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Influence of the Slope and Delay on Passenger Evacuation from a Fire Along a Railway Tunnel with Natural Ventilation

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Abstract. Passenger safety is one of the main goals of railway tunnels design, being the evacuation of a burning train one of the worst scenarios, where any delay to start the evacuation is crucial for passenger's survival. Previous research works have separately studied the evacuation of railway tunnels due to fires and the effect of tunnel slope on gas and smoke spread, but none of them has addressed both factors together. In this work, we developed a quantitative approach to assess the time delay to start the evacuation, depending on the tunnel slope. The methodology is based on statistical analysis of simulation results. The proposed model, based on linear multiple regression with an R-square value close to 90%, explains the number of fatalities as a function of the time delay to start the evacuation and the tunnel slope. The statistical model used in this study predicts more than one fatality for each second of delay in starting the evacuation. Moreover, tenable conditions for safe evacuation in case of fire cannot be easily guaranteed in inclined tunnels with more than 1 km length and natural ventilation.

Keywords: Railway tunnel, Pre-evacuation time, Tunnel slope, Natural ventilation

1. Introduction

Fires in transportation tunnels can have devastating consequences. Catastrophic fires in road and railway tunnels are well known and documented. Examples include accidents and casualties in the Baku Metro (Azerbaijan) in 1995, Channel Tunnel (1996), Mont Blanc fire (1999), Daegu (2003) and Modane (2005).

Simulation techniques allow predicting real behaviours in a safe and economic way [1]. They are useful even though they have some limitations. These techniques make possible to simulate non-reproducible situations on a real scale due to their harmful effects. Within these studies, we can explore the effects of a fire and the evacuation of people in these situations. Several researches [2–13], based on Com-

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putational Fluid Dynamics (CFD), carried out studies in roads and rail tunnels. These studies simulate the environmental conditions and their evolution, including or combining the following factors: natural ventilation, forced ventilation systems, the effects of a fire and the evacuation of people. Liu et al. [13] present a research study oriented exclusively to ventilation systems in tunnels. Other studies simulate fires in combination with tunnel ventilation [4, 6, 8, 9]. The main limitations related with simulation of fire models [14, 15] are related with numerical assumptions in the model, that are ever an approximation to the real world, and the influence of the numerical techniques adopted, mesh size and assumed boundary conditions.

In this paper, we examined passenger evacuation from a train fire within a railway tunnel. Many works have been published in thin field, of which only a few are cited here [16–18].

In this type of study, the slope of the tunnel is a very relevant factor, since the critical velocity varies with this slope. From the standard NFPA 502 [19], the critical velocity is "the minimum steady-state velocity of the ventilation airflow moving toward the fire within a tunnel that is required to prevent backlayering at the fire site". Thus, depending on the relative direction of the slope and evacuation, there will be a higher or lower number of injured passengers and fatalities, since fire and smoke effects are worst upwards, at least with natural ventilation [20]. Several researchers have found a relationship between the critical velocities in inclined and flat tunnels [7, 20, 21]. Yi et al. [20] show a statistical correlation for slopes between -3% and 3%, centred on the analysis range of this paper. This correlation is shown in Eq. 1, as a quotient between the critical velocity $u_{c(s)}$ of a tunnel with slope s, expressed as a percentage, and the critical velocity of a horizontal tunnel, u_{c0}.

$$\frac{u_{c(s)}}{u_{c0}} = 1 - 0.034s \tag{1}$$

Although fires and evacuation in railway tunnels have been extensively studied, the combined situation of a fire in an inclined tunnel and the time delay in the start of evacuation has not yet been quantitatively modelled. Thus, we carried out a study to analyse how these parameters influence, performing CFD (SMARTFIRE, [22]) and evacuation (buildingEXODUS, [23]) simulations of a train fire scenario in a long, inclined, standard section tunnel with natural ventilation. The study considers one of the worst possible combinations of fire factors in a tunnel, when the effects of the slope and the time delay in the start of the evacuation are severe. For this reason, the train is assumed to be far from the nearest exit, and only natural ventilation is considered.

From the simulations results, the influence of both factors (the time delay in starting the evacuation and the slope of the rail tunnel) on passengers' survival was quantified by a statistical model.

2. Materials and Methods

The developed methodology is based on three models: two different types of simulations and a statistical model, according to Fig. 1. In the first stage, CFD simulations provide the evolution of the effects of a burning train inside a railway tunnel on a three-dimensional basis. The second stage simulates the dynamic evacuation of train passengers, considering the environmental results from the CFD simulation as inputs: the temperature and different gas concentrations. Evacuation models simulate several scenarios for different evacuation starting times and slopes. Finally, the applied methodology provides a reliable statistical model based on standard linear multiple regression.

The Following Sections Systematically Explain this Methodology.

2.1. Simulation Models

2.1.1. CFD Model SMARTFIRE [22] implements a computational fluid dynamics model under RANS approach to simulate the evolution of environmental conditions (temperature and gas concentrations) throughout the fire emergency situation.

