

ACCEPTANCE CRITERIA FOR DESIGN OF LONGITUDINAL VENTILATION SYSTEMS IN ROAD TUNNELS: THEORETICAL FRAMEWORK

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ABSTRACT

This paper investigates the relationship between fire risk and tunnel ventilation and its integration into the ventilation design process. Longitudinal ventilation is commonly applied in road tunnels with unidirectional traffic, as it confines smoke downstream of the fire and protects road users upstream of the incident. The risk of fatalities among road users in case of fire is primarily associated with the potential smoke propagation and exposure of road users. In addition, elevated temperatures during tunnel fires may cause damage to structural and electro-mechanical components, resulting in economic losses.

Both life safety and economic risks are related to the installed ventilation capacity and to air velocity in the tunnel for different fire sizes, fire locations and wind conditions. Two formulations are derived to quantify the equivalent risk indicators for road users and for the structural damage. These indicators are expressed as functions of tunnel geometry, traffic intensity, and traffic composition, enabling specific risk evaluation for each tunnel.

The proposed indicators are then applied to a case study in which the same tunnel is analysed under different traffic conditions. The results show that the tunnel ventilation design should not be based solely on critical velocity evaluation; but it should also consider other factors such as traffic conditions and tunnel connectivity. A comprehensive design should address both the risk associated with road user safety and with the business continuity in the event of a fire.

Keywords: Tunnel ventilation, risk, life safety, business continuity.

1. INTRODUCTION

Tunnel ventilation has been widely investigated as a safety measure to protect road users. Historically, ventilation was required to maintain acceptable air quality levels within tunnels [1]. However, as vehicle emissions progressively decreased, this problem became less severe. Conversely, catastrophic fires that occurred in tunnels have revealed new risks to road users and the infrastructure [2]. Mechanical longitudinal ventilation is typically required above a certain length and/or traffic intensity in road tunnels. However, its design is independent of the traffic conditions and the tunnel's functional role within the road network [3]. A longitudinal ventilation system is a widely adopted solution for unidirectional tunnels because it allows smoke to be confined downstream of the fire and protects road users [4]. In recent years, research has primarily focused on the calculation of the required velocity to confine or limit smoke spreading upstream of the fire [5][6][7]. This paper proposes a risk-based

framework for the design of the ventilation system that integrates the road-user safety and structural integrity risks in the design process.

2. ACCEPTABILITY CRITERION BASED ON LIFE SAFETY

The risk of fatalities due to fires in tunnels is commonly investigated with quantitative risk analyses [8]. However, these are often uncoupled from the design of the life safety systems. A longitudinal ventilation system is often installed in unidirectional tunnels because of its effectiveness and lower cost when compared to other solutions [12]. A longitudinal ventilation system confines smoke downstream of the fire, keeping a tenable environment upstream where road users may be trapped assuming no traffic congestion, **Figure 1**. The longitudinal velocity which confines the smoke downstream of the fire is referred to as critical velocity.

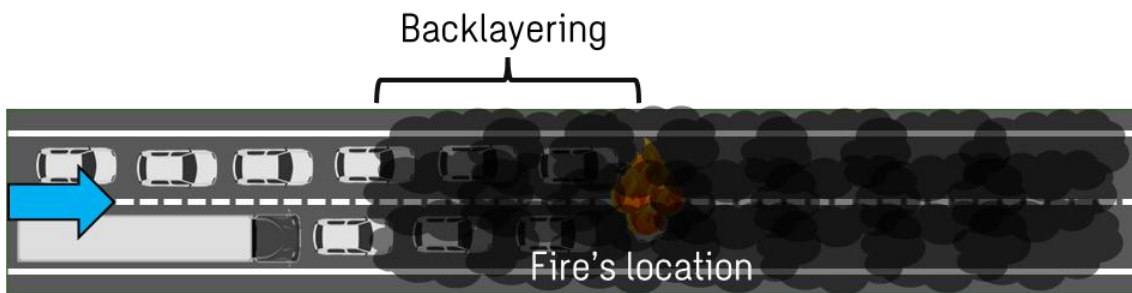


Figure 1: Schematic view of the ventilation conditions.

In several countries, the ventilation system is designed to guarantee that the longitudinal velocity in the tunnel exceeds the critical velocity in 95% of scenarios [10][11][12]. This residual risk accounts for unfavourable wind conditions or fire locations when the velocity does not meet the required criterion.

Nevertheless, applying a fixed acceptance criterion for the longitudinal ventilation design in tunnels with different traffic conditions results in different safety levels in case of fires. Tunnels with high traffic volumes and large fractions of heavy good vehicles (HGV) have higher frequencies of larger fires than tunnels with low traffic intensities and a higher fraction of passenger cars. Therefore, a fixed acceptance criterion might under-protect tunnels with higher fire risks while it overprotects tunnels with lower fire risks.

