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Modelling the Impact of Emergency Exit Signs in Tunnels

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Abstract. This paper addresses the problem of representing the impact of different emergency exit signs during the evacuation of a tunnel when using two different evacuation models (i.e. FDS + Evac and buildingEXODUS). Both models allow the user to represent the impact of smoke upon the evacuee. The models are calibrated (1) considering the nature of the models themselves, (2) by deriving assumptions from previous experiments and literature, (3) using new data produced from experimental work performed by Lund University. The purpose of this paper is to demonstrate the activities required of the user to configure sophisticated egress tools given the scenario examined and the alternatives available in representing evacuee behaviour. Model results show that the differences in terms of emergency exit usage are affected by the degree of modelling sophistication employed and user expertise. It is demonstrated that evacuee performance may be misrepresented through indiscriminate use of default settings. Results are instead consistent between the models when their input is calibrated implicitly (given the availability of experimental data) or explicitly (employing the exit choice sub-algorithms embedded in the model). The scenarios examined are deliberately designed to be a superset of experimental trials currently being conducted about exit choice in a tunnel. The scope is to allow a blind model comparison to take place once the experiments are completed. This will be reported in a future article.

Keywords: Evacuation modelling, Emergency exit signs, Exit selection, Human behaviour, Tunnel safety, FDS + Evac, buildingEXODUS

1. Introduction

The impact of signage on route choice during a tunnel fire poses different challenges to other building types. During building evacuations, the choice for evacuees is often between using an emergency exit, side exits or going towards the main entrance. In accordance with affiliation theory [1], occupants may consider the

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main entrance as the safest place to evacuate (given their familiarity with it), causing a sub-optimal use of exits (elsewhere specifically addressed in regards to tunnel evacuee [2]). The quick development of untenable conditions during tunnel fires [3, 4] indicates the importance of a quick and effective evacuation. Exit/route choice plays a fundamental role given the limited number of egress options available and the potentially rapidly developing hazard. In order to make the selection process more efficient, it is important to consider the influence of signage upon exit/route choice. In critical situations, conditions can quickly become untenable [5] with an increasing risk of exposing an evacuee to deteriorating conditions (e.g. toxic smoke products).

The design of emergency exits and signs plays an important role in exit selection. The tunnel population may be not familiar with the surroundings [6] and staff may be not immediately on hand to provide assistance [7]. To address these issues, tunnel safety regulations provide information on the types of signs to be used for indicating emergency exits [8–10].

Signage can be used as a procedural measure to impact route selection. The impact of signage upon route selection is subject to a number of factors that combine to represent the process by which the information on the sign influences action. The process includes whether the sign is visible (given the environmental conditions and the design of the sign, e.g. light-reflecting, self-emitting objects, etc.) [11]; whether the sign is noticed when visible; whether the information in the sign is understood when noticed [6, 12, 13]; and whether this is information is acted upon when understood. This process is described in detail elsewhere [14–16].

The visibility of exit signs under smoke conditions has been investigated since the 1950s [17]. However, this research does not fully describe the visibility levels reached in different environmental conditions, given different sign designs, colour schemes and individual attributes [18, 19]. Relatively little research has been completed on the impact of different emergency exit designs on people's exit choice [6, 15, 20]. This poses a problem for design engineers who have to find conservative measures to examine scenarios involving the presence of smoke. These engineers need to evaluate the data available and often extrapolate beyond the context of the source material to fit their work.

The purpose of this paper is to demonstrate the activities required of the user to configure sophisticated egress tools given the scenario examined and the alternatives available in representing evacuee behaviour within these tools. Often, numerous preparatory actions are required to configure the data available for use with the model.

In the present work, the term *agent* is used when referring to models. The term *participant* is used when referring to experiments and *occupant* for the general descriptions of the behaviours.

A case study is presented, involving the simulation of exit choice in a smoke-filled tunnel provided with different types of emergency exit signs; namely, standard European back-lit signs, green flashing lights, and strong white lights. Three different degrees of modelling sophistication have been employed, ranging in complexity. The analysis of the results provides information on the differences in terms of emergency exit usage derived from the modelling approaches employed.

The paper also provides specific information on the calibration of the model input for two evacuation models; namely, FDS + Evac and buildingEXODUS, which provide dedicated sub-algorithms to directly represent the impact of smoke on exit choice. Results provided by the evacuation models are discussed.

2. Engineering Case Study: Methods

This paper presents a case study of a tunnel engineering application. Figure 1 presents a schematic representation of the methods employed to perform this engineering case study. This involves comparing the impact of three signage systems upon evacuee performance given that the systems are situated in a hypothetical tunnel design in a smoke-filled environment ([1] in Figure 1). Scenarios were selected in order to represent a superset of tunnel evacuation experiments to be performed.

In support of this case study, relevant data is derived from a set of controlled experiments performed at Lund University in 2004 that are presented here for the first time ([2] in Figure 1). This informs the modelled visibility levels given the presence of smoke. A brief review of relevant literature is then conducted ([3] in Figure 1) [6, 11, 21, 22]. This determines how the empirical data should be modified to fit the case study and also what other assumptions need to be made in order to describe the use of the signage information by the evacuees.

This information is used to configure two evacuation models ([4] in Figure 1): (1) FDS + Evac [23], and (2) buildingEXODUS [24, 25]. These models are then used to compare the three signage systems employed. These models were selected as they simulate the interaction between occupant, smoke and signage, and do so in different ways [26–32].

The data configuration required is different for the models used and their underlying assumptions. This data configuration is typical of engineering applications using simulation models; i.e. identifying relevant data and theory, and then compiling this to configure the models for use in scenarios of interest. In addition to these internal differences, the models are applied in three separate ways ([5] and [6] in Figure 1): (A) a posteriori—implicit approach—exit use is implicitly represented through imposing exit use—the standard method of representing known conditions using a top-down perspective, (B) a priori simulation—default sign representation—blind analysis given omissions in understanding of initial conditions (C) a posteriori—explicit approach—*agent* exit selection is informed by the data available, and explicitly modelled within the tools from a bottom-up perspective. As mentioned, the exact method adopted by each of the models differs given the functionality available. The methods have been coupled as closely as possible to allow direct comparison ([7] in Figure 1), although they are certainly not identical.

This method (see Figure 1) has been adopted to establish the importance of user assumptions, model functionality, the data available, and the subsequent sensitivity of the results produced [27], as applied to typical engineering applications ([8] in Figure 1).

