CFD and Evacuation simulations for three railway tunnels. Challenges in case of natural ventilation

J. Ignacio Abad Martínez
INCOSA
Dr. Zamenhoff, 36
Madrid, 28027, Spain
e-mail: iabadm@incosa.es

F. Javier Pérez Mas
GEOCONSULT
Dr. Zamenhoff, 36
Madrid, 28027, Spain
e-mail: fj_perez@geoconsult.es

ABSTRACT

Although they are not common, and the latest standards make them highly improbable, the fires in trains can create critical situations due to the amount of people involved as passengers, remarkably if this situation happens inside a tunnel. Therefore, it is highly important to consider the necessity of installing mechanical ventilation in the railway tunnels, being this something that must be studied individually for each tunnel considering its specific characteristics.

Three railway tunnels were studied, with different characteristics in length, cross section and slope. For them, CFD and evacuation simulations were carried out with Pyrosim and Pathfinder, being coupled between them in order to obtain more accurate results in terms of evacuation time and poisoning. Visibility, temperature and FED were analyzed to verify the tenability conditions during the evacuation.

The results showed that evacuation was feasible, but visibility was a matter of concern, and mitigation measures were needed. Finally, mechanical ventilation was judged as not necessary considering the evacuation conditions and the probability of this kind of incidents.

INTRODUCTION

During the design and construction stages of the railway tunnels, it is becoming more common to carry out Performance-Based Designs of some of the tunnel safety facilities, and more specifically, the combination of mechanical ventilation and means of egress.

This paper presents a specific case study in which three tunnels of a same high-speed train line were analyzed by means of CFD fire simulations and evacuation simulations with the aim of verifying the adequacy of the means of egress in case of fire inside the tunnel, as well as the necessity or not of mechanical ventilation.

For this purpose, the worst-case scenario for each tunnel was sought, considering distances between emergency exits, travel time of the trains once the fire was initiated, tunnel slope, and external and internal ambient conditions.

Then, combined simulations of fire and evacuation were conducted using Pyrosim and Pathfinder, obtaining ASET and RSET times based on tenability conditions, as well as calculating the potential poisoning due to CO_2 presence and Oxygen absence by means of in-built FED calculation.

METHODOLOGY

The methodology proposed was based on the widely spread fire safety analysis tool of comparing the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET), that seeks to demonstrate that the time available to escape from a fire event is enough. The following figure shows the relationship and composition of these two times:

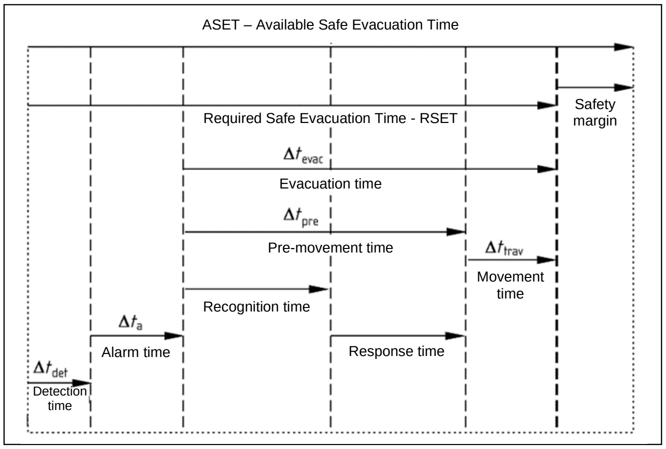


Figure 1. ASET and RSET times

In order to obtain both times (ASET and RSET), two types of simulations were proposed:

- On the one hand, for the calculation of RSET, evacuation simulations were considered. These simulations allow to know the movement time, being added the rest of times (detection and alarm, recognition, and response) as a function of other parameters.
- On the other hand, the calculation of ASET is performed by fire simulations, in which RSET is obtained depending on how the smoke layer develops, and how this affects the survival conditions along the evacuation route.

In addition, due to the use of Pyrosim and Pathfinder software, a complete integration of the fire and evacuation simulations was possible, so that the cumulative degree of poisoning (FED) for each evacuating user was considered to be calculated, as well as the fact of taking into account the reduction in evacuation speed due to lack of visibility. This last characteristic of Pathfinder is considered to be of high importance in those spaces in which the smoke reduction can be severe such as the railway tunnels, as they are considerably narrower than other tunnels.