To address this limitation, the ventilation system should be designed to guarantee a consistent risk level for road users in case of fire among different tunnels. The risk per unit of length for road users R_f [n_f/year/km]. can be used as a design criterion. This is calculated as the sum of different risks that combine the consequences and the frequencies of different fire scenarios (S) as in the equation below:

$$R_f = \sum_S F_f N_f < R_{lim,f} \quad (1)$$

where F_f is the frequency of fire scenarios per unit of length [1/year/km] and N_f is the number of fatalities associated with them [n_f]. The scenarios (S) represent the different events that can occur in the tunnel as combinations of fire size, fire location, wind conditions. The risk R_f should be limited to an acceptable level $R_{lim,f}$ [n_f/year/km]. The limit risk can be represented as societal risk which is a function of number of fatalities and frequency or as individual risk which can be treated as a constant [13]. For the sake of simplicity in this first study, individual

risk is used, but conclusions are still valid with societal risk. The frequency of fires per unit of length F_f [1/year/km] is calculated in the equation below:

$$F_f = \sum_S f_S I_S = f C S N_{lanes} \sum_S X_S \quad (2)$$

The frequency of fire for a specific type of vehicle associated to the scenario S is the product of the number of vehicles driving through the tunnel I_S [veh/year] times the frequency of fires per driven kilometre f_S [1/veh/km]. The fire frequency is assumed to be constant for different types of vehicles in first instance (f) [1] so the equation can be rewritten as function of the traffic composition X_S [-], the number of lanes in the tunnel N_{lanes} [-], the lane's capacity C [veh/year] and the traffic saturation factor S [-].

The number of fatalities for a specific fire scenario is proportional to the number of road users exposed to untenable conditions in the specific scenario. Assuming the longitudinal ventilation system blows smoke downstream of the fire and road users are only blocked upstream of the fire, fatalities can occur when extensive backlayering takes place. The number of fatalities is calculated in the equation below:

$$N = D_{Occ} N_{lanes} \min(BL_S, x_{fire}) \quad (3)$$

For a specific scenario, the number of fatalities can be estimated as first approximation as the product of the number of lanes N_{lanes} (that represents the number of rows of vehicles impacted) times the backlayering length BL [m], times the occupants' density D_{Occ} [pers/m]. In this study, BL is computed as a function of longitudinal velocity and tunnel geometry following reference [5]. Near the entry portal the backlayering can exceed the distance between the fire and the portal itself. In this case the affected zone is the minimum between the position of the fire measured from the entry portal and the backlayering length. The total risk obtained combining the equations above is written below:

$$R = f C S D_{Occ} N_{lanes}^2 \sum_S \min(BL_S, x_{fire}) X_S \quad (4)$$

In the equation above, the fire frequency per kilometre, the lane's capacity and the occupant density are assumed to be constant values. The saturation factor, the number of lanes and the fractions of vehicle types are specific to the tunnel. The backlayering length is a function of the fire scenario, the ventilation system, the tunnel geometry, and the wind conditions. A simplified risk index R_{eq} [m] is derived from the equation above:

$$R_{eq,f} = \frac{R_{lim,f}}{f C D_{Occ}} = S N_{lanes}^2 \sum_S \min(BL_S, x_{fire}) X_S \quad (5)$$

From the formulation above the following conclusions can drawn:

- The risk can be computed for the whole tunnel as an average risk over the length or locally for each fire location.
- The ventilation system has a direct impact on the backlayering length, the stronger the ventilation regime the lower the backlayering length and the equivalent risk.
- The traffic composition has a direct impact on the risk because a larger share of HGV (high Heat Release Rate (HRR)) increases the risk of larger fires while a larger share of light vehicles (low HRR) reduces this risk.

- The risk is proportional to the traffic intensity, the risk is linear in the saturation factor which ranges between 0 and 1 and quadratically proportional to the number of lanes. A larger number of lanes means that more road users are exposed to smoke and that the tunnel has more traffic.
- The risk is not a function of the tunnel's length because the risk is calculated per running km. Nevertheless, in short tunnels the risk is limited by the proximity of the fire to the entry portal.
- Fire locations close to the entry portal are less critical for the risk profile of the tunnel because the fire exposes less road users. Fire scenarios near the entry portal can be critical for the ventilation design of sunken tunnel which have large slopes near the portals.

On the other hand, this approach also requires simplifications to be applicable in a design process:

- The presence of emergency doors along the tunnel or means to stop the traffic outside the tunnel are not considered in the proposed formulation.
- At very low traffic intensities the model can overestimate the risk because it computes the backlayering length, however, the tunnel might be still empty because there are no vehicles in the tunnel or entering the tunnel.
- The calculation of the risk is a function of the traffic intensity and composition which can vary over time while the design should be valid for few decades. This requires foreseeing variations in traffic intensity and composition over a large span of time.
- The backlayering length provides a simple formula to correlate the longitudinal speed in the tunnel with the estimated number of fatalities. However, this can be overly conservative, because if the smoke layer does not remain high above road users it does not pose a direct threat to them. A more accurate estimate would require extensive CFD analyses that are specific for a specific tunnel geometry, and this is impractical for the purpose of the tunnel ventilation design. In this paper the formulation proposed by Ingason [5] is used to calculate the backlayering length as function of the tunnel's geometry and the longitudinal velocity.
- The reliability and availability of the ventilation system is not accounted in the current formulation. All the jet fans are assumed to work correctly if the temperature remains within the operating range.
- The acceptable risk is not discussed and investigated in this paper because other stakeholders should be involved in the discussion as well. It is also not decided whether the maximum risk along the tunnel or the average risk should be used as design criterion.
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3. ACCEPTABILITY CRITERION BASED ON BUSINESS CONTINUITY

