Toward an Accurate Microscopic Passenger Train Evacuation Model Using MassMotion

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TOWARDS AN ACCURATE MICROSCOPIC PASSENGER TRAIN EVACUATION MODEL USING MASSMOTION

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ABSTRACT

During emergency situations in trains, rapid and safe evacuation is crucial for saving lives of passengers. Computer models such as EvacTrain, STEPS, Pathfinder and FDS+Evac are making use of either a discrete space network or a continuous space network, and allow determining egress times for various emergency passenger train designs and conditions. These models offer insights into potential difficulties and offer possible solutions to evacuation challenges in a short time and at low cost. This paper focuses on the application of MassMotion (a commercial available evacuation software commonly used for evacuation planning in buildings) to passenger train evacuation. Key performance indicators such as mean total evacuation times, standard deviations, maximum evacuation times, minimum evacuation times, and 95th percentile of egress times are determined to evaluate the accuracy and reliability of MassMotion. In the validation test, actual occupant egress rates from a fire drill conducted by the Spanish Railroad Administration in a passenger train are used to measure the reliability of MassMotion for producing accurate egress time predictions. Further, the MassMotion passenger train simulation model is verified and compared to other existing microscopic passenger train evacuation models for a hypothetical case study. The comparison shows that microscopic models with continuous-space representation predict passenger evacuation times more accurately than discrete networks. Also, the force-based model MassMotion provides consistent and reliable egress time predictions. The findings of this study contributes to the field of egress models for passenger train emergencies and can be used by evacuation modellers and authorities to support their decisions.

Keywords: Computer modelling, Egress models, Train evacuation, Social Force Model, Cellular automata model, MassMotion

1 INTRODUCTION

In emergency situations in trains, rapid and safe evacuation is crucial for saving lives of passengers (1, 2). Numerous disasters such as the fire at King's Cross station (London, 1987), in the Hirschengraben tunnel (Zurich, 1991), in the Baku Metro (Azebayjan, 1995), in the Gletscherbahn Kaprun (Austria, 2000), in the Daegu subway (South Korea, 2003), and in the Rinkeby Station (Stockholm, 2005) resulted in many deaths and injuries (3) due to unsafe and delayed evacuation. Investigation studies of past evacuations identified a number of elements that influenced the egress time of train passengers: the characteristics and behaviours of passengers (e.g., age, gender, passenger loads), the geometry and configuration (e.g., the geometry of the train and the railway station, barriers within an enclosure, the number and dimensions of exit doors), the operating environment (e.g., bridge, tunnel, hazard conditions), safety facilities (e.g., presence of emergency signs, lighting), emergency announcements and procedures, staff training, passenger assistance and the orientation of the coach (4, 5, 6, 7, 8, 9, 10, 11, 12). It was observed that a safe evacuation to a high platform or an adjacent coach has the egress flow rate of just below 1 person per second. Baseline safety codes and standards have been defined to ensure passenger safety in emergency train evacuations (13, 14). For instance, a minimum flow rate of 0.5 person per second during evacuations to the track level and a minimum flow rate of about 0.66 person per second to the adjacent coach are acceptable performance targets for ensuring passenger safety in the Association of Train Operating Companies (ATOC) (13, 15). However, the devastating outcomes of recent train accidents highlight the need for improving rail safety standards and evacuation techniques.

Evacuation time studies for passenger train emergencies are limited to fire drills (practices of a set of emergency procedures for a safe and rapid evacuation) and computer models. Computer models allow determining egress time predictions for various emergency conditions and multiple train designs. Validation and Verification (V&V) tests determine the degree to which these computational models and their results are accurate and reliable (16). This paper investigates a new microscopic model, the MassMotion model, for train passenger evacuation. The contributions of this paper are as follows:

- MassMotion, an agent-based microscopic model commonly used for building evacuation, is applied to train passenger evacuation.
- The results of defined key performance indicators (mean total evacuation times, standard deviations, maximum evacuation times, minimum evacuation times, and 95th percentile of egress times) are compared to real data obtained from a fire drill conducted by the Spanish Railroad Administration (RENFE) in a passenger train.
- The MassMotion model is verified and compared to other existing passenger train evacuation models using the Percent Error of the Mean (PEM) total evacuation time and the Percent Error of the 95th Percentile (PEP) of the total evacuation time in a hypothetical case study.

The fundamental principles of existing passenger train evacuation models are reviewed in Section 2. Egress times from a fire drill in a specific passenger train scenario are used to validate the evacuation time results using MassMotion in Section 3. The egress time predictions of MassMotion are compared with other passenger train evacuation models using a hypothetical case study under various conditions in Section 4. Section 5 summarises the findings and gives suggestions for future works.

