

# Numerical Simulation and Full-scale Tests of a New Approach for Fire Management in Passenger Trains

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## ABSTRACT

The aim of this paper is to analyse an innovative alternative developed by Spanish railway manufacturer CAF, based on a smoke extraction system to guarantee safe conditions during evacuation processes in a passenger train. Several full-scale experiments in a new CAF's commuter unit were designed to assess the extraction performance, supported by the application of fire computer modelling. The new smoke exhaust system must extract the smoke generated during a fire in the passenger area by exhaust fans, allowing the ingress of fresh exterior air in the lower part of the rear ends, all of them located in the body ends of the car, avoiding the smoke propagation in the other coaches. Full-scale fire tests were developed in the train unit following the Australian standard AS 4391. A fire of 140 kW was used and the smoke was generated by a clean smoke machine. Measurement points included 6 thermocouple trees, 10 gas flow velocity probes and 2 GoPro HD video cameras (for the estimation of the visibility). The expected objective was that visibility and temperature at the first vestibule of the non-fire car does not fail the tenability criteria. The system performance was successful with the tenability criteria, since the value of visibility at the non-fire car was greater than 30 m and the temperature was lower than 30 °C during all the tests at a height of 1.7 m above the car floor level. Experimental results were used to validate the computational model. The computational model results show a good accuracy compared with the tests.

**KEYWORDS:** Railway vehicles, fire safety, smoke control, fire tests.

## INTRODUCTION

Over the last decades some major fire incidents have occurred in railway transport systems, causing hundreds of deaths [1]. For that reason, several research initiatives, as research done by NIST [2], FIRESTARR [3] and TRANSFEU [4], have been carried out to analyse fire safety in railway transport systems. These research programmes involved small-, medium- and real-scale fire tests, but also the combination of small-scale and full-scale test has been used to analyse the fire behaviour of high-speed trains' interior materials [5]. Additionally, the influence of the location of the ignition source for different compartment sizes and configurations has been analysed by Parkes et al. [6], and it has been found that these parameters significantly influence the fire development.

In addition to the experimental tests, fire computer models have been used to analyse fire safety conditions in trains. The CFAST fire model was used by NIST to predict the fire hazard within a passenger rail car [7]. Comparison of times to untenable conditions for a range of fire sizes determined from experimental measurements with those calculated by CFAST showed agreement that averaged approximately 13 percent. Another computational model, Fire Dynamic Simulator (FDS), has been also used to analyse the smoke movement in high-speed passenger trains [8].

Fire development in a train carriage was also investigated by numerical simulations in [9]. They applied two methods to perform the simulations, i.e., the simple ignition model and the kinetic

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pyrolysis model. The model parameters were estimated and calibrated based on data obtained from ThermoGravimetric Analysis (TGA) tests and cone calorimeter tests. The use of computational fire modelling combined with the results provided by cone calorimeter experiments demonstrated important advantages over the traditional approaches in fire safety applied to passenger trains [10].

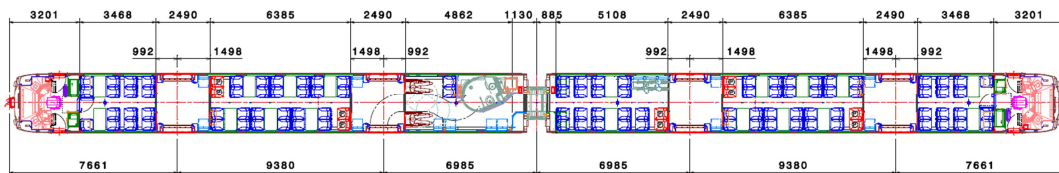
Moreover, manufacturers, operators, regulatory entities, etc., have been working on new regulations and innovative measures that might well improve life safety in trains. Around the world, countries have defined their own standards, considering distinct requirements and methods for fire-testing railway products and systems. The European Standard EN 45545 [11] specifies the measures for fire protection of railway vehicles in UE and the methods for verifying these measures.

Part 3 of this standard states the requirements for barriers fire resistance. Compartmentation of passenger cabin, considered in regulations, aims to avoid fire propagation inside the occupied areas. In this sense, 15 minutes of fire resistance is a common requirement in EU passenger trains [12]. However, fire rated construction is unlikely to be implemented due to the complex services penetrations through partition and lack of practical installation methodology. In order to meet life safety requirements over the early stages of the fire, the fire safety solution will need to mitigate the impact of smoke on passengers and to contain smoke spread within affected areas only until the vehicle can reach a safety point.