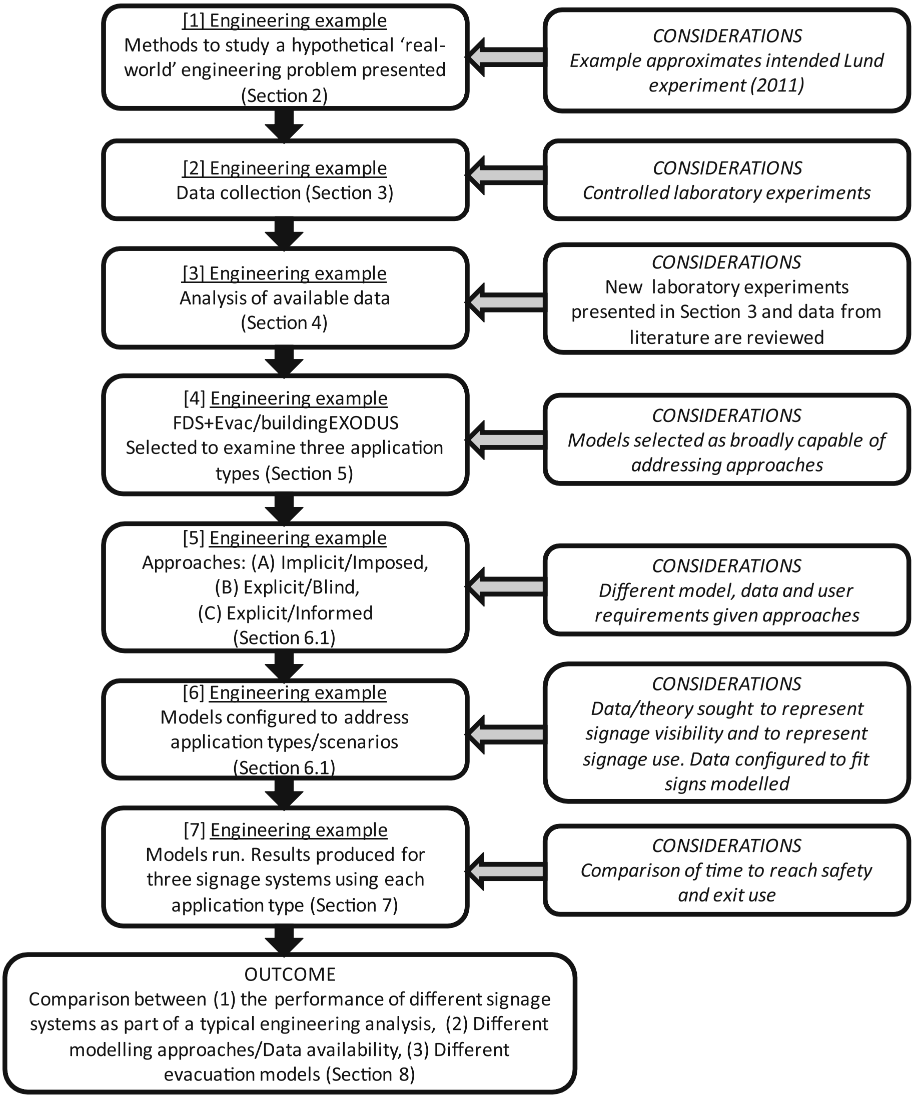

Figure 1. Overview of the methods adopted.

3. Experiment on Sign Visibility in Smoke

Data from a controlled experiment at Lund University is used to estimate the visibility of three signage systems: back-lit European emergency exit signs, green lights and white lights. The controlled experiment was performed at Lund University in 2004 but they are presented in this paper for the first time. This data forms the basis of the visibility levels assumed in the case study presented here. This data has to be adapted and augmented with additional data in order to fully describe evacuee response for the simulation tools employed.

The experimental trials involved a student participation of 35 men and 14 women, with an average age of 23 years. All but two of the population had normal/corrected vision. All participants were unfamiliar with the structures and the environment.

The test site was an empty room in the V-building at Lund University. The windows were covered to prevent ambient light entering. The ceiling florescent lights were lit during the entire experiment. Artificial smoke was used to lower the visibility in the room and acetic acid was used to produce eye irritation. At one end of the room there was a display with different way-finding systems, namely (1) a back-lit emergency exit sign, (2) a green light, and (3) an orange light. There was also a black and white sign that was used as a reference.

When the participants were informed about the procedure they were lead, one at a time, into the smoke-filled room. The participants then moved through the smoke towards a display with the way-finding systems and the reference sign. When a participant noticed a way-finding system he or she told an observer in the smoke filled room who made a note of the distance to the display. When a system had been noticed by a participant it was switched off, e.g., lights were turned off, and the participant continued to walk towards the display until the next system or sign was noticed. This procedure was repeated until all systems and the reference sign had been seen by the participant.

The results of the controlled experiment consisted of the recorded visibility of the tested way-finding systems and the reference sign. For this study, the data for (1) the back-lit emergency exit sign, (2) the green light (3) the orange light are employed in the subsequent egress simulations (see Table 1).

4. Configuring Lund Experimental Data for Engineering Case Study

Two key areas needed to be addressed in order to configure the evacuation models employed here: the visibility of the signs and the probability of the information in the signs being used. Data relating to these two areas is available, but needs to be further translated to be used within the two models.

Visibility in relation to smoke can be described by the following correlation [33]:

Table 1
Visibility Distance for the Back-Lit Emergency Exit Sign, the Green Light and the Orange Light

	Visibility (m)		
	Back-lit exit sign	Green light	Orange light
Average (range)	5.2 (2.5–7.4)	7.7 (4.0–10.5)	9.6 (5.0–13.5)

$$S = \frac{KS}{K_s} \tag{1}$$

where S is the visibility in m, K_s is the extinction coefficient in m^{-1} and KS is a constant. According to Jin [33], the value of KS can be approximated as a constant for a given type of way-finding system or sign. The Lund data-set is used to calculate the visibility factors in conjunction with supporting material. For back-lit emergency exit signs the value of KS has been shown in previous analysis to be approximately 8 [33, 34]. Consequently, this KS value of back-lit exit signs is used as a reference for calculating the visibility factors of the other two types of signs. This procedure has been divided in two steps:

(1) Calculating the extinction coefficients during the Lund trials (given the simulated smoke levels) by applying Equation 1 (KS and S are known variables) and using the visibility factor of the back-lit sign as reference.
(2) Using the calculated extinction coefficient, K_s, and the visibility, S it was possible, with Equation 1, to calculate a value of KS for the green light and orange light (shown in Table 2).

In the calculations, it was assumed that the extinction coefficient was constant for each trial and each participant. Table 2 shows the average value of KS for the green light and orange light together with the standard deviation.

Based on the results, it seems reasonable to assume a value of KS of 12 for green lights and 15 for orange lights (see Table 2). The orange light is therefore the way-finding system that is expected to be most clearly visible through smoke.

In reality, the visibility of orange lights is expected to be very similar to the visibility of white lights (represented within the simulations described below). The reason for this is that white light contains an orange/red component, i.e., visible light with long wavelength. Scattering of light by small particles, (e.g., soot or small droplets), depends on the wavelength of the light [11]. Short wavelength light (e.g., blue), scatters more than long wavelength light (e.g., orange/red). This phenomenon is commonly observed at sunset when mainly the orange and red component of the sun's white light reaches the observer, since the shorter wavelength light is scattered on the way through the atmosphere. Similarly, white lights will appear orange at a distance in a smoke filled environment, since most of the shorter wavelength light will have scattered on the way to the observer. The similarity between white and orange lights at a distance in a smoke filled environment therefore makes it reasonable to assume a value of KS of 15 for white lights (to

Table 2
The Average Value and the Standard Deviation for *KS*

Way-finding system	Average value	SD
Green light	11.9	1.1
Orange light	14.9	1.8

be simulated). The method used in the study to calculate *KS* assumes that the extinction coefficient is independent of the wavelength of the light; this is certainly a simplification. However, research has shown that the extinction coefficient is approximately constant for many different fuels at wavelengths above 400 nm, i.e., most of the visible colours [21].

In reality, the likelihood of a person understanding and using information provided a sign (given that it is seen) is dependent upon a number of factors [35]. In the case study, the key design difference between the signs is their colour. Therefore these are factors examined. Nilsson's previous experimental works [6] include findings on:

- The probability of emergency exits being used given associated sign with green lights and standard sign design.
- People's associations with different colours near exit signs (green and orange lights).
- People's associations in general with different colours (green, orange and white lights).