2 FUNDAMENTAL PRINCIPLES OF COMPUTER MODELS FOR PASSENGER TRAIN EMERGENCY EVACUATION

Computer models can be divided into two main categories based on the underlying science principles for reproducing human behaviour and movement: macroscopic hydraulic models and microscopic fluid dynamics (individual-movement) models (17). Both hydraulic models and fluid dynamics models describe people movement by distance, speed, flow, and density relationships. Hydraulic computer models consider some optimistic assumptions about people's knowledge of the evacuation routes or shortest evacuation path, for instance. However, fluid dynamics models consider more realistic assumptions and integrate human behaviour by taking into account individual characteristics, human decision-making processes and the operating environment (18). Microscopic fluid dynamics models can provide detailed information about the behaviour and movement of passengers in longer run times compared to macroscopic hydraulic models. Since macroscopic models cannot incorporate individual movement behaviour of passengers when calculating the flow rates, features of existing microscopic models are summarised in Table 1 and discussed in this section for passenger train evacuation. As shown in Table 1, microscopic simulation models such as STEPS (Simulation of Transient Evacuation Pedestrian movementS) (20), Pathfinder (21), FDS+Evac (Fire Dynamics Simulators with Evacuation) (22), MassMotion (28), and EvacTrain (19) follow a number of different approaches and methods for modelling individual behaviour, space and time representations and human movement. The methodologies used to validate these passenger train evacuation models are listed in column 6 of Table 1.

TABLE 1 : Features of existing computational models for simulating passenger train evacuations

Model Name	Behaviour	Representation		Movement	Validation
		Space	Time		
STEPS (20)	Implicit behaviours	Discrete (fine network)	Continuous	Potential	Code requirements / Past experimental literature
Pathfinder (21)	Steering behaviours	Discrete (fine network)	Continuous	Density correlation	None
FDS+Evac (22)	Conditional behaviours & artificial intelligence	Continuous	Continuous	Inter-personal distance	Past experimental literature
MassMotion (28)	Conditional behaviours & artificial intelligence	Continuous	Continuous	Conditional	Code requirements / Fire drills / Past experimental literature
EvacTrain (19)	Probabilistic	Discrete (coarse network)	Continuous	Unimpeded flow	Fire drills

STEPS: Simulation of Transient Evacuation Pedestrian movementS
FDS+Evac: Fire Dynamics Simulator with Evacuation

Modelling the behaviour of train passengers needs to include passenger characteristics, environmental conditions and human intelligence in the movement models of evacuation scenarios. Looking at the models listed in Table 1, STEPS considers implicit individual behaviours by taking into account passengers response delays. Pathfinder includes three steering behaviours to follow the shortest path and to avoid collisions with obstacles and other passengers along the intended path of agents. Both STEPS and Pathfinder explain the movement of agents from a starting to a destination point by considering congestion and queuing disciplines. FDS+Evac and MassMotion

consider behavioural changes based on environmental conditions and artificial intelligence. These models use the behavioural modelling approach which incorporates the interaction between agents when moving towards a destination by defining physical and socio-psychological forces between the agents (23). A path-finding algorithm is usually added to these models to capture human intelligence and to move agents towards the destination through the shortest or fastest path (24, 25, 26). EvacTrain uses a partial behaviour model and determines occupant movements using probabilistic distributions of the pre-movement times and the walking speeds.

Looking at column 3 and 4 of Table 1, existing passenger train evacuations make use of either a discrete space network or a continuous space network, and allow determining egress times for various emergency passenger train designs and conditions. On the one hand, models with fine networks divide the layout into small grid cells and allow agents to move from and to these cells. Grid cells only allow one agent to occupy the space at a time. Thus, grid sizes are usually equal to the shoulder width of an average person (0.5 m by 0.5 m). On the other hand, the floor plan of a building or a train can also be split into sections (e.g., corridors, stair and rooms). These sections can be occupied by multiple agents at the same time (coarse network). Assuming a continuous space, occupants are not tied to a specific cell on a 2-D floor plan and move anywhere in the environment. STEPS, Pathfinder and EvacTrain use a discrete network while MassMotion and FDS+Evac operate on a continuous space network. All these models are based on behavioural assumptions, activity sets and route choices in continuous time.

