Polytechnic University of Bari

Faculty of Engineering

European PhD in

Transportation engineering, land use and technological innovation

EVACUATION MODELLING IN ROAD TUNNEL FIRES

Doctoral thesis

Bari, 2012

PhD candidate:

ENRICO RONCHI

Tutor:

Prof. PASQUALE COLONNA

This thesis entitled:

EVACUATION MODELLING IN ROAD TUNNEL FIRES
written by Enrico Ronchi

has been approved by the Board of Examiners of the European Doctorate of Philosophy (European PhD) in *Transportation engineering, land use and technological innovation* at the Polytechnic University of Bari, Italy.

Karen Boyce, Senior Lecturer, University of Ulster, United Kingdom
Member of the Board of Examiners

____

Michele Agostinacchio, Full Professor, University of Basilicata, Italy
Member of the Board of Examiners

____

Stefano De Luca, Associate Professor, University of Salerno, Italy
Member of the Board of Examiners

____

Maurizio Diomedi, Associate Professor, University of Basilicata, Italy
Member of the Board of Examiners

____

Bari, 23/03/2012

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards.

Evacuation modelling in road tunnel fires

Enrico Ronchi
Illustrations: Enrico Ronchi

Keywords: Evacuation Modelling, Human Behaviour in Fire, Tunnel Safety, Fire Safety Engineering, Performance Based Design

Abstract. Evacuation model capabilities are rapidly improving, allowing the simulation of ever more complex scenarios in different types of environments. The definition of the best evacuation modelling approach for safety assessment is a key point for optimizing engineering work and ensuring the desired safety conditions. In the present thesis, a wide comparison between modelling approaches has been provided for the study of road tunnel evacuations. The models employed are FDS+Evac, buildingEXODUS, Gridflow, STEPS, Pathfinder and Simulex while the calculations provided in the Society of Fire Protection Engineering handbook have been used to compare the results of the computational models to the hydraulic method. Models have been used individually and a new framework has also been presented, namely the multi-model approach. The predictive capabilities of the modelling approaches employed have been tested for both hypothetical evacuation scenarios and a set of new tunnel experiments performed at the Department of Fire Safety Engineering and Systems Safety of Lund University, Sweden. The aim was to identify the appropriate approach in relation to the complexity of the scenario under consideration. Two key aspects have been analysed through modelling tools: 1) the influence of smoke on movement speeds and 2) the impact of way-finding installations on exit choice. Models are tested through an *a priori* vs *a posteriori* result comparison based on the collected experimental data. Results show that: 1) analytical calculations are not a sufficient method to simulate evacuation scenarios involving exit choice, 2) the use of model default settings produces significant differences in the results, 3) the calibration of model input requires different degrees of effort in relation to the embedded sophistication of the model, 4) an individual use of the model is sufficient if the evacuation modeller has the necessary information to calibrate the input, 5) the presented multi-model approach is required in the case of very complex scenarios; it has been used to test the sensitivity of the results to the model employed and provide an estimate of the uncertainty related to the input, the models and the data-sets embedded in the models.

Dipartimento di Vie e Trasporti
Politecnico di Bari
Via Orabona 4
70100 Bari
Italia

enronc@poliba.it
www.poliba.it
Telefono: +39 0805963389
Fax: +39 0805963329

Department of Roads and Transportation
Polytechnic University of Bari
Via Orabona 4
70100 Bari
Italy

enronc@poliba.it
www.poliba.it
Telephone: +39 0805963389
Fax: +39 0805963329

Summary

The Performance Based Design approach (PBD) is currently used to ensure safe conditions for people in many environments. The first decision that a safety designer faces prior to an egress study using the PBD method is the selection of the appropriate modelling approach for the analysis. These may vary from simple analytical calculations to a computational model or a combination of different tools. This work focuses on the identification of the appropriate approaches in relation to the scale and the complexity of the road tunnel evacuation scenarios under consideration. Modellers need to understand how to differentiate between various approaches when simulating evacuation in road tunnels. In fact, the evacuation reviews have so far mostly categorized the different features of the models by the published description of their characteristics, i.e., there are not a great deal of studies comparing model results for underground environments. The evacuation models employed in the present work are FDS+Evac, Gridflow, buildingEXODUS, STEPS, Pathfinder and Simulex while the SFPE hydraulic method has been used to compare the results of the computational models to the analytical calculations.

The case of road tunnel fires requires the analysis of many complex factors and processes related to human behaviour, such as pre-evacuation times, e.g., reluctance to leave the vehicle, interactions between occupants, interactions between occupants and smoke, etc. However, models have different capabilities and may represent a different sub-set of the factors listed. Each model has its own specific features and often practitioners do not have a thorough understanding of the variables that may be inserted in each model and how they affect the results; i.e., the model has limitations, which are exaggerated by the expertise of the user.

This work focuses on the study of two main aspects affecting the simulation of road tunnel evacuations, namely 1) the influence of smoke on movement speeds and 2) the impact of way-finding installations on exit choice. The analysis of different evacuation scenarios (ranging in complexity) has been carried out in order to check the differences in the results produced when using the above mentioned approaches. They vary from hypothetical scenarios to the representation of actual tunnel evacuation experiments performed at the Department of Fire Safety Engineering and Systems Safety of Lund University, Sweden. Data from these experiments were used to compile information on movement speeds in different tunnel surfaces/inclinations and the impact of different way-finding installations on exit choice.

Research methods include 1) literature reviews and surveys to identify the most common tools/approaches employed and the characteristics of the evacuation model users, 2) *a priori* simulation techniques, including sensitivity analysis of single variables 3) the analysis of data from field experiments designed to collect information for the simulation of tunnel evacuation scenarios, 4) *a priori* vs *a posteriori* modelling techniques employing the collected experimental data as benchmark for the *a posteriori* step.

Different degrees of modelling sophistication are used for the analysis of the evacuation scenarios. In the first step, evacuation models have been used independently when performing the simulations. Default settings are used for the input configuration and differences within the obtained results are identified. Evacuation times are also predicted through the analytical calculations described in the Society of Fire Protection Engineering handbook. Then the same scenarios are simulated through a process of input calibration based on the literature available on each specific variable.

The second step is the identification of the sources of uncertainty in the models, e.g., different modelling assumptions and algorithms, absent features in a specific model, etc. This analysis has been performed through sensitivity analyses and comparisons between model results and experimental data. A novel method has also been presented here, the multi-model approach in which each model is used at its best. Modellers may try to adjust the input variables within the models through an iterative process of configuration using other models as a benchmark i.e. the sub-algorithms of each model makes it possible to better configure the inputs of the others.

The last step deals with the identification of an efficient use of different approaches in relation to the differences among the methods employed. The scope is to allow modellers to properly select the right approach to study road tunnel evacuation scenarios of increasing complexity.

Model comparisons also make it possible to evaluate the differences in the results derived from the use of model default settings. This is reflected in the degree of embedded sophistication within each model, i.e., the effort required of the modeller is dependent on the complexity of the model employed. The use of analytical calculations has been identified as effective only in the case of very simple evacuation scenarios i.e. this type of solution is not able to represent people's behaviours which may be crucial during evacuations in complex scenarios. The individual use of evacuation models has been effective if the available literature provides sufficient data to calibrate the input and the models employed include sub-algorithms to simulate all the behaviours involved. If there are discrepancies in the possible manner of implementing the input, a sensitivity analysis is required to test the sensitivity of the models to that specific variable. In the example presented, the sensitivity analysis performed with six models to study the representation of the impact of smoke on agent movement speeds has demonstrated that differences in model results are relevant.

The new framework of the multi-model approach has been identified as a useful tool to test the predictive capabilities of models, in particular making it possible to provide an estimate of the uncertainty related to different variables in relation to the embedded data-sets and algorithms.

Sommario (Italiano)

La progettazione basata sull'approccio prestazionale (Performance Based Design, PBD) è attualmente utilizzata per garantire le condizioni di sicurezza delle persone in svariate tipologie di infrastrutture. La prima decisione che un progettista della sicurezza deve prendere prima di effettuare lo studio dell'esodo utilizzando il metodo PBD è la scelta dell'approccio di modellazione appropriato per l'analisi. I metodi da impiegare potrebbero variare tra semplici calcoli analitici, modelli computazionali o una combinazione di diversi modelli. Questo lavoro si concentra sull'identificazione dell'approccio appropriato da utilizzare in funzione della scala e della complessità degli scenari di esodo in esame per il caso di gallerie stradali. Gli utilizzatori dei modelli hanno la necessità di valutare i fattori che influenzano la scelta tra diversi approcci di simulazione di esodo in gallerie stradali. Infatti, le valutazioni dei modelli di esodo finora effettuate si basano principalmente su una classificazione delle loro caratteristiche in relazione alle descrizioni pubblicate dai loro sviluppatori: non vi sono numerosi studi comparativi dei risultati prodotti dai modelli per il caso di infrastrutture sotterranee. I modelli di evacuazione utilizzati nel presente lavoro sono FDS+Evac, Gridflow, buildingEXODUS, STEPS, Pathfinder e Simulex, mentre il metodo idraulico descritto nel manuale della Society of Fire Protection Engineers (SFPE) è stato utilizzato per confrontare i risultati dei modelli computazionali con dei calcoli analitici.

Il caso di incendio in gallerie stradali richiede l'analisi di numerosi fattori e processi complessi legati al comportamento umano, quali la fase di pre-evacuazione, ovvero la riluttanza degli utenti ad abbandonare il veicolo, le interazioni tra gli occupanti, le interazioni tra occupanti e fumo, ecc. Tuttavia, i modelli presentano diverse caratteristiche e non sempre permettono di simulare tutti i fattori elencati. Ogni modello possiede le proprie specifiche caratteristiche e spesso gli utilizzatori dei modelli non hanno una conoscenza approfondita delle variabili che possono essere inserite in ciascun modello e la maniera in cui esse influenzano i risultati. Ogni modello ha dei limiti che possono essere aggravati dall'inesperienza dell'utilizzatore.

Questo lavoro si concentra sullo studio dei due aspetti principali che influenzano la simulazione dell'esodo in gallerie stradali, vale a dire 1) l'influenza del fumo sulla velocità di movimento e 2) l'impatto dei sistemi di way-finding sulla scelta della via di fuga. Le differenze nei risultati ottenuti utilizzando i metodi sopra citati sono state studiate attraverso l'analisi di differenti scenari di evacuazione (che presentano diversi gradi di complessità). Essi variano da scenari ipotetici fino alla simulazione di un insieme di esperimenti reali di evacuazione in galleria effettuati presso il Dipartimento di Fire Safety Engineering and Safety Systems dell'Università di Lund in Svezia. I dati derivanti da questi esperimenti sono stati analizzati per ottenere informazioni sulla velocità di

movimento degli utenti in caso di diverse superfici interne alla galleria e diverse pendenze longitudinali. Sono stati studiati inoltre gli effetti dell'utilizzo di diversi sistemi di way-finding sulla scelta della via di fuga da parte degli utenti.

I metodi di ricerca utilizzati sono: 1) analisi della letteratura disponibile e indagini/questionari atti ad identificare i software e gli approcci più comuni e le caratteristiche degli utilizzatori dei modelli di esodo, 2) tecniche di simulazione *a priori*, compresa un'analisi di sensibilità di specifiche variabili, 3) compilazione di dati da esperimenti di campo, progettati al fine di raccogliere informazioni sull'esodo in gallerie stradali, 4) tecniche di simulazione *a priori* e *a posteriori* che impiegano i dati sperimentali raccolti durante gli esperimenti di campo come punto di riferimento per la modellazione *a posteriori* degli scenari di evacuazione.

Sono stati impiegati diversi gradi di complessità di modellazione per analizzare gli scenari di evacuazione. In una prima fase, i modelli di evacuazione sono stati utilizzati in forma indipendente durante le simulazioni. Le impostazioni di default sono state utilizzate per la configurazione dei dati di input dei modelli e si sono studiate le differenze nei risultati ottenuti. La previsione dei tempi di evacuazione è stata inoltre effettuata attraverso i calcoli analitici descritti nel manuale della SFPE. Gli stessi scenari sono successivamente stati simulati attraverso un processo di calibrazione degli input relativi ad ogni singola variabile basato sulla letteratura disponibile.

La prima fase è stata l'identificazione delle cause di incertezza all'interno dei modelli, quali le ipotesi di base riguardanti la modellazione e gli algoritmi inclusi negli stessi, eventuali caratteristiche assenti in un modello specifico, ecc. Tale studio è stata eseguita attraverso analisi di sensibilità ed attraverso confronti tra i risultati forniti dai modelli e dati sperimentali. In questo lavoro è stato inoltre presentato un nuovo approccio multi-modello in cui vengono utilizzati i modelli al meglio. Gli utilizzatori potranno infatti modificare le variabili di input dei modelli attraverso un processo iterativo di configurazione basato sul riferimento ad altri modelli. Ciò implica che i migliori sotto-algoritmi di ciascun modello permettono di configurare al meglio i dati di input degli altri software.

L'ultima fase riguarda l'identificazione di un uso efficiente dei diversi approcci di modellazione in relazione alle differenze tra i metodi da impiegare. Lo scopo è quello di permettere agli utilizzatori di selezionare l'approccio appropriato da impiegare in funzione della complessità degli scenari di evacuazione da simulare.

Il confronto tra i modelli permette inoltre di valutare le differenze nei risultati derivanti dall'uso delle impostazioni di default. Ciò si riflette nel grado di sofisticazione incorporato in ciascun modello, in quanto lo sforzo richiesto all'utilizzatore dipende dalla complessità del modello impiegato. L'utilizzo di calcoli analitici è stato identificato come un metodo efficace solo in caso di scenari di evacuazione molto semplici in quanto questo tipo di soluzione non è in grado di rappresentare alcuni fattori comportamentali che possono essere cruciali durante l'evacuazione in caso di scenari complessi. Un uso individuale dei modelli di evacuazione è stato efficace nel caso in cui la letteratura scientifica disponibile fornisca dati sufficienti per la calibrazione dell'input dei modelli i quali devono anche includere sub-algoritmi adatti a simulare tutti i fattori comportamentali coinvolti. Nel caso in cui ci siano differenze durante la fase di implementazione dei dati di input dei modelli, un'analisi di sensibilità deve verificare l'incertezza dei risultati dei modelli in funzione di quella specifica variabile. Nell'esempio presentato, l'analisi di sensibilità svolta con sei modelli è stata effettuata per studiare la rappresentazione dell'impatto del fumo sulla velocità di movimento delle persone. Questa analisi ha dimostrato che le differenze nei risultati sono rilevanti.

