A COMPARATIVE STUDY OF FIRE SAFETY PROVISIONS EFFECTING EVACUATION SAFETY IN A METRO TUNNEL

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Abstract

This paper utilizes Computational Fluid Dynamics (CFD) and evacuation modeling to compare different evacuation configurations in a metro rail tunnel. Different configurations are based on variations in the exit spacing, walkway width and elevation, and the use of longitudinal ventilation for smoke control. The interaction of these evacuation configurations with the tunnel grade and tunnel area are also considered. The different configurations are quantitatively compared on the basis of standard tenability criteria such as visibility, but also using a Fractional Effective Dosage concept regarding asphyxiates.

1. INTRODUCTION

1.1. Background

A rail tunnel is a relatively simple geometric structure. However, complexities and uncertainties associated with a fire event mean that designing for evacuation of a train in a tunnel is not a simple process [1]. If a fire is detected on a train, the typical strategy is to continue to the next station. This allows detrainment to be better managed with egress routes that are more familiar to people [1].

There is still a residual risk that a fire occurs on the train while in the tunnel and the train is unable to reach the station. This could be the result of mechanical failure or congested network conditions. While this scenario might be unlikely, it is usually deemed credible enough to require tunnel evacuation provisions. However, the evacuation provisions can impact the overall structural design and project cost. A balance is therefore required between cost and safety.

Typical evacuation provisions for rail tunnels vary between countries. In general terms, walkway widths tend to be between approximately 0.7m to 1.5m, exit spacings between approximately 240m to 500m and there is differing guidance on the walkway location and elevation [2–5]. The use of longitudinal ventilation for smoke control also varies. In countries such as the United States, United Kingdom and Australia, it is the authors' experiences that longitudinal smoke control is typically provided. In other countries, such as Sweden, this is not as common. Longitudinal smoke control in rail tunnels may also be perceived to increase the risk to life safety [2].

Given the number of rail tunnels worldwide it is interesting, but not surprising, that there is so much variation in requirements and standard practice. Performance-based fire engineering is usually employed when it comes to rail tunnel design and this is necessitated by the nuances with each system. However, when a provision is viewed in isolation this can be misleading when benchmarking a design, or be confusing for stakeholders or other design disciplines.

This paper aims to investigate a range of tunnel evacuation design configurations and the impact that these have on evacuation safety. The inputs and scenarios are focused on a metro tunnel, but the concepts are likely applicable to other rail tunnel systems. This paper is not intended to provide a 'solution' to rail tunnel evacuation, and this approach is in no-way advocated. Instead, this paper provides a comparative set of results that can be used by fire safety designers when developing their own options for further assessment.

1.2. Previous Research

A detailed review of previous research into rail tunnel evacuation, smoke control strategies and operational strategies is beyond the scope of a paper. The focus of this short literature review is relevant studies that provide similar insight and approaches, and for context for later discussions.

The concept of longitudinal smoke control is well developed in the literature [4, 6–9]. Achieving critical velocity provides a clear path for evacuation on one side of the fire, and is also beneficial for fire service intervention. This is often a key criteria to demonstrate fire safety in rail tunnels in countries where longitudinal smoke control is typically provided [4, 10]. The alternative point of view is that knowing which way to direct the smoke may depend on the fire location and require a level of judgment that could result in smoke being directed over evacuating people [11].

Guidelines and standards typically provide maximum recommended or allowable tunnel exit spacings [2]. The final spacing might be a function of other considerations such as geology or stakeholder requirements. Edenbaum et al. [12] used SIMULEX [13] to investigate the spacing of rail cross-passages accounting for different walkway widths in view of the requirements of NFPA

130 [4, 2003 Ed.]. This work concluded that a performance based approach allows for trade-offs between cross-passage spacing, walkway width and fire-hardening of the rail vehicle.

The elevation of a tunnel walkway can determine the ease of detrainment. In some instances detrainment could also be via the ends of the train to a central track-level walkway [1]. A wider walkway should increase people flows, reducing the evacuation time. Lundström et al. [14] studied walkway design and the effect this has on evacuation behavior in rail tunnels. This work outlined that an elevated walkway may be beneficial for mobility impaired, but might also result in a fear of falling and reduced movement speeds. This work considered different walkway widths and an empirical relationship was developed for the flow of people with differing widths.

Fridolf [15] provides a detailed review of human behavior in rail tunnels, including a significant database of empirical and field observations of rail tunnel evacuation. The database is a compilation, which consists of data and information related to train evacuation in rail tunnels as well as the succeeding tunnel evacuation and exit choice. It includes the work of empirical studies conducted by others, and is complemented with Fridolf's own work in both the laboratory and field (among other things, a full-scale evacuation experiment in the Stockholm Metro, including 135 participants). In addition, suggestions and recommendations on the application and design use of that data is also given.

Kučera and Bradáčová [16] undertook FDS modeling of a bi-directional, 700m long rail tunnel fire. Fires were modeled on 5% grade and with an applied velocity of 1m/s with a maximum fire size of 12MW. Evacuation simulations were undertaken with FDS+Evac [17], with 640 people, a maximum exit distance of approximately 660m and 1.5m wide walkway on both sides of the tunnel. For the scenarios considered they concluded that no people would be exposed to untenable conditions.

