

METHODOLOGY FOR THE PERFORMANCE ENHANCEMENT OF LONGITUDINAL VENTILATION SYSTEMS DURING TRANSIENT STAGE OF A FIRE

Miguel del Moral, Alexander Gratch, Davide D'Eustacchio, Álvaro Meneses, Justo Suarez

Soler&Palau Ventilation Systems SLU, ES

DOI 10.3217/978-3-99161-087-8-010 (CC BY-NC 4.0)

<https://creativecommons.org/licenses/by/4.0/deed.de>

This CC license does not apply to third party material (attributed to other sources) and content noted otherwise.

ABSTRACT

Ventilation systems in tunnels are designed for a maximum fire load. However, during the initial stages of a fire, the fire would not be completely developed and the activation of the system at maximum speed may disrupt smoke stratification, compromising occupants' evacuation.

This paper presents a methodology to assist designers in defining the optimal activation protocol for a longitudinal ventilation system, focusing on the response of the ventilation system during the transient stage of the fire. This methodology would aim to:

1. Enhance Available Safe Egress Time (ASET) over Required Safe Egress Time (RSET).
2. Assess the effectiveness and robustness of the ventilation system and its response in the design stages.
3. Help to define the safest procedures for the control centers, advising on how to operate the ventilation system depending on the real conditions in the event of a fire.

The methodology is presented in a case study, which is provided with a longitudinal ventilation system designed to achieve a specific air velocity for a given fire load. This methodology is not limited to a specific critical/confinement velocity model and a different formulation is also assessed in the process for comparison.

For the case study and the considered model, critical/confinement velocity is numerically estimated along time to serve as starting point in the process of defining the activation protocol for the ventilation system. This considers both sequential activation for jet fans and activation through variable speed drive.

Once the activation protocol is defined, the effectiveness of the response is assessed through Computational Fluid Dynamics (CFD) software, and the results are analyzed together with models for Required Safe Egress Time.

Keywords: Smoke control, critical velocity, CFD, ASET, transient-stage.

1. INTRODUCTION

Longitudinal ventilation systems are generally designed to overcome a certain critical or confinement velocity, and different models are available ([1], [2]). Both concepts, critical and confinement velocity, refer to the air inlet velocity necessary to effectively sweep downstream the smoke generated by a certain fire load (completely or allowing backlayering, respectively),

which would naturally provide for tenable conditions upstream but would inevitably disturb smoke stratification, affecting visibility and temperature after the fire. **Figure 1**, obtained from a real test, illustrates the fast destratification produced when jet fans are activated.



Figure 1: Smoke layer on a real test at TST. From left to right and up to down: an instant before the ventilation activation; 5 seconds after; 10 seconds after; 15 seconds after

The approach commonly used to prevent smoke stratification disruption consists of activating jet fans far away from the fire or, in some cases, even not activating any at all in the first stages, accepting smoke spread in all directions, and activating the ventilation only after a delay long enough to allow some time for occupants' evacuation. However, that time may not necessarily be enough to ensure all occupants' safe egress. Furthermore, while allowing smoke spread in both directions generally suffices to provide acceptable conditions at breathing height in the vicinity of the fire, after some meters the smoke layer tends to go to lower levels and, eventually, to cover the whole section of the tunnel, which is especially critical for occupants distant from the fire and with a reaction time much larger than those close to the fire. That strategy could also be particularly dangerous in sloped tunnels, where smoke would spread even faster in upward direction.

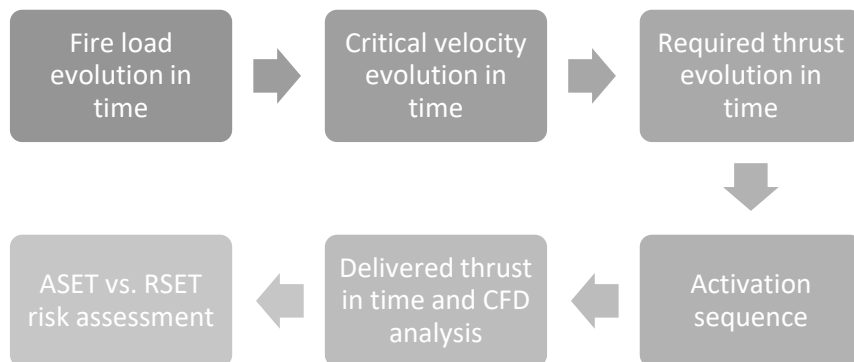


Figure 2: Methodology workflow.