Il nuovo approccio multi-modello è stato identificato come uno strumento utile per testare le capacità predittive dei modelli, in particolare rendendo possibile fornire una stima dell'incertezza legata a diverse variabili in funzione dei dati sperimentali e degli algoritmi incorporati.

ACKNOWLEDGMENTS

The concept of *maestro* in Italian culture refers to a person particularly skilled in his field of activity, representing an example to follow. It is usually used in a musical context, but the meaning can be extended to any field, including academia. I must make this clear in order to speak of those people who have been to me the point of reference during the writing of this thesis. I was fortunate enough to meet *maestros* who not only shared with me their scientific expertise, but also created in me the passion for research and especially the study of human behaviour through computer modelling. The first person I would like to thank is my tutor at the Polytechnic University of Bari, Pasquale Colonna, who believed, supported, advised and guided me. He was my first *maestro*, the one without whom this thesis would not exist.

I would also like to thank those who have shared with me my time at my Italian University, Nico Berloco and Alessandra Aquilino. Nico, in particular, shared with me many wonderful experiences (our trip to the World Road Congress in Mexico will remain forever etched in my memory) and his precious advice has always helped me to make the right choices.

The search for another *maestro* led me for 2 semesters (fall 2009 and fall 2010) to collaborate with the GIDAI group at University of Cantabria, Spain. I would like to express my thanks to Jorge Capote and Daniel Alvear, who believed in me and gave me their trust. Special thanks must also go to Arturo Cuesta, who was one of the first architects of my passion for the study of human behaviour in fire and with whom I shared many hours of fruitful scientific conversation. His perspective as a "non-engineer" was for me a fundamental starting point in order to try to understand the mechanisms which regulate human behaviour. I thank those who shared with me my time in Spain: Phil Borowiec (a great co-worker and housemate), Eduardo Puente, Virginia Alonso and Alejandro Perez and all the other guys at the GIDAI group. Many, many thanks to all of you for your support.

Special thanks also to the team at the Department of Fire Safety Engineering and Systems Safety at Lund University where I was welcomed in 2011. From the very beginning they made me feel at home, not easy given the different cultural and climatic premises. I would also like to express my thanks to Daniel Nilsson, a *maestro* whose scientific knowledge I think unlimited, and from whom I learned to approach various problems. Thanks also go to all the research team with whom I shared my Swedish experience, Håkan Frantzich, Karl Fridolf and Axel Jönsson. I thank Anne Dederichs from DTU for her helpful advice during my time in Sweden. Thanks also to Rita Fahy, with whom I had the good fortune to share an office during my wonderful time in Lund. I also thank my sponsors in my Swedish period, the Lerici Foundation and the Swedish Institute, who believed in the validity of this thesis project.

I thank the team at www.Evacmod.net, in particular, Michael Kinsey, who asked me to join the team of the website and with whom I shared many interesting debates and discussions. Special thanks also to Steve Gwynne, a *maestro* who has always provided me with great advice and suggestions, given his vast knowledge in the field of evacuation modelling. This thesis would not have been the same without his valuable help.

I thank all the model developers who provided me with their software for my research: Thunderhead Engineering (Pathfinder), Mott Macdonald Simulation Group (STEPS), Timo Korhonen for FDS+Evac (thank you for patiently answering my endless questions about FDS+Evac).

In particular, I thank both Dave and Jenny Purser for their valuable advice from a scientific point of view (for me a wealth of wisdom), but especially for all those words which guided me during my PhD. Every word, comment, suggestion has been a mainspring to go forward. Thank you!

Finally, I would like to thank my mother, my father, my brother Ciccio and all my family who always supported me and given me the words needed to see "light at the end of every tunnel" (the primary goal of this thesis!).

Bari, March 2012

Enrico Ronchi

INDEX

ABBREVIATIONS/ACRONYMS

ANAS: Italian National Company of Roads (Azienda Nazionale Autonoma delle Strade)

ASET: Available Safe Egress Time

FDS: Fire Dynamics Simulator

FDS+Evac: Fire Dynamics Simulator + Evacuation

FED: Fractional Effective Dose

FSE: Fire Safety Engineering

HGV: Heavy Goods Vehicle

ISO: International Standards Office

MC: Motorcycle

NCHRP: National Cooperative Highway Research Program

NFPA: National Fire Protection Association

NIST: National Institute of Standards and Technology

PBD: Performance Based Design

RSET: Required Safe Egress Time

TRB: Transportation Research Board

SA: Sensitivity Analysis

SFPE: Society of Fire Protection Engineers

STEPS: Simulation of Transient and Pedestrian movementS

V&V: Validation and Verification

TABLES AND FIGURES

1. INTRODUCTION

Road tunnels are complex infrastructures made to meet the designer's needs to create links between different parts of a road network. Several aspects should be considered by designers while considering the option of an underground infrastructure. The construction of a tunnel generally requires higher costs than infrastructures in open space. Tunnels may represent a valid solution in the case of road layout issues, i.e., they may be used in the process of road design optimization because they make it possible to shorten the path and/or connect inaccessible areas to each other.

Tunnels may represent the crucial nodes of a road network, thus requiring special attention by the designer during the definition of their geometric characteristics. Safety measures must be designed consistently with several problems, including engineering and road layout issues as well as purely economic aspects. This must be done without forgetting the most important aspect of the design process of any infrastructure, i.e., the user's safety. The identification of the optimal safety design methods that meet all the criteria listed above is a subject of debate in the scientific community and all organizations/individuals involved in the design stage.

This thesis addresses the problem of road tunnel safety, focusing on the safety processes related to the evacuation of people in the case of fire. The analysis of tunnel evacuations in the case of fire assumes particular relevance among possible accidents due to the serious consequences which there may be in terms of loss of lives. Public awareness on this topic has been attracted by many tragic events, such as the fire in the Mont Blanc Tunnel between Italy and France [Duffé & Marec, 1999] or the Tauern tunnel fire [Leitner, 2001]. Recently, the NCHRP of the TRB provided a document [Maevski, 2011], in which an extended review of the most recent tunnel fires was made. This report highlighted that tunnel fires are far less frequent than fires in other environments. However, because of the unique nature of a tunnel fire, they showed several issues that contribute to make it more difficult to suppress and extinguish the fire, often leading to tragic consequences.

The frequency of road tunnel fires is dependent on many variables such as tunnel length, traffic density, speed control and slope of the road [Shields, 2005]. Each of these variables has to be taken into account when comparing different safety measures. As mentioned above, although the possibility of a significant fire accident in road tunnels is low, the importance of the design safety can not be underestimated. An example is that in tunnel environments, a crucial risk factor is that the probability of significant fires from HGV is higher than from passenger cars [Maevski, 2011]. The consequence is that the severity of a tunnel fire may be very high, involving a possible rapid development of untenable conditions. This problem has been shown in past tunnel fires [Carvel & Marlair, 2011]. In order to show a comprehensive description of possible tunnel fire characteristics, Table 1 and Table 2 include a list of the most important tunnel fires in the last 40 years, together with their main characteristics, i.e., year, location, tunnel length, fire duration, people and vehicles involved.

Table 1. List of the most important road tunnel fires in the last 40 years [Maevski, 2011].

Year	Tunnel	Country	Tunnel Length (m)	Fire duration	Damage		
					Injured	dead	vehicles
1970	Wallace	US	1000	/	/	/	/
1974	Mont Blanc	France/Italy	11600	15 min	1	/	/
1974	Chesapeake Bay Bridge	US	2440	4 h	1	0	1 truck
1976	Crossing BP	France	430	1 h	12	0	1 truck
1978	Velsen	Netherlands	770	1 h 20 min	5	5	4 trucks, 2 cars
1979	Nihonzaka	Japan	2045	159 h	2	7	127 trucks, 46 cars
1980	Kajiwara	Japan	740	1.5 h	0	1	2 trucks
1982	Caldecott	US	1028	2 h 40 min	2	7	3 trucks, 1 bus, 4 cars
1982	Lafontaine	Canada	1390	/	0	1	1 truck
1983	Pecorila Galleria	Italy	662	/	22	9	10 cars
1986	L'Arme	France	1105	/	5	3	1 truck, 4 cars
1987	Gumefens	Switzerland	343	2 h	0	2	2 trucks, 1 van
1989	Brenner	Austria	412	/	5	2	/
1990	Røldal	Norway	4656	50 min	1	0	/
1990	Mont Blanc	France/Italy	11600	/	2	0	1 truck
1993	Serra Ripoli	Italy	442	2 h 30 min	4	4	5 trucks, 11 cars
1993	Hovden	Norway	1290	1 h	5	0	1 MC, 2 cars
1994	Huguenot	South Africa	3914	1 h	28	1	1 bus
1995	Pfander	Austria	6719	1 h	4	3	1 truck, 1 van, 1 car
1996	Isola delle Femmine	Italy	148	/	20	5	1 tanker, 1 bus, 18 cars
1999	Mont Blanc	France/Italy	11600	2.2 days	0	39	23 trucks, 10 cars, 1 MC, 2 fire engines
1999	Tauern	Austria	6401	15 h	49	12	14 trucks, 26 cars
2000	Seljestad	Norway	1272	45 min	6	0	1 truck, 4 cars, 1 MC
2001	Prapontin	Italy	4409	/	19	0	1 truck
2001	Gleinalm	Austria	8320	/	4	5	/

Table 2. List of the most important road tunnel fires in the last 40 years [Maevski, 2011].

Year	Tunnel	Country	Tunnel Length (m)	Fire duration	Damage		
					Injured	dead	vehicles
2001	Ville Marie Tunnel	Canada	8400	/	0	0	/
2001	Guldborgsund	Denmark	460	/	6	5	/
2001	St. Gottard	Switzerland	16900	over 2 days	0	11	2 trucks, 23 vehicles
2002	Tauern	Austria	6401	/	0	1	/
2002	A86	France	618	6 h	0	2	1 car, 1 MC
2002	Ted Williams	US	2600	/	0	0	1 bus
2002	Homer	New Zealand	/	/	3	0	1 bus
2003	Locica	Slovenia	800	/	0	0	1 truck, 1 car
2003	Fløyfjell	Norway	3100	10 min	0	1	1 car, 1 MC
2003	Golovec	Slovenia	700	/	0	0	1 bus
2003	Baregg	Switzerland	1390	/	21	2	4 trucks, 3 fire engines
2004	Baregg	Switzerland	1080	/	1	1	1 truck, 1 car
2004	Dullin	France	1500	/	0	0	1 bus
2004	Kinkempois	Belgium	600	/	0	0	1 truck
2004	Frejus	France/Italy	12900	/	0	0	1 truck
2005	Frejus	France/Italy	12900	6 h	21	2	4 HGV, 3 fire fighting vehicles
2006	Viamala	Switzerland	760	/	6	9	1 bus, 2 cars
2006	Crap-Teig	Switzerland	2171	/	0	0	1 HGV
2007	Burnley	Australia	2900	/	0	3	4 HGV, 7 cars
2007	Caldecott	US, Canada	1028	/	0	0	1 car, 1 MC
2007	Santa Clarita I-5	US, Canada	165	/	23	3	33 tractor, 1 car
2007	San Martino	Italy	/	>45 min	10	2	1 HGV
2009	Eiksund	Norway	7700	/	0	5	1 HGV, 1 car
2009	Gubrist	Switzerland	/	/	4	0	2 cars
2010	Trojane	Slovenia	885	/	5	0	1 HGV
2010	Wuxi Lihu	China	/	/	19	24	1 bus

Road tunnel safety has been identified as an important topic in the context of Italian transportation research for different reasons. Italy is highly involved in this problem because of its orographic characteristics, which often require tunnels to cross mountain areas. In fact, Italy is the country with the largest tunnel network in Europe [Federal Highway Administration, 2006]. Hence, the problem of studying in detail the methods to assess tunnel safety has great relevance among the possible issues of its road network. The current trend shows that an increasing number of complex road tunnels are being built [Ingason & Wickström, 2006]. On the other hand, the safety systems are often "*based on traditions that were developed for much simpler applications*" [Ingason & Wickstroem, 2006].

The debate on this theme is based on the study of different strategies for fire safety design. Methods need to be suitable to ensure adequate levels of safety as well as to optimize the available economic resources. In this context, the assessment of the best procedure for the design of the means of egress is a fundamental issue for the tunnel safety analyst.

As for the case of the design of building infrastructures, the case of tunnel safety presents the contraposition between the traditional prescriptive codes and the application of the new concepts of Performance Based Design (PBD). The second approach is associated with the new tools and models of Fire Safety Engineering (FSE). Prescriptive codes simply provide a set of measures to be applied by designers in a systematic way. Performance Based design methods are based on a comparison between the ASET (Available Safe Egress Time) and the RSET (Required Safe Egress Time) in order to verify the achievement of the desired performance. ASET is a threshold that indicates the tenability limit after which the conditions of the given environment become unacceptable. RSET is instead the time needed by occupants to perform a safe evacuation of an infrastructure. In some cases, the application of prescriptive codes may cause a situation in which the suggested measures are not sufficient to guarantee the safety of occupants [Tavares, 2009].

The PBD approach generally applies a simple time-line model [BS PD7974, 2004, Purser & Gwynne, 2007] to simulate evacuation. It consists in the description of the course of events as a list of sequential steps. The interpretation of occupant behaviour is then made through the sum of different times. The time-line method is currently used in engineering analysis since it allows the easy evaluation of the margin of safety by the comparison between the RSET and ASET.