Winkler and Carvel [11] investigated ventilation and egress strategies for passenger train fires in tunnels. This work concluded that if passengers are on both sides of the fire that longitudinal ventilation should not be used as people could be exposed to untenable conditions within a few minutes. The authors put particular emphasis that the conclusions are only applicable to the scenarios modeled. The fire curves used were intended to represent high-speed rail, and included a linear growth from 0 to 45MW in 4 minutes and a linear growth from 0 to 10MW in 20 minutes. The larger fire was intended to account for the impact that applied ventilation could have on the fire size.

2. INPUTS AND METHODOLOGY

2.1. Limitations

The intent of this paper is to develop a comparative set of results for different evacuation configurations in a metro tunnel. However, the work in this paper is no substitute for a project specific fire safety analysis. It should be understood that to simplify the number of simulations and to provide direct comparison of key parameters, some inputs have been kept constant that might vary in reality. This is discussed in the following sections.

The inputs and assumptions in this paper are nominal, and while informed by project experience, they do not represent any particular project. Furthermore, the presentation of results is nominal and comparative, and no result should be interpreted as being acceptable to the authors or any particular jurisdiction. Considerations such as stakeholder requirements and other practical constraints might govern the fire safety provision for a particular project and what is deemed acceptable. A risk analysis might also be used to justify the credible design fire scenarios. No consideration of likelihood has been considered in this paper.

Tunnel aerodynamics at the time of a fire event, particularly in metro systems, can be complex and vary with many factors including non-incident train movements, atmospheric conditions, normal operations ventilation and incident train piston flows. To properly implement boundary conditions for a project specific CFD analysis a 1-D aerodynamic model such as SVS [9] could be used. For this comparative study the boundary conditions used are intended to represent possible flow conditions during a fire with limited consideration of airflow transients.

2.2. Scenario Selection

Table 1 shows a simplified set of parameters that were considered for the CFD and evacuation modeling. If each parameters is considered independent, then combining these in a parametric evacuation study would require over 100,000 separate evacuation simulations. To limit the number of scenarios the values in *italics* were selected. This resulted in 12 separate CFD models and 144 evacuation scenarios. The parameters selected are intended to focus on the interaction of the walkway width and elevation, exit spacing, tunnel area and grade, and in-tunnel velocity conditions on evacuation outcomes. Figure 1 shows a schematic of the scenarios modeled.

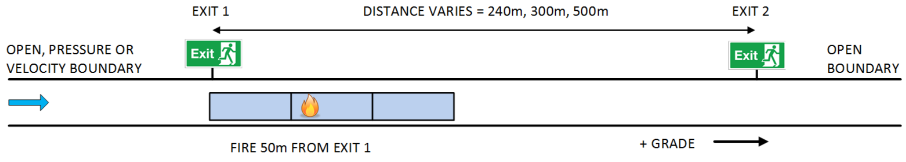


Figure 1. Scenario Modeled.

The front of the train is assumed to come to a stop at a tunnel exit. For a tunnel without ventilation the worst case could be a fire at the front of the train that blocks an exit and results in the greatest distance to an alternative exit. For a tunnel with ventilation the smoke control strategy is likely to be dependent

CFD Scenario Parameters				
Fire location in train	-	Front	*Middle*	Back
Fire size	MW	2	*5*	>10
Fire growth rate	kW/s^2	0.003	*0.012*	0.047
Tunnel grade	%	-4	*0*	*+4*
Tunnel velocity	-	*No velocity*	*2m/s wind*†	*Critical velocity*
Tunnel area	m^2	*22*	*28*	45‡
Evacuation Scenario Parameters				
Walkway width	m	<0.8	*0.8*	*1.2*
Pre-movement ◇	s	120	*240*	360
Occupant load	p	600	*900*	1200
Exit separation	m	*240*	*300*	*500*
Walkway elevation	-	*Track*	Semi	*Elevated*

† Modeled as a pressure boundary ‡ Double track geometry

◇ Agents in the fire car, other agents have a pre-movement time of +120s

Table 1. Example Parameters For Scenario Selection

on the location of the fire on the train. This requires an operator decision or control loop that is simple if the fire is at one end of the train, but may require judgment if the fire is located towards the center of the train. For this reason the fire was located in the middle car, but biased towards the closest exit. This is considered a reasonable scenario to compare a ventilated and non-ventilated solution.

The walkway and exit spacing were guided based on a possible design in a particular jurisdiction. For instance, a tunnel with an 800mm elevated walkway, 240m exit spacing and longitudinal ventilation to achieve critical velocity might be representative of (or exceed) a NFPA 130 compliant design [4], that might also be applicable in other countries such as Australia [10]. On the other hand, a 1200mm track level walkway, 300m or 500m exit spacing and no tunnel ventilation might be representative of a European design [2]. The walkway width could also govern the structural design and resulting tunnel cross-section. This is discussed as part of the CFD geometry.

A single fire curve (5MW, medium t-squared, $\alpha = 0.012kW/s^2$) was used for all evacuation scenarios. In reality, this may not necessarily be the case with varying ventilation [11] and tunnel geometries [18] impacting the fire curve. However, a constant fire curve allowed the impact of the evacuation configurations to be compared. A value of 5MW may not represent a worst-case for metro rollingstock. Based on project experience this value is considered reasonable in view of a possible project design requirement or a 'credible' tunnel evacuation design case.

Other parameters such as pre-movement time and occupant load were nominally selected. These parameters could vary significantly between projects, but the values selected were considered somewhat typical based on project experience. The grade could also vary significantly. Tunnel grades of 0% and 4% were nominally selected, albeit a 4% grade could be towards the higher end for a metro system. The grades are relative to the main people movement with a positive grade having more potential for buoyant smoke to move in the direction of evacuation towards the furthest exit.

