The effect of longitudinal ventilation on tenability during egress from passenger trains in tunnels during fire emergencies

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ABSTRACT

If a fire occurs on a passenger train in a tunnel, it is possible that passengers will be present both ahead of and behind the fire location. If the circumstances of the fire force the train to stop in the tunnel, the ventilation system should be used in such a way as to facilitate egress for as many passengers as possible. A study has been carried out which compares the tenability of the tunnel environment on both sides of a fire on a passenger train, along the length of the egress paths, for the duration of the evacuation process. Tenability conditions are compared in scenarios using longitudinal ventilation to control smoke, with scenarios using only natural ventilation. The effect of ventilation on fire growth is considered. It is shown that the use of longitudinal ventilation will rapidly lead to untenable conditions for any passengers downstream of the fire, whereas natural ventilation should allow sufficient time for egress of all passengers, on both sides of the fire, to reach a cross-passage before untenable conditions are reached.

1 INTRODUCTION

To blow or not to blow; that is the question: could there ever be an emergency scenario in in a vehicle tunnel where the appropriate strategy would be *not* to use the installed ventilation system?

This paper considers the specific case of emergency egress from a high-speed passenger inter-city style train in a long tunnel with cross-passages. It is important to stress from the outset that the conclusions which will be drawn here relate exclusively to this specific scenario, and may not be transferrable to other vehicle types or tunnel configurations.

In an ideal world, incidents would not occur in tunnels and passenger egress from trains in tunnels would never be required. As this is not an ideal world we need to put systems in place to protect passengers in the event of an incident occurring.

In an ideal incident, the driver should retain full control of the train for an extended period of time (current industry standards aim for 15 minutes), and have the ability to bring the train to a controlled stop, either outside of the tunnel, in an emergency station in the tunnel (e.g. Gotthard Base Tunnel), in a designated fire-fighting station (e.g. Channel Tunnel), or with the primary train egress doors aligned with the cross passage doors, so that escaping passengers should spend the minimum time possible between leaving the train and entering the safety of the cross-passage.

Ideal incidents rarely happen. For example, in the January 2015 Channel Tunnel fire, the strategy should have been to drive the train to a fire-fighting station or drive the train out of the tunnel. In reality, neither strategy was possible and the train had to stop at an unintended location in the tunnel. It is clear that we need to develop fire strategies for unplanned and uncontrolled stops of trains in tunnels. For our purposes, an uncontrolled stop is the situation where the train is unable to stop with the egress doors aligned with the cross passages (1).

2 DEFINITION OF THE SCENARIO

Here we consider a typical, modern, high-speed passenger train. Specific dimensions used in this study are based on French TGV and Eurostar trains, but many other train types have similar dimensions. The envisaged train, see Figure 1, has two locomotives/power cars at the front and the rear (designated PC1 and PC2), two end carriages (designated C1 and C18) and sixteen intermediate carriages (C2 to C17). The train has a length of about 450 m and carries up to 800 passengers (here we will assume 750 passengers).

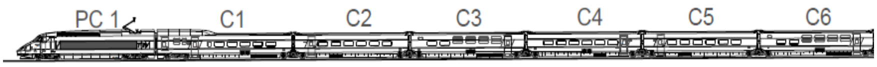

Figure 1 – The front portion of the typical passenger train considered.

During an emergency fire egress, the strategy adopted is generally for passengers to make their way, away from the fire, along the train to either carriage C1 or C18, and leave the train through the main exit doors in these carriages. Once in the tunnel the passengers need to make their way to the nearest cross-passage exit.

Spacing of cross-passage exits varies from tunnel to tunnel. In the Channel Tunnel, for example, the passages are 375 m apart, in the Gotthard Base Tunnel, they are 325 m apart. These distances are broadly consistent with the length of typical trains.

In an ideal scenario, the front and rear train exit doors would both align with cross passages to facilitate rapid egress and minimise time in the tunnel environment. If this does not happen, the worst case scenario would be one where the fire is positioned beside a cross passage, rendering that route unavailable. In this scenario, passengers near the fire location would have to walk about 375 m, with part of the route on the train and the remainder of the route in the tunnel environment. The proportion of the distance on the train compared to that in the tunnel will, of course, depend upon the location of the fire on the train. This study considers the tenability of that egress path under different fire and ventilation scenarios.

A fire event could occur on any of the carriages in the train. If the fire occurs on either of the power cars or carriages C1 or C18, all passengers may be taken to be on the same side of the fire and it is clearly appropriate to use the ventilation to blow the smoke away from the passengers. These situations are not considered further in this paper.

The situations considered here are those where there are passengers on both sides of the fire location. For simplicity, only three situations have been considered:

- Fire between C2/C3 (or C16/C17); with 104 passengers on one side of the fire and 646 passengers on the other side of the fire. (The passenger distribution has been based on the passenger distribution on a typical Eurostar shuttle.)
- Fire between C5/C6 (or C13/C14); with 272 and 478 passengers on each side of the fire, respectively, and
- Fire at the mid-point of the train (between C9/C10); with 375 passengers on each side of the fire.

