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Effect of Passenger Physical Characteristics in the Uptake of Combustion Products during a Railway Tunnel Evacuation Due to a Fire Accident

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Abstract: The current study examines how different types of passengers (elders, travelers with luggage, travelers without luggage, and mixed population) affect the evacuation process in railway tunnels after a fire accident based on Fractional Effective Dose (FED) index values. A 20 MW diesel pool fire in an immobilized train located inside a straight, rectangular railroad tunnel that is ventilated by a longitudinal jet fan ventilation system is the scenario under consideration. Two fire scenarios were examined, one with and one without ventilation, combined with four evacuation scenarios. The numerical simulation of the fire and the evacuation process is conducted with the Fire Dynamics Simulator and Evacuation code (FDS + Evac) which is a Large Eddy Simulator (LES) for low-Mach thermally driven flows. The results (evacuation times, walking speeds, and mean and max FED values) are compared for each passenger type. It is found that during the evacuation from a railway tunnel fire accident, the most affected population are the elderly because of their lower movement speed, and travelers with luggage because of their increased dimensions. It is also shown that a non-homogenous population has increased uptake of combustion products and longer evacuation times than a homogenous population with similar geometrical characteristics.

Keywords: FDS; railway tunnel fire; tenability analysis; numerical simulation; tunnel ventilation; pathfinder; passenger characteristics

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1. Introduction

A tunnel fire is different from a building fire due to several factors, including the unique characteristics of a tunnel environment, the potential for rapid spread of fire and smoke, and limited access for firefighting efforts. Tunnel fires exhibit several distinctive characteristics that distinguish them from open fires and building fires. An open fire, in this context, refers to a fire that is not influenced by its surrounding geometry or enclosure. This can occur when a fire is located outside a building in a still environment or within a building of significant size, where the fire is not impacted by the building's presence [1].

Tunnel fires pose many risks to the safety of passengers. In fact, 85% of deaths were found to be caused by inhalation of toxic smoke and few people immediately died from exposure to fire [2]. The process of evacuating an underground public transportation system can be difficult, and how things turn out relies on a variety of factors. Factors that can affect walking speed and the likelihood of safe evacuation include visibility, train and tunnel design, and human physical condition. Experiments have shown that populations with mixed or temporary disabilities move more slowly than homogeneous populations without people with disabilities [3]. Zhang and Huang [4] analyzed the most recent research and advancements that will lead to a better and safer evacuation in tunnel fires.

Evacuation from underground public transportation networks is a difficult process, and the result of an evacuation scenario is determined by a variety of factors. Visibility, the architecture of the railway tunnel, and people's physical condition are all factors that can affect walking pace or the ability to safely evacuate [3]. Elevated platforms are built into tunnels to aid passengers to escape in the event of an accident. An elevated platform is either at the same level as the train floor or between the rail level and the train floor level. The METRO project studied how difficult it is for people with mobility problems to get off a train and onto the tracks [5].

In a railway tunnel fire accident, one of the key criteria for passenger safety is the amount of toxic pollutants inhaled during the incident and the evacuation process [5]. To calculate the exposure of humans to toxic gases, the Fractional Effective Dose (FED) index is used. Purser [6] presented the FED index which has been adopted by different national organizations such as the NFPA [7]. It is a measure used in toxicology and fire safety engineering to assess the risk of injury or death from exposure to combustion products during a fire or other hazardous event. FED is based on the concept of "effective dose", which is a measure of the amount of a toxic substance that is likely to cause harm to an individual. The FED value is expressed as a fraction or percentage of a lethal dose and is used to assess the risk of injury or death to individuals in the affected area. For example, a FED of 0.5 indicates that an individual has been exposed to half of the lethal dose of a particular substance, while a FED of 1.0 indicates that the individual has been exposed to a lethal dose.

There are several methods that can be used for evacuation simulations such as real-life experiments, augmented or virtual reality simulations, and computer simulations. One of the most widely used computational methods for evacuation simulations is the "agent-based simulation" method. It models the movement and behavior of individual agents, such as people or vehicles, in a defined space and considers their characteristics and interactions with the environment. This method helps in simulating different scenarios, testing of evacuation strategies, and the identification of potential problems.

The evacuation time, the response time of the passengers, the effect of wind on the evacuation process, and the passenger's comfort are widely discussed in the literature. The majority of the topics examined are the effects of obstacles or physical characteristics of the tunnel on the ventilation flow rate [8–11], the behavioral characteristics of the occupants such as the comfort of movement within confined spaces, and decision making regarding the evacuation process such as escape route and exit choice, visibility of light signs, and identification of emergency exits, as well as the technical means installed in the tunnels to facilitate the evacuation process [3,12–18].

