Numerical investigation over the impact of longitudinal velocity on tenability conditions in longitudinally ventilated road tunnels

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Abstract: Longitudinal ventilation is designed to limit or prevent smoke spread upstream the fire and to create a safe environment for tunnel's occupants. Critical velocity and backlayering length are often used as criteria for the design of ventilation systems. However, tenability conditions for tunnel's occupants should be also included in the design process. Through computational fluid dynamics analyses smoke spread and tenability conditions are investigated in a tunnel with a large fire (200 MW), varying the longitudinal velocity (2.0 m/s, 2.5 m/s and 3.0 m/s). The results show that with a ventilation speed of 3.0 m/s the smoke remains confined at the fire seat. With a ventilation speed of 2.5 m/s the smoke spreads under the ceiling for a short distance, but the smoke layer doesn't descend at occupants' level. Therefore, the tenability conditions are comparable with those obtained for higher ventilation speed. With a ventilation speed of 2.0 m/s the smoke spreads under the ceiling for a longer distance and later descends at occupants' level, however, the impacted area is smaller than the backlayering length itself. For all ventilation regimes, thermal radiation is the most critical parameter, coming directly form the fire and from the hot smoke layer, if present.

Keywords: Critical velocity; Smoke backlayering; Computational Fluid Dynamics; Tenability conditions

1 Introduction

Critical velocity in tunnels is a highly debated topic due to its large impact on design and cost of the ventilation installation. In the last years mainly due to the revisions of the NFPA502 there was an active debate on the definition and the calculation of critical velocity itself (NFPA 502, 2023) (Stacey, & Beyer, 2020). The paper proposes a new focus on tenability conditions rather than smoke spread studying different ventilation regimes.

2 Methodology

Computational fluid dynamics (CFD) is chosen to study the smoke behaviour and tenability conditions in the tunnel. The software Fire Dynamics Simulator (FDS 6.8.0) is used for the purpose thanks to its extensive use in fire safety related analyses (McGrattan et al 2023). The tunnel under analysis is 11 m wide, assuming two traffic lanes, and 6.15 m high. In the tunnel a large truck (double trailer) is set on fire with a nominal heat release rate (HRR) of 200 MW (Huijben at al. 2005). Standing vehicles upstream the fire and the burning vehicle are included in the model to account for their impact on the flow field. The numerical domain is extended 200 m upstream and downstream the fire to allow possible smoke backlayering and the flow development in the tunnel. The longitudinal ventilation speed (u), calculated on the nominal section, is set at 2.0 m/s, 2.5 m/s and 3.0 m/s.

3 Results

The results obtained with different ventilation regimes are compared together by showing: smoke front, visibility, temperature, CO concentration and thermal radiation.