It takes these passengers some time to travel along the train, possibly queue to get through the train exit door, then walk along the tunnel to the cross-passage exit. The primary concern of this study is to investigate the tenability of the tunnel environment during the egress process. This involves a careful study of a number of inter-related factors, which are discussed below.

3 CONSIDERATIONS

In order to adequately answer the question of tenability it is essential to understand the fire behaviour of trains in the tunnel environment, the production of smoke from these fires, the effects of tunnel ventilation on this smoke, the movement of people in this environment, and the effects of smoke on the escaping passengers. Of crucial importance is understanding the interactions between some of these considerations. We will consider these in turn.

3.1 Fire behaviour of passenger trains

As with all fires, understanding fire behaviour in tunnels involves an understanding of the nature of the fuel, the release and dissipation of the heat produced by the fire, and the movements and interactions of incoming air and outflowing smoke. Vehicle fires in tunnel environments are typically characterised by high heat release rates, fairly rapid fire development and very high temperatures being developed (2).

Only a handful of fire tests involving railway carriages in tunnels have been carried out to date, and none involving current or recent generations of railway rolling stock. Graphs of the heat release rate data from fire tests carried out as part of the EUREKA EU499 Project (3), the Metro Project tests (4) and at Carleton University (5) are shown in Figures 2 to 4, below. Each of these tests are described in more detail by Carvel & Ingason (2) and in the references given above.

The fire behaviour observed in the joined half-carriage test, see Figure 2, was due to a very unusual configuration of fuel, the location of the initial ignition, and abrupt changes in the ventilation flow in the tunnel, thus it is not possible to make any generalisations about rail carriage fire behaviour on the basis of this test.

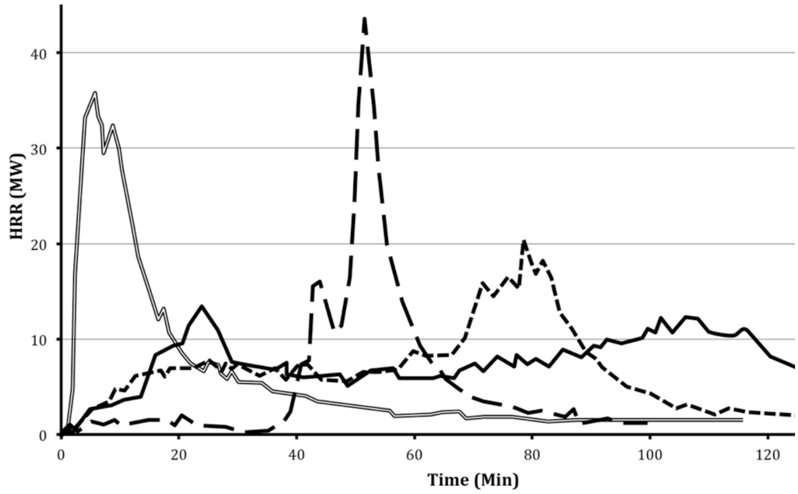

Figure 2 - Approximate HRR data from Hammerfest IC train test F11 (solid line), ICE train carriage test FS2 (short dash), joined half-carriage test FA3 (long dash) and subway carriage fire test F42 (double line), adapted from (3).

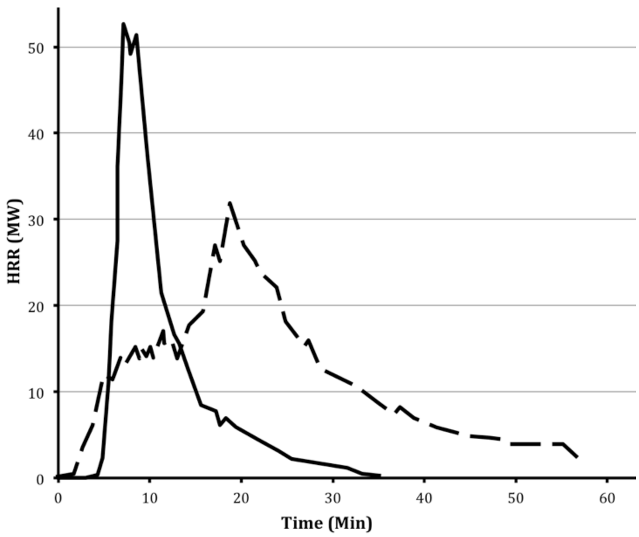

Figure 3 - Approximate representation of HRR data from the Carleton University fire tests. The rail car is indicated by the broken line and the subway car by the continuous line, adapted from (5)

The Carleton fire tests were carried out in a tunnel-like facility, but not a true tunnel. It may be important to note that the ventilation in this facility is generated by exhaust fans, pulling the smoke, not jet fans driving the fresh air. Also, there was no significant length of 'tunnel' upstream of the carriage, only a reduced height opening to the open air, see Hadjisophocleous, et al. (5) for details.

