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A probabilistic approach to evaluate the risk due to a fire in unidirectional road tunnels ventilated by jet fans

D. Martinelli & P. Oreste
Department of Environment, Land and Infrastructures Engineering, Politecnico di Torino, Italy

ABSTRACT: The risk produced by a fire is one of the most important aspects to be analysed for the safety of a road tunnel. In one-way ventilated tunnels with jet-fans it may happen that during a fire the fumes move in the opposite direction to that of the fresh air entering the tunnel. This phenomenon (back-layering) can involve people fleeing towards the mouth of the mountain with dramatic consequences. Since many parameters that characterize the phenomenon are known only with a certain approximation, it is necessary to adopt a probabilistic approach. In this work this approach is illustrated, applying it to a road tunnel in Northern Italy. The probability that the fumes of the fire can reach people fleeing has been plotted as a function of the total number of jet-fans in the tunnel, so that the definition of the ventilation system can be carried out in the design phase in relation to safety during the emergency phase.

1 INTRODUCTION

The risk associated with a fire in road tunnels represents a very complex problem to analyse; it can have severe consequences for the people in the tunnel, who must leave immediately to be safe (Lombardi & Rossi 2013; Guarascio et al. 2009). The ventilation system can be a valuable tool to ensure the safety of people during the early stages of fire evolution and its full development. Especially in one-way road tunnels, ventilation plays a crucial role, containing the amount of fumes that can flow against the direction of fresh air and road traffic, allowing users trapped upstream of the fire to escape on foot against the current towards the tunnel entrance when there are no other escape routes placed in intermediate positions between the fire and the tunnel entrance.

Due to its simplicity and the low costs required, the ventilation system consisting of jet fans anchored to the tunnel's roof or the side walls represents one of the most used solutions in unidirectional road tunnels (Colella et al. 2010; Eftekharian et al. 2014). The jet fans are usually arranged in pairs at various points along the tunnel development.

In order to analyse the effectiveness of such a ventilation system during a tunnel fire, it is necessary to verify its effects on the amount of fresh air pushed along the tunnel and able to cross the point where the fire develops. In particular, it is necessary to understand whether the phenomenon of back-layering can occur, which consists of the flow of part of the toxic and incandescent fumes against the current towards the entrance of the tunnel (Oka & Atkinson 1995; Thomas, 1958; Vauquelin & Wu 2006; Li et al., 2010). This event can cause the most significant risks for people fleeing on foot towards the tunnel entrance: toxic fumes can move at a consistent speed and quickly reach people fleeing on foot.

The parameters governing the back-layering phenomenon are different and also difficult to determine. For this reason, it is helpful to refer to a probabilistic approach, able to consider the uncertainty of these parameters and quantitatively assess the risk of involvement of people on the run. Therefore, the sizing of the ventilation system of a road tunnel could be carried out by

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ensuring that the probability that the toxic fumes can reach a user of the tunnel during the first phases or the full development of the fire is lower than specific values deemed acceptable.

In this work, a probabilistic approach is presented to analyse the influence of longitudinal mechanical ventilation with jet fans during the evolution of a tunnel fire. This approach is applied to unidirectional tunnels of different lengths to evaluate the back-layering phenomenon and verify the possible interaction of fumes with people on the run.

2 FIRE CHARACTERISTICS IN A ROAD TUNNEL

Inside a road tunnel, the three fundamental elements that allow combustion may be present: the fuel, the comburent, and the primer. The fuel is generally made up of the materials transported by the vehicles passing through the tunnel; the comburent from the oxygen present in the air and the ignition may be due to the malfunction of the vehicles or to a collision between them or with systems and components of the tunnel. In some cases, the fire released can be of considerable size, reach very high thermal powers, and last several hours. All this is aggravated by the confinement of space, with very high temperatures of the fumes released, so much to make possible the degradation of the cladding structures and also the consequent collapse of the tunnel in the area of the fire.

In general, starting from the ignition, the fire foresees a phase of increase of the power ends (an increase of the Heat Release Rate HRR) up to the so-called flash-over, after which the fire continues with the emission of a thermal power approximately constant; finally, there is a phase of decay until natural extinction, generally due to the exhaustion of the fuel (Drysdale 2011) (Figure 1).