These findings are based on three evacuation experiments conducted by Nilsson [6]. Different way-finding systems were installed in a corridor, including emergency exits equipped with signs of different colours. The experiments consisted of the participant's choice between two exits in a corridor, the choice of an alternative exit in a corridor and comparison between different flashing lights and strobe lights. Test participants performed the experiments and they were then asked to fill a questionnaire.

Results are used to estimate the likelihood of the information from the various modelled signs being adopted. According to this analysis, a European standard sign design is assumed (see Figure 2) to be used by approximately 50% of those seeing it, while green lights would be used by 90% of those seeing it.

These are only approximations, but are derived from previous estimates [6]. However, comparable exit usage data relating to white and orange lights is not available. Further analysis is therefore required. As it is previously described, white lights will be seen as orange/red lights under smoke, consequently there is a need of collecting information on orange signs for providing a qualitative and quantitative analysis of exit usage. Table 3—derived from Nilsson, who conducted questionnaires after an evacuation experiment about the associations to lights in the context of an emergency exit sign—shows an increased positive association to green flashing and strobe lights, compared with orange strobe lights. The experiment conducted by Nilsson [6] consisted in participants facing the choice between

Figure 2. Standard design of European emergency exit sign.

Table 3
Associations Collected from the Nilsson's Experiments [6]

Type of light	Positive associations (%)	Neutral associations (%)	Negative associations (%)	Total number of participants
Green flashing light	72	0	22	18
Green strobe light	59	7	31	29
Orange strobe light	36	14	50	14

two emergency exits in a corridor which were equipped with different way-guidance systems, namely green flashing light, green strobe light and orange strobe light. Participants took part in a controlled experiment (i.e. announced experiment) one at a time and different starting positions in the corridor were investigated. Associations to different colours in emergency were defined through a questionnaire on the experiment asking to choose between five alternatives, namely *Nothing in particular, Danger, Warning—Keep away, Warning—Look out* and *Safety*.

The analysis of the data and theory available provides the starting point for configuring the tools for application to the scenarios of interest.

Experimental data provided information (the *KS* values) on the actual visibility conditions of each type of emergency sign examined (i.e. if participants see a sign). In the scenarios presented here, the process of understanding and using the information provided by each exit sign is determined according to the colour of the light in use. This relationship is complex, given that some colours may be more visible than others, while not encouraging use in an emergency. The values used as a basis in this analysis are shown in Table 4. These are approximations required given omissions in the data and theory available. However, this type of approximation is typical of the engineering process—especially when it is applied beyond the most basic egress calculations. Although these percentages are certainly approximations, they do broadly reflect current understanding in this area [6].

The combined probability of choosing an exit is then dependent on two factor i.e. (1) visibility, if the sign is visible or not and (2) the probability of using the

Table 4
Derived Percentages that Information will be Adopted From Modelled Signs

Sign type	Location	Likelihood of people using information (%)
Standard back lit sign	Near	50
	Far	0
Sign with green flashing lights	Near	90
	Far	70
Sign with white light	Near	90
	Far	60

exit once the sign is seen. This combined probability of choosing an exit is lower than the probability reported in Table 4.

These percentages are then used as a hypothetical benchmark during this analysis; i.e. what is assumed to be a realistic estimate as part of this analysis. The accuracy of these assumptions (and the benchmark produced) will be examined in a subsequent companion paper where the impact of these signage systems (on exit use) will be examined experimentally.

5. Evacuation Models

Evacuation models are a useful tool for establishing the impact of procedural measures upon evacuee performance [15]. This can include the impact upon evacuee response, route use and travel speeds attained. In this instance, evacuation models are used to examine the impact of including different signage systems upon route selection, given the presence of smoke. This paper provides an example of the activities required to calibrate the model input and the impact of the degree of sophistication of the modelling approach employed.

Two evacuation model are employed here: (1) FDS + Evac [23], developed by VTT Technical Research Centre of Finland together with NIST, the National Institute of Standards and Technology and (2) buildingEXODUS [24, 25] developed by the Fire Safety Engineering Group of the University of Greenwich. These models have been chosen because they both represent smoke, signage, and local decision-making.

VTT Research Centre of Finland has developed FDS + Evac—the evacuation module of the Fire Dynamics Simulator (FDS) developed by the NIST, the National Institute of Standards and Technology. The model permits fire and evacuation processes to be simulated within the same environment. It is a continuous model that applies the Social Force Model by Helbing [36] for simulating people's movement. *Agent* movement and decisions are influenced by the conditions produced by the fire model (FDS). Smoke and speed correlation is based on experimental data-sets by Frantzich and Nilsson [37]. The incapacitation model is a simplified version of the FED concept introduced by Purser [38]. buildingEXODUS is an evacuation modelling package developed by the Fire Safety Engineering Group at the University of Greenwich. It is designed to simulate the evacuation of large numbers of people from complex structures. The model comprises five core interacting sub-models: the *Agent*, Movement, Behaviour, Toxicity and Hazard sub-models. The software is rule-based, with the motion and behaviour determined by a set of heuristics or rules, interpreted on an individual basis. The Toxicity sub-model determines the physiological impact of the environment upon the *agent* using an FED toxicity model [38]. The buildingEXODUS toxicity model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, the narcotic and irritant gases. When *agents* move through a smoke filled environment their travel speed and behaviour is modified according to the experimental data of Jin [33]. The thermal and toxic environment is determined by the Hazard sub-model. This distributes hazards throughout the environment as a function of time and location. buildingEXODUS can accept experimental data or numerical data from other models. The fire hazards are specified at two arbitrary heights that are intended to represent a nominal head height and crawling height.

6. Engineering Case-Study: The Tradskolevagen Tunnel

The Tradskolevagen tunnel in Stockholm (Sweden) is used as a case-study during this paper. The tunnel has been selected as it is currently used by the Lund University for performing evacuation exercises and experiments. This allows the future comparison of the results obtained to a set of evacuation experiments to be performed.

6.1. Evacuation Scenarios

The purpose of this analysis is to examine the impact of different signs on route selection given the presence of smoke. Table 5 and Figure 2 present a summary of the main characteristics of the tunnel geometry. The tunnel length is approximately 180 metres. During the analysis, 160 metres of the tunnel are represented. Two different parts of the tunnel are considered: (1) an inclined section, 80 m in length and (2) an horizontal section, also 80 m in length.

In order to study the impact of exit signs on exit choice given the presence of a smoke-filled environment, a set of general assumptions have been considered. An additional emergency exit is added into the model representation of the tunnel in order to study the exit selection. A sign is associated with this emergency exit (see Figure 3). The emergency exit is placed on the side of the tunnel, while the other available exit is the end of the tunnel (effectively presenting a large opening). The tunnel is assumed to be smoke-filled. However, only the impact on visibility (which is considered constant throughout the tunnel and during each scenario) is addressed here (i.e. the effects of toxic gases are not considered). The smoke is assumed to have an extinction coefficient of 1 m^{-1}. This value was chosen because it represents a superset of the visibility conditions of evacuation experiments to be performed. Artificial cold smoke will be used during the tunnel experiments to be performed; the extinction coefficient is therefore approximately constant. During each simulation a single *agent* moves from one end of the tunnel to the other, being faced with a choice between the emergency exit and the end of the tunnel. The *agent* is assumed not to be able to see the end of the tunnel until beyond the

Table 5
Resume of the Tunnel Geometry Features Relevant for the Evacuation Scenarios