That approach also transfers the responsibility of the proper activation of the system to the control center, which we can expect will be under great stress in the case of the fire, and would

have to deal with many more variables than the activation of the ventilation system. Although manual activation should always be available for control centers to properly adjust the response depending on the actual on-site conditions, relying solely on it also gives much more space for human mistakes.

Alternatively, this paper proposes a methodology (depicted in **Figure 2**) to assess the definition of a sequence of activation for the ventilation system, that would start at the very moment of the fire detection, and evaluate its risk implications for occupants.

The methodology is presented in a case study and estimates theoretically the required thrust at each moment depending on the growth type of the fire [3]. However, this methodology could also be used to implement automatized systems able to adapt the ventilation system response to the on-site real-time measurements related to the fire load, such as the temperature [4] or the air velocity in the inlet of the tunnel.

2. CASE STUDY

The methodology will be applied in a virtual unidirectional tunnel with a longitudinal ventilation system and the following characteristics:

Table 1: Characteristics of the case study tunnel

| Parameter | Value |
|-----------------------------------|--------------------------------------|
| Width | 12.8 m |
| Height | 6.4 m |
| Length | 600 m |
| Slope | 0% |
| Lanes | 2 |
| Evacuation doors every | 200 m (100 m of evacuation distance) |
| Rows of jet fans | 7 |
| Jet fans per row | 2 |
| Distance between rows | 90 m |
| Lateral distance between jet fans | 4 m |
| Jet fan thrust | 809 N |

The ventilation system was sized to provide tenable conditions (visibility and temperature levels compatible with life) upstream in case of a fire up to 50 MW while having slightly adverse wind conditions and dense traffic. Also, a 10% thrust redundancy was considered.

For simplicity purposes, a short tunnel with no slope was considered, although this methodology could be deemed especially useful in those cases. The simulation was carried out not considering the presence of cars, apart from the vehicle in flames, which would correspond to a large bus (50 MW). The presence of wind may have a significant impact in air velocity in short tunnels, but wind was not considered to allow a clear assessment of the methodology and the activation sequences analyzed. Consequently, the pressure drop inside the tunnel in the considered scenario is below the total pressure drop that the ventilation system would be able to overcome.

CFD simulations were carried out using FDS. Fire detection is considered to be produced by visual identification by the control center, at the beginning of the simulation. Fire growth is considered to start at the same instant for simplicity purposes.

3. METHODOLOGY

3.1. Analytical assessment: required thrust vs. delivered thrust

The methodology rests upon the concept of adapting the delivered thrust at each moment, adjusting the number of active fans and/or their speed using variable speed drive (VSD), to meet the thrust requirements of the tunnel in order to provide critical/confinement velocity upstream the fire, and consequently, sweeping the smoke in one direction (or delaying its upstream spread).

Critical velocity is estimated using the Thomas-Kennedy [1] and Beyer's models [2]:

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f} \right)^{1/3} \quad (1)$$

$$U_c = K_F \left(\frac{gL_n^3}{D_h^2} \frac{\Delta T_p}{T_a + \Delta T_p} \right)^{1/2} \quad (2)$$

Critical and confinement velocity would depend on the fire's heat release rate (HRR), which increases over time, typically following an at^2 curve, with a growth coefficient determined by the fire development rate. To estimate the fire evolution, an ultra-fast fire (as defined by [3]) was considered for the case study.

Once the heat release rate at each point in time is defined, critical/confinement velocity is calculated for that moment, and the required upstream velocity can be plotted in time:

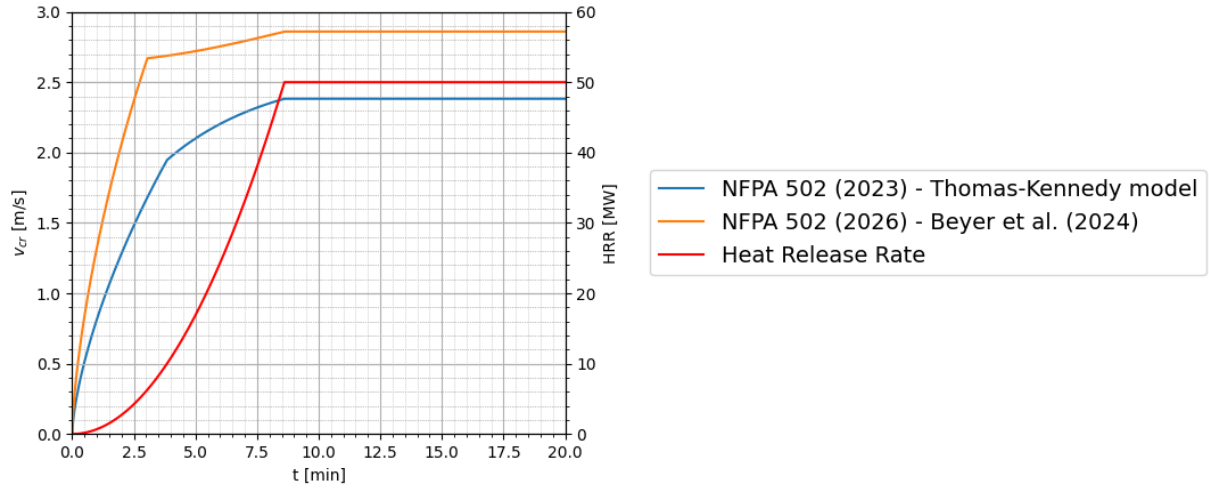


Figure 3: Required upstream velocity (critical or confinement) and HRR along time.

Different critical velocity models are plotted for information, but it is not the purpose of this paper to look into their differences. Also, the depicted methodology can be applied to both. Therefore, for practical purposes, the rest of the methodology is described using only Beyer's model for critical velocity.

For certain conditions (i.e. wind load and fire load and location) the confinement velocity would define the air profile in the tunnel, as well as the pressure drop between the inlet and the outlet. With this information, the required thrust could be easily calculated through momentum conservation. Following traditional PIARC's handbook formulation [5]:

$$F_{required} = \sum F_j = (\Delta p_{veh} + \Delta p_{tu} + \Delta p_{MT} + \Delta p_{fire} + \Delta p_{th}) \cdot A_T \quad (3)$$

Then, the real challenge arises: to deliver the required thrust at each point in time. This may be done with sequential activation of the jet fans and/or adjusting their speed. There are many possible combinations (see **Figure 4**), but a much smoother correlation can be achieved using both VSD and sequential activation. **Figure 5** shows one specific activation sequence (tagged as AS 4) considered for the case study, depicting each jet fan row's ramp-up time activation, referenced in percentual over its own maximum thrust capacity.

At this point a general remark is needed: meeting the required thrust with the delivered thrust would provide for tenable conditions upstream of the fire but would not necessarily avoid smoke destratification. For that purpose, lower air velocities may be required, depending on the case, hence delivered thrust will have to be, more often than not, below the required thrust.

There are available models to predict smoke destratification [6], however they were not assessed in the development of this paper (although the authors consider that they may be useful for further analysis).

Instead, CFD simulations were used to verify the performance of the considered activation sequences (defined in 3.2).

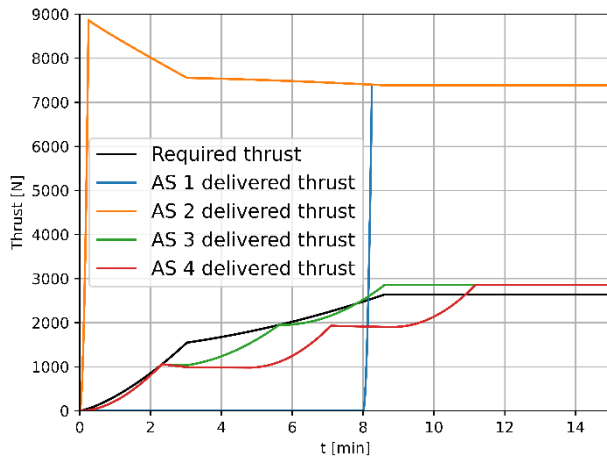


Figure 4: Required thrust vs. delivered thrust with different activation sequences.