When designing ventilation systems for tunnels, it is also crucial to consider the consequences of the tunnel closure after a fire. The tunnel closure causes direct costs due to the required refurbishment and indirect costs due to increased travel time and possible lost income [17]. The economic risk associated with tunnel closure can be used as design criterion to effectively protect the tunnel as an infrastructure in the road network. The acceptable economic risk R_b [€/year] should be limited to an acceptable value ($R_{lim,b}$) [€/year].

$$R_b = \sum_S F_b N_b < R_{lim,b} \quad (6)$$

where F_b is the frequency of fire in the whole tunnel [1/ year] and N_b are the consequences [€]. In Eq (2), the frequency of fire F_f is normalized per unit length, while Eq. (7) calculates the total frequency of fire for a specific tunnel considering its length.

$$F_b = L \sum_S f_S I_S = Lf C S N_{lanes} \sum_S X_S \quad (7)$$

Where L is the length of the tunnel [m]. The consequences (N_b) in this case are not fatalities, but economic losses and are calculated as the product of the length of the damaged zone requiring repair (D_S) [m] and the economic loss associated with damage of the tunnel per unit length [€/m]. In Eq (8), the direct and indirect cost are both proportional to the length of fire damage in the tunnel. Direct costs are the cost of repair of both the structure and the equipment of the tunnel. The direct costs are generally much lower in magnitude than the indirect costs [18][19] and therefore have been ignored in the current study for simplification. Considering that the tunnel needs to be closed during the repair process, the indirect costs can be linked to the amount of traffic (I) that must be redirected, the time loss per road user (Δt_i) [h] associated with the tunnel's closure during repair.

$$N_b = \sum_S D_S I \Delta t = \Delta t C S N_{lanes} \sum_S D_S \quad (8)$$

When combining Eq (7) and Eq (8), the risk for loss of business continuity can be evaluated as follows:

$$R_b = Lf C^2 S^2 N_{lanes}^2 \Delta t \sum_S X_S D_S \quad (9)$$

In the equation above, the fire frequency per unit length (f) and the lane's capacity can be assumed constant. The length of the tunnel, the saturation factor, the number of lanes and the traffic composition are specific to the tunnel, while the length of the damage zone is function of the smoke temperature. A stronger longitudinal flow can enhance the cooling effect on the smoke and limit the damages associated with elevated temperature in the tunnel. Considering these aspects, a simplified risk index $R_{eq,b}$ [m²/h] is obtained as:

$$R_{eq,b} = \frac{R_{lim,b}}{C^2 f} = L S^2 N_{lanes}^2 \Delta t \sum_S X_S D_S \quad (10)$$

Similar conclusions from the formulation for life safety can be drawn also for structural safety but with some differences:

- The impact of tunnel length appears explicitly in the risk formulation because a fire at any point of the tunnel can force closure of the entire infrastructure.
- Risk is quadratically proportional to the traffic intensity, since traffic affects both fire frequency and the number of road users who must be rerouted when the tunnel is closed.
- Network robustness is accounted for via the difference in travel times with and without the tunnel. Isolated tunnels with few alternatives have higher rerouting times — and thus higher risk — than urban tunnels with multiple alternative routes.
- Ventilation affects the extent of damage: higher longitudinal flow can cool smoke, reducing the zone exposed to damaging temperatures.

The proposed approach also requires assumptions and simplifications:

- The damaged length is estimated from average tunnel temperature. This may be inaccurate near the fire source, where a one-dimensional model underestimates peak temperatures; the choice of critical temperature for damage requires further study.
- The impact of fire fighters' operations trying to suppress the fire or the impact of active fire protection are not considered.
- Other damages (e.g. explosions) are not accounted for in the current study but should be considered in tunnel design decisions if relevant.

4. APPLICATION OF THE PROPOSED CONCEPT TO A SAMPLE TUNNEL

The proposed approach to tunnel ventilation design is applied to a sample tunnel. The tunnel is 600 m long, 11 m wide and 6 m high with two traffic lanes. The tunnel is flat and has no longitudinal grade. The tunnel is equipped with jet fans at the entry portal and each fan has a nominal thrust of 1000 N. Different ventilation configurations are investigated for this exercise by varying the number of jet fans: 2, 4, 6 and 8.

Three different fire scenarios are evaluated: a car fire with an HRR of 10 MW, a bus or small truck fire with a HRR of 30 MW, and a HGV fire with a HRR of 200 MW [12][7][20].

The tunnel is simulated with a one-dimensional tunnel ventilation model considering the different fire sizes, fire locations, wind speeds and directions. A total of 3,180 simulations were performed to cover the combinations of variables for each jet-fan configuration. The model provides distributions for the different scenarios of the temperature, velocity and backlayering length inside the tunnel.

The critical velocity and the backlayering lengths are calculated for the different fire sizes with the formulation proposed in [7]. The critical velocity is close in all scenarios when referred to the gross tunnel area because of the different obstruction factors created by the vehicles. The critical velocity referred to the net area is presented for the sake of completeness, but it is not used.

Table 1: Critical velocity for the different fire scenarios.