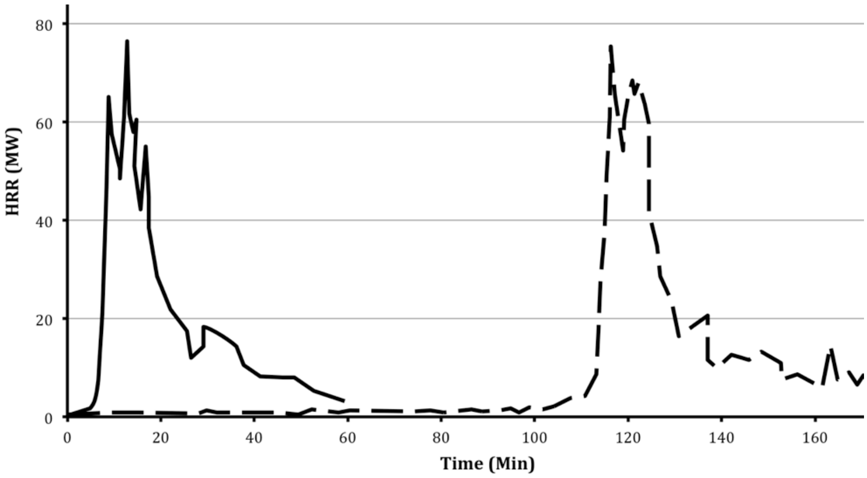

Figure 4 - Approximate representation of HRR data from the METRO project fire tests. Test 2 is indicated by a solid line and Test 3 with a broken line, from (4).

From the data presented above it is apparent that there are broadly two types of fire behaviour observed:

- Type A: Rapid fire growth (only 2-5 minutes duration) to a peak above 30 MW, fairly short duration fire, then a rapid decay as the fire runs out of fuel. This is observed in the EUREKA subway car test, the Carleton subway car test and the two Metro Project tests.
- Type B: Slower fire growth (15 to 25 minutes) to a peak of about 10 MW, long duration of burning (hours, not minutes) then a slow decay. This is observed in both the EUREKA railway carriage tests.

The Carleton railway carriage test had aspects of both types of behaviour, but appears more like a Type A fire, but with a slower growth rate and decay.

It is tempting to think that Type A behaviour corresponds to subway carriages and Type B behaviour corresponds to rail carriages, but this may be just coincidence as analysis of other fire test data involving road vehicles and various cargo commodities (2) shows the same two forms of behaviour. The distinction in these instances (as well as in the tests described above) is that Type A behaviour is consistently observed in fire tests with mechanically supplied ventilation (generally above 2 m/s) and Type B behaviour is consistently observed in fire tests with natural ventilation and low flow velocities.

Thus it is clear that a fire on a train carriage subject to mechanically forced ventilation will burn in a different way from a fire on a train carriage under natural or low flow conditions. This observation is incorporated into our study.

It has previously been shown (6) that tunnel fires do not grow in the form of a 't^2' fire, which is a common assumption in other fire types in the built environment. Fires in tunnels generally appear to grow in a two-step linear manner, the first stage of which is characterised by slow fire growth, when the fire is smaller than one or two MW, followed by a period of much faster fire growth. The first stage (referred to in the literature as the 'initial', 'delay' or 'incipient' phase) can be as short as one or two minutes and as long as nearly two hours (see, for example, Figure 4). At present, we have no clear understanding of the factors which influence this duration, so for design purposes it should be assumed that this stage is short. In the present study we have assumed that the incipient phase of the fire occurs while the train is in motion, and the more rapid growth phase of the fire development begins as the train comes to a halt. It is also assumed, for simplicity, that this is when passenger egress begins, so the 'pre-movement' time of the passengers is taken to be while the train is in motion.

In this study, two fires have been used:

- Type A: Linear growth from 0 to 45 MW in 4 minutes, thereafter constant until the end of the egress time (about 22 minutes, see below).
- Type B: Linear growth from 0 to 10 MW in 20 minutes, thereafter constant until the end of the egress time.

These fire types conform well to the patterns observed in the data in Figures 2 to 4, erring slightly on the conservative side.