2.3. CFD Modeling

The CFD modeling was undertaken with FDS version 6.1.2 [19]. The fire was modeled with the spread-rate function used to approximate the medium t-squared growth rate. Once the fire reaches peak heat release rate it is kept at this value with no decay modeled. A soot yield of 0.1kg/kg and a CO yield of 0.1kg/kg were used, along with a heat of combustion of 20MJ/kg.

Grid sizes of 0.2m were used across the train length and approximately 10m beyond the train ends. In the open sections grid sizes of 0.4m were used. This resulted in characteristic fire parameters [19] of $D^*/dx = 9.1$ and $Q^* = 0.6$ in the vicinity of the fire. A grid convergence study was not undertaken, however, grid sizes are considered adequate based on previous experience.

The tunnel was modeled as being 900m in length. This allows for the maximum exit spacing of 500m. At least 100m of tunnel was allowed beyond each exit to keep the areas of interest away from the boundary conditions. The two tunnel cross-sections were modeled as per Figure 2. The width varies to allow for different cross-sectional areas. The tunnel height was kept constant to eliminate another variable for consideration.

A walkway of 1200mm can be accommodated in both tunnel cross-sections and is included in the evacuation scenarios. For the 22m^2 tunnel this might be impractical due to tunnel services or curvature reducing the effective walkway width, but is still considered to compare the impact of the reduced tunnel area. For the 28m^2 tunnel a 800mm walkway on the opposite side to the evacuation walkway could be accommodated, but this was not used in the evacuation analysis.

The train was modeled with a cross-sectional area of approximately 11m^2 with a length of approximately 140m. The train is a three car consist, although each car is modeled as being a separate unit without inter-car doors (i.e. smoke cannot spread inside the train between cars). The train doors were modeled to be closed until the start of evacuation. Windows stayed in-tact for the duration of the simulation. The fire was not oxygen limited.

2.4. Evacuation Modeling

A simple 1-dimensional model was developed to undertake the evacuation assessment. The model was programmed in Perl [20], with inputs defined in text files and batch scripts used as drivers to the main program. This enabled the 144 evacuation simulations presented in this paper to be undertaken with minimal human input once the base files were setup. This approach was considered suitable for the current investigation due to the relatively simple evacuation

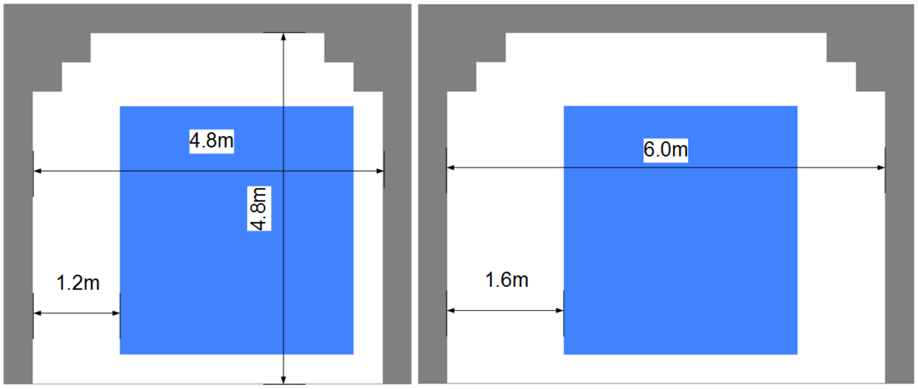


Figure 2. 22m^2 tunnel (left) and 28m^2 tunnel (right). Blue blockage indicates train.

routes. This approach also provides complete control of the evacuation correlations and flow rates. It is acknowledged that the model does not include the more complex interactions in software such as Pathfinder [21] and STEPs [22]. However, the 1-D model has been used to produce results that are comparable to these more advanced methods for similar tunnel situations.

Agents are tracked in the evacuation model along a walkway path defined in the FDS model. Along the path FDS devices are used to record visibility, temperature, CO, CO_2 and O_2 at the track level (2m) and elevated (3.2m) walkway tenability heights. A temporal resolution of 1 second and an averaged spatial resolution of 5m are used to record these values. A quasi-Lagrangian method is used to track agent locations which enables their exposure to reduced visibility and their accumulated Fractional Incapacitating Dose (FID) to be calculated.

The agent FID at each time-step is calculated using the same equations implemented in Pathfinder [21] and FDS+EVAC [17], which are based on the work of Purser [23, 24]. The contribution from HCN and other irritants are not included in the calculation of FID. The FID is only accumulated once the occupants are leaving the train and while in the tunnel. Therefore, results may not be conservative for agents in the fire car, but the same simplification is used across all scenarios.

A hydraulic model is used to regulate the movement of agents along the walkway accounting for crowding and the walkway width. For the flow rate of agents along the walkway, the same correlation was used independent of the walkway elevation. A fixed correlation enables a direct comparison of the impact of the agents being closer to the smoke layer for the elevated walkway. Equation (1) shows the correlation used [14, 25]:

$$Flow\ rate\ of\ people[p/s] = 1.27 \cdot walkway\ width[m] + 0.07 \tag{1}$$

When agents are walking adjacent to the train this situation is considered similar to a corridor. The correlation given in the Swedish building guidelines for analytical fire safety design [26] was adopted and shown as equation (2).