The calculation of ASET is based on different tenability criteria, i.e., smoke layer heights, intoxication, etc. One of the main criteria is related to the doses of toxic products inhaled by occupant during the passage of time. ASET is generally calculated in this case through the Fractional Effective Doses (FED). FED concept has been presented by Purser [2008] and then introduced in several international technical guidance, e.g., NFPA502 [NFPA, 2011], ANAS recommendations for road tunnel safety [ANAS, 2009], etc. The basic concept is that the body of an exposed individual can be regarded as acquiring a “dose” of toxic products over a period of time. An occupant is considered incapacitated or dead if he/she inhales a certain dose of toxic gases. For use in the modelling of life threat, this is generally considered as the main risk factor, although there are other factors to be taken into account, e.g., heat effects, smoke obscuration levels, etc.

The analysis of the safety conditions of an infrastructure is then calculated through the determination of the time which individuals have inhaled a toxic dose of gases. This may be estimated through the integer of the area under the fire profile curve of the toxicant under consideration. Occupants can be assumed to be incapacitated when the integer of this area corresponds to the toxic dose. The dose inhaled at a certain time (C*t*) can also be divided by the toxic dose (C*toxic*) (see Eq. 1). This makes it possible to calculate a fraction which gives information on the risk conditions within the infrastructure at a certain time. These fractional effective doses are summed during the exposure until the fraction reaches unity, i.e., this is the moment when the inhaled dose is toxic [Purser, 2008].

$$FED = \frac{C_t}{C_{toxic}} \qquad \text{[Eq. 1. Purser, 2008]}$$

The need for an in-depth analysis of the methods of calculating the RSET during tunnel evacuations comes from the fact that the analysis of the RSET has not been the object of the same amount of studies as the ASET. This is a general concept that has been stated for the case of building design by Averill et al. [2008], but which can also be applied to the case of tunnel safety. This problem is the consequence of the challenging nature of RSET due to the presence of components related to human behaviour.

The context of International codes concerning tunnel safety includes both the two above described possible types of method, i.e., prescriptive and performance based. Current standards may also include the possibility to use both methods, e.g., the European Directive 2004/54/EC [Council Directive, 2004], where different methods may be applied to justify the safety design solutions employed.

The European Directive 2004/54/CE [Council Directive, 2004] is the reference for the definition of the minimum safety requirements for tunnels belonging to the Trans-European network. Following the general purpose of any European Directive, the 2004/54/CE provides information on the general objectives to be achieved and among them it states the need for the application of risk analyses as the tools to be used for assessing road tunnel safety. This means that the technical guidance of each nation based on this Directive can provide its own methodology to carry out this kind of analysis. International standards, e.g., the American code NFPA502 [NFPA, 2011], also include information on the application of the new PBD methodologies.

As in the case of building regulations, another important aspect is the inconsistency in standards. This was pointed out in a recent analysis of the available technical guidance for tunnel safety made by Maevski [2011]. Considerations may also been made on the type of road tunnel under consideration, whether it is a road tunnel for vehicles or designed for a mixed use - pedestrian and vehicles. For example, NFPA502 [NFPA, 2011] differentiates the two cases and provide different requirements for the two types of tunnels. In contrast, Italian legislation does not provide for specific regulations for mixed-use tunnels. In particular, the case of mixed-used urban tunnels may present issues completely different than other tunnels [Ronchi et al., 2009].

The innovation of PBD methods derives from the fact that designers can use computational simulation tools to reproduce the evacuation scenarios. This makes it possible to test the level of safety of the tunnel through the analysis of a numerical output. The current state-of-the-art presents many methods and models [Kuligowski, 2010], but these are often designed and validated for environments other than tunnels, i.e., buildings; therefore their use requires a thorough study in order to verify their applicability to the specific issues of a road tunnel.

These models represent a useful tool to perform risk analysis in tunnels. Their flexibility makes it possible to simulate a large number of scenarios in a relatively short time. The strengths of these methods are also related to the fact that several parameters may be easily modified, thus allowing sensitivity analysis (SA) to be performed, i.e., to test how the variation (uncertainty) in the output of a model can be attributed to different variations in the input of the model. In contrast, traditional methods of tunnel risk analysis [ANAS, 2009] are generally probabilistic, often based solely on historical accident databases. The applicability of probabilistic method is then linked to the availability of accident databases. As previously pointed out, the frequency of road tunnel accidents is lower than in open space [Maevski, 2011] and this lack of data highlights the difficulties in collecting information from actual events about accident probabilities, types of evacuation, etc.

The lack of behavioural data for the calibration of evacuation models is also reflected in international codes. These often provide only general information, e.g., Italian ANAS Guidelines [ANAS, 2009] or NFPA502 [NFPA, 2011] on issues related to the people performance during evacuations and the methods to simulate them.

Safety designers need then to simulate road tunnel evacuations without full information on the input to be considered within the models and the models themselves. This problem is further amplified in those countries where there are no (or few) specific academic courses aimed at training fire safety engineers (and tunnel engineers), e.g., Italy, and the PBD approach is relatively new. This creates a gap of knowledge in both designers and authorities that should decide the approval of the tunnel safety design.

Hence there is a serious risk to society because of the consequences in terms of loss of lives due to the deficiencies in fire safety design, as has been seen in previous tragic events in tunnels. The research objectives of the present work are designed in order to fill this gap of knowledge and solve the above described issues. They are presented in next section 1.1.

1.1 Research objectives

The previous section has identified the key problems related to the study of road tunnel evacuation. The use of evacuation simulation tools is here proposed to solve these issues. Several aspects of the application of these tools have been studied in the present work. A set of the most used evacuation models has been analysed together with specific studies addressed to solve different problems of the simulation of tunnel evacuations. Several simulation methods have been tested in order to simulate the main processes affecting users' behaviours.

The research is based on three key objectives:

1) The first objective is to identify the most known available simulation tools and test them for the case of road tunnel evacuations. This is made considering different aspects of the modelling process, including:

- The impact of the model on results, i.e., model capabilities and features, default settings and assumptions, single or multiple use of models.
- The modeller's impact on results, i.e., the choice of the model input, modeller's experience, availability of experimental data.

This analysis is based on the test of the characteristics of the models as well as a set of examples. The use of experimental data also makes it possible to perform an *a priori* vs *a posteriori* modelling analysis, thus allowing the testing of the predictive capabilities of the models.

2) The second objective is to analyse and utilize new data for the calibration of the model input for tunnel evacuations. This is made through a set of experiments which have been carried out at the Department of Fire Safety Engineering and Systems Safety of Lund University, Sweden. Experimental data need to be compiled and presented in order to be directly employed for modelling purposes. In particular, data have been collected on two fundamental aspects of the tunnel evacuation:

- The influence of smoke on an occupant's movement speeds and behaviours.
- The influence of smoke on an occupant's exit choice.

3) The third objective - which is the ultimate goal - is to demonstrate the applicability of evacuation models as a useful tool for studying road tunnel safety, identifying the most appropriate approaches in relation to the complexity of the scenarios. The aim is to provide a description of the methods to apply these tools. A new method able to employ together different models needs to be identified in order to address very complex scenarios. Examples and applications need to be provided in order to assist the designer in choosing the approach to simulate the tunnel evacuation scenarios under consideration.

1.2 Limitations

All research studies contain limitations and this thesis is no exception. Identification of relevant limitations is crucial for a correct interpretation of the results and the methods employed. This also makes it possible to extrapolate the findings to new applications. The main limitations of this thesis are presented in this paragraph together with some suggestions about the interpretation of the results.

A set of comments about the way in which safety designers may interpret the presented work is required. The application of the PBD approach shows the difficulty *per se* of performing a standardization of the methods to be employed. The reason is that this is an extremely flexible methodology strictly connected to the needs of the scenarios to be studied and the needs of the safety designer. In addition, the constant development of new techniques/methods for optimizing the evacuation process may lead to a need for a constant update of the presented methods and procedures, i.e., simulation tools should always take into account advances in technology.

This thesis gives the tunnel safety designer a global view of the problem of road tunnel evacuation in the case of fire. At the same time, this work tries to define the best modelling strategy to be used without representing a strict method to be applied; tunnel safety designers have the freedom to use any other tool or modelling approach different than the one presented in this work if they think it is more suitable for the scenario under consideration. However, the main strength of this work is a comparison of a relevant number of evacuation models and techniques for assessing tunnel safety analysis. To date, scientific literature does not currently include this type of study, i.e., an extended model comparison among models and experimental data applied for tunnel environments. The comparison between different simulation tools needs an additional effort by the reader to fully understand the causes of the differences in the results; the identification of their causes is in fact crucial for the correct interpretation of the results.

A key aspect on this issue is the choice made by the regulators of the different national and international technical guidance to give the tunnel safety designer a certain level of freedom about the tools and approaches to use when applying evacuation models. A possible interpretation of this choice is an attempt to avoid a sort of *prescription within the performance* that would arise in the case of a too detailed method presented within the technical guidance. On the other hand, this field is relatively new and the evolution of the available models and experimental data-set is rapid. The consequence may be that this guidance would be not up to date with the most recent advances in research. Consequently, current technical guidance may be interpreted as a prudential approach by regulators. In addition, the currently available models may present some limitations in their Validation and Verification (V&V) and the debate within the International Research Community has not produced a standard method to perform V&V for this type of model.

The other main issue is the lack of a unique, well consolidated behavioural theory able to explain human behaviour in fire [Kuligowski, 2011a]. Hence, the task of the evacuation modeller becomes difficult because it often has to tackle problems where the empirical information is extremely scarce and gaps are evident in current behavioural prediction techniques.

Another point that may be questionable is the definition of the aspects that have been considered in the present work as crucial for the simulation of the tunnel evacuation process. The two considered aspects are the influence of smoke on an occupant's movement speeds and the occupant's exit choice. The smoke effects are investigated only from the point of view of the effect of visibility conditions on human behaviour. The toxic effects of smoke have been only partially taken into account because they were already object of detailed studies, including in tunnel environments [Purser, 2008, Purser, 2009]. In addition they are usually part of fire modelling analysis which is out of the scope of this thesis. Consequently, it is suggested that readers should first make an appropriate review of the available material concerning this issue before reading this thesis.

Another limitation of the present work is the lack of a dedicated analysis on vulnerable users, i.e., people with disabilities, children, etc. whose behaviour may strongly affect the final outcome of a fire engineering analysis. Little research has been carried out on this topic [Bernardi, 1999, Boyce & Shields, 1999a, 1999b, 1999c, Boyce et al., 1999, Hedman, 2009, Larusdottir & Dederichs, 2010, Sime, 1987, Ronchi et al., 2011], including the development of dedicated evacuation modelling tools [Christensen & Sasaki, 2008, Christensen et al., 2006], but the variability of the possible impairments and the subsequent effects on human performances show the need for further experimental work. From a tunnel evacuation modelling perspective, a dedicated analysis on this issue is still needed.

A crucial aspect of tunnel evacuation is the phenomenon of group interactions, intended as the effects of the presence of others on individual behaviours. Current evacuation models present algorithms to simulate group behaviours, e.g., the herding behaviour sub-model in FDS+Evac [Korhonen & Heliövaara, 2011]. Unfortunately, the lack of knowledge on actual human performance means that making the validation of these algorithms is very difficult. This aspect may have a fundamental role during tunnel evacuations, but the current information available on this topic is scarce. In particular, the case of road tunnel evacuations has its own specific problems related to the presence of an underground environment. The consequence is that - due to the lack of knowledge – the application of the available evacuation tools for simulating this aspect is complex. However modellers should try to evaluate the consequences of this factor during their safety analysis. Hence this thesis does not want to neglect the importance of this variable. For this reason, there is a brief section dedicated to a review of literature on this topic; thus permitting modellers to use the information provided to identify conservative enough assumptions and take this aspect into consideration.

1.3 Outline of the thesis

The present thesis consists of six chapters and one appendix. In Appendix I, the 6 papers are presented. Each paper explores different aspects of the simulation of evacuation during tunnel fires. The chapters present the fundamental aspects to be considered for simulating evacuation in road tunnels as well as the description of the research methods employed. The detailed analysis of each single aspect is then presented in the six papers, where the single issues have been investigated.

In Chapter 1 (Introduction), the research problem is described, paying attention to the research objectives and the reasons leading to the investigation of this theme. The limitations of this work are also presented. The outline of the thesis is explained and relevant publications are given in the final part of Chapter 1.

In Chapter 2 (Methods), there is the description of the research methodologies employed to perform the study of the simulations of road tunnel evacuations. In particular, the focus is on the methods to evaluate the current knowledge on actual tunnel fires as well as different strategies to test the applicability of modelling tools.

Chapter 3 (Evacuation modelling) deals with general information about evacuation modelling. The chapter includes a description of the basic modelling assumptions made by models with particular attention to the different types of structures employed by the models. In particular, the characteristics of six evacuation models have been briefly summarized, namely FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], Gridflow 3.03 [Bensilum & Purser, 2003], buildingEXODUS 4.1 [Galea et al., 2004], STEPS 4.1 [Mott Macdonald simulation group, 2011], Pathfinder 2011 [Thunderhead Engineering, 2011] and Simulex 5.8 [Thompson & Marchant, 1995]. A discussion on the impact of different factors on evacuation model results is also provided.

Chapter 4 (Evacuation modelling in road tunnel fires) provides information on the time-line model which is embedded in evacuation models with the subsequent data needed to calibrate the input in the case of road tunnel evacuation. Data-sets available are summarised from a modeller perspective, i.e., the analysis of the data is made in a way that relevant information for the simulation of human behaviour in tunnel fires is highlighted. Different factors have been discussed, including the variables affecting the simulation of the pre-evacuation phase and the travel time. The analysis is based on the available literature as well as the compilation and use of new experimental data included in this thesis. In fact, the author of the present work has been involved in the planning, execution and analysis of a set of tunnel evacuation experiments performed at the Department of Fire Safety Engineering and Systems Safety of Lund University, Sweden within the METRO project [www.metroproject.se]. A multi-model approach has also been proposed; this method makes it possible to simulate very complex scenarios, starting from an iterative process of input calibration. The final part of this chapter describes the benefits to be had from the application of different approaches in accordance with the scenario complexity and the variables to be considered.

Chapter 5 (Conclusions) contains the conclusions. This chapter briefly summarises the recommendations to road tunnel safety designers when applying evacuation models. Suggestions about future research topics are provided in Chapter 6 (Future research).