SIMULATION HYPOTHESIS AND INPUT DATA

Geometry

For each one of the three tunnels, the geometry was generated based on the 3D CAD model of the tunnels, imported into Pyrosim as a solid. Images below show the geometry imported for the tunnels (including the emergency exits and a basic shape of the train):

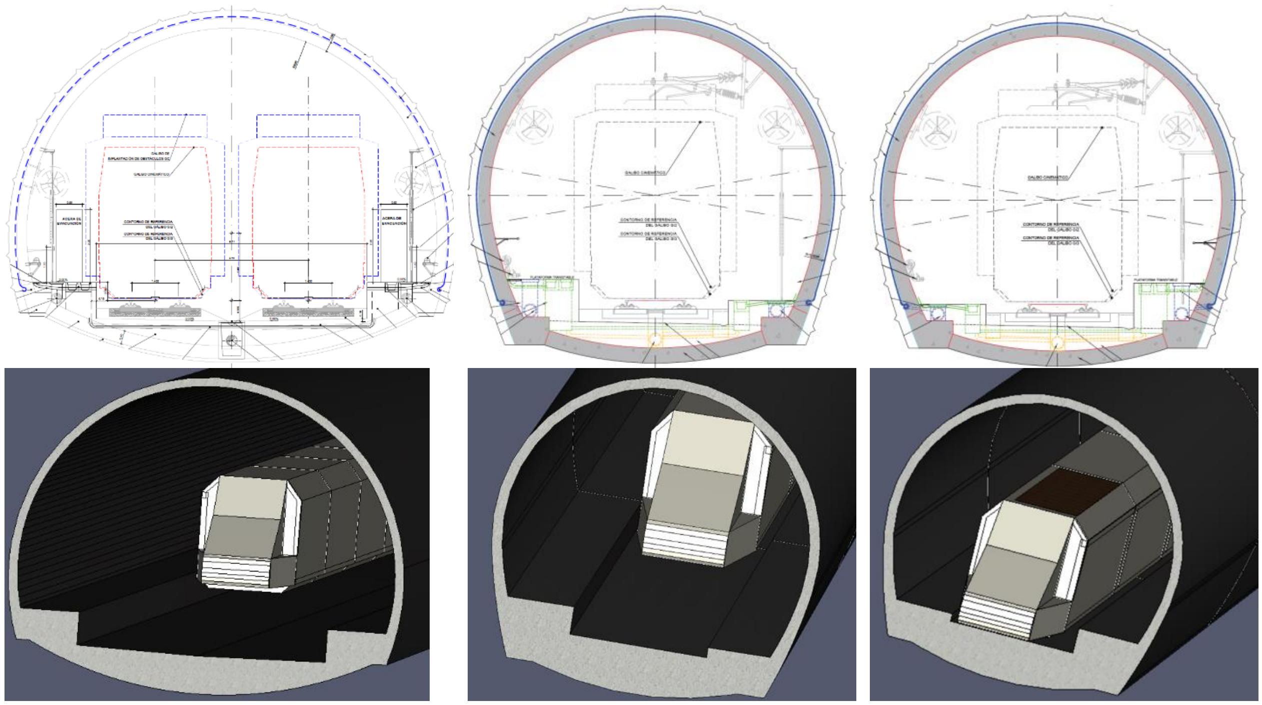


Figure 2. Cross sections of the tunnels (1 to 3 from left to right) and 3D modelling in Pyrosim

As it can be seen in the previous figure, tunnel 1 has a wider geometry, whereas tunnels 2 and 3 have the same cross section, having differences in the slope of the tunnel, which in one case grows in the same direction than the travel direction of the trains (tunnel 2), and in the other case is the contrary (tunnel 3).

The geometry of the tunnels presents two key aspects regarding the simulations and the results:

- The cross section of the tunnels. This will have a significant impact on the distribution of the smoke generated by the fire, as well as to the height reached by the smoke layer.
- The width of the evacuation walkways. This will determine how fast the passengers can evacuate from the train and from the tunnel.

The following table shows these two critical characteristics for the tunnels, as well as their slope.