In this study, the aim is to show the correlation between the physical characteristics (dimensions and walking speed) of passengers and the uptake of combustion products (FED index values) during an emergency railway tunnel evacuation due to a fire accident, and to compare how a homogeneous and a non-homogeneous population is affected.

To carry out this research, two different fire scenarios, regarding the activation or not of the ventilation system, were designed. For the ventilated fire scenario, the jet fans are activated simultaneously +300 s after the fire ignition. In both scenarios, a pressure difference of 5 Pa is applied in the tunnel openings to simulate the wind blowing outside the tunnel. Next, the toxic gas volume fractions calculated from numerical simulations are used to calculate FED values for passengers evacuating the train. Four different scenarios for the passenger types are studied, one for a homogenous population, one for an elder only population, one for a traveler only population, and one with a mixed population.

Section 2 discusses the methodology, the geometry, the boundary conditions, and the mesh size. Section 3 describes the validation method using empirical formulas obtained from the bibliography. The passenger's characteristics are critical for the evacuation process which is discussed in Section 4.

2. Numerical Model

The code used for the numerical simulation is Fire Dynamics Simulator (FDS) developed by NIST in collaboration with the VIT Research Center in Finland. It numerically solves the Navier–Stokes equations and applies to low velocity (less than Mach 0.3) heat-driven flow, smoke generation, and mass and heat transfer. To define the turbulent characteristics, the Smagorinsky model is applied.

The mass and momentum conservation equations are defined as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = \dot{m}_b''' \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{u}\right) + \nabla \cdot \rho \vec{u}\vec{u} + \nabla \cdot \vec{p} = \rho g + \vec{f_b} + \nabla \cdot \tau_{ij} \tag{2}$$

where g is the gravity acceleration, ρ is the density, p is the pressure, u is the velocity, t is the time, $\tau_{ij} = \mu\left(2S_{ij} - \frac{2}{3}\delta_{ij}(\nabla u)\right)$ is the stress tensor where, μ is the dynamic viscosity of the fluid, δ_{ij} is the Kronecker delta, and S_{ij} is the strain tensor.

The turbulent coefficient is defined by Smagorinsky as:

$$\mu_{LES} = \rho(C_s\Delta)\left(2\overline{S}_{ij} : \overline{S}_{ij} - \frac{2}{3}(\nabla\overline{u})^2\right)^{\frac{1}{2}} \tag{3}$$

where $\Delta = (\delta x \delta y \delta z)^{\frac{1}{3}}$ is the spatial filter.

The energy conservation equation is defined as:

$$\frac{\partial}{\partial t}(\rho h_s) + \nabla \rho h_s u = \frac{Dp}{Dt} + q''' - \nabla q'' + \varepsilon \tag{4}$$

where h_s is the sensible enthalpy, q'' are the radiative and conductive heat fluxes.

The species conservation equation is defined as:

$$\frac{\partial}{\partial}(\rho Y_a) + \nabla \cdot \rho Y_a \vec{u} = \nabla \rho D_a \nabla Y_a + \dot{m}_a''' + \dot{m}_b''' \tag{5}$$

where $\dot{m}_b''' = \sum_a \dot{m}_{b,a}'''$ is the species production rate as particles.

During the computation process, the time steps are adjusted by FDS so that the CFL conditions (Courant, Friedrichs, Lewy) are satisfied. The value of the time step size is defined as [19]:

$$DT = \frac{5(\delta x \delta y \delta z)^{1/3}}{\sqrt{gH}} \tag{6}$$

where δx, δy, and δz are the dimensions of the smallest mesh cell, H is the height of the computational domain, and g is the acceleration of gravity. For the first 1.5 s, the time step is 1, from 1.5 s to 13 s simulation time, the time step is 10, and from 13 s to 1200 s simulation time, the time step is 100.

2.1. Model Details

The tunnel in which the evacuation process takes place has a rectangular cross-section with dimensions of y = 11 m, z = 7 m and the total length is 1.5 km (Figure 1). The fire with a 20 MW intensity is set in the middle of the tunnel, which is equivalent to a train fire. The fire's area is 12.5 m^2 with a HRRPUA (Heat Release Rate Per Unit Area) of 1.6 MW/m^2 and is located on the roof of the train. The fuel used is diesel with a typical composition of $C_{12}H_{23}$, with a combustion product yield of 0.1 for CO and 0.09 for soot. A pressure difference of 5 Pa is applied to the tunnel openings to simulate the wind blowing outside the tunnel. This creates a draft inside the tunnel with a velocity of 0.5 m/s.