Emergency exit position	20 m far from the end of the tunnel
Length of the path (m)	80 (slope) + 80 (horizontal) = 160
Cross section width (m)	8
Slope factor (%)	10

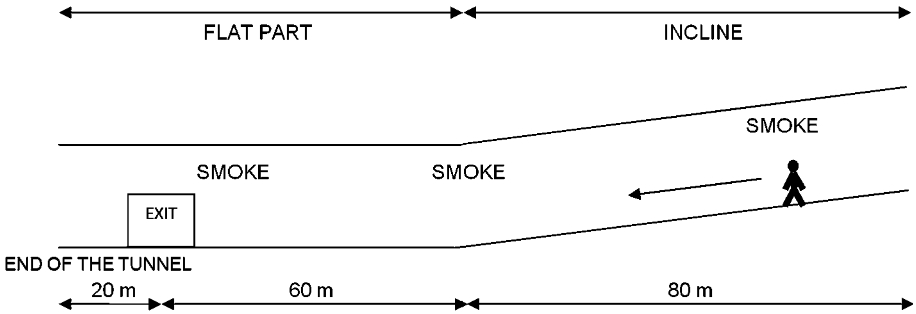

Figure 3. Schematic representation of the evacuation process. The *agent* has to evacuate through either the emergency exit or through the end of the tunnel.

emergency exit. The *agent* is assumed to move off immediately; i.e. there is no pre-evacuation time.

Two initial locations of the *agents* have been considered (see Figure 4) to account for the varied use of the tunnel during an evacuation. The first is on the side of the emergency exit (Location N), while the second is on the far side (Location F). These locations are tested to compare the *agent*'s likelihood of using an exit given his position in the tunnel cross section.

The influence of three types of emergency exit signs has been simulated: Type 1 (Standard back-lit sign), Type 2 (Green flashing lights), and Type 3 (Strong white light). Given the two initial locations of the *agents* and the three different types of emergency exit design, a total of 6 scenarios are simulated by each model (see Table 6), where the percentage in use are in line with Table 4.

6.2. Modelling Approaches

Three different approaches have been used for modelling the selected evacuation scenarios in an attempt to approximate the hypothetical benchmarks conditions. These have been selected to represent the three 'typical' approaches that might be employed by an engineer according to the functionality of the model, the detail

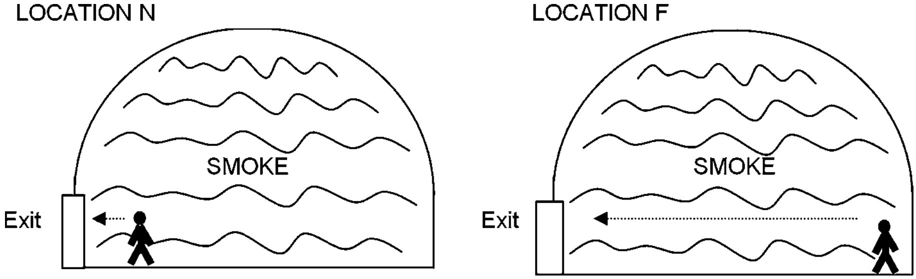

Figure 4. Initial position of the *agents* in the cross section of the tunnel.

Table 6
Summary of the Scenarios

Scenario	Emergency exit design	Initial position of the *agent*
1.N	Type 1	Location N
1.F	Type 1	Location F
2.N	Type 2	Location N
2.F	Type 2	Location F
3.N	Type 3	Location N
3.F	Type 3	Location F

available regarding the scenario description, the data available, and their expertise.

6.2.1. Approach A: Implicit-Imposed. Approach A is an attempt to represent the expected performance described in Sections 3 and 4 through the *imposition* of participant behaviour. This approach is based on an a posteriori understanding of the required evacuee exit choice; i.e. that the performance of the *agents* was known and open prior to the simulations being performed. In this case, the input values of the evacuation models are configured to provide results in accordance with this expectation. The effects of different emergency exit design on exit choice are based on the available previously described literature (see Sections 3 and 4). The approach tries to reproduce the changing conditions in the scenario by simply modifying the *agent*'s awareness/use of the exit; i.e. implicitly representing the impact of the signs. The manner in which this is achieved differs between the models employed.

No specific information about the visibility conditions of the different emergency exit designs are implemented in this approach as the *agents* are simply assigned routes based on the benchmark behaviours; i.e. the interaction between the *agents* and the signage is not explicitly modelled. Instead, the likelihood of people seeing and using the exits is imposed according to the *agent*'s position within the tunnel (location N and F during the original trials) and the type of emergency exit signs available. The previously described literature review and the collected experimental data described in Sections 3 and 4 allow an estimate of the

Table 7
Imposed Values of Emergency Exit Use for the Approach A Both for FDS+Evac and buildingEXODUS

Scenario (no.)	Likelihood of people using signage information (%)
1.N	50
1.F	0
2.N	90
2.F	70
3.N	90
3.F	60

interaction to be *imposed* by the user. Table 7 describes the percentages used in the models to reflect the expected use of the signs.

6.2.1.1. FDS + Evac. FDS + Evac has several methods for simulating the evacuee exit selection. Evacuee behaviours are simulated by taking into account environmental conditions, personal knowledge of the environment and the actions of other individuals (this last factor is not important in this study because we are considering individual behaviours). These are deliberately simplified here to impose the desired responses.

In FDS + Evac, an exit is usable as long as visibility is greater than half the distance to the exit. The constant visibility factor *KS* is by default 3 (a light-reflecting object according to Jin and Mulholland, [33, 34]). The default *KS* value cannot be changed in the current version of FDS + Evac (version 2.3.1). Some additional model configuration has been required to compensate for this (discussed below). *Agent* familiarity with an exit is provided by the user. By default each exit is assumed to be known by every *agent*. Users are able to assign a probability to determine whether an *agent* is familiar with a particular exit by using the KNOWN_DOOR_PROBS command. If an exit is regarded as known, then the *agents* will try to use it unless the smoke affords visibility of more than half the distance to the exit. If an exit is not known, then the exit will not be used, unless the FLOW_FIELD_ID is set such that the evacuation mesh includes this exit. In this case, the soot is used in the visibility checks (i.e. the FED parameter is not considered).

The different types of exit sign designs have been reproduced within the model by varying the KNOWN_DOOR_PROBS parameter about. Thus, the general visibility conditions are the same in the whole space, but six different values of probabilities of knowing the emergency exits have been used in accordance with the imposed values of emergency exit use (based on the values in Tables 4 and 7).

The initial walking speed of the *agents* is selected following the default values of the Adult category within the model (a uniform distribution with mean value of 1.25 m/s, as described in the FDS + Evac manual [23]). The *agent*'s speed is automatically modified by the model when they encounter smoke, based on the Frantzich and Nilsson's experimental data-set [37].

6.2.1.2. buildingEXODUS. buildingEXODUS includes several methods to represent *agent* exit knowledge. These can be simplistic (use of nearest exit), local (based on familiarity), and/or dynamic (exits become aware through *agent* interaction with their environment). This final dynamic approach can involve an explicit attempt to represent real-world phenomena (e.g. communication, interaction with signage, etc.), or an implicit attempt to represent the effect of such phenomena. This latter approach is adopted here to represent the likely adoption of signage information and subsequent use of exits.

Redirection Nodes provide a means of providing new routes to an evacuee within buildingEXODUS. If an *agent* is tasked with visiting a Redirection Node he/she can adopt any new information or tasks that the node conveys. The Redirection Node allows the adoption of the new information to be probabilistic, allowing complex behaviours to develop. In this instance, the probabilities associated with the Redirection Nodes (position along the inner or outer walls) have been modified to reflect the derived values shown in Table 7. As such, signs were not explicitly modelled; however, their effect was modelled.

