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Fire risk analysis focused on damage of the tunnel lining

Jan Sýkora [*], Daniela Jarušková, Michal Šejnoha, Jiří Šejnoha

Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague 6, Czech Republic

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ABSTRACT

In this paper, risk is calculated as the probable damage caused by a fire in the tunnel lining. The model is intended to be as simple as possible and still able to reflect the reality. In the first part, focused on probabilistic modeling, the traffic flow is described as a stationary Markov chain of joint states consisting of a combination of trucks/buses (TB) and passenger cars (PC) from adjoining lanes. The heat release rate is then taken for a measure of the fire power and two probability mass functions of this variable are suggested for one TB and two TBs, respectively. The intensity λ_f reflecting the frequency of fires was assessed based on extensive studies carried out in Austria [15] and Italy [16,17]. Eventually, the traffic density AADT, the length of the tunnel L, the percentage of TBs, and the number of lanes are the remaining parameters characterizing the traffic flow. In the second part, a special combination of models originally proposed by Bažant and Thonguthai [28], and Künzel & Kiessl [29] for the description of transport processes in concrete at very high temperatures creates a basis for the prediction of the thickness of the spalling zone and the volume of concrete degraded by temperatures that exceeded a certain temperature level $\overline{\theta}$. The model was calibrated by fitting its parameters against a macroscopic test on concrete samples placed into the furnace. Though effective and easy to apply, there is room for the model as a whole to be gradually improved. These possibilities are outlined in conclusions.

1. Introduction

The aim of this paper is to propose a methodology for fire risk analysis focused downright on damage of the tunnel lining. This allows the designer estimating the probable damage to the lining and, in the end, making use of this prediction when deciding on Fire Safety Strategy. Throughout the paper, we therefore rely on a standard definition of risk as the product of the probability of a fire incident and damage, i.e. the probable amount of money to be spent to eliminate the consequences of the fire incident. Such an approach can be extended considering a group of incident scenarios, which could affect a defined area. In fire risk-informed evaluations one is concerned with how the performance of fire protection systems (FPS) mitigates an existing risk level. According to [1, Chap. 88], the following three factors play a decisive role: (i) frequency of the initiating event, (ii) probability of the failure of FPS performance, (iii) expected consequences (damage). Apart from the installation of automatic FPS in tunnels, the following loss prevention and mitigation measures are recommended, see. e.g. [1, Chap. 88] [11],: (i) use of non-combustible and non-toxic construction materials for the tunnel structure and pavement, (ii) provision of emergency ventilation and the smoke control system to maximize the exhaust rate in the ventilation zone that contains the fire and to minimize the amount of outside air that is introduced, (iii) establishment of adequate emergency response planning.

Thus, the risk analysis monitors both probabilistic and economic viewpoints and interacts with the risk management and live safety. A large number of papers have been published on this topic. Handbooks [1,2] represent a rich seam of knowledge and experience. The probability of a fire is related either to the frequency of a traffic accident (a collision of two or more vehicles) or of any event causing the vehicles' inflammation (overheating of the engine, brakes, leakage of fuel, etc.).

In order to address the fire risk assessment as a whole, the paper is composed of two parts. In the first part, the probabilistic concept of the fire appearance in a road tunnel will be outlined. The second part then concentrates on the prediction of the amount of material degraded during a fire.

Probabilistic analysis of tunnels has been studied for many years in Japan (see e.g. Refs. [3,5]). A summary of the Japanese approach to the road tunnel safety is contained in Refs. [6,9]. The data concerning the USA can be found in e.g. [2, Chap. 1] [4,7,8], and/or Australia (see e.g. Ref. [2]). In this paper, to demonstrate that our methodology is viable, we focus our attention on the findings of two extensive studies carried

* Corresponding author.
E-mail addresses: jan.sykora.1@fsv.cvut.cz (J. Sýkora), Daniela.Jaruskova@cvut.cz (D. Jarušková), sejnom@fsv.cvut.cz (M. Šejnoha), sejnoha@fsv.cvut.cz (J. Šejnoha).

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Table 1
Frequency of fires in Austrian tunnels, see Ref. [15].

Type of vehicle	Number of fires	10^9 [veh· km] traveled in tunnels (2006–2012)	Number of fires per 10^9 [veh· km]
all	67	10.3	6.5
PC	38	9.1	4.5
TB	30	1.2	25.0

out in Austria [15] and Italy [16,17], which will be now briefly commented on and exploited. According to the ASFiNAG report [15], a spontaneous ignition prevails against the fire as an after effect of the collision, namely as for passenger cars (PC) in the ratio of 86 [%] : 14 [%] and 97 [%] : 3 [%] in the case of trucks and buses (TB). The Austrian study carried out in 2006–2012 keeps a record of 67 fires per $10.3{\cdot}10^9$ vehicle-kilometers [veh· km] traveled in tunnels. The results are put clearly in Table 1[1].

The results of an analogous study carried out in Italy within the period of 2006–2009 have been summarized in Ref. [16]. The study covers 195 one-way tunnels, from which 172 have two lanes and 23 three lanes, and records 762 serious accidents (662 in two-lane and 94 in three-lane tunnels). During the study period, the fire was recorded in 45 tunnels out of all investigated (35 in two-lane and 10 in three-lane tunnels).