Therefore, a suitable control of smoke manifestations may well fulfill this technical ambition. In response to this challenge, the Spanish manufacturer CAF developed an innovative alternative for compartmentation, based on a smoke extraction system, to guarantee safe conditions during evacuation processes in a passenger unit. A real scale experimental programme, supported by the application of fire computer modelling, was carried out in a new CAF's two-car rolling stock to assess its performance.

## TRAIN GEOMETRY AND SMOKE EXHAUST SYSTEM

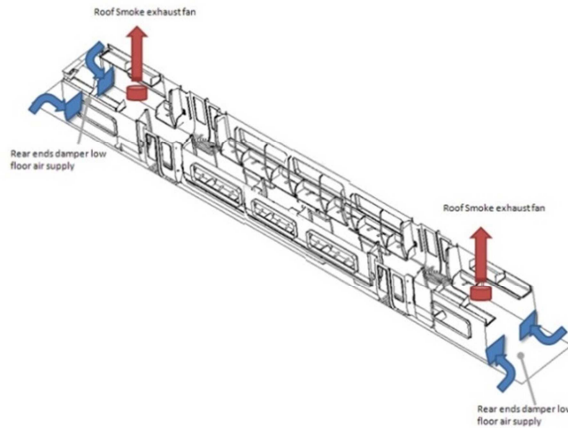
Since this study should be representative of real end-use conditions, a real train unit of two coaches with an intercommunication gangway was selected, specifically, a new CAF's DMU two-car rolling stock. This configuration might be also considered a worst scenario due to the limited available volume for smoke propagation. The train included all the real materials and furniture (pairs of seats on either side of the aisle, tables, luggage racks, ceiling and wall panels, universal toilet, cabinets, etc.) and the new exhaust system. Figure 1 shows the layout and dimensions of the train.



**Fig. 1.** Layout of the train unit.

The new smoke exhaust system aims to extract the smoke generated during a fire in the passenger area, allowing the ingress of fresh exterior air in the lower part of the rear ends. These key elements are located in the body ends of the car (Fig. 2), creating an air flow that evacuates the smoke generated by the fire to prevent people from coming into contact with smoke. The smoke exhaust system is activated by a smoke detection system available in the train. The exhaust fans that are used for smoke extraction will blow a flow rate of 1500 m<sup>3</sup>/h. These fans are mounted at each end of the vehicle roof structure, connecting the interior of the passenger area with the roof exterior side.

Additionally, we should highlight that all the doors of one side were opened within 5 minutes of the start of the fire, representing the event of arrival to a station or evacuation platform, when the evacuation begins.



**Fig. 2.** Key elements of the Smoke Exhaust System.

## METHODOLOGY

To begin with, a data collection campaign was carried out to understand the actual features of the new exhaust system and obtain values in the critical areas by monitoring gas flow velocities. This information was used to implement input data for the simulations, which facilitated the design of the real scale experiments. 24 simulations were performed by using the fire computer model Fire Dynamics Simulator (FDS) [13]. These simulations enabled us to adjust the parameters of the new exhaust system and to define the critical scenarios to perform the real scale test. For reasons of space, these previous works will not be included in this article.

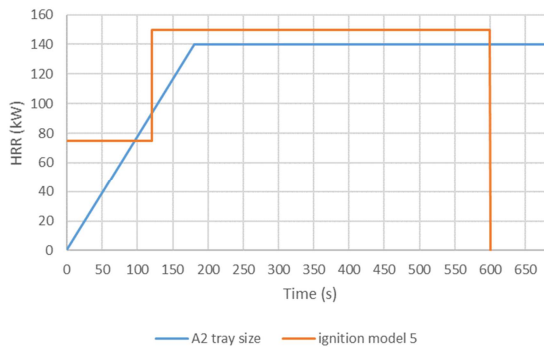
Having completed these preparatory stages, during the fire experiments, the smoke movement was analysed by monitoring different parameters, such as temperature, visibility and gas flow velocities. These may well estimate both the interface of the hot smoke layer and the impact of the fire manifestations on the sustainability of users during the emergency actions. The tenability criteria applied at height of 1.7 m above floor level for the cabin adjacent to the room of fire origin are: (1) the visibility shall not be less than 6 meters, this is judged to be a sufficient distance to be able to locate an external body side door from anywhere in the saloon, and (2) the temperature shall not be greater than 60 °C [14]. It should be noted that clean smoke was used in the tests, so tenability criteria could not include effects from irritants and toxic gases.

