DEVELOPMENT OF A FULL PROBABILISTIC RISK MODEL TO ASSESS THE PERFORMANCE OF LONGITUDINAL VENTILATION SYSTEM FOR FIRES IN TUNNEL

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ABSTRACT

The current paper investigates the coupling of quantitative risk assessment (QRA) methods with one-dimensional (1D) tunnel ventilation models. The coupled approach allows to perform multiple simulations with different fire scenarios with a limited computational cost. This provides a holistic view of the response of the ventilation system in case of fire. The analysis is applied to a case study where four variables are considered in the model: the Heat Release Rate (HRR), the location of the fire, the wind pressure and the effectiveness of the ventilation system to operate on demand (described by the number and reliability of jet fans). The ventilation conditions in the tunnel are analysed considering different number of jet fans installed. The QRA allows to compare the failure probability associated with the ventilation strategy and the number of installed jet fans.

Keywords: Tunnel ventilation, risk analysis, HRR, fire location, wind

1. INTRODUCTION

Tunnels have always been considered strategic structures for the transportation of people and goods. Severe fires occurred in the late 90’s with large damages for the structure and fatalities, (Carvel & Beard, 2005) (Ingason, Li, & Lönnermark, 2015). These disasters led to a renewed interest in fire safety in tunnels with several research projects (Haukur, Kumm, Nilsson, Lönnermark, & Claesson, 2012), (Ingason, Li, & Lönnermark, 2015). These research projects highlighted how fires in tunnels can be more severe than similar fires in an open environment, with HRR peaks higher than 200 MW.

In the design phase the choice of the fire scenario plays an important role in the creation of a fire safety design which meets the objectives and boundary conditions set by the different stakeholders. By means of a deterministic approach, the designer defines one or more fire scenarios that are used to design the ventilation strategy. The choice of the design scenario is either imposed by national regulations or in the case these are not available, the designer relies on his experience and ethics. The quantitative risk based methods provide a possibility to analyse fire safety systems and to take the variety of possible scenarios into account. The latter approach, although more complicated, provides a holistic view of the safety level of the structure (Fernandez, Fraile, Del Rey, & Alarcon, 2013) (Deckers, Lappano, Van Weyenberge, & Merci, 2016) (Van Weyenberge & Deckers, 2014) (Van Weyenberge, Deckers, Caspeele, & Merci, 2018).

With quantitative risk based methods, the ventilation strategy is associated with a failure probability which takes into account the possible fire scenarios with their occurrence probability. Acceptable safety levels and performance criteria can be different, depending on the scope of the project. Where the objective is to assess life safety, results in terms of smoke spread, evacuation times and eventually the number of fatalities are required. The FN curves relate the number of fatalities to the occurrence probability.

In this paper, the scope of the analysis is different, as the evacuation process is not taken into account and the performance criteria are based on the smoke propagation in the tunnel. A longitudinal ventilation strategy works properly if the velocity induced by the ventilation system is greater than the velocity required to confine the smoke (Li, Lei, & Haukur, 2010). Alternative performance criteria could allow a limited smoke backlayering, which can be estimated with (Li, Lei, & Haukur, 2010). In order to estimate the velocity along the tunnel for several scenarios an efficient computational tool is required to simulate the ventilation (Carvel & Beard, 2005). Therefore, a simplified 1D model has been developed to estimate the longitudinal velocity and to consider the effect of the different variables on the flow field in the tunnel. The 1D models have a limited accuracy compared to three-dimensional models. However, in a preliminary design phase it is useful to study several scenarios, rather than giving accurate results for few selected cases.

A case study is designed considering a specific tunnel configuration. The paper presents the failure probability of the ventilation system, linking the results in a straightforward way to the involved variables. The proposed approach provides an overview over the aerolic response of the flow in the tunnel. The sensitivity of the assumptions in the ventilation design are clearly represented. The operational reliability of the ventilation system in the tunnel can be determined, which is useful in the design of new tunnels or to evaluate the safety level in existing tunnels.

