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A new approach for modelling passenger trains evacuation procedures

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Abstract

This paper presents EvacTrain 2.0 a new model to simulate and explore the results of different evacuation strategies in passenger trains. This model is stochastic and can generate several results within a few seconds. This is why it is intended to be used for decision support during emergencies. EvacTrain is compared with another evacuation model and partially validated against a fire drill. Results show that this model can provide an accurate representation of real evacuation process. The general findings suggest a new paradigm for the application of evacuation modelling in passenger trains: their potential use for supporting emergency decisions in real-time.

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1. Introduction

In most emergency situations, a successful evacuation and rescue can mean the difference between life and death. In passenger trains, the crew are responsible for passenger safety. However, many accident reports have described a lack of training and preparedness in emergency procedures (Independent Transport Safety & Reliability Regulator, 2004). To address this problem, rail companies usually perform full-scale drills. These tests have various problems such as their lack of realism and their economic cost.

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It is well known that single trials produce little information on the variety of potential outcomes seen in evacuation process. In addition, there are standards describing the general requirements for ensuring passenger safety. For example, the ATOC (Association of Train Operating Companies) Vehicles Standard stipulates a passenger evacuation time of 90 s, a minimum flow rate of 30 per/minute in evacuation to the track level and a minimum flow rate of 40 per/minute to the adjacent coach when the vehicle in question is at the end of the train (ATOC, 2002).

If we consider them as optimal values, they may be achievable but not realistic. The standards do not consider the effects of different procedures in a variety of changing scenarios. To address this, the authors have previously demonstrated the importance of using evacuation modeling based on reliable data to predict the impact and benefits of different crew procedures in case of fire emergency onboard passenger trains (Capote et al, 2012). This work provides safety recommendations based on a priori analyses for training and prevention. Other attempts have been used evacuation modeling to estimate the evacuation times in trains. First studies were conducted by the National Institute for Standards and Technology (NIST) (Peacock et al, 2002). Egress calculations were performed to estimate the minimum necessary egress time. As the report states, different assumptions were considered showing the lack of empirical data and the absence of a specific tool for this kind of scenarios. Another contribution was carried out by the Department of Fire Safety Engineering (Lund University) publishing a report about safety conditions in case of fire in an intercity train (Kendal and Nilson, 2002). However, inputs were assumed and the model limitations to represent the specific conditions of this kind of scenarios were highlighted. Other attempt to simulate evacuation in rail vehicles was performed in (Zarbotius et al, 2007). In the agent based model, passengers are modelled as adaptive agents obeying rules of behaviour. One of the last contributions to simulate evacuation process in trains is presented in (Capote et al, 2012b; Capote et al, 2011). The proposed model has the capability to represent different scenarios (High platform, Low platform and the R.O.W) and was compared to results from experiments.

However, apart from the works described above, there is an expansion of application opportunity for the evacuation modelling such as real-time mode in which the user can acquire feedback from the model during an actual emergency and, therefore, explore the impact of different evacuation strategies during the course of the emergency, even before to declare the evacuation. This requires inputs from the situation to the model, which should run significantly faster than real-time. One of the main problems is the lack of sophistication in the simulations due to time constrains. To address this, Monte Carlo methods can be used by considering the key parameters and capture all the potential situations in which the train may be evacuated. Furthermore, there is a need that the model can process the results by itself and then provide information easy to interpret and with a confidence level. For instance, given a scenario the main output parameter could be the percentile (0.90, 0.95 or 0.99) of total evacuation time, here considered as a powerful criterion for decision making. This paper presents EvacTrain 2.0 a new evacuation model for passenger trains that operates in the manner described above.