$$Flow\ rate\ of\ people\ [p/s] = 1.2 \cdot walkway\ width[m] \tag{2}$$

In reduced visibility conditions the walking speed is based on the relation by Fridolf et al. [27]. This is shown as Equation (3), where x is the extinction coefficient. A maximum speed of 1.2m/s is allowed, with a minimum speed of 0.3m/s. There is no reduction in walking speed with grade which is consistent with field measurement with grades of 4.5% [28].

$$Walking\ speed\ [m/s] = -1.1423 \cdot x + 1.177 \tag{3}$$

There are seven doors per car that enable agents to evacuate onto the walkway. Detrainment is based on a door flow of 0.2p/s regardless of the walkway height. There is considerable variation in field measurements for detrainment to an elevated or track-level walkway [15, Table 6], however a value of 0.2p/s appears to be plausible, albeit conservative, for both configurations. Agents can only leave the train if the walkway density is less than 4p/m^2 which ultimately determines the detrainment rate. The tunnel exits are assumed to be 2m wide with a door flow of 2p/s.

Agents are evenly distributed along the train (i.e. 3 cars x 300 agents per car). Each agent is randomly assigned a group which defines their maximum walking speed. The varying agent groups are intended to provide a spread of capabilities which could represent that of the general population. To do this 10% of agents were assigned a maximum walking speed of 0.8m/s which could be indicative of mobility impaired or children. A further 70% were assigned a maximum walking speed of 1.0m/s to represent the majority of the population. The remainder were assigned a maximum walking speed of 1.2m/s. It should be noted that the walking speed achieved by each agent is ultimately a function of crowding, visibility conditions and walkway flow rates.

To estimate occupant tenability accumulated FIDs were calculated for each agent. As defined by ISO 13571 [29], an accumulated FID of 1.0 corresponds to a log-normal distribution of responses, with statistically 50% of the population expected to experience tenable conditions, with 50% then expected to experience compromised tenability. The threshold criteria of accumulated FID ≥ 0.3 used for this assessment translates to 11.4% of the population being statistically susceptible to compromised tenability [29].

3. RESULTS

3.1. Visibility and Other Tenability

Visibility results from the CFD simulations are shown in Figure 3 and Figure 4. Results are only shown for the 22m^2 tunnel. Results for the 28m^2 tunnel are very similar, albeit visibility is slightly improved due to the larger cross-section. However, the variation in visibility is better quantified with the results presented with the evacuation assessment.

The visibility results are displayed as a function of distance from the fire (X) and increasing time (T). XT figures provide a convenient way of representing a large amount of transient data without having to display numerous contours. These figures were produced with the FDS device output for visibility and post-processed in GNU Octave [30].

Exit 1 is the exit closest to the fire and the multiple exit options are also indicated as vertical lines. The XT contours have been clipped such that visibility greater than 10m is shown as white space. Visibility is based on a light emitting surface (C = 8 [19]). The contours are produced for a track-level walkway (2m above track) and elevated walkway (3.2m above track). The figures show 30 minutes of simulation time as outcomes are obvious after this period, although the simulations were run for 60 minutes.

XT figures were also used to check all components of tenability (i.e. temperature, CO, CO_2, and O_2). For reasons of space these are not presented, but are part of the FID assessment. For all scenarios, temperatures at tenability heights were less than 60 °C away from the immediate vicinity of the fire site, and less than 40 °C beyond the ends of the train.

For the still air conditions on 0% grade there is a somewhat symmetrical spread of smoke which is biased one way due to the asymmetry in the fire location relative to the train length. When the still air conditions are modeled on 4% grade the smoke buoyancy induces a significant airflow in the tunnel. For a real system the magnitude of this airflow could vary depending on many factors, but for the scenario modeled, the high grade results in a situation similar to a tunnel with forced ventilation.

When a pressure boundary is applied the smoke is biased towards the direction of evacuation, but significant backlayering still occurs. While the pressure boundary is based on a velocity of 2m/s, the velocity achieved in the tunnel is much lower (~0.3-0.5m/s for 0% grade) due to pressure losses associated with tunnel friction, the train blockage and fire. The achieved velocity could vary for another model setup. A pressure boundary was used to allow smoke to overcome the upstream boundary and to illustrate a velocity condition less than critical velocity. With a 4% grade, the flow is biased toward the direction of egress for the reasons noted above.

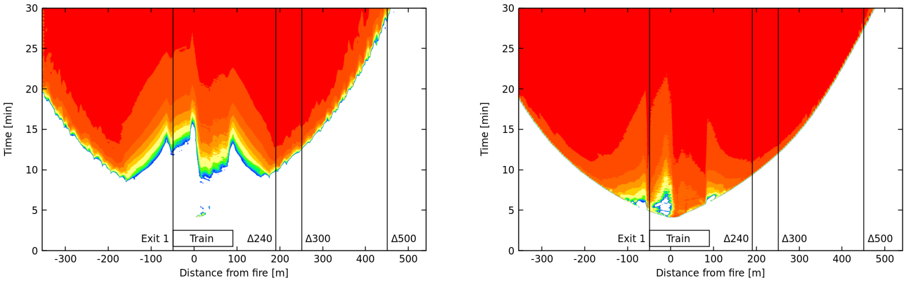
When a critical velocity is modeled the outcome is as expected. The tunnel ventilation is started at 300 seconds and ramps to capacity in 60 seconds. The calculated critical velocity for each area and grade varied, but was generally estimated [4] to be 1-1.3m/s upstream of the 5MW design fire in the clear tunnel area. Once this occurs smoke is driven in one direction. There is a small amount of back-layering noticeable for the 0% grade simulations suggesting the critical velocity used was slightly under-sized, but this does not impact the evacuation assessments. For the fire size used, this is likely corrected by the latest critical velocity calculations from NFPA [31].