2. DESCRIPTION OF THE NUMERICAL MODEL

The 1D models are often used to design the ventilation system in tunnels. However, the results are strongly dependent on the operating conditions and the configuration of the tunnel. The fire load, the atmospheric conditions and the location of the fire cannot be controlled by the designer, who should choose a conservative scenario for the design of the ventilation strategy. If the choice is too conservative the cost of the project will rise due to the high redundancy of the ventilation system. The designer should accept a low level of risk in order to limit the possibility of smoke spread and the installation costs under an acceptable level.

Some input variables are chosen in order to consider the possible operating conditions of the tunnel:

- The wind at the portal can induce an over- or underpressure depending on the wind direction and on its magnitude. The wind conditions are recorded near the site of the tunnel and these data can later be used as boundary conditions at the portals.
- The power of the fire can change depending on the vehicle type. Different values for the HRR are considered for cars, busses or HGV. The HRR of the single vehicle is also combined with the traffic density of the vehicle type.
- The position of the fire affects the temperature distribution along the tunnel and the pressure losses in the tunnel.
- The reliability of the ventilation system, here taken as the number of jet fans operating on demand, has a direct effect on the effectiveness of the system which can be described as the capability of the ventilation system to confine the smoke.

The variables presented before are integrated in a risk model where they are sampled and used as boundary conditions for the 1D ventilation model. The first three variables are considered continuous, so they are sampled using a random model. There are several methods able to sample continuous variables: Monte Carlo Sampling, Latin Hypercube Sampling, Orthogonal Sampling and Sobol Sequences,. The first three methods generate random sequences, while the last one generates quasi-random low-discrepancy sequences. The Latin Hypercube Sampling (LHS) is chosen because of its simplicity and its capability to evenly spread the samples over the domain of research. The possibility of failure of one or multiple jet fans is taken into account in the study with an event tree method. The failure probability of a ventilation system can be calculated by multiplying the probability of failure of the single event by the probability of the event to occur.

$$P_f(u < u_{cr}) = \sum_{i=1}^{n} P(u < u_{cr} | \, scen_i) \; P(scen_i) \qquad \text{Eq. 1}$$

The failure occurs when the longitudinal velocity at the fire section is lower than the corresponding critical velocity and the smoke can spread upstream the fire. The critical velocity is chosen in this paper as the failure criterium, but a reduced backlayering length could be used instead. The critical velocity can be estimated with several methods (Wu & Bakar, 2000) (Li, Lei, & Haukur, 2010) (Oka & Atkinson, 1995) (Thomas, 1958) (Kennedy, 1996), but in the current study the proposed correlation in (Li, Lei, & Haukur, 2010) is used.

$$u_{cr}^{*} = \begin{cases} 0.81 Q^{*1/3} & if \; Q^{*} < 0.15 \\ 0.43 & if \; Q^{*} > 0.15 \end{cases} \qquad \text{Eq. 2}$$

Where u_{cr}^{*} and Q^{*} are the non-dimensional velocity and the non-dimensional HRR, the critical velocity is later corrected for sloped tunnels (Atkinson & Wu, 1996) (Carvel & Beard, 2005).

$$u_{cr}^{*}(\vartheta) = u_{cr}^{*}(0°)(1 + 0.033 \, \vartheta) \qquad \text{Eq. 3}$$

This allows to consider the variation of the critical velocity in the different parts of the tunnels.

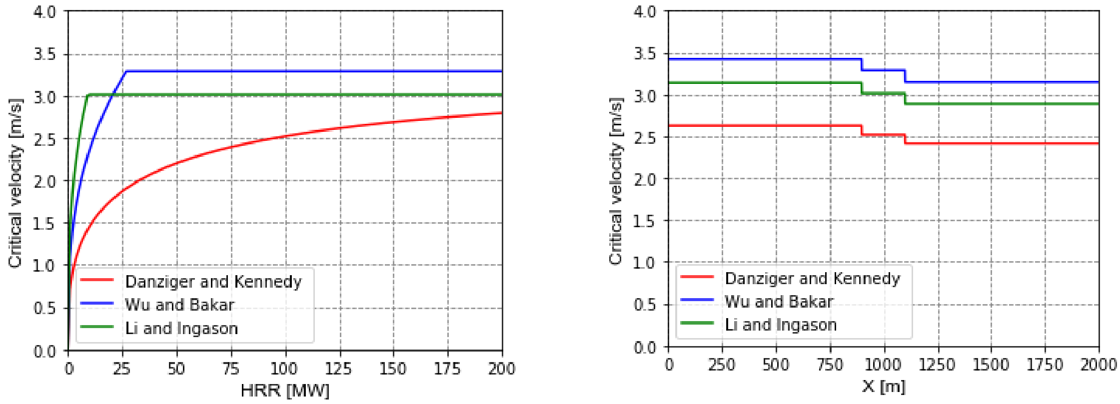

Figure 1: Critical velocity as function of the HRR and of the fire location.