3.2 Passenger egress

A realistic estimate of passenger egress time is required. The movement time calculations used in this study are based on Nelson & Mowrer's equation (7):

$$t_m = \frac{N}{W \cdot F_s} + \frac{L}{S}$$

where:

- t_m is the movement time [s]
- N is the total population [-]
- W is the width of the exit [m]
- F_s is the specific flow of the exit [ppl/m/s]
- L is the travel distance [m]
- S is the movement speed [m/s]

The first part of the equation indicates the time needed in order to pass N people through the train exit door, whereas the second part stands for the travel time of the last passenger from the exit door to the cross passage. In end of train evacuations, passengers have to overcome a vertical distance from the train to the walkway. Fridolf (8) shows that this distance affects the flow rate through exit doors. However, suitable bridging between the train and the tunnel walkway can be expected, as for example required in the Channel Tunnel (9). Therefore a low vertical distance can be assumed. Based on a collection of intercity and international train egress data made by Fridolf (8), a specific flow in the range of 0.574 to 0.935 ppl/m/s for vertical distances from 0.3 to 0.7 m is realistic. The exit widths in Fridolf's study varied between 0.9 and 1.4 m. In order to carry out a conservative estimation of the overall movement time, an exit width of 0.9 m and a specific flow of 0.574 ppl/m/s were used in this analysis. (A sensitivity analysis was carried out as part of this project but is not presented here. Variations in these input parameters were found to influence the numerical values of the results obtained, but not to change the overall conclusions of the project.)

Findings by the Metro Project (4) recommend an average walking speed of 0.9 m/s in smoke filled environments. This value was determined experimentally in a smoke logged tunnel with visibility ranges from 1.5 to 3.5 m. As it is not guaranteed that a visibility of 1.5m can be maintained, a conservative walking speed of 0.5 m/s has been used throughout this analysis.

The egress routes on the 'left' of the fire are shown diagrammatically in Figure 5 (note: in each case, the fire is considered to be between carriages, not in the middle of a carriage, as shown) and details of the distance and calculated duration of egress, for each of the scenarios, are summarised in Table 1.

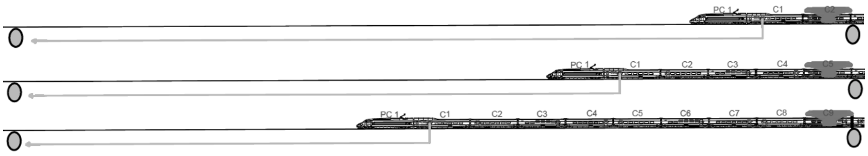

Figure 5 – Schematic of the 'left side' egress routes considered for fires on Carriages C2, C5 and C9. The cross passages are indicated by ovals. In each case, the cross-passage nearest the fire is deemed to be inaccessible.

Table 1 – Summary of egress travel times and distances used in this study.

Fire location	*Egress side*	*Number of passengers*	*Maximum travel distance on train*	*Travel distance in tunnel*	*Total egress time in tunnel*
C2	Left	104	40 m	335 m	872 s
	Right	646	320 m	55 m	1361 s
C5	Left	272	100 m	275 m	1077 s
	Right	478	260 m	115 m	1156 s
C9	Left	375	180 m	195 m	1116 s
	Right	375	180 m	195 m	1116 s

Of particular concern in our analysis is the tenability of the tunnel environment, between the train exit door and the cross passage exit, for the duration of the egress process. This has been estimated using computational fluid dynamics (CFD), as discussed below.

3.3 Use of CFD for tenability estimation

According to Purser (10), the following parameters each need to be identified to allow an estimation of tenability on the egress route:

- carbon monoxide, carbon dioxide and oxygen concentrations
- radiant heat flux
- smoke temperature, and
- optical density of the smoke.

Current computer fire models are able to simulate most of these parameters with an acceptable degree of accuracy, given a pre-defined fire scenario (11). In this study, Fire Dynamics Simulator (FDS, version 6) was used as it has been validated for most of these predictions (12). However, given the size of the computational domain required here, it was not deemed practical to use sufficiently small computational cells to provide acceptably accurate predictions of CO production and transport, so these data were estimated in post-processing, as described below. The tunnel and train were modelled in FDS using a 0.25 m grid, as shown in Figure 6.

In each instance, the computational domain was defined to be two carriage lengths (i.e. 40 m) longer than the zone of interest, and the simulation was started 60 s before the fire started growing and before the egress began, to allow the flow to become established throughout the domain. The concrete walls were modelled with typical heat loss and roughness properties. In ventilated scenarios, air is supplied at the upstream (right) end of the domain at a rate of 100 m^3/s, which is the flow rate used for emergency ventilation in the Channel Tunnel (13).

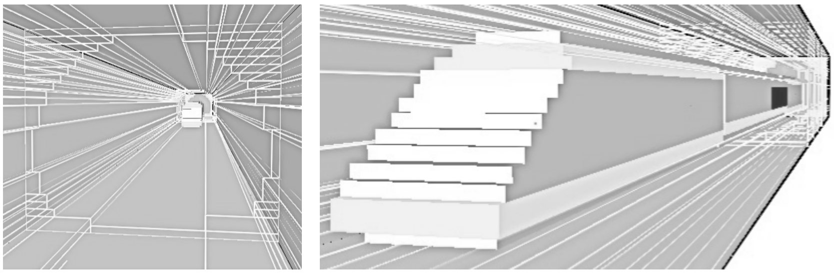

Figure 6 – The tunnel and train geometries used in this study.

