

EFFECT OF ROAD TUNNEL FITOUT ON SMOKE CONTROL

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ABSTRACT

A CFD model, previously validated against the Memorial Tunnel fire tests with longitudinal ventilation, is used to investigate the influence of ceiling-mounted road tunnel equipment on upstream smoke propagation in case of a road tunnel fire. Typical road tunnel installations, including cable trays, hangers, lighting, signage, misting pipes, speakers, etc. were incorporated into a representative three-lane TBM tunnel geometry and compared with an otherwise identical tunnel without ceiling obstructions.

The study examines differences in smoke behaviour for both the critical velocity case, defined by the prevention of upstream backlayering, and the confinement velocity case, defined by limiting the upstream backlayering length to 30 m. The observed differences are interesting as the tunnel equipment does not materially alter critical velocity required to prevent backlayering. However, for the confinement velocity case, the presence of ceiling obstructions significantly affects upstream smoke propagation, resulting in increased backlayering lengths for the same applied ventilation flow rate.

The results are configuration-specific and reinforce the need for project-specific, validated CFD assessments when determining confinement velocity in tunnels with obstructed ceiling spaces.

Keywords: Smoke control, smoke propagation, confinement velocity, critical velocity, backlayering.

1. INTRODUCTION

In 2023, NFPA 502 [1] changed the design criteria for road tunnels from the absolute prevention of backlayering (critical velocity) to allowing some backlayering (confinement velocity). That made sense from a tunnel safety perspective regarding avoiding over-ventilation and consequent oversizing of the ventilation system. However, it is not clear how to determine a design confinement velocity. NFPA 502 does not provide a calculation method for determining confinement velocity as there is no such reliable method that can be used for real (full-scale) tunnels. It is recommended to use a CFD model validated against appropriate full-scale data to explore appropriate confinement velocity values.

It is noted that the absolute prevention of smoke backlayering is not universally adopted as a primary design objective in European tunnel fire safety practice. In several European guidelines and design approaches [2], [3], [4], [5] limited upstream smoke propagation may be considered acceptable as part of a balanced smoke control strategy, recognising that excessive longitudinal ventilation can disrupt smoke stratification and, under certain conditions, promote faster fire growth, higher peak heat release rates, and increased fire spread, as also discussed here [6], [7]. The low velocity philosophy, which seeks to balance smoke control effectiveness against adverse fire ventilation interactions, aligns with the

underlying rationale of the confinement velocity concept as a design criterion introduced in NFPA 502.

A previous study [8] explored some key influences on confinement velocity based on a validated CFD model [9], but the example tunnel used had no fittings, equipment or any other installations included. This may be appropriate for most tunnels in Europe where the tunnel ceiling is smooth and usually free of any equipment with considerable obstruction of the air path. In other regions, especially in Australia, it is common and more cost efficient to have cable trays, trusses, lights and other equipment hanging from the ceiling, potentially influencing the upstream smoke propagation.

To better understand the influence of obstructed ceiling space on smoke propagation, the same tunnel geometry and CFD methodology used for the previous study [8] was modified to incorporate tunnel equipment, with an example in Figure 1 (left). Using this updated geometry, the simulation parameters, methodology, and target flow conditions to achieve critical velocity (preventing the onset of backlayering) and confinement velocity (i.e., limiting upstream smoke propagation to a backlayering length of 30 m) were maintained as established previously [8]. The effect of the installed tunnel fitout on smoke propagation was then investigated.



Figure 1: Typical tunnel fitout in Australia (left, Heysen tunnel) and in Austria (right, Niklasdorftunnel [10])

2. CFD METHODOLOGY

The CFD model was created based on the methodology used for evaluating critical velocity by Beyer & Stacey [9]. The simulation software ANSYS Fluent [11], [12], [13] was used.

Following the previous study [8], the modelled example tunnel has a typical 3-lane TBM profile with a cross-section area of 93 m², a hydraulic diameter of 9.9 m, and a height from floor to ceiling of 8.92 m. The tunnel domain has a total length of 500 m. The fire source was placed 300 m downstream of the inlet portal on the floor in the middle of the tunnel. The “clean” tunnel geometry (no ceiling mounted equipment) was modified to include a typical tunnel fitout (i.e. lighting, cameras, cable trays, speakers, signage, misting pipes, and hangers or cross-tunnel beam mountings for all that equipment) as illustrated in Figure 2. The surface of the fitout was conservatively considered to be adiabatic, therefore not removing any heat from the smoke. The change to the unobstructed tunnel cross section at the fire front due to the added equipment is negligible (<0.1%). However, even with the overall tunnel area being about the same (resulting in about the same average air velocity for the same tunnel air flow rate), the lower flow around the obstructions can still have a considerable impact on the local and overall velocity distributions.