In case a limited smoke backlayering is allowed, this is estimated with the equation proposed in (Li, Lei, & Haukur, 2010):

$$\frac{L}{H} = \begin{cases} 18.5 \ln(0.81 \, Q^{*\frac{1}{3}}/u^{*}) & if \; Q^{*} < 0.15 \\ 18.5 \ln(0.43/u^{*}) & if \; Q^{*} > 0.15 \end{cases} \qquad \text{Eq. 4}$$

The risk model is coupled with a fluid dynamic model which is capable to simulate the tunnel with a 1D approach. The 1D model is chosen due to its suitability for tunnels and thanks to its limited computational cost. The model used in this research was developed at FESG to simulate a single branch tunnel. In a single branch model, the equation of mass conservation is automatically fulfilled. The momentum equation, Bernoulli equation, is solved for steady state conditions along the whole tunnel:

$$\frac{1}{2}\left(f\frac{L}{D_h} + \sum \beta\right)\rho u^2 + \Delta P_{fan} + \Delta P_{fire} + \Delta P_{wind} + \Delta P_g = 0 \qquad \text{Eq. 5}$$

The buoyancy force in the tunnel is modelled with the approach proposed by Merci (Merci, 2008), considering the density of the gas ρ variable as function of the temperature.

$$\Delta P_g = \int_0^L \rho g \sin(\alpha)\, dx \qquad \text{Eq. 6}$$

The pressure rise induced by the jet fans is calculated with a momentum source change (Tarada & Brand, 2009):

$$\Delta P_{fan} = \frac{A_f}{A_t}\rho(u_f - u_t)u_f \qquad \text{Eq. 7}$$

The wind pressure is calculated based on the weather conditions at the portals. The wind velocity and the angle are calculated based on the one site measurements. The wind pressure at the portals is calculated as:

$$P_{wind} = \frac{1}{2}\rho\, u_{wind}^2\, c_p \qquad \text{Eq. 8}$$

The coefficient c_p is calculated based on (Blendermann, 1975), **Figure 2**, for a given wind condition the pressure difference at the portals is calculated, **Figure 3**. A negative pressure induces a velocity that is opposite to the ventilation flow, while a positive pressure induces a velocity in the same direction to the ventilation flow.

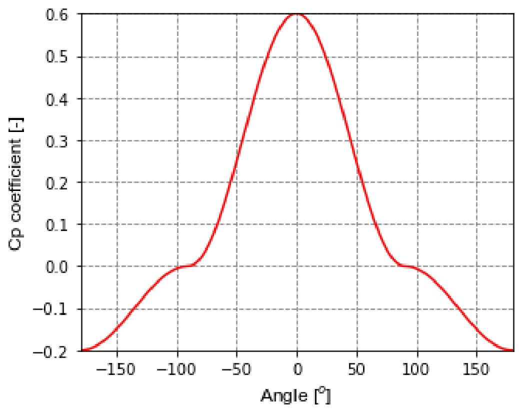

Figure 2: Wind pressure coefficient.

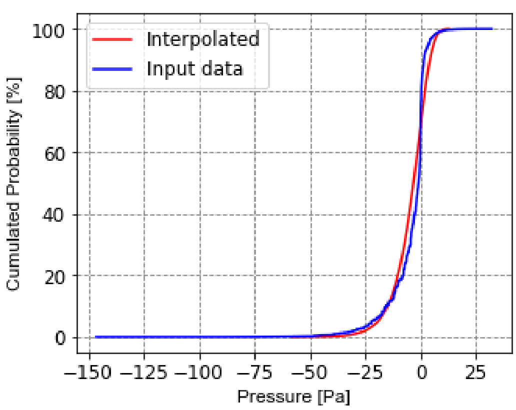

Figure 3: Cumulative wind pressure distribution.