The FDS simulations provide predictions of CO_2 concentration, oxygen concentration, optical density and temperature throughout the computational domain. In order to estimate CO concentrations, a series of hand calculations have been developed which correlate CO production with CO_2 production, soot production and the local equivalence ratio at the fire location. These calculations are described in full in (14). The equivalence ratio (15) inside the carriage on fire is dependent on the number of ventilation openings and the mass loss rate of the fuel (assumed to be polyurethane in the simulations, as FDS only allows a single fuel type). Assuming several windows break early in the fire development (a reasonable assumption, based on observations from the tests described above) it can be shown that the fire in the naturally ventilated scenario remains well ventilated at all times, but the fire in the mechanically ventilated scenario becomes under-ventilated after about 150 s, when the fire grows larger than about 10 MW. Thus, the production of CO in the carriage increases significantly beyond this time in the mechanically ventilated scenario. It must also be noted that 'external' burning (outside the carriage, but inside the tunnel) will consume 75 to 90% of this CO (16), this has been accounted for in the calculations.

Following this analysis, we have sufficient predictions to estimate the tenability effects in the tunnel environment.

3.4 The toxicity model

The effects of the conditions in the tunnel have been assessed using a modified form of Purser's Fractional Effective Dose (FED) model (10,17). Two quantities are assessed: the fractional effective dose for asphyxiants (FEC_{IN}) and the fractional effective dose for heat (FED_{heat}). In each case, a value of unity or above would indicate conditions leading to incapacity or fatality for about 50% of a population. FED values above 0.3 can lead to serious consequences for some people (17), so values above this threshold are generally to be avoided, if possible. It should be stressed that the FED predictions made using this model should not be taken as absolute measures of toxicity, but rather to give a relative ranking of scenarios. In any comparison between options, the strategy leading to the lower FED value should always be preferred.

In Purser's analysis, the fractional effective concentration of smoke (FEC_{smoke}) is also assessed to provide an estimate of an occupant's response to visibility. This has been neglected here as even in low levels of visibility, it may still be possible to navigate along the tunnel wall, indeed in the Channel Tunnel and elsewhere a handrail is provided which may assist egress in low visibility.

The FED quantities used here are calculated as follows:

$$F_{IN} = F_{I,CO} \cdot V_{CO2} + FED_{I,O2}$$

where:

$$F_{I,CO} = 3.317 \cdot 10^{-5} \cdot [CO]^{1.036} \cdot 25 * t/30$$

$$V_{CO2} = exp([CO_2]/5)$$

$$FED_{I,O2} = \frac{t}{exp\left(8.13 - 0.54 \cdot (20.9 - [\%O_2])\right)}$$

and

$$FED_{heat} = \sum_{t1}^{t2} \left(\frac{1}{t_{I,rad}} + \frac{1}{t_{I,conv}} \right) \Delta t$$

where:

$$t_{I,rad} = \frac{133}{q^{1.33}} \quad (T > 200°C)$$

$$t_{I,conv} = 5 \cdot 10^7 \cdot T^{-3.4}$$

The FED model can be applied to any evacuee travelling from the exit door of the train to the cross-passage door in the tunnel. For simplicity, characteristic values of each of the quantities of interest are sampled from the FDS results every minute of simulation time and the FED model assesses the toxic effects each minute. As the toxicity model is a cumulative model, the FED for any given evacuee increases with longer exposure times. For simplicity in the results, presented below, tenability will only be assessed for the first and last passengers to leave the train.

4 RESULTS

Figure 7 shows the carbon monoxide concentrations experienced by the first passenger escaping to the 'left' in both mechanically and naturally ventilated conditions, for each of the three fire locations considered. Note that the passengers in the case of a C2 fire spend longer in the tunnel than do passengers from a C5 fire, who likewise spend longer in the tunnel than in the case of a C9 fire, hence the different lengths of the graph lines. Equivalent data for temperature, heat flux, CO_2 concentration, O_2 concentration and optical density were calculated (14), but cannot be presented here due to limitations of space.

From Figure 7 it is immediately apparent that the passengers in the mechanically ventilated case experience much greater exposure to high levels of CO than passengers in the naturally ventilated case. This is to be expected as the ventilation in this instance is blowing all the smoke towards the passengers considered here. Of course, this observation must be considered together with the fact that there are also many passengers escaping to the 'right' in a smoke free environment.