1.4 Publications

The present thesis is mainly based on the 6 papers that are presented in Appendix I. However, the author has been involved in the study of other aspects of evacuation research, such as general issues about road tunnel safety, the study of urban tunnels, etc. Some of this research is relevant for the study of road tunnel evacuations and results from these studies are therefore mentioned in the thesis. The following sections include references to both the thesis papers and related publications. The degree of responsibility and work effort of the author for the different stages of the six papers is also provided.

1.4.1 Thesis papers

The six papers of the present thesis have been submitted to either scientific journals or presented at conferences. To date, three papers have been already accepted, while the others are currently under review. An extended abstract has been reviewed for paper I, while the other 5 papers have been submitted for full review (Paper II, III, IV, V and VI).

The VI papers of the thesis are:

Paper I	**Ronchi E** & Kinsey M (2011). *Evacuation models of the future. Insights from an online survey on user's experiences and needs.* In Capote J (ed) et al: Advanced Research Workshop Evacuation and Human Behaviour in Emergency Situations EVAC11, Santander, pp. 145-155**.**
Paper II	**Ronchi E**, Colonna P, Capote J, Alvear D, Berloco N, Cuesta A (2012). *The evaluation of different evacuation models for assessing road tunnel safety analysis*. Tunnelling and Underground Space Technology - In Press
Paper III	**Ronchi E,** Gwynne SMV, Purser DA, Colonna P (2012). *Representation of the impact of smoke on agent movement speeds in evacuation models.* (Manuscript submitted for publication to Fire Technology)
Paper IV	**Ronchi E**, Nilsson D, Gwynne SMV (2012). *Modelling the impact of emergency exit signs in tunnels*. Fire Technology - In Press.
Paper V	Fridolf K, **Ronchi E**, Nilsson D, Frantzich H (2012). *Movement speed and exit choice in smoke-filled rail tunnels.* (Manuscript submitted for publication to Fire Safety Journal)
Paper VI	**Ronchi E** (2012). *Testing the predictive capabilities of evacuation models for tunnel safety analyses*. (Manuscript submitted for publication to Safety Science)

The author of the present thesis has been actively involved in all steps of the six papers. Table 1a and Table 1b present an approximate estimation of the degree of responsibility and work effort for the different steps of each paper. Three different categories have been identified to describe the degree of responsibility and work effort according to the following classification:

Minor	The author's responsibility was minor and a small proportion of the work was performed by the author (less than 1/3 of the responsibility and work effort).
Medium	The author's responsibility was medium and approximately half of the work was performed by the author (between 1/3 and 2/3 of the responsibility and work load).
Major	The author was the one mainly responsible for the work and performed a large proportion of the work (more than 2/3 of the responsibility and work load).

Five consecutive steps according to *Table 3* and *Table 4* have been found to divide the paper's work load. *Step 1*, which is called *planning and preparation*, includes the definition of the idea of the paper and the work to gather the data useful for starting the work. This work includes, for example, the formulation of research objectives, design of the study, development of study procedures and definition of the simulation work to be made. *Step 2*, which is called *execution*, includes, for example, the simulation work, including the calibration of the model input, definition of the assumptions to be made and running the simulations. Hence, the analysis of the results is made and relevant conclusions are described in *Step 3*, which is called *analysis*. The analysis includes activities for examining the data in relation to the research objectives, such as performing statistical analysis of the simulation results. The *preparation of paper* is *Step 4*. This includes writing up and submitting the paper. *Step 5* is the *presentation at conference* and is only relevant for the paper which has been presented at a conference. Paper I has been presented at a conference by the author of the present thesis.

All of the simulation work was performed by the author of the present thesis. The only exception is the application of the buildingEXODUS model for which Dr. Gwynne assisted. Dr. Gwynne executed the buildingEXODUS simulations in accordance with the definition of the scenarios and the necessary input information provided by the author of the present work.

Table 3. The degree of responsibility and work load of the author for papers I, II, III.

Step	**Degree of responsibility and work load**		
	Paper I	Paper II	Paper III
Planning and preparation	Medium	Major	Major
Execution	Medium	Medium	Medium
Analysis	Medium	Major	Major
Preparation of paper	Medium	Medium	Major
Presentation at conference	Major	N/A	N/A

Table 4. The degree of responsibility and work load of the author for papers IV, V, VI.

Step	**Degree of responsibility and work load**		
	Paper IV	Paper V	Paper VI
Planning and preparation	Medium	Minor	Major
Execution	Major	Minor	Major
Analysis	Medium	Major	Major
Preparation of paper	Medium	Medium	Major
Presentation at conference	N/A	N/A	N/A

1.4.2 Related Publications

Along with the six papers presented here, the author has also contributed to additional publications that are relevant for the study of evacuation modelling for road tunnel safety analysis. Part of the research covered in related publications is transferable to the problems that are studied in the present research. These related publications include one paper accepted for publication in a full peer-reviewed journal (in Spanish) and 5 papers presented at conferences (all these papers were presented by the author of this thesis):

1) Capote J, Alvear D, Berloco N, Colonna P, Cuesta A, **Ronchi E** (2012). *Análisis comparativo de diferentes métodos de simulación para el análisis de la evacuación en túneles de carretera* [in Spanish]. (*Comparative analysis of different simulation methods for the analysis of road tunnel evacuation*). Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería. (International Journal of Numerical Methods for Engineering Calculations and Design) Vol. 28, Nº 2.

2) **Ronchi E**, Gwynne SMV, Purser DA (2011). *The impact of default settings on evacuation model results: a study of visibility conditions vs occupant walking speeds*. In Capote J (ed) et al: Advanced Research Workshop Evacuation and Human Behaviour in Emergency Situations EVAC11, Santander, pp. 81-95.

3) **Ronchi E**, Berloco N, Colonna P, Alvear D, Capote J, Cuesta A (2011). *Sviluppo di un database per la simulazione di persone disabili nei modelli computazionali di evacuazione* [in Italian]. (Developing a Database for simulating disabled people within evacuation models), Sicurezza Sistemi Complessi, Bari (Italy).

4) **Ronchi E**, Berloco N, Colonna P (2011) *Human behaviour in road tunnel safety design: evacuation modelling vs Italian risk analysis method (IRAM)*. XXIV PIARC World Road Congress, Mexico City (Mexico).

5) **Ronchi E**, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2010). *Human behaviour in road tunnel fires: Comparison between egress models (FDS+Evac, STEPS, Pathfinder)*. In Proceedings of the twelfth international Interflam 2010 Conference, Nottingham (UK), pp. 837-848.

6) **Ronchi E**, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2009). *Human Behaviour in case of Fire inside an Urban Tunnel through Computer Modelling*. In Proceedings of the Advanced Research Workshop on Fire Protection and Life Safety in Buildings and Transportation Systems 2009, Santander, Spain, pp. 349-361.

2. METHODS

The choice of a proper research strategy is a crucial point to solve a scientific problem. Evacuation modelling is a multi-disciplinary science that involves different research fields, i.e., psychology, fire safety engineering, physics, mathematics, chemistry, computer science, etc. [Kuligowski, 2011b]. In order to achieve the key objectives of the work it is necessary to tackle the problem from different perspectives and then apply the knowledge acquired to each specific aspect. Research methods should then be aimed to collect the information needed to solve the scientific problem, eventually applying different strategies. A poorly considered strategy can dramatically reduce the quality of the research and affect the reliability/applicability of the results.

This chapter deals with the methodological aspects applied during the research, including the logical *iter* within them.

2.1 Quality of Research – reliability and validity

The analysis of two fundamental aspects is required to define the quality of research, namely result validity and reliability. Reliability refers to the repeatability of a study, i.e., the possibility to apply the methods and data presented in other studies. It is strongly affected by the experimental data and modelling techniques employed. The work must be documented in detail in order to ensure that it can be repeated. The calibration of the input must be clearly stated as well as the model limitations.

The validity of a study refers to the correctness of the results. Validity can also be interpreted as the extent to which a study measures what it is supposed to measure. One of the most difficult tasks during every type of measurement is the interpretation of the results obtained. For this reason, the reliability of a procedure/method gives only information about the measurement itself, without providing information on the nature of the studied issue. In the field of evacuation modelling, this problem is demonstrated by the fact that a model should be capable of reproducing specific processes, scenarios or behaviours; those represented issues must be in line with certain hypothesis. Difficulties derive from the fact that validation can be tested within a system of pre-defined hypothesis on the evacuation process, but these hypotheses may also not be correct.

The definition of validation itself in the context of simulation models is still controversial [Rykiel, 1996]. Validation is not necessarily simply a procedure for testing scientific theory or certifying the correspondence between the model and reality, i.e., the current understanding of a problem. Rather, validation, in a more general sense, can mean that a model is suitable for its intended use because it meets specified performance requirements.

Before the problem of validating a model/approach, several aspects must be addressed, such as 1) the purpose of the model/approach, 2) the performance criteria and 3) the model/approach context. Validation may be part of the model building process [Overton, 1977] and tests are required after the model is built. The majority of simulation models are built to meet practical engineering needs. The validation process reflects ambiguity about the certification of the capabilities of a model. The key objective is to define if the model/approach is 1) acceptable for its intended use, i.e., if the model/approach is able to reproduce reality well enough for its intended purpose [Giere, 1991] and 2) scientific hypothesis testing, i.e., how much confidence to be placed in its representation of the real system [Curry, 1989]. This means that the scope of the tunnel safety analyst should be both to test the ability of the model to reproduce reality as well as to evaluate its usability in its context of use. Empirical data and measures are then necessary to perform these two analyses.

The effectiveness of simulation tools and methods are affected by several problems:
- The selection of the appropriate scenario to be modelled;
- The calculations made by the chosen model;
- The correct interpretation of the results provided by the model calculations;
- The need to provide appropriate inputs to the scenario to be modelled.

This last problem is strongly affected by the expertise of the users, generating what is called in the present work the *user effect*. The *user effect* is the process of calibration of the model/s input that is determined by different factors such as the experience of the user with the model/s and the familiarity of the user with the scenario to be simulated. Different degrees of expertise may cause different assumptions in the application of evacuation models and the subjective user's influence may be even more important than the model itself [Ronchi et al., 2011b]. This means that the research of an ideal tool should be found in the search for a method/model able to leave as little space as possible to the *user effect*, and find methods that can be effectively employed by users with different degrees of expertise. Inaccurate assumptions about the ways of simulating human response during emergencies may otherwise easily arise [Kuligowski, 2011a].

2.2 Research Methods

The solution of a research problem is strongly dependent on an appropriate choice of the research methods to be used. There are many different research methods, including literature reviews, experiments, case studies, surveys, etc. Not all methods are suitable for a specific problem [Yin, 2003]. The choice of the appropriate research methods is strongly dependent on the research objectives and on the problems that the research is trying to address. For example, experiments and case studies are useful for the definition of *how* and *why* a process works in one way. These types of questions are difficult to address with literature reviews and surveys, which are more suitable for answering questions like *who*, *what*, *where*, *how much* and *how many* [Yin, 2003].

The methods eventually employed are then driven by the research objectives of the research. The present work is formulated to answer questions such as: *what* are evacuation models? *How* are they designed? And *how* and *why* should they be used to study the evacuation processes in the case of a road tunnel fire? Consequently, the starting point of the thesis is understanding 1) *what* are evacuation models and *who* is part of the evacuation modelling community 2) *how* they work, 3) *why* and *when* people should use them for road tunnel evacuation studies. The first question may be addressed through a literature review about their current features and a survey about model users. At the same time, the second step - a more detailed analysis of the model capabilities and features – should be made through the analysis of hypothetical scenarios, i.e., evacuation model simulations, and simulation of experiments, i.e., detailed studies on human behaviour in tunnel fires. The final scope is then to evaluate the model's strengths and limitations and test different approaches for their use in tunnel fire evacuations.

Two different sets of research methods are discussed in this section. The first set deals with the study of the information about the process of evacuation in road tunnel fires, i.e., how people behave in a tunnel fire. The second set of methods relates to the techniques that may be employed to test the features and the predictive capabilities of evacuation models.

2.2.1 Real evacuation scenarios

This section provides the research methods that can be applied for studying Human Behaviour in road tunnel fires. This is a pre-requisite to the modelling step and researchers need to evaluate these methods in order to find the optimal research strategy for their objectives.

2.2.1.1 Case studies

Road tunnel fires can provide detailed information about the performances of people and consequently be a significant help to the evacuation modeller to correctly simulate evacuation scenarios. Nevertheless, accidents need to be analysed systematically to correctly evaluate the information provided. Information obtained through this type of accident analyses is collected in their actual context, i.e., they happen in their natural environment. Consequently, the context is not artificial as it may be during evacuation experiments.

Official investigations of road tunnel fires are a possible example of case studies. They may include valuable information about human behaviour in the case of fire. Several examples are available in the literature, such as the reconstruction of the Mont Blanc accident between France and Italy made both by Purser [2009] and the report by Duffé and Marec [1999], the report on the Burnley fire in Australia made by Johnson & Barber [2007] or the study of the Tauern fire in Austria [Leitner, 2001]. Different sources of information are generally used during the analysis of the accidents: 1) interviews, 2) observations and 3) computer simulations. The validity of the study is increased by the convergence of different analyses.

Case studies may also be focused on the analysis of multiple case-studies [Yin, 2003]. An example is the report made by Maevski [2011] for the NHRCP of TRB on tunnel fires. This document includes a discussion about the factors related to human behaviour based on several road tunnel fire accidents. Data from official reports were extracted and useful information about the simulation of the evacuation process was provided. An extensive review of underground accidents has been provided by Fridolf et al. [2011] where the current findings coming from the analysis of the most important underground evacuation situations have been summarised.

Official tunnel fire reports generally focus on the reconstruction of the chain of the events, providing details and information that may be useful for the definition of the input of an evacuation model. Unfortunately, detailed reports are scarce and the lack of knowledge about human behaviour processes is evident.

2.2.1.2 Experiments

Different types of experiments may be performed, including experiments performed in controlled laboratory environments or in real life settings, i.e., field experiments [Christensen, 2007]. Experiments may present several differences but they have some main features in common. They are all based on the observation of a certain phenomenon. Another common point of any experiment is that the situation is controlled by the researcher and the test participants are observed by them. The degree of control of the situation may vary and it is dependent on the nature of experiments. Different types of phenomena may be studied, but they should be designed in a manner that researchers can record the information observed applying different data collection techniques, e.g., questionnaires, interviews, observations, etc.