The heat losses through the walls of the tunnel are not calculated by solving the energy equation, but are modelled with a simplified approach proposed by Ingason (Carvel & Beard, 2005). The temperature rise induced by the fire is equal to:

$$\Delta T_{fire} = \frac{2\dot{Q}}{3\,\dot{m}\,c_p} \qquad \text{Eq. 9}$$

While the temperature decay downstream the fire is described by the following equation:

$$T(x) = T_{Amb} + \Delta T_{fire}\exp\left(-\frac{hPx}{\dot{m}\,c_p}\right) \qquad \text{Eq. 10}$$

The current approach solves the equation controlling the fluid motion in a simplified way. But in this study several simulations are required, therefore these simplifications are acceptable. The results of the 1D model have been compared with those provided in (Carvel & Beard, 2005)(Merci, 2008) in order to evaluate the capabilities of the proposed model. However, the results are not reported here for sake of brevity.

The fire load in the tunnel changes depending on the vehicles that are allowed in the tunnel: cars, busses and trucks. The possible fire loads in the tunnel are related to the traffic conditions and to the HRR of the single vehicle. The traffic conditions considered for this specific case-study are summarized in **Table 1**.

Table 1: Traffic conditions in the tunnel

Vehicle	Car	Bus	HGV	Tanker
HRR average	7 MW	30 MW	100 MW	200 MW
Traffic %	70 %	20 %	8 %	2 %

The values of the HRR for the different vehicles are calculated based on (Ingason, Li, & Lonnermark, 2015) (NFPA 502, 2010) (Yuguang & Spearpoint, 2007). The distribution of the HRR for the given traffic conditions is presented in **Figure 4** and **Figure 5**.

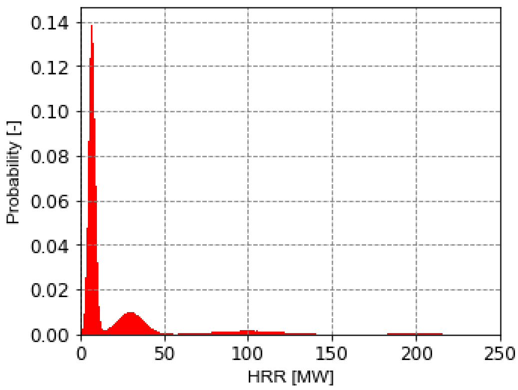

Figure 4: HRR of vehicles.

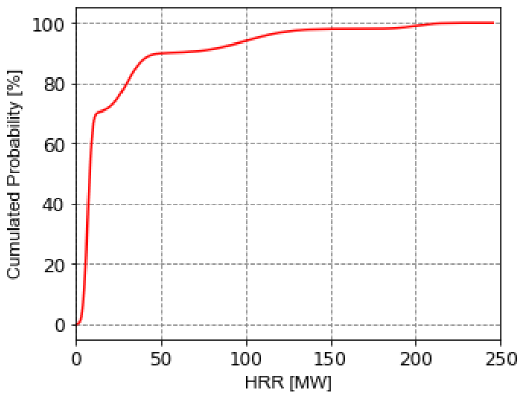

Figure 5: Cumulated distribution of HRR.

3. DESCRIPTION OF THE TUNNEL UNDER INVESTIGATION

The case study proposed in the paper is a road tunnel dug under a river or a canal. The tunnel is 2.0 km long and it has a V shape, the lowest point of the tunnel is at -20 m with respect to the portals, **Figure 6**. The orientation of the north portal is -135° and the orientation of the South portal is 45°, **Figure 7**.

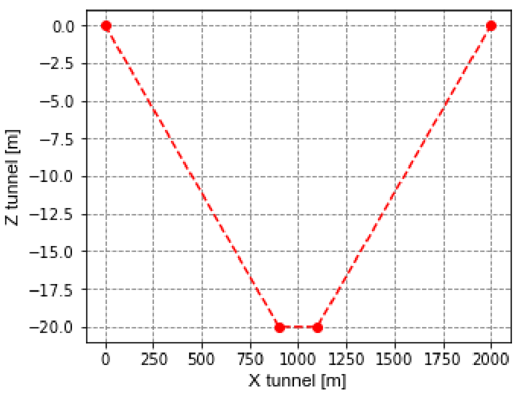

Figure 6: Tunnel's z-profile.