2.1.1.1. Tunnel Geometry To obtain valid results for many railway tunnels, a standard tunnel section defined by Maidl et al. [24] has been selected. The cross section has 11.70 m width and 7.82 m high, according with Ril 853 dimensions for tunnels for high-speed traffic (velocities between 230 km/h and 300 km/h). The tunnel geometry is obtained by extruding this section along 1400 m in the SMARTFIRE program. A structured mesh (with minimum length side, 10 cm) approximates the section, as shown in Fig. 3. Two simple openings complete the tunnel model. The zone of interest is 1000 m long. This zone is located just in the centre of the simulated CFD model. In addition, there are 200 m of tunnel before and after of this study zone, with same tunnel section. At each opening, there is a free volume of 4 m length and a rectangular section occupying the outer contour of the parallelepiped blocks used to represent the tunnel section. The model also includes the train volume. The train has been modelled as a simple geometrical obstruction. SMARTFIRE wall default material has been used for all the geometry (thermal conductivity, 0.69 W m^{-1} K^{-1}; specific heat, 840 J kg^{-1} K^{-1} and density, 1600 kg m^{-3}). Therefore, fire-people interaction will be studied inside the tunnel but outside the train. Figure 2 shows a geometry scheme including tunnel

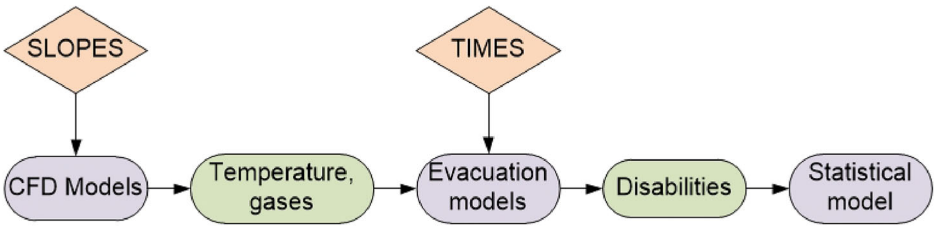

Figure 1. Methodology scheme.

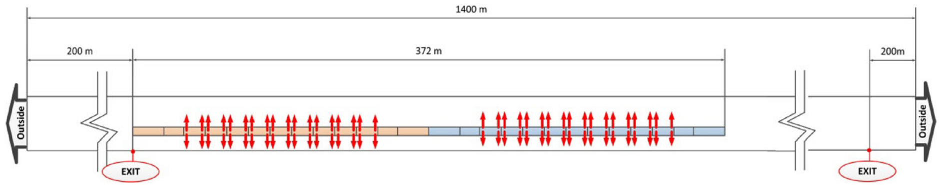

Figure 2. Geometry scheme.

and train dimensions, emergency exits at the tunnel and train doors from which occupants will start evacuating.

The SMARTFIRE software was used to implement nine CFD simulations, one per slope. For computational cost and memory reasons, the simulations were limited to 1500 s.

Figure 3 shows the mesh layout of the tunnel cross section, while Table 1 indicates the number of cells in each direction. The tunnel mesh contains 7,372,456 cells altogether.

The tunnel simulation includes sensors placed in 57 zones to measure the evolution of environmental variables during fire emergencies. These areas cover those 1000 m that are accessible to passengers.

2.1.1.2. Environmental Conditions Ventilation These simulations take into account only natural (longitudinal) ventilation. No additional ventilation system has been taken into account, to consider one of the worst possible cases.

Heat Release Rate (HRR) There are several HRR curves for railways, with maximum firepower of up to 100 MW (e.g., the Baku subway train, Azerbaijan, 1995). In the literature, lower HRR peak values are observed, from 13 MW to 43 MW, after 5–80 min [25]. This study considers an intermediate curve obtained from the literature [26], which reaches a peak of 23 MW. This curve corresponds to model F42 of Fig. 4 (subway car fire).

The fire modelled in SMARTFIRE is a "simple fire"-type fire source comprising 13 × 4 × 3 m and simulating the space of the technical car end. This element allows associating a calorific power curve with variable smoke production.

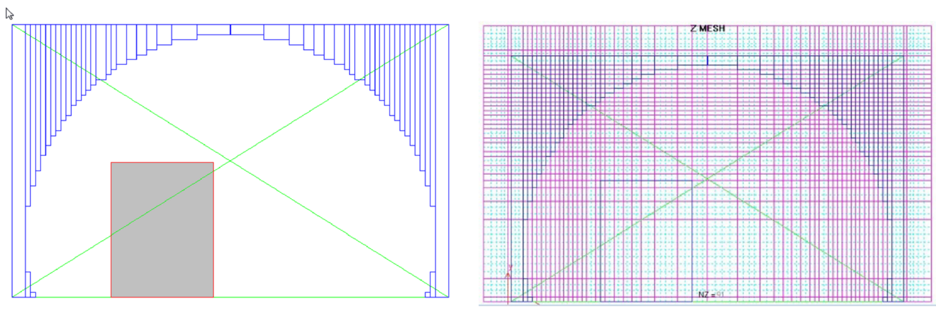

Figure 3. CFD tunnel cross section and mesh cells.