The overall mesh size in the modified domain and especially within the vicinity of the fire was kept the same as employed in the model without the tunnel fitout. A finer surface mesh (~10 mm) was applied to the tunnel fitout to resolve geometric details, resulting in increased mesh density and a three times higher total cell count relative to the original model [9]. To manage computational demands, tunnel equipment was only included around the fire and for 110 m upstream. Adopted design fire parameters as proposed in [14] for a 50 MW fire, and other input parameters, are listed in Table 1.

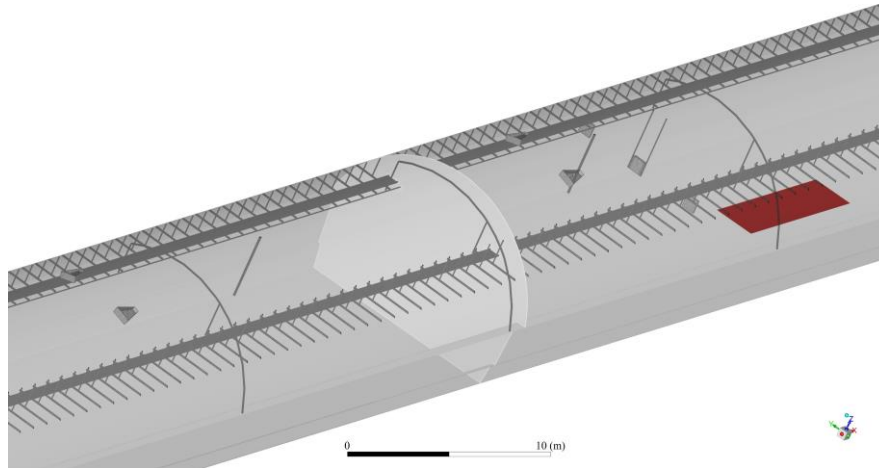


Figure 2: Adopted tunnel fitout for CFD study, including hangers for equipment.

Table 1: Input parameters used for the CFD model.

Parameter	Value
Tunnel air temperature	30°C
Tunnel wall temperature (constant)	30°C
Tunnel wall roughness height K_s	1.5e-03 m
Wall roughness height K_s of fitout	1.6e-04 m
Tunnel slope	Flat (0%)
Total Fire HRR	50 MW
Radiative fraction	0.2
Fire width	2.5 m
Fire intensity	2.25 MW/m ²
Fire length	8.889 m
Fuel	Fuel-oil (C ₁₉ H ₃₀)
Combustion efficiency based on total HRR (relevant for additional CO ₂ and H ₂ O source)	0.95

The required flow rate for just preventing smoke backlayering and confining the backlayering length to 30 m as previously concluded in the “Empty” tunnel was applied in the modified tunnel to explore the change in the smoke propagation with the obstructions in the ceiling space. The results are discussed and compared in Section 3 below.

3. RESULTS OF CFD STUDY

For the previously assessed tunnel without ceiling obstructions, the critical and confinement velocities were 3.54 m/s and 3.28 m/s respectively, for the assumed fire parameters in a flat tunnel. The confinement velocity corresponds to a controlled upstream backlayering length

of 30 m in the tunnel without the fitout. For the tunnel including ceiling-mounted equipment, the same upstream flow rates were applied for both cases, enabling a direct comparison of upstream smoke propagation with and without the additional equipment. In a further step, the smoke propagation of the confinement velocity case was also compared with and without the tunnel fitout in the 4% downgrade tunnel.

The characterisation of the flow regime, as well as a detailed discussion of the fire plume and smoke backlayer dynamics, is presented in previous work [8] and not repeated here.

3.1. Critical velocity (flat tunnel)

The critical velocity is 3.54 m/s in the example tunnel without the fitout [8]. The same flow rate applied with the ceiling-mounted equipment present resulted in the ceiling smoke jet right above the fire being more diluted (cooler) and pushed slightly further back (see

Figure 3 and Figure 4). Based on the example chosen, the results indicate that the ceiling obstructions do not significantly change the critical velocity required to prevent backlayering, and perhaps reduce it.