The *agent* was assumed to have base travel speed of 1.5 m/s, in line with the default value for an individual *agent* provided by buildingEXODUS. This was increased by 10% when the *agent* descended the ramp given the instructions provided [39]. The *agent*'s speed was then modified when they encountered the modelled smoke conditions. Within the model, the environmental conditions were assumed to be constant throughout the tunnel area modelled. The smoke was set (at both lower and upper level) to an extinction coefficient of approximately 1/m in order to broadly represent visibility of 3 m.

The Jin data-set was employed to determine the impact that the smoke had on travel speed [33]. In addition, behaviours derived from the Jin experiments were also enabled: sub-optimal staggering within the smoke, and a general attempt to navigate towards a target using walls and boundaries [30]. Crawling is also represented within buildingEXODUS [24]. However, this was disabled during this analysis.

6.2.2. Approach B: Explicit-Blind. Approach B assumes the use of default values, with no specific information on the nature of the signs, the *agent* behaviour or the impact of the environmental conditions (an a priori analysis); however, the interactions with the signs are explicitly represented. As such, these represent a blind representation of the type of scenario described in the hypothetical benchmarks, with no knowledge of the details (types of sign, etc.). The results produced can only then be indicative of those that might occur—any similarity with the expected data is largely coincidental. FDS + Evac and buildingEXODUS are employed using general default settings and/or activities typical of representing this type of scenario.

6.2.2.1. FDS + Evac. FDS + Evac represents, by default, each exit as a "known exit". Consequently, the decision-making process about the exit choice is dependent on the visibility criteria and disturbing conditions; i.e. if the exit is visible or not under the global visibility condition of 3 m. In addition, the model considers by default the case of light-reflecting sign ($KS = 3$). There is only a single default setting, producing a single scenario for Approach B. The flow field associated with the pre-defined evacuation direction is the main entrance of the tunnel. This is in accordance with the assumption that *agents* that are not able to see any exit usually go towards the end of the tunnel. This assumption is in line with data from previous studies and the affiliation theory [1, 37].

The individual walking speeds and the smoke influence was assumed to be same as that adopted in Approach A.

6.2.2.2. buildingEXODUS. During Approach B, the buildingEXODUS model employed its Sign Behaviour, and associated functionality, to explicitly represent *agent*-sign interaction, albeit in an uninformed manner. In order to differentiate between the approaches adopted, a brief description of the EXODUS signage functionality is provided. This is also necessary in order to understand the subtle differences between the representation of Sign Types 1/2/3.

The signage functionality represents four key elements (a–d) of the signage/*agent* interaction: (a) the physical area from which a sign can be seen, (b) the likelihood of an *agent* actually seeing the sign given the angle at which they approach the sign (c) the likelihood of them paying attention to the sign and absorbing the information and (d) the likelihood of them using the information provided to them. Element (a) is a property of the sign. During Approach B, this was determined from the three default libraries provided in the model. These libraries are based on guidance derived from British and US standards [40–42], producing visibility ranges of 13.2 m, 6.6 m and 30 m respectively. For Element (b) buildingEXODUS includes a simple equation that modifies the likelihood of seeing the sign given the angle of approach. This drops off quickly, as the angles diverge from the perpendicular. This was enabled and remained constant for all of the Approach B simulations.

buildingEXODUS allows several approaches to be adopted for Elements (c and d). Given that Approach B was an attempt at representing a blind simulation of the benchmark conditions, the default method was selected. This was based on empirical data collected and implemented by FSEG to represent the likelihood for people absorbing the information on the sign and then using it [20, 31].

The *agent* speed and interaction with the smoke conditions was assumed to be same as that adopted in Approach A, and the crawling behaviour has again disabled. Typically, in buildingEXODUS unusual or difficult terrain would be represented as impeding movement. Therefore, the default mechanism was employed (in this case raising the *Obstacle* value of the relevant arcs) to reduce the *agent* travel speeds when descending the ramp to 1.35 m/s.

6.2.3. Approach C: Explicit-Informed. In Approach C, an a posteriori analysis is performed assuming detailed information of the benchmark conditions and *agent* actions, along with a degree of user expertise. Results are generated by a joint evaluation of the information available (i.e. empirical data collected in Section 3, supported by available literature in Section 4) while employing the most sophisticated signage functionality within each of the tools employed to explicitly represent *agent*-sign interaction. This approach employs the most relevant capabilities of the models available and an open, informed, calculation, in order to reproduce specific problems and the expected behavioural response.

6.2.3.1. FDS + Evac. This approach uses the experimental data described in Sections 3 and 4 in order to simulate the influence of the emergency sign design on door selection. Three values of the visibility factor *KS* have been derived from the empirical data and from literature (Section 3): 8, 12 and 15. It is not possible to directly implement these factors within FDS, given that the model employs a set value of $KS = 3$. To compensate for this, the soot density has been scaled near the emergency exit in order to reproduce the effects of the "gained" visibility obtained by using different emergency exit design. It is possible to calculate the visibility of the presented types of exit signs in any kind of smoke environment by applying Equation 1. Given that an extinction coefficient of $K = 1/\text{m}$ is assumed and *KS* values of 8, 12 and 15 are assumed, then the visibility levels afforded can be established. However, before this can be completed, the basic FDS assumption regarding *KS* ($KS = 3$) needs to be addressed. Consequently, the visibility distance V_g gained by applying the Type 1, 2 and 3 of emergency exits are given by the following Equation 2:

$$V_g = \frac{KS_n}{K} - \frac{KS_{ls}}{K} \tag{2}$$

where KS_n is the non-dimensional visibility factor previously calculated for the three types of exit signs, K is the assumed extinction coefficient, and $KS_{ls} = 3$ is the non-dimensional visibility factor for the light reflecting sign assumed within FDS. The calculated gained visibility distances within FDS for the three type of exit signs are $V_{g1} = 5$ for backlit signs, $V_{g2} = 9$ for green flashing lights and $V_{g3} = 12$ for the white light. The effect of the gained visibility distances is therefore introduced in FDS + Evac by scaling the soot density in the correspondent visibility catchment area near the emergency exit in order to obtain the desired visibility conditions. The represented visibility produced is 8, 12 and 15 m according to the sign designs examined (see Figure 5).

If the visibility is less than half the distance to the exit, the exit is not visible and the *agents* will not go towards that exit (unless the underlying FLOW_FIELD in FDS + Evac is pointing that direction).