Table 1
Number of Cells in Each Direction

Direction	Number of divisions
Longitudinal	1558
Vertical	52
Lateral	91

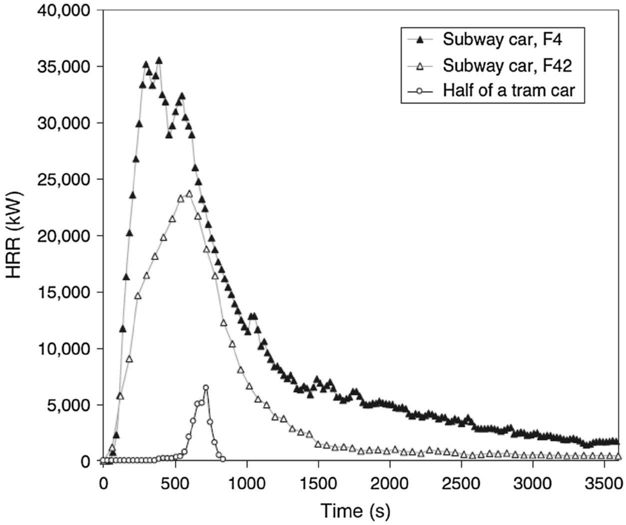

Figure 4. HRR curves of railway cars [26].

SMARTFIRE has used default values to define a constant smoke rate production proportional to HRR (2.5×10^{-6} kg/s smoke/kW HRR).The effective heat of combustion used is 5×10^{7} J/kg, then, the soot yield can be calculated as follows:

$$Y_{soot} = 2.5 \times 10^{-9} \times 5 \times 10^{7} = 0.125\ g/g$$

This value is within the range defined by Weyenberge et al. [27] for railway tunnel fires, which is from 0.03 to 0.15.

Toxicity By activating the toxicity submodel, the simulations provide the effects of the variation of some gas concentrations. The toxicity model uses correlations between the yields of species and equivalence ratios. These values, derived from small-scale experiments, are used to predict the generation and transport of toxic gases within fire enclosures. SMARTFIRE is used with the default values which have been discussed by Wang et al. [28].

2.1.1.3. Tunnel Slope The effect of the slope was simulated by considering two components of the gravity acceleration, according to the tunnel reference system: vertical and horizontal. Figure 5 shows how the longitudinal and vertical components of gravity are projected in an inclined tunnel.

The values of these components will affect the smoke movement, with a higher amount of smoke flowing uphill in any case. These components have to be entered manually via text in a SMARTFIRE configuration file (*.smc extension).

2.1.2. Egress Model The buildingEXODUS [23] software considers multiple interactions: *people–people*, *people-fire* and *people-structure*. The model tracks the trajectories of individuals as they make their way out of the simulated enclosure, from a rail car to the tunnel exit in this case. In addition, the models check for people overcome by fire hazards such as heat, smoke and toxic gases in the way-out zones. Some heuristics or rules determine the behaviour and movement of each person. These rules are categorized into five interacting sub-models: *occupant, movement, behaviour, toxicity* and *hazard.*

The egress simulations are based on the next assumptions:

- Geometry has been meshed using buildingEXODUS default nodal spacing of 0.5 m. The train geometry has been created from real measurements. Figure 6 shows the train layout composed of 13 cars: 9 passenger railcars, two locomotives at the ends and a technical car next to each locomotive. The fire is considered to occur only at the technical car closest to the mouth of the tunnel.
- The outside region of the train is connected to train exits and it is extended 1000 m from the first locomotive to the available exit. Figure 7 shows the mesh of the tunnel on both sides of the train and throughout the width of the tunnel where the train is not, which is maintained until the available exit.
- Doors in this composition, 0.8 m wide, were approximated by one node (0.5 m).

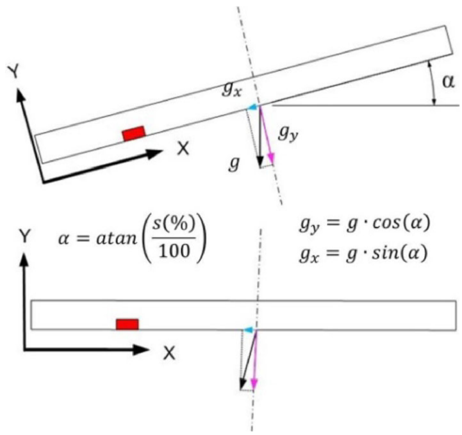

Figure 5. Gravity component scheme.

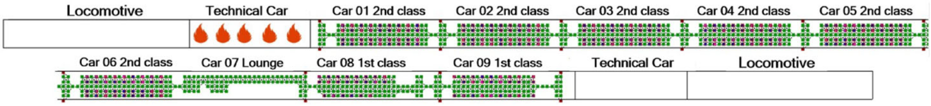

Figure 6. Train mesh for evacuation scenarios.

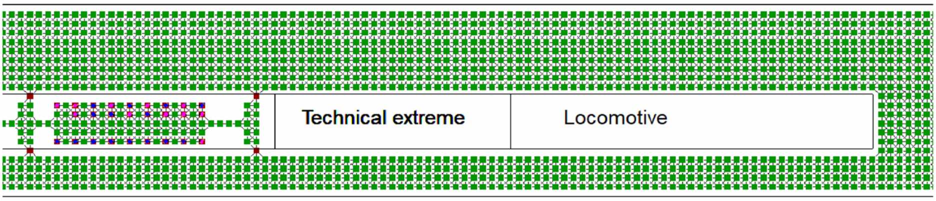

Figure 7. Tunnel mesh detail.

- All doors, including the lounge car doors, are available for evacuation tasks.
- The effect of the internal sliding doors is ignored.
- For the evacuation from the railcars to the track level, the time spent by the crew to set the evacuation elements up (ladders/ramps) is ignored.
- Train doors have been modelled as buildingEXODUS internal exits without flow restrictions. This means that they behave as if under free-flow conditions.
- Tunnel available exit has a flow rate of 1.33 occ/m/s.