The XT figures also show the variation in walkway elevation and tunnel cross-section. In general terms, visibility conditions are more favorable for a track-level walkway with a larger tunnel cross-section. This result is expected as the smoke layer is higher relative to the agents on the walkway.

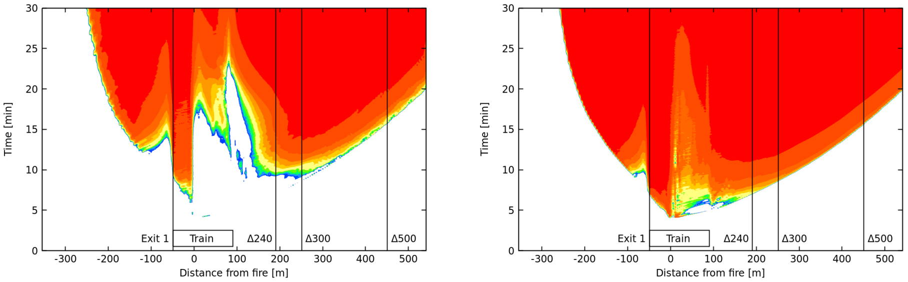
For the models with a significant airflow in the tunnel, a region of increased visibility occurs between the fire location and the end of the train. This is due to the increased velocity associated with the restricted (annulus) area across the train. This causes dilution of the combustion gases relative to the full tunnel cross-section. This effect is more noticeable for the track-level walkway than for the elevated walkway which suggests that even with tunnel ventilation applied a degree of smoke layering is still present for the fire considered.

Track-level walkway (left figures) **Elevated walkway (right figures)**

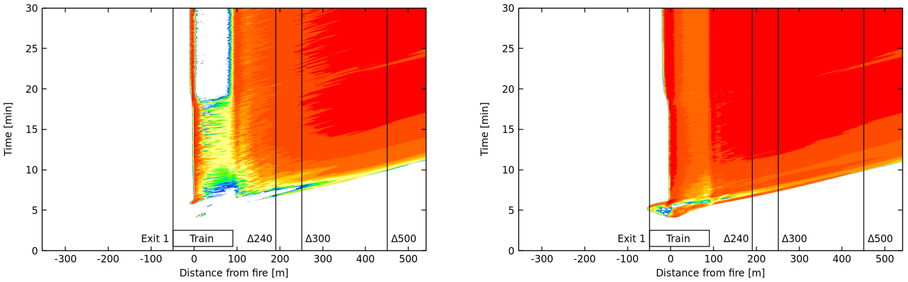
Visibility at 2m above track Visibility at 3.2m above track



(a) Still conditions (open boundaries at each end)



(b) Pressure boundaries based on 2m/s portal wind (applied on left side)



(c) Critical velocity, started at 5 minutes (applied on left side)

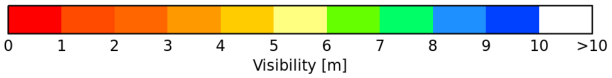
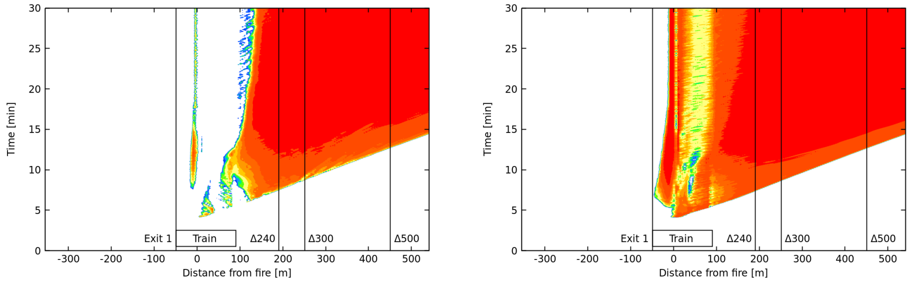


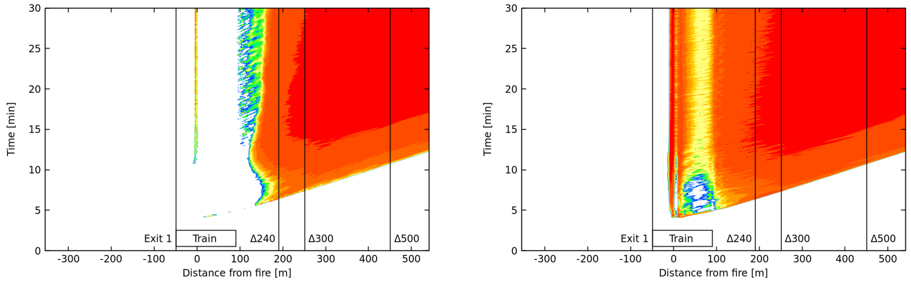
Figure 3. Visibility [m] for 0% grade and 22m^2 tunnel section.