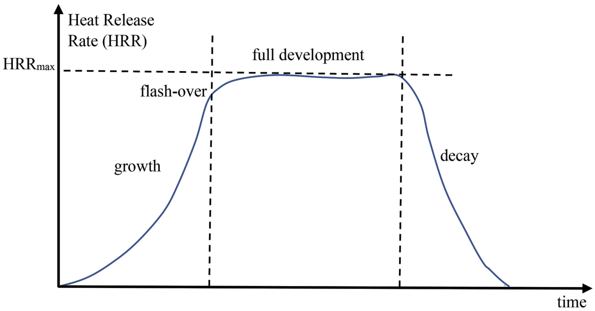

Figure 1. Phases of the development over time of a fire in a confined space (re-edited by Beard & Carvel 2005; Drysdale 2011).

The first phase of the fire, the growth, is critical in road tunnels. In those initial minutes, the thermal power of the fire is still relatively low, and the exodus of tunnel users can begin towards the escape routes. To analyse the possible consequences of a fire on the people present in the tunnel, therefore, attention must be focused on that first phase, which is considered, for simplicity, with a parabola branch with a vertex at the origin of the HRR-time diagram (NFPA 2021; Lombardi 2008). Figure 2 is showing the simulation of this first growth phase of a tunnel fire for different values of the maximum thermal power reached (HRRmax). From the same figure, it is also possible to detect the duration of this phase before it enters the full development of the fire, with thermal powers that remain approximately constant for a relatively long time.

The maximum heat output (HRR_{max}) achieved depends on the characteristics of the fuel present and the amount of oxygen that reaches the fire. Based on in situ experiments and the detailed analysis of fires that occurred in the past in road tunnels, it is possible to associate the HRR_{max} values to the different types of vehicles that can transit (Bettelini 2003):

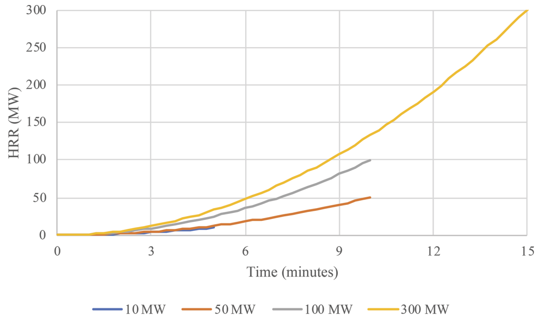

Figure 2. Simulation of the first growth phase of a tunnel fire.

- car/van: HRR_{max}=5-15 MW
- bus: HRR_{max}=30 MW
- loaded heavy vehicle: $HRR_{max} \leq 100$ MW
- heavy vehicle with dangerous goods: $HRR_{max} \leq 300$ MW

The fuel present characterises the fire and the type of material suitable for intervening with the aim of containment or induced extinction. However, each type of fire involves, in addition to the production of heat and flames, the emission of fumes and combustion gases. Incandescent fumes are the biggest problem in road tunnels: their high temperatures, high toxicity if inhaled and reduced visibility, are the leading cause of the loss of life that can occur in the presence of a fire. The amount of toxic fumes produced in the unit of time can also be estimated according to the type of fire and the thermal power reached (Bettelini 2003).

Numerous studies on tunnel fires have been developed in recent years; in addition to simulating with reliable calculation codes (Computation Fluid Dynamics - CFD) the fire inside the confined space, fire tests were carried out in true magnitude, carefully monitored in order to understand its evolution and the consequences in terms of power thermals, temperatures, quantity of fumes. The analysis of catastrophic tunnel accidents at the turn of the new millennium was also instrumental: Mont Blanc Tunnel (France-Italy, 1999, 39 deaths); Tauern Tunnel (Austria, 1999, 12 deaths); St. Gotthard Tunnel (Switzerland, 2001, 11 deaths) (Vuilleumier et al. 2002).

From the analysis of these accidents, it emerged that fires triggered on heavy vehicles carrying dangerous goods (fuels with high calorific value) are hazardous. In these cases, the thermal power of 300 MW was reached and exceeded, and the fire duration was several hours. Due to the high temperatures reached (above 1000°C), the rescue teams could not intervene, and it was necessary to wait for the natural extinction of the fire to allow them to approach the critical area.

The severe consequences of these accidents have highlighted shortcomings in communication with tunnel users to allow them an immediate start of the exodus towards the escape routes. A delay in the activation of the exodus can have severe consequences for the possible involvement of people in the section of the tunnel affected by toxic fumes and high temperatures.