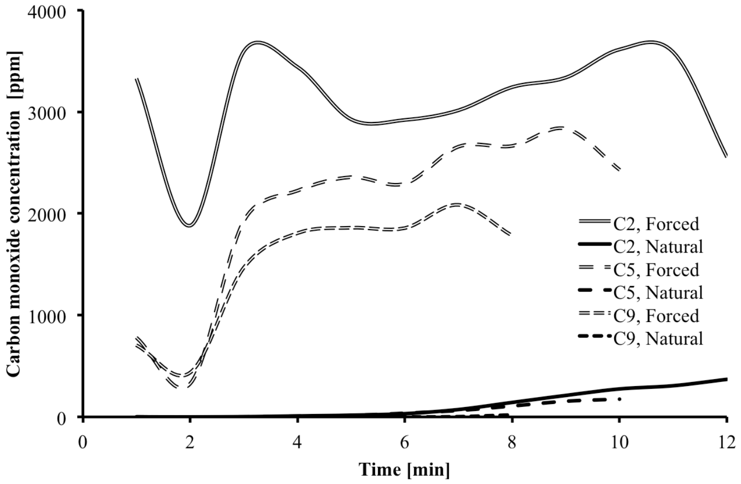

Figure 7 – CO concentrations experienced in the tunnel by the first passenger escaping to the 'left', for each of the scenarios considered.

The cumulative effect of exposure to the tunnel environment for the first escaping passenger in each of the scenarios considered is shown in Figures 8, 9 and 10 for fires on C2, C5 and C9, respectively.

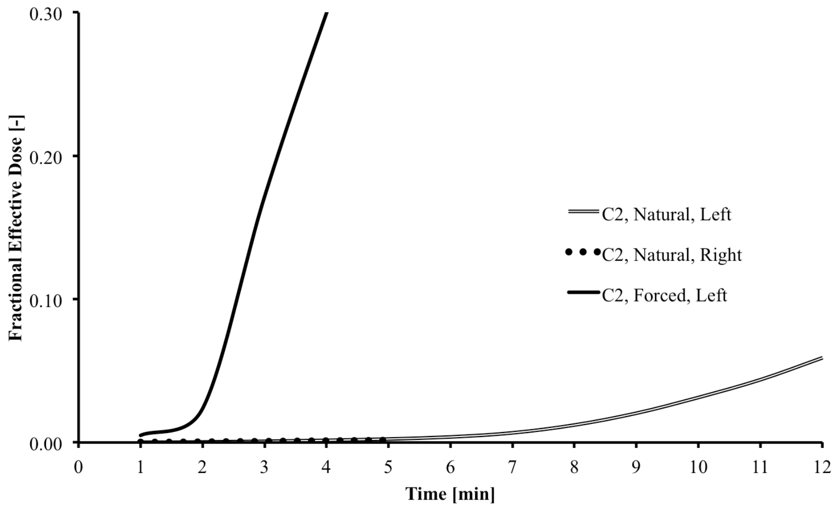

Figure 8 – FED_{IN} as a function of time for the first escaping passenger, fire in C2

It is clear from Figures 8, 9 and 10 that the environment in either direction in a naturally ventilated fire is considerably more tenable for the first escaping passenger than the environment downstream of a ventilated fire. In all instances, the FED_{IN} of the first escaping passenger exceeds 0.3 before they have reached the cross passage exit, and in the case of a fire in C2 exceeds unity well before the cross passage would be reached.

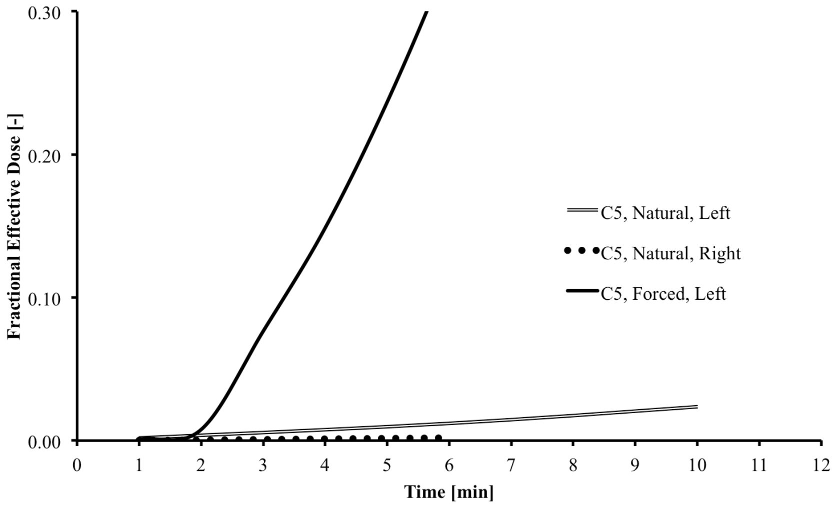

Figure 9 – FED_{IN} as a function of time for the first escaping passenger, fire in C5