Table 1: Relevant geometric characteristics of the tunnels

Tunnel	Cross section	Evacuation walkway width	Slope
Tunnel 1	89 m^2	1.26 m	-1.7%
Tunnel 2	53 m^2	1.60 m	-1.8%
Tunnel 3	53 m^2	1.73 m	1.8%

<u>Materials and Surfaces</u>

The tunnel was built in reinforced concrete so the main material considered for the simulations was this one, with the properties that can be seen in the table below. Other materials such as the steel for the trackway or the materials of the train were not considered due to two reasons: they were much less massive than the concrete of the tunnel; and as the fire was in the external part of the train, the train materials would not cause relevant effects in the simulation during the time considered for the evacuation.

Table 2: Properties of the materials included in the model (Concrete).

Property	Value
Density	2280 kg/m³
Specific Heat	1.04 kJ/kg K
Thermal Conductivity	1.8 W/m-K
Emissivity	0.9

Regarding the surfaces, the concrete walls of the tunnel were considered as surface "Concrete" with the properties described in the table below, and the rest of surfaces (train) were considered Inert. This simplification was made because the combustible fraction of the train is considered in the HRR curve fixed for the scenario, and, from a conservative perspective, the lack of heat absorption at the train walls generates higher temperatures at the tunnel, worsening the evacuation conditions.
The thickness of the walls was considered from the construction project, and for the temperature of the wall and the backing, please refer to the Ambient Conditions section.

Table 3: Properties of the surface "Tunnel Wall".

Property	Value
Material	100% Concrete
Thickness	30 cm
Internal temperature	6 ºC
Backing temperature	6 ºC

Ambient Conditions

The ambient temperature and the temperature inside the tunnel are relevant from the point of view of smoke stratification. Consequently, considering the temperatures from the closest weather stations to the three tunnels, the outside temperature was considered to be the 5% percentile of the temperatures, and the temperature of the tunnel walls to be the average temperature of the coldest month (January). The following table shows the temperatures considered:

Table 4: Tunnels air and walls temperatures

Tunnel	Wall temperature	Air temperature
Tunnel 1	6.00 ºC	-1.68 ºC
Tunnel 2	5.95 ºC	-1.41 ºC
Tunnel 3	5.95 ºC	-1.41 ºC

Fire Characteristics

For the fire HRR curve, as the tunnels were located in Spain, the Spanish railway safety standard IFI (Infrastructure Railway Instruction) was considered as the reference standard, proposing the following fire HRR curves:

Table 5: Fire HRR curves according to Spanish standard IFI

Type of traffic	Maximum HRR	Fire duration
Only passengers' trains	15 MW	1
Passengers and Freight trains	30 MW	2
Dangerous goods trains	100 MW	2

Considering that the worst evacuation conditions will be obtained in the case of a passenger's train (in freight trains only the driver is travelling with the train), the HRR considered is 15 MW, with the following curve obtained from the IFI standard.

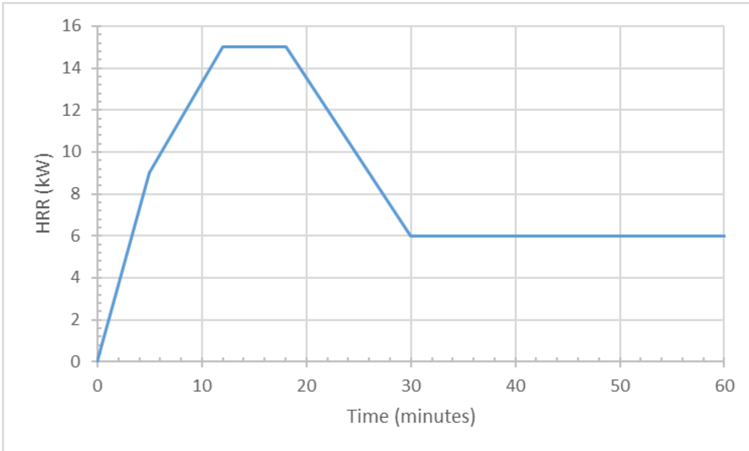


Figure 3. HRR curve according to Spanish standard IFI

Evacuation Parameters

Regarding the evacuation parameters, this kind of evacuation scenarios are usually modelled based on three different groups of data: number of occupants and location, population characteristics, and pre-movement time.