Current literature includes experiments where human behaviour in road tunnel fires has been investigated. Fridolf et al. [2011] reviewed the main areas of empirical research in this field, including 1) information to initiate evacuation, 2) flow constraints, 3) movement speed and 4) information for way-finding. Examples include real-setting experiments performed to study these different aspects, such as time to abandon the vehicles [Boer & Veldhuijzen van Zanten, 2005, Nilsson et al., 2009], flashing lights impact on way-finding [Nilsson, 2009], movement speeds in smoke [Frantzich & Nilsson, 2003, Bellamy & Geyer T, 1990], etc. Controlled laboratory experiments are also useful to study evacuations in smoke-filled environments. The collected information may be extrapolated and applied for road tunnel evacuations, e.g., the experiments made by Jin, [1976], Xie [2011] and Zhang [2010]. Virtual tools, e.g., driving simulators, were also employed to design experiments to collect information on particular aspects of the tunnel evacuation process such as the time to leave vehicles in relation to the safety information provided to users. This type of experiments was made by TNO during the UPTUN project [Khoury, 2003].

The task of the evacuation modeller is to review the relevant empirical information that may be useful for the application of simulation tools. The scope is in fact to use the collected information to calibrate the input of the simulation method employed.

2.2.2 Modelling evacuation scenarios

This section describes the research methods that can be used to evaluate the features and predictive capabilities of evacuation models. These methods include archive analysis and surveys aimed to study the model capabilities. The analysis of V&V techniques and tests of model uncertainty have been identified as useful techniques to study the applicability of evacuation models for road tunnel environments.

2.2.2.1 Archive analysis and surveys

The first step to define the applicability of evacuation models in the case of road tunnel fires is the analysis of the current features of the models. In order to address this point, this section describes a list of the available model reviews made in the past. These have been useful to define *what* evacuation models are.

There are six evacuation model reviews useful for the definition and characterization of evacuation model capabilities which can be considered as most relevant. The most important and recent review of evacuation models was made by Kuligowski et al. [2010], where the main characteristics of 26 models was presented. A detailed categorization of the model features was also provided. Most important features include the definition of the modelling methods to represent model agents, sub-algorithms, validation methods, etc.

Another detailed review was conducted by Gwynne et al. [1999] at the Fire Safety Engineering Group of the University of Greenwich in 1999. Sixteen evacuation models were reviewed in this study. The Combustion Science and Engineering Institute also created a publicly available webpage with the collected information about fire and egress models [Olenick & Carpenter, 2003]. Other evacuation model reviews have been performed by Santos et al. [Santos et al. 2004], Watts [1987] and Friedman [1992].

As pointed out by Kuligowski [2010], there are different problems connected to this type of evacuation model review. The key issue is related to the rapid advances in the evacuation model capabilities which make it difficult to provide up-to-date information.

To help address this issue the team at www.Evacmod.net has developed a model directory (the author of the present work is part of this project) in collaboration with Erica Kuligowski at NIST based on her review of evacuation models. This project allows model developers to provide up to date information about models on the site themselves. This provides a central resource for existing and potential future model users to find out more information about each model. Both existing and potentially new model users can use this model directory to assess criteria that should be considered when selecting/using an evacuation model. To date, the www.Evacmod.net model archive includes approximately 60 evacuation models.

Further aspects of the applicability of these reviews should be considered. The available reviews give a global picture of the evacuation model features and provide useful information for the choice of a model. On the other hand, they are essentially based on the analysis of the model characteristics provided by the model developers, i.e., there is no comparison test made by the reviewers of all the models included. This is mostly caused by the difficulties in comparing such a high number of models for an incredibly vast range of scenarios and uses. Model users are then required to make an additional effort to decide whether a tool is suitable for their scope.

2.2.2.2 Model uncertainty

The application of evacuation models requires a discussion on the methods for testing their predictive capabilities. Since road tunnel evacuations in the event of fire present a lack of knowledge on several aspects of human behaviour, there is a need to apply solutions able to tackle the uncertainty of the results obtained. Two main methods may be employed to tackle model uncertainty, namely 1) safety factors and 2) sensitivity analysis.

The simplest method to be used is the application of safety factors. Safety factors are generally used in engineering analysis when a modeller is aware that the model in use is affected by uncertainty. They are often used when comprehensive testing is impractical. In the case of evacuation analysis, safety factors may be applied in the input calibration step, i.e., input is chosen in a conservative way by modifying the value provided in the literature for that specific variable/parameter. The alternative use of safety factors is during the output analysis. In this case, the modeller provides an estimate of the uncertainty related to a certain aspect of the evacuation process and defines a number to be added/multiplied for the RSET in order to obtain a new RSET*. The margin of safety between ASET and RSET* is then re-calculated. The choice of the numerical values of the safety factors may be based on a modeller's evaluation determined by his/her experience or based on numerical outputs provided by other users/models/experimental data for a similar scenario.

An alternative method for testing the uncertainty of the evacuation predictions is the application of a sensitivity analysis (SA). SA is the study of the uncertainty in the output of a model in relation to different variations in the input of the model [Saltelli et al. 2008]. The application of SA is useful for computer modellers for a range of purposes, such as increasing the understanding or quantification of the studied system. This means that SA may be used to evaluate the importance of a single variable in the total outcome produced by the model/s. A method for applying SA for evacuation models has been described by Lord et al. [2005] for building environments. To date, there is no evidence of the application of this method for road tunnel evacuation scenarios.

2.2.2.3 V&V

There are various research methods used to study the Validation and Verification of a model. Verification tests of the models are performed by verifying that the implementation of the underlying conceptual model works as it is supposed to do. This is generally done by the model developers and evidence of the results is usually available in the evacuation model technical references, e.g., FDS+Evac [Korhonen and Hostikka, 2010], STEPS [Mott Macdonald simulation group, 2011], Pathfinder [Thunderhead Engineering, 2011], etc.

Validation is instead a sensitive area in the evacuation modelling community because of the lack of an international standard on the way to perform it. The reliability of models is also generally affected by the lack of experimental data on people's performance.

Several examples of evacuation model validation exercises are available in the literature, e.g., the works made by Frantzich et al. [2008], Galea [1998], etc. The validation of an evacuation model is generally performed through testing its predictive capabilities within a set of standard environments, e.g. buildings, or standard layouts such as the IMO tests [2007]. Unfortunately, non-expert users may consider model results as reliable in unique environments as well, and extend their use to applications where no *ad hoc* validation tests have been performed. A clear example is the application of building evacuation models to road tunnel environments. The use of a model beyond its validation evidence requires then an additional effort by the evacuation modeller to understand the model limitations in representing the evacuation process in that specific environment.

Different methods can be employed to perform validation [Kuligowski, 2010]. It may be performed against code requirements. The model predictions may also be tested against experimental data from evacuation experiments, fire drills or trial evacuations. This type of test makes it possible to isolate single aspects of the evacuation process, as experiments with the specific aim of testing a single variable can be designed. This produces a high internal validity of the results produced by the model for that specific issue.

The second method for performing validation tests is to compare the model predictions against some other models. Model comparisons are available in the literature [Korhonen & Hostikka, 2010, Kuligowski & Milke, 2005, Lord et al., 2005, Thunderhead Engineering, 2011] but are scarce in the case of road tunnel evacuations [Ronchi et al, 2010].

In accordance with the definitions provided by Lord et al. [2005] there are three different levels to perform the evaluation and comparison of evacuation model results:

1) Blind Calculation – This type of calculation is based on a basic description of the scenario to be modelled, including information on the geometry of the infrastructure. The model user has the freedom to decide the additional details needed to run the simulations. The benefits coming from this type of analysis are the possibility to verify different input calibrations.

2) Specified calculation – A detailed description of model inputs is provided here. This includes the geometry of the infrastructure as well as the occupant characteristics, the range of numerical constants to be used in each model.

3) Open calculation – The most possible information about the scenario to be simulated is provided here. Two possible references may be used, i.e., actual evacuation data or benchmark model runs completed from other models that are validated for that scenario.

The definition of the possible comparisons among models is still under discussion in the scientific community. Evacuation scenarios may be simulated employing either *a priori* or *a posteriori* modelling techniques. In the present work, *a priori* modelling consists of the process of simulating evacuation scenarios relying on the assumptions made by the models. No specific experimental data about the scenarios to be simulated are available and relevant literature is reviewed in order to calibrate the model input. Default settings are employed where no relevant information is available for calibrating a specific factor of the evacuation scenarios. The degree of detail about the description of the scenarios to be simulated is dependent on the *a priori* modelling technique employed (blind or specified calculations) and the models in use, i.e., the degree of sophistication to represent the scenarios. *A posteriori* methods are instead based on the availability of dedicated experimental data for calibrating the input of the models. Data compiled from evacuation experiments are therefore used to insert the model input in line with the modelling assumptions employed, e.g. agent speed distributions, pre-evacuation times, exit usage, etc. Blind and specified calculations represent the process of *a priori modelling* where the evacuation modeller has no benchmark to evaluate the results produced by models. Open calculations are instead based on the availability of all the required information to calibrate the input, i.e., *a posteriori modelling*. The comparison of the *a priori* and *a posteriori* results makes it possible to evaluate different information in relation to the type of calculation which has been performed (blind vs specified vs open calculation). The comparison between open and blind calculation helps to identify deficiencies in the input. Specified calculation is instead appropriate for comparing the algorithms embedded within the models.

2.3 Selection of research strategy

The possible methods which can be used to achieve the research objectives of this thesis have been described in the previous section (see Sec 2.2). The choice of the methods employed is based on an analysis of the advantages and disadvantages that are related to each specific method and their suitability for the specific sub-aims of the thesis. Several factors should be taken into account when selecting the method to be used for a research project. There is no unique method that is valid for any type of research study and often a combination of different techniques is required to ensure high validity and reliability of the results produced.

The choice of the appropriate strategy is determined by the research objectives [Maxwell, 2005] (see Sec. 1.1). The final aim is to provide the safety designers with recommendations on the modelling approaches to employ for simulating evacuations in the case of road tunnel fires and subsequently apply the PBD approach. In order to develop these recommendations, a set of the most known available models and methods have been investigated and tested. In addition, a new approach has been presented - the multi-model approach - to help designers analyse the evacuation processes in the case of very complex scenarios. The chosen strategies should therefore be based on several aspects. The first step is the analysis of the current knowledge on human behaviour in road tunnel fires. The knowledge of the phenomena to be represented is in fact the fundamental pre-requisite for any type of modelling work.

Different steps are required to determine the suitable research strategy for the aims to be achieved. The first is an analysis of the methods employed in similar research, although, the selection of a method based on the previous choice made by other researchers may be not sufficient [Maxwell, 2005].

To date, there is no evidence of an attempt to quantitatively compare the results of a relevant number of evacuation models for road tunnel environments. In addition, there is a severe lack of data for use in predicting evacuation times from road tunnels [Fridolf et al., 2011], and only few attempts have been made to quantify the uncertainty and variability in the evacuation model results [Lord et al., 2005]. In particular, there is a lack both in current international technical guidance and legislations, e.g., ANAS [2009], NFPA502, [NFPA, 2011] and EU/54/2004 [European Council, 2004] and in scientific literature on the different approaches to be used in relation to the complexity of the tunnel scenarios under consideration.

A possible strategy for analysing the approaches to employ is the comparison with evacuation experimental data of a chosen scenario. This comparison is affected by the methods used to collect the empirical data. A standardization of the procedures to be used has been presented by Gwynne [2010] in the NIST report GCR 10-928 "*Conventions in the collection and use of human performance data*". Gwynne states that the data requirements depend on the sophistication of the model employed, e.g., analytical calculations, computational models, etc. In addition, even if the appropriate data are available for an analysis, it does not automatically mean that they are correctly used. The process of data collection needs decisions to be made at several stages, affecting the refinement of the data and their applicability. For this reason, modellers should always be aware of the process in which data have been collected.

The fundamental step towards the development of a research strategy is the identification of the methods that are suitable to study the problem. One of the main problems of the application of modelling techniques is the difficulty in showing evidence of the reliability of the predictions made. This is mainly caused by the scarce availability of experimental data. With regards to case studies, they have been successfully used in the past to study human behaviour in fire emergencies. While they have been largely employed to study the event of tunnel fires [Ingason and Wickström, 2006], tunnel evacuations have not been the subject of the same amount of studies [Ronchi et al., 2010].

There are several reasons why case studies are not always the appropriate method to employ. The first issue is that fire is not a common event and the probability of tunnel fires occurring is lower than for building fires. The review on fire evacuation in underground transportation systems made by Fridolf et al. [2011] showed that there is a relevant lack of information in many aspects of the evacuation process in underground systems, e.g., people's movement on different surface materials, evacuation of people with disabilities, effectiveness of way-finding aiding solutions, etc. This lack of knowledge makes it very difficult to simulate user's performances which may occur during a tunnel evacuation only considering data from real events.

The reconstruction of the evacuation process in a real fire through modelling techniques requires data for the calibration of the input which are often difficult to collect. Modellers are often required to collect and analyse data from different sources and then apply them to the scenario of their interest. There are specific variables for which information is not available [Fridolf et al., 2011]. To address this issue, dedicated experimental campaigns, should be designed and performed. Hypothetical scenario experiments can be potentially very effective, giving the researcher a high degree of control, thus causing high internal validity of the results obtained. The main limitation of hypothetical scenario experiments is the degree of accuracy of the prediction of how people really behave in the case of a fire. The external validity of this type of experiment is then linked to the perception of the test participants of the system in which the experiment takes place. The way to improve external validity is to use a comparative approach to apply to the data collected, i.e., the final objective should be to rank different solutions.

The definition of the ideal modelling solution for different tunnel scenario requires a set of tests aimed to test the applicability of the methods to simulate scenarios ranging in complexity. Once the solution has been proposed, both safety factors and sensitivity analysis may be used to provide results. The use of sensitivity analysis is in particular very useful for testing the impact of single variables on evacuation results.

