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

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ABSTRACT

Fire safety is an important aspect of underground road tunnels' operation. Undertaking high traffic volumes, they are one of the most critical infrastructure for the daily operation of modern urban networks. Aiming to guarantee their safety, risk assessment has been established as a valuable tool. However, the deterministic approach of existing methods has weaknesses in addressing the embedded uncertainty included in important parameters of the system. This paper, applying a stochastic-based approach, proposes a novel quantitative risk assessment method, named SIREN. Initially, the system's parameters are investigated and the ones which should be treated as stochastic are identified. Subsequently, the method considers both tunnel airflows and trapped-users' evacuation in order to estimate their potential losses. Finally, the system's level of safety is provided through the distribution of the trapped-users losses, which occurred by accumulating the results that derived from the Monte Carlo Simulation. The proposed method is illustrated through the case of an urban underground road tunnel during rush hour. The outcome highlights a significant proportion of scenarios that exceed the number of losses estimated by the traditional methods. Meanwhile, the method examines the parameters' criticality supporting, thus, safety analysts in selecting additional to standard safety measures, if needed. Furthermore, the proposed method aids analysts to act consistently with the as low as reasonable practicable principle.

1. Introduction

The level of urbanisation is expected to rise from 54% in 2014 to 66% by 2050 worldwide (UN, 2015; World Bank, 2016). As a result of this trend, the global demand for transport services in urban areas is expected to continue rising. Given that the transport sector is a major global resource-consuming sector with 63% of total oil consumption (World Energy Council, 2016), policymakers, authorities and analysts have to focus more on planning transportation networks, as well as on upgrading transportation technologies to be more efficient and less polluting (EC, 2011). Despite the development of alternative means (e.g. underground rail), recent studies indicate that the road transportation network still has the highest position amongst urban transport systems (i.e. 46% of the transported goods and passengers in urban areas are transferred by road (EDT, 2012)). Thus, it remains one of the most critical systems for the daily operation in urban areas.

Urban areas are characterised by the high density of population as well as the high occupation on the surface and the extended perimeter of the city centres, all of which result in growing the demand for travel and mobility. Aiming to meet the requirements for efficient and less polluting urban road networks, authorities have put pressure on vehicles' technology by imposing tighter emission and noise standards (e.g. EURO 6 emission standard (EC, 2007)). Nevertheless, the steadily growing traffic volumes have caused urban road networks suffering by traffic congestion, which subsequently results in multiple adverse effects such as the excessive environmental pollution and noise deriving from vehicles' fumes and engines. Furthermore, traffic congestion is responsible for drivers' frustration while the cost of fuel as well as the significant loss of productive hours in every day movements increase the financial losses (Ernst et al., 2006; Menelaou et al., 2017). Thus, the enhancement of the road network's infrastructure constitutes a crucial parameter in order to reduce traffic congestion and its adverse effects, establishing a sustainable road network and providing simultaneously high-quality services.

Underground road tunnels respond to the aforementioned needs by providing an efficient underground road corridor to move people and goods in urban areas preserving concurrently the land above for other uses, like residential (e.g. homes, office buildings, etc.) or public use (e.g. parks, etc.). Due to the growing land values in urban areas along with the advance of construction technology, underground

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infrastructures have become an economically viable solution compared to the classic ground network in the development of modern urban road networks (Ernst et al., 2006; Legacya et al., 2017). They meet specific environmental requirements by achieving accessibility and connecting remote urban areas, bypassing the difficulties arising from existing inner city build environment, and thus, relieving environmental noise and pollution.

Despite the aforementioned benefits to city centres and urban areas in general, the construction of underground road tunnel conceals a significant endogenous weakness, which is the severity of accidents that might occur. If an accident occurs in an underground road tunnel with the usual high traffic volume, it might have significant adverse effects in terms of human losses and infrastructure destruction (Beard and Carvel, 2012). Based on previous accidents, these impacts seem to be maximised in case of fire accidents (AADT, 1999; Ntzeremes et al., 2018).

In order to address fire accidents, risk assessment is considered a valuable tool (PIARC, 2008, 2013). Still though, the fact that important parameters during the operation of the system have significant uncertainty poses challenges to risk assessment (PIARC, 2016). Despite that, current approaches keep treating deterministically tunnel system's parameters such as, for example, the fire behaviour, the daily traffic volume or the behaviour of trapped-users during evacuation, and ignore their embedded uncertainty. Modelling deterministically these parameters affects the risk assessment process and so questions arise for the accuracy of the results. To tackle this issue, we propose a novel quantitative risk assessment method that applies a stochastic-based approach. The aim of the method is to estimate the level of safety of the tunnel by integrating the stochastic behaviour of certain parameters. By doing so, the fallacies embedded in deterministic approaches are mitigated and the actual level of safety of the tunnel, is estimated more accurately. As a result, tunnel managers and safety analysts have a more representative view in order to decide about the need of additional to standard safety measures.