As far as the type of the smoke test is concerned, we selected the Australian standard AS 4391 - 'Smoke management systems - hot smoke test' [15]. This method has the endorsement of hundreds of tests and multiple works on its use for the verification of installed safety solutions and for obtaining input data to validate computer models [16-18]. The standard indicates a combination of a tray with a liquid fuel (methylated spirit) with a smoke machine for the generation of clean smoke. In this way, a plume of hot gases is obtained through the tray but without the generation of toxic smoke, due to the characteristics of that fuel. The required amount of smoke can be set in the smoke machine. Note that the fuel considered is Denatured Industrial Grade Methylated Spirit (Grade 95), which is cost effective and produces clean combustion products, having a low radiation output.

In the case of trains, fire behavior tests on materials and products (described in Standards EN 45545-2 and EN 45545-3) and design requirements (described in Standards EN 45545-4 and EN

45545-7) consider five different types of ignition models (EN 45545-1 [19]). Ignition model 5 describes the most serious fires, such as baggage fires and arson. In the study, the railway operator defined ignition model 5 as target design fire, taking into account also that only the initial stage of the train fire is considered because all the doors of one side were opened within 5 minutes of the start of the fire, representing time of arrival at a station and beginning of the evacuation.

For experimental purposes, a fire of 140 kW was considered, provided by a tray of size A2 (fire curve with approximately 3 min fire growth, 10 min steady-state burn time and 3 min fire decay). As we can see in Fig. 3, the duration of the tests was adjusted to 11.5 min to obtain the same fire severity in terms of energy released as the curve of the ignition model 5. Additionally, the amount of smoke generated was given by the clean smoke machine. Taking into account some previous simulation results (visibility between 1.3 m and 2.5 m in 5 min without the system), we used 168 mg/s, equivalent to 20 psi in the input pressure of the smoke machine.

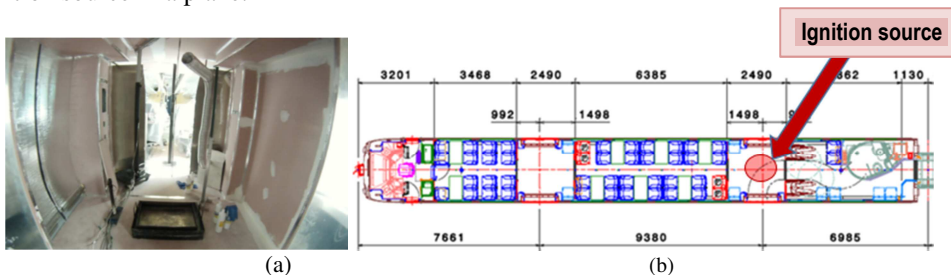


**Fig. 3.** Comparison between the HRR curve produced with a tray of size A2 and the curve of ignition model 5.

## FULL-SCALE TEST SETUP

### Fire Scenario

Three non-destructive tests were carried out to study the response of the innovative system in case of fire on-board. The fire was located in the vestibule closer to the intercommunication gangway and near the PRM WC area. Additionally, it is necessary to indicate that all elements near the source of ignition (walls, doors, roof, floor, furniture and systems such as cameras, television screens, etc.) were protected with fireproof materials, as we can see in Fig. 4a. Figure 4b displays the location of the ignition source in a plane.

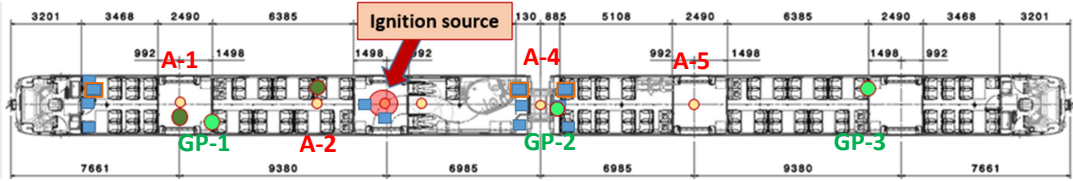


**Fig. 4.** (a) View of the train protection in the elements close to the ignition source  
(b) Localization of fire scenario.

For the test, both the fire tray and the smoke machine were located at floor level.