After the analysis of the available experimental data and the assessment of the approaches to employ, a test of the proposed methods is also required. This should be performed in order to produce external validity of the results, i.e., the recommended approach may be applied to any road tunnel evacuation scenario having similar characteristics. The chosen strategy must be capable of helping to identifying the key issues arising during the simulation of road tunnel evacuations in the case of fire and suggest the approach to simulate different scenarios. An effective method to study the uncertainty of the output produced is the comparison of *a priori* and *a posteriori* simulations [Lord et al., 2005] (open, blind and specified simulations). During the open calculation, scenarios are simulated starting from the output provided by the experimental work.

The present work therefore combines different research methods in order to provide an effective research strategy. These methods include a survey, the analysis of data from an evacuation experiment and ways of studying uncertainty, i.e., a sensitivity analysis. The comparison between *a priori* and *a posteriori* modelling (blind vs specified vs open calculation) is also used to test the effectiveness of the approaches proposed. *A priori* modelling techniques are employed because they permit to test the relationship between the evacuation results and the process of input calibration (*user effect*), i.e., the predictive capabilities of the models are tested in relation to the modeller expertise and the modelling assumptions. *A posteriori* methods are used to test the model sub-algorithms, given the availability of experimental data to calibrate the input consistently in different models. The strategy presented is an extrapolation of the research strategy proposed by Nilsson [2009] and it has been adapted for the scope of this thesis. Three different steps, which correspond to the different papers, have been identified (see Figure 1):

1) Identify problem – Survey on models and model users (Paper I) and application of current methods: analytical calculations and individual use of models (Paper II).
2) Solve problem – A priori modelling techniques (Paper III, IV), including the use of sensitivity analysis techniques; compilation of data from an evacuation experiment (Paper V) and a new modelling approach, i.e., the multi-model method (Paper VI).
3) Test system – A priori vs a posteriori modelling comparison (Paper VI).

Step 1 (identify problem) focuses on studying the current methods employed for the simulation of road tunnel evacuations. This part includes the analysis of a set of approaches, i.e., analytical calculations and individual use of evacuation models. The analysis, i.e., a survey, of the current evacuation models has also been made focussing on the identification of the most common models and types of users. Step 2 (solve problem) deals with the *a priori* modelling techniques that may be used to simulate road tunnel evacuation scenarios. This step also includes the analysis of data from experimental campaigns focused on the study of specific variables affecting human performance in tunnels. A new method to apply to evacuation models, i.e., the multi model approach, has also been presented. Step 3 (test system) provides a test of the suggested solutions based on the *a priori* vs *a posteriori* modelling of the tunnel evacuation experiments described in the Step 2.

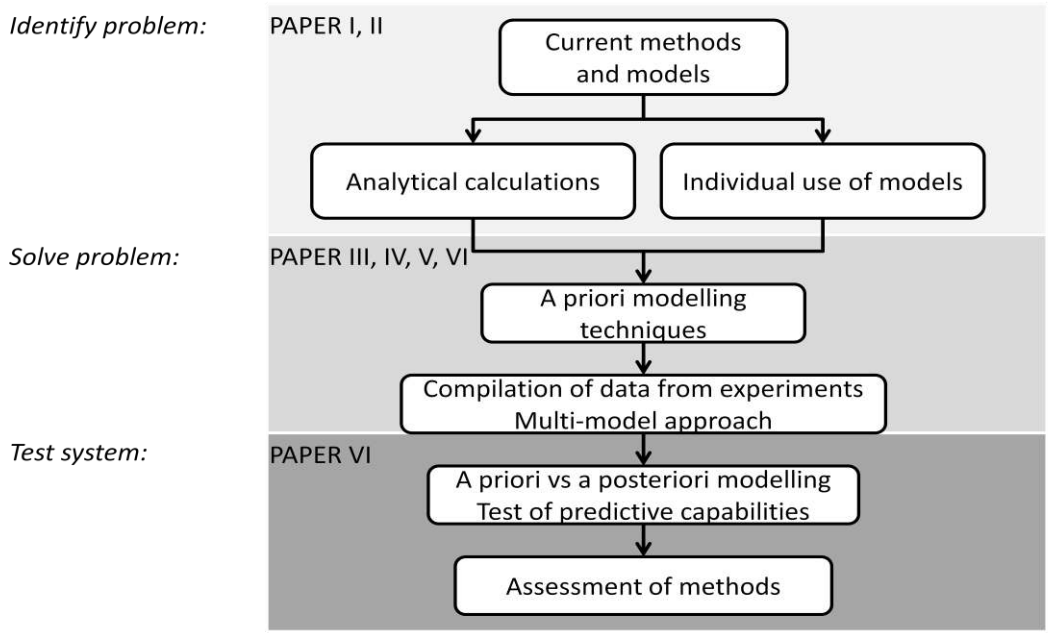

Figure 1. Schematic representation of the Research method

2.3.1 Identify problem – Papers I and II

An online survey on the experiences and needs of model users was performed at the webpage www.Evacmod.net (Paper I), an evacuation modelling portal for the simulation of human behaviour during emergencies. The scope of the survey was to evaluate the evacuation modelling community itself, e.g., its model users' education, background, etc., and the most common tools currently in use. The survey addressed issues such as the perception of the importance of model features, usage/awareness of models, knowledge of model V&V, training and usage of multiple models. In order to achieve a relevant number of participants belonging to different areas, different methods of dissemination have been used. The survey was made available in six languages and the different versions made the survey accessible to an international participant base. The main aim of the survey within the context of the present work was to define the most used models and have a picture of the degree of expertise of evacuation model users.

Paper II provided a test of three models, namely FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], STEPS [Mott Macdonald simulation group, 2011], Pathfinder 2009 [Thunderhead

Engineering, 2011] and the analytical calculations provided in the SFPE handbook [Gwynne and Rosenbaum, 2008] for hypothetical evacuation scenarios in a single bore tunnel, i.e., the Lantueno tunnel in Spain. This is a two-bore road tunnel with an emergency link between the two bores. Evacuation scenarios were defined and simulated in order to identify the critical aspects affecting human behaviour in road tunnel fires. For example, some scenarios included the case of agents that had to choose between using the emergency exit or going towards the end of the tunnel. Since exit choice has been identified as a critical factor in road tunnel evacuations [Gandit, 2009, Nilsson, 2009], these scenarios made it possible to evaluate the sub-algorithms embedded in different models to reproduce this issue. The main limitations of a set of tools - chosen from the most common in the market, identified in Paper I – were also identified. A simple method, i.e., the use of safety factors, was the solution employed here to take into account the uncertainty in model results. A more detailed method was also presented, describing a first attempt to calibrate simpler models starting from more complex algorithms available in other models. Since the method has been identified as potentially very effective, it represents the basis of the multi-model approach discussed in detail in Paper VI.

The scope of this step of the research was to identify the main issues concerning the modelling of tunnel evacuation. To address this problem, hypothetical scenarios were simulated. Differences among the model results were used to identify inconsistencies among models and critical issues. The main issues identified in Paper II deals with the study of the impact of smoke on agent speeds and the impact of emergency exit signage on exit choice. The modelling work confirmed therefore that occupant-fire interaction is the main cause of differences between the models. The modelling issues arising from this problem were then investigated in Step 2.

2.3.2 Solve problem – Paper III, IV, V, VI

Step 2 includes different research strategies used to solve the problems of effectively simulating the process of tunnel evacuations. The analysis of the simulation results obtained in Paper II permitted to identify occupant-fire interaction as the most critical problem to be simulated within models. Two papers (Paper III and IV) have been therefore dedicated to the study of the associated issues, namely the impact of smoke on agent speeds and the impact of emergency exit signage on exit choice. Evacuation models present different modelling assumptions to simulate the above mentioned issues. It was then required to perform studies aimed to identify the influence of the models employed on results as well as the *user effect*. The analysis of the available literature also demonstrated the necessity of collecting new data to assess specific factors that were not addressed in previous studies. New data were then compiled from an evacuation experiment (Paper V).

The scope of Paper V within the context of the present work is to analyse information useful to calibrate model inputs as well as provide a benchmark for testing the predictive capabilities of evacuation models.

Paper III deals with the simulation of the impact of smoke on agent movement speed. Since different hypotheses and data-sets are currently employed to study this problem, a sensitivity analysis has been identified as the research method suitable for this type of problem. Six different evacuation models, namely FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], Gridflow 3.03 [Bensilum & Purser, 2003], buildingEXODUS 4.1 [Galea et al. 2004], STEPS 4.1 [Mott Macdonald simulation group, 2011], Pathfinder 2011 [Thunderhead Engineering, 2011] and Simulex 5.8 [Thompson & Marchant, 1995] – based on different modelling assumptions - were chosen and then employed in this study. Models were selected here because they employed different assumptions with regards to default settings, embedded data-sets and interpretations about the impact of smoke on agent speeds. They either embedded the experiments by Jin [2008] or Frantzich & Nilsson [2003] or had no default settings/data-set at all.

The impact of the representation of the correlation between movement speed and visibility conditions was tested in different tools. A case-study of a hypothetical evacuation scenario, i.e., a straight corridor that may represent a tunnel, was investigated in order to study the sensitivity of the two key variables affecting this issue: 1) initial agent speeds in clear conditions and 2) visibility conditions (generally represented through extinction coefficients). This type of analysis was made in order to evaluate the uncertainty in the results of different models in relation to the data-sets employed as well as their interpretations to configure the model inputs. The *user effect* was also discussed in terms of the degree of user's expertise to take the decision to eventually modify model default settings and re-calibrate the model input.

Another key aspect of tunnel evacuation has been investigated in Paper IV. This paper addressed the problem of reproducing the effect of different emergency exit signs during tunnel evacuations. The two models employed, namely buildingEXODUS 4.1 [Galea et al. 2004] and FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], have been identified in Paper I as the models users are most aware of. These models were also listed in the top 7 most used models in the survey of Paper I; They were chosen and employed because they are able to directly represent the influence of emergency exit design on the agent's exit choice in smoke-filled environments.

The research method employed was a comparison of two models with each other, using as benchmark a set of laboratory experiments performed at Lund University in 2004. In particular, the calibration of model input about emergency exit signs required detailed information on the visibility of different systems. Different approaches were used to compare model results, namely blind and specified calculations. The methods employed in Paper IV represented a superset of the experimental trials conducted in Paper V. In fact, the assumptions made in the different approaches were used for the *a priori* simulation method of Paper VI where the applicability of the models/methods employed was tested.

Paper V deals with the data collected during the tunnel evacuation experiments. In the research framework of this thesis, data were compiled from the experiments for modelling purposes. Results from a field experiment – which in the present thesis is defined as an experiment that is performed in a field environment, i.e., a tunnel - were analysed in order to obtain information on some crucial aspects of tunnel evacuation modelling. The experiment is part of a project (www.metroproject.se) about the study of rail tunnels, although the tunnel of the experiment was a tunnel used in the construction of a road tunnel, i.e., it was not a rail tunnel. Nevertheless, the characteristics of the tunnel under consideration corresponded to those of a road tunnel, i.e., layout, the installed emergency exit, etc. The only exception was a zone of the tunnel that was filled with a surface - the ballast - typical of rail tunnels, although during the experiments this was identified as having no significant impact on people's way-finding process. The relevance of the data to be collected for the modelling purposes of the present work led the author of the thesis to start collaborating with the Department of Fire Safety Engineering and Systems Safety at Lund University. The author participated in the planning and execution stage of the experiments, but his main role was to contribute in the analysis of the data collected in order to compile information for the calibration of the evacuation models input.

These types of experiments are generally designed in a manner to increase their external validity and isolate the single variables under consideration and extrapolate information useful also for other environments [Nilsson, 2009]. An example is a set of previous tunnel evacuation experiments that are currently used as reference for modelling the impact of smoke on occupant speeds in any type of environment [Frantzich & Nilsson, 2003], i.e., this data-set is embedded in the FDS+Evac model for any type of environment [Korhonen & Hostikka, 2010].

The aspects investigated during the experiments were selected because the lack of knowledge regarding these was identified in the available literature [Fridolf et al., 2011], thus making calibration of the correspondent model inputs difficult. The variables investigated were the impact of way-finding installations on evacuation and the impact of tunnel surface/inclination on movement speeds. The experiment was carried out in a single bore tunnel in Stockholm, Sweden. The tunnel had been equipped with emergency signage and an emergency exit and was filled with artificial smoke including acetic acid. The effectiveness of various technical installations was tested. The conditions of the experiment were controlled by eliminating many of the confounding factors that would occur in an actual fire emergency. For example, test subjects took part one at a time to avoid social influence and group behaviours. The experiment was designed to be similar to a real fire emergency in order to increase external validity. Test participants were not told specific information about the scenarios under consideration, i.e., they did not know about the tested systems or the layout of the tunnel they walked in during the trial. A first person perspective film was shown to test participants before entering the tunnel, representing a person travelling in a train that eventually came to a stop inside a tunnel.

Three data collection techniques were used during the field experiment, namely questionnaires, interviews and observations. A thermal imaging camera was used to allow observations of the test subjects' performance in the smoke-filled tunnel. In order to improve the reliability of the results, the three different data collection techniques were used together to draw conclusions about people's behaviours. One example is that data from both interviews and observations were used to define the impact of the different way-finding installations on the likelihood of using the emergency exit. The use of multiple measures of the same phenomenon has, in fact, been identified as an important way to improve validity [Yin, 2003].

The questionnaire included closed-ended questions, multiple choice or scale questions and open-ended questions. It included questions on the general information about the participant and then specific questions about the experiment and participants' experience during the experiment. Questions about the degree of realism of the experiment were asked in order to understand the perception of test participants about the experiment. The questionnaire also included questions about the technical installations employed and the perceived benefit coming from the different systems. The final part of the questionnaire included questions about the participants' feelings during the experiments both from a physical and psychological point of view. Interviews were also employed in order to improve the reliability of the study. They were non-structured i.e. questions could be adapted to the participant.

Video recordings were analysed in order to reconstruct the evacuation patterns of the participants during the passage of time, thus making it possible to derive information about the movement speed and exit choice. The observations focused mainly on evacuation patterns, which were determined according to a well-defined procedure that combined the films and measurements in CAD drawings. The analysis of the videos also made it possible to obtain a qualitative description of the way-finding behaviours, e.g., use of tactile or visual information.