Both studies serve as a source of information on the traffic intensity, which is of paramount importance when estimating the probability of extraordinary events. It ensues from the available data (see, e.g. Ref. [16]) that the severe accident rates in the investigated tunnels due to traffic are in general higher than those on free stretches of corresponding motorways. Moreover, it has been suggested in Ref. [16] that severe accident cost rates of road tunnels are higher than those on the respective motorways in about four-fifths of the monitored tunnels. However, this piece of knowledge should not be overestimated and even go as far as to claim that the safety in tunnels is always lower than on motorways. And besides, this finding contradicts that in Ref. [9]. Apart from the behavior of drivers and visibility, the frequency of severe accidents is affected by the geometric and traffic characteristics of the tunnel (ascending, descending, curvature, etc.). Combining these attributes may yield higher or lower safety in tunnels compared to free stretches. Another statistical analysis of traffic accidents and interesting complementary data can be found, e.g. in Refs. [18] and [19]. With reference to fire accidents, a comparison between fire accident rates and traffic accident rates in tunnels was made in Ref. [16] without distinguishing between two-lane and three-lane tunnels. More especially fire accident rate was found to be between one half and one fourth of that due to traffic.

From the probabilistic point of view the fire occurrence is regarded as part of the Poisson process characterized by its intensity (see the last column in Table 1), which is equal to both the mean value and the variance of the process. In many situations, however, incident counts appear to be "overdispersed" with respect to the prediction based on the Poisson model. To overcome this discrepancy, Caliendo et al. [17] recommended utilizing the negative binomial model. Exploiting the generalized linear model of regression analysis, the following variables were detected as most affecting the process: (i) the traffic density AADTL (annual average daily traffic per lane), (ii) the length of the tunnel L [m], (iii) the percentage of trucks and (iv) the number of lanes.

The second factor affecting the extent of damage due to a fire in a tunnel and corresponding financial costs is, barring the probability of fire occurrence, the evolution of the fire. In this regard the ASFiNAG report draws attention to these two parameters:

- The first one is the evolution rate (Entwicklungsgeschwindigkeit in the original report). The statistics of ASFiNAG distinguishes between the slow rate of fire after a smoke (langsam nach Rauch) and explosion. The latter one, however, is not considered in this paper.
- The second parameter accentuated in Ref. [15] is the peak of the heat release rate (HRR).

As stressed in [1, Chap. 26], the HRR is the essential characteristic that describes quantitatively "How big is fire?" It has been described in Ref. [10] as the single most important variable in fire hazard. Undoubtedly, explosions and fires are different phenomena which need to be treated as such. Similarly, the HRR is a complex and transient phenomenon that is strongly affected by ventilation and vice versa[2]. These problems are discussed in detail elsewhere (see, e.g. Refs. [1,2]). With regard to the risk analysis it should be emphasized that there are a number of scenarios affecting both the maximum value of the HRR and its evolution in time. The problem lies not only in the configuration of vehicles involved in a fire or in the fire-wall linings interaction, but also in selecting the models considering certain dangerous goods, see e.g. Ref. [12]. While studies of a fire can be carried out either numerically using e.g. the CFD code, or experimentally on macro-scale or in a 1/3 scale tunnel [13] (differences between numerical and experimental data being around 19 [%]), the probabilities of individual scenarios are not known and need to be estimated - based on expert judgment and experience.

A prevailing portion of fires with a known cause (60 events, i.e. 92 [%] reported in Ref. [15]) originates from self-ignition (Selbstentzündung in the original paper), i.e. with no foregoing accident. The remaining 5 events, i.e. 8 [%], may be split in around two halves - accidents of single cars and the collision with other vehicles. Two causes were unknown. The spontaneous ignition of PCs was mostly followed by a slow evolution of the fire (92 [%]) while explosion arrived in 8 [%]. On the other hand, as an aftereffect of the accident the slow evolution of the fire and the explosion of PCs were equally probable. The fire evolution of TBs is different. The spontaneous ignition was followed by a slow evolution (80 [%]) and the explosion was triggered out in 20 [%] of cases. Just one explosion after the collision of two cars (1 TB and 1 PC) was reported in Ref. [15]. These data come from fire incidents reported in Austria. In other countries they could be different, which must be taken into consideration in particular risk analyses. It follows that there are uncertainties on both parts of the model and both the assessment of the event's probability and consequences should be balanced out. As to the fire of PCs, fully developed and undeveloped (doused) fires are distinguished. In the case of TB, the fire of the cab must be differentiated from the fully developed fire of the whole vehicle. Due to insufficient data, HRR and the frequency of the fire occurrence have been predicted in an expert way by means of event tree analysis [15]. More details about the traffic flow and the fire itself are summarized in Sec. 2.

Based on the data about the traffic flow and fire characteristics, a simple probabilistic model is proposed in Sec. 3. The traffic flow in multiple lanes is described as the stationary Markov process with a given number of states. The data on fires will be exploited in the second part of this paper to analyze the degree of degradation afflicting the tunnel lining. This includes the total volume of material loss and the volume of material exhibiting a strength reduction due to exposure of concrete to high temperatures. Both outcomes are affected by spalling. A number of popular fire spalling theories are available in literature. Their summary can be found, e.g. in Ref. [47]. In the present study, when making reference to this phenomenon, we consider its direct consequence, i.e. the reduction of thickness of structural members. The volume of material loss will be thought to be caused by the buildup of pore pressure, see Sec.

[1] Table 1 implies that in one case two cars were involved in the fire as a consequence of the collision of PC and TB.

[2] In relatively old tunnels the main purpose of ventilation was to evacuate toxic flames released from vehicles only. In more recent tunnels, in all cases the use of existing emergency ventilation systems, intended to remove smoke and heated gases has resulted in aggravated damage to tunnel's concrete structure and to whatever was inside them (see Ref. [11]).