Looking at column 5 of Table 1, each cell in STEPS is associated with a potential value calculated based on for instance familiarity of agents with the environment. Using potential values, agents move within the environment towards a certain direction. In Pathfinder, each cell is associated with a speed and flow rate based on the density of the space. In FDS+Evac, each agent keeps a certain distance from its nearby agents and obstacles using repulsive forces. In MassMotion, agents tend to analyse the conditions of their preferred route based on for instance distance, congestion or fire. In EvacTrain, the unimpeded movement of agents is determined.

As shown in column 6 of Table 1, the egress models are usually validated using code requirements, fire drills and past experimental experiments. In Section 3, MassMotion is validated using data from a fire drill in a Spanish passenger train.

3 APPLICATION AND VALIDATION OF MASSMOTION USING DATA FROM A FIRE DRILL CASE STUDY

One of the reasons for the severe consequences in passenger train evacuations is the enclosed nature of trains. In emergency situations, real-world passenger train evacuations have two stages: the pre-evacuation stage and the evacuation stage (10, 19) as illustrated in Figure 1. The pre-evacuation stage consists of the following passenger response steps (10, 19):

- $t_{detection}$: The fire detection time;
- t_{alarm}: The fire alarm activation time;
- $t_{recognition}$: The time that passengers require to recognise the fire alarm and react (e.g., stand up);
- $t_{response}$: The time to decide how and which direction to move to exit the train;
- $t_{pre-evac-movement}$: The pre-evacuation movement time within the train before it stops.

After the train has stopped, the evacuation stage follows a number of sequential steps (10):

- t_{door}: The time to open the exit doors of the train and locate ladders;

- $t_{evac-movement}$: The evacuation movement time for passengers to get off the train.

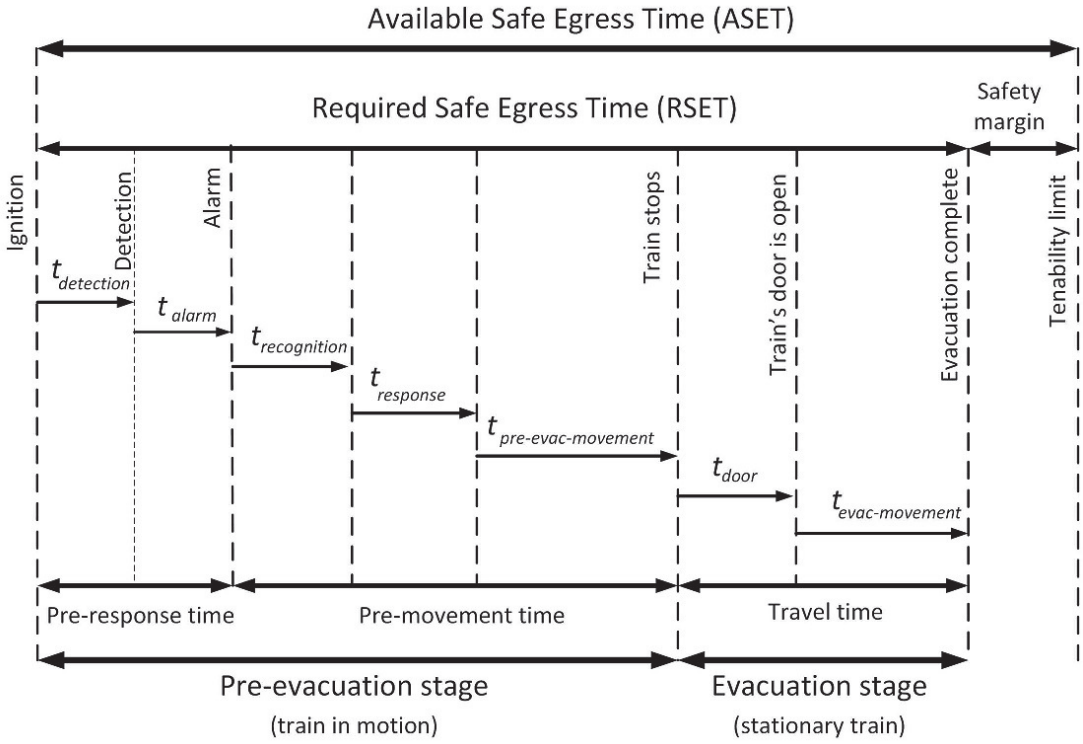

FIGURE 1 : Sequence of passenger responses in a fire train emergency (19)

The sum of the pre-evacuation and evacuation time is defined as Required Safe Egress Time (RSET). RSET can be estimated using fire drills or computer models. Usually this estimation does not consider panic situations during the evacuation procedures. Hence, an appropriate safety margin is applied to the model time.