Occupants and locations

The occupants in the three scenarios will be located inside the train, not being any occupancy in the tunnel at the beginning of the simulation.
Regarding the number of occupants, the different models of train that can use these tunnels were assessed, and the one with the highest capacity was chosen for the simulations. This train had a maximum capacity of 730 people in a double composition of the train. The following figure shows the train considered and modelled for the three scenarios.

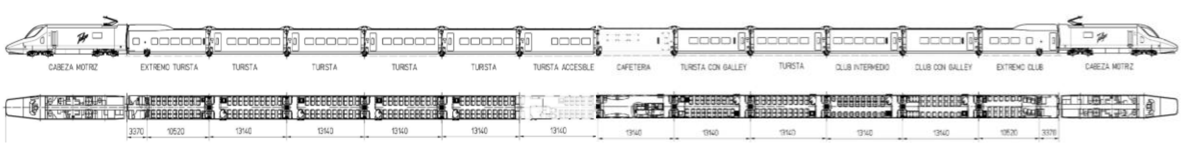


Figure 4. Train considered for the simulations.

Population characteristics

The population characteristics are mainly defined by the size of the agents and the walking speed. These two parameters have been defined according to population groups, and more specifically those included in the Report of the International Maritime Organization (IMO): MSC/CIR 1533 "Revised Guidelines on Evacuation Analysis for New and Existing Passenger Ships".

According to the previous considerations, the population groups, their relative weight considered for the simulation, and the walking speeds are the following ones:

Table 6: Populations groups and movement speeds

Type of passengers	Relative weight (%)	Horizontal speed (m/s)		Speed on stairs (m/s)	
		Avg.	Range (uniform)	Avg.	Range (uniform)
Female < 30 yrs.	12%	1.24	0.93-1.55	0.75	0,56-0,94
Female 30-50 yrs.	12%	0.95	0.71-1.19	0.65	0,49-0,81
Female > 50 yrs.	16%	0.75	0.56-0.94	0.6	0,45-0,75
Female PRM 1	10%	0.57	0.43-0.71	0.45	0,34-0,56
Male < 30 yrs.	12%	1.48	1.11-1.85	0.86	0,76-1,26
Male 30-50 yrs.	12%	1.3	0.97-1.62	0.86	0,64-1,07
Male > 50 yrs.	16%	1.12	0.84-1.4	0.67	0,50-0,84
Male PRM 1	10%	0.85	0.64-1.06	0.51	0,38-0,64
PMR 2	-	0.69	0.13-1.29	-	
PRM: Person with Reduce Mobility PMR 1: People with mobility problems PMR 2: People in wheelchair					

Additionally, due to the fact that the descent from the train to the evacuation platform could have a step larger than the size of a normal step, and that this circumstance is not contemplated in the table above, an evacuation speed reduction factor of 0.5 has been included in all exits from the train to the evacuation pavement (formed by a single step modelled by a ramp).

It should be noted that Pathfinder includes an additional consideration for movement that, in conditions of reduced visibility, users will move at a slower speed depending on how the visibility is reduced and their usual speed. For this, the fire and evacuation simulations were combined.

Pre-movement time

As previously indicated, evacuation simulations allow to calculate the time required for evacuation, and more specifically, the movement time, being necessary to indicate the pre-movement time, i.e. the time that each occupant needs to realize that there is an emergency situation in which it is necessary to evacuate, react, and begin evacuation.

Usually, these times are unknown, and it is common to use guides that propose them according to the type of facility to be evacuated, the familiarity of the users with it, and the degree of attention it is considered that they may have at that moment.

For the case considered, as it is a train with a public address system and on-board staff, it is considered that the recognition and response times will be minimal, even more so as it will have made an out-of-station stop, which will have been previously notified to passengers. Therefore, can be considered that the recognition and response time is nil, and that people will start to exit the train as soon as the doors open. However, a period of 30 seconds is considered from the moment the train stops (instant zero of the simulation) until the doors are open and evacuation starts.

Regarding the detection time and alarm times, they are considered to be prior to the start of the simulation, since it has been considered that from the start of the fire on the train until it stops, a time of 92.6 s elapses (corresponding to braking from a speed of 300 km/h until it stops), which is sufficient to carry out the detection and alarm process.

