (Kraussmann and Mushtaq, 2005; PIARC, 2007, 2008, 2012). These methods rely on several factors, the selection of which is still at the discretion of the authorities of each member state. However, the Directive as well as the EU white paper in transport, lack examples or recommendations as to how various factors of risk assessment might be combined in order to achieve the policy objectives (EC, 2011; Justen et al., 2014). Member states risk assessment methods use specific parameters to come up with the results. The values of the parameters are selected taking into account the driving behaviour, traffic conditions, transported goods, etc. and may differ strongly amongst member states. However, one would expect that certain parameters’ values (e.g., heat release rates – HRRs) would be used uniformly to allow fair comparison in regard to the safety level of TERN’s tunnels. Unfortunately, this is not the case and thus, different methods may result in different level of safety for tunnels with the same characteristics that are part of the TERN.

The aim of this paper is to investigate how discrepancies of national policies regarding non-country-specific parameters, within the context of risk analysis methodologies, can influence the estimated level of safety for the tunnels belonging to TERN. At first, the general framework of the risk assessment methods that member states apply to tunnels is presented. Next, it is examined the same fire accident changing model parameters under the implication of different member states policies of two methods, the French and the Greek, which share the highest degree of similarities amongst EU methods. The outcome results in considerable different level of safety and consequently in different accident prevention level for the same tunnel.
2 The role of risk analysis in tunnel safety

Resiliency of the crucial elements of the road’s infrastructure, such as bridges and tunnels in unpredictable catastrophic accidents is an important trait sought by authorities, designers, and constructors. Road tunnels are at the centre of attention as these are considered potentially hazardous environments. This label stems from the potential consequences of accidents which are related to some special inherent attributes of these infrastructures (Calvi et al., 2012; Mühlberger et al., 2012; Yeung et al., 2013; Wong et al., 2014). Often, tunnels exhibit:

a. no light from the external environment passing through them
b. arranged air movement
c. difficulties in approaching and rescuing users in case of accidents, particularly in case of fires
d. fire combustion irregularity (Ingason, 2008; Hansen and Ingason, 2011; Beard and Carvel, 2012; Maschio et al., 2012; Ronchi et al., 2013).

Particularly, fire accidents, though they are less frequent than those occurring in open roads, they can have far more disastrous consequences in the whole tunnel system (Beard and Cope, 2008; Caliendo et al., 2012). The aforementioned attributes, in conjunction with the steadily increasing the number of road tunnels, may result in increasing number of users that may become trapped in case of an accident, which is a serious concern (Naevstad and Meyer, 2014). Thus, tunnels are recognised as one of the most sensitive structures of the road network in terms of human casualties in case of an accident (Caroly et al., 2013). Hence, the need to establish optimal and consistent safety policies to assist risk reduction management emerges.

Figure 1 Risk assessment flowchart

Source: Adapted from PIARC (2008)
After the launch of the Directive 2004/54/EC, the approach followed towards tunnel safety has changed. Safety analysts deal with tunnel safety both by fulfilling all prescriptive requirements and analysing tunnel systems using a risk-based approach (Manca and Brambilla, 2011). The risk-based approach is implemented in order to facilitate the examination of specific accidents and the observation of possible residual risks while accounting for their intrinsic attributes (PIARC, 2012; Bjelland and Aven, 2013). To this respect, risk assessment has been recognised by tunnel managers and safety analysts as the approach to follow for all the different tunnel life cycle phases (construction, commissioning and operation). The general risk assessment framework for road tunnels in operation, which has been followed by all member states’ methods are presented in Figure 1.

It basically consists of:

- **Risk analysis**, which is a systematic approach for identifying and calculating road tunnel’s risks, technical and man-made. This step includes: system definition, hazard identification, and risk estimation.

- **Risk evaluation**, which aims to determine whether estimated risks are acceptable when compared with predefined risk criteria. This step strongly relies upon the risk analysis method selection. Thus, it cannot be chosen arbitrarily.

- **Risk reduction**, which aims to mitigate or eliminate non-acceptable risks by imposing additional safety measures.

Despite the adoption of the aforementioned reference framework for risk assessment by the member states, detailed specifications of different national policies may still result in significant differences in regard to the perceived level of safety. Initially, performing an overview of the existing risk assessment methods, a relevant categorisation is proposed by looking at three principal axes (Figure 2):

a the type of risk approach

b the type of transported goods

c the type of method used (Ntzeremes et al., 2016).

