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FIRE SIMULATION IN RAILWAY TUNNELS: TOWARDS THE DESIGN REQUIREMENTS FOR EMERGENCY EXITS

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Abstract

Emergency exits are one of the most critical elements during fire safety design in railway tunnels, allowing for a quick evacuation from the endangered area to the nearest safe location. At the present-state, there is lack of a comprehensive regulation framework for the design of the ventilation systems protecting the exits from smoke and other by-products during a tunnel fire and the design is normally case-tailored. With the ultimate goal of finding the most appropriate design requirements as the main parameters involved vary, this paper discusses the simulation of two scenarios identified as highly critical for a mixed traffic line: a 10 MW fire of a passenger couch and a 250 MW fire of a freight wagon. The method used is the Computational Fluid Dynamics (CFD) supported by the Fire Dynamics Simulator (FDS). The key requirement is the minimum airflow needed to keep the exits safe according to the variability of parameters, such as position of fire, wind, single or twin tunnel. The scenarios are a short cross-connection between single-track twin tunnels and a connection to a safe zone in a double-track single tunnel. In each case, temperature, pressure and smoke entering the compartment demonstrate to be relevant parameters affecting the results. The results of an extensive simulation campaign pave the ground for next developments aimed at setup a design handbook covering a large set of infrastructure and operation conditions represent a step ahead a recognized standards in railway tunnels design.

Keywords: railway tunnel, railway safety, fire simulation, fluid dynamics, tunnel ventilation

1 Introduction

In tunnels, fire prevention and mitigation play a key role in safety due to the confined spaces, which can produce two very serious effects:

- The high temperatures can seriously damage the structures;
- The closed environment amplifies the risks of a high concentration of toxic substances in the smoke during the evacuation and rescue phase.

The check of damages to the structures are usually according to the state regulations, although Computational Fluid Dynamics (CFD) proven to reliable to support the design and verification process [1]. The evacuation problems have been the object of deep systematic studies [2] and simulation approaches, both in rail [3] and road [4] tunnels.
On the other hand, there is lack of a comprehensive regulation framework for the design of the ventilation systems protecting the emergency exits from smoke and other by-products and the design is normally case-tailored.

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The present paper illustrates the results of an extensive CFD simulation campaign focused on the safety exits in different scenarios, with the ultimate goal of finding the most appropriate design requirements of the ventilation systems as the main parameters involved vary. The key requirement is the minimum airflow needed to keep the exits safe according to the variability of parameters, such as:

- Tunnel and safety exits shape and size: scenarios of short cross-connection between single-track twin tunnels and connection to a safe zone in a double-track single tunnel;
- Fire position and intensity: scenarios consisting of a 10 MW fire of a passenger couch and a 250 MW fire of a freight wagon;
- Longitudinal airflow (wind) speed: progressively increased from 0 to 10 m/s along the tunnel;
- Slope.

The results of this work fit in the effort to set-up a design handbook covering a large set of infrastructure and operation conditions.

2 Methodology

2.1 Software modeling

Large-scale experiments are rare [5] and, in particular for rail tunnels, not operationally and economically affordable to recreate a significant variety of configurations, reason why the simulation approaches progressively permeated this research sector, starting from road tunnels [6] and progressively moving to railway tunnels applications.
Computational Fluid Dynamic (CFD) with the support of Fire Dynamics Simulator (FDS) are nowadays the prevalent methods and tools to address such topics [7]. CFD is a software that solves the Navier-Stokes equations, adapted for fire-driven fluid flow using an appropriate low speed (Mach < 0.3) developed by the National Institute of Standards and Technology (NIST) after an extensive validation work [8].
In addition to the Navier-Stokes equations, used to describe the transport of mass, momentum and energy, another equation governs the chemical reactions and estimates the by-products of the fire. The environment of the simulations is divided into a mesh of cells, the density of which can be optimized in connection with the characteristic fire diameter [8], to obtain an appropriate calculation time. In the present study, the mesh was made of cubic cells of 0.5 meters width, appropriate for a 10 MW fire. As the grid's density has influence on the software approximation and on the outcomes, a finer mesh is required where a wider one is not compatible with the structure: In this case, the same mesh, used in place of the one suggested for a 250 MW fire, brought a noticeable increase in the simulation times.
The computation time can substantially decrease by using the Multi-Processor (MP) analysis, by dividing the mesh in different separate sections assigned to different cores of the processor. To do so, the software needs to compute also the exchanges between the sections and to respect some requirements, such as:

- Fire included in a single section;
- Mesh of every section aligned with the neighbouring ones, thickened were needed and with neighbouring sections made of dimensionally multiple cells;
- Number of subdivisions equal or less to the maximum number of cores of the processor, with unassigned cores not used.

This allows at the reduction of the computation time and the fine-tuning of the mesh accordingly to the scope of the simulation.