The model is ready to start the simulation with a defined time delay since the fire begins. For any evacuation starting time, the model forms queues beside each door before the simulation begins. Altough buildingEXODUS simulations run initially with passengers in a seated position, once the doors are opened, the queue is already formed. Figure 8 shows the initial state of the evacuation simulations for this train.

2.1.2.1. Hazard Model The hazard model [23] distributes pre-determined fire hazards such as heat, smoke and toxic products throughout the atmosphere. CFD simulations in SMARTFIRE provide these values. Each of the 57 defined zones has its own evolution for different hazards over time. SMARTFIRE calculates,

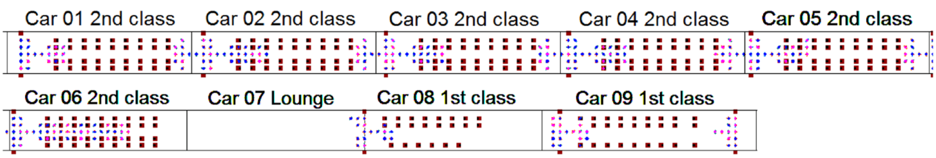

Figure 8. Passenger initial positions.

along the simulation time, mean values for each zone and each parameter (temperature, smoke, radiation, CO_2, CO and O_2). These values are calculated for two high ranges on each zone. One for the upper zone, with walking head height range from 1.5 m to 2 m high and the lower layer, for crawling head height range, from 0.3 m to 0.8 m. These values are written into a text file used further in buildingEXODUS software. In these cases, the time increment of each measure is 15 s. There are 16 zones on each side of the train. On each side, the width of the zone is from the train external side to the opposite wall. As Fig. 9 shows, the lengths for these zones are 20 m for the first locomotive, 13 m for the technical cars with fire and 24.21 m for the 14 zones to the end of the train composition. The rest of the zones have the same width as the tunnel and a length of 25 m up to the last one, with 28 m. Thus, a total of 1000 m has been checked.

The toxicity model uses hazard model information to determine the physiological state of each passenger. A behavioural model modifies the physical behaviour of each individual based on the hazard model information.

2.1.2.2. Toxicity Model BuildingEXODUS uses a fractional effective dose (FED) toxicity model [29, 30]. FED models assume that the effects of certain fire hazards are related to the received dose rather than to the exposure concentration. Therefore, the egress simulation uses the standard Purser FED model, enabling the VCO_2 hyperventilation model and modelling the intake of CO.

A toxicity model has been taken into account, including the following attributes:

- FIH, include the effects of radiative and convective heat.
- $FICO_2$, include the effects derived from CO_2 concentration.
- FIN, include the effects of low concentrations of O_2 (FIO) and CO (FICO). Incapacitations by lack of oxygen or poisoning due to CO concentrations could occur. FIN, also estimates the hyperventilation effect caused by exposure to CO_2 trough VCO_2 attribute.

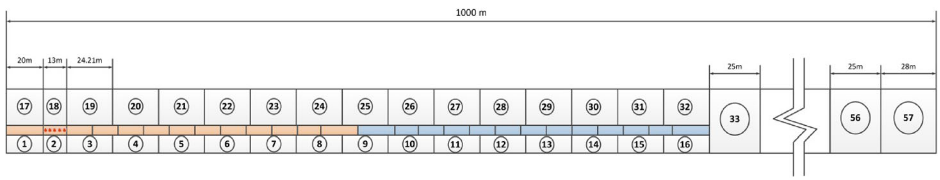

Figure 9. Hazard zones scheme.

$$
\begin{aligned}
FIN &= FICO \cdot VCO_2 + FIO \\
FIH &= FIH_r + FIH_c \\
FIO &= \frac{t}{e^{(8.13-0.54\cdot(20.9-O_2))}} \\
FICO_2 &= \frac{t}{e^{(6.1623-0.5189\cdot CO_2)}} \\
VCO_2 &= e^{\left(\frac{CO_2}{5.0}\right)} \\
FIH_c &= t\cdot 2.0\cdot 10^{-8}\cdot T^{3.4} \\
FIH_r &= \frac{q^{1.33}}{D_r}\cdot t\cdot 60.0, \quad with \quad q\left[\frac{kW}{m^2}\right], \quad radiative flux
\end{aligned}
\tag{2}
$$

$D_r\left[s\left(\frac{kW}{m^2}\right)^{\frac{4}{3}}\right]$, is the radiative denominator. Two values are used as default, 80, critical value for pain threshold and 1000, critical value for incapacitation. Both values are subjective and depend on many variables such as age of the occupant, state of health, amount and type of clothing worn, amount of skin exposed, etc.

By using a model of damage accumulation, this model calculates the accumulated dose ratio over time related to the effective dose that causes incapacitation or death. When the ratio reaches 100%, the model assumes the toxic effect, so this person is unable to finish the evacuation task. This person could be dead or enoughly injured. In this work, fatalities are considered once FED achieves the value of 1.

2.1.2.3. Population The *Occupant Model* manages the population attributes, both dynamic and constant. The default population of buildingEXODUS was used. The main features of the population have been extracted from the Clinical Examination Book [31].

Each population group has its own lower and higher attribute limits (speeds, psychological attributes, respiratory volume per minute and toxicity borne levels before incapacitation). Their attributes are assigned by using a random uniform distribution.