## Instrumentation

During the fire tests, different instruments were used for measuring various parameters (Fig. 5). Measurement points included five thermocouple trees (10 therm. each tree), one thermocouple tree (8 therm.) on the axis of the ignition source, 10 gas flow velocity probes and 3 HD video cameras (for the estimation of the visibility).



**Fig. 5.** View of the setup of the real fire tests: ignition source, thermocouples (○), velocity probes (■), velocity probes-outgoing flow (■), GoPro HD video cameras (●) and video cameras (●).

All gas-phase thermocouples used herein were type K with a stainless steel sheath and mineral fibre insulation of diameter 1.5 mm (Reference: TC Direct 12-K-10000-118-1.5-2I-3P2L-1MTR C40KX). The thermocouples were deemed to be accurate between -200 and 1250 °C. The response time of the thermocouples is 0.3 s, and their tolerance is in accordance with IEC 584.2, class 2 ( $\pm 2.5$  °C between -40 °C and 333 °C, and  $\pm 0.0075 \cdot |t|$  between 333 °C and 1200 °C) [20].

Three thermocouple trees were located in the car with the fire source, one in the gangway and one more in the adjacent coach. Ten thermocouples were attached to each tree at different heights. The upper thermocouple was placed 2.1 m from the floor, and the rest of them were placed at a separation of 0.2 m. Additionally, one tree (with eight thermocouples) was located on the axis of the fire tray.

For the measurement of the gas flow velocity, thermal flow sensors (Reference: KIMO CTV 100) were used. Kimo's CTV 100 measures temperature and air velocity from 0 to 30 m/s and from 0 to 50°C. For the measurement of air velocity, the accuracy is  $\pm 3\%$  of reading  $\pm 0.3$  m/s, the response time is 1/e (63%) 2 s, and the resolution is 0.1 m/s. Three probes were placed to measure the velocity of the gases extracted and five probes to measure the velocity of air that enters in the train. Two additional probes were placed near the ignition source to control the ventilation conditions during the tests for safety reasons.

For the estimation of the visibility in both cars and in the gangway, three GoPro HD video cameras were placed at a height of 1.7 m. These video cameras pointed to an element that was used as reference. Finally, the results were analyzed with Matlab software and an approximate method was used which, through the light intensity of the pixel, allows us to estimate the level of visibility through its inverse (coefficient of extinction) according to the expression [21-23]:

$$K_e = -\frac{1}{L} \ln \left( \frac{I_{in}}{I_{out}} \right), \quad (1)$$

where  $K_e$  is the extinction coefficient ( $\text{m}^{-1}$ ),  $L$  is the distance between the camera and the reference (m), and  $I$  is the light intensity. The distance used between the cameras and the reference was 6.4 m.

Finally, two video cameras were placed to record and control in real time all the tests (ignition source-smoke machine, general view, etc.).

## FULL-SCALE TEST RESULTS

In this section, the results of one of the three full-scale fire tests are presented. The results of the other two tests were similar to the one described.

### Visibility

Figures 6 and 7 show a series of photographs taken at 1 min, 5 min (opening of the doors) and 10 min from the start of the test, by the GoPro cameras located according to Fig. 5.



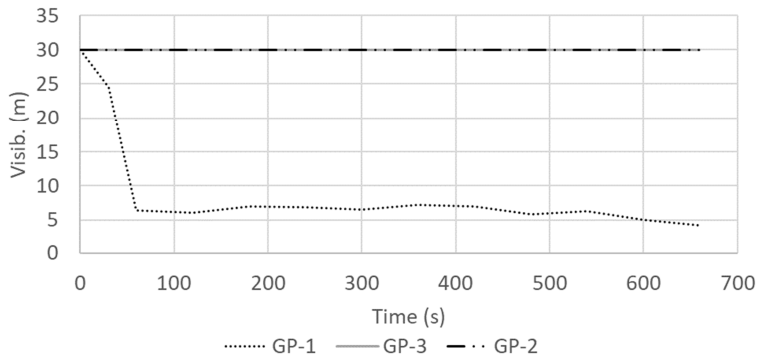
**Fig. 6.** View of GoPro HD video cameras in position GP-1 at 1, 5 and 10 min.

Only in the camera located in the car in which the fire source was placed (GP-1), smoke appeared and might reduce the visibility of the occupants.

Additionally, Fig. 8 shows the estimated results of visibility in each of the points previously indicated (GP-1, GP-2 and GP-3).