2. Overview of the model

2.1. Motivation

Emergencies in passenger trains can constitute a significant risk to life. This can happen in a fire on-board the train. In this case, it is necessary to define effective passenger evacuation strategies, both when the fire is detected in the moving vehicle and when evacuating a vehicle that has stopped. The first priority is to direct passengers away from fire and inform the train operations center about the situation. The second priority is to determine when and how perform the evacuation. For instance, whether to reach an appropriate place for the evacuation (i.e., the closest station, platform) or stop the train as soon as possible and perform evacuation to the tracks. Furthermore, the crew needs to know the number of passengers on-board, the dangers present inside and outside the train, a safe area where passengers should be moved and which doors should be opened. Therefore, it is not easy to make the correct decisions. The use of computer modelling analyses in real-time could improve such decisions under a variety of emergency conditions.

2.2. Description of the model

EvacTrain 2.0 is an object-oriented evacuation model developed by GIDAI Group. The purpose of the model is to simulate different evacuation strategies in trains. The train spaces are represented by a coarse network. Each node represents a passenger coach with exits. Due to the fact that this evacuation model is a model tailored to the intended train, data related to the train characteristics are included by default in the model. The model considers the following basic scenarios:

1. Emergency evacuation to platform (tunnel).
2. Emergency evacuation to track level.
3. Evacuation to platform.
4. Evacuation to track level.
5. Evacuation to other train.

Evacuation scenarios 3-5 are not considered as emergency situations. Therefore, they are excluded from the present description. It is assumed that passengers are ready to start evacuation once the train stops. However, the model includes the preparation time. This is a random variable defined as the time elapsed from the stop of the train until passengers start evacuation. The values vary according to the emergency evacuation scenario. In evacuation to platform (it is assumed that all the doors are available for evacuation), this variable is the time spent in opening the train doors. In evacuation to track level, this variable represents the time spent to set up the portable ladders or ramps. This evacuation model focuses on the simulation of the flow through the available exits. The model considers the flow as a random variable individually assigned to each passenger from normal distributions. The values of the distributions vary according to the different exit conditions (to platform, directly to track and through emergency ladders). The values used by default in the model are obtained from (Capote et al, 2012a, Capote et al, 2012b; Norén and Winér, 2003). It should be noted that the model is flexible and allows the user to modify these data.

Some exits may be unavailable in case of evacuation. The user has the option to block the exits (or to set up the available exits for evacuation) in order to reproduce the real situation or to explore the potential outcomes of an evacuation strategy. In these cases, the model simulates the relocation process providing a realistic distribution of the number of passengers at each exit. Then the critical exit is defined as the exit used by the maximum number of passengers. The model performs 250 iterations by default. The evacuation time of *i*-th iteration is given by:

$$t_{e_i} = t_{p_i}^{(k)} + t_{crit_i}^{(k)} \Big|_{i=1, n_{iter}} \tag{1}$$

Where:

k - The scenario (emergency evacuations to platform or to track level);

$t_{p_i}^{(k)}$ - Preparation time for the *k* scenario and *i*-th iteration;

$t_{crit_i}^{(k)}$ - Critical exit time:

$$t_{crit_i}^{(k)} = \sum_{j=1}^{m_{pas}} \frac{1}{f_j^{(k)}} \tag{2}$$

Where:

m_{pas} - Number of passengers that use the critical exit;

$f_j^{(k)}$ - Random flow of *j*-th passenger according to the evacuation conditions (*k*).

The critical exit is that exit which will be used by the maximum number of occupants. It is assumed that this exit will define the most unfavourable situations and the longest evacuation time for an emergency situations. For instance for evacuation to track level, the critical exit is the door where the portable ladder or ramp is set up (it should be noted that all passenger will use this exit). In case of two ladders or ramps are used, the exit used for the maximum number of passenger is considered as the critical exit. Due to its intended use, the presented model is quick and easy to set-up. The input parameters consist of:

- Fraction of the full load: value between 0 and 1 known by the train crew.
- Type of incident: 1) fire, 2) collision, 3) derailment, 4) technical failure.
- Evacuation destination: 1) platform, 2) track level or 3) other train (only for transfers).
- Number of available exits.