3.1 Fire drill in a passenger train

The simulation results using MassMotion are validated using the data obtained from a fire drill in a passenger train conducted by RENFE Operadora (Spanish Railroad Administration) (10). In this experiment, a fire started in a lounge coach and an emergency announcement was made to the passengers before the train stopped. Some of the passengers had handbags and jackets and no one had any luggage. As shown in Figure 2, the train is 21 m long with one exit door and 40 passengers taking part in this study. The fire drill was recorded using two video cameras, one in front of the exit door and one inside the coach (see Figure 2). The time to open the exit door of the train was 53 s. The flow rate of passengers through the exit was observed as 0.58 person per second.

The input parameters used to validate MassMotion using fire drill data are presented in Table 2. The walking speed distribution, the pre-evecuation movement time distribution and the evacuation movement time distribution are defined based on the data obtained from two fire evacuation during fire drills conducted by the Spanish Railroad Administration (RENFE) in high-speed trains S-103 and S-130 (19, 27)

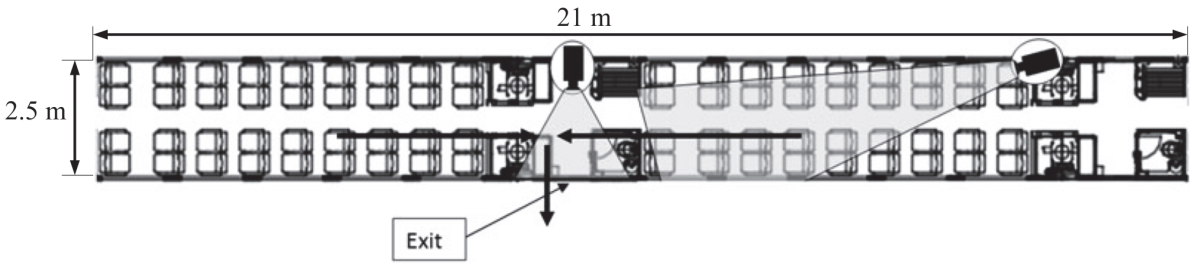

FIGURE 2 : Geometry and configuration of the passenger train (19)

TABLE 2 : Input parameters for the simulation using MassMotion

Number of passengers	Flow rate (per/s)	Walking speed (m/s)	Pre-evacuation movement time before the exit door is open (s)	Time to open the exit door (s)	Evacuation movement time after the exit door is open (s)
40	0.58	Normal distribution 0.99±0.6 $\sigma = 0.27$	Log-normal distribution Min: 5 Max: 120 Mean: 53 S.D.: 47	53	Log-normal distribution Min: 0 Max: 6 Mean: 1.74 S.D.: 0.68

3.2 Simulating a fire drill in a passenger train using MassMotion

In general, egress times of train passengers are influenced by the random sampling of the pre-evacuation movement time. Hence, running a simulation for a similar case study may result in different egress times. As shown in Figure 3, the mean egress time for 10, 30 and 100 simulation runs in the described case study vary with a maximum of 7.3% difference. Thus, 100 simulations were undertaken to eliminate the randomness of the sample and give overall predictions that can reflect the range of assigned parameters.

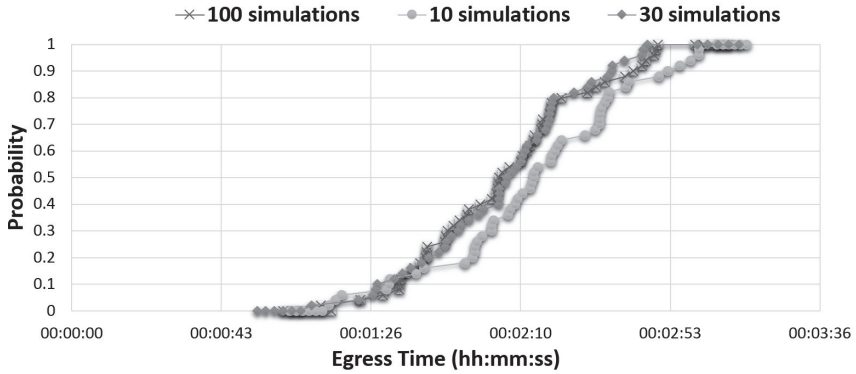

FIGURE 3 : Passengers egress times of 10, 30 and 100 simulations

Table 3 shows the results from 100 simulation runs using MassMotion. Also shown in Table 3 are the results from the fire drill in the passenger train conducted by RENFE Operadora. Table 3 summarises the average predicted evacuation time obtained by MassMotion and the evacuation time from actual drill being 119 s and 121 s, respectively.