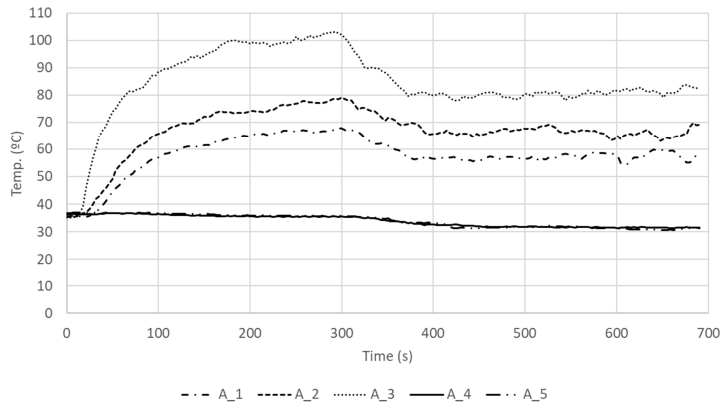
**Fig. 7.** View of GoPro HD video cameras in position GP-2 at 1, 5 and 10 min.



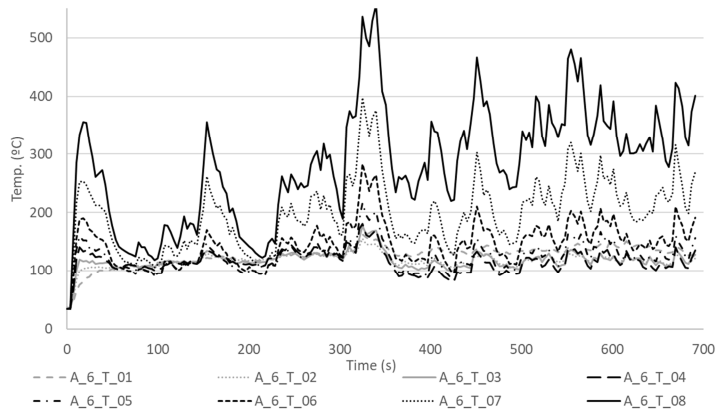
**Fig. 8.** Curve of the estimated results of visibility at 1.7 m height.  
(Note: The results of GP-2 and GP-3 are superimposed).

## Temperature

Figure 9 shows the results of the thermocouples at 1.7 m height on three thermocouple trees placed inside the car where the fire source was located and inside the adjacent car. There is no smoke spread into the adjacent cabin, but within the cabin of fire origin the temperature can exceed 100 °C at the monitored height of 1.7 m. Additionally, Fig. 10 shows the results of the thermocouple tree placed on the axis of the fire plume. Finally, Table 1 includes a summary of the maximum temperature in each thermocouple tree.



**Fig. 9.** Results of the thermocouples at 1.7 m height on the thermocouple trees placed inside the car where the ignition source was located (A\_1, A\_2 and A\_3) and inside the adjacent car (A\_4 and A\_5).



**Fig. 10.** Results of the thermocouple trees placed on the axis of the ignition source.

**Table 1. Maximum temperature in the thermocouple trees.**

	A-1	A-2	A-3	A-4	A-5	A-6 (Ignition source)
Maximum temp.	78 °C	93 °C	112 °C	47 °C	38 °C	557 °C
Time to peak	300 s	300 s	279 s	42 s	75 s	340 s

We can see maximum temperatures inside the car where the fire source was placed between 78 °C and 112 °C, and this maximum value was reached at about 300 s (at the time when the doors of one

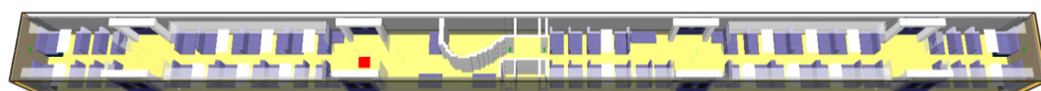


of the sides were opened). Inside the adjacent car the maximum temperatures were lower than 50 °C and the maximum value was reached close to the start of operation of the exhaust system.

