Probabilistic approach to damage of tunnel lining due to fire

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Abstract. In this paper, risk is perceived as the probable damage caused by a fire in the tunnel lining. In its first part the traffic flow is described as a Markov chain of joint states consisting of a combination of trucks/buses (TB) and personal cars (PC) from adjoining lanes. The heat release rate is then taken for a measure of the fire power. The intensity $\lambda_f$ reflecting the frequency of fires was assessed based on extensive studies carried out in Austria [1] and Italy [2, 3]. 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 [4], and Künzel & Kiessl [5] 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 exceed a certain temperature level. The model was validated against a macroscopic test on concrete samples placed into the furnace.

1. Introduction

High temperatures produced by a fire may cause damage to structures, particularly to the tunnel lining. This sub-structure then would be deteriorated not only by concrete spalling but also by a drop of strength in the volume stricken by the temperatures substantially acceding a hundred degrees Centigrade.

The large-scale fires (Mont Blanc tunnel, Tauern tunnel, Saint Gotthard road tunnel) are not typical and cannot be incorporated in the scope of standard statistics-based approaches, and as such, must be analyzed ad hoc. On the other hand, there exists a considerable volume of data on standard–size incidents which may be exploited in a risk analysis of fire in road tunnels and will be briefly discussed in the sequel. The risk analysis monitors both probabilistic and economic viewpoints. The probability of a fire is closely related to the probability of a traffic incident, which could be not only the consequence of a collision of two or more vehicles but also any event causing the vehicles’ inflammation (e.g. overheating of the engine, brakes, leakage of fuel, etc.) Fire incidents in road tunnels are prevalingly caused by electrical and/or mechanical defects of vehicles.

In order to address the fire risk assessment as a whole, this paper is composed of two parts. In the first part, the probabilistic concept of the fire appearance in a road tunnel will be outlined. To this end, the findings of two extensive studies carried out in Austria [1] and Italy [2, 3] will be utilized in this study.

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 characterized by the following attributes: (i) the evolution rate (slow after smoke vs. explosive), (ii) the peak of the heat release rate (HRR).
As predicted in [1], the spontaneous ignition of TBs was followed by a slow evolution (80 [%]) and the explosion was triggered out in 20 [%] of cases. In the case of TBs, the fire of the cab must be distinguished 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 [1]. More details about the traffic flow and the fire itself are summarized in Section 2. Based on the data about the traffic flow and fire characteristics, a simple probabilistic model is outlined in Section 3.

In the second part of this paper, the data on fires will be used to analyze the degree of degradation affecting the tunnel lining exposed to high temperatures. In quest for a cogent yet effective model, a special combination of approaches originally proposed in [4, 5] is presented in Section 4. The report [6] on the results of the Runehamar tunnel fire tests sets forth simple yet reliable formulas for the description of the phenomena accompanying a fire. It becomes a basis for the hygro-thermo-mechanical model for the prediction of damage due to a fire. Next, a case study under simplified assumptions demonstrates a prediction of the risk of a fire in a road tunnel, see Section 5. Conclusions and possibilities of further work on the fire risk analysis are outlined in Section 6.

2. Available statistical data as a basis of a probabilistic model

The results of studies carried out in Austria and Italy serve not only as representatives of fire occurrences in Europe but also as a guideline for their prediction that provides the data allowing us to assess the rate of fires as the number of fires per 10\(^9\) [veh.km] travelled in tunnels, see Tables 1 and 2.