2.2 Case studies modelling and setup

The simulations refer to the following scenarios:
- 10 m cross-connection between single-track twin tunnels of 32 m^2 area;
- 18 m connection to a safe zone in a double-track single tunnel of 59 m^2 area.

Proper modeling of the structures is critical to the accuracy of simulation results. To overcome these problems, the customized approach consists in discretizing the circular shape into a stepped conformation. To optimize the time, a spreadsheet parameterize the section of the tunnel for the best possible approximation of the curved surfaces of the shell modeled in blocks.

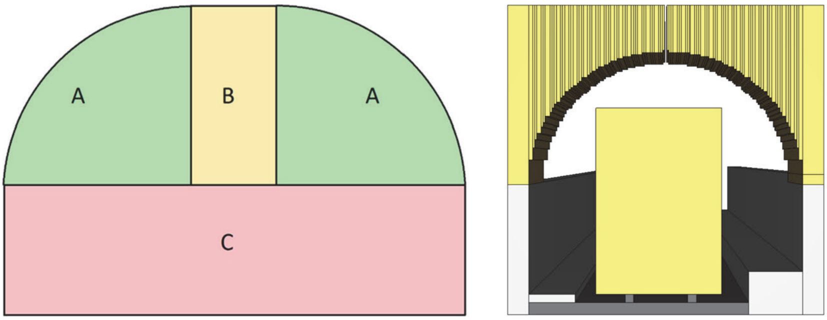

Figure 1 Discretized tunnel infrastructure modeling

The software allows to measure different parameters during the simulation. In the case studies, the focus was on temperature, pressure and air velocity. The Temperature measurements was by thermocouples located close to the ceiling every 20 m and set along the tunnel. The temperature measurement is critical as the threshold for the accessibility of the exits was set to 80°C according to [9], above which the simulation ends, except for the simulation with the access door closed, where the check towards filtration of smoke through the gaps is for a fixed 2-hours window. The pressure measurements are along the tunnel and within the compartment, mainly with slices: an excessive pressure prevents the emergency doors from opening.
The preliminary designed ventilation system was able to deliver a flow capable to produce an increase of internal pressure up to 30 Pa, computed through the simplified equation (1) by Butcher and Parnell [10]:

$$Q = KAP^{1/N} \tag{1}$$

where:

Q [m^3/s]	- is the quantity of air released into space;
A [m^2]	- is the total area of the passing through losses between inside and outside spaces; with closed doors, it is the product of the length of the edges and an estimated discharge surface of 0.0035 m^2/m/door [7];
P [Pa]	- is the desired pressure difference between internal and external spaces;
K	- represents the discharge coefficient of the paths through which the losses occur, here set to 0.827 according to [11];
N	- represents a coefficient, normally set to 2 for doors and 1.6 for windows.

A similar report is included in EN 12101-6 [12] with the recommendation to apply a safety factor of 1.5 to consider the cracks appearing explicitly in term A. Indeed, the REI 120 doors usually used in tunnels fire exits are airtight, but a possible leak might come from other sources or improper maintenance over or under the doors. Lastly, the airflow velocity measurements are along the tunnel and on doors and leaks, to check the velocity required to prevent the smoke passing into the compartments with open doors.

2.3 Simulation scenarios

As mentioned, there the main infrastructural situation are: A) a short cross-connection between single-track twin tunnels; B) a connection to a safe zone in a double-track single tunnel. In both cases. The articulation of scenarios is depending on the following variables:
- Position of the doors: closed or open;
- Position of the fire: 0-250 m from the emergency exit;
- Longitudinal velocity of airflow (wind): 0-10 m/s;
- Maximum time with temperature ‹ 80 °C in front of the emergency exit [s];
- Airflow through the open doors, to compensate by the ventilation equipment: 0.5-7.5 m^3/s.

The simulations started with the reference scenario, characterized by a cross-section area of 32 m^2, a 10 MW firepower and absence of wind depicted to assess the distribution of the temperatures along the tunnel (2 km length) (Figure 2). The obtained results allow to value the time period inside wich the safe zones can be used (time period to reach the temperature of 80 °C in front of the exit at fire distance variation). Table 1 summarizes the times in which the reference thermocouples begin to detect temperatures around 80°C, used to set up the simulations in the reference scenarios.