TABLE 3 : Total evacuation times of the MassMotion simulation (100 runs) and the evacuation of fire drill

	Mean evacuation time (s)	Standard deviation (s)	Max. (s)	Min. (s)	95th percentile
MassMotion	119	30	172	49	171
Evacuation drill	121	-	-	-	-

4 VERIFICATION OF MASSMOTION USING EXISTING PASSENGER TRAIN EVACUATION MODELS

A detailed comparison and verification of MassMotion (28) to other egress models including EvacTrain, STEPS, Pathfinder and FDS+Evac is presented in this section. Details regarding the hypothetical case study and the verification results for various conditions are explained in Sections 4.1 and 4.2, respectively.

4.1 Hypothetical passenger train evacuation case study

The geometry and configuration of the train for the verification tests is shown in Figure 4. The length of the coach is 21 m with a 50-passenger capacity. The width of the train and aisle inside the coach are 2.5 m and 0.62 m, respectively. The coach is upright with one exit to the platform. Safety announcement are made in advance. There is no smoke and no crew member inside the coach. It is assumed that passengers do not carry any large luggage during the evacuation procedures.

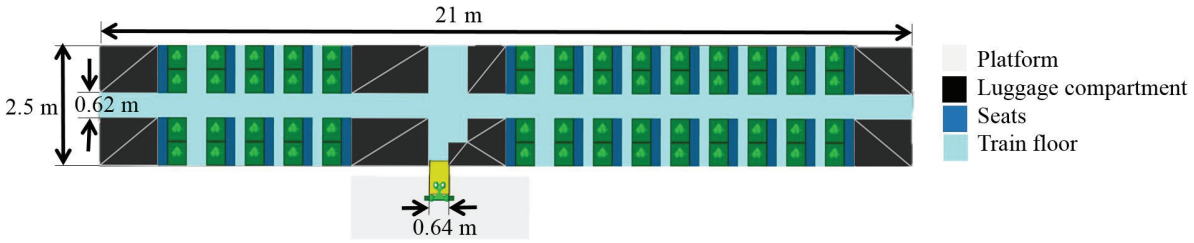

FIGURE 4 : The plan view of the train geometry and configuration used in the hypothetical case study

Table 4 illustrates the inputs considered for the comparison of three emergency evacuation tests to the platform. Test 1 is defined to allow comparing the passenger train egress models with minimum passenger actions and with an open exit door. The flow rates of 0.79 person per second and 0.66 person per second considered here are based on the National Fire Protection Association (NFPA) and the Society of Fire Protection Engineers (SFPE) standards (29, 30). Test 2 is defined to test how interactions between passengers affect the egress time prediction in different models. The speed profile and behavioural variables (evacuation movement times for passengers before and after the exit door is open) are obtained from an announced evacuation reported in (19). In Test 3, there is a low flow rate of passengers through the exit door since the passengers are carrying a large luggage in this case. Also, the exit door is opening after a shorter delay compared to Test 2.

TABLE 4 : Inputs for the comparison of emergency evacuation to platform

	Number of passengers	Flow rate (per/s)	Walking speed (m/s)	Pre-evacuation movement time before the exit door is open (s)	Time to open the exit door (s)	Evacuation movement time after the exit door is open (s)
Test 1	50	0.79 & 0.66	1	Log-normal distribution Min: 5 s Max: 120 s Mean: 53 s S.D.: 47 s	0	Log-normal distribution Min: 0 Max: 8 Mean: 2.27 S.D.:1.26
Test 2	50	0.58	Normal distribution 0.99±0.6 s = 0.27		53	
Test 3	50	0.44	Normal distribution 0.99±0.6 s = 0.27		35	

4.2 Comparison of MassMotion to other passenger train egress models

The predicted mean egress times, the standard deviations, maximum evacuation times, minimum evacuation times, and the 95th percentile of egress times obtained from five egress models, MassMotion (28), EvacTrain (19), STEPS (20), Pathfinder (21), and FDS+Evac (22), for the explained case study in Section 4.1 are reported in Table 5. In Table 6, the level of agreement between all models in comparison to MassMotion is quantified by the Percent Error of the Mean (PEM) total evacuation time and the Percent Error of the 95th Percentile (PEP) of the total evacuation time as described below:

$$\text{PEM} = \left|\frac{\text{Mean Evatuation Time}_{MassMotion} - \text{Mean Evatuation Time}_{Model}}{\text{Mean Evatuation Time}_{Model}}\right|.100$$

$$\text{PEP} = \left|\frac{\text{95th Percentile of Egress Time}_{MassMotion} - \text{95th Percentile of Egress Time}_{Model}}{\text{95th Percentile of Egress Time}_{Model}}\right|.100$$