Figure 5 compares a contour plot of the velocity component along the tunnel axis in the tunnel cross section at the fire front, for the case with and without the ceiling-mounted equipment. The obstructions in the ceiling locally increase the velocity everywhere else in the cross section, including in the unobstructed ceiling area, compared to the case without the equipment in place. At the front of the fire, this is further enhanced by the plume front also creating some sort of obstruction for the oncoming flow, and pushing the air around, both sideways and up towards the ceiling. The left plot of Figure 6 shows the x-velocity vertical profiles at the centre of the fire front for both cases, which quantifies the higher ceiling velocity at the centre line. The right plot of Figure 6 compares the x-velocity profiles on a horizontal line at 6.4 m height at the fire front, going across the cable tray props which also support the lights, misting pipes etc.). The right plot also shows the higher upstream velocity in the unobstructed ceiling area. The slightly higher ceiling velocity in the unobstructed area and in the tunnel centre may be an explanation for the slight push back of the hot ceiling jet right above the fire source. The minor differences observed in smoke propagation for the critical velocity case are also related to the specific configuration of the tunnel fitout and the arrangement of certain installations (e.g. signage) relative to the fire location. In the example analysed, the fire is centred in the tunnel, and the obstructed ceiling areas are at the sides. Also, the larger signs could be local to the fire, or further away (12 m upstream in this example - Figure 4). The results here could be different if those things change. Therefore, the findings reported herein should not be interpreted as universally applicable, and project-specific assessments remain necessary.

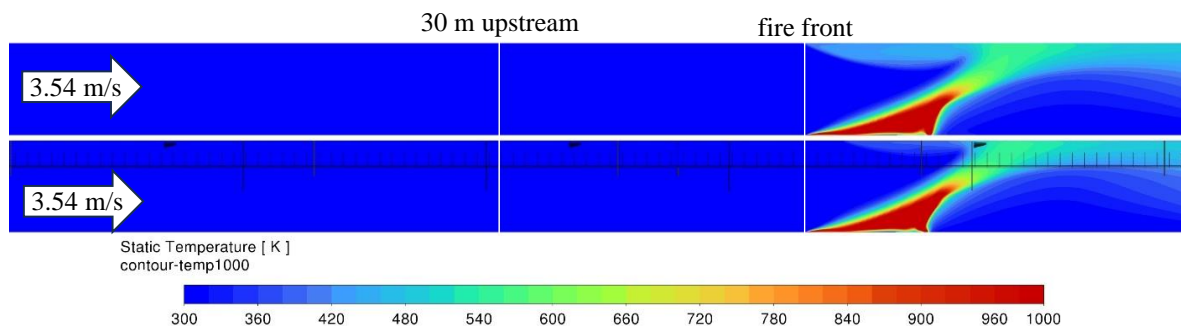


Figure 3: Contour plot of temperature distribution through the centre of the tunnel for the tunnel without fitout (top) [8] and with the fitout (bottom) for the critical velocity case. Temperature is clipped to 1000 K for better presentation.

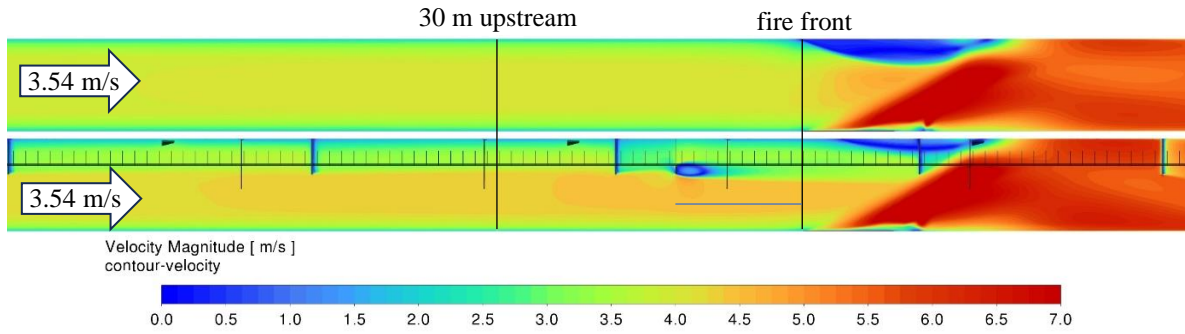


Figure 4: Contour plot of velocity distribution through the centre of the tunnel for the tunnel without fitout (top) [8] and with the fitout (bottom) for the critical velocity case. Velocity is clipped to 7 m/s for better presentation.