The model generates and process results in a few seconds. The outputs produced by the model are displayed at the screen and they can be saved in txt files as well. The model statistically treats the sample of total evacuation times and fits it to a known distribution (if possible). Otherwise, density estimations are given. The main output parameter is a percentile of egress times (0.90, 0.95 and 0.99 th). It also provides other statistical characteristics: mean, variance, maximum and minimum values. Additional outputs include the number of available exits, the critical exit and the number of passengers that use it.

3. Verification cases of the model

3.1. Comparison with STEPS model

In this section we describe a detailed comparison between EvacTrain 2.0 and STEPS model (version 5.0). The comparison presented here is performed for a high speed train S 102. This is a train 200 m length with 11 passenger coaches (+1 lounge) and capacity for 316 passengers (see figure 1). As explained above, the proposed model is a model tailored to the intended vehicle and the characteristics of the train are directly implemented into the model.

Two sets of evacuation scenarios are considered: emergency evacuation to platform (see figure 2a) and emergency evacuation to track level (see figure 2b). Figure 3 shows the schema of emergency evacuation scenarios to platform. In emergency evacuation scenarios to platform, two consecutive dynamic processes have to be simulated: 1) evacuating passengers to a place of relative safety along the train (pre-evacuation activities) and 2) evacuating from the train.

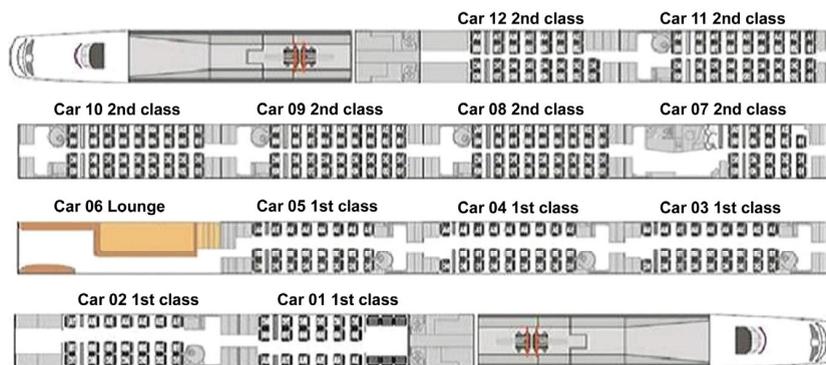


Fig. 1. Layout for high speed train S 102.



a) Evacuation to platform.



b) Evacuation to track level.

Fig. 2. Views of the evacuation scenarios.

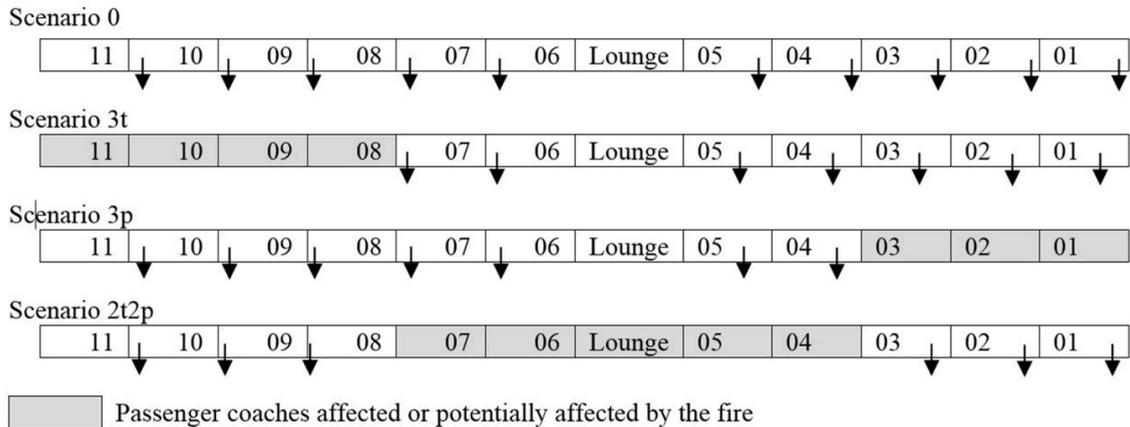


Fig. 3. Emergency evacuation scenarios to platform.