Finally, a fundamental role in safety in the event of a fire can be played by tunnel ventilation. An effective ventilation system can contain or limit the effects of the fire and allow users to be rescued before very high thermal powers are reached.

3 FIRE CHARACTERISTICS IN A ROAD TUNNEL

Different ventilation systems are now used in road tunnels (Li & Chow 2003). In the longer ones, transverse ventilation is generally adopted: two different circuits are provided along the tunnel for fresh air and exhausted air, with autonomous and compartmented regulation systems for individual sections that cover the entire length. In tunnels of small or medium length, longitudinal ventilation tends to be adopted, which is conceptually more straightforward and much less expensive: fresh air enters from one end of the tunnel and is pushed along it through jet fans (Figure 3) until you reach the other end. This system is particularly suitable for one-way tunnels (Colella et al. 2010; Eftekharian et al. 2014): in these cases, the air moves in the tunnel in the same direction as the vehicular flow.

Figure 3. Jet fans positioned in pairs on the roof of a one-way road tunnel (left) and a detailed view of a single jet fan (right).

In the presence of a fire along the tunnel, the jet fans are activated (also automatically, directly by the sensors that detect the fire) at the maximum available power to push the fresh air and the fumes produced along the direction of the vehicular flow. Users downstream of the fire can move away quickly in their vehicles at speeds much higher than the fumes. Those trapped upstream of the fire can undertake the exodus on foot towards the escape routes, opposite the vehicular flow and fresh air moved by the jet fans. In many cases, for tunnels with a length of less than 1.5-2.5 km, the exodus generally involves walking through the entire tunnel until reaching the entrance from which to go out into the open.

Unfortunately, however, a particular phenomenon can occur in these cases: the back-layering of the fumes produced by the fire (Oka & Atkinson 1995; Thomas 1958; Li et al. 2010). It consists of the counter-current movement (upstream) of a portion of the toxic and incandescent fumes in the opposite direction to that of the fresh air entering the tunnel. These fumes initially tend to settle on the roof of the tunnel but quickly involve the entire section at a certain distance from the fire, being able to reach people fleeing, quickly causing their death.

To guarantee the safety of users, it is, therefore, necessary to size the ventilation system (number and characteristics of the jet fans) so that the back-layering phenomenon does not occur or is significantly attenuated so as not to involve the users on the run during the exodus.

This analysis must consider that if the fresh air entering the tunnel (in the area upstream of the fire) has a speed higher than a critical speed v_c, the back-layering phenomenon does not occur. The v_c can be estimated from the following equations (NFPA 502-Annex D, 2017), based on laboratory tests and on a large scale:

$$v_c = K_{Fr} \cdot \sqrt[3]{\frac{g \cdot H \cdot HRR}{\rho \cdot C_p \cdot A \cdot T_f}} \tag{1}$$

where g is the gravity (9.81 m/s^2); H is the tunnel height (m); ρ is the air-specific mass upstream of the fire (kg/m^3), depending on the temperature and atmospheric pressure (1.225 kg/m^3 in standard conditions); C_p is the air average specific heat (kJ/(kg°K)) (1.009 kJ/(kg°K) for standard conditions); Tf is the average temperature of the fire gas (°K), estimated by the following equation:

$$T_f = \frac{HRR}{\rho \cdot C_p \cdot A \cdot v} + T \tag{2}$$

K_{Fr} is the Froude number factor, which can be expressed as a function of HRR in kW by the following expressions:

1. $K_{Fr} \cong 3.7136 \cdot HRR^{-0.157}$ when HRR is between 10,000 and 100,000 kW

2. $K_{Fr} = 0.87$ when HRR ≤ 10,000 kW; KFr=0.606 when HRR ≥ 100,000 kW

The critical speed, therefore, varies during the evolution of a fire by varying the heat output HRR. In the initial phase of growth, it tends to increase until it reaches a limit that depends on the height of the tunnel H.