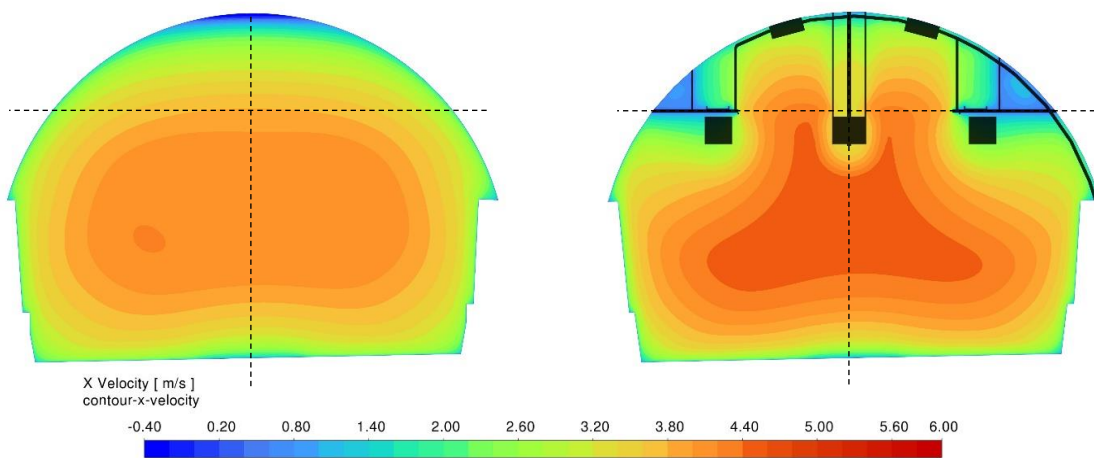


Figure 5: Contour plot of velocity along the tunnel (x-velocity) in the tunnel cross section at the fire front for the critical velocity case with fitout (right) and without the tunnel fitout (left) [8]. Detailed comparison of velocity profiles along the dashed lines is shown in Figure 6.

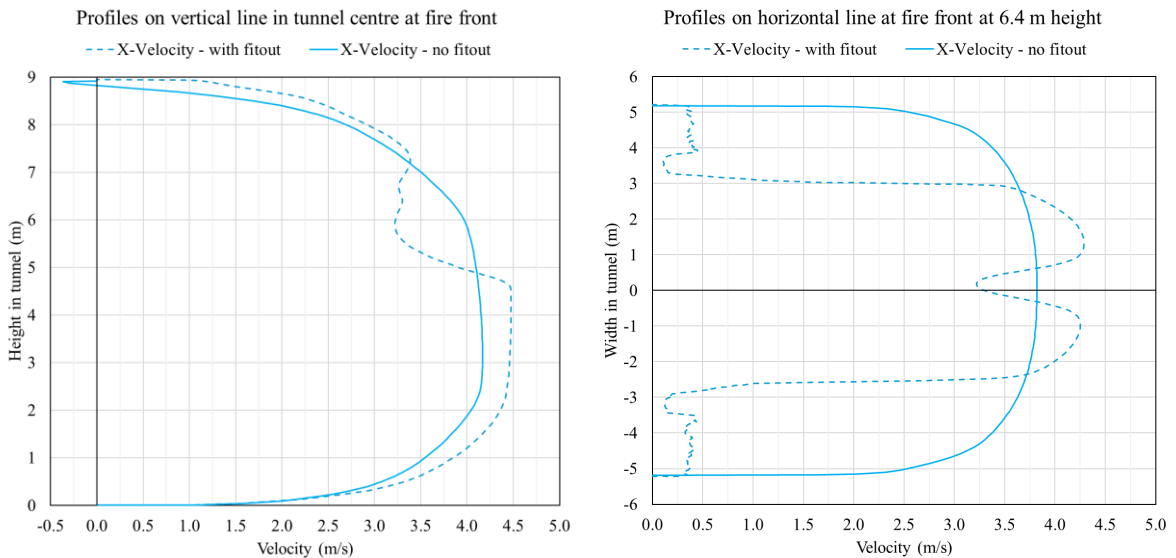


Figure 6: Velocity profile at the fire front for the critical velocity case with and without the tunnel fitout. Left: The profiles were taken on a vertical line from tunnel floor to ceiling on the centre line of the tunnel at the fire front. Right: The profiles were taken on a horizontal line from tunnel wall to tunnel wall at the fire front at 6.4 m height.

3.2. Confinement velocity (flat tunnel)

The influence of the tunnel fitout on the smoke propagation is quite different for the confinement velocity case where a hot smoke layer upstream of the fire is already present to a certain distance (here 30 m upstream of the fire front). With the same fire scenario and the same upstream flow in both tunnels (with and without the fitout) the backlayering length increases by about 50% (from 30 m to 43 m) in the tunnel with the fitout (see Figure 7 and Figure 8).