On the other hand, STEPS allows the user to change the availability of certain exits during the course of the simulation by using “exit events”. Using this feature, the user can open, close or make exits unavailable. When an exit is set to closed, the agents will still consider the exit when choosing their target and form a queue in front of it. When the exit is unavailable, it cannot be usable, and nobody moves towards that exit. Table 1 displays the inputs considered for the comparison of the emergency evacuation scenarios to platform. The values are obtained from an announced evacuation drill (Capote et al, 2012b).

Table 1. Inputs for the comparison of emergency evacuation to platform.

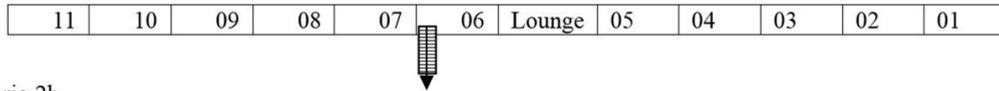
Inputs	EvacTrain 2.0	STEPS
N of passengers	316	316
Flow through the exits (per/s)	0.44±0.20	0.44
Walking speed (m/s)	Not considered	0.99±0.20
Time to open the doors (s)	35	35

Scenario 1b and Scenario 2b in Figure 4 represent emergencies in which passengers have to evacuate to the track level by using 1 and 2 emergency ladders respectively. Table 2 displays the inputs considered for the comparison of the emergency evacuation scenarios to track level. The emergency ladders are 3 m long and consist of two separate

parts that have to be assembled. These evacuation elements hold two passengers simultaneously. It is considered an average time of 3 s spent by each passenger to negotiate the emergency ladder (flow of 0.33 per/s).

This value is derived from Volpe Center egress trials to track level (Markos and Pollard, 2013; Galea et al, 2013). The preparation time is a random parameter for the presented model. However, it is set as a constant value of 300 s to represent the same conditions in both models.

Scenario 1b



Scenario 2b

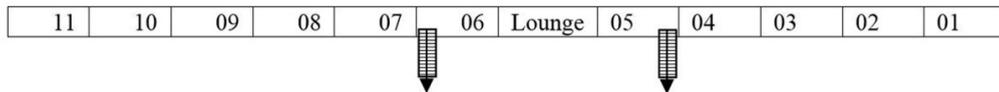


Fig. 4. Emergency evacuation scenarios to track level trough emergency ladders.

Table 2. Inputs for the comparison of evacuation to track level

Inputs	EvacTrain 2.0	STEPS
Occupation 100%	316	316
Flow through the exits (per/s)	0.33±0.10	0.33
Walking speed (m/s)	Not considered	(0.99±0.20)*0.80
Time to install the emergency ladder (s)	300	300
* Factor for the walking speed on the emergency ladder		

As mentioned previously, it is assumed that passengers are ready for evacuation once the train stops.

The model focuses on the simulation of exit performance and the flow is represented as a random time spent by each passenger to negotiate the exit. Therefore, as Tables 1 and 2 show, walking speed is not included as an input variable in the proposed model.

Each scenario was run 100 times with both models. It is assumed that the passengers are compliant with the train crew's commands. This assumption is a basic requirement for seeing the effects of the procedures that are implemented. For the evacuation to the track level, no alternative escape routes, such as other exit doors where the passengers have to climb higher than 1.1 m, are considered.

Figures 5 and 6 display the cumulative distribution functions of total evacuation times. The statistical characteristics are shown in Tables 3 and 4. It is possible to see a wider variability on the sample provided by EvacTrain 2.0 in Scenario 1b (see figure 5). This is because of the random flow in the single exit simulated by the proposed model, not reproduced by STEPS model which uses a constant value. However, there is a good agreement between both models. Based on these results, it can be argued that the proposed model is capable of producing reliable predictions of total evacuation times. More detailed values are displayed in Table 5.