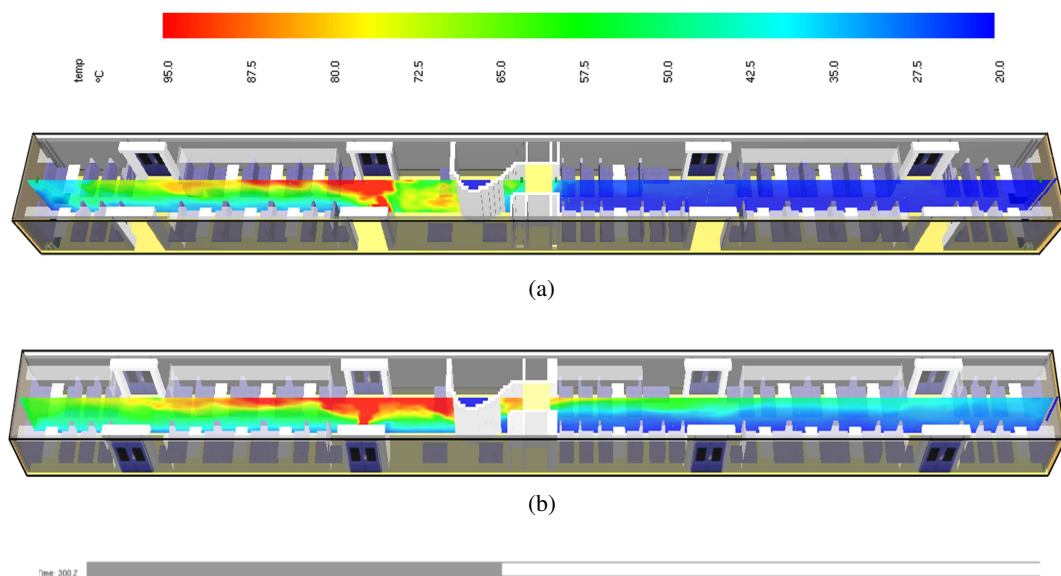
## NUMERICAL SIMULATIONS

Before the fire tests, several simulations were carried out. The fire model ‘Fire Dynamics Simulator (FDS)’, version 6 [13] was used. This model has been developed by the Building and Fire Research Laboratory of the National Institute of Standards and Technology - NIST (USA). FDS is a Computational Fluid Dynamics (CFD) model, designed specifically for fire simulations. FDS solves numerically a form of the Navier-Stokes equations, which is appropriate for low-speed, thermally-driven flows with an emphasis on smoke and heat transport from fires.

The computational domain that represented the scenario geometry was divided into cubic cells of 0.1 m length. This resulted in the division of the computational space in a total of 267960 cells. Figure 11 shows the representation of the train in the FDS model.



**Fig. 11.** Representation of the train in FDS model.



**Fig. 12.** Temperature longitudinal slice at 300 s: (a) with the system; (b) without the system.

The model included the characteristics of the extraction system, with two extraction points per car of 1500 m<sup>3</sup>/h and openings for the entry of air at the ends of the cars.

The ignition source was represented in the same position and with the same theoretical HRR curve previously indicated, and the measurement points were placed in order to compare the results with those obtained in the real tests.

Various longitudinal slices were also placed to analyze in a more global way the phenomena that were taking place inside the train. In Fig. 12, we can see a slice with temperatures at 300 s (the time



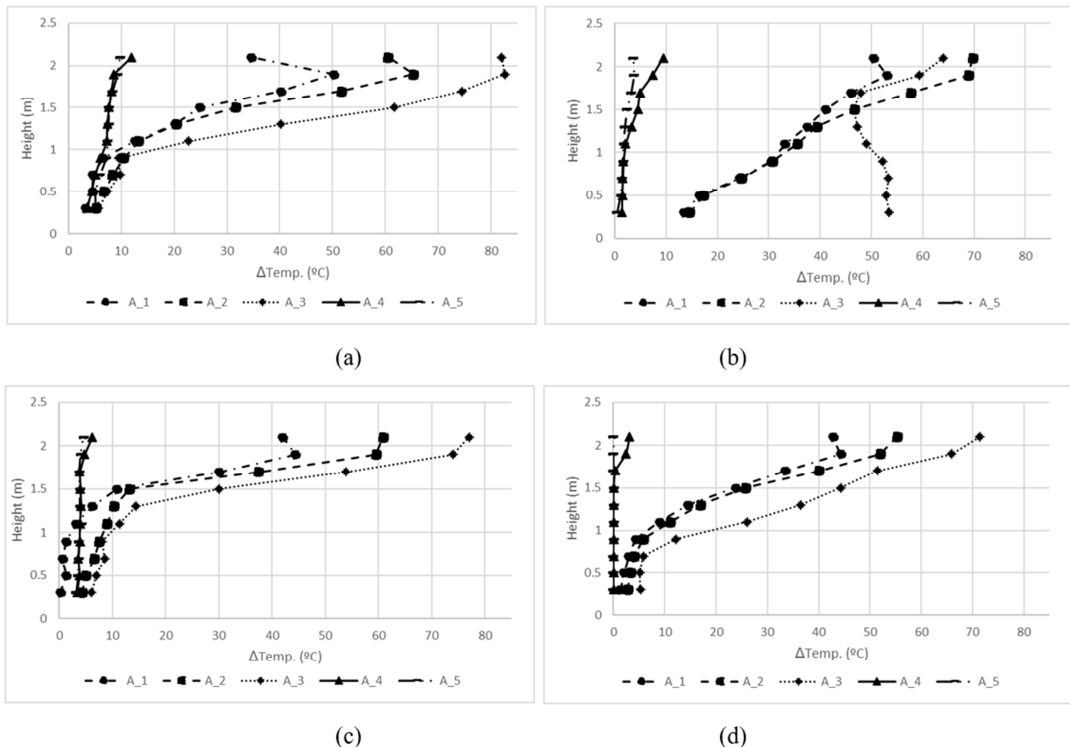
at which the highest temperature is reached, corresponding to opening of the doors), comparing the results with the system (Fig. 12a) and without the system (Fig. 12b).