Timeline of the Scenarios

The timeline imposed to the scenarios is the following:

- Time 0 s. Beginning of the fire
- Time 92.6 s. The train is fully stopped in the tunnel. Beginning of the simulation.
- Time 122.6 s. Train doors are open. Beginning of the evacuation.

The rest of the events (evacuation of the passengers from train and tunnel) are simulated.
For convenience reasons, the times in the simulations are referred to the moment at which the train stops, and the simulations start. Therefore, the train doors are open at time 30 s, and the evacuation time is referred to the moment at which the train stops.

RESULTS

Below, the results for the cases studied are presented. Visibility and temperature are shown along the evacuation walkway, as well as the calculated FED for the occupants.

Tunnel 1

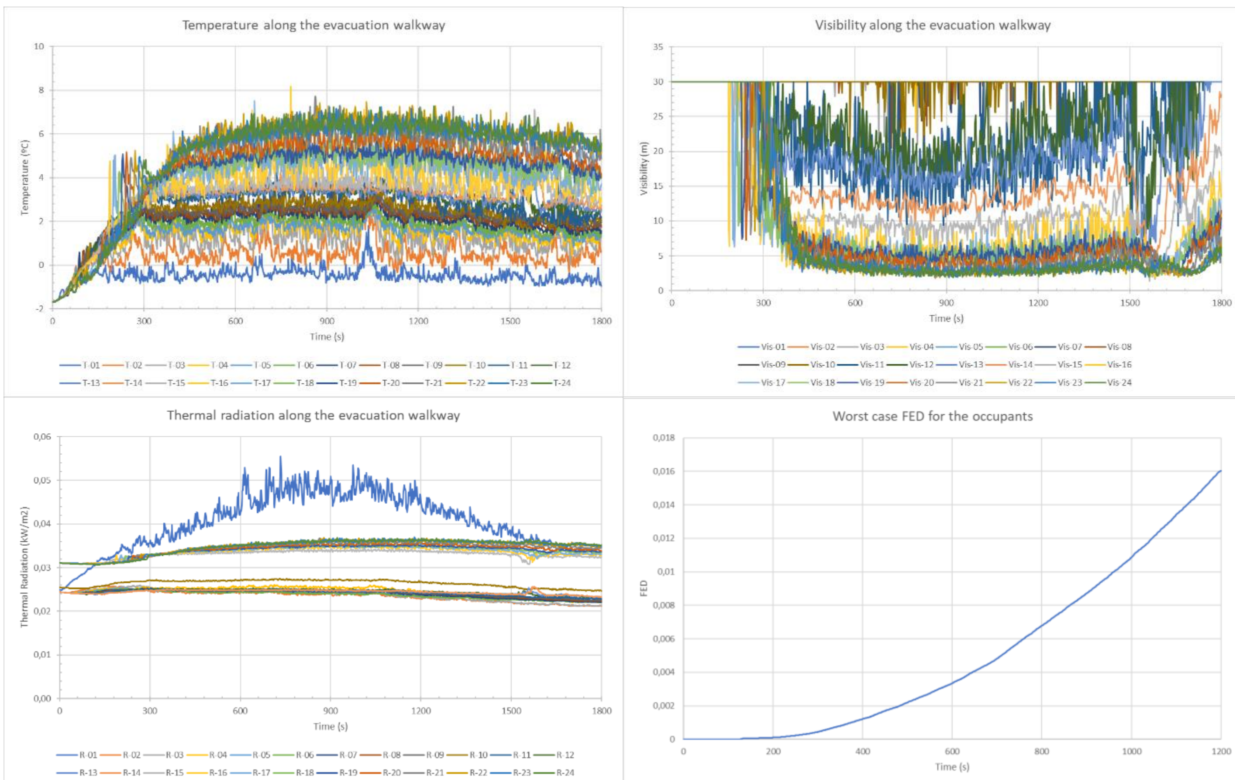


Figure 5. Results for scenario 1.

In this scenario, thermal radiation, temperature and FED were not limiting factors, as they were clearly below the limits usually considered: Temperature increase was about 10 degrees, maximum thermal radiation was lower than 60 W/m^2 and FED was lower than 0,016. Nevertheless, there was a visibility reduction from early moments being lower than the common limit of 10 m in general along the evacuation walkway from time 300 s. Some points of the walkway had a visibility of 3 m.