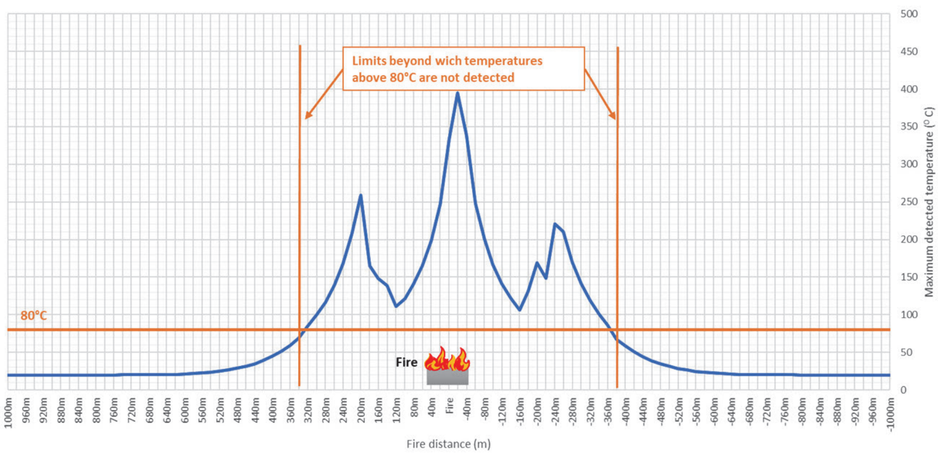

Figure 2 Temperature distribution along the tunnel

Table 1 Time period to reach 80°C as a function of the distance from the fire (Scenario A – Firepower 10MW)

Distance from fire (reference thermocouples) [m]	**Time window during which 80 °C is reached** [s]
20	36
140	597
260	5160
380	Temperature always ‹ 80° C

3 Results of the simulations

The key design parameter of the present analysis is the airflow Q through the open doors of the cross connection towards the safety area, balanced by a ventilation equipment. Figure 3 shows an example of the transversal (Y-Z) air velocity at the opening of the doors of this connection in scenario A, with the fire at a distance of 125 m, absence of longitudinal airflow and ventilation system airflow Q = 2 m^3/s. Figure 4 shows an example of the transversal (Y-Z) air velocity at the opening of the doors of this connection in scenario B.

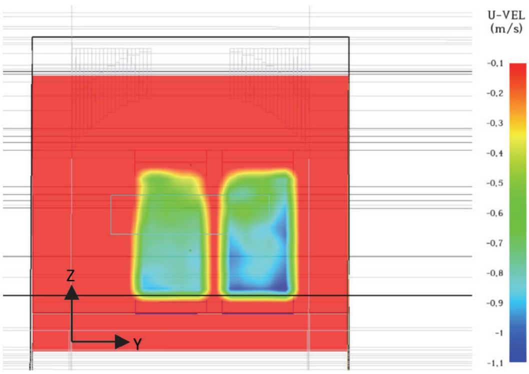

Figure 3 Y-Z air velocity at the opening of the connection doors in scenario A

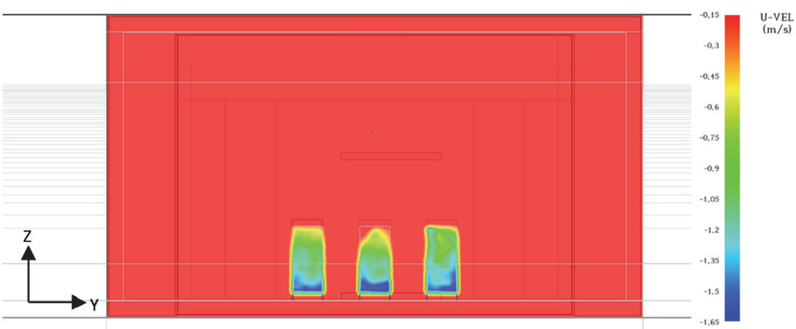

Figure 4 Y-Z air velocity at the opening of the connection doors in scenario B

Table 2 summarizes the results of a selection of the simulations carried out, where it has been possible to determine the values of the design parameter required airflow of the ventilation; the results refer to the main significant combinations of the relevant variables for a 10 MW fire.

Table 2 Summary of the results of a selection of simulations

Position of the door	Closed	Open					
Distance fire - emergency exit [m]	0	0		125		250	
Max velocity of airflow (wind) [m/s]	0	0	10	0	2	0	10
Max time with temperature < 80 °C [s]	Any	36	36	600		5160	
Required ventilation airflow [m^3/s]	0.5	0.5	5.0	2.0	5.0	2.0	7.5

4 Conclusions

The moves towards closing the existing gap in the regulation framework for the design of the ventilation systems protecting the exits from smoke and other by-products during the fire in railway tunnels. The target is finding the most appropriate design requirements according to the variability of the relevant parameters. The paper deals with critical scenarios by using the most consolidated simulation techniques. The key requirement is the minimum airflow needed to keep the exits safe according to the variability of parameters, such as position of fire, wind, single or twin tunnel. The extensive simulation campaign provides useful elements for the preliminary dimensioning of the ventilation equipment in various fluid-dynamics conditions. The results pave the ground for next developments towards a design handbook for railway tunnels covering a variety of infrastructure and operational conditions. In this framework, the research identified as most promising open fields for further investigation developments, such as the effects of the firepower and longitudinal airflow, which demonstrated to be only partially manageable by the proposed simulation approach.

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