In the results of the simulation, it can also be observed how, with the ventilation system, the car adjacent to the fire compartment is free of the manifestations of the fire. Without the system, the tenability conditions would turn worse in both cars of the train.

## DISCUSSION

The expected objective was that visibility and temperature at the first vestibule of the non-fire car did not fail the tenability criteria. As it was possible to verify, the system performance was successful with the tenability criteria, since the value of visibility at the non-fire car was greater than 30 m and the temperature was lower than 30 °C during all the tests at a height of 1.7 m above the car floor level.

With regard to the comparison of the results of the tests with those obtained by the model, Fig. 13 shows the average temperature increase profiles registered at different heights in the thermocouple tree sited inside the train (Fig. 5) for the full-scale test and the FDS simulation.



**Fig. 13.** Temperature increase profiles results for full scale test and FDS model in all the thermocouple trees (A\_1, A\_2, A\_3, A\_4 and A\_5). (a) Test at 300 s; (b) Simulation at 300 s; (c) Test at 600 s; (d) Simulation at 600 s.

During the tests, it can be observed how the temperature increases to values greater than 30 °C at heights above 1.5 m, with the only exception of the tree closest to the ignition source (A\_3) at the time instant of 300 s, when this tree shows a temperature increase of 60 °C at that height. However, the simulation predicted increases above 30 °C for all points higher than 1 m and greater heating of

the lower zones. The A\_3 tree simulation also reached higher temperatures than the experimental test at lower heights, which may be caused by differences in the HRR definition.

These differences may be also due to the difficulty to represent the natural air intake through the grids of the exhaust system placed at the end of each car. When the doors are opened, this effect disappears and the results between the test and the model come to better agreement.

Regarding the operation of the smoke exhaust system, it can be observed, both in the test and in the simulation, how the manifestations of the fire (mainly temperature and smoke) are confined to the car in which the fire is located, keeping the adjacent car in safe conditions. It can be observed that in the adjacent car there were maximum temperature increases below 10 °C at all heights.

## CONCLUSIONS

A non-destructive full-scale test was carried out, in order to assess the performance of an innovative smoke exhaust system in case of fire on-board of a DMU two-car configuration. The safety criteria were defined by visibility levels not less than 6 meters at a height of 1.7 m above the car floor level and temperatures not greater than 60°C at a height of 1.7 m above the car floor level, both measured at the first vestibule off the non-fire affected car. Moreover, experimental results were used to validate the computational model.

The system performance was successful in achieving those tenability criteria, since the value of visibility at the non-fire car was greater than 30 m and the temperature was lower than 30 °C during all the test.

In most cases, the computational model results show a good accuracy compared with the tests. When the doors of the cars were closed and therefore the exit of the smoke and air intake was limited by the exhaust system, the results of the model were similar to the ones from the tests in the car where the ignition source was not located and in the upper thermocouples of the car where the ignition source was located. The simulation results in the lower thermocouples of the car where the ignition source was located were far from the results of the test. Once the doors were opened, the results were more accurate at all locations.

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