Track-level walkway (left figures) **Elevated walkway (right figures)**

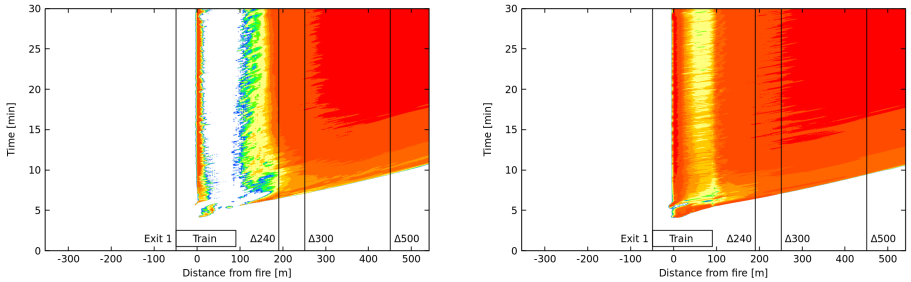
Visibility at 2m above track Visibility at 3.2m above track



(a) Still conditions (open boundaries at each end)



(b) Pressure boundaries based on 2m/s portal wind (applied on left side)



(c) Critical velocity, started at 5 minutes (applied on left side)

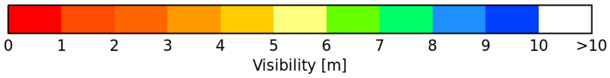


Figure 4. Visibility [m] for 4% grade and $22m^2$ tunnel section.

3.2. Evacuation and Accumulated FID

Four sets of results are presented that compare the different parameters selected from Table 1. Accumulated FID results have been truncated at unity. Other results have been normalized to present values between zero and unity. The normalization used for each result is provided in the figure title and is convenient to show a fraction of the worst-case outcome across the scenarios considered.

The results for the evacuation assessment are generally as expected. As the exit spacing increases and the walkway width decreases, the maximum accumulated FIDs (Figure 5), number of agents exposed to accumulated FID ≥ 0.3 (Figure 6), number of visibility exposures (Figure 7) and total evacuation time (Figures 8) all increase. The walkway width and exit spacing directly affect the time that occupants are in the tunnel and exposed to combustion gases. The relative magnitude of these increases for different exit spacing and walkway widths is a function of the walkway elevation, tunnel boundary conditions and tunnel grade.

Two walkway elevations were investigated. Accumulated FID and low visibility exposures are generally reduced with a track-level walkway compared to the elevated walkway. This is because the walkway elevation affects the height of agents relative to the smoke layer. It could be argued that an elevated walkway facilitates more rapid detrainment, particularly for mobility impaired and children. For the two walkway elevations the same detrainment flow rate was assumed and crowding of the walkway reduced the effective detrainment flow rates. This, however, does not consider nuances associated with mobility impaired detrainment to a track level walkway or onto an elevated walkway with insufficient width to enable turning of mobility aids.

The use of longitudinal smoke control and a high grade are similar. As discussed for the visibility results, the models with tunnel grade resulted in an airflow that effectively provided a critical velocity across the fire site, preventing backlayering and directing the products of combustion towards the majority of evacuating agents. However, a velocity due to the tunnel ventilation or grade effect caused dilution across the train and improved tenability. This is in contrast to a flat grade without an applied velocity where exposures are generally higher. However, the results are not as definite with a 500m exit spacing without an applied velocity. For some 500m exit spacing configurations agents start to out-pace the worst of the naturally developing smoke layer.

The effect of an applied velocity is interesting and somewhat counter-intuitive particularly when compared to the conclusions drawn by Winkler and Carvel [11]. But direct comparison between the data sets is difficult due to the different fires and intended rollingstock. While fire size and ventilation interaction were not considered in the current work, it does seem reasonable that as the fire size increases, any dilution effect is diminished due to the increased formation of combustion products. What is interesting from the current results is that if high grades exist then a non-ventilated solution could in-fact be similar to a ventilated tunnel, but without the control possible with mechanical ventilation.