Table 1. Frequency of fire occurrence (the number of fires per 10\(^9\) [veh.km] in Austria, source [1]).

| Type of vehicle | The number of fires per 10\(^9\) [veh.km] | Self-ignition [%] | Subsequent [%] |
|----------------|------------------------------------------|-------------------|----------------|
| All            | 6.5                                      | 6.0               | 92             | 0.5 | 8  |
| PC             | 4.2                                      | 3.6               | 86             | 0.6 | 14 |
| TB             | 25.0                                     | 24.3              | 97             | 0.7 | 3  |

Table 2. Frequency of the fire occurrence \(\lambda_f\) [fires (veh.km)\(^{-1}\)] (the number of fires per 10\(^9\) [veh.km] in Italy, source [2]).

| Type of vehicle | Type of tunnel | Frequency of fire occurrence |
|----------------|----------------|------------------------------|
| All            | 2 lanes        | 33.3                         |
|                | 3 lanes        | 40.8                         |

The results in Table 2 were calculated from the following formula:

\[
\lambda_f [\text{fires (veh.km)}^{-1}] = \frac{N_f}{365 \text{AADT} L_{\text{ref}}} \tag{1}
\]

where \(N_f\) [fires year\(^{-1}\)] is the average annual number of fires monitored in tunnels with their total length \(L_{\text{ref}}[\text{km}]\) and the average annual daily traffic \(\text{AADT} [\text{veh.day}^{-1}]\) (see Tab 3).

Table 3. Summary statistics of the characteristics of tunnels with recorded fire occurrence, source [2]

| Type of tunnel | \(N_f\) | \(L_{\text{ref}} = \Sigma L_i [\text{km}]\) | \(\text{AADT} [\text{veh.day}^{-1}]\) |
|----------------|--------|------------------------------------------|-----------------------------------|
| 2 lanes        | 9.5    | 46.2                                     | 16931                             |
| 3 lanes        | 5.0    | 8.3                                      | 24247                             |
The second characteristic of a fire is the maximum value of the heat release rate $Q_{\text{max}}$ [MW], which is a measure of the fire power. The HRR per square meter of exposed fuel is generally found for most vehicles to be in a very narrow range ($0.27 \text{ [MWm}^{-2}\text{]} - 0.4\text{[MWm}^{-2}\text{]})$, see [7]. The resulting fire power depends on the critical scenarios that give the most significant contribution to the overall risk. In this paper, we used as an illustrative example the Austrian model which considers three representative scenarios of fires (5[MW], 30[MW], 100[MW]). The distribution of $Q_{\text{max}}$ [MW] was obtained in [1] for trucks and buses (TB) as a combination of databases and expert assessment exploiting an Event Tree Analysis (ETA).

The results of ETA are a suitable point of departure when estimating the probability mass function of $Q_{\text{max}}$ [MW] conditional on the fire developed on one truck/bus, $p_{Q_1}(q_1)$. This function is displayed in Fig. 1(a). If two trucks/buses are involved in the incident giving rise to a fire, the resulting HRR is a composition of both HRRs, i.e. $Q = Q_1 + Q_2$, see Figure 1b.

**Figure 1**: (a) Probability mass function of $Q_{\text{max}}$ [MW] (one truck/bus) (b) probability mass function of $Q_{\text{max}}$ [MW] (two trucks/buses).

### 3. Probabilistic model for the prediction of fire risk in road tunnels

In this chapter a pragmatic probability-based model will be proposed. In doing this, the following factors will play a decisive role in the model: (i) the probability of a certain configuration of vehicles involved in the fire accident, (ii) the probability that the subsequent fire will ensue a collision (see Tab. 1), (iii) the distribution of heat developed in a given configuration of vehicles engulfed by the fire (Figs. 1(a) and (b)), and (iv) the damage of the tunnel lining as a result of the fire with a known HRR.

The probable configurations of vehicles potentially involved in a fire incident in the traffic flow with two lanes are sketched in Fig. 2, where V stands for the empty space (Void).

**Figure 2.** Two-lane traffic flow.

For two stationary (homogeneous) independent parallel traffic flows, the probabilities of joint states, e.g. $(V,V)$, $(PC,V)$ etc., can be simply calculated as the product of the probabilities of individual states in adjoining lanes.