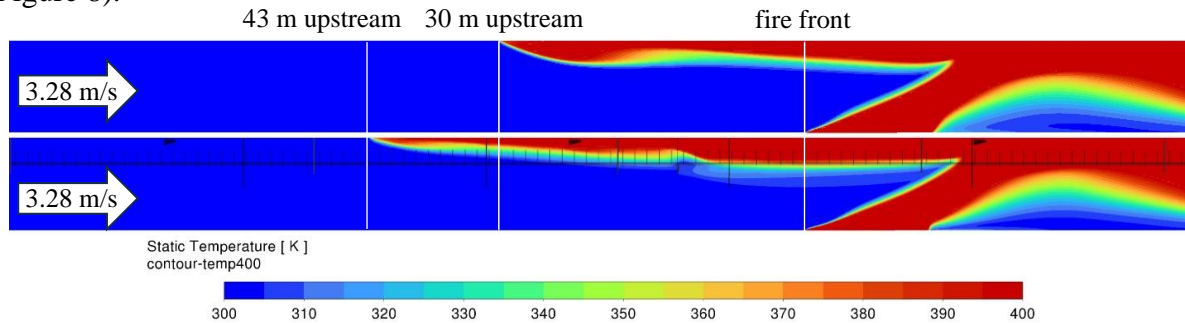


Figure 7: Contour plot of temperature distribution through the centre of the tunnel for the tunnel without (top) [8] and with the fitout (bottom) for the confinement velocity case. Temperature is clipped to 400 K for better presentation.

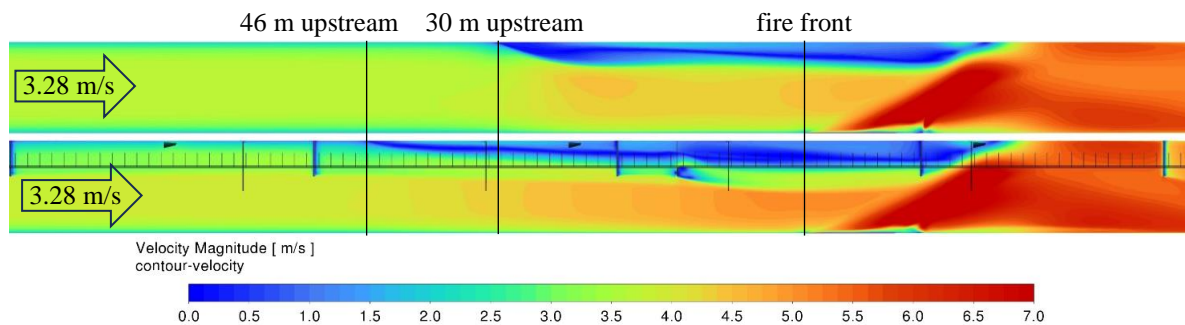


Figure 8: Contour plot of velocity distribution through the centre of the tunnel for the tunnel without fitout (top) and with the fitout (bottom) for the confinement velocity case. Velocity is clipped to 7 m/s for better presentation.

This is believed to be related to two factors. First, the comparison of the velocity profile in the middle of the tunnel for the two cases (Figure 9, left plot) shows that the oncoming velocity close to the ceiling is approximately 10% lower in the tunnel with the fitout. The lower velocity along the ceiling reduces the near-ceiling momentum of the approaching flow that opposes the advancing smoke layer. The velocity profiles shown in the left plot of Figure 9 were taken further upstream of the backlayering (58 m upstream of the fire front). At that location, there is no additional blockage due to either the fire plume (which displaces air sideways and up) or the hot smoke layer that also displaces the oncoming air. The higher ceiling velocity is only present at the fire front but not further upstream. The incoming velocity profile at the upstream extent of the smoke layer is then a different circumstance between the backlayer location at critical and confinement velocities. Secondly, the average velocity gradient in the shear layer between the approaching air and the hot smoke in the backlayer is approximately 35% lower in the tunnel with the fitout compared to the case with the unobstructed ceiling (see Figure 9, right plot). This reduces the shear stress and counteracting force on the backlayer, consistent with a greater upstream propagation of the hot smoke. The air speed around the obstructed areas in the ceiling is reduced, which provides more scope for the backlayer to develop upstream and to increase in thickness (see Figure 7 to Figure 8). The reduction of flow at high level increases the airspeed onto the plume underneath the smoke layer (see Figure 8), which obviously does not strongly influence the

plume behavior at the fire (see Figure 7). The thickness of the backlayer increases significantly, while the relative velocity between smoke backlayer and approaching air is not much changed. This is consistent with a reduced shear stress. This is depicted by the temperature and velocity profile at the fire front as shown in the right plot of Figure 9.