Paper VI introduced the new framework of the multi-model approach for simulating road tunnel evacuations. The description of the test of this approach and the other methods employed, i.e., analytical calculations, individual use of models, are presented in section 2.3.3.

2.3.3 Test System - Paper VI

During Step 3 all the collected information and methods employed in Step 1 and Step 2 were used to provide recommendations on the approaches to be used to simulate different road tunnel evacuation scenarios. The previous papers were all pre-requisites for this final step.

Paper VI presents the new framework of the multi-model approach where the features of different evacuation models can be used together. Each model was used here at its best, i.e., one model may be used as reference for a specific variable while another may be the reference for another variable. The differences between the results were analysed in order to check their causes. In the simplest cases, these sources were easily found because a certain model was not able to reproduce a specific problem. In the more complex cases, there may be a need to perform a sensitivity analysis in order to check how a certain variable can influence the final results. The second method used to determine the reference model/s for each specific problem was a comparison with experimental data, i.e., if there was evidence of the correspondence between the numerical results produced by a single model and people's actual performance.

Different methods were employed in Paper VI in order to simulate the evacuation scenarios described in Paper V. The availability of experimental data made it possible to provide the *a priori* and *a posteriori* comparison between the results obtained. Analytical calculations [Gwynne & Rosenbaum, 2008] were the simplest approach employed. The second method was the individual use of the models. The methods and information provided in Paper III and IV were used to calibrate the model input in the *a priori* simulations. Different degrees of modelling efforts were employed in order to investigate the *user effect*. Simulations were performed either employing default settings/embedded data-sets or calibrating the input in relation to the available literature on the single aspects investigated, i.e., the impact of emergency exit signs on exit choice and the effect of smoke on occupant behaviour.

Both blind and specified calculations were provided employing six evacuation models, namely FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], Gridflow 3.03 [Bensilum & Purser, 2003], buildingEXODUS 4.1 [Galea et al. 2004], STEPS .4.1 [Mott Macdonald simulation group, 2011], Pathfinder 2011 [Thunderhead Engineering, 2011] and Simulex 5.8 [Thompson & Marchant, 1995]. Evacuation models were selected because they are based on different modelling assumptions and represent a significant sample of the models currently employed by the evacuation modelling community in line with the result of the survey described in Paper I. Open calculations were also made in order to simulate *a posteriori* the evacuation scenarios under consideration. The comparison among the different methods employed (blind, specified and open calculations) made it possible to identify the causes of the differences between model results. In addition, this analysis allows a classification of the tunnels in relation to the most appropriate approach to use, i.e., what type of approach is suitable for a specific evacuation scenario. The final scope of Step 3 then, is to prove the effectiveness of different approaches and assess the methods to employ in relation to scenarios ranging in complexity.

2.4 A proposed research strategy

The previous sections (see Section 2.3) described in detail the research strategy employed in the present work, i.e., the combination of different research methods aimed to assess the best approach to study road tunnel evacuations. It is believed that this strategy is not only appropriate for the present work, but that it can also be used for future research in environments other than road tunnels. Figure 2 shows a schematic representation of a proposed universal strategy for the study of the applicability of evacuation modelling tools in any environment. The strategy is divided into three steps, namely identify problem, solve problem and test system, according to the description provided in Section 2.3.

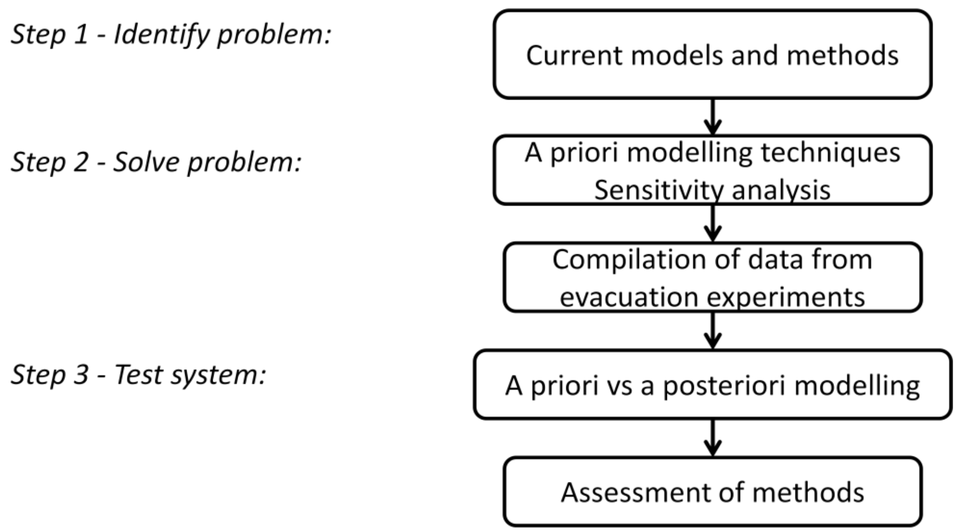

Figure 2. A proposed research strategy for the assessment of the best approach to simulate evacuation scenario in any environment.

Step 1 (identify problem) of the research strategy deals with the analysis of the current methods and models used to study the evacuation of a specific environment. This may include both analytical calculations and individual use of models. The appropriate methods to assess this step have been identified as the use of surveys and literature reviews.

Step 2 (solve problem) focuses on studying the possible simulation approaches for the specific environment of interest. Different *a priori* modelling techniques (including the multi-model approach) should be analysed in order to simulate the key factors affecting the evacuation process of the environment under consideration. The analysis of the impact of single variables may be performed through the application of sensitivity analysis. One example is the occupant-fire interaction in the case of road tunnel evacuations. Another example may be the simulation of queuing in environments where high occupant loads may easily arise, e.g., pedestrian tunnels, underground stations, etc. Experiments should then be designed in order to collect data for which the current available literature does not show enough information and provide a benchmark for the modelling work.

Step 3 (test system) focuses on the definition of the most appropriate approach in relation to different scenarios ranging in complexity. In order to run this test, *a priori* vs *a posteriori* simulation is performed. The comparison between blind, specified and open calculations will allow the investigation of several issues, e.g., the *user effect*, testing of the underlying algorithms in the model, deficiencies in the default settings, etc.

3. EVACUATION MODELLING

The application of evacuation modelling techniques needs some consideration on their advantages and disadvantages in relation to the traditional prescriptive approaches. The limitations coming from the application of a prescriptive code for tunnel safety come from the fact that they may not provide the best safety measures for each specific case. In fact, each infrastructure presents its specific problems and issues and an optimization of the available economic resources is a starting point for addressing the desired level of safety. The application of the PBD approach for assessing road tunnel safety gives designers the flexibility to adopt the optimal measures for obtaining the desired level of safety. Nevertheless, a case by case evaluation of the safety solutions is required in order to test the measures employed and ensure the safety conditions of the infrastructure under consideration.

One of the main disadvantages of evacuation modelling techniques is related to the difficulties that may arise in the calibration of the input of the model. In particular, some of the variables about the behavioural aspects of evacuation may be assigned considering the so called *magic numbers*, i.e., values lacking the support of experimental data. An appropriate design needs a careful evaluation of the model input. Modellers should be aware of the modelling assumptions as well as the default settings embedded in the models.

The present chapter briefly reviews the main modelling assumptions made by evacuation models, including a review of the characteristics of the models employed in this thesis. A discussion about the factors influencing evacuation results is also provided.

3.1 Evacuation modelling assumptions

Evacuation modelling is a virtual representation of reality that relies on the theory and the data collected. This technique is used to simulate the course of the events that may occur during emergency scenarios. The final aim is to predict the consequences of an hypothetical emergency scenario, i.e., stress the infrastructure with a pre-defined load (the fire scenario) and verify that it is able to bear the weight of that load (a safe evacuation).

Existing evacuation models present different characteristics and assumptions, since there are no international standards on the way they should be designed. This is reflected in the modelling techniques and methods used to simulate evacuation. According to Kuligowski et al. [2010], modelling methods may be classified into three main categories, including:

1) Coarse network approach, e.g., EXIT89 [Fahy, 1996]. The infrastructure is modelled as an abstract network made of nodes connected by arches. Each node represents a specific part of a building such as a room or a portion of a tunnel.
2) Fine network approach, e.g., STEPS 4.1 [Mott Macdonald simulation group, 2011], buildingEXODUS 4.1 [Galea et al. 2004], etc. The infrastructure is modelled as a grid of small uniform cells. Each cell may be occupied by one occupant at a time. The movement of the agents is simulated through a series of small steps in the cells of the network.
3) Continuous approach, e.g., FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], Gridflow 3.03 [Bensilum and Purser, 2003], Pathfinder 2011 [Thunderhead Engineering, 2011], Simulex 5.8 [Thompson and Marchant, 1995], etc. This approach simulates the agents through a system of coordinates within the environment. It offers the flexibility to simulate occupant behaviours which may be sensitive to occupant location, orientation and inter-distance among the agents. This method is particularly effective for infrastructures with the presence of high densities because it does not have the problem of being sensitive to the dimensions of the network employed.

The three approaches may be described as an increasing resolution in the representation of the agent behaviours. These approaches are widely represented among models and they may be applied for the study of road tunnel evacuation. The course network approach has been abandoned by model developers and users because it does not make it possible to represent many of the behaviours that may occur during evacuation. This was confirmed in the survey presented in Paper I. For this reason, the models employed in the present work do not include this type of approach. The models employed in this thesis were therefore selected from the other two approaches, namely the fine network approach and the continuous approach.

Apart from the modelling approach, evacuation models make different assumptions regarding people's performance during evacuation, and employ different data-sets, sub-algorithms, etc. The present work includes six evacuation models, namely FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], Gridflow 3.03 [Bensilum and Purser, 2003], buildingEXODUS 4.1 [Galea et al. 2004], STEPS 4.1 [Mott Macdonald simulation group, 2011], Pathfinder[1] 2011 [Thunderhead Engineering, 2011], Simulex 5.8 [Thompson and Marchant, 1995] together with the analytical calculations described in the SFPE Handbook [Gwynne and Rosenbaum, 2008].

Table 5 and Table 6 show a summary of the features of the evacuation models employed in accordance with the classification made by Kuligowski et al. [2010] in their review (please note that the information provided in Table 5 and Table 6 is updated to January 2012).

[1] The simulations performed in Paper II were made with Pathfinder 2009

Kuligowski et al. used category labels to describe the models. Further explanations on the labels used by Kuligowski et al. can be found in their review [Kuligowski et al., 2010]:

Purpose. (1) Models that can simulate any type of building, (2) Models that specialize in residences, (3) Models that specialize in public transport stations, (4) Models that are capable of simulating low-rise buildings (under 15 stories) and (5) Models that only simulate 1-route/exit of the building.

Grid/Structure. (C): Coarse network, (F): Fine network and (Co): Continuous

Perspective of the model/occupant. (G): Global perspective and (I): Individual perspective Each model is categorized by both the perspective of the model and of the occupant. If only one entry is listed in this column, both the model and occupant have the same perspective.

Behaviour. (N): No behaviour, (I): Implicit, (C): Conditional or rule-based, (AI): Artificial intelligence and (P): Probabilistic.

Movement. (D): Density, (UC): User's choice, (ID): Inter-person distance, (P): Potential, (E): Emptiness of next grid cell, (C): Conditional, (Ac_K): Acquired knowledge, (Un_F): Unimpeded flow and (CA): Cellular automata

Fire Data. (N): The model cannot incorporate fire data, (Y1): The model can import fire data from another model, (Y2): The model allows the user to input specific fire data at certain times throughout the evacuation and (Y3): The model has its own simultaneous fire model

CAD. (N): The model does not allow CAD importing and (Y): it does allow CAD importing

Visual. (N): The model does not have visualization capabilities, (2-D): 2-dimension visualization available and (3-D): 3-dimension visualization available

Validation. (C): Validation against codes, (FD): Validation against fire drills or other people movement experiments/trials, (PE): Validation against literature on past experiments (flow rates, etc.), (OM): Validation against other models, (3P): Third party validation and (N): No validation work could be found regarding the model

Table 5. Summary of the evacuation model characteristics.

Model title	Modelling method	Purpose	Grid/structure	Perspective of M/O	Behaviour	Movement	Fire data	Cad	Visual	Validation
FDS+Evac 2.3.1	PB	1	Co	I	I, C, P	ID	Y3	N/Y	2,3-D	FD, PE, OM
Gridflow 3.03	PB	1	Co	I	I	D	Y2	Y	2D	FD, PE
STEPS 4.1	B	1	F	I	C, P	P, E	Y1,2	Y	2,3-D	C, FD, PE
BuildingEXODUS 4.1	B	1	F	I	C, P	P, E	Y1,2	Y	2,3-D	FD, PE, OM, 3P
Pathfinder 2011	PB	1	Co	I	C	D, ID	N	Y	2,3-D	C, FD, PE, OM
Simulex 5.8	PB	1	Co	I	I	ID	N*	Y	2D	FD, PE, 3P

Table 6. Summary of the evacuation model characteristics.

Model title	Counter-flow	Exit block	Fire conditions	Toxicity	Groups	Disabled / slower	Delays / Pre-evacuation	Elevator use	Route choice
FDS+Evac 2.3.1	Yes	Yes	Yes	Yes	No**	Yes	Yes	Yes	Optimal, conditional, user-def
Gridflow 2.3.1	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Shortest, random, user-def.
STEPS 4.1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Conditional
BuildingEXODUS 4.1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Various
Pathfinder 2011	Yes	No	No	No	Yes	No	Yes	Yes	Shortest, User-def.
Simulex 5.8	Yes	Yes	No*	No*	Yes	Yes	Yes	No	Shortest or altered distance map

**This feature has been implemented in a research study, but it is not embedded in the model.*
*** This feature has been implemented in the model but it is still not fully validated*

3.2 Factors influencing evacuation model results

The features embedded in models are one of the crucial factors affecting evacuation model results (together with the above mentioned *user effect*). The first aspect that needs to be considered when employing evacuation models is the impact of default settings on results. Default values or settings range in complexity according to the evacuation model in use. They can vary according to the transparency of the defaults being used, the range of model parameters, scenarios represented by default settings and the impact of default settings on the evacuation results, amongst other things. According to Gwynne & Kuligowski [2010], models may broadly present three different categories of default settings:

A. No default settings. Users need to configure the input applying a full data-set(s) to run the model
B. Default. Models have a single "factory" setting that is embedded into the model. This allows the user to speed up the process of configuring the input.
C. Pre-defined. Models have an initial set of possible default settings or libraries. They are usually associated with different scenarios/conditions.