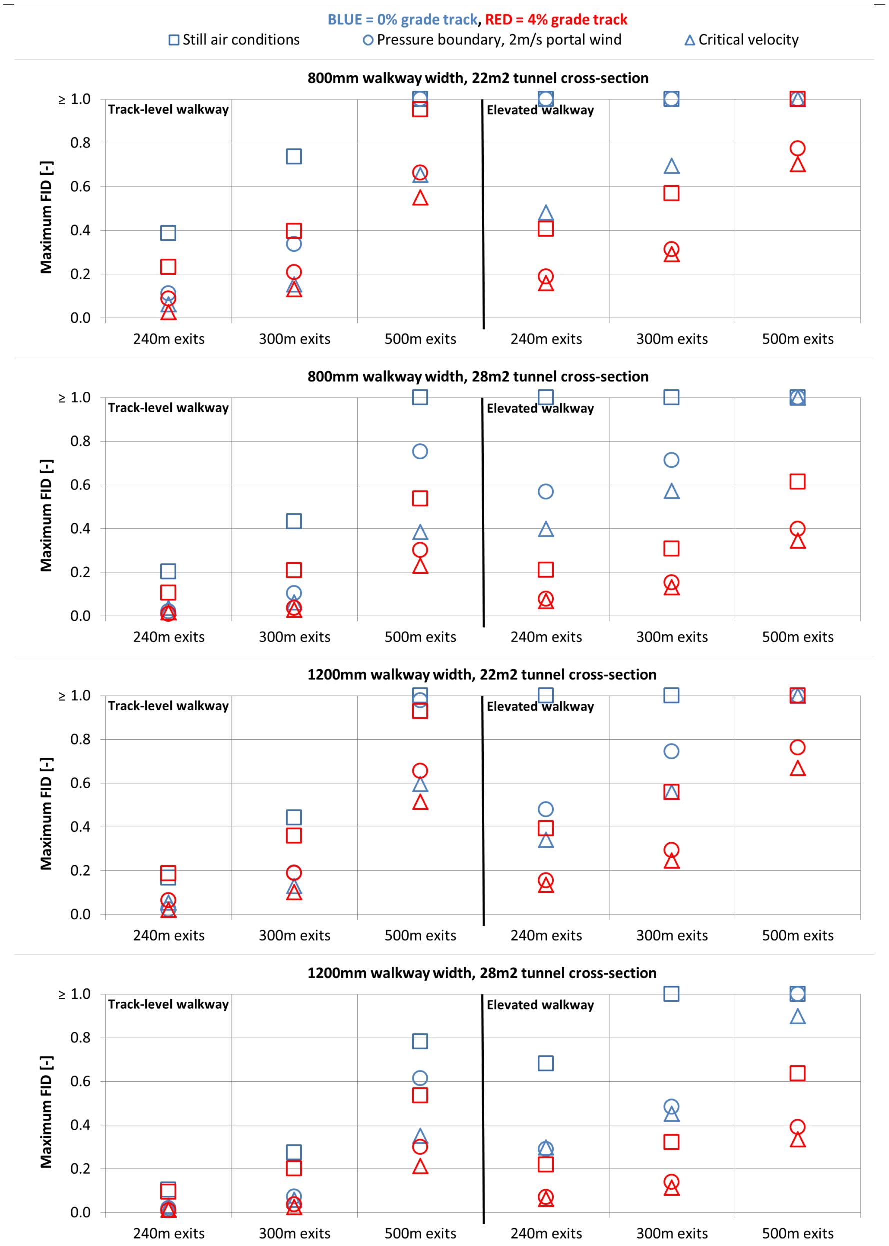


Figure 5. Maximum accumulated FIDs across all agents. Values truncated at unity.

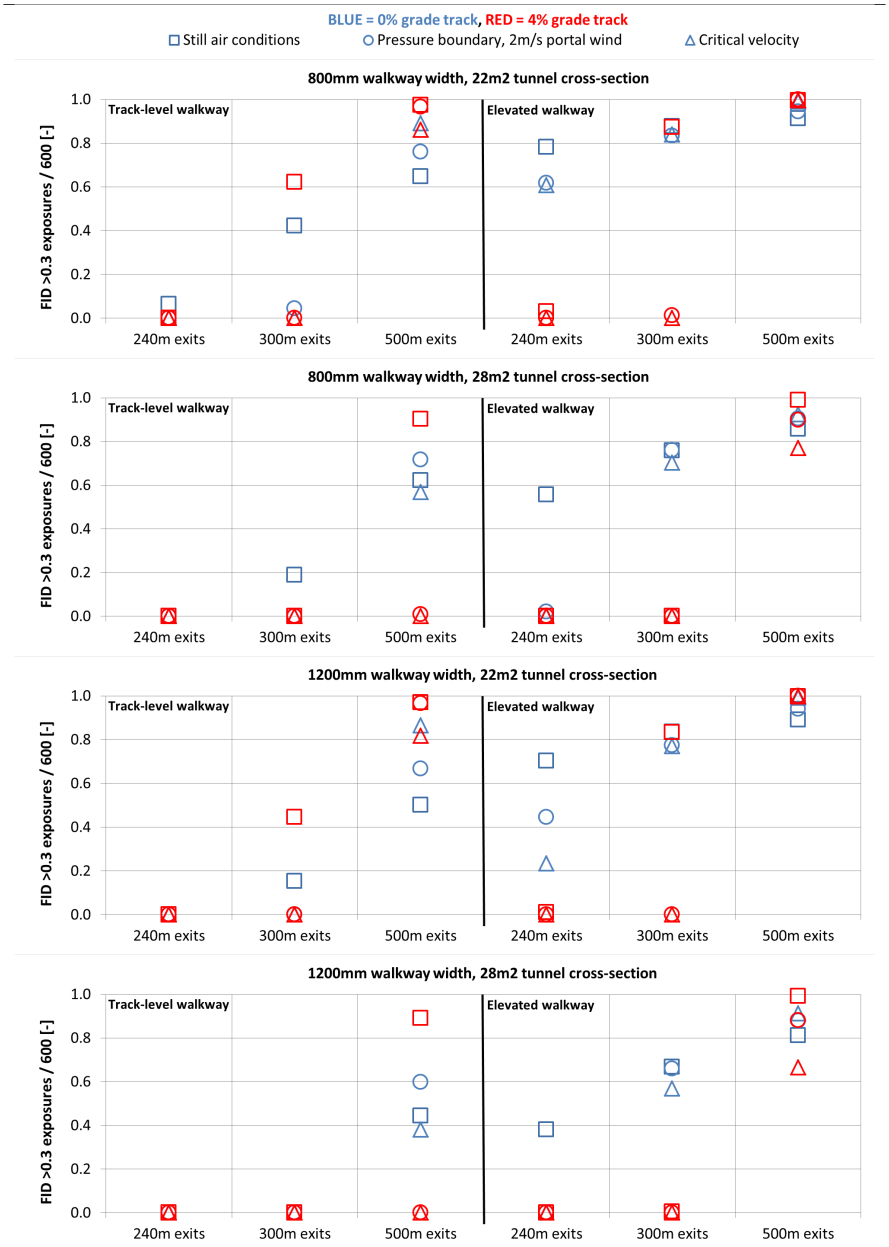


Figure 6. Number of agents exposed to accumulated FID ≥ 0.3. Values normalized by 600 (number of agents moving towards furthest exit).