Fire scenario	Obstruction area	Critical velocity (gross area)	Critical velocity (net area)
10 MW	3 m ²	2.77 m/s	2.90 m/s
30 MW	10 m ²	2.80 m/s	3.30 m/s
200 MW	10 m ²	2.80 m/s	3.30 m/s

4.1. Car fire scenario 10 MW

The median longitudinal speed, Figure 2, and the median backlayering length, Figure 3, are calculated for different wind conditions and are presented as a function of the fire location for the fire scenario of a burning car 10 MW

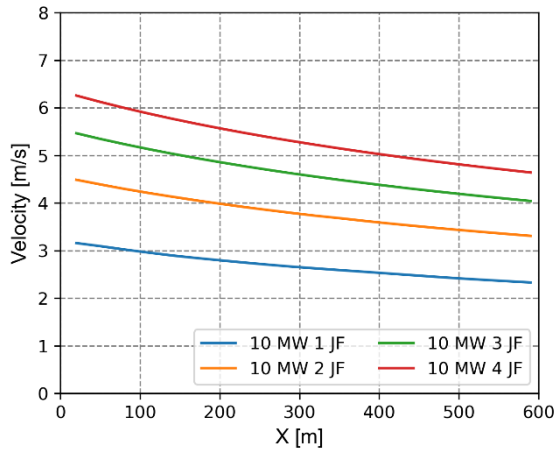


Figure 2: Longitudinal velocity as function of the fire location (scenario Car fire 10 MW)

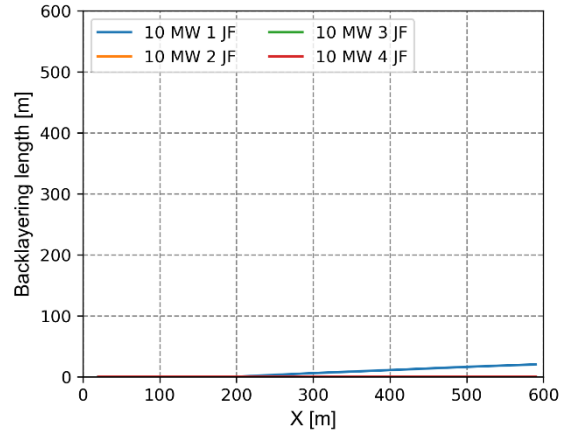


Figure 3: Backlayering length as function of the fire location (scenario Car fire 10 MW)

The cumulative distributions of the longitudinal velocity considering for ventilation configurations are presented in Figure 4. The length of the tunnel where the average temperature exceeds 400 °C is considered damaged and is shown for different ventilation configurations in Figure 5. The damaged length is negligible in this case due to the limited temperature rise induced by the fire.

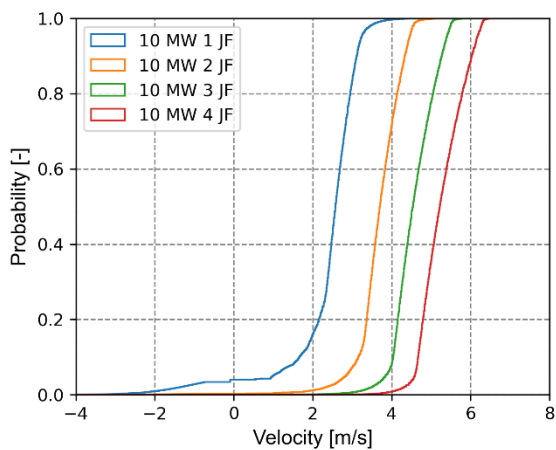


Figure 4: Distribution of the longitudinal velocity for a car fire.

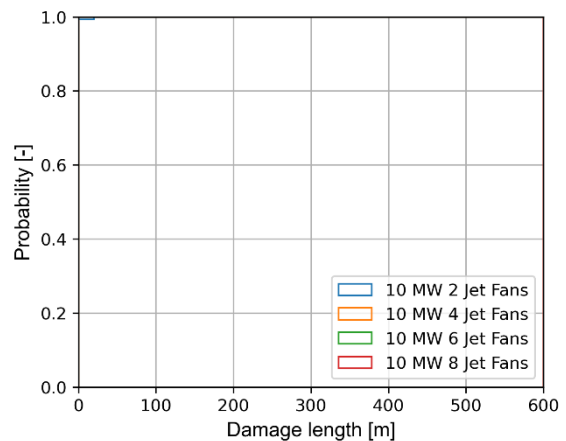


Figure 5: Distribution of the damaged length for a car fire.

4.2. Bus fire scenario 30 MW

The median longitudinal speed, Figure 6, and the median backlayering length, Figure 7, are presented for the fire scenario of a burning bus or small truck 30 MW.