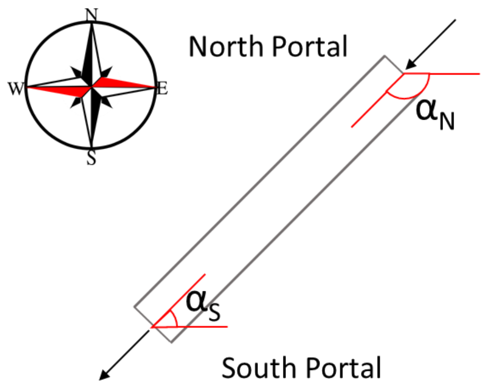

Figure 7: Orientation of the tunnel.

The cross section of the tunnel is rectangular and constant along the length of the tunnel, **Figure 8**. The width of the tunnel is 11.0 m and the height is 5.0 m, in the tunnel there are 3 lanes plus a pedestrian way for evacuation. The hydraulic diameter of the tunnel is 6.875 m and the area of the cross section is 55 m^2. **Figure 8** shows that there is no space to allocate the jet fans above the traffic lanes. There is only 1.3 m available on the side due to the space required for the installation, 0.2 m. The installed jet fans have an external diameter of 1.3 m and an internal diameter of 1.1 m, the discharge velocity is 30 m/s and the installation efficiency 0.80 (Beyer, Sturm, Saurwein, & Bacher, 2016) (Rijkswaterstaat, 2005).

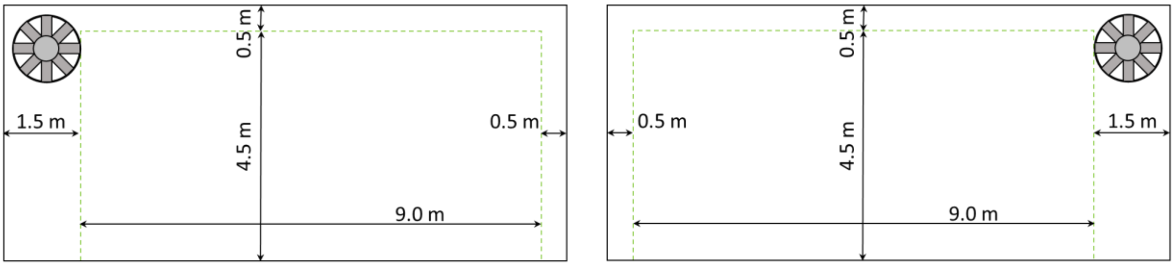

Figure 8: Cross sections of the tunnel.

4. RESULTS

In the case study different configurations are investigated. First, the number of jet fans operating on demand is modified in order to show how the probability of failure (being described as not reaching the critical velocity) changes. Before executing the simulations, it is necessary to perform a sensitivity analysis to evaluate the reliability of the calculation. The accuracy of the calculation varies with the number of evaluated samples. Therefore, it is necessary to determine the minimum number of samples required to perform an analysis which is independent from the number of chosen samples, **Table 2**.

Table 2: Sensitivity analysis for the Latin Hypercube Sampling method.

N sample	10	100	1’000	10’000	100’000	1’000’000
Failure	1	3	67	708	6928	69496
Failure %	10 %	3 %	6.7 %	7.08 %	6.928 %	6.9496 %
Error %	3 %	4 %	0.3%	0.13 %	0.022 %	-
Time	3 s	5 s	37 s	246 s	2196 s	21056 s

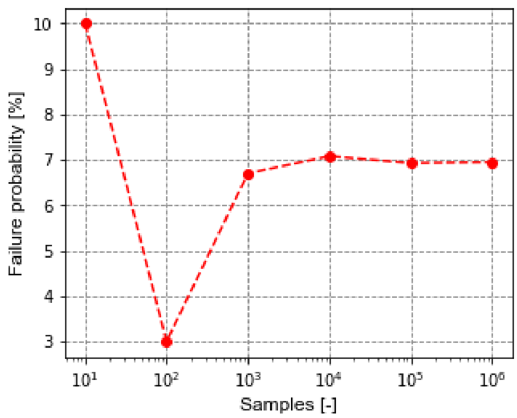

Figure 9: Sensitivity analysis: failure probability.