Looking at the results of Test 1 in Table 5, the mean evacuation times obtained from STEPS (69.0 s), Pathfinder (80.3 s), FDS+Evac (68.0 s) and EvacTrain (68.8 s and 80.6 s) vary by less than a second for the flow rates of 0.79 and 0.66 person per second. Looking at the PEM results of Test 1 in Table 6, the total mean evacuation time obtained from MassMotion is substantially smaller (by up to 11%) compared to other models. Also, it can be seen that MassMotion has the minimum evacuation time difference with FDS+Evac which has - equivalent to MassMotion - a continuous representative of space. The flow rates of passengers at the exit door of trains is positively correlated with the egress time as shown in Table 5. One can conclude that in continuous networks agents are less constrained in space and they might be squeezed into a confined area with physical contact. As a result, evacuation times of continuous space models are shorter than discrete based models.

Looking at the results of Test 2 in Table 5, STEPS and PathFinder return the shortest prediction evacuation times in comparison to the results obtained by FDS+Evac, MassMotion and FDS+Evac. Also, the egress time of MassMotion has the highest level of agreement with FDS+Evac considering the PEM results shown in Table 6. It can be seen in Figure 5 that results from STEPS, PathFinder, FDS + Evac, and EvacTrain have less variability in comparison to the results by MassMotion. Predicted evacuation times of MassMotion have the largest variability with a mean of 135.46 s and a standard deviation of 29.43 s as shown Table 5. In force-based models such

TABLE 5 : The outputs of the verification tests

	Model Names	Flow rate (Person per second)	Mean evacuation time (s)	Standard deviation (s)	Max. (s)	Min. (s)	95th percentile (%)
Test 1	STEPS*	0.79	69.0	-	-	-	-
	Pathfinder*	0.66	80.3	-	-	-	-
	FDS+Evac**	Not considered	68.0	-	-	-	-
	MassMotion**	0.79	61.8	-	-	-	-
		0.66	71.9	-	-	-	-
	EvacTrain*	0.79	68.8	-	-	-	-
		0.66	80.6	-	-	-	-
Test 2	STEPS*	0.58	105.25	7.73	143.00	88.00	115.05
	Pathfinder*		117.80	8.75	174.35	103.90	131.09
	FDS+Evac**		130.45	17.53	253.00	113.10	147.94
	MassMotion**		135.46	29.43	189.10	68.50	186.78
	EvacTrain*		144.93	22.72	224.00	110.10	209.45
Test 3	MassMotion**	0.44	137.00	36.00	203.00	57.00	198.00
	EvacTrain*		137.00	13.00	178.00	117.00	171.00

* Models with discrete-space representation
** Models with continuous-space representation
STEPS: Simulation of Transient Evacuation Pedestrian movementS
FDS+Evac: Fire Dynamics Simulator with Evacuation

TABLE 6 : PEM and PEP obtained for each verification evacuation test.

	Model Names	Flow rate (Person per second)	MassMotion' s PEM (%)	MassMotion' s PEP (%)
Test 1	STEPS*	0.79	10.43	-
	Pathfinder*	0.66	10.46	-
	FDS+Evac**	Not considered	9.11	-
	EvacTrain*	0.79	10.17	-
		0.66	10.79	-
Test 2	STEPS*	0.58	28.70	62.34
	Pathfinder*		14.99	42.48
	FDS+Evac**		3.84	26.25
	EvacTrain*		6.57	10.82
Test 3	EvacTrain*	0.44	0	15.78

* Models with discrete-space representation
** Models with continuous-space representation
STEPS: Simulation of Transient Evacuation Pedestrian movementS
FDS+Evac: Fire Dynamics Simulator with Evacuation
PEM: Percent Error of the Mean total evacuation time
PEP: 95th Percentile of the total evacuation time

as MassMotion and FDS+Evac, the evacuation times dependent on the movement of individuals whose actions are defined with interpersonal repulsive forces to keep a minimum distance from other passengers and obstructions within the aisle. This modelling concept in a continuous space results in higher variance of egress time and more realistic results.