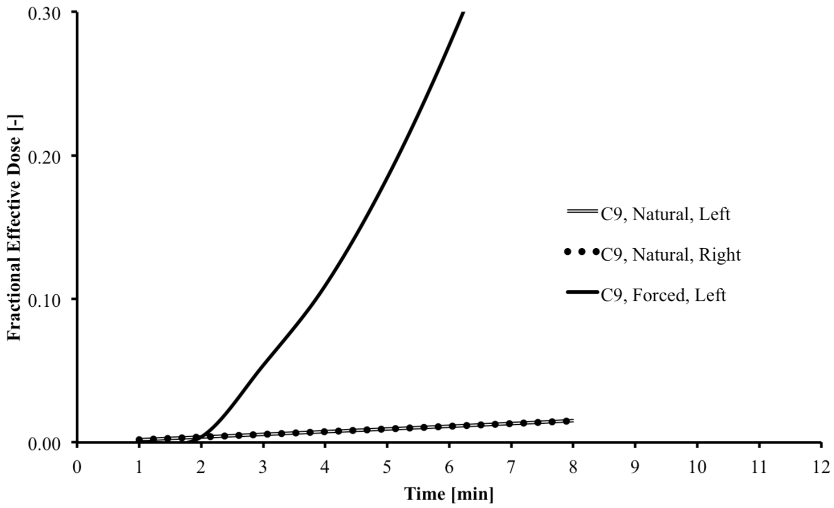

Figure 10 – FED_{IN} as a function of time for the first escaping passenger, fire in C9

Thus it would appear that in the case of a fire in C2, using mechanical ventilation to provide fresh air for the majority of passengers (i.e. the 646 passenger to the 'right') would result in conditions likely to incapacitate and lead to terminal consequences for all 104 of the passengers to the 'left'.

Figure 11 shows the FED calculations for the last escaping passenger in natural ventilation conditions, both to the left and right, for all three scenarios.

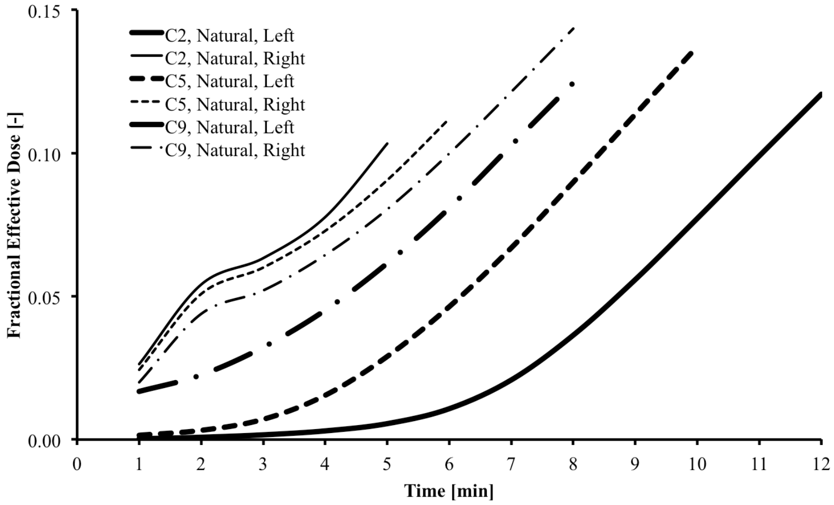

Figure 11 – FED_{IN} as a function of time for the last escaping passenger in each direction, in each scenario, under natural ventilation conditions.

While the FED calculations should not be understood in terms of absolute predictions of toxicity here, it is clear that the predicted FED values for the last escaping passenger in all naturally ventilated scenarios are considerably lower than the predicted values for the first passenger escaping to the left in any of the mechanically ventilated scenarios.

Figure 12 shows the results for the FED_{IN} and FED_{heat} for the last escaping passenger downwind of the fire in the mechanically ventilated scenarios. While it appears that conditions likely to incapacitate the last passenger on the basis of asphyxiant gases might not be reached in the C9 egress scenario, once FED_{heat} predictions are taken into account, it is clear that lethal conditions are attained well within the egress time predicted. Thus it is apparent that in none of the forced ventilation scenarios is the survival of all passengers expected.

If these calculations are deemed reliable, the conclusion of this study is that in any scenario where there are passengers on both sides of the fire, adopting a natural ventilation strategy should allow all passengers to reach the nearest cross passage in smoky but tenable conditions. Using a mechanical ventilation strategy will lead to lethal conditions downstream of the fire before all passengers have safely reached the cross passage exit. In the case of a fire near to the exit door, i.e. a fire on C2, it is not expected that any passengers downwind of the fire would survive.

5 DISCUSSION

Common practice in the event of a fire in a tunnel is to use the ventilation system, if there is one, to blow the smoke away to provide a smoke free egress path for most, if not all, of the escaping people. This strategy was established for use in road tunnels and is now the default strategy in almost all uni-directional road tunnels. In the road tunnel situation the benefits of this strategy are clear; if there is an incident in the tunnel, all vehicles ahead of the incident are unaffected by it and may therefore safely make their own way out of the tunnel. The strategy is designed to protect the queue of vehicles that will undoubtedly form behind the incident. The ventilation should thus be used in the direction of traffic flow. If longitudinal ventilation is not used in this scenario, the smoke would spread in both directions from the fire location, most likely at a velocity faster than walking speed (18), so tunnel occupants in the queue of vehicles would be caught in the smoke.