Hence

$$P_l = p_{l1}^1 p_{l2}^2, \quad i, j = V \equiv 0, \quad PC \equiv 1, \quad TB \equiv 2, \quad l = 1, \ldots, 9. \quad (2)$$
The aforementioned simplistic approach will now be enhanced based on the Markov chain model. This model describes the evolution of the probabilities of joint states at a given position \( x_0 \) and at discrete times. Recall that a random sequel \( \{ X_n : n = 0, 1, 2, \ldots \} \) is the Markov chain if

\[
P(X_{n+j} = j | X_n = i, X_{n-1} = i_{n-1}, \ldots, X_0 = i_0) = P(X_{n+j} = j | X_n = i) .
\]  

(3)

If the transition probabilities (3) do not depend on \( n \), the Markov chain is called homogeneous. The probabilities expressing the distribution of the Markov chain at a time step \( n \)

\[
p_i(n) = P(X_n = i), \quad i = 0, 1, 2, \ldots, n = 0, 1, \ldots
\]

(4)

In case of a non-homogeneous chain it holds

\[
p_i(n + 1) = \sum_{j} p_j(n) p_{ji}(n), \quad i = 0, 1, 2, \ldots, n = 0, 1, \ldots
\]

(5)

The individual states, \( 0 \equiv V, 1 \equiv PC, 2 \equiv TB \), can be combined to obtain \( 3^2 = 9 \) initial joint states. Admitting the possibility of switching lanes increases the number of joint states to a total of fifteen states. The three of the six supplementary states are displayed in Figure 3. They demonstrate the newly emerged joint states, the process of a TB changing lanes, \( 1 \rightarrow 2 \), has been phased in.

![Figure 3. The process at a time instant \( t = x/c \) in which a TB pulls from lane 1 to lane 2; \( c \) is the velocity of traffic flow.](image)

In what follows, individual states \( n \) will be identified with time \( t \) and Eq. (5) will be formally rewritten into this matrix form:

\[
p(t + \Delta t) = P^T(t) \cdot p(t)
\]

(6)

The current entries of the transition probability matrix \( P(t) = [p_{ij}(t)] \) need to be updated at the end of the previous step. The entries of the column matrix \( p(t) \) correspond to nine initial joint states \( 00, 01, 02, \ldots, 22 \) supplemented with six additional states \( 02^1*, 02^2*, 02^3*, 20^1*, 20^2*, 20^3* \) reflecting the switching of lanes.

As the illustrative example, let us consider a two-lane traffic flow with a configuration depicted in Fig. 2. To be specific, let in the initial state there be 8 PCs and 1 TB detected in lane 1, and 8 PCs and 2 TBs in lane 2. The best likelihood estimates now can be used to obtain the transition probabilities. The whole transition probability matrix cannot be presented here because of the limited scope of the paper.
The two models of switching lanes are assumed in this illustrative example: (i) any PC ≡ 1 switches both lanes with the same probability $p_{1}^{12} = p_{1}^{21} = 0.5$ and, analogously, as to a TB $p_{2}^{22} = p_{2}^{21} = 0.05$, (ii) the probabilities of switching the lanes are different, namely $p_{1}^{12} = 0.5, p_{1}^{21} = 0.8, p_{2}^{12} = 0.05, p_{2}^{21} = 0.1$.

The non-stationary solution was carried out based on randomly chosen four non-zero initial probabilities: $p_{11}(0) = 0.64, p_{12}(0) = p_{21}(0) = 0.16, p_{22}(0) = 0.04$.

The probabilities of joint states in the initial phase strongly depend on the initial conditions and may swiftly vary and differ from each other. As an example, the evolution of the probabilities of joint states 02 and 12, respectively, are displayed in Fig. 4a, b considering distinct assumptions about transition probabilities with which the vehicles switch lanes 1 and 2.