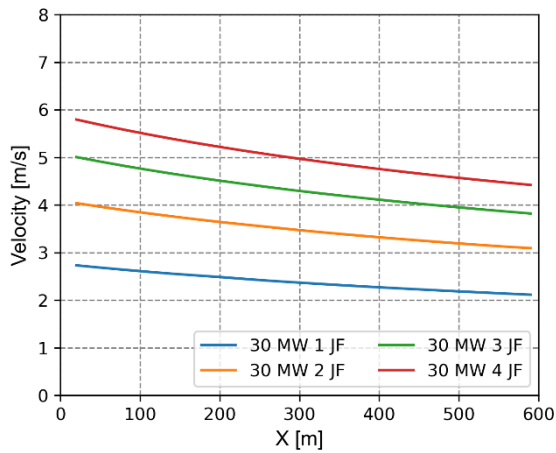


Figure 6: Longitudinal velocity as function of the fire location (scenario Bus fire 30 MW)

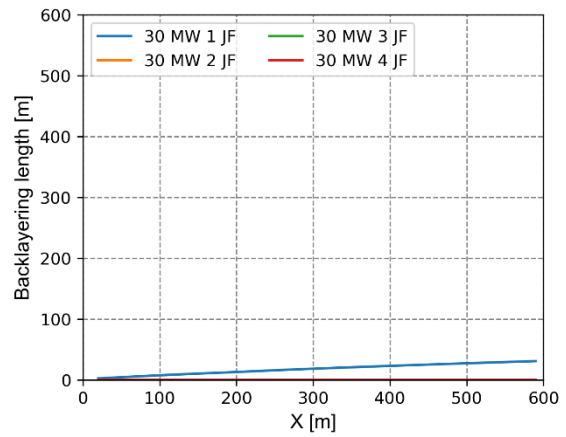


Figure 7: Backlayering length as function of the fire location (scenario Bus fire 30 MW)

The cumulative distributions of the longitudinal velocity as a function of the different ventilation configurations are presented in Figure 8. Again, the length of the damaged zone of the tunnel where the average temperature exceeds 400 °C is negligible for different ventilation configurations, see Figure 9.

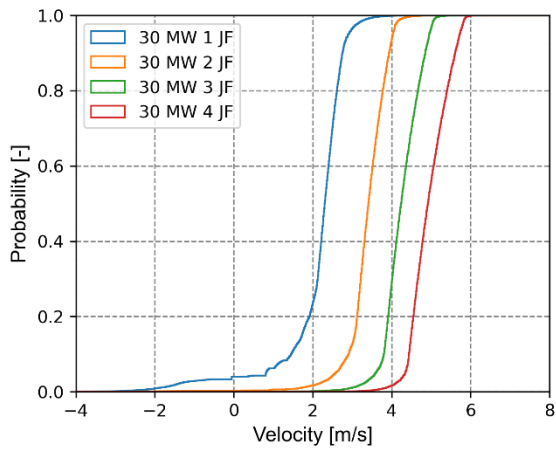


Figure 8: Distribution of the longitudinal velocity for a bus or small truck fire.

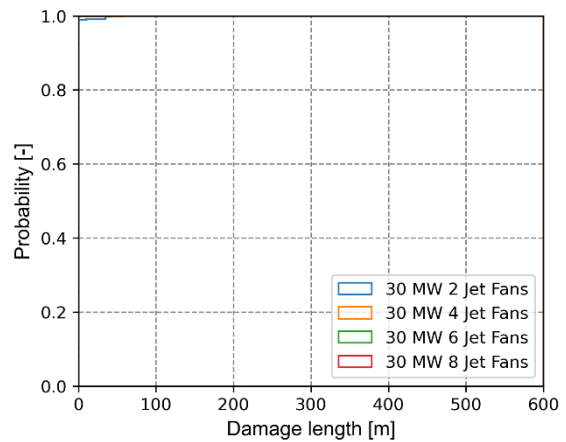


Figure 9: Distribution of the damaged length for a bus or small truck fire.

4.3. HGV fire scenario 200 MW

The median longitudinal speed, Figure 10, and the median backlayering length, Figure 11, are presented for the fire scenario of a burning HGV 200 MW.

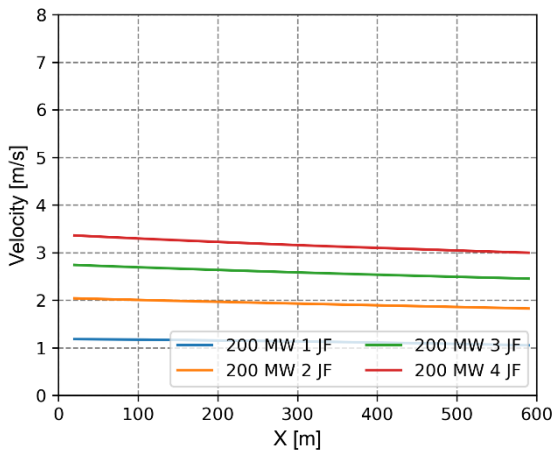


Figure 10: Longitudinal velocity as function of the fire location (scenario HGV fire 200 MW)

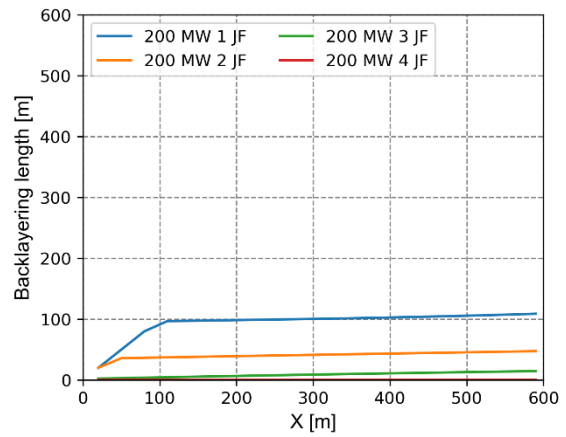


Figure 11: Backlayering length as function of the fire location (scenario HGV fire 200 MW)

The cumulative distributions of the longitudinal velocity as a function of the different ventilation configurations are presented in Figure 12. In Figure 13, as expected, the damaged length of the tunnel with average temperature higher than 400 °C is considerably higher than the previous two fire scenarios with lower fire load.