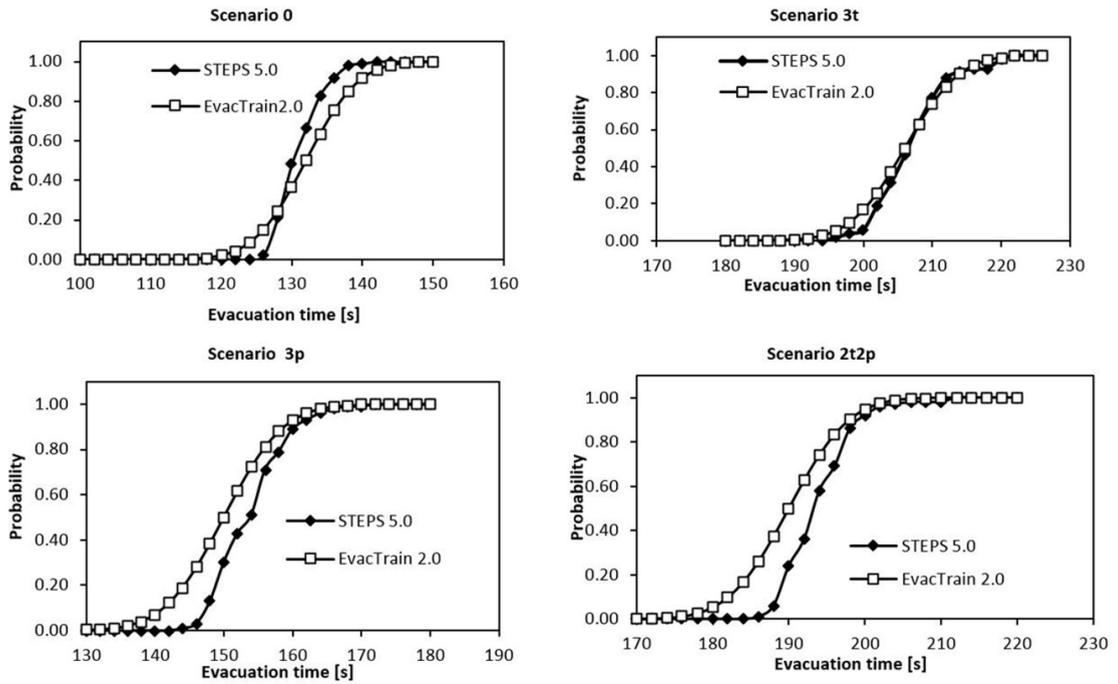


Fig. 5. Cumulative distribution functions of evacuation times to platform.

Table 3 - Distributions of the total evacuation times to platform (s).

Scenario	EvacTrain 2.0				STEPS 5.0			
	Mean	S.D.	Range	Perc. 95th	Mean	S.D.	Range	Perc. 95th
Scenario 0	132	5.8	116-151	143	131	3.2	126-142	139
Scenario 3t	206	6.2	183-220	217	207	5.4	195-222	214
Scenario 3p	150	6.8	130-171	160	154	5.3	144-171	161
Scenario 2t2p	190	6.2	169-206	200	194	4.7	186-212	205

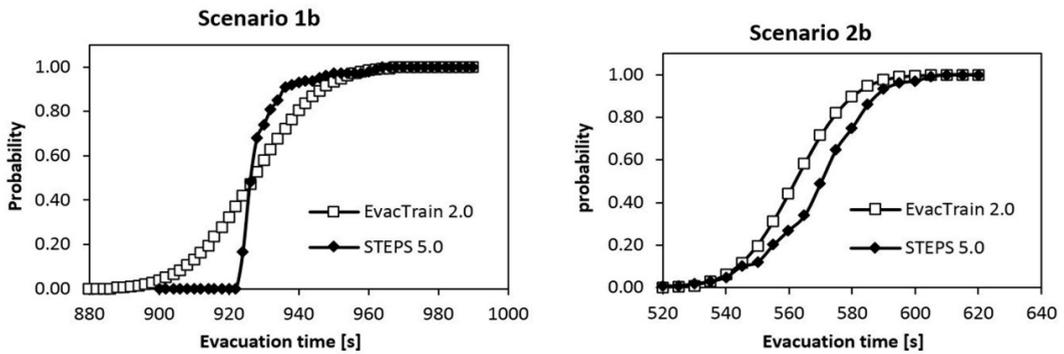


Fig. 6. Cumulative distribution functions of total evacuation times to track level.