On the other hand, the actual speed of the air in the upstream section of the fire (v) will tend to decrease with the increase in thermal power. In fact, with the increase of the latter, the temperature of the air (and fumes) downstream of the fire also increases and, therefore, the overall resistance that the air has in moving inside the tunnel. The air velocity is obtained from the equilibrium between the pressure increase provided by the jet fans (Δp_{jf}) (3) and the overall pressure losses due to the friction of the air on the side walls of the tunnel and the other resistances due to the presence of the fire and the inlets (Δp_{tot}) (4).

$$\Delta p_{jf} = \frac{n \cdot \eta \cdot P}{A \cdot v} \tag{3}$$

$$\Delta p_{tot} = \frac{1}{2} \cdot \rho \cdot v^2 \cdot \left\{ 1 + \frac{T_f}{T} + \frac{\lambda}{D_{hyd}} \cdot \left[L_{fire} + \frac{T_f}{T} \cdot \left(L_{tot} - L_{fire} \right) \right] \right\} + \Delta p_{fire} \tag{4}$$

where n is the number of jet fans upstream of the fire (those downstream must be neglected because the high temperatures reached by the fumes can put them out of action quickly); P is the power absorbed by each jet fan; η is the efficiency of the single jet fan; λ is the friction coefficient of the tunnel wall, also known as the Moody coefficient (0.015-0.020 for concrete walls); D_{hyd} is the hydraulic diameter of the tunnel cross-section; L_{tot} is the total length of the tunnel; L_{fire} is the distance of the fire from the tunnel entrance. T_f is the average temperature of the fire gas (°K), defined by the following equation:

A is the tunnel cross section (m^2); Δp_{fire} is the pressure loss concentrated in correspondence with the fire, which can be estimated as a function of the HRR reached: $\Delta p_{fire} \cong 0.4 \cdot HRR$ (Δp_{fire} in Pa and HRR in MW).

By placing the equality between the terms of (3) and (4), the air velocity v upstream of the fire can be obtained by solving the third-degree equation; known v, the air temperature downstream of the fire can be subsequently determined from (5).

The air velocity upstream of the fire is also valuable for evaluating the distance covered by the fumes in the opposite direction to the flow of fresh air (back-layering length L_{bl}); based on experimental evidence, Thomas (1958) obtained the following equation:

$$L_{bl} \cong k \cdot \sqrt[3]{\frac{g \cdot H^2 \cdot HRR}{\rho \cdot C_p \cdot T \cdot v^3}} \tag{5}$$

where k is a dimensionless constant experimentally estimated around 2-2.5 (Oka and Atkinson, 1995); the other quantities expressed in congruent units.

Based on the analysis developed, it is possible to detect how to evaluate the back-layering phenomenon. It is necessary to know many parameters, some of which are known only with a certain approximation. For example, the resistance of the tunnel walls to the flow of air inside it (through the coefficient of friction λ) or the actual localised resistance due to fire (Δp_{fire}). Not only that but also the response of users when they detect the presence of the fire can be assessed with a certain approximation. The escape speed depends, in fact, on the psycho-physical conditions of each person.

In order to be able to analyse organically the risk that the toxic fumes of the fire can reach people during the exodus, a probabilistic treatment is therefore necessary, in which every influential parameter that has an uncertain evaluation can be represented by its probabilistic distribution.

4 A PROBABILISTIC APPROACH TO THE PROBLEM OF BACK-LAYERING OF TOXIC FUMES AND ESCAPING OF USERS TOWARDS THE TUNNEL ENTRANCE

To evaluate the extent of the back-layering phenomenon, it is necessary to evaluate the air velocity v upstream of the fire by placing the equality between the pressure increase produced by the jet-fans (3) and the pressure that the air has in moving along the tunnel (upstream and downstream of the fire), in entering and exiting the tunnel and in crossing the same fire (4). From equality, a third degree equation is obtained, which, when solved with the Cardano method, allows us to obtain v:

$$\mathrm{v} = -\frac{\mathrm{b}}{3\cdot\mathrm{a}} + \sqrt[3]{-\frac{\mathrm{q}}{2} + \sqrt[2]{\frac{\mathrm{q}^2}{4} + \frac{\mathrm{p}^3}{27}}} + \sqrt[3]{-\frac{\mathrm{q}}{2} - \sqrt[2]{\frac{\mathrm{q}^2}{4} + \frac{\mathrm{p}^3}{27}}} \tag{6}$$

where: $p = \frac{c}{a} - \frac{b^2}{3\cdot a^2}$; $q = \frac{d}{a} - \frac{b\cdot c}{3\cdot a^2} + \frac{2\cdot b^3}{27\cdot a^3}$; $a = \frac{\rho\cdot A\cdot L_{tot}}{2\cdot n_{tot}\cdot\eta\cdot P\cdot L_{fire}}\cdot\left(2 + L_{tot}\cdot\frac{\lambda}{D_{hyd}}\right)$