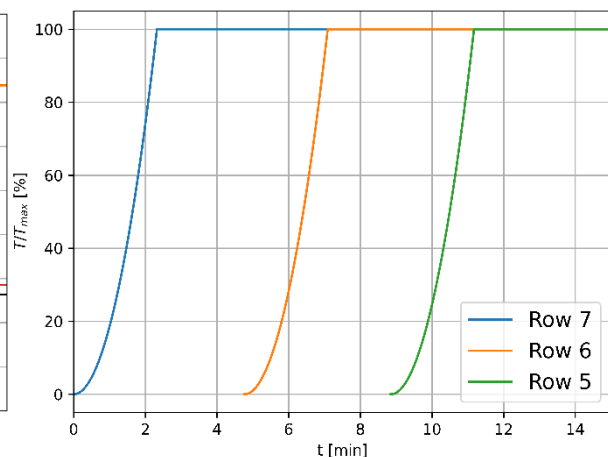


Figure 5: Activation Sequence 4, with percentual activation in time of each row of jet fans.

3.2. Numerical assessment: CFD simulation

For comparison purposes, four Activation Sequences (AS) are considered:

1. AS 1: the ventilation system remains off up to 480 s, when it is activated at high speed, all the fans at the same time.
2. AS 2: the ventilation system is activated at maximum speed upon fire detection.
3. AS 3: the ventilation system is activated sequentially and with VSD, aiming to provide closeness between the delivered thrust and the required thrust during transient stage.
4. AS 4: the ventilation system is activated sequentially and with VSD, delivering thrust below the required thrust during transient stage.

The CFD results for the different AS are show in **Figure 6**. Visibility at 1.8 m from the floor is shown, since it represents one of the critical indicators for tenability conditions for occupants' evacuation.

Note that AS 2 delivers a thrust much bigger than required thrust (see **Figure 4**). This is because the ventilation system was sized for a fire load higher than the one considered in the case study. The authors defined this intentionally to give proof that the bigger is not always the better: especially when a lot of thrust is available, a fast activation sequence may affect the occupants' visibility levels, hindering occupants' evacuation downstream the fire.

CFD results show that delaying the activation of the jet fans maximizes the time in which tenable conditions are provided downstream of the fire (right side of the tunnel). However, in unidirectional tunnels, occupants after the fire (right side of the tunnel) are generally the fastest ones to evacuate, since they usually can escape by driving. Results also show that after a certain time (around 420 s) the smoke layer goes down naturally in both directions, dropping visibility very quickly. This is especially dangerous upstream of the fire, where occupants would probably escape on foot and would take longer to react.

On the other hand, AS 3 and AS 4 can maintain clean conditions upstream permanently, but downstream visibility drops a bit sooner than in AS 1, so eventually, an ASET vs. RSET assessment is necessary to evaluate if the improvement in the upstream or downstream conditions can minimize the risk the occupants will be exposed to in the event of a fire.