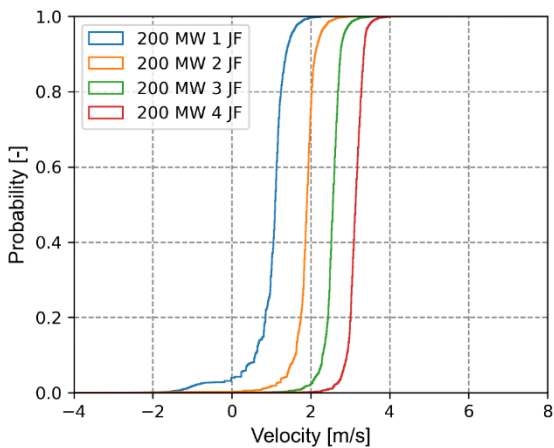


Figure 12: Longitudinal velocity distribution for an HGV fire

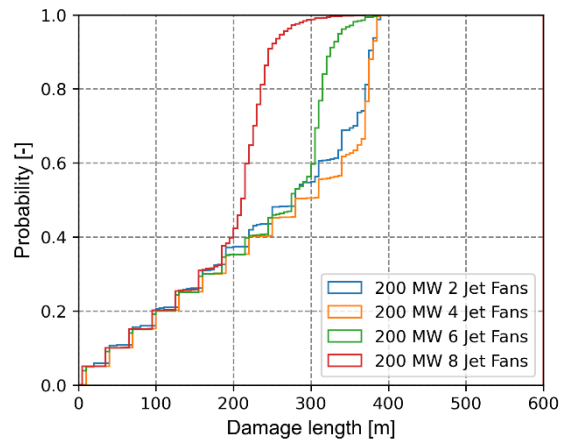


Figure 13: Distribution of the damaged length of the tunnel of an HGV fire.

4.4. Risk evaluation

The results discussed above present the longitudinal velocity, the backlayering length, and the damaged length for the different fire sizes and ventilation configurations. As fire size increases, longitudinal velocity decreases because the fire induces greater resistance, and backlayering increases accordingly. The damage to the tunnel due to elevated temperatures is negligible for the car- and bus-fire scenarios but becomes clearly visible for the HGV fire scenario. Typically, increasing the number of ventilators reduces the damaged length because ventilation cools the smoke in the tunnel.

Given the results of the analyses discussed above, the risk for road users and for the structure can be calculated considering different traffic conditions in the tunnel. Four hypothetical cases are considered for the study, and they are summarized in Table 2. In the first three cases the traffic intensity and the traffic composition are varied while the number of lanes is fixed to two. In the last case, the number of lanes is reduced to one to show the impact of the number of lanes on the risk.

Table 2: Input parameters of the four different test cases

	Case 1	Case 2	Case 3	Case 4
Saturation	0.3	0.5	0.8	0.5
Cars %	0.90	0.50	0.50	0.50
Bus %	0.05	0.20	0.20	0.20
HGV %	0.05	0.30	0.30	0.30
N _{lanes}	2	2	2	1

The equivalent risk for road users is summarized in Table 3 as a function of the number of jet fans installed in the tunnel. Both the maximum risk and the average risk indicators for life safety are presented for all the considered cases.

Table 3: Summary of the maximum and average risk indicator [m] for road users along the tunnel.

	Case 1		Case 2		Case 3		Case 4	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
2 jet fans	65.6	38.0	150.1	106.8	240.2	170.8	37.5	26.7
4 jet fans	7.0	4.9	36.0	29.9	57.6	47.8	9.0	7.5
6 jet fans	1.4	0.9	10.4	7.0	16.7	11.2	2.6	1.8
8 jet fans	0.14	0.08	0.55	0.36	0.87	0.57	0.14	0.09

The results for the considered cases are presented in Figure 14, Figure 15, Figure 16 and Figure 17. The risk profile is strongly affected by the percentage of vehicles in the tunnel because this affects the chance of an accident and the number of exposed users. There is a clear impact from the traffic composition, larger volumes of HGV can be associated to higher risks because of the higher frequency of large accidents. The number of lanes has a strong impact on the results because it affects both the fire frequency and the exposed number of road users. Therefore, ventilation-system design should not rely solely on critical-velocity criteria; design must also account for traffic saturation, HGV share, and lane count.

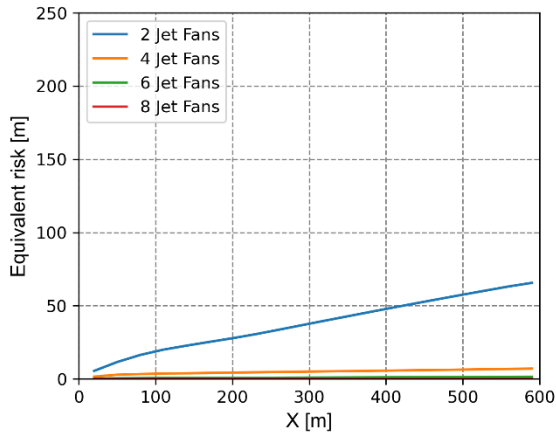


Figure 14: Risk profile for road users, Case 1.