Based on the example chosen, the results indicate that the confinement velocity needs to be appropriately increased in the tunnel with the obstructed ceiling space, if it is desired to restrict the backlayer to the same length observed in the tunnel without the fitout.

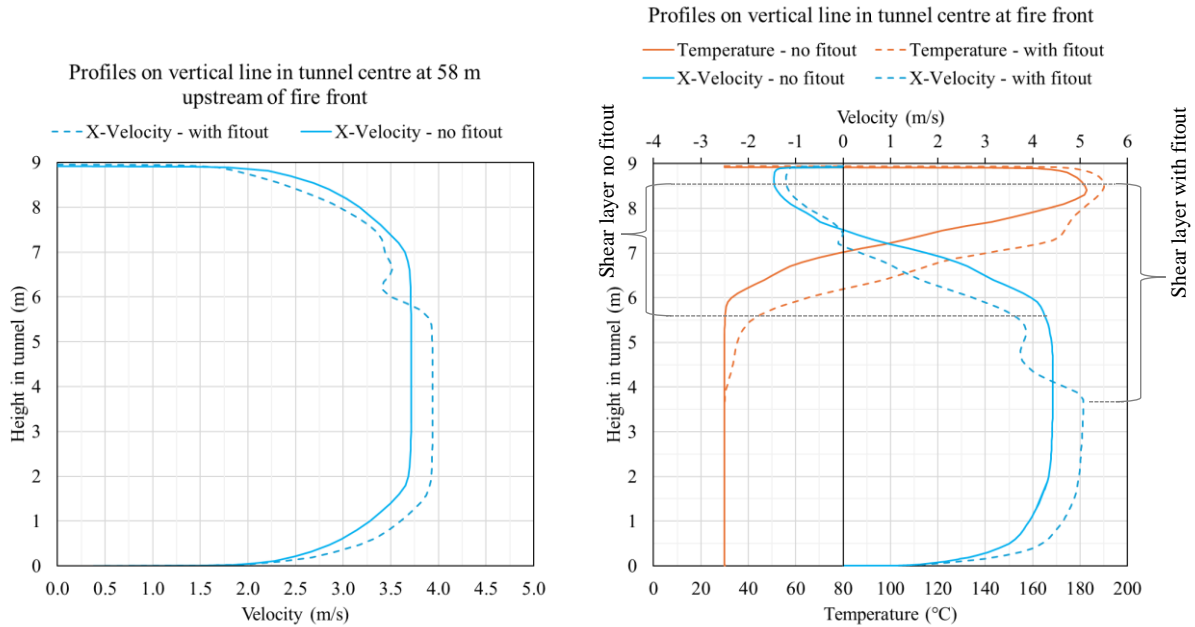


Figure 9: Velocity profiles 58 m upstream of the fire front (left) and at the fire front (right) for the confinement velocity case with and without the tunnel fitout in a flat tunnel. The profiles were taken on a vertical line from tunnel floor to ceiling on the centre line of the tunnel profile.

3.3. Confinement velocity (4% downgrade)

Figure 10 and Figure 11 plot contours of temperature and absolute velocity on a plane through the centre of the tunnel and compare the confinement velocity case results for 4% downgrade. The simulations are for the same fire scenario as before, and have the same upstream flowrate as for the flat tunnel confinement cases, but in a 4% downgrade tunnel.

The instability of the backlayering in the downgrade tunnel due to the additional buoyancy force in the smoke backlayer is already well explained in previous work [8] and will not be discussed again here.

Figure 12 compares the x-velocity vertical profiles in the centre of the tunnel at 58 m upstream of the fire front (left plot) and the x-velocity and temperature profile at the fire front (right plot). The left plot again shows that the approaching air velocity along the obstructed ceiling is about 10% lower than in the case without the fitout. In both cases, the velocity profiles at the fire front show that the initial velocity of the smoke propagating upstream is much higher in the downgrade tunnel compared to the flat tunnel (Figure 12 right plot vs. Figure 9 right plot).

The ceiling-mounted equipment reduces the momentum of the near-ceiling flow. This allows the smoke to propagate more freely upstream as discussed in Section 3.2, leading to much longer backlayering. The additional buoyancy force in the backlayer in the downgrade tunnel increases the backlayering length by approximately 10% compared to the flat tunnel case,

when comparing the two cases with the tunnel fitout (Figure 7 bottom vs. Figure 10 bottom). Also, the backlayering in the downgrade tunnel was seen to be more stable, without the oscillations that were observed in the tunnel without the ceiling mounted equipment.