Tunnel 2

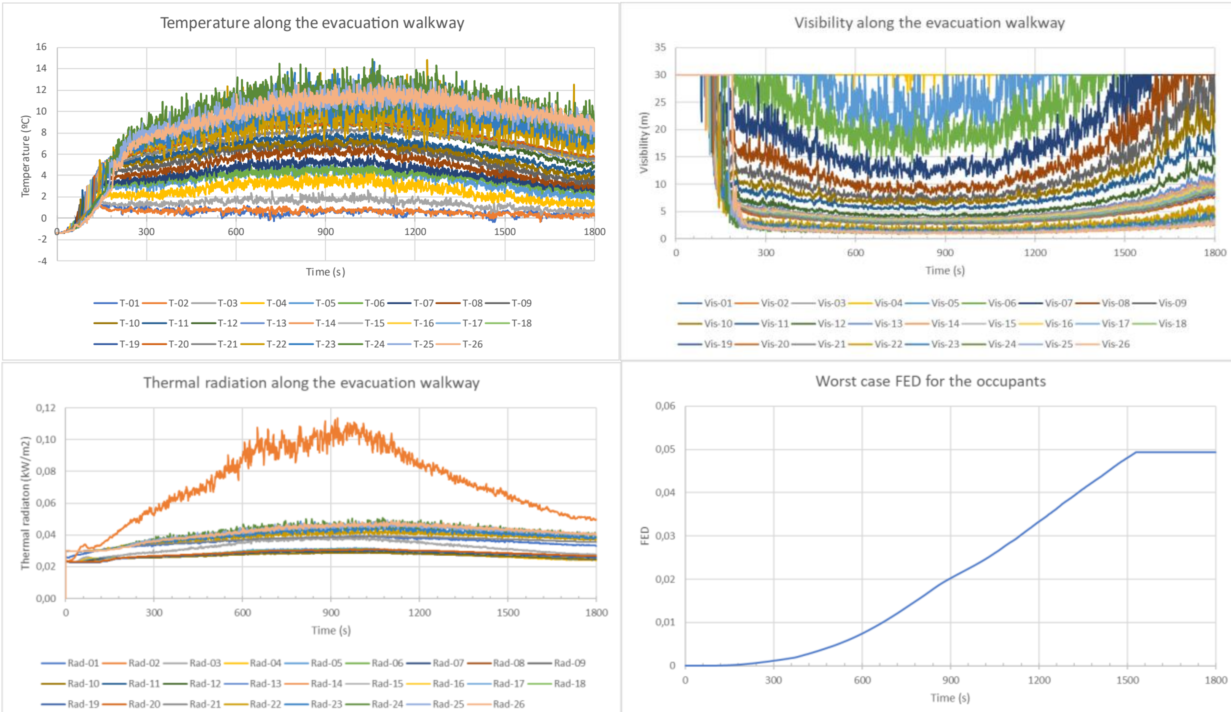
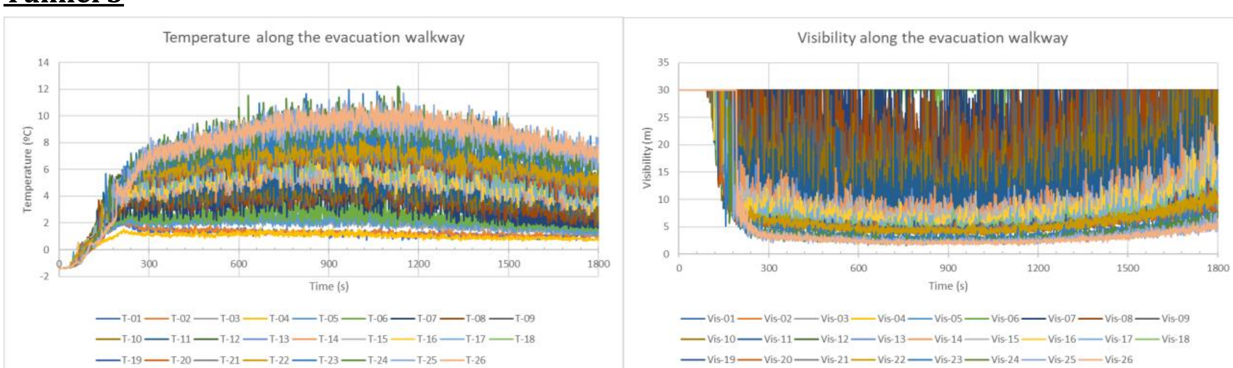


Figure 6. Results for scenario 2.