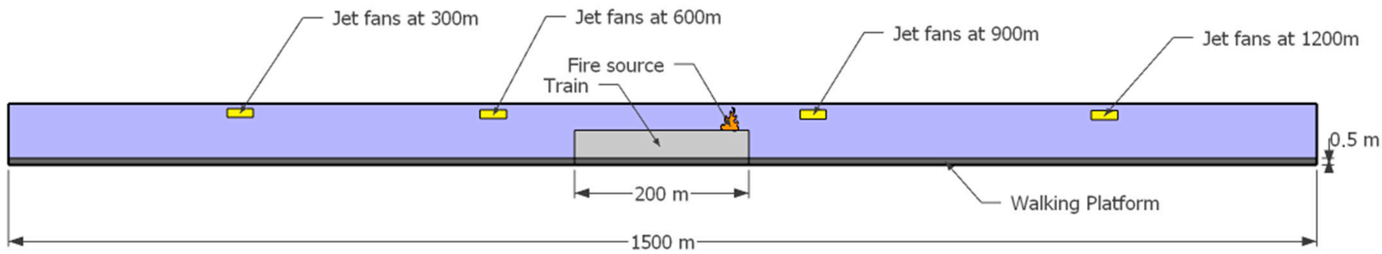


Figure 1. Side sketch of the tunnel with dimensions, the jet fans' placement along the tunnel at positions x = 300, 600, 900, and 1200 m, and the walking platform.

The jet fans are 3 m long and have a 1 m^2 cross-section. Four pairs of jet fans are positioned every 300 m at a 5 m height and 1 m off the side walls.

The dimensionless formula $D^*/\delta x$ is applied to estimate the fire's local mesh resolution, where δx is the nominal size of the mesh (m).

The characteristic length of D^* is expressed as [8]:

$$D^* = \left(\frac{\dot{Q}}{C_p T_\infty \rho_\infty \sqrt{g}} \right)^{2/5} \tag{7}$$

where T_∞ is the ambient temperature (K), Q is the fire's heat release rate (HRR) (W), C_p is the specific heat capacity (J/kgK), ρ_∞ is the air density at ambient temperature (kg/m^3), and g is the gravity constant (m/s^2). According to the NUREG-1824 guidelines published by the United States Nuclear Regulatory Commission (USNRC) and the Electric Power Research Institute (EPRI), a value between 4 and 16 is the optimum analysis range suitable for the FDS code [9].

A grid independence study is performed for three different size meshes: (a) a coarse mesh with 269,865 cells, (b) a medium mesh with 924,000 cells, and (c) a fine mesh with 4,254,149 cells.

The Grid Convergence Index (GCI), which provides the discretization error, is calculated using the following equation [20]

$$GCI = \frac{f_2 - f_1}{1 - r^p} \tag{8}$$

where f_1 and f_2 are the solutions from each used grid. r is the refinement factor between the two computational grids, and p is the accuracy of the algorithm, which is 3 for the present study.

The GCI is defined for 28 sampling points which are situated in the position with coordinates (x = 1100 m, y = 5.5 m, z = 0–7 m) downwind of the fire for values related to the U velocity and the carbon monoxide concentration. Three different scenarios are examined for a coarse, medium, and fine grid to define the flow field error. After examining the three scenarios, another finer mesh is examined for the field around the fire and an intermediate mesh for the rest of the tunnel. More precisely, a mesh size of 0.25 m is used in the fire perimeter areas (50 m downstream and 50 m upstream) and a mesh size of 0.5 m is used in the rest of the tunnel. The total number of cells is 1,355,200.

The U velocity error is approximately 14% between coarse and medium meshes, 5% between medium and fine meshes, and 4% between medium and final applied meshes. The error values for CO concentration are 16% for coarse and medium meshes, 8% for medium and fine meshes, and 6% for medium and final applied meshes [21–23].

A medium grid of 0.5 m is used in most of the tunnels, and a fine grid of 0.25 m is used near the fire site.

Numerical simulation work was performed at ARIS, a national HPC facility, and computational time was provided by National Infrastructures for Research and Technology

S.A. (GRNET S.A.). Each scenario used 22 cores and 56 GB of memory, and the typical time taken to complete each computation was 24 h.

2.2. Results Validation Method

In order to validate the computational results, empirical formulas are used. Rosignuolo et al. [24] defined a formula for calculating the temperature values as a function of distance from the fire source. As a function of the distance from the fire source, the empirical formula that describes temperature is written as follows:

$$\frac{\Delta T(x)}{\Delta T_{max}} = 0.55\exp\left(-0.143\frac{\chi-\chi_v}{H}\right) + 0.45\exp\left(-0.024\frac{\chi-\chi_v}{H}\right) \tag{9}$$

where H is the tunnel's height, χ is the distance along the fire position, and χ_v the origin, which is calculated as:

$$\chi_v = \begin{cases} L_f - 10H, & L_f > 10H \\ 0, & L_f \leq 10H \end{cases} \tag{10}$$

where L_f is the length of the flame (m).