3.1 Smoke front

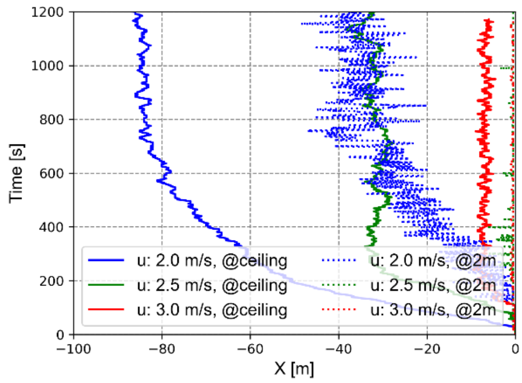


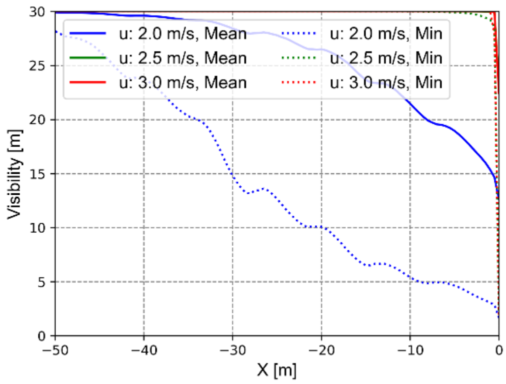
Figure 1 Smoke front volution

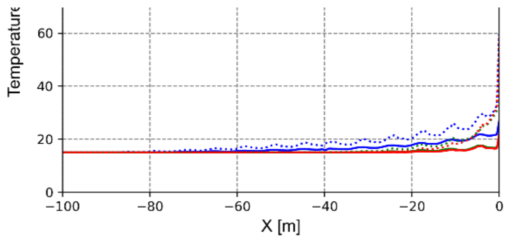
The evolution of the smoke front is monitored under the ceiling and at 2 m high, figure 1. The maximum soot density, above the limit of 0.02 g/m³, is used as criterium to define the front location. With 2.0 m/s ventilation regime the smoke front exceeds 80 m under the ceiling, and it fluctuates between 30 and 40 m at 2 m high. With a 2.5 m/s ventilation regime the smoke front is confined to 30 m under the ceiling and at the fire seat at 2 m high. With 3.0 m/s ventilation regime the smoke front is confined to less than 10 m under the ceiling and at the fire seat at 2 m high. The smoke front stabilities after 800 s, and this time is chosen for the results averaging.

3.2 Visibility

Figure 2 Visibility along the tunnel

The minimum and average visibility at 2 m high is presented





in figure 2. With 2.0 m/s ventilation regime the smoke travels along the ceiling and once cooled down descends on occupants creating zones of limited visibility. The minimum visibility is lower than 10 only in the last 20 m from the fire which is much shorter than the backlayering length under the ceiling. With higher ventilation regimes the visibility is not affected at 2 m high.

3.3 Temperature

Figure 3 Temperature along the tunnel

The maximum and average temperature at 2 m high is presented in figure 3. The temperature remains well below the 60 °C for all ventilation regimes.

3.4 CO concentration

The maximum and average CO concentration at 2 m high is presented in figure 4. With a 2.0 m/s ventilation regime the maximum CO concentration exceeds 100 ppm only close to the fire seat, less than 5 m. With higher ventilation regimes the CO concentration remains at ambient level.

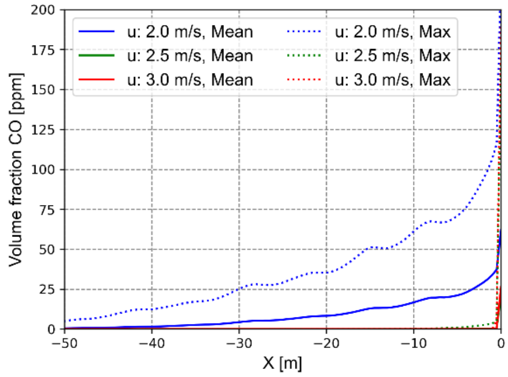


Figure 4 CO concentration along the tunnel

3.5 Thermal radiation

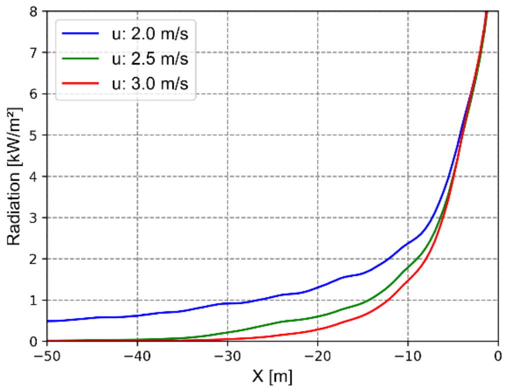


Figure 5 Radiative heat flux along the tunnel

The radiative heat flux at 2 m high is monitored between the traffic lanes and it is presented in figure 5. The heat flux exceeds 1 kW/m at 25.5 m, 14.0 m and 12.5 m respectively for 2.0 m/s, 2.5 m/s and 3.0 m/s ventilation regimes. The impacted length at lower ventilation regimes is larger because of the radiation of the smoke layer under the ceiling.

4 Conclusions

The paper investigates the impact of the ventilation regime on the tenability conditions inside a road tunnel. The results show that a limited backlayering under the ceiling has negligible impact on the tenability conditions at occupants' level. Lower ventilation regimes, with long backlayering under the ceiling, can cause smoke recirculation at occupants' level, however, the smoke is highly diluted by fresh air. Thermal radiation coming from the fire source, or the upper smoke layer, is the most critical tenability criterium.

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