![Figure 4](image1.png)

**Figure 4.** The evolution of the probabilities of joint states (a) 02 and (b) 12 (data1 - no switching lanes; data2 - switching lanes with the same probabilities; data3 – switching lanes with divers probabilities)

In what follows, the fire incidents are regarded as components of the Poisson process with the intensity $\lambda_f$. As by far a largest number of fires are attributed to self-ignition, the rate of fires per $10^9$ veh.km, see Eq. (1), will be taken for the intensity of the process. For a more detailed risk analysis, the total counts should be split at least into two sub-categories involving one TB and/or two TBs. In more detailed modeling, series configurations may be allowed for as well.

Denote the probabilities of states conditional on the fire accident as $p_{f}^{[i]}$, $[i] = 1, 2$, and express the respective fire intensities as

$$
\lambda_{f}^{[i]} = \kappa^{[i]} \lambda_{f}, \quad \sum_{i=1}^{2} \kappa^{[i]} = 1.
$$

The probability mass function of heat, $Q$, developed during a fire, $p_{Q}(q)$, has already been discussed in Section 2. In the optimal case, functions $p_{Q}^{[i]}(q)$ would be desirable for all possible configurations of vehicles. However, the reduction of these configurations into two sets of the utmost importance seems to be acceptable in this pragmatic model, so only the two functions displayed in Figs. 1 (a) and (b) will be adequate.

On the other hand, we should not disregard the fact that, in general, the parameters $p_{f}^{[i]}, \kappa_{[i]}, \lambda_{f}$ may vary along the length of the tunnel.
Considering that risk is the probable damage and with regard to the chain rule of conditional probabilities, a general formula allowing us to predict the average risk of a fire in road tunnels takes this lucid form

\[
RISK = T \langle AADT \rangle \sum_{[i]} \sum_{(q)} P_{[q]}^{[i]}(q) \int_{L} C^{[i]}(q, x) P_{f}^{[i]}(x) \kappa[x](x) \lambda_{f}(x) dx, \tag{8}
\]

where \( T \) [day] is the period of time for which the risk is calculated, \( L \) [km] is the length of the tunnel, \( C^{[i]} \) is the cost that must be expended to eliminate the damage caused by a fire. It should be pointed out that \( C^{[i]} \) is a non-linear function of \( q \) and, therefore, any simplifications of Eq. (8), no matter how tempting, cannot be recommended. This variable is also a function of \( x \) due to the varying effect of a fire along the tunnel. Putting the accent on the technological aspects of damage, the cost \( C^{[i]} \) in Eq. (8) may be alternatively substituted by the volume of the damaged concrete lining to be restored. We should further remember that AADT is the annual average daily traffic per direction [veh.day\(^{-1}\)] and as such it is held constant in Eq. (8).

4. Hydro-thermo mechanical model for the prediction of fire risk in road tunnels

The mathematical formulation of the material model consists of two governing equations representing the conservation laws of heat and mass. Their detailed description along with the corresponding boundary and initial conditions as well as numerical solution can be found in [8]. In the same source the model parameters have been identified based on a macroscopic test carried out on large scale panels made from fly ash concrete reinforced with FORTA-FERRO fibers and loaded in furnace (RWS fire curve). The results of numerical simulations are compared with those obtained from measurements in Figure 5.

5. Risk assessment of fire in a road tunnel, case study

In this section we adopt formulas presented in [6] and references therein. The maximum ceiling temperature \( \theta_{\text{ceil,max}}[^{\circ}\text{C}] \) in a specific region is expressed as

\[
\theta_{\text{ceil,max}} = \begin{cases} \theta_{\text{reg,1}} & \theta_{\text{reg,1}} < 1350[^{\circ}\text{C}], \\ 1350 & \theta_{\text{reg,1}} \geq 1350[^{\circ}\text{C}], \end{cases} \quad \theta_{\text{reg,1}} = 17.5Q^\frac{2}{5}H_{\text{eff}}^{-\frac{5}{3}}, \tag{9}
\]

Figure 5. Numerical result for an optimized set of material parameters in different time steps: (a) Evolution of temperature, (b) evolution of pore pressure.