Figure 7. Number of agents exposed to less than 5m visibility for greater than 10 minutes. Values normalized by 600 (number of agents moving towards furthest exit).

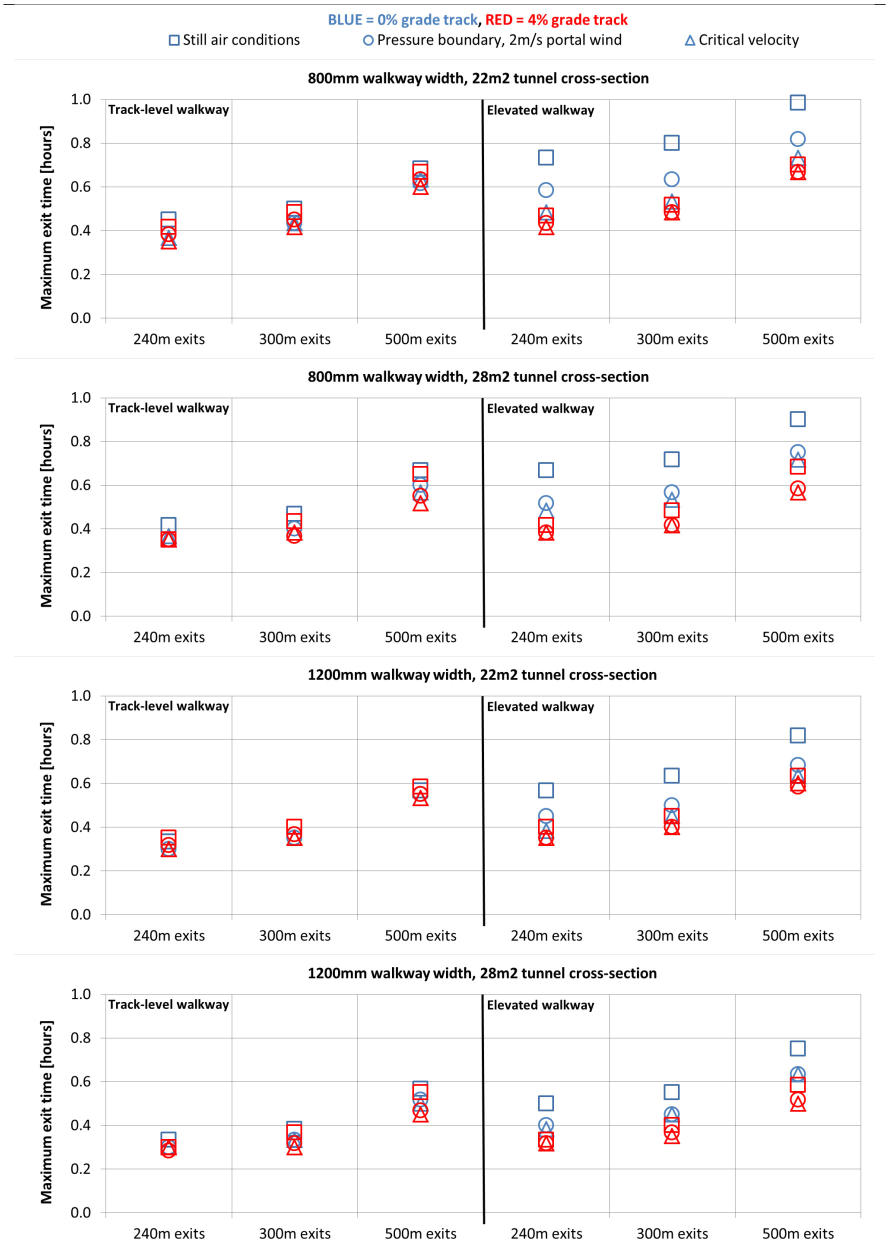


Figure 8. Maximum exit time. Values shown in hours because the maximum evacuation time across all simulations is approximately 1 hour.

4. CONCLUSION

This paper utilized CFD and evacuation modeling to compare different evacuation configurations in a metro rail tunnel. This was based on a specific set of inputs and assumptions. While likely applicable to a broad-range of projects, the complexity of metro systems makes it impractical to investigate all possible configurations and inputs. Simplifications were used to focus on particular configurations of exit spacing, walkway width and elevation, and in-tunnel velocity conditions. The interaction with tunnel grade and area were also considered.

The tunnel fires were modeled with FDS and the output used to visualize visibility for different configurations. Visibility provides an insight into the smoke movement which is a broad indication of tenability conditions. These results showed the influence of tunnel grade on smoke movement and the effect that an applied velocity has on conditions across the length of the train. These results also showed the difference in visibility between a track level and elevated walkway.

An evacuation assessment was used to further understand the influence that different evacuation configurations could have on tenability. The results for the evacuation assessment are generally as expected. As the exit spacing increases and the walkway width decreases, the maximum accumulated FIDs, number of agents exposed to accumulated FID ≥ 0.3, number of visibility exposures and total evacuation time all increase. However, the relative magnitude of these increases is a function of the walkway elevation, tunnel boundary conditions, and tunnel grade and cross-section.

From a purely fire safety perspective, a larger tunnel cross-section with wide walkways and closely spaced exits is likely to be preferred. With this configuration the walkway elevation, tunnel grade, atmospheric conditions and use of longitudinal ventilation may not be as critical to the outcome. This result is somewhat obvious, but the reality is that an ideal configuration from a fire safety perspective is rarely practical or cost effective. In real projects trade-offs are required to arrive at an optimized solution that accounts for project-specific constraints and other practicalities.

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