The maximum temperature of the air gases depends on the maximum value of the roof's maximum temperature (ΔT_{max}) which is calculated for two different ranges depending on the dimensionless ventilation rate:

$$\Delta T_{max} = \begin{cases} 17.5\frac{\dot{Q}^{2/3}}{H_{ef}^{5/3}}, & V' \leq 0.19 \\ \frac{\dot{Q}}{u_0 b_{f0}^{1/3} H_{ef}^{5/3}}, & V' > 0.19 \end{cases} \tag{11}$$

where H_{ef} is the effective height of the tunnel (the height from the fire source to the ceiling) (m), $\dot{Q}$ is the total heat release rate (kW), u_0 is the ventilation velocity, b_{f0} is the radius of the fire source (m), and V' is defined as:

$$V' = \frac{u_0}{w^*} \tag{12}$$

where w^* is the characteristic velocity of the plume and is expressed by the following equation:

$$w^* = \left(\frac{g\dot{Q}}{b_{f0}\rho_0 C_p T_0}\right)^{1/3} \tag{13}$$

where g is the gravitational acceleration, (m/s^2), T_0 is the ambient temperature (K), b_{f0} is the radius of the fire source (m), ρ_0 is the density of air (kg/m^3), and C_p is the specific heat capacity (J/kg K).

Numerical results are compared with an empirical model for a non-ventilated scenario measured using thermocouples in the tunnel. Figure 2 shows the significant difference in temperature readings. This figure shows that the air temperature curves at 0 m are in good agreement for the early time after the fire ignition. Following that, the temperature reaches its peak and starts to scatter. The empirical and real temperature measurements above the pool fire consistently differ by about 400 °C. For the rest of the locations (except the 100 m mark) the temperature difference is around 500 °C. Due to these discrepancies, it is assumed that there is insufficient oxygen for the fire to spread because the flame's length (about 5.63 m) exceeds the tunnel's effective height (3 m). This causes the flame to crawl along the ceiling and the generated smoke to engulf the fire source, depriving it of oxygen, so that the fire is controlled from the ventilation.

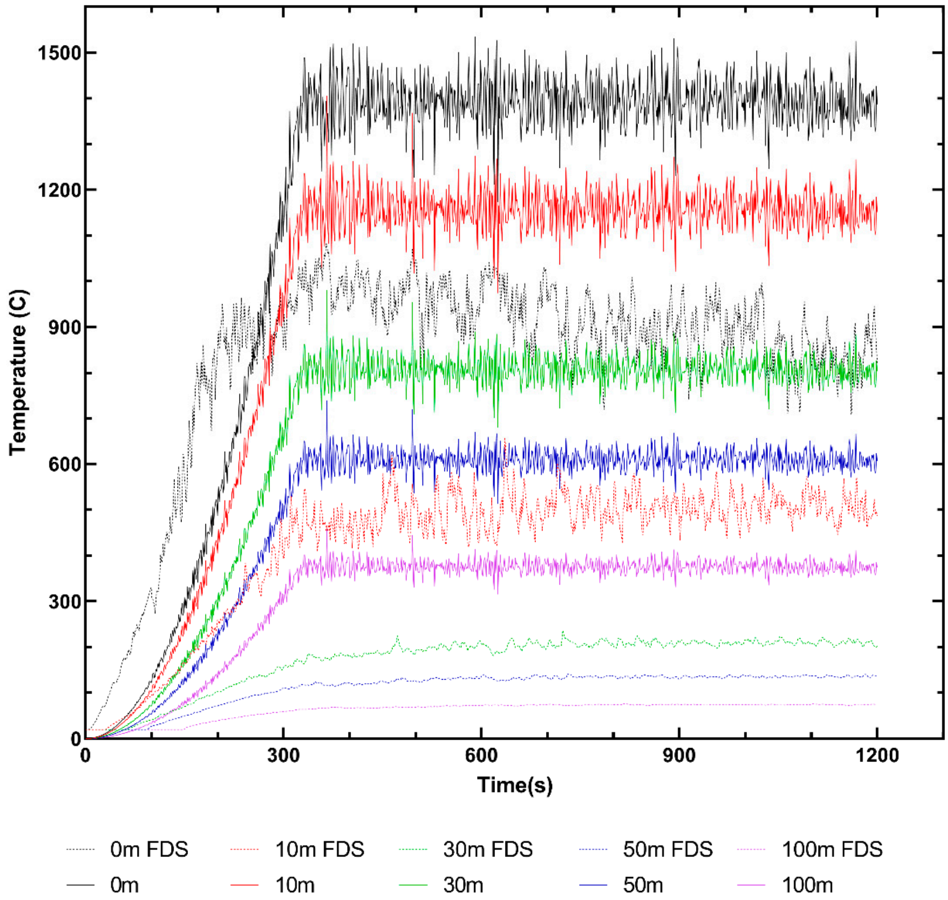


Figure 2. Comparison of the tunnel ceiling gas temperatures calculated with the empirical model with the values extracted by the numerical simulation at different distances above the fire source.