After defining if an exit is visible or not, the FDS + Evac user has to reproduce the decision-making process of each *agent* as well. The input regarding the likelihood of learning about the door (i.e. attending and using the information from the sign) is again set in line with the values assumed for the Approach A. This is achieved by modifying the *agent* familiarity with a certain exit in advance using the KNOWN_DOOR_PROBS function. Familiarity modified through interaction with signage is simulated by creating a dummy door and an exit behind it in order to activate the function EXIT_SIGN within the model. The primary predictive element in this analysis therefore relates to the likelihood of the *agent* seeing the sign. The *agents*' decision making process regarding exit choice is consequently

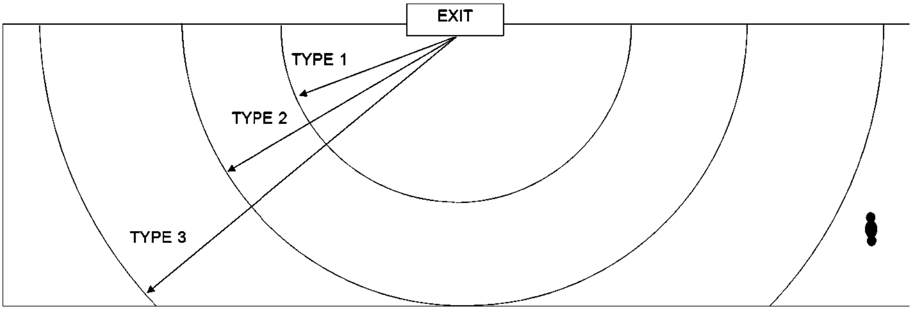

Figure 5. Approximation of the visibility catchment areas inserted in FDS+Evac by scaling soot densities for the three types of sign.

based on the evaluation of the smoke conditions near the exits and the initially defined familiarity with each exit (via the KNOWN_DOOR_PROBS function).

The subsequent conditions produced within the model were examined. This confirmed that these calculations produced the required visibility conditions within FDS + Evac.

Walking speeds are selected in accordance with Jin's suggested value for the considered extinction coefficient (approximately 0.5 m/s). Jin's initial walking speed is assumed, and is then subject to the default speed reduction calculation (derived from Frantzich and Nilsson's experiments [37]) employed within FDS + Evac. Walking speeds are increased in the incline by 10% accordingly with Kumm [39].

6.2.3.2. buildingEXODUS. During Approach C, the buildingEXODUS model again employs its Sign Behaviour. buildingEXODUS represents *agent* interaction with signs in four key elements. Given that Approach C requires the *estimation* (as opposed to the *imposition*) of *agent* performance, the configuration of the four elements reflected this need. In essence, the model was attempting to reproduce the hypothetical benchmark described in Tables 4 and 7 from the bottom up, rather than having these values initially imposed upon the *agents*. Element (a) is a property of the sign, and has been set according to the information provided; i.e., the signs were visible from 8 m, 12 m, or 15 m depending on their type. For each of the signs, this is consistent throughout the Approach C simulations. Element (b) is still represented using a simple equation that modifies the likelihood of an *agent* seeing the sign given the angle of approach, consistent with Approach B. This was enabled and remained constant for all of the Approach C simulations. Element (c), reflects whether information was absorbed from the sign. Every time that an *agent* occupied a new location within the catchment area of the sign they had a chance (a probability) of receiving data from the sign (and then acting on it). For Sign A this was set to 20%; for Sign B this was set to 33%; for Sign C this was set to 31%. These percentages interacted with Element (b) in a complex manner, with the exact angle of an *agent*'s approach affecting (typically reducing) the overall likelihood of information being absorbed and acted upon. During test simulations, these probabilities were configured (derived through iteration) for *agents* as they walked along the inner edge of the tunnel to better approximate the expected exit use outlined in Tables 4 and 7. Once the model was configured in this manner, the *agent* was then repositioned to the outer edge of the tunnel for the next round of simulations, and the same probabilities applied for each sign. There was therefore one probability applied for each sign—derived from performance along the inner wall—that was then applied to the *agents* located at the inner and the outer wall starting positions. No additional refinements were applied to the outer wall—the results were estimated from the inner wall performance. The differences produced between the signs along the outer wall were therefore a combination of (Elements (b) and (c)) and the manner in which the catchment area differed between the signs (Element (a)). This type of model configuration might not normally be available. However, the ability to manipulate the low-level actions of the *agents* to generate known outcomes might allow the model to more confidently be applied to a broader range of related scenarios.

7. Results

7.1. Approach A

7.1.1. FDS + Evac. The use of Approach A produces the simulated conditions by imposing an a priori degree of *agent* familiarity with an exit, depending on its type. The visibility conditions of 3 m have been achieved by scaling the soot density in the whole tunnel environment, but no direct information about the type of signage in use is given. The only information available is their potential impact on *agent*'s exit choice, as previously described. Results are shown in Table 8. They show that the exit usage is in accordance with the benchmark use provided in the command line KNOWN_DOOR_PROBS for all the considered scenarios. Consequently, a change in that command line will produce different exit usages in line with the selected input. Evacuation times are different in accordance with the exit choice; i.e. scenarios with a lower number of *agents* evacuating from the emergency exit generally provide higher evacuation times.

7.1.2. buildingEXODUS. In this approach, the use of the signage is represented implicitly through the use of Redirection nodes; i.e. signs were not represented, only their potential impact according to the research cited in previous sections. The results produced are shown in Table 9. The results produced accurately reflect the percentages associated with each hypothetical benchmark; i.e. the likelihood that someone will follow the signage. It is expected that should these percentages be changed, then the results produced would follow accordingly. The times to

Table 8
Approach A Results for FDS+Evac

Scenario	Use of emergency exit (%)	Evacuation time (s)
A.1.N	54	130
A.1.F	0	140
A.2.N	93	122
A.2.F	67	136
A.3.N	90	125
A.3.F	62	129

Table 9
Approach A Results for buildingEXODUS

Scenario	Use of emergency exit (%)	Evacuation time (s)
A.1.N	46	286
A.1.F	0	295
A.2.N	86	278
A.2.F	71	282
A.3.N	88	279
A.3.F	63	283

reach the final exit include those either redirecting to the emergency exit or continuing on. The actual distances covered are broadly similar, with the journey to the end of the tunnel slightly longer. This is reflected in the results with times/distances increasing as the percentage of those using emergency exits reduce. However, the use of the Jin behaviours (i.e. staggering slightly through the smoke) reduces the impact of the differences in the route length. This adds some noise into the calculation and reduces the differences in completion time that might have otherwise have been more apparent.

This scenario demonstrates the user is able to impose evacuee movement to test the consequences of the subsequent behaviour.

7.2. Approach B

7.2.1. FDS + Evac. In Approach B, the FDS + Evac model is applied by using as many default values as possible. The visibility conditions of 3 m have been represented by scaling the soot density in these scenarios. This represents the desired environmental conditions (rather than the impact that is has on the *agent* behavioural response, while will be left to the default capabilities). FDS + Evac assumes by default that the *agents* are aware of each exit. The current version of the model (2.3.1) does not allow different visibility factors to be associated with different emergency exit types. As a consequence, no information is provided related to the different types of exit being simulated. Given this, the results produced are only sensitive to the visibility of the exit; i.e. the starting locations of the *agents* (see Table 10). This means that if an *agent* can see the exit, the exit will be used. The consequence of this is that *agents* on the same side of the tunnel as the emergency exit (location N, scenario B1.1) can always see the exit (as their position is closer than the 3 m of the visibility assumed in these scenarios). For the same reason, *agents* on the far side of the tunnel to the emergency exit (scenario B1.2) are approximately 8 m from the emergency exit and will never be able to see the exit: the emergency exit usage from this starting position is then 0. As expected the use of default information (in this case the familiarity with the emergency exit) produces results that are not in line with the benchmark use presented in Tables 4 and 7.

7.2.2. buildingEXODUS. In Approach B, the signs were explicitly represented within the model; however, no detailed empirical data has been employed to describe the performance of the signs and their impact on behaviour (i.e. represent the hypothetical benchmark). Given this, three default sign libraries have been used to describe the performance of the three signs examined, and the default

Table 10
Approach B Results for FDS+Evac

Scenario	Use of emergency exit (%)	Evacuation time (s)
B.1.N	100	125
B.1.F	0	144

behaviours employed. The performance of each sign does not correlate directly with the three sign types described earlier; i.e. the three sign types tested are not represented by default libraries within EXODUS. Given that there is no direct correlation between the simulated and target exit types, the distribution of results produced is of more interest than any direct comparison with each of the original signs (see Table 11).