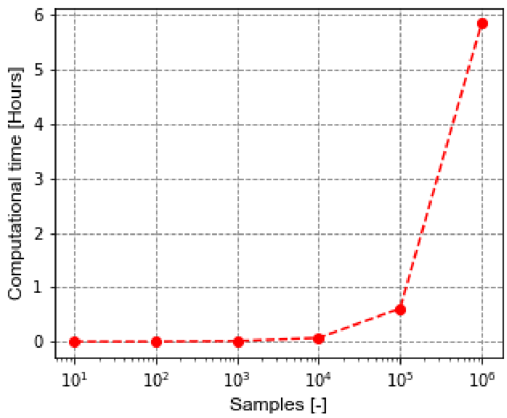

Figure 10: Sensitivity analysis: computational time.

The failure probability is presented as function of the number of samples in **Figure 9**. The computational time grows together with the size of the samples; therefore, it is necessary to make a trade-off between the accuracy of the method and the computational time. Due to low discrepancy between the results obtained with 10^5 and 10^6 samples, about 0.02%, the fist sample size is chosen for the next analysis.

The tunnel is simulated with different number of jet fans operating on demand. The results are later combined together in order to consider the effect of the failure of some devices. This is done by combining the failure probability in the tunnel with less jet fans installed and the reliability in terms of operating on demand. The probability of one jet fan to fail on demand (maintenance) is assumed to be 5%. The probability of two jet fans to fail on demand is 0.25% and the probability of all jet fans operating on demand is 94.75%. The total probability of failure of one configuration with n jet fans is:

$$P_f(u < u_{cr}) = P_f(u < u_{cr})\big|_{n_b} 0.9475 + P_f(u < u_{cr})\big|_{n_b-1} 0.05 + P_f(u < u_{cr})\big|_{n_b-2} 0.0025 \qquad \text{Eq. 11}$$

In order to reduce the complexity of the model once there is a failure of one of the jet fans, the remaining ones are evenly distributed along the tunnel. This simplification avoids the addition of another variable which controls the jet fans that is not operating on demand.

Table 3: Failure probability.

N jet fans	Simple P_f	Combined P_f
0	98.9 %	98.9 %
1	96.0 %	96.2 %
2	78.8 %	79.7 %
3	46.2 %	48.0 %
4	23.3 %	24.6 %
5	12.1 %	12.7 %
6	7.8 %	8.1 %
7	4.9 %	5.1 %
8	3.4 %	3.5 %
9	2.7 %	2.7 %
10	2.2 %	2.2 %

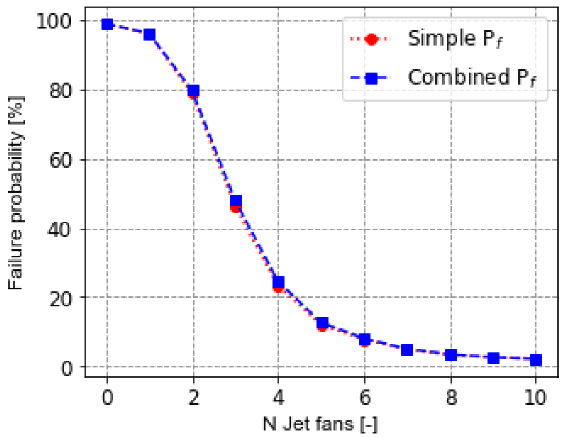

Figure 11: Failure probability as function of the number of installed jet fans.

In **Figure 11** and **Table 3** the failure probability for different jet fans configurations is presented. The failure probability is presented before and after taking into account the failure probability of some jet fans. The results show that the increase of failure probability is limited when the jet fans' reliability is taken into account, less than 2%.