2. Fire safety of underground road tunnels

2.1. Tunnel accidents

Recent studies have shown that road tunnels are as safe as the rest of the road network or safer than that (Beard and Cope, 2008; Amundsen and Engebretsen, 2009; Nævestad and Meyer, 2014; Kirytopoulos et al., 2017). They are safer because on one hand their closed environment compels users to drive carefully (Kirytopoulos et al., 2017) and on the other hand junctions, pedestrians or advertising signs and bicyclists are not present (Amundsen and Engebretsen, 2009). All these elements are either sources for accidents or aggravating factors during accidents' evolution. Furthermore, modern tunnels follow strict regulatory guidelines, like the Directive 54/200/EC in Europe and the National Fire Protection Association's standard 502 in the USA (EU, 2004; NFPA, 2014). Therefore, the necessary equipment is installed and infrastructure requirements are adhered to in order to ensure tunnels' safety in case of a fire accident.

Although the accident rates confirm that accidents are lower in tunnels than on the open roads, if an accident occurs, it might have greater severity than in the rest of the road network. To this respect, a study from Italy showcases that severe accidents are more frequent in road tunnels. In particular, it is reported that between 2006 and 2009, road tunnels had a severe accident rate between 9.13 and 20.45 crashes/10^8 veh.km, while on the associated motorways the rate was between 8.62 and 10.14 crashes/10^8 veh.km (Caliendo and Guglielmo, 2012). Another study in Norway, the country that already has over 1000 tunnels with 800 km total length, shows that the average number of tunnel fires sparking from vehicles covering the period between 2008 and 2011 was 21.25 per year per 1000 tunnels (Nævestad and Meyer, 2014). Not all of them resulted in people getting harmed, but still the statistics tell that there is a serious threat for tunnel users.

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

In particular, the disastrous consequences of fire accidents are indicated in the post-accident reports. The trans-Alpine accidents occurred in the Mont Blanc – France, 1999; Tauern – Austria, 1999; and St. Gotthard – Switzerland, 2001 tunnels cost the life of 39, 12 and 11 people respectively, and also caused an extended destruction of their facilities and significant economic losses that by far exceeded the rehabilitation of the infrastructure (Ntzeremes et al., 2018). For instance, the accident in the Mont Blanc cost around 300 million euro for its rehabilitation (Voeltzel and Dix, 2004). Subsequently, several issues of tunnels' vulnerability were enlighten along with the weaknesses regarding preparedness towards these accidents (AADT, 1999; Voeltzel and Dix, 2004; Beard and Carvel, 2012). Likewise, the worst tunnel accident in Japanese history is the Sasago, 2012, where the tunnel ceiling collapsed causing fire, which cost the life of 9 people. In addition, the road network of the region remained closed for almost two months (Maskura et al., 2015). On the contrary, the accident that occurred in the Burnley urban tunnel in Sydney in 2007 resulted in minor adverse effects. The quick reaction of both the tunnel operator and the emergency response units along with the correct reaction of users prevented the fatal consequences (Fridolph et al., 2013).

2.2. Fire effects on underground tunnel systems

Underground road tunnels are considered risky environments due to their enclosed environment since they feature: (a) no physical light passing through them, (b) arranged air movement, (c) difficulties in approaching and rescuing trapped-users in case of accidents, particularly in case of fire accidents and (d) fire combustion irregularity (Caliendo et al., 2012; Calvi et al., 2012; Maschio et al., 2012; Mühlberger et al., 2012; Caroly et al., 2013; Yeung et al., 2013; Wong et al., 2014; Ntzeremes et al., 2018). Additionally, tunnel managers must also handle the particular features of the urban environment as, since tunnels traverse densely populated urban areas, they increase the societal risk of potential accidents. Being usually part of cities' main motorways, tunnels accommodate high traffic volumes. As a result, a potential accident can affect an extended part of the urban road network causing significant casualties, as well.

Because each tunnel is unique as it differs by type, length, width, method of construction, and type of traffic, it is difficult to generalise the evolution of fires (Ingason, 2008; Hansen and Inganson, 2011; Caliendo et al., 2012; Ronchi et al., 2013). Generally, tunnel fires are complex phenomena due to the existence of complex interactions between the fire and the tunnel environment (e.g. turbulence, fire combustion and radiation). Especially the heat feedback in tunnel fires tends to be more effective than that in open fires (Beard and Carvel, 2012; Ingason et al., 2015). Existing studies have concluded that the Heat Release Rate (HRR) of a tunnel fire could be four times higher compared to that of the same material burning in the open road. Concurrently, heavy amount of heat is transferred to the vicinity of fire by radiation, approximately 33% of HRR, and to an extended tunnel area, approximately 67%, which results to convection between hot air and various objects or tunnel ceilings. Furthermore, there is also the risk of explosion, like a Boiling Liquid Expanding Vapor Explosion or BLEVE, mainly when dangerous goods (DGs) are involved (INERIS, 2005). Besides the heat, tunnel fires can also cause hazards due to the availability of propagated toxic gases along with the limited availability of oxygen.

Finally, the developed aerodynamic disturbance reverses tunnel