In the type of risk approach axis, the two components contain a totally different perspective. The system-based approach provides risk estimation for the overall tunnel system, in which all relevant accident scenarios are investigated whereas the scenario-based approach is conducted when there is need to investigate the road tunnel system under predetermined conditions. In the type of transported goods through road tunnels axis, a major division also arises. Goods are separated between dangerous and non-dangerous according to the ADR agreement (UNECE, 2015). The consequences from accidents that involve dangerous goods (i.e., air pollution, form of fire, number of users affected) often are far more devastating when compared to those from accidents which do not involve dangerous goods. Thus, the consequences of accidents involving dangerous goods are recognised at a social-impact scale whereas those involving non-dangerous goods at an individual-impact scale. In the type of method used axis, quantitative methods require numerical data for identifying risk values (i.e., F/N curves, expected value) and often have a high degree of complexity, whereas qualitative methods
involve qualitative or non-numeric data (i.e., expert judgement, risk matrix, checklists). Thus, qualitative methods are more flexible and have lower complexity.

**Figure 2** Risk assessment methods’ axes (see online version for colours)

Due to the aforementioned categorisation, the existing methods adopt certain approaches that become now apparent. For example, a system-based approach, which provides risk estimation for all relevant accident scenarios and thus needs a large sum of data, can hardly be compared to a scenario-based approach, which takes into account only a subset of stand-alone relevant scenarios, even if respective parameters are exactly the same. Moreover, a risk assessment method may involve elements that belong to different axes as, for instance, a scenario-based approach that is performed to evaluate risks arising from the transportation of dangerous goods. Finally, there are semi-quantitative methods standing in-between the elements of a principal axis which combine aspects of both qualitative and quantitative approaches.

Proceeding at a deeper level of examination, key parameters of the tunnel systems that affect risk assessment results can refer to:

- a vehicles
- b users
- c infrastructure
- d facilities
- e transportation management
- f permanent and emergency operational personnel
- g special features of crucial events.
Although most of these parameters are dictated from the different national situations and the specificities of the case at hand (e.g., traffic volumes), other parameters (e.g., fire evolution) are usually state imposed national policies. To allow for a fair and uniform comparison of the level of safety of the TERN tunnels, the latter parameters should be used uniformly across member states. For instance, the different standardisation of fire behaviour, through the HRR should be the same regardless the member state. Furthermore, the estimation of the tenable environment [the use or not of fractional effective dose (FED)] is also an important issue which differentiate amongst member states. So, a common ground towards the aforementioned issues should be a concern for the European authorities.

In order to explore the impact of the aforementioned variations to the level of tunnel safety, the French (CETU, 2003) and the Greek (AAT, 2011) tunnel risk assessment methods’ regulatory guidelines respectively, are selected. The choice is not arbitrary as these methods share a high degree of similarity in their inherent approaches and assumptions, 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.

3 Research method

Focusing on illustrating the emerging risks that arise in all the parts of the tunnel system due to the differences mentioned above, a deductive approach is used. This approach aims at showcasing the discrepancies that arise in the estimated level of tunnel safety when different methods affected by different national policies are used. Therefore, an existing theory is challenged and a source for research questions and possible answers is provided (Saunders et al., 2009).

The research process follows a reasoning path from theory to data. Theory is defined as the whole set of national policies that govern risk assessment in road tunnels belonging to TERN. The main hypothesis (H0) for this paper is the following:

H0 Different methods used by member states for TERN tunnels’ risk assessment should lead to similar results regarding the estimated level of safety when imposed to the same tunnel infrastructure and conditions.

At the observation stage, a simulated experiment is performed making use of different national risk assessment regulatory frameworks, the French and the Greek one, in an indicative case of a road tunnel, fulfilling best-practice requirements and Directive 2004/54/EC’s infrastructure and tunnel equipment minimum requirements. This stage is further divided in two stages. First, the two risks assessment frameworks are compared in order the authors to present their similarities but to also identify their differences. This stage creates the ground so that, subsequently, a quantitative risk analysis (QRA) can be carried out in a scenario-based accident involving fire in the most vulnerable points of the tunnel. In the conclusion stage, the differences in the estimated level of safety are investigated and derived by accounting of the method’s inherent assumptions.
4 Indicative case study