2.2. Procedure

This hypothetical scenario aims to simulate a fire emergency that is unfavourable for evacuation due to the relative position of the train, the emergency exits, and the evacuation distance to be traversed. The topology of the train, as well as the number of passengers to evacuate, corresponds to an unidentified commercial train, since the exact model is not relevant for the objective of this research.

Based on this objective, all simulation scenarios have the same topology: 1400 m of double track tunnel, a double train composition located near an internal tunnel exit and a fire in the technical car or auxiliary rail car closest to the tunnel exit. A total of 528 passengers will try to evacuate the train and reach the farthest exit, located 1000 m from the far end of the train composition. The nearest exit has been supposed unavailable for passengers.

Since the emergency exit gap is the maximum indicated by the Official Journal of the European Union [32], this layout is one of the worst scenarios for an emergency evacuation. Figure 10 shows the studied geometry: a 1400 m tunnel, with two exits at 200 m from each exit of the tunnel.

A standard circular section for a two-way monotube type tunnel defined in RIL 853 has been used [24]. This section is recommended for train speeds from 160 km/h to 230 km/h. Table 2 summarizes the main data of this simulation.

2.2.1. Scenarios According to the statements indicated herein, 45 different scenarios are established, combining the following two factors: the slope and time delay to open the doors from the beginning of the fire.

2.2.1.1. Slope This study selects railway slopes in order to collect a representative real range. Table 3 shows the maximum slopes for some tunnels [33]. Therefore, the maximum gradient in railway tunnels considered in this study is 4%. As a bidirectional tunnel is going to be studied, positive and negative slopes will be studied, which will constrain the evacuation of the passengers to occur in the direction of smoke advancement or in the opposite direction.

2.2.1.2. Fire Development Times According to Fig. 11, an updated diagram interpretation for evacuation times has been implemented based on the scheme used in other research [17].

The fire development time (FDT) is defined as the time elapsed since fire sparks to the moment when the train evacuation starts. This key time has been used as a variable for the simulation definition. The FDT can be related to the classic egress timeline as follows:

$$FDT = RSET - Movement_{time} \tag{3}$$

The review by Markos and Pollard [34] indicates that there are few publications on the evacuation times of current trains. The authors conclude that the times available in other areas, such as buildings, are not adequate for train evacuation simulations. Although there are recent databases [35] of pre-evacuation times published for various groups (business occupancy, residential occupancy, road tunnel occupancy and other clusters), times have not yet been published for trains in tunnels.

The detection time, t_{det}, was set to 60 s, taking as reference other authors [17]. For an emergency brake deceleration of 1 m s^{-2} and the speed limits defined for

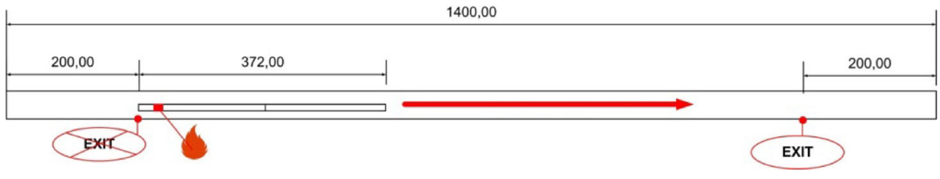

Figure 10. Scenario scheme.

Table 2
Main Simulation Data

Features	Details
Train model	Hybrid train (diesel and electric), max speed 250 km/h
Train layout	2 Compositions of 13 cars
Train exit doors	38 Doors
Train capacity	264 passengers/composition (528 both)
Tunnel cross section	79.2 m^2
Tunnel walkway length	1400 m/967 m used for evacuation
Tunnel cross-passageway widths	2.6 m/6.6 m

Table 3
Maximum Slopes for Major Rail Tunnel Projects [33]

Tunnel	Gradient (%)
Seikan, Japan	1.2
Kanmon, Japan	2.2
Shin-Kanmon, Japan	1.8
English Channel	1.1
Mersy, England	3.7
Severn, England	1.1
Mt. Macdonald, Canada	0.7
Bosphorus, Turkey	1.8

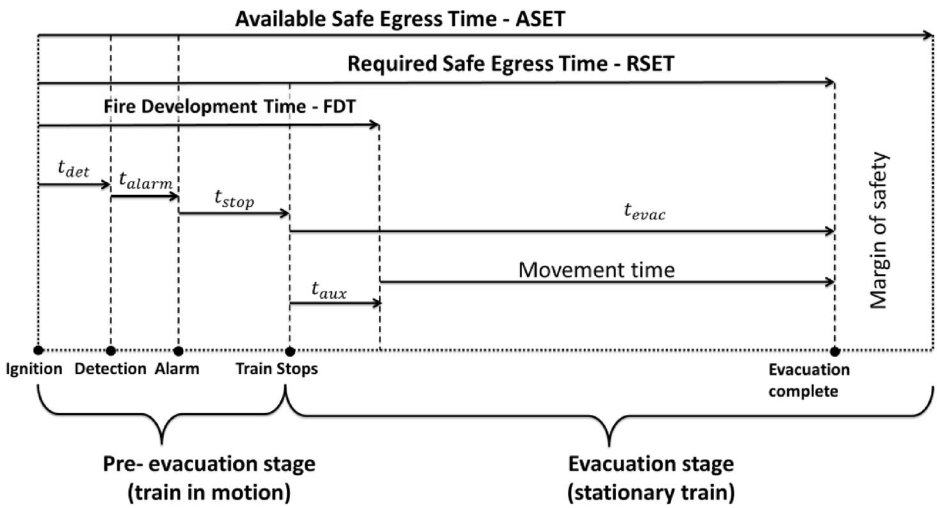

Figure 11. Egress time model.

the used tunnel section, the train requires a minimum of 44–64 s to stop, depending on the speed. Therefore, t_{stop} is set to 60 s for stopping the train during braking operation, after the time to detect the fire, t_{det}.