Scenario number two presented worse results than the previous scenario for all the parameters. Temperature increase was up to 17ºC compared to the original temperature of the tunnel, thermal radiation increased up to 110 W/m^2, FED raised up to 0.05, and visibility reduction happened earlier and in a more markedly manner. These results were considered normal, as the tunnel had a very similar slope than scenario 1 and the fire was the same, but the dimensions of the tunnel were clearly lower, resulting in a fastest filling of smoke and bigger thermal effects.

Tunnel 3



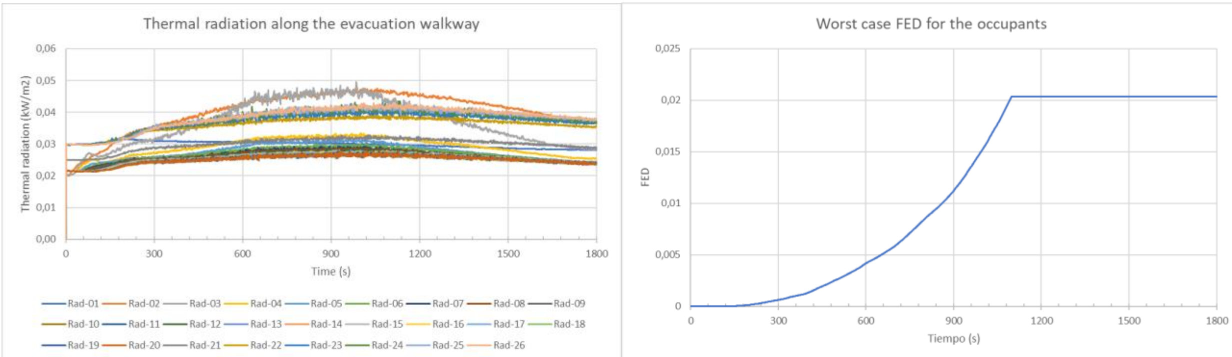


Figure 7. Results for scenario 3.

The third scenario, identical to the second one but with a different slope (in this scenario it is favorable for the evacuation), presented a temperature difference of about 13ºC referring to the original temperature of the tunnel, a thermal radiation of 50 W/m^2, and a FED of 0.02. All these parameters were lower than for the scenario number two. Regarding the visibility, it was again the most limiting factor, being reduced from early moments of the simulation, but with one important difference regarding the previous scenario: it was about 2 m higher in a general way all along the evacuation walkway.

CONCLUSIONS

The results from the three scenarios studied showed that the absence of mechanical ventilation in the tunnels, and the consequent free flow of the smoke resulted on a very relevant reduction in the visibility along the evacuation walkway of all the tunnels, being higher for those with lower cross section. Regarding the rest of the tenability parameters analyzed (Thermal radiation, Temperature and FED), they were clearly below the commonly used limits for all the scenarios, meaning that the major risk for the evacuation was the lack of visibility, and those fire products usually associated with this lack of visibility which are not accounted in the FED.

Based on the previous results, and considering the advances in the construction materials used for trains (based on some standards as the EN-45545) which are reducing dramatically the fire power and the smoke generation, the following conclusions can be summarized:

- For those railway tunnels in which old trains are serving, mechanical ventilation must be considered, as the effects of smoke over visibility are very marked.
- In case of not being possible to install mechanical ventilation, mitigation measures to help the users reaching the emergency exit should be considered. These mitigation measures may include low height lighting, handrails, backlit evacuation signs, and light beacons along the evacuation pathway.

REFERENCES

National Fire Protection Association (2023) "*NFPA 130, Standard for Fixed Guideway Transit and Passenger Rail Systems*"

Society of Fire Protection Engineers (2016) "*SFPE Handbook of Fire Protection Engineering, 5th edition*"

Spanish Government (2023) "*Railway Instruction for the Design and Construction of the Infrastructure Subsystem (IFI)*"

International Maritime Organization (2016) "*MSC/CIR 1533 Revised Guidelines on Evacuation Analysis for New and Existing Passenger Ships*"