4.1 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 300 m, in 2003 (CETU, 2003). Greece imposed an equivalent method for all road tunnels longer than 500 m, in 2011 (AAT, 2011). 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 (i.e., the users, the facilities, the infrastructure and the vehicles) and by examining interactions among 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 aforementioned principal axes classification, both methods are scenario-based because they suggest that a number of two or three crucial accident scenarios should be examined. Both methods are quantitative with respect to the risk assessment process. Also, both methods do not consider the transport of dangerous goods. In both countries, the study of dangerous goods by heavy good vehicles (HGVs) through road tunnels is subject to separate regulatory framework that foresees detailed quantitative risk assessments using the QRAM software (INERIS, 2005). However, both methods use standardised fire scenarios, which could specifically account for HGVs carrying dangerous goods (i.e., fire scenarios with maximum HRR, HRRmax; 200 MW).

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 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 among accident-causing situations, trigger events and aggravating factors, in which recorded risks are also separated among users, personal
staff, internal and external space. In contrast, the Greek method provides a guide for some main triggering events and in a subsequent step challenges the experts to determine and document the sequence of hazards → trigger 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 3.

Figure 3  French and Greek methods characteristics (see online version for colours)

4.2 The French vs. the Greek approach

4.2.1 Case study description

A typical road tunnel, meeting the infrastructure and equipment requirements as specified by of Directive 2004/54/EC for tunnels belonging to the TERN, is selected. Table 1 reports the main attributes of the tunnel.
The examination of risk assessment is performed for three accident scenarios each involving a fire event from HGV at distances of 350 m, 1,500 m and 2,350 m 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).

Table 1  Tunnel attributes

<table>
<thead>
<tr>
<th>Designing features of the tunnel</th>
<th>One dimension – single sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>3,000 m</td>
</tr>
<tr>
<td>Slope</td>
<td>-1.5%</td>
</tr>
<tr>
<td>Number of exit doors</td>
<td>6</td>
</tr>
<tr>
<td>Number of traffic interruptions</td>
<td>7</td>
</tr>
<tr>
<td>Starting time of traffic lights after the ignition of the fire</td>
<td>5 min.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System of mechanical ventilation</th>
<th>Number of jet-fan-array</th>
<th>8+1 (backup)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of jet fans making up the array</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Progressive function</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Starting time of the system after the ignition of fire</td>
<td>2 min.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure difference between entrance – exit</th>
<th>95% of max velocity based on local estimations regardless direction</th>
<th>28 Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment conditions</td>
<td>Temperature</td>
<td>12°C</td>
</tr>
<tr>
<td></td>
<td>Altitude</td>
<td>600 m</td>
</tr>
</tbody>
</table>

| Transport 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 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 100 MW at peak (maximum HRR: HRR_max = 100 MW). 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, a 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, which is a computational fluid dynamics (CFD) modelling tool developed and supported by the Tunnel Study Center (Vincent et al., 2005).
4.2.2 Research 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 100 s 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 1,200 m and 2,000 m from the entrance of the tunnel for the accident scenarios occurring at 1,500 m and 2,350 m from the tunnel’s entrance respectively or directly at the entrance for the accident scenario occurring at 350 m 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, Figures 4–6 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. Unavoidably, mechanical ventilation needs more time to reverse backlayering when the fire is closer to the tunnel’s entrance. The evolution of fire and the respective effectiveness of the mechanical ventilation are presented in Figure 7, 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, (Figures 4–6). 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 100 MW, this value is reached in ten minutes according to the French standardisation but only in five minutes according to the Greek standardisation.

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.
Figure 4  Air temperature (°C) and opacity (m$^{-1}$) along with escaping lines of trapped users, x = 2,350 m, (a) fire scenario according to the French method (b) fire scenario according to the Greek method (see online version for colours)

Figure 5  Air temperature (°C) and opacity (m$^{-1}$) along with escaping lines of trapped users, x = 1,500 m, (a) fire scenario according to the French method (b) fire scenario according to the Greek method (see online version for colours)
Another major consequence due to the difference in fire standardisation occurs with respect to the longitudinal ventilation system. For fire accidents located at 350 m, only one jet fan array is destroyed at 180 s in the French method as opposed to two jet fan arrays destroyed at 110 s and 280 s respectively in the Greek method. A similar situation occurs for the fire accidents located at 2,350 m from the tunnel’s entrance: in the French method, no jet fan array is destroyed, whereas, two jet fan arrays are destroyed at 110 s and 260 s 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 4–6 also illustrate the crucial part of the evacuation lines of trapped users, specifically during the first 350 s. Table 2 presents the movement of users in a fire environment, which is used for these calculations (PIARC, 1999; CETU, 2003; AAT, 2011).