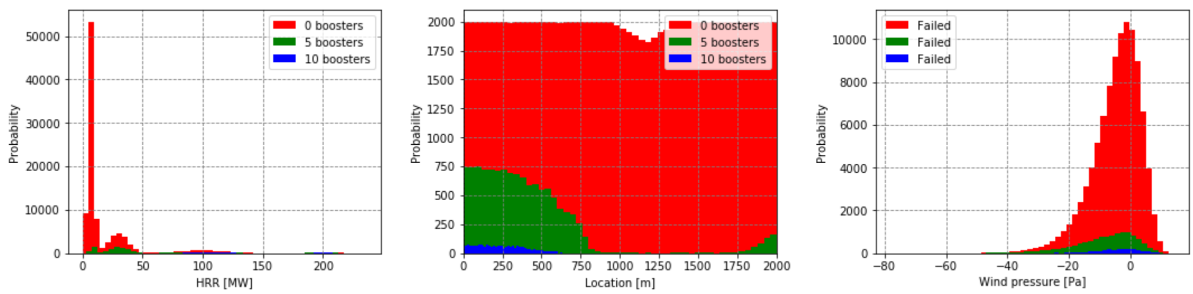

Figure 12: Probability distributions for HRR, fire location and wind pressure with 0, 5 and 10 jet fans.

The results are presented also in a graphical way showing the operative conditions that lead to a failure of the ventilation system for few selected configurations, **Figure 12**.

5. DISCUSSION

The results from the case study indicate that by increasing the number of jet fans, the risk of smoke spread and associated backlayering decreases **Figure 11**. However, this information doesn't give a complete understanding of the response of the ventilation to a fire event. The possibility to combine several parameters for a specific tunnel allows to define design criteria specific for each project, new or existing. On top of that the developed model allows to answer questions relevant to many parties. For instance, what is the maximum design fire that a specific ventilation system is able to handle? And how does this change if not all the jet fans are available? The largest fire where the ventilation system will still avoid back-layering can then be determined based on the available number of jet fans. **Figure 13** describes, how for a ventilation system with 10 available jet fans, the maximum HRR is around 28 MW when the most conservative location in the tunnel and the most conservative wind conditions are taken into account. If 1% of the scenarios (combinations of wind load and fire location in the tunnel) are allowed to have smoke spread larger than the objective (no back-layering), than it is possible to increase the HRR limit to 60 MW. Similarly, if 5% of the cases are allowed to be exceeded, then the largest fire is 75 MW.

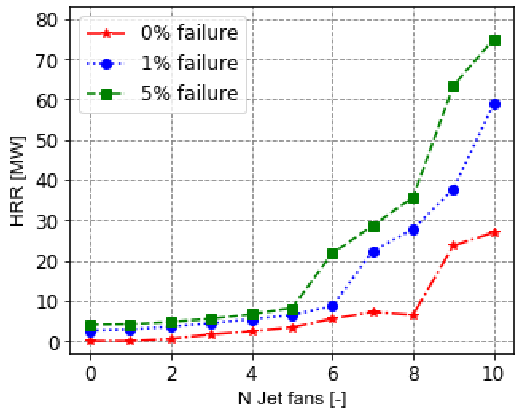

Figure 13: Critical HRR for different failure probabilities.

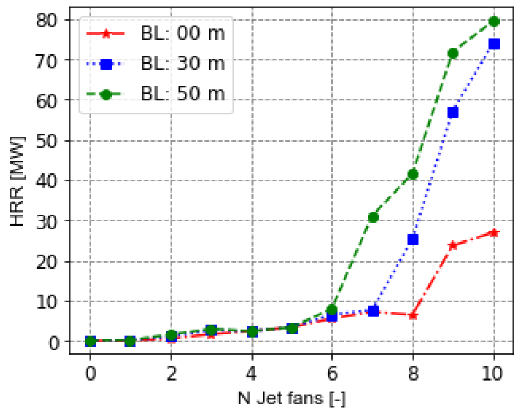

Figure 14: Critical HRR for different performance criteria.