The ineffectiveness of parameters such as tunnel geometry and fire area is another likely cause of these disparities (FDS fire seats have different dimensions than those used in the experiments).

2.3. Evacuation and Tenability Analysis

For the evacuation analysis, two scenarios are examined: one with the ventilation system activated and one with no ventilation. In the ventilated scenario, the jet fans are engaged at +300 s after the fire ignition. In both scenarios, the evacuation process is started +60 s after the fire's ignition. Passenger evacuation is achieved along the walking platform on the tunnel's side. The total number of passengers ranges from 60 to 80% of the capacity of a usual intercity train with 8 wagons and 80 passengers. Evacuation simulations and FED index calculations are performed using Pathfinder, an interface to the FDS + EVAC code developed by NIST [19].

Eight occupant sources were created for the two evacuation scenarios, each simulating a wagon door. The occupant sources remain active for 300 s. The total number of evacuees differs for each passenger profile. This happens because the dimensions of the source (train door) and the passengers' physical characteristics limit the flow rate. Three passenger profiles are created with different physical characteristics [13,25,26] as shown in Table 1. Default passengers have a diameter between 0.4 m and 0.5 m, a height between 1.6 m and 1.82 m, and a walking speed of 0.9–1.19 m/s. Elder passengers have a diameter between 0.4 m and 0.5 m, a height between 1.6 m and 1.82 m, and a walking speed of 0.7–1 m/s. Travelers have a diameter between 0.9 m and 1 m to simulate their luggage size, a height between 1.6 m and 1.82 m, and a walking speed of 0.9–1.19 m/s. The mixed population consists of 50% travelers, 10% elders, and 40% default passengers. For simplicity, the entrance of the tunnel is marked as the exit point to which the passengers move.

Table 1. Passenger profiles and their physical characteristics.

Passenger Type	Walking Speed (m/s)	Height (m)	Width (m)
Default	0.9–1.19	1.6–1.83	0.4–0.5
Elder	0.7–1.05	1.6–1.75	0.4–0.45
Traveller	0.9–1.19	1.6–1.83	0.9–1

3. FDS Simulation Results

Two different fire scenarios are considered, with and without a ventilation system. All fans operate simultaneously in a ventilated housing. Scenarios were created using the Pyrosim interface provided by Thunderhead Engineering. The extracted results were temperature, flow rate, gas volume fraction, and heat release rate (HRR) values.

According to Figure 3, the defined fire curves correspond with the HRR numerical results.

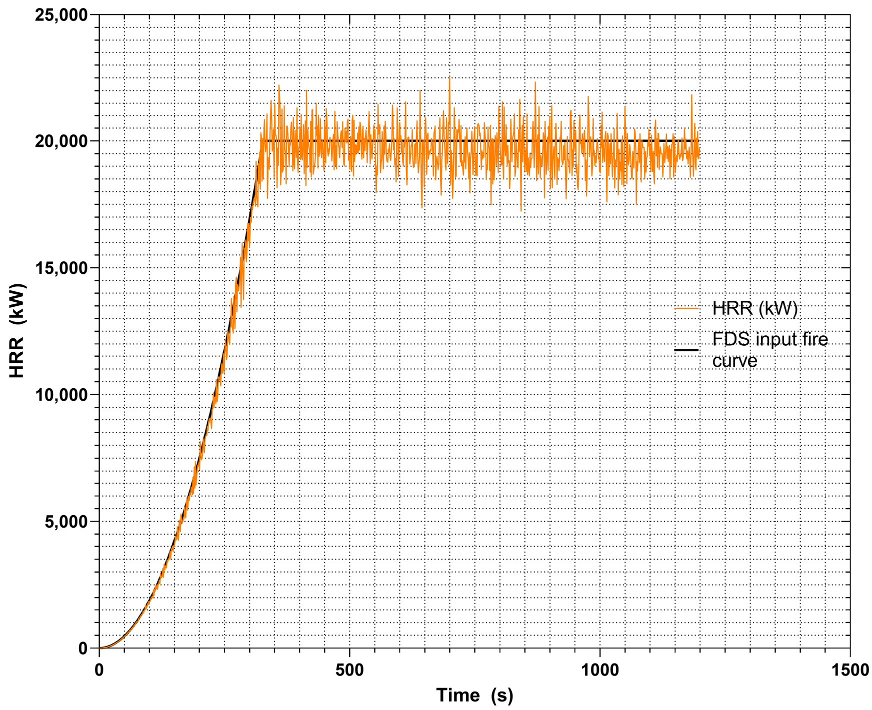
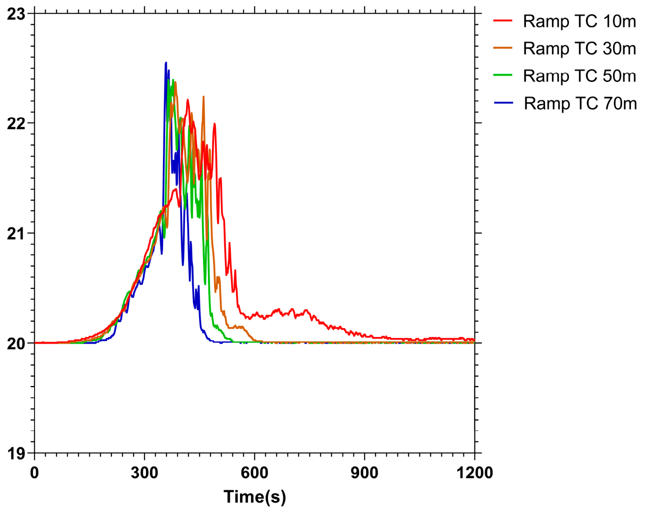