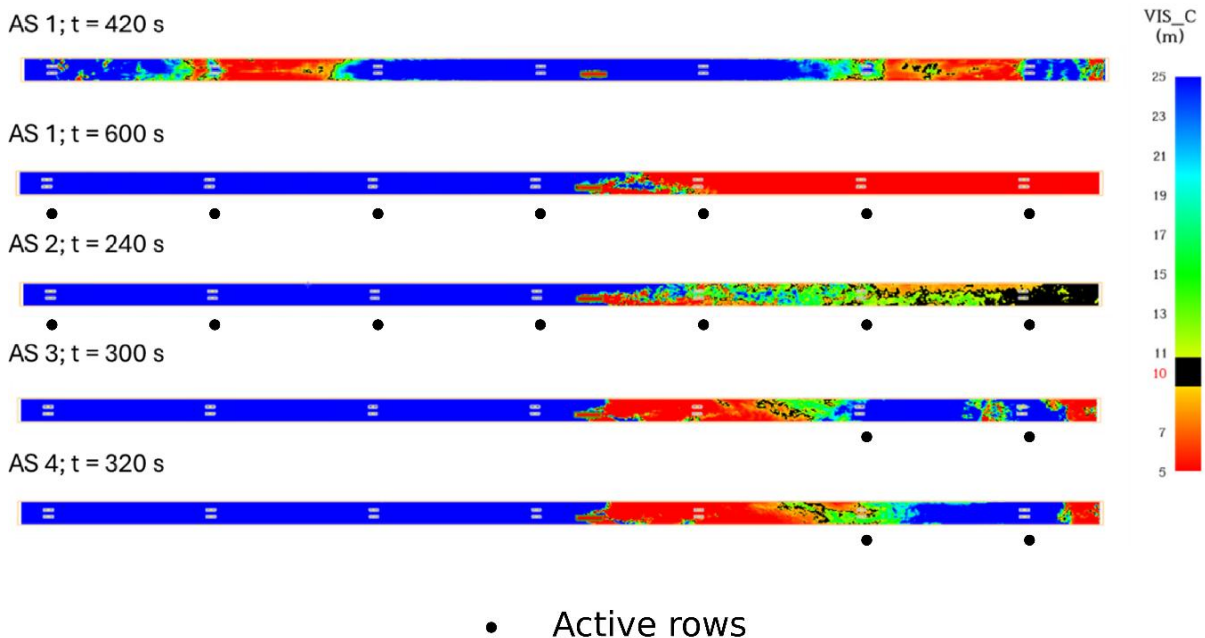


Figure 6: Visibility at 1.8 m from the floor on different moments, for the AS considered.

3.3. Risk assessment: ASET vs. RSET

For the Available Safe Egress Time (ASET) vs. Required Safe Egress Time (RSET) analysis, MARTE methodology [7][8] is considered.

The CFD results for each AS are simplified into a one-dimensional visibility profile, where the minimum visibility in the cross-section of the tunnel is saved over time. When visibility at some longitudinal point of the tunnel drops below 20 m, tenable conditions for the occupants are considered to be no longer provided.

This allows to plot when the conditions become unsafe at every point along the tunnel, which at the same time can be compared with the movement of the occupants in the tunnel and, consequently, assess how much time (and how many of them) spend in unsafe conditions.

For the occupants' movement estimation, a random occupant distribution is considered, with the following conditions:

- Walking pace: from 0.6 (people with reduced mobility) to 2 m/s (fast pace) before the fire. From 1 m/s (average walking speed) to 5 m/s (slow drive) after the fire.
- Reaction time: from 0 seconds (people after the fire already exiting by car the tunnel) to 5 minutes (people before and far away from the fire with a significant attachment feeling to the car).

Both unsafe conditions along time in the tunnel length and people movement are represented in **Figure 7** and **Figure 8**. Downstream of the fire, escape is considered to be carried out by car in dense traffic conditions. Evacuation routes are plotted as pointed vertical lines. Occupants' movement is also represented by lines, which appear continuous or dashed depending on whether they are located upstream or downstream of the fire, respectively. These lines become pointed once they cross an evacuation door (given that normally occupants should be able to escape through them).

These figures show that, with AS 1, occupants will be exposed to smoke inhalation especially upstream of the fire, where escape by foot is expected. Once the ventilation is activated, tenable conditions are recovered after a time that could be estimated with the following expression, where k is a coefficient greater than 1 and that would depend on each case:

$$t_{recovery} = k \cdot \frac{d_{fire-entry}}{V_{inlet}} \quad (4)$$

On the other hand, ASET vs RSET analysis for AS 4 shows permanently tenable conditions upstream the fire and a slight exposure downstream of the fire, for the occupants immediately after the vehicle in flames on their way to the exit.