$b = \frac{HRR\cdot L_{tot}}{2\cdot C_p\cdot T\cdot n_{tot}\cdot\eta\cdot P\cdot L_{fire}}\cdot\left[1 + \left(L_{tot} - L_{fire}\right)\cdot\frac{\lambda}{D_{hyd}}\right]$; $c = \frac{0.4\cdot HRR\cdot A\cdot L_{tot}}{n_{tot}\cdot\eta\cdot P\cdot L_{fire}}$; $d = -1$

Once the air velocity upstream of the fire has been obtained, it is possible to compare this with the critical velocity v_c (1): the back-layering phenomenon occurs only if $v < v_c$. Finally, the length of the fumes in the upstream section of the fire is determined with (5).

It is also interesting to check whether the distance traveled by the fumes upstream of the fire is such as to involve people fleeing towards the tunnel entrance. In this regard, it must be borne in mind that before embarking on an escape, people tend to wait for a period of time (t_{wait}) of a few minutes from the start of the fire; it is subjective and therefore varies from person to person. Furthermore, the escape velocity (v_{esc}) is also highly variable from person to person. The users' response must also necessarily be analyzed in probabilistic terms.

The most critical moment is the end of the growth phase of the fire, a few minutes after ignition, upon reaching the maximum power (HRR_{max}). For this it is useful to compare for $t = t_0$ the section traveled by the fumes towards the entrance of the tunnel L_{bl} and the length covered by the people fleeing L_{esc}:

$$L_{esc} = (t_0 - t_{wait})\cdot v_{esc} \tag{7}$$

The risk situation occurs when $L_{bl} > L_{esc}$ at time t = t0.

By carrying out a probabilistic analysis on the particularly uncertain parameters, it is possible to determine the probability that the above condition will occur. The sizing of the fans (their total number n_{tot}, but also the power of each one) can be carried out in relation to the containment of the risk that during a fire in a one-way road tunnel the fumes can reach people fleeing towards the tunnel entrance.

The probabilistic approach was applied to a unidirectional road tunnel in Northern Italy, with a section of 52.5 m^2 (height H = 8 m, width B = 6.56 m) (Figure 4) and a length L_{tot} of 2000 m.

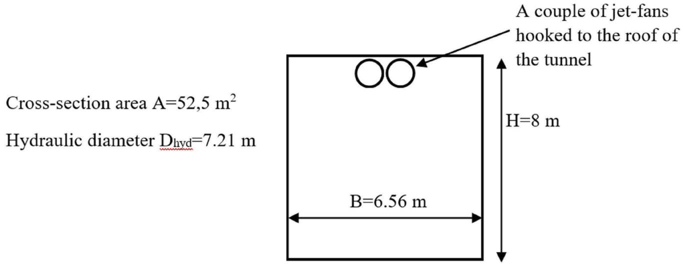

Figure 4. Representative scheme of the section of the studied one-way road tunnel.

The fans used have a maximum nominal power of 21 kW and an efficiency η of 0.6. A fire of vast proportions (HRR_{max} = 300 MW) was considered at a distance of 500 meters from the entrance to the tunnel. The fire was hypothesized with an initial growth phase with a parabolic trend (vertex of the parabola positioned at the origin of the ignition) (Figure 2).

The following parameters were considered uncertain in the analysis: the time of the growth phase t_0, the friction coefficient λ, the Thomas coefficient k (5), the waiting time t_{wait} and the v_{esc} escape rate. For all these, a probabilistic normal distribution (Gaussian) was assumed, the mean and standard deviation of which were obtained by evaluating a range of variability, associated with a 95% probability that the real value falls within it:

– t_0 = 8÷12 min, mean value: 10 min, standard deviation: 1.02 min
– λ = 0.017÷0.023, mean value: 0.020, standard deviation: 0.00153
– k = 2÷3, mean value: 2.5, standard deviation 0.255
– t_{wait} = 3÷5 min, mean value: 4 min, standard deviation: 0.510 min
– v_{esc}=30÷75 m/min, mean value: 52.5 m/min, standard deviation: 11.479

Considering the average values of each variability interval, it is possible to determine the trend of the velocity v and critical velocity v_c (Figure 6) and of the fumes' temperature T_f (Figure 6) over time, during the growth phase of the fire.