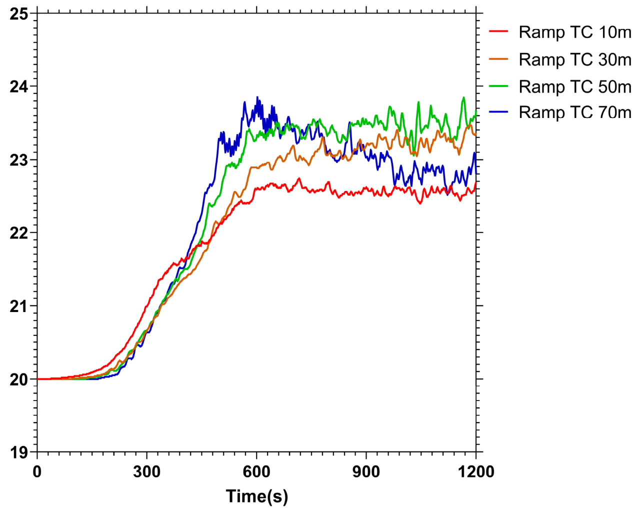
Figure 3. Input fire ramp curve and numerical results.

4. FED Index and Temperature

Increased ambient temperature may make it more difficult for a person to move or do light work such as the evacuation of a train. The critical temperature for enclosed spaces such as tunnels where human movement and behavior are restricted is 60 °C [27]. Figure 4 shows that the temperature at the height of 2 m along the walking platform did not exceed 24 °C in the non-ventilated scenario. Evacuation can be successfully carried out under these circumstances.



(**a**)



(**b**)

Figure 4. Upwind fire temperature distribution at y = 0.5 m (symmetry plane of the walking platform) and 2 m height for (**a**) the ventilated scenario and (**b**) the non- ventilated scenario. The temperature does not exceed 24 degrees; thus, the evacuation can be carried out.

Another factor that plays a significant role in the evacuation is the movement speed of the population as it can affect the amount of time a person is exposed to the toxic gases and smoke generated by the fire. The longer someone is exposed to these toxic gases and smoke, the higher their overall dose will be, which could increase the FED. Therefore, if someone walks at a slower speed, they may be exposed to the toxic gases and smoke for a longer period of time, potentially increasing their FED. As shown in Figure 5a, the average walking pace differs for each passenger group. The default and traveler groups have almost the same walking speed, but the mixed group shows higher speed than the elder group and lower speed than the default and traveler groups. The reason is that the mixed group consists of 10% elders and 50% travelers. This affects the flow rate of the train doors (the number of passengers getting on the platform each second) and the total evacuation time. Figure 5b shows the correlation of the passenger type to the total number of evacuees on the platform and the total time it takes for the passengers to reach the exit (the tunnel opening). Although the highest passenger number on the platform is that of the elder and default group, their evacuation times differ significantly. It is also observed that the groups of passengers with similar dimensions (elders and default) show almost identical flow rates toward the platform. This is also seen for the traveler and mixed group.