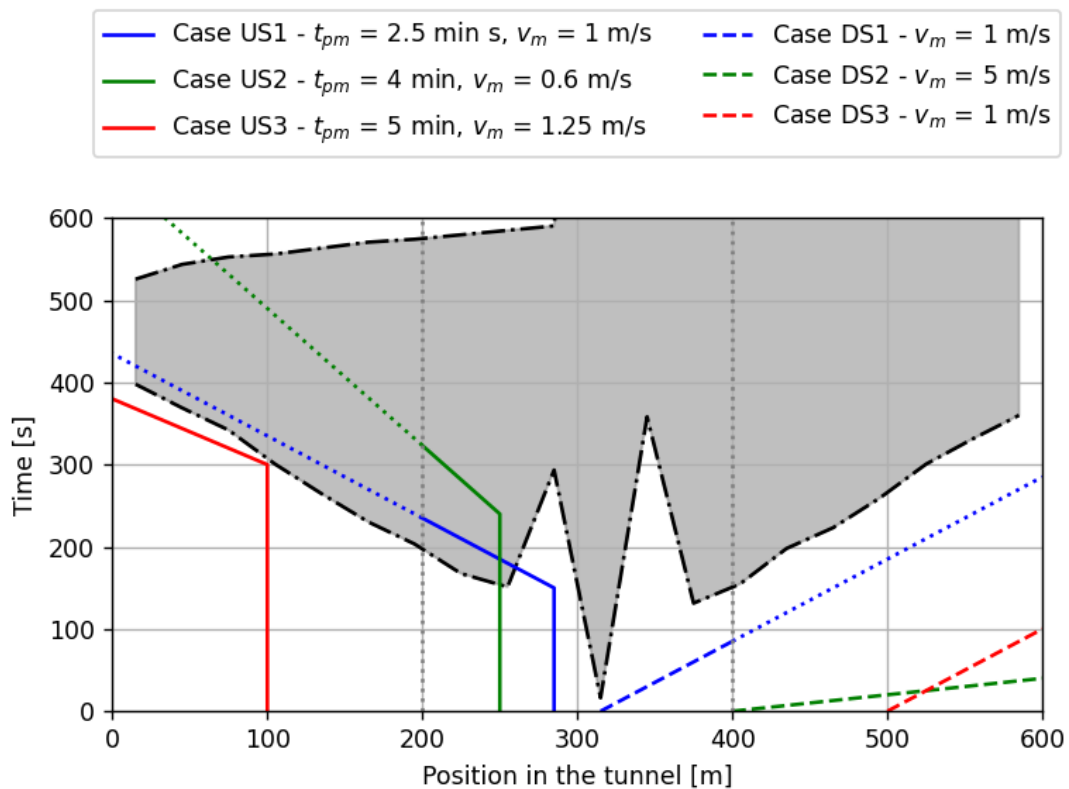


Figure 7: Tunnel conditions along time in the tunnel length and occupants' movement for AS 1

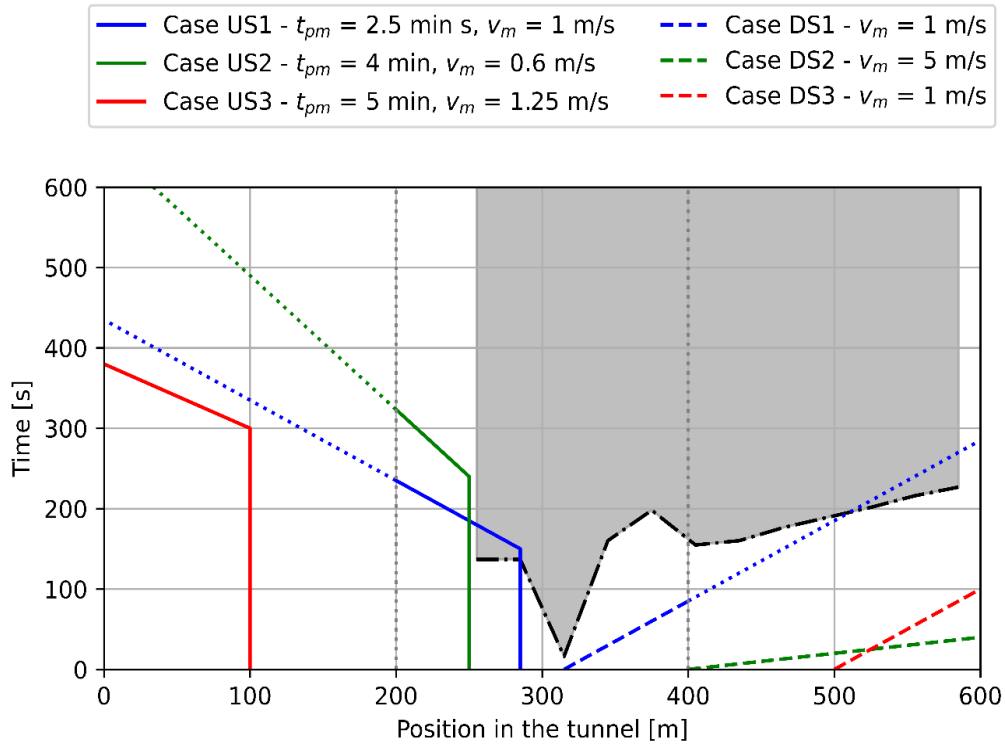


Figure 8: Tunnel conditions along time in the tunnel length and occupants' movement for AS 4

4. SUMMARY AND CONCLUSION

Delaying activation of the ventilation system (AS 1) in case of a fire in a unidirectional tunnel could lead to fatal results, especially for the occupants before the fire. A fast activation at maximum speed (AS 2), on the other hand, would provide good conditions before the fire but would worsen conditions after the fire, hindering vehicles and occupants' egress in that area. An automatic gradual response in which the ventilation is smoothly activated (AS 3 and AS 4) could optimize conditions upstream of the fire, maximizing the available time for the occupants before the fire while maintaining the available evacuation time downstream. It also avoids transferring the whole responsibility for the ventilation activation system to the control centers, giving them more tools to respond in the event of a fire and helping to prevent human mistakes. There are many options for this sequential activation, and some of them could even rely on on-site real-time data, adjusting the response depending on the actual fire load.