Assuming a constant pre-evacuation time of 53 s as obtained by Capote et al. [36] for a train layout similar to the one studied, it is observed that this time is less than the time for stopping the train, which justifies that passengers are already prepared for the evacuation task as soon as the evacuation aids are installed and the doors are opened. Although published data are scarce, Fridolf et al. [37] measured times exceeding 70 s in an experiment in which the passengers themselves helped place 2 ladders. An auxiliary time, t_{aux}, of 80 s has been assumed, which includes the placement of stairs or aids to go down to the platform and the opening of doors. This auxiliary time will depend on the device used to descend to track level [38, 39]. As a reaction time to start braking the train, t_{alarm}, a minimum value of 10 s has been assumed, given the severity of the emergency. Substituting the assumed values, we have a minimum FDT value of 210 s, which is the minimum time delay that we can consider at the beginning of the evacuation, once the fire has started.

$$FDT = t_{\text{det}} + t_{alarm} + t_{stop} + t_{aux} = 60s + 10s + 60s + 80s = 210s \quad (4)$$

Thus, FDT values from this minimum value of 210 s to 330 s will be studied, two minutes more than the minimum value. This time interval could thus include an increase in the stipulated times as well as the time delay when exiting the carriage, which has not been explicitly modelled. The aim is to assess the importance of the speed of the stages prior to the evacuation of the train.

2.2.1.3. Scenarios A full factorial experiment based on these two variables, FDT (5 values) and slope (9 values), defines a total of 45 scenarios. The values for these variables are:

- Slope (%): − 4, − 3, − 2, − 1, 0, 1, 2, 3, 4. Positive slope means that people egress uphill.
- Fire development time, FDT (seconds): 210, 240, 270, 300 and 330.

CFD software, SMARTFIRE, was used to implement nine simulations for the corresponding slopes. The design of the experiment (combination of simulation conditions) consists of 45 different scenarios that have been studied, taking into account all combinations between these nine slopes and those five FDTs. In buildingEXODUS, each scenario was simulated 100 times to obtain average results and accommodate a possible atypical value. Thus, a total of 4500 simulations were carried out. To determine the sensitivity of these models, 100 simulations of each scenario were considered as statistical samples and the standard deviations were also calculated.

2.2.2. Statistical analysis Fatalities mean values provided from each group of 100 simulations of each case were statistically modelled and analysed. This work selected a standard linear multiple regression (LMR) method to relate the number of people unable to finish the evacuation (designated fatalities) to the slope and FDT time. A p value ≤ 0.05 were considered significant. Statgraphics Centurion 18 is the software tool used to perform this statistical analysis. These analyses provided the linear relationship shown in Eq. 5.

$$y = a_0 + a_1 \cdot b_1 + a_2 \cdot b_2 + \cdots + a_{n-1} \cdot b_{n-1} + a_n \cdot b_n \tag{5}$$

y response variable, a_i regression coefficients, b_i independent predictor variables.

A statistical model is considered valid if it reaches a high-adjusted R^2 value and fulfils the homoscedasticity and multicollinearity hypotheses.

To avoid non-multicollinearity problems [40], these performed analyses have been carried out under the assumption that explanatory variables are independent from each other when there is more than one independent predictor variable. The multicollinearity assumption can be checked [28] by calculating the variance inflation factor (VIF), as shown in Eq. 6.

$$VIF = \frac{1}{1 - R_i^2}, \quad i = 1, 2, 3, \ldots, n \tag{6}$$

R_i multiple correlation coefficient of ith, variable with the remaining $(n - 1)$ variables.

The homoscedasticity hypothesis is graphically tested by observing the tendency of the residuals relative to the predicted values.

3. Results and Discussion

The purpose of this study is to analyse train evacuation inside a tunnel 1400 m long for different slopes and time delays. The CFD simulation in three dimensions determines the environmental conditions and the fire effects on passenger zones.

In Fig. 12, temperature contours predicted by the CFD simulations show the well-known effect of a slope on fire evolution, where downhill temperatures are lower than uphill temperatures in the evacuation route. Figure 10 show this variation in temperature at two different moments of the CFD simulation. The evacuation results reflect these effects.

For a constant slope, the increase in the starting evacuation time (and FDT time) results in a steep rise in fire development. A 2 m horizontal plane was selected for the study of fire evolution near people. Generally, fire effects at a height of 2 m are the most undesirable, considering the average human height. Figure 12 highlights the dramatic change that occurs between cases 6 and 7 (positive slopes 1% and 2%).