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\]
where $H_{\text{eff}}$ [m] is the effective height of the tunnel and $Q$ [MW] is the heat release rate. This term is then used in the definition of the ceiling temperature $\theta_{\text{ceil}}(t,x)$ [°C], which is a function of location and time as

$$\theta_{\text{ceil}}(t, x, z) = c_{\text{time}}(t)c_{\text{loc}}(x, z)\theta_{\text{ceil, max}}.$$  \hspace{1cm}(10)

The evolutions of $c_{\text{time}}$ [-] for typical values of $Q$ [MW] and $c_{\text{loc}}$ [-] used as example in this study are shown in Figure 6. The 3D nature of the problem is captured by using a parabolic function of vertical coordinate $z$ to describe the distribution of the gas temperature along the tunnel lining.

The typical values of $Q$ (5, 10, 30, 50, 70, 100, 105, 130, 200[MW]) representing the power of fire due to the ignition of one and/or two vehicles, respectively, were considered to take into account the selected scenarios in two-lane road tunnel. The damaged volum [m$^3$] of the tunnel lining at the end of simulation (after 3 hours) is displayed in Figure 7 (a). In this study the volume $V_{\text{dam}}$ [m$^3$] is limited to the material volume loss when the temperature exceeded a limit value $\bar{\theta}$ given the specified value of $Q$. It consists of the volume $V_{\text{spal}}$ [m$^3$] destroyed by spalling, and the volume $V_{\text{deg}}$ [m$^3$] degraded through the passage of high temperature. Both volumes constitute a material basis of risk analysis.

The right hand side of Eq. (8) is graphically represented in Figure 7(b) and can be regarded as the damage randomly caused by a single fire accident. To be specific let us consider a two-lane road tunnel, 2 [km] long, with AADT= 17000 [veh.day$^{-1}$], see Table 3, and $T = 1$ [year] = 365 [days].
Finally, make a tentative guess of the fire intensity \( \lambda_f = 30 \cdot 10^{-9} \text{[fires (veh.km)]} \), see Table 2 and permit \( \theta = 150 \text{[°C]} \) as the maximum temperature the tunnel lining is able to support without an essential repair.

It follows from Eq. (8) and Fig. 7(b) that RISK ranges from 13 to 20 [m³ year⁻¹]. Considering that a total volume of the lining struck by a fire along a 520 [m] long stretch is \( V = 3463 \text{[m³]} \), we arrive at the value of risk relative to this volume \( RISK_{rel} = (0.38 \div 0.58)\% \) of damaged concrete per year.

6. Conclusions

In this paper, we proposed a pragmatic model for the risk analysis of road tunnels engulfed by a fire. In the probabilistic description of the traffic flow the Markov chain model, non-homogeneous in general, appeared to be a suitable tool to cover this problem. Admitting the possibility of switching lanes increases the number of joint states, for which the Markov chain must be developed. Apparently, the probability of changing lanes must be known or reasonably estimated. Our numerical experiments with varying initial conditions (see Section 3) imply that the traffic flow becomes homogeneous (stationary) within 300 – 400 m from the initial position (semaphore). This fact considerably simplifies the assessment of the probable damage due to a fire.

The probabilistic modelling of the heat release rate is another factor worthy of improvement. The probability mass functions of the respective HRRs strongly depend on the scenarios that must be taken into account when estimating the consequences of a fire.

Last but not least, the fire intensity, \( \lambda_f \), should not be omitted in this discussion. Insufficient data on the type of vehicles involved in the fire incident do not allow for the fire intensity of joint states to be grasped sufficiently well. Moreover, we have inadequate knowledge of the variability of \( \lambda_f \) along the tunnel, but taking this quantity for a constant seems to be a reasonable compromise.

All things considered, the proposed model is applicable for risk analyses in sufficiently long tunnels and in all cases where the traffic flow is already homogeneous. It will be further augmented while estimating damage caused by fire incidents at the proximity of portals. Except for exploiting the methods based on CFD, the expert approaches to the prediction of the upstream/downstream gas flows are close at hand.

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