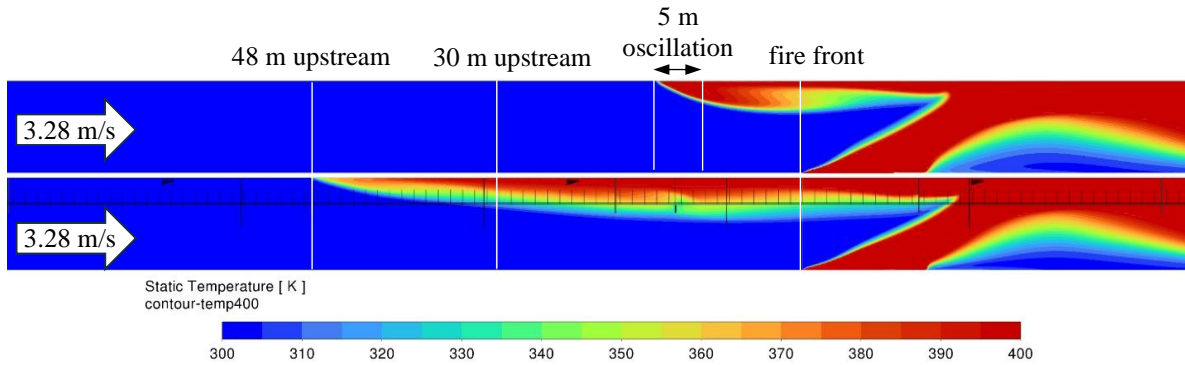


Figure 10: Contour plot of temperature distribution through the centre of the tunnel for the tunnel without fitout (top) and with the fitout (bottom) for the confinement velocity case with 4% downgrade. Temperature is clipped to 400 K for better presentation.

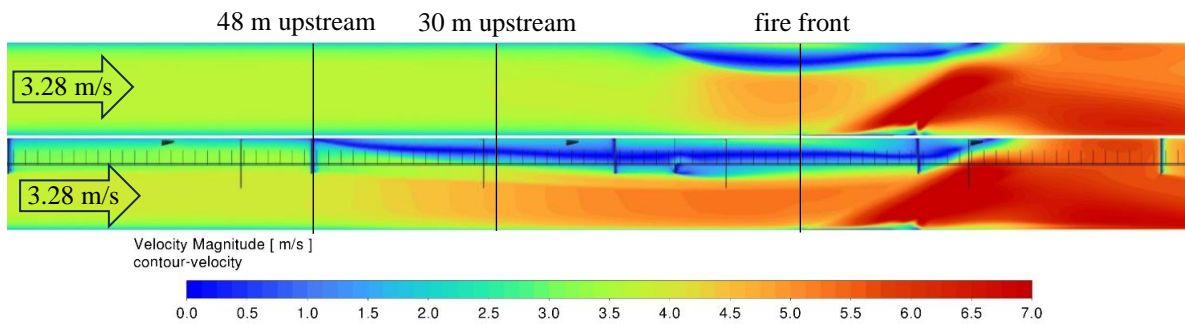


Figure 11: Contour plot of velocity distribution through the centre of the tunnel for the tunnel without fitout (top) and with the fitout (bottom) for the confinement velocity case with 4% downgrade. Velocity is clipped to 7 m/s for better presentation.