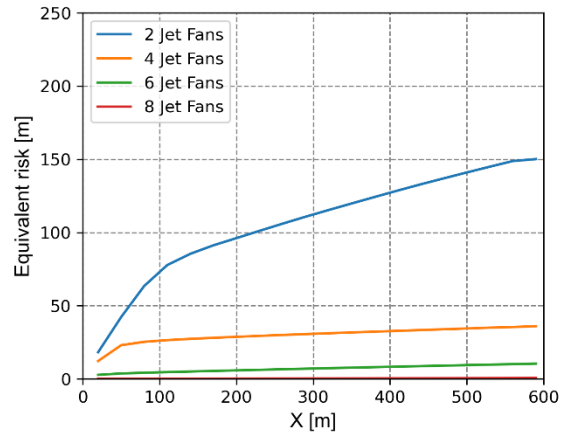


Figure 15: Risk profile for road users, Case 2.

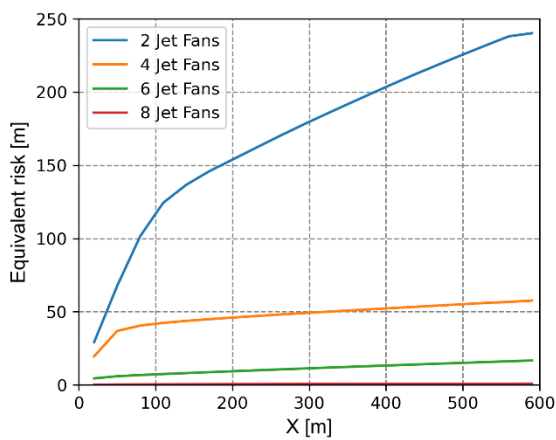


Figure 16: Risk profile for road users, Case 3.

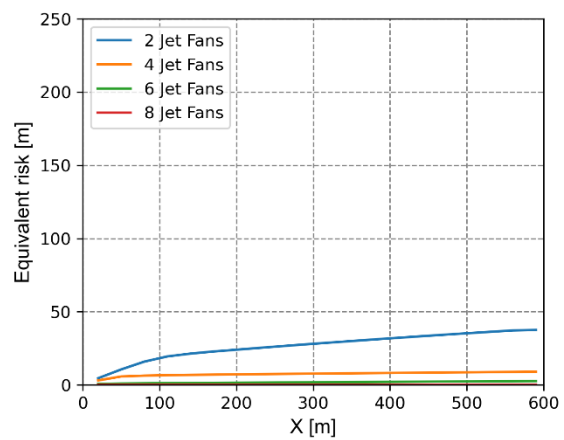


Figure 17: Risk profile for road users, Case 4.

The equivalent risk for the structure is calculated assuming that the rerouting due to the tunnel closure is 30 min (0.5 h). The equivalent risk for the structure is summarized in Table 4 as function of the number of jet fans installed in the tunnel. Both the maximum risk and the average risk for structural damage indicators are presented for the different cases.

Table 4: Summary of the maximum and average risk indicator [m²/h] for the structure along the tunnel.

	Case 1		Case 2		Case 3		Case 4	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
2 jet fans	1916	1345	31645	22206	81010	56848	7911	5552
4 jet fans	2027	1375	33780	22916	86477	58666	8445	5729
6 jet fans	1737	1238	28955	20646	74124	52855	7239	5162
8 jet fans	1319	989	21988	16484	56289	42200	5497	4121

The results are presented in Figure 18, Figure 19, Figure 20 and Figure 21. Given the limited damage associated to the smaller fires (10 MW and 30 MW) the risk is directly proportional to the share of HGV in the tunnel. The risk is also quadratically proportional to the total traffic intensity (saturation factor times number of lanes), and this is visible comparing cases 1, 2 and 3. The figures highlight how the ventilation has a positive effect on cooling the smoke and limiting the damage caused by the fire. In the zone of the tunnel near the exit portal the damage is mostly limited by the length of the tunnel itself. The area affected by elevated temperature

cannot be longer than the distance between the fire and the exit portal. The equivalent risk level with 2 jet fans is lower than that with 4 jet fans because the configuration with 2 jet fans often has negative longitudinal flows induced by wind. This naturally limits the temperature inside the tunnel and the extent of the damage. Overall, these results demonstrate that traffic intensity, tunnel length, and lane count materially influence business-continuity risk and must be included in ventilation design decisions.

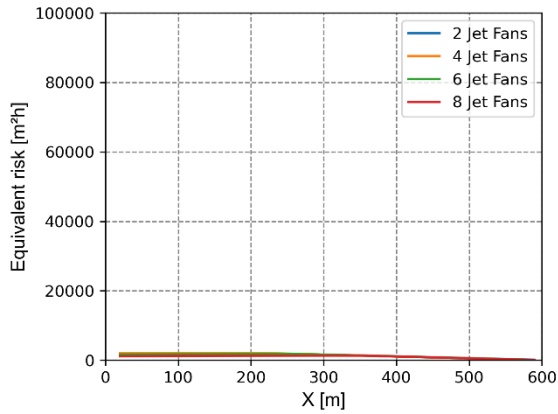


Figure 18: Risk profile for the structure, Case 1.