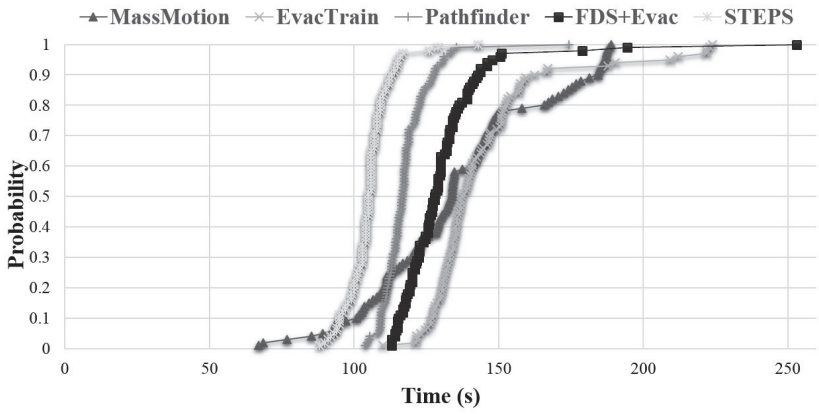

FIGURE 5 : Cumulative distributions functions of evacuation times for Test 2 for MassMotion, EvacTrain (19), STEPS (20), Pathfinder (21), and FDS+Evac (22)

Looking at the results of Test 3 in Tables 5 and 6, both models, MassMotion and EvacTrain, produced the same mean egress time of 137 s with a flow rate of 0.44 person per second. The standard deviation from the MassMotion simulation run is 36 s which is about three times larger than the standard deviation from simulations using EvacTrain. It can be concluded that the continuous existence of repulsive force models affects passenger movements in confined areas (e.g., in aisles) and increases the egress time of the passengers.

The results of the three tests demonstrate the importance of passenger behaviour and their interaction as well as how these affect egress times. It can be argued that MassMotion provided consistent results in all three verification tests and the algorithms based on social forces are sufficient to represent the movement of passengers during passenger train evacuations.

The level of passenger comfort which is based on the level of crowding (number of people per square metre) during a train evacuation is defined as the Level-Of-Service (LOS) (31). LOS is classified using a ranking from A to F, with A being the best and F being the worst experienced comfort. Figure 6 illustrates LOS for train passenger evacuation during the conducted case study. The congestion LOS C, D, E and F are represented in green, yellow, orange and red, respectively (see Figure 6a). It can be seen that congestion increases as passengers move towards the aisle after the pre-movement activities. As shown in Figure 6b, passengers are squeezed in the narrow aisle in front of the exit door resulting in congestion and physical contact between passengers. Figure 6c reports on the number of people experiencing congestion over time and Figure 6d shows a positive linear relationship between the egress time and congestion time throughout the evacuation process. The open space in front of the bottleneck reduces the congestion at the exit as passengers tend to wait in this area for the exit door to open. Once the train door opens, the bottleneck and the exit door are heavily congested with the LOS being ranked E and F.