Until now the ventilation was considered to fail if the critical velocity was not reached, but a limited backlayering length can be also used as a design criteria. When is it acceptable to have some back-layering and to what extend? In order to tackle this problem, also the performance criteria was taken as a variable. This can typically range from no back-layering to 30 m or 50 m. It is the authors' point of view the proposed criteria might be acceptable depending on the case, as long as the stratification is maintained (has to be proven by CFD). Allowing a backlayering length of 30 m or 50 m it is possible to extend the acceptability range for the ventilation system. The maximum HRR considered to be safe for a given ventilation configuration is presented in **Figure 14** for different accepted backlayering lengths. Adjusting the performance criteria for smoke spread and allowing a limited back-layering the ventilation system can still operate successfully for larger design fires. Therefore, the critical HRR that is confined by the ventilation increases allowing a larger backlayering length.

The wind pressure plays an important role in the tunnel and affects the longitudinal velocity in the tunnel. Strong wind at the portals have a low probability to occur, **Figure 3,** because these values lay on the tails for the probability curve. In deterministic design, typically the 90 or 95 percentile of the wind is taken into account. If the wind pressure exclude those extreme values that have low probability to occur the largest fire where the ventilation system will still avoid back-layering increases, **Figure 15**. The combination of different performance criteria and boundary conditions allows to create different limit conditions for the HRR, **Figure 16**.

Accepting a limited backlayering and excluding the extreme wind conditions it is possible to extend the critical HRR for all the different ventilation configurations. Considering the configuration with 10 jet fans the maximum HRR increases from 27 MW to 74 MW when allowing 30 m backlayering and limiting the wind conditions between 5 and 95 % of the cases. The maximum HRR can be further extended to 79 MW allowing 50 m backlayering and limiting the wind conditions between 10 and 90 % of the cases.

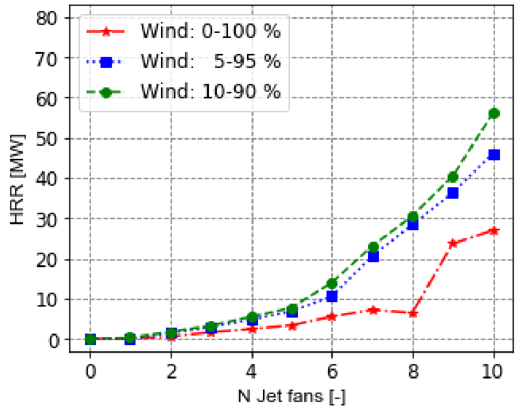

Figure 15: Critical HRR for different wind pressures.

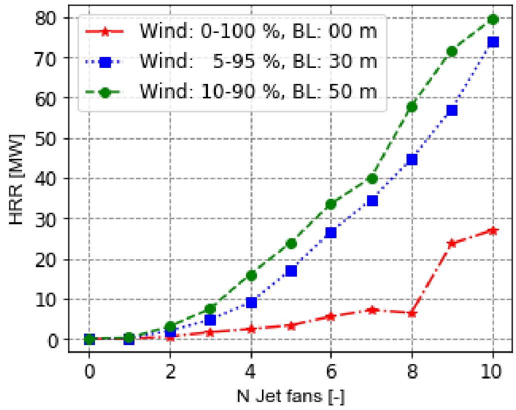

Figure 16: Critical HRR for different back-layering lengths and wind pressures.

6. CONCLUSIONS

The current paper presents the capabilities of a combined tool for the analysis of the ventilation in tunnels. A risk assessment method is combined with a one-dimensional model for the analysis of the longitudinal ventilation in case of fire. With the risk analysis the operative conditions of the tunnel were varied based on the possible fire scenarios (position and HRR), weather conditions (wind pressure), and effectiveness of the ventilation system to operate on demand (described by the number and reliability of jet fans). The approach shows in a quantitative way how the probability of the ventilation failure is influenced by the number and reliability of the jet fans. The results allow to evaluate the maximum fire size that a specific ventilation system is able to handle. It is possible to represent the largest fire size where the back-layering will be limited (e.g. 30 m) and the wind pressure is not exceeded in 90% of the time. The current approach can be used to verify the operative conditions of tunnels which are already built providing a holistic view of the response of the ventilation system to the fire event. The current method could also be used also to design a new tunnel or to determine the cost-benefit of limiting the residual risk (extreme wind) in discussions on the acceptable risk level. This allows the designer to support the decision maker and client in setting up the functional requirements on design and minimal operating conditions.

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