As expected, the results produced are different from the hypothetical benchmark; i.e. the visibility catchment areas and the behavioural interaction with the signs were different, producing different outcomes. The nature of the geometry limits the impact of the default signs implemented, given the relatively small visibility differences involved. The impact of the smoke upon sign visibility is not accounted for in these simulations. The results are consistent given that the default *agent* interaction with the signs is simulated and the differences between the signs are minimized by the space represented. The evacuees approach the end of the tunnel, interact with the signs given the calculated visibility and then the model estimates whether the evacuee absorbs and uses the information available.

This scenario demonstrates the *agent* interaction with signage can be modelled; i.e. the information from the signs can influence performance. However, the impact of the signs is sensitive to the sign represented in the model and would need to be configured appropriately to reflect the conditions associated with the hypothetical benchmark.

7.3. Approach C

7.3.1. FDS + Evac. The results produced are shown in Table 12. The predicted emergency exit usage is in line with the benchmark conditions. Results of Approach C are comparable with Approach A as the actual exit usage was imposed; however, this was modified by the model given the joint analysis of the visibility conditions of the exits. The results are affected by the initial positions of *agents* in the cross section. The exit sign impact on evacuations conditions have been reproduced using the soot for scaling the visibility of the exit signs. This will affect the exit selection algorithm. The soot is used in the visibility checks for calculating whether an exit is visible or not. The probability of using an exit is then simulated by the KNOWN_DOOR_PROBS parameter. This parameter typically describes the familiarity of the *agents* with the available exits and subsequently

Table 11
Approach B Results for buildingEXODUS

Scenario	Use of emergency exit (%)	Evacuation time (s)
B.1.N [NFPA]	32	304
B.1.F [NFPA]	30	308
B.2.N [BS2000]	32	305
B.2.F [BS2000]	28	309
B.3.N [BS1999]	30	307
B.3.F [BS1999]	20	308

Table 12
Approach C Results for FDS+Evac

Scenario	Use of emergency exit (%)	Evacuation time (s)
C.1.N	50	307
C.1.F	0	328
C.2.N	85	293
C.2.F	64	317
C.3.N	85	292
C.3.F	59	315

influences exit selection. In this approach, this function is used for representing the probability of choosing a certain exit. The KNOWN_DOOR_PROBS parameter is then given two different roles in Approach A and Approach C, in line with the necessity of imposing exit use at different levels. In Approach A it is used for imposing the probability of using a door, starting from pre-defined visibility conditions (the emergency exit is always visible or not). In Approach C the same parameter represents the probability of using information from a sign, i.e. walking towards a sign, if it is noticed. The EXIT_SIGN function ensures that only those *agents* that have the emergency exit in their known door list (i.e. are familiar with an exit) can use it. Otherwise, the model by default considers that all the *agents* closer than the visibility distance will use the exit (that is what actually happens in Approach B). When the *agents* do not know the emergency exit (given the values generated by the KNOWN_DOOR_PROBS function), their only option is then to go towards the main entrance (it is assigned as the main direction of *agents* by the command line FLOW_FIELD_ID).

The difference in the evacuation times produced is due to the initial walking speeds being set by approximating Jin's suggested values (approximately 0.5 m/s) instead of inserting an initial walking speed without smoke (1.25 m/s is the mean value by default for Adult category in FDS + Evac) and letting the Frantzich and Nilsson's correlation modify the rate accordingly.

7.3.2. buildingEXODUS. In Approach C, the model *estimated* the performance of the *agents*. This *estimation* was based on the underlying algorithms embedded within the model describing the interaction between the *agent* and the signage. These algorithms were configured according to the hypothetical benchmark conditions derived from the experimental and literature review described earlier. This reflected the visibility of the signs (given the smoke, see Figure 6) and the likelihood of the information being adopted. The algorithms were calibrated accordingly. As mentioned previously, no special algorithmic modifications were made to account for the different starting positions. In effect, the combination of starting position, visibility and interaction were employed to account for the conditions experienced.

The signs were then visible from different locations within the geometry. Depending on the path adopted, the *agent* could possibly have observed the sign. Once there was the potential for the sign being observed, the model then deter-

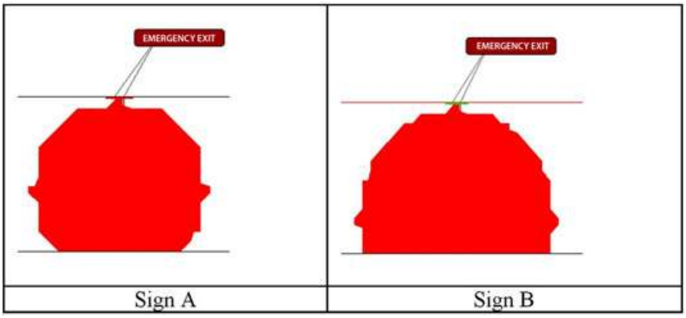

Figure 6. Example visibility catchment areas calculated by buildingEXODUS.

mined whether the signed was actually observed and whether the information was then used. Given that each scenario was repeated and that the performance of the *agents* was stochastic the exact routes adopted by the *agents* varied (see Figure 7) introducing slight differences in the numerical results produced and the qualitative *agent* behaviours produced.

The results produced are shown in Table 13. The overall times are consistent with the previous times produced. Typically, the larger the proportion of *agents* that used the emergency exit, the shorter the distance that had to be travelled and the smaller the arrival time; however, the difference between the cases is reduced given the noise introduced by the presence of smoke and the sub-optimal movement produced (enabled by the embedded behaviours derived from Jin [30, 33]).

The results produced in Table 13 should be compared against those produced in Approach A (see Table 9) where the behaviour was imposed (and where the hypothetical benchmark conditions were closely replicated). Given that the results in Table 13 are explicitly estimate (albeit that the model configuration was informed by empirical/derived data), they compare favourably with Approach A where the conditions were imposed. As such, given that the algorithm is appropriately con-

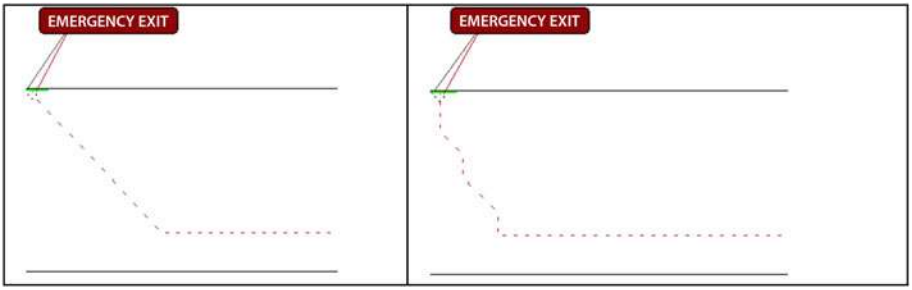

Figure 7. Examples of routes adopted when starting on the outer wall.

Table 13
Approach C Results for buildingEXODUS

Scenario	Use of emergency exit (%)	Evacuation time (s)
C.1.N	51	283
C.1.F	0	297
C.2.N	84	273
C.2.F	63	283
C.3.N	84	280
C.3.F	46	287

figured according to expected initial conditions, the buildingEXODUS model is able to estimate the outcome and produce credible results.