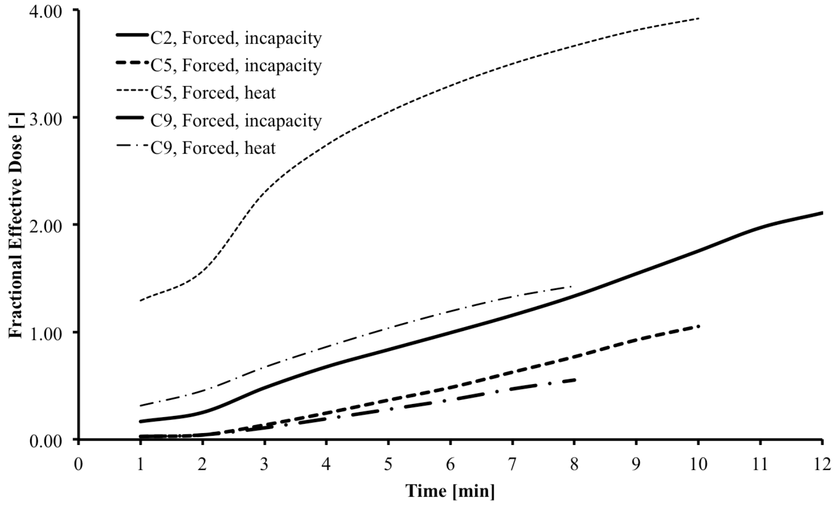

Figure 12 – FED_{IN} and FED_{heat} as a function of time for the last escaping passenger, in each scenario, under forced ventilation conditions. Note that the graph for FED_{heat} in the C2 scenario is not shown as it was entirely off the scale.

This line of reasoning has, quite rightly, dominated road tunnel ventilation design for the past few decades, but has also been largely adopted by the rail tunnel industry, despite the considerable differences between the two tunnel types. The crucial difference between the road tunnel scenario and the rail tunnel scenario considered here is that the carriages ahead of the fire incident cannot simply drive away from the fire location.

The question of whether or not longitudinal ventilation should be used to facilitate egress comes down to a question of the location of the fire. If there are passengers on both sides of the fire, and if they are unable to get past the fire to the 'upstream' side of it, then any use of ventilation to blow the smoke longitudinally will enflame the fire and, hence, result in untenable conditions on the 'downstream' side of it. As we have shown the conditions may become lethal within a few minutes. Thus if a fire occurs, and its location (relative to the passengers) cannot be precisely identified (e.g. in the Channel Tunnel the smoke and heat detectors are fixed in the tunnel, so cannot precisely locate the fire on a train), the only justifiable course of action is to assume that there may be passengers on both sides of the fire, and control the ventilation appropriately.

Once egress has begun it is important that the ventilation strategy remains the same until all passengers have reached the cross passages as changes in ventilation flow during a fire can have very negative consequences on the fire behaviour and the movement of smoke (19).

While absolute predictions of FED exposure have been made above, it must be stressed that due to the uncertainties in the model, these numbers must be treated with caution. It may be that the conservative assumptions built into the above analysis will tend to overestimate the incapacitating effects of the smoke in the tunnel. In other words, it may be that lethal conditions will not be attained as quickly as predicted above. Nevertheless, the relative values of FED are not subject to such a great uncertainty. Even if the absolute values contain systematic errors, the results clearly indicate that the escape route in both directions in a naturally ventilated tunnel is about ten times more tenable than the environment downstream of a ventilated fire.

The primary factor leading to this outcome is the very rapid growth of the fire when longitudinal ventilation is used. This leads to the situation of a very large fire while the egress process is still ongoing. In the case of a naturally ventilated fire, the fire continues to grow beyond the duration of the egress process, and is relatively small during the evacuation phase.

It is possible to choose between a rapidly growing large fire and a slower growing smaller fire. Using longitudinal ventilation may lead to the former scenario. Using natural ventilation, or using the ventilation system to minimise flow at the fire location will lead to the latter scenario. These effects must be considered as part of any fire strategy decision making.

6 CONCLUSIONS

An analysis of the tenability conditions in a tunnel on both sides of a fire on a passenger train has been carried out, taking into account changes in fire behaviour due to the ventilation, egress times and fire locations. Scenarios using natural ventilation and mechanically forced ventilation have been compared.

On the basis of this analysis it is predicted that:

- If a natural ventilation strategy is adopted, even if the fire blocks one cross-passage exit, all passengers can make their way to another cross passage exit before conditions in the tunnel become untenable.
- If mechanical ventilation is used, conditions on the downstream side of the fire will become untenable within a few minutes, possibly leading to lethal conditions for all escaping passengers.
- Thus, if there are passengers on both sides of the fire, mechanical ventilation for smoke control should not be used.

These conclusions relate specifically to the studied scenarios, and should not be generalised to any other tunnel fire situations.

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