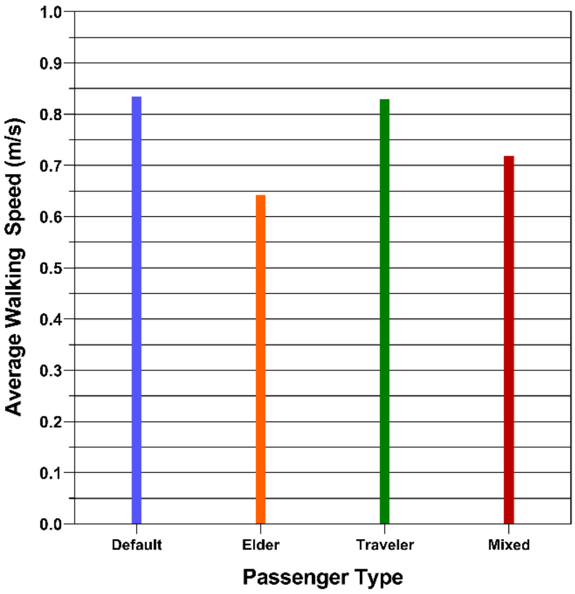
The FED calculation was effectuated with Pathfinder software, which uses the formula given in the SFPE Handbook [28]. Only the CO_2, CO, and O_2 concentrations are used for the FED value calculation.

$$FED = FED_{CO} \cdot V_{CO_2} + FED_{O_2} \tag{14}$$

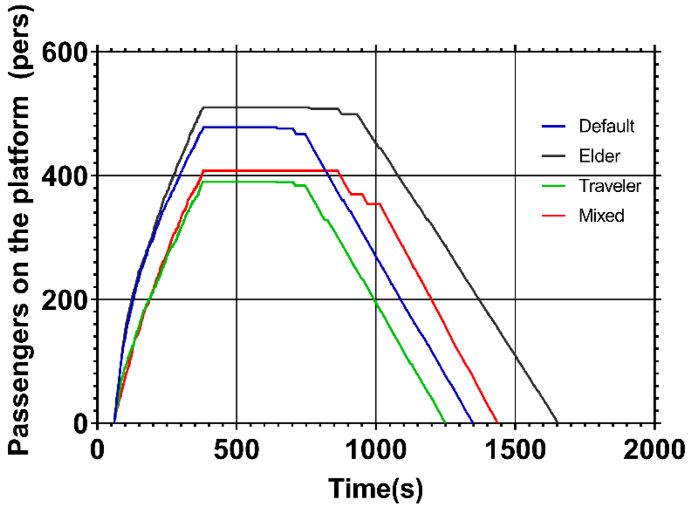
The effect of hydrogen cyanide (HCN) is ignored, and the CO_2 effect is only due to hyperventilation. Carbon dioxide is non-toxic up to a concentration of 5%, but it stimulates respiration and facilitates absorption of other fire products.

$$FED_{CO} = 3.317 \cdot 10^{-5} \cdot CO^{1.036} \cdot V \cdot t / D \tag{15}$$

where CO is the carbon monoxide concentration (ppm v/v 20 °C), V is the volume of air breathed per minute (L/min), and the activity level for light work (walking to escape) has a value of 25 L/min. Time is measured in minutes, and the light work activity level value is 30% exposure (% COHb).



(a)



(b)

Figure 5. (**a**) Average passenger walking speed and (**b**) evacuation times for each passenger profile. As shown, the mixed population has lower average walking speed than the default and traveler group. As for the evacuation times, travelers may have the same speed as the default passengers, but their dimensions do not allow for a higher flow rate through the train doors. This limits the number of passengers that can evacuate to the platform in a given time.

Hyperventilation with carbon dioxide may increase the rate of uptake of burn products. The multiplication factor is given by the formula:

$$V_{CO_2} = \exp(0.1903 \cdot \%CO_2 + 2.0004)/7.1 \tag{16}$$

where $\%CO_2$ is the volume fraction of CO_2 (v/v). The fraction of an incapacitating dose of low O_2 hypoxia is calculated as:

$$FED_{O_2} = \frac{t}{\exp\left[8.13 - 0.54 \cdot (20.9 - \%O_2)\right]} \tag{17}$$

where $\%O_2$ is the oxygen volume fraction (v/v) and t is the time (min). The measurement position for FED bulk sampling is 90% of the passenger height. For example, FED data for a passenger of 1.8 m height are sampled to be 1.62 m above the passenger's location. If the passenger is not within the FDS mesh, FED calculations are halted until the passenger enters another mesh area [19].