8. Comparison Between the Results Produced

The comparison between the results indicated the impact that the specific use of the model might have on the results produced; i.e. whether the model is run using default settings, implicitly representing the evacuee behaviours, or explicitly representing the evacuee behaviours. These approaches require different levels of user expertise, data, and model capabilities. The results produced will allow comparison between the sub-models embedded within two different evacuation models to simulate the same problem, i.e., the impact of emergency exit signs on exit choice. Figure 8 presents the results produced from buildingEXODUS and FDS + Evac when examining the performance of the signs given changes in the *agent*'s starting locations. During Scenario A, the performances of the *agents* were imposed. There was no attempt to explicitly represent the interaction between the *agent* and the sign. As expected, the results produced by both buildingEXODUS and FDS + Evac are similar to expectation (differing from the expected use by only 3.5% and 3.2% respectively), indicating that if the use of the sign is know, it can reliably be imposed.

Scenario B required the use of the default characteristics of the models employed, i.e., the default values are not specific to the signs to be represented. Direct comparison between each of the default values used and the benchmark conditions is of little value given that the order of the comparison would only ever be arbitrary. Without some information on the signs being simulated, buildingEXODUS is able to generate representative value ranges using the default values, although would not be able to discriminate between sign types employed without prior information. The default values employed produce relatively low use of the signs implemented. By default, FDS + Evac either assumes that an individual is aware or unaware of an exit in relationship to his initial location. This is reflected in the results produced.

Scenario C represents the most sophisticated use of the models—representing an attempt at estimating performance from the bottom up, given the model capabilities. The models were then configured to explicitly represent the impact of differ-

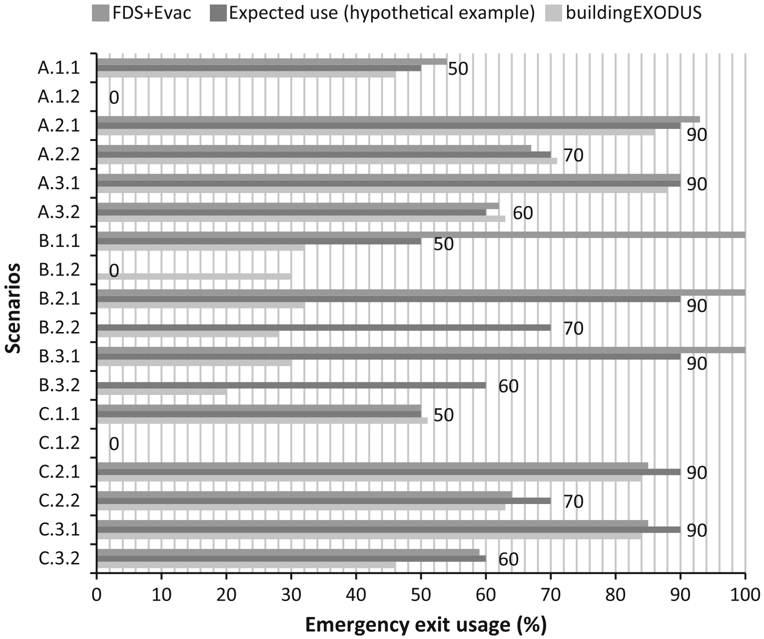

Figure 8. Summary of emergency exit usage. The labels show the expected use.

ent types of emergency exit sings. Both models are able to generate the exit use of the emergency exit, given that they have been suitably configured. The exit use produced by buildingEXODUS is within 8.1% of expectation, while the results produced by FDS + Evac are within 3.6% of expectation. The similarity between the FDS + Evac results produced for Approach A (3.1% difference from benchmark) and Approach C (3.6% difference from benchmark) is not surprising given that the same base probabilities were employed; these probabilities were modified by the environmental conditions simulated in Approach C. The key difference between the two scenarios was the impact that visibility had upon the availability of information to the *agent*. buildingEXODUS represents the various stages of the *agent*-sign interaction, although does not automatically reduce signage visibility given the presence of smoke (this was manually configured as part of this analysis). Given this, the similarity of the predicted percentages (dependent on visibility, angle of approach and then use) is promising.

The overall evacuation times produced by the models can also be compared against each other, although at this stage there is no expectation as regards the benchmark evacuation times other than the (Jin and Frantzich and Nilsson) datasets embedded within the models. This information may become available once Lund University have completed their experimental work in 2011.

It should be remembered that as well as the smoke conditions faced, the exit door selected will have had an impact on the overall evacuation times recorded; as

Table 14
Summary of Simulated Evacuation Times

	Evacuation time (s)	
Scenario	buildingEXODUS	FDS + Evac
A	278–295	122–140
B	304–309	125–144
C	273–297	292–328

such, a number of factors influenced the times produced. Given this the range of times produced for each of the scenarios are shown (see Table 14). FDS + Evac produced reasonably consistent evacuation times in Scenario A and B, where the Lund data was used. The FDS + Evac times produced when the Jin data-set was employed were, as expected, significantly longer reflecting differences in the underlying data-sets. The results produced by the FDS + Evac model and the buildingEXODUS model were comparable when similar walking speeds were used (i.e. taken from the Jin data-set in Scenario C). The buildingEXODUS results were consistent across all of the scenarios given that the Jin data-set was used throughout.

9. Conclusions

This paper has described several attempts to represent the impact of different signage systems in a smoke-filled environment as part of an engineering analysis. Data was derived to produced a benchmark performance; i.e. an estimate of expected occupant performance. Two evacuation models were selected (buildingEXODUS and FDS + Evac) and were then configured to simulate the impact of the different signage systems. The two models were applied in a range of ways—typical of the approaches adopted in engineering applications (e.g. default settings, implicit representation of *agent* behaviour, explicit representation of *agent* behaviour, etc.). Configuring these models for these applications required different levels of data and different levels of user expertise. As expected, the more information provided to the models, the closer the models can to reproducing the benchmark results. Both models were also able to employ implicit (top-down) and explicit (bottom-up) approaches (to a greater or lesser extent). Both models produced promising results in this regard, with the bottom-up approaches producing comparable results when suitably configured. However, it took some time to configure the models when explicitly representing *agent*-sign interaction for the benchmark case, detailed information and user expertise. These resources may not always be available in all cases, although where they are available, they may allow the model to be applied with more confidence and credibility to a broader range of scenarios.

This paper compares the results produced when (a) different evacuation models are used, and (b) different approaches are used to represent the interaction between the evacuees and the signage system. These approaches require different levels of user expertise, data, and model capabilities. In particular, it was shown that evacuee performance can be misrepresented should the models not be appropriately configured (e.g. default settings blindly used), and that great care should be shown by the user when employing third party data when configuring sophisticated evacuation tools. A detailed understanding of the model, of the algorithms employed, of the data and of the evacuee behaviour being represented should be acquired. In addition, the detailed description of the input configuration of the two models provided will be useful for future engineering applications in tunnels.

This paper is intended to strike a cautionary note. The case represented is deliberately simple in order to focus on the complexities involved in the compilation of data, model configuration and then manipulation of the models to represent the scenarios of interest at different levels of sophistication. It is not suggested that any one method is, by definition, better than another. It is suggested that the scenario being represented, the data employed and the model being used require expert understanding before attempting to represent even the simplest case. If this is not the case, then even the most sophisticated model can be misused, data misinterpreted and the evacuee performance during a scenario misrepresented. If this is the case, then the results produced may provide useful insight.

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