The methodology presented allows to mathematically determine, for a specific fire load model, the required thrust to reach critical velocity at each point in time and thus define a baseline to be met by the fans at every moment. The methodology does not address how to define the activation sequence but allows the consideration of any activation protocol. That activation protocol is then analyzed using CFD simulations to provide an ASET/RSET risk assessment, which eventually can lead to a risk comparison between different activation sequences.

The paper neither dives into proportional-integral (PI) forms of adjusting fan velocity on-site so measured air velocity meets a specific value, but rather on the tools to evaluate, at project stage, the performance of any specific activation sequence (which does not necessarily need to be PI) and their risk to occupants during the first stages of the fire, which may lead to compensation actions, like using information technologies to ensure safe occupant's egress (such as phone advice to enhance evacuation time and image recognition software to evaluate how many cars are still in the tunnel after the fire).

Although the methodology focuses on analysis purposes, the mathematical model presented could also be used to estimate the required thrust or critical velocity in a real fire scenario with on-site temperature readings. However, for that case, an additional physical model to translate those readings into Heat Release Rate (HRR) should be included. This could be interesting both for tunnels where there are no air velocity readings (and thus no PI is possible) and for those where there are velocity readings, in which case the mathematical model could help to set up a velocity instruction (which does not necessarily need to meet critical or confinement velocity, since this may lead to destratification of the smoke layer in early stages).

For the analyzed case study, the methodology proved to be useful in assessing the risk the occupants are exposed to, allowing a clear comparison of the risk implications between different activation sequences. This analysis also suggests that a smoother activation sequence, where the delivered thrust does not necessarily meet the required thrust (such as AS 4) may help to increase RSET than those which prioritize meeting the required thrust (such as AS 3). This also reflects the importance of the presented methodology to enhance activation sequence (and assess its risk) instead of relying on simpler alternatives for the control systems (such as PI) or those which focus on providing critical velocity in the early stages of the fire.

This methodology may be of special interest in sloped tunnels and tunnels where adverse conditions may be expected, given that those conditions may lead to a fast spread upstream the fire, hindering occupants' egress. It may also be of special interest to long tunnels or where large fast-growing fires may be expected (for example, large electric vehicles). The methodology, however, would be completely sterile when not accompanied by the necessary equipment to allow sequential activation, which is still common in many tunnels throughout Europe, some of them even of new construction.

5. REFERENCES

- [1] NFPA 502, "Standard for Road Tunnels, Bridges and Other Limited Access Highways," The National Fire Protection Association, US, 2023.
- [2] M. Beyer, C. Stacey, G. Brenn, "A Mixed Convection Model for Estimating the Critical Velocity to Prevent Smoke Backlayering in Tunnels", *Fire Technology* 61, 295–342, doi:10.1007/s10694-024-01607-8 US, 2025.
- [3] NFPA 92, "Standard for Smoke Control Systems," The National Fire Protection Association, US, 2024.
- [4] J. Bielawski, D. Luan, X. Zhang, W. Xie, X. Huang and W. Węgrzynski, "Distributed temperature sensor model for linear heat detection in tunnel fires," *Tunneling and Underground Space Technology* 167, Elsevier publishing, doi:10.1016/j.tust.2025.107092, US, 2025.
- [5] PIARC, "AIPCR 2006.05.16.B: Ventilation", World Road Association, FR, 2006.
- [6] Y. Guo, Z. Yuan, Y. Yuan, X. Cao, P. Zhao, "Numerical simulation of smoke stratification in tunnel fires under longitudinal velocities," *Underground Space* 6, 163-172, Elsevier publishing, doi:10.1016/j.undsp.2019.11.001, US, 2019.
- [7] ATC, "Metodología de Análisis de Riesgos en Túneles de Carretera" Asociación Técnica de Carreteras, ES, 2024.
- [8] PIARC, "2nd International Conference on Road Tunnel Operations and Safety, Volume II", ATC, 219-240, ES, 2022