FED values did not reach the critical value of 1, where a person is considered incapacitated, but the maximum and mean FED values presented and compared in Figure 6 show some interesting results. Comparing the ventilated and non-ventilated scenarios shows that the values in the non-ventilated scenario are an order of magnitude higher than the values in the ventilated scenario. This is due to the smoke back-layering effect. As for the passenger type, elders seem to be more vulnerable to exposure to toxic gases than the default profile. This is due to the limitations in their movement by their physical characteristics and their slower walking pace. Moreover, the results show that a mixed population group (including default, elders, and travelers) is affected more than a homogenous group (only default). Elder and mixed groups have the lowest walking speeds, and consequently the longest evacuation times. This explains their higher FED values in comparison to the default and traveler groups.

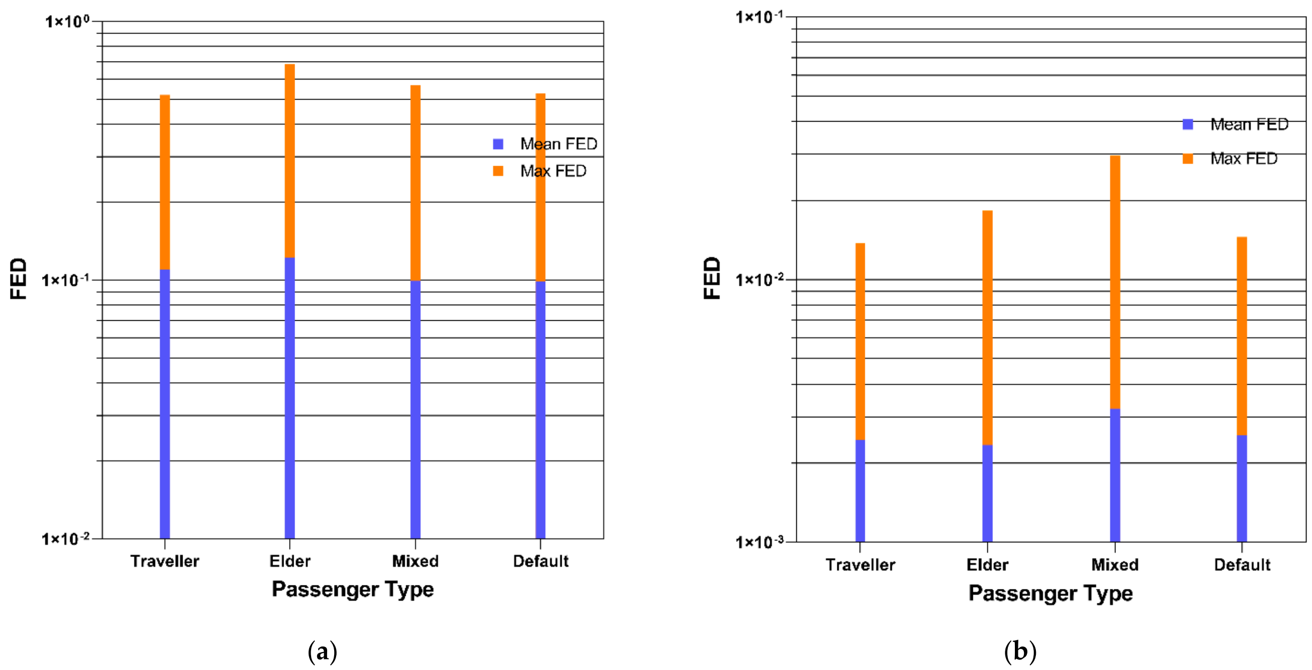


Figure 6. Mean and max FED index values for each passenger type for the (**a**) ventilated and (**b**) non-ventilated scenarios. The values never exceed the critical value of 1 but in the ventilated scenario the FED values are an order of magnitude higher than the non-ventilated one.

5. Discussion and Conclusions

Two studies for each fire scenario combined with four evacuation scenarios, one for each passenger type, were presented in this study. FED values never reached the critical value of 1 which corresponds to the person being incapacitated or dead. However, interesting results were shown for homogeneous and mixed populations. In the ventilated scenario, travelers and the elderly, due to increased diameter and decreased walking pace, respectively, were those affected the most by toxic combustion products. In the non-ventilated scenario, the most affected population was the mixed one. The two scenarios present large differences between them. Moreover, FED values for the non-ventilated scenario are an order of magnitude higher than the ventilated one.

This study showed that during a fire accident inside a railway tunnel, it is recommended for travelers not to take their luggage with them, as it is more difficult to move in the confined space of the walking platform

As for the evacuation times and the walking speed, it is concluded that walking speed affects the evacuation time while the physical characteristics affect the flow rate through doors. Some interesting results were shown for the traveler and mixed groups. Although the flow rate was the same, the evacuation times show a 200 s difference. This is due to the reduced average walking speed of the mixed population. Moreover, a slower walking speed results in longer evacuation times and increased FED values due to staying longer in places where concentrations of combustion products are present.

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