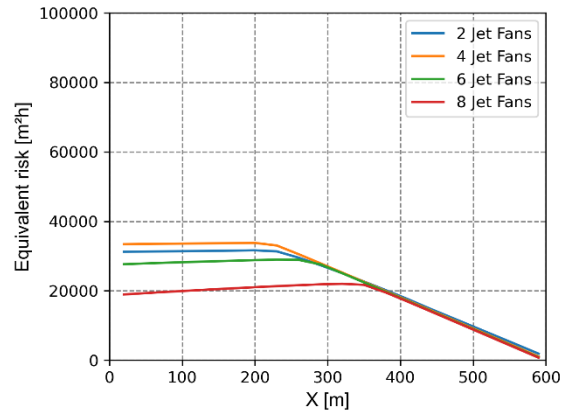


Figure 19: Risk profile for the structure, Case 2.

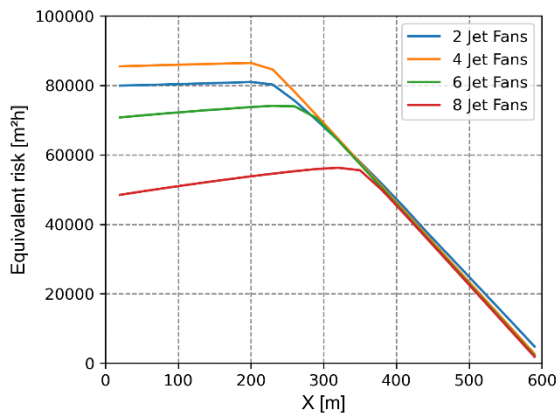


Figure 20: Risk profile for the structure, Case 3.

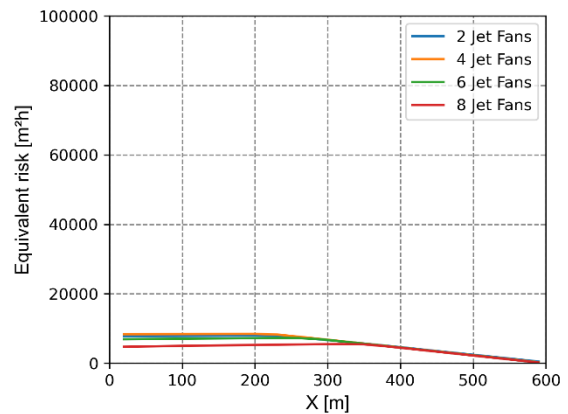


Figure 21: Risk profile for the structure, Case 4.

5. CONCLUSIONS

This paper proposes a risk-based framework for the design of longitudinal ventilation systems in road tunnels. Equivalent risk indicators are developed to address the risk to road users and the risk associated with the economic consequences resulting from tunnel fires. These indicators enable ventilation design to be driven by a target risk level, providing a uniform safety level across tunnels. The risk indicators are linked to tunnel geometry, traffic intensity, and traffic composition.

Tunnel ventilation can reduce backlayering and thus the number of road users exposed to smoke during a fire. The life-safety risk for road users can be related to backlayering length, and it also depends on traffic composition, traffic intensity and number of lanes, because these parameters affect fire frequency and the number of exposed users. Higher traffic intensities and larger shares of HGV increase the frequency of severe fires and therefore raise the overall risk.

For large fires, ventilation can also reduce smoke temperature and mitigate thermal damage inside the tunnel. The economic-loss risk is related to the damaged length, and is also influenced by tunnel geometry, traffic intensity and composition, and the rerouting time following tunnel closure, since these parameters affect both the frequency and the economic impact of fires. High traffic intensity and larger heavy-vehicle shares increase the likelihood of severe fires and the number of vehicles that must be rerouted, increasing economic risk.

Setting fixed acceptance criteria for backlayering length or longitudinal velocity simplifies ventilation design but can be inappropriate because it ignores differences in frequency and consequences of fires in different tunnels. Starting from a common acceptable risk level across tunnels, it is possible to derive tunnel-specific design criteria that reflect each tunnel's traffic, geometry, and exposure.

In practice, this means tunnels with high traffic intensity and large shares of HGV would receive greater protection through a better performing ventilation system, while tunnels with lower risk would receive proportionally less. This enables more efficient allocation of resources across the network. This paper aims to provide a conceptual basis for further development and practical implementation. The following topics should be investigated in future work:

- Stakeholder-based definition of acceptance criteria: analysis of acceptable thresholds for fatalities and economic damage, involving civil society, road authorities, emergency services and other stakeholders to define socially and politically acceptable risk levels.
- Expanded fire-scenario analysis: study of a broader set of fire sizes, locations, and vehicle types; compare the effect of different national/design fire recommendations on ventilation design.
- Validation and refinement of damage and backlayering correlations: further investigation of temperature thresholds that cause damage to electro-mechanical equipment and structural elements, and improved quantification of repair time and downtime.
- Tenability and occupant behaviour under blocked conditions: improved backlayering calculations that include tenability criteria (toxic and thermal exposure) and consider how blocked traffic and human behaviour influence exposure and evacuation outcomes.
- Uncertainty and sensitivity analysis: quantify uncertainty in input parameters (traffic projections, fire frequency, rerouting time, damage cost) and perform sensitivity studies to investigate the most important drivers of risk.

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