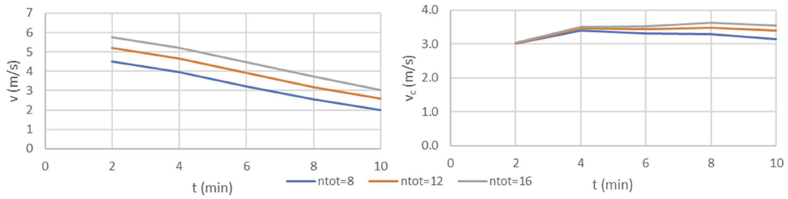

Figure 5. Air velocity upstream (left) and critical velocity (right) of the fire during the growth phase of the fire (n_{tot} = 8, 12, 16).

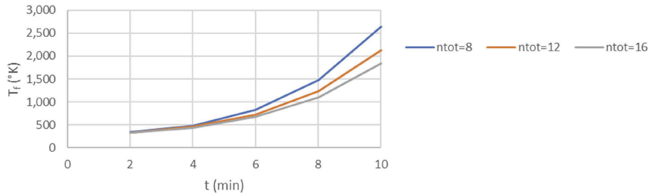

Figure 6. Fumes temperature during the growth phase of the fire (n_{tot} = 8, 12, 16).

10,000 values for each of the 5 uncertain parameters were extracted based on probabilistic distributions. Data extraction is easily accomplished by considering for the specific Gaussian normal distribution the characteristic data of each uncertain parameter (mean and standard deviation). These values samples made possible to use a Monte Carlo procedure and determine at time t = t_0, for every five values group: the air velocity v upstream of the fire, the critical velocity v_c, the back-layering length L_{bl}, the length covered by the people fleeing L_{esc}. The number of cases (out of 10,000 analysed) in which L_{bl} is greater than L_{esc} (probability of the critical event) was then determined.

This probability was then represented by varying the number of jet-fans expected in the tunnel. Figure 7 shows the trend of the probability of the critical event occurring (smoke from the fire reaching people fleeing towards the upstream entrance) as the total number of jet-fans expected in the tunnel varies (n_{tot}).

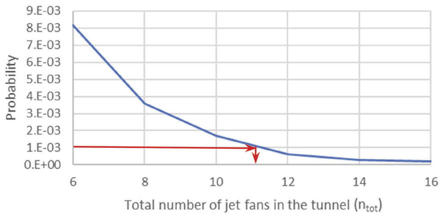

Figure 7. Trend of the probability of the critical event occurring.

If, for example, it is considered acceptable that the probability of the fumes reaching users fleeing in the event of a large fire (HRR_{max}=300 MW) is less than 0.001, it will be necessary to adopt a total number of jet-fans equal to 12.

The illustrated case therefore allows us to show how it can be useful, in the design phase, to define the number and power of the fans, not only to guarantee acceptable environmental parameters in standard operating conditions, but also to allow to keep the probability of critical events occurring during emergency situations (such as a large fire) below acceptable values.

5 CONCLUSIONS

A fire in a road tunnel represents the most serious risk of all those that must be analysed for safety purposes. In one-way tunnels, when longitudinal ventilation with jet-fans is adopted, it may happen that the fumes produced by the fire move in the opposite direction to that of the air entering the tunnel and to the vehicular flow (back-layering), involving the people fleeing towards the mouth of the mountain.

In order to analyse the back-layering phenomenon, a probabilistic approach is necessary due to the presence of many parameters of uncertain evaluation. Even the response of the users of the tunnel cannot be treated in a deterministic way, as both the waiting time before taking the escape and the escape speed itself vary greatly from person to person.

In this work, the probabilistic approach to the problem presented was applied to a one-way road tunnel in Northern Italy. The identified five parameters of uncertain evaluation were represented by probabilistic distributions, used for the random extraction of 10,000 values and the Monte Carlo simulation. The study made it possible to determine the probability that the smoke from the fire reaches people fleeing (a critical event) as the total number of jet-fans present in the tunnel varies. This probability trend allows to define the number of jet-fans to be foreseen in the tunnel to reduce the risk to values that can be considered acceptable.

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