Table 4. Distributions of the total evacuation times to track level (s).

Scenario	EvacTrain 2.0				STEPS 5.0			
	Mean	S.D.	Range	Perc. 95th	Mean	S.D.	Range	Perc. 95th
Scenario 1b	927	15.3	878-970	950	929	9.5	922-984	939
Scenario 2b	562	14.2	512-597	585	569	16.3	519-606	590

3.2. Comparison with evacuation drill

The results from EvacTrain 2.0 are compared with an evacuation drill fire drill in a passenger train conducted by RENFE Operadora (Spanish Railroad Administration). The evacuation drill took place on 19th September 2009. The train was a high-speed S 130.

A total of 239 participants took part in the evacuation drill (80 % of the maximum load). The participants included staff members and some of their families. The evacuation drill consisted of a simulated fire that had started in coach 04 (the lounge coach), and the relocation procedure was performed coach by coach along the length of the train before the train stopped inside the Guadarrama Tunnel. The evacuation scenario is the same that the one previous analysed named 2t2p with 80 % of the full occupant load of the train.

The drill procedure followed the preferred method of train evacuation in which the driver stops and then opens the doors onto the platform. The time spent in opening the train doors was 34 s. A total of 250 iterations were performed with EvacTrain 2.0. The sample of total evacuation times produced by the model fit to a normal distribution with a mean value of 119 s and a standard deviation of 7.4 s.

Figure 7 shows the histogram and the cumulative distribution function. The evacuation time observed in the evacuation drill (vertical broken line) is shown in the figure. Results shown that the average predicted evacuation time obtained by the proposed model and the evacuation time from actual drill are very close.

Therefore, it can be argued that the proposed model provide reliable and consistent results. However, as mentioned the main output parameter provide by the model is the percentile of total evacuation times. In this case the 95th percentile is 131 s which is considered as a best reference of the potential outcomes for decision makers.

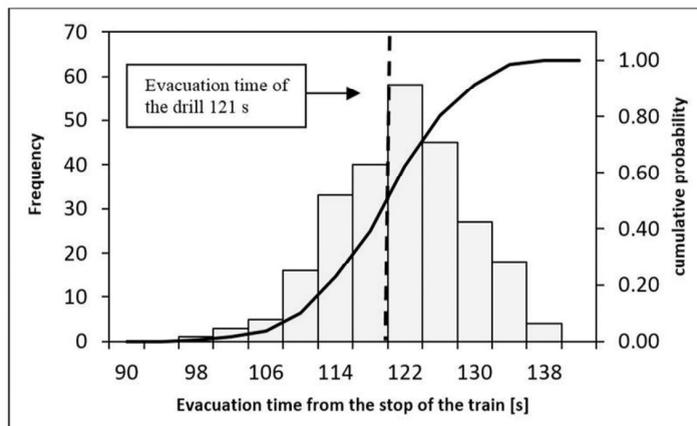


Fig. 7. Histogram and Cumulative distribution functions of total evacuation times predicted for the evacuation drill scenario.

4. Discussion of results

Making decisions is certainly the most important task and it is often a very difficult one. For this reason, a good decision should not be supported by an outcome alone. Deterministic models are likely to produce an inaccurate representation of the evacuation process as they only consider one or a few potential situations. The stochastic simulations generate more reliable and consistent results as they explore all potential situations in which a given

scenario may be evacuated. Furthermore, the use of distributions of the total evacuation times provides more powerful criteria for decision making. For instance, the use of percentiles (90, 95 or 99 th).