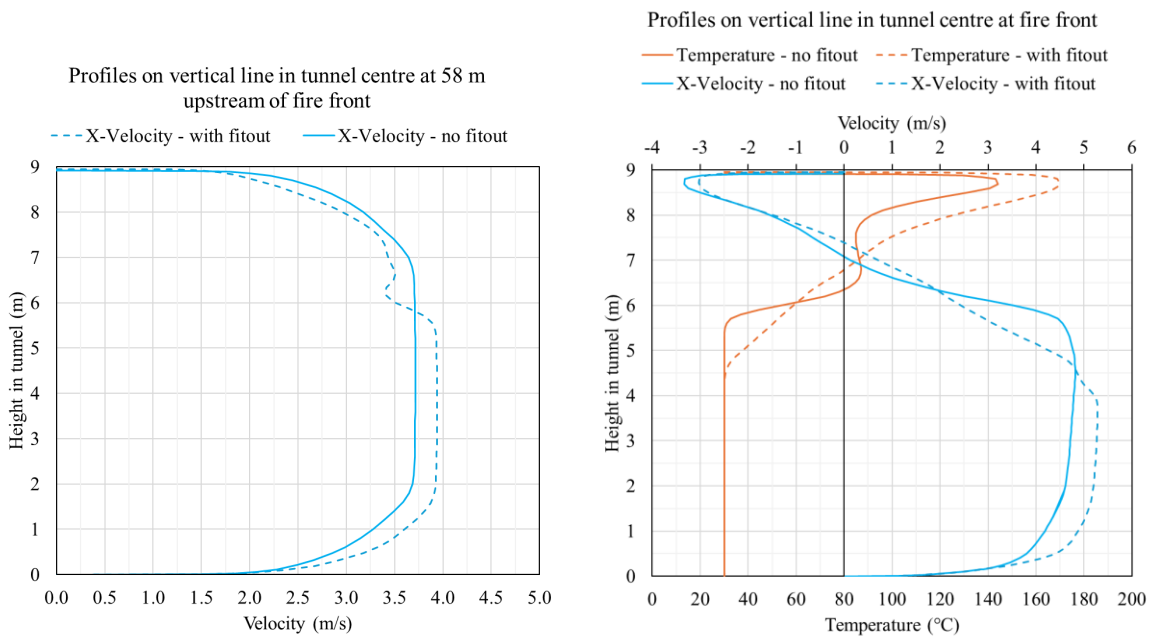


Figure 12: Velocity profile 58 m upstream of the fire front (left) and at the fire front (right) for the confinement velocity case with and without the tunnel fitout in a 4% downgrade tunnel. The profiles were taken on a vertical line from tunnel floor to ceiling on the tunnel centre line.

4. SUMMARY AND CONCLUSION

This study examined the influence of ceiling-mounted tunnel fitout on smoke propagation under longitudinal ventilation using a CFD model validated against the Memorial Tunnel fire tests. A representative three-lane TBM tunnel was analysed with and without typical ceiling-mounted equipment to assess the implications for fitout on critical and confinement velocity concepts adopted in NFPA 502.

For the critical velocity case, the inclusion of ceiling-mounted equipment did not result in a meaningful change in the velocity required to prevent upstream smoke propagation. Local redistribution of the approaching flow was observed near the ceiling, caused by both the presence of equipment and the fire plume acting as an obstacle to the oncoming air. This led to locally increased velocities in unobstructed ceiling regions at the fire front, resulting in slightly enhanced smoke dilution and a marginal displacement of the upstream ceiling jet right above the fire source. These effects were minor and strongly depend on the specific configuration of the tunnel fitout and their arrangement relative to the fire source. Therefore, no generalised influence of ceiling-mounted equipment on critical velocity should be inferred based on the results presented. However, it seems that critical velocity is not sensitive to ceiling fitout. Some sensitivity had been anticipated.

In contrast, the confinement velocity case showed a strong sensitivity to ceiling obstructions. For the same upstream flow rate that limited backlayering to 30 m in the clean tunnel, the inclusion of ceiling mounted equipment increased the backlayering length by approximately 50% in the flat tunnel. This behaviour is attributed to reduced approaching air velocity near the ceiling and a significantly lower velocity gradient across the shear layer between the incoming airflow and the hot smoke backlayer, resulting in reduction of the shear stress opposing upstream smoke propagation.

In the 4% downgrade tunnel, these effects were further amplified by the increased longitudinal component of buoyancy forces in the smoke layer, leading to longer and more stable backlayering relative to the tunnel configuration without the fitout. That is the opposite trend to that we found without the fitout, where the backlayer length in the downgrade tunnel reduced compared to the flat tunnel [8].

Overall, the results indicate that ceiling-mounted tunnel fitout has little influence on critical velocity but can significantly affect confinement velocity and backlayering behaviour, particularly where an established upstream smoke layer is present. The confinement velocity is highly sensitive to local ceiling-level flow conditions, which may be substantially affected by tunnel equipment even when the overall tunnel cross-sectional area is largely unchanged.

The findings presented in this study are based on a specific tunnel geometry, ventilation configuration, fire scenario, and a representative arrangement of ceiling-mounted tunnel fitout. While the CFD methodology has been validated against relevant experimental data obtained from full-scale tunnel fire tests, the results are sensitive to the detailed geometry, arrangement of the tunnel fitout, as well as tunnel slope, fire location, and design fire size.

For tunnels incorporating significant ceiling-mounted installations, the determination of critical and confinement velocity should therefore be undertaken on a project-specific basis, using CFD models validated against appropriate full-scale data and reflecting the actual tunnel geometry and fitout arrangement. Simplified or generic design values may not adequately capture the impact of ceiling obstructions on upstream smoke propagation.

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