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>1.50</th>
<th>1.00</th>
<th>0.50</th>
<th>0.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opacity (m^{-1})</td>
<td>(0)</td>
<td>(0, 0.30)</td>
<td>(0.30, 0.50)</td>
<td>(0.50, 10)</td>
</tr>
</tbody>
</table>

Users are trapped at 0 m, 10 m, 20 m, 30 m and 40 m 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 is depicted in Figure 8.
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Figure 7  Evolution of the air temperature at fire locations for Greek and French scenarios (see online version for colours)

Figure 8  Total time needed for users to find themselves out of the smoke cloud (see online version for colours)
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 (Figures 4–6). 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 + 10 s and + 22 s for the three distance scenarios examined.

It is important to note that for air opacities above 0.7 m\(^{-1}\) 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 (Figures 4–6).

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 is calculated as:

\[
FED_{\text{conv}} = \sum (\frac{1}{t_{\text{conv}}} + \frac{1}{t_{\text{rad}}}) \times \Delta t
\]  

where \(t_{\text{conv}}\) is the time duration for convective heat, which is calculated as:

\[
t_{\text{conv}} = (5 \times 107) \times T^{-3.4} \quad \text{for light clothing}
\]  

where \(\{t\}\) the time in minutes and \(\{T\}\) the temperature in °C, and where \(t_{\text{rad}}\) is the time duration for burning of skin, which is calculated as:

\[
t_{\text{rad}} = 4 \times q^{-1.36}
\]  

where \(\{t\}\) the time in minutes and \(\{q\}\) the radiant heat flux in kW/m\(^2\) (for \(q > 2.5\) kW/m\(^2\); for \(q < 2.5\) kW/m\(^2\) this time is equal to 30 min).

For example, as it can be inferred from Figure 4 for the accident scenario located at 2,350 m, 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 values greater than 0.3. Based on this assumption, it is estimated that a user could tolerate approximately 13.50 s 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, it can be shown that users located at 2,330 m and at 2,310 m experience air-temperatures of approximately 150°C which allows them to hold for approximately 54 s 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 1,500 m and 350 m.
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As a conclusion for all accident locations, by using Greek method trapped users located 20 m and 40 m 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), 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.

The consequences of the aforementioned differences may significantly impact the overall estimated level of safety as model results combined with FED calculations have shown that these may lead to estimates of additional losses among 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.

5 Conclusions and further research

The establishment of a uniform framework that the European legislation has imposed to improve safety in tunnels of TERN was a necessary first step but, still, it seems that it is not a sufficient condition for achieving the same level of safety across TERN tunnels in different member states when traffic and tunnel conditions are the same. European legislation certainly enforces the safety level of TERN tunnels, as tunnel disasters have decreased based on accidents numbers. However, in regard to the imposed risk assessment, the presented study shows that the use of different parameters’ values under the influence of national policies that each member state has imposed in the adopted methods, despite the high degree of similarity that the methods may share, can result in significant discrepancies on the estimated level of tunnels’ safety. The diversity of the existing methods may only further highlight these discrepancies.

By performing 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
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.

Certainly, every assessment method is formed to meet the special requirements of each member state which might not be the same. But, the TERN aims in providing users with a high and uniform level of services and safety. To test methods against this aim, a deductive approach was used. The initial hypothesis is that different methods used by member states for TERN tunnels’ risk assessment should lead to similar results regarding the level of safety when imposed to the same tunnel infrastructure and conditions.

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 reasonably 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. A highly stricter method, would result in more safety measures taken and in turn lead to potentially unnecessary increased expenses on the tunnel. However, if the relevant member state’s funds were spent on another infrastructure, the overall population safety could have increased more.

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

In conclusion, it has been demonstrated that even for methods that share a high degree of similarity in terms of tunnel risk assessment framework and process, the differences in key parameters’ values of the process could suffice to shift the safety level perceived by the risk analyst. This raises concern as one would expect that harmonisation of the road tunnel risk assessment framework at the European level would result in similar safety assessments for road tunnels sharing the same infrastructure, traffic and safety equipment characteristics and 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.

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References