On the other hand, real-time evacuation models have to be a simplified representation of the actual situation. For the analysis of evacuation process in passenger trains, we suggest that the dominant parameters are the time spent to prepare for evacuation and the flow through the available exits. The first parameter involves specific evacuation procedures such installing the emergency ladder. The second parameter depends on the evacuation conditions defined by the number of passengers per available exit and the evacuation destination (platform, track level).

Clearly, the results suggest that the additional complexity of STEPS may not yield significantly different results than the proposed model.

The level of agreement between both models has been quantified by the Percent Error (PE) of the mean (PEM) and the 95 th percentile (PEP) of total evacuation times. Note that the results of the proposed model are considered as the “approximate” values while the results of model of the comparison are considered as the “actual” values. As Table 5 shows, in the emergency evacuation to platform both the PEM and PEP are lower than 3%. Furthermore, in the emergency evacuation to track level scenarios, the PEM and PEP are lower than 1.3 %. Additionally, the comparison of EvacTrain 2.0 results with the evacuation drill demonstrates that the software is capable of producing plausible results with regards to relative performance in this case. Therefore, it can be argued that the presented model provide consistent and reasonable results.

But one of the advantages is that the proposed model generates and processes the results within a few seconds. This is a basic requirement for the model to be used as supporting tool for decisions during the emergency. Tables 6 show a comparison of the simulation times and capabilities between the evacuation models used for this study. The information provided in Table 6 is based on our experiences and estimations for 100 runs, once the scenarios have been implemented (geometry, number of passengers, etc.). The batch run is defined as the capability of the model to run several simulations by itself.

The plotting data defines whether the model provides the outputs from several simulations on the same file. The statistical processing means that the model can process the samples of data by itself (i.e. fit samples to known distributions or density estimations. The information provided in this paper show that EvacTrain 2.0 can perform several simulations in less than 5 s while providing accurate results. Therefore, it is suggest that the proposed model could be used to make critical decisions during the first stages of the emergency. The model user can explore different evacuation processes by changing the basic input parameters. This allows choosing the evacuation strategy that produces the shortest required safe egress time. For instance, if a fire is detected in the running train whether to stop as soon as possible or reach a platform for the evacuation.

Table 5. PEM and PEP obtained for each evacuation scenario (%).

Scenario	PEM	PEP
0	0.76	2.88
3t	0.48	1.40
3p	2.60	0.62
2t2p	2.06	2.44
1b	0.22	1.17
2b	1.23	0.85

Table 6. Comparison of simulation times and capabilities for train evacuation analyses.

Model	Batch run?	Batch run time (100 runs)	Plotting data?	Statistical processing?
EvacTrain 2.0	Yes	<5 s	Yes	Yes
STEPS	Yes	70-130 s (Evacuation to platform) 210-390 s (Evacuation to track level)	No	No

5. Conclusions

From this work it is concluded that evacuation calculations could be used for supporting timely decisions during actual emergencies in passenger trains. It is proposed the use of a stochastic model with the capability to perform several simulations by changing key random parameters to capture all potential situations. This model should process the results by itself and provide information easy to interpret for decision making. All this process should be performed within a few seconds.

EvacTrain 2.0 an evacuation model for passenger trains which operate in the manner describe above have been presented and partially validated against other evacuation model and results from an evacuation drill. Note that the evacuation model presented here can also be used for other applications such as performance base assessments and/or risk analysis.

Most of the input parameters included in the model are obtained from empirical research. However, it should be noted that the flexibility of the model allows the user to change these values. Therefore, it is recommended as a good practice the use of reliable data from trials and/or evacuation drills in the scenarios where the evacuation models are going to be implemented.

The current version of the proposed model have limitations and new challenges to be addressed. Future research will include further validation against experiments and evacuation drills for a set of new possible scenarios: evacuation to track level, low platform, etc.

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