3.1. Averaged Results

Table 4 shows the mean number of fatalities that occur for each increment of time and for each tunnel slope. To accommodate atypical data, the following collected

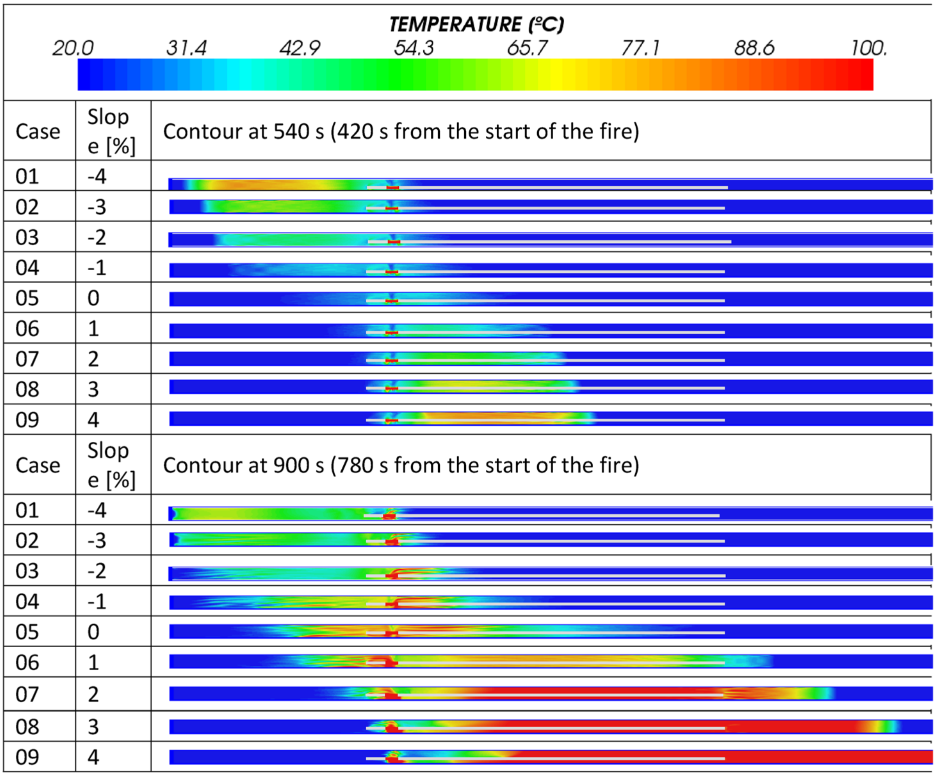

Figure 12. Temperature contours of horizontal plane, 2 m high at 540 s and 900 s of CFD simulation.

Table 4
Number of Fatalities

Fatalities (Mean value – No)

	Fire development time (s)				
Slope (%)	210	240	270	300	330
− 4	0	0	0	0	0
− 3	0	0	0	0	0
− 2	0	0	0	0	0
− 1	0	0	0	0	0
0	0	0	0	0	0
1	13.1	23.1	39.1	55.7	77.3
2	55.4	95.4	137.8	203.9	216.0
3	56.7	106.2	156.0	213.3	216.5
4	59.2	116.3	176.1	216.0	228.8

data are the average of 100 simulations per each combination of five fire development times and nine slopes (4500 simulations altogether).

Fatalities appear for positive slopes only, that is, when the fire effluent propagate in the evacuation direction. Increasing the value of the positive slope results in an increase in fatalities, that prevent passengers from reaching the tunnel exit. The increase in smoke concentration and higher temperatures for the same areas explain this increment. The largest increase in fatalities occurs between the 1% and 2% slopes.

The increase in time to start the evacuation supposes a general increase in the number of disabled people to finish the evacuation, increasing with an increasing positive slope of the tunnel.

The standard deviations of the maximum movement time have a maximum variation of 2.5% with respect to the mean parameter of each case. When analysing the standard deviation of fatalities occurred for positive slopes, a higher impact of program sensitivity appears for the small FDT and the small positive slope tested, 1%. This standard deviation corresponds to approximately 8% of the mean value. For more than 1% of the slope, this value drops to less than 2%. Thus, the mean value is a good predictor for the simulated scenarios. This result is coherent with the standard NFPA502 [19], which formulate a correction factor, k_g, for critical velocities in sloped tunnels:

$$\begin{aligned} V_{cr} &= V_{cr}(0) \cdot K_g \\ K_g &= 1 + 0.0374 \cdot s^{0.8} \end{aligned} \tag{7}$$

where "s" is the slope angle in degrees (i.e. $s = 2.9°$ for a 5% slope). This equation gives a higher increment of K_g for 1% slopes than for higher slopes, as shown in Table 5.

3.2. Statistical Model

LMR can model the disability data for slopes from 1% to 4%, as shown in Table 4. After several iterations, the system obtains a relationship between the variables used here with an adjusted R-squared value of 89.9%. Equation 8 shows this relation:

Table 5
NFPA 502 Correction Factor Variation for Different Tunnel Slopes

Slope (%)	Kg	Increment
0	1	0
1	1.0239529	0.0239529
2	1.04170109	0.01774819
3	1.05767167	0.01597058
4	1.0725826	0.01491093

$$F = -155.975 + 1.21345 \cdot FDT - 339.95 \cdot e^{-S} \tag{8}$$

F Fatalities, *FDT* fire development time, S tunnel slope.

Table 6 presents a summary of this analysis, including the variance. Since the *P* value in the ANOVA (analysis of variance) table is less than 0.05, there is a statistically significant relationship between the variables with a confidence level of 95.0%.