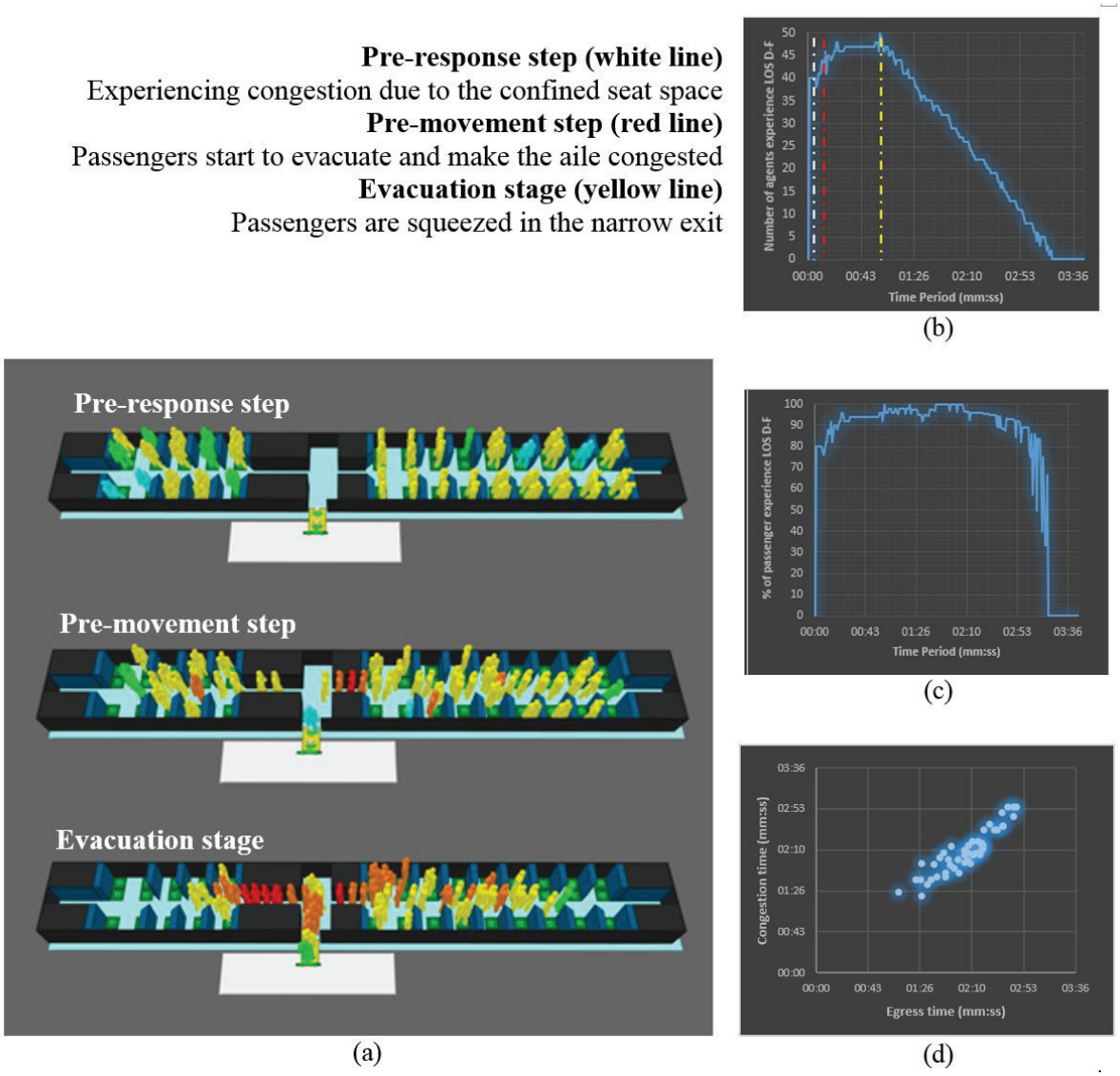

FIGURE 6 : (a) LOS experienced by passengers during the train evacuation case study, (b) Evacuation stages over time, (b) % of passengers experiencing congestion over time and (c) Relationship between the egress time and congestion time

5 CONCLUSIONS AND FUTURE WORK

In this paper, MassMotion was successfully applied to passenger train evacuation. The simulation results show that the model developed in MassMotion is capable of representing the interactions between train passengers during a train emergency evacuation. MassMotion was validated using data from a fire drill being able to reproduce a mean egress time that is close to real data. The force-based model developed in MassMotion was verified and compared to four existing passenger train egress models (EvacTrain, STEPS, Pathfinder, and FDS+Evac) in three evacuation scenarios. The results demonstrate that the force-based model MassMotion can provide consistent and reliable results. It can be concluded that the socio-psychological and physical forces in these type of models are suited to describe the fatal pressures people are exposed to during evacuation scenarios. Running multiple simulations for different passenger train designs can help choosing the design with lowest risk for passenger causalities. It was observed that continuous network models predict a shorter evacuation time compared to models with a discrete network. Also, MassMotion produced a higher variance of egress time in comparison to STEPS, FDS+Evac, PathFinder and EvacTrain which is reasonable considering its underlying principles for capturing the complex behaviour of humans and their interactions with other passengers in trains.

Egress time predictions using MassMotion might become more accurate by considering pre-movement times such as the time that passengers require in the aisle to collect their luggage. It is recommended to focus future work on defining multiple pre-evacuation times and further developments of the model for various hazard conditions, diverse seating arrangements within a passenger train and multiple passenger trains. Validation and verification is an on-going process and further validation tests are required to reinforce the usage of MassMotion for train evacuation. The egress analysis of this paper has been conducted for a specific emergency egress scenario and there is a need to validate the model using various passenger characteristics, different operating environments, and multiple hazard conditions to understand different aspects that may hinder rapid and safe emergency evacuation.

The comparison results presented here show the effect of behavioural and movement rules on egress times when using computer models for passenger train evacuation. Simulation models can provide insights into potential evacuation difficulties in a shorter time and with less cost compared to fire drills and real-world experimental studies. For instance, authorities can change the geometry and configuration of passenger trains and determine their impact on the egress time considering the comfort level of passengers. Also, evacuation modellers can integrate human intelligence in their behavioural models in order to better replicate human movements in complex environmental conditions.

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