Equation 8 shows the fatalities produced, depending on the slope (%) and FDT:

- For the same slope, the number of people unable to finish the evacuation increases by 12 persons for every 10 s taken to start the evacuation (FDT increase).
- For a constant FDT, the slope relation is more complex. For each 1% increase, the variation of Eq. 8 is expressed in Eq. 9.

$$\Delta D = \frac{339,95\left(1 - \frac{1}{e}\right)}{e^{S}} \tag{9}$$

ΔD Disabilities increment, S tunnel slope, here starting slope = S, final slope = $S + 1$.

Therefore, this study obtains the following estimations for any evacuation start delay:

- from 1% to 2%, fatalities increase is 85.
- from 2% to 3%, fatalities increase is 30.
- from 3% to 4%, fatalities increase is 11.

A VIF (variance inflation factor) calculation requires the correlation coefficients between any two independent variables used in the LMR model. In this case, with only two independent variables, only one correlation coefficient must be calculated between the FDT and e^{-S} variables (with a value of − 0.16). Equation 10 shows that the calculated VIF value is 1.03, much lower than 5, so the non-collinearity assumption is fulfilled.

Table 6
ANOVA Table for Fatalities LMR Model

Source	Sum of squares	Degree of freedom	Mean square	*F*-value	*P*-value
Model	96,282.20	2	48,141.1	85.09	0.0000
Residual	9617.86	17	565.757		
Total	105,900.00	19			

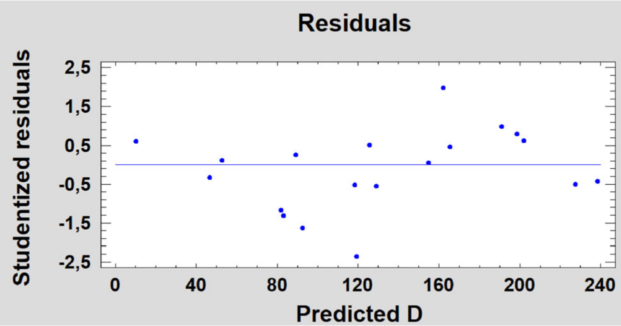

Figure 13. Studentized residuals vs predicted fatalities from Eq. 8.

$$VIF = \frac{1}{1-(-0.16)^2} \cong 1.03 \tag{10}$$

Figure 13 shows the studentized residuals vs the predicted values obtained by the statistical model explained by Eq. 8. As there is no tendency, this model presents homoscedasticity, in addition to a high value of adjusted R^2 and non-collinearity.

It is well known that the pre-evacuation time is crucial for survival in a railway tunnel fire. Several investigations [35, 36] confirm the research focus on the pre-evacuation time and highlight its importance. However, the presented model allows us to quantify this importance in terms of survival. Thus, for every second less than this time, at least one more person can be saved.

On the other hand, there have also been several previous investigations on the dynamics of fire and smoke movement in inclined tunnels. In this case, these studies have also modelled the expected number of fatalities, whose greatest increase occurs with a slope increase from 1% to 2%.

These results are subjected to simulation tools limitations and modelling assumptions, such as fire source modelling, which supposes low combustion intensity as a volumetric fire source. In a real fire, the fire source would be inside the technical car with higher combustion intensity [41, 42] and with different propagation patterns. Nevertheless, the main objective of this work aims to assess the importance of shortening the evacuation times as much as possible.

4. Conclusions

In this paper, CFD simulations were performed to monitor the fire development in a 1400 m tunnel with natural ventilation for different values of the slope of the tunnel. The environmental outputs of these CFD simulations were the inputs for a simulation model of dynamic evacuation of people. For each of nine CFD simulations, five evacuation starting delays were considered. A full factorial experiment defined 45 scenarios that were simulated 100 times each, obtaining mean egress values.

Several publications have already cited this type of simulation (evacuation in a fire emergency, ventilation, etc.). However, this research work has quantified the importance of the combination of these two parameters: the tunnel slope and the evacuation starting delay. Thus, a linear multiple regression model relating the number of people who cannot finish the evacuation with these variables has been developed. This model has an adjusted R-square value near 90%, fulfilling the homoscedasticity and non-collinearity hypotheses.

As a result, the model predicts 12 fatalities every 10 s of FDT increment, independent of the slope if the evacuation takes place uphill. This confirms how vital it is to start the evacuation as soon as possible. This study also determines that the most dramatic change in terms of the increase in fatalities at the end of the evacuation occurs when going from a slope of 1% to 2%. The paper shows that, in case of a fire in inclined railway tunnels with a length of more than 1 km, tenable conditions for safe evacuation cannot easily be guaranteed if the tunnel is only naturally ventilated. Understanding this phenomenon at an early stage of the design process would allow to provide the tunnel with additional measures such as mechanical ventilation systems, intermediate exits or smoothing slope in ceiling (mainly for trains without panthograph), that if properly designed can significantly mitigate the risk to life safety.

To summarize, the developed methodology (CFD model, evacuation model and statistical analysis) is useful to quantify the fire effects on passengers evacuating railway tunnels with natural ventilation.

However, the modelled fire should be improved. In a real situation, the fire source should had a combustion intensity about 1.2 W/m^3 [41, 42] and this source could be inside the technical car where the fuel is stored. The actual model has supposed a combustion intensity of 0.15 W/m^3 referred to the external volume of the train car.

Therefore, future work can use this method to vary the scenario layout, including the train position, fire position, tunnel length and forced ventilation effects. Further, next investigations will include the impact of fire load on the outcomes of tunnel fire evacuation.

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