The awareness of evacuation modellers with regards to the default settings employed is dependent on the documentation provided with the model and the type of model itself. In fact, transparency is a fundamental point for understanding the underlying default settings/embedded data behind each model. Often, the basic assumptions of a model are not immediately apparent. In contrast, open source models allow the user to fully control the model predictive capabilities by eventually modifying the default settings/embedded data in use. However, this can provide the user (especially the inexpert user) with too much control over the fundamental settings of the model. In addition, if the model has a single default setting (category B), it means that the user may not be able to modify the input, unless the source code is open, requiring additional effort and expertise.

The difficulty and complexity of the model interface, e.g., if it is based on a text-based or windows-based interface, can also impact upon the manipulation and understanding of the model settings. The more complex and less intuitive the interface, the more likely the user is to misunderstand the assumptions being made (and their impact). This problem is exaggerated by the composition of the evacuation modelling community itself. In fact, Paper I has highlighted that the evacuation modelling community is very young and users often employ models as a peripheral activity. In addition, evacuation modelling is a multi-disciplinary subject, thus requiring knowledge about various fields of science [Kuligowski, 2011b]. The consequence is that non-expert users may apply these tools without a deep understanding of the assumptions and limitations of the model in use.

The assumptions employed and the data-set assumed may only be appropriate for specific scenarios. If the model is then employed to different scenarios (beyond the original purpose of the model) or the data-set is extrapolated, this may influence the credibility of the results. This problem is particularly important for the simulation of road tunnel evacuation scenarios because very few experimental data are available on the topic [Fridolf et al., 2011]. The consequence is that evacuation models require several assumptions to be made in order to extrapolate the available data to the context of road tunnel evacuations. An example is provided in Paper III, which highlights that current models may employ different data-sets as equivalent to simulate the same problem, i.e., the impact of visibility conditions on occupant walking speeds.

Another aspect to be discussed is that evacuation models generally simulate approximately straight evacuation patterns, i.e. they do not simulate the actual evacuation paths made by people. Reduced agent speeds, i.e., speeds including the time spent during zigzag behaviours and stops, may be introduced in models to take account of this modelling aspect. This modelling assumption may be overcome if the model is able to simulate specific paths, as it may be necessary in the case of reconstruction analysis (forensic).

4. EVACUATION MODELLING IN ROAD TUNNEL FIRES

The six papers of this thesis explore different aspects of the modelling process of human behaviour in road tunnel fires in accordance to the research strategy described in Section 2.3. In the present chapter, the focus is on the description of people's performance in road tunnel fires and the relevant information needed for its simulation. The current theoretical framework - embedded in evacuation models - has been summarised, i.e., the time-line model. Relevant Literature has been summarised together with the new findings coming from the papers presented in this thesis. The aim of this chapter is then to provide information needed for the simulation of evacuation in road tunnel fires. This chapter includes a review of the main data useful for the simulation of the evacuation time, including information about both pre-evacuation time and travel time. With regards to the simulation of the evacuation time, three main human behaviour-related aspects have been discussed in the present chapter, namely 1) the influence of smoke on movement speed, 2) information for way-finding in smoke-filled tunnels and 3) group behaviour. Flow constraints are generally relevant for rail tunnels [Fridolf et al.], for this reason it is argued that they may be omitted in this context.

The last part of this chapter deals with the multi-model approach and gives recommendations on the appropriate modelling approaches to employ in relation to the complexity of the tunnel evacuation scenario to be simulated.

4.1 Identified needs – What is the representation of road tunnel evacuation within computational models?

The first chapter identified a major need for the study of human behaviour in the case of road tunnel fires. This is reflected in the necessity of identifying the modelling approaches to be applied for the study of road tunnel safety in relation to the scenarios under consideration. The identified methods should take into account the current framework embedded within evacuation models, i.e., the time-line model.

4.2 Human Behaviour in road tunnel fires: the time-line model

The concept that a fire might cause 'panic' in evacuees has been abandoned by the scientific community [Fahy et al. 2011]. The definition of panic itself has been questioned in various research works [Quarantelli, 1954, Sime, 1980, Sime 1984]. Although evacuees might be stressed or anxious, and often use the word 'panic' to describe their own or others' behaviours, they do not behave in an irrational or antisocial manner [Fahy et al. 2011]. In fact, evacuees tend to behave in a rational manner, and irrational and antisocial behaviours may occur only in rare occasions, mostly generated by extreme conditions, i.e., when the probability of salvation is considered very low by the occupants [Fahy & Proulx, 1996].

Evacuation may be considered as a rational process and can therefore be studied through theoretical frameworks. Fire evacuation in underground systems has been thoroughly analysed by Fridolf et al. [2011], who reviewed the four main models currently in use to represent people's performances, namely the 1) behaviour sequence model [Canter et al. 1980], 2) the role-rule model [Canter et al. 1980, Tong & Canter, 1985], 3) the affiliative model [Sime, 1984] and 4) social influence [Latané & Darley, 1968, Deutsch & Gerard, 1955]. From an engineering perspective, these theoretical frameworks may be difficult to apply since the engineering design step often requires quantitative analysis to be performed. The above-mentioned theories are instead useful to interpret the behavioural fundamentals that take place and perform a qualitative analysis.

The model that is currently applied during engineering analysis is the time-line model [BS PD7974, 2004, Purser & Gwynne, 2007], which describes the course of events as a list of sequential steps. The interpretation of occupant's behaviour is then made through the sum of different times. This model may be considered as a simplification of the problem, but enables the safety analyst to perform a quantitative analysis in a relatively short time. The reliability of the time-line model results is linked to the process of input calibration and the complexity of the system under consideration. The increasing level of control on human behaviour, e.g., the use of automatic detection systems, better people training, etc. will permit to increase the reliability of this model. In fact, the identification of the times to be included in the model would become easier since the prediction of behaviours is affected by factors under control.

An evacuation scenario may be therefore represented through a list of different times which constitute a time-line of the events. The characterisation of these times makes it possible to estimate the time required for a safe evacuation (RSET) and then use this time in engineering applications within the PBD approach. The numerical quantification of the time needed for the evacuation is in fact one of the two times needed to assess the safety conditions in the infrastructure under consideration. The second step is the comparison between the calculated RSET and the time when the conditions become untenable through the calculation of the ASET.

The time-line model has been divided into four main times by Purser [2003]. This categorization has been included in several international legislations, e.g., ISO TR16738 [2009], BS PD 7974-6, [2004], etc.:

$$RSET = \Delta t_{det} + \Delta t_{warm} + \Delta t_{pre} + \Delta t_{trav} \qquad \text{[Eq. 2. Purser, 2003]}$$

Where:
Δt_{det} Detection time. This is the time from fire ignition to first occupant detection.
Δt_{warm} Alarm time. This is the time from detection to a general alarm.
Δt_{pre} Pre-evacuation or pre-movement time. This time includes two behavioural elements for each individual, namely recognition time Δt_{rec} and response time Δt_{resp}. Recognition consists of a period after an alarm is evident, but before occupants begin to respond. Response time consists of a period after occupants recognize the alarm cues and begin to respond to them, but before starting the travel phase.
Δt_{trav} Travel time. This is the time required for occupants to walk to a safe place, e.g., an exit or escape route and the time required to flow through exits and escape routes.

The evacuation time Δt_{evac} is the sum of the pre-evacuation time Δt_{pre} and the travel time Δt_{trav}. The difference between ASET and RSET shows the available margin of safety (see Figure 3).

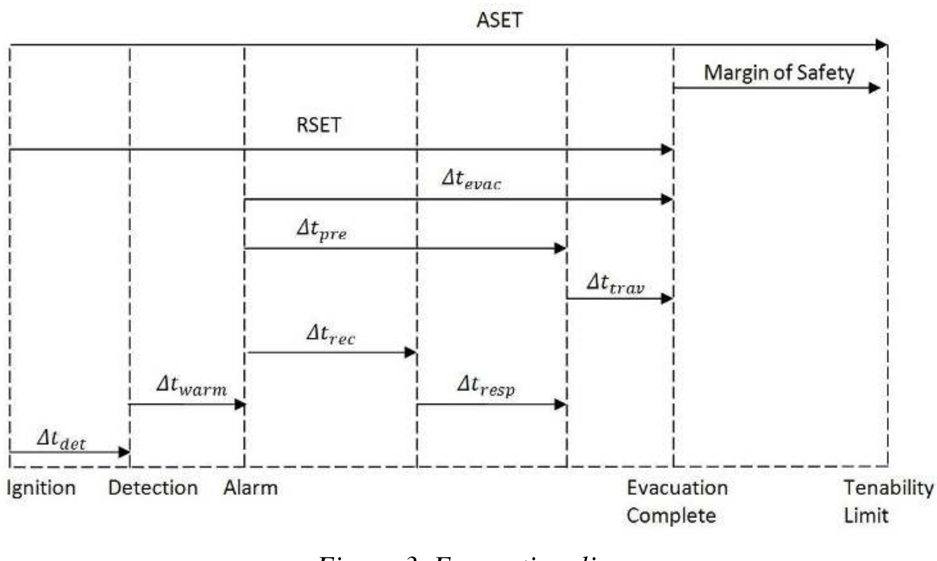

Figure 3. Egress time-line

Evacuation models are generally focused on the calculation of the evacuation time Δt_{evac}, although recent studies [Gwynne et al., 2010, Gwynne et al. 2011] have highlighted the importance of the variables affecting the first two times included in the RSET, i.e., Δt_{det} and Δt_{warm}. The calculation of the evacuation time is then currently based on the calibration of the variables affecting the pre-evacuation time Δt_{pre} and the travel time Δt_{trav}.

4.2.1 Pre-evacuation time

The estimation of the pre-evacuation time in road tunnel fires may be done through a review of the currently available literature on the topic, including experimental work and case studies, i.e. reports of actual accidents.

Pre-evacuation times are dependent on several factors, including physical and psychological factors. Among these factors, the perception of the environment has been identified as crucial [Shields & Boyce, 2004, Gandit et al., 2009], together with the personal and cultural background [Galea et al. 2010]. Past fire experiences and training level should also be taken into consideration. In particular, different behaviours may arise in relation to the knowledge of the safety equipments available in the tunnel [Gandit, 2009], e.g., the behaviour of professional drivers [Banuls Egeda et al., 1996]. Group behaviour has been identified as crucial and different theoretical frameworks have been applied to study people's behaviour in tunnel environments that may be applied for the pre-evacuation time, e.g. the theory of affordances [Nilsson, 2009], and the above-mentioned four theories analysed by Fridolf [2011], namely 1) behaviour sequence model [Canter et al. 1980], 2) the role-rule model [Canter et al. 1980, Tong & Canter, 1985], 3) the affiliative model [Sime, 1984] and 4) social influence [Latané & Darley, 1968, Deutsch & Gerard, 1955].

Pre-evacuation times are also affected by the presence of way-finding installations [Nilsson, 2009, Boer & Veldhuijzen van Zanten, 2005], including emergency signage, lighting, etc. The perception of danger may also be dependent on the position of the occupants with respect to the fire. Occupants may either have a direct perception of the danger or only see the smoke or the actions of other individuals [Ronchi et al., 2009].

Several actions may be performed by the tunnel occupants. There may be occupants inside the vehicles or pedestrians outside the vehicles, e.g., the case of mixed-used tunnels. Motorists may show vehicle property attachment and be reluctant to leave their vehicles [Gandit, 2009]. This behaviour has been observed in both real accidents [Purser, 2009] as well as during experimental studies [Boer & Veldhuijzen van Zanten, 2005, Nilsson et al., 2009].

The two main sets of tunnel evacuation experiments aimed to study the pre-evacuation time have been made in the Benelux tunnel in the Netherlands [Boer & Veldhuijzen van Zanten, 2005] and in the Göta tunnel in Sweden [Nilsson, 2009]. These experiments were aimed to estimate the pre-evacuation times during partially un-announced tunnel evacuation scenarios. Different experimental conditions were considered, i.e., occupant loads, vehicles involved, time for the alarm and type of alarm, etc., but the collected data may be comparable.

Norén & Winér [2003] performed a review of the tunnel experiments made in the Benelux tunnel and actual tunnel accidents aimed to classify the different steps taking place during tunnel evacuations. They identified four main steps, based on the model of Passenier & Van Delft [1995], which was adapted for underground environments. The analysis of the different actions which may be performed by tunnel occupants is therefore relevant as it provides an estimation of the input to be inserted within the time-line model. These actions may be summarised as:

1) Motorists are passive inside their vehicles and wait for the clearing up of the congestion. They do not recognize a dangerous situation.

2) Threat assessment; motorists become aware of the danger and some of them may start to act in order to find more information.

3) Preparation for the flight. The dangerous situation is evident and occupants decide the actions to be performed, i.e., to abandon their vehicles. Few occupants may consider their car as the safest place to be and decide to remain there. Other occupants may try to extinguish the fire. The fleeing actions of the other occupants are a strong signal of threat and imitation may arise, i.e., the group effect.

4) The last stage is the choice of the evacuation direction. During this phase, the factors influencing people’s performances are the evidence of the escape route as well as the actions of other occupants. Tunnel operator instructions have also been identified as strong factors during this step [Boer & Veldhuijzen van Zanten, 2005, Frantzich & Nilsson, 2009]. People will walk to the exit. Some of them may keep looking back or walk slow, concerned about their vehicle or curious about the fire.

These four stages identified by Norén and Winér are difficult to apply during observational analysis. Hence, the authors identified a pragmatic definition of these steps, including, time in car, hesitation time, i.e., a time between leaving the car and going towards the exit and the walking time.

During engineering analysis, the pre-evacuation time should include all the above mentioned actions except walking time, which is estimated through the movement of sub-algorithms embedded in the evacuation model in use.

From a quantitative perspective, the experiments in the Benelux tunnels [Boer & Veldhuijzen van Zanten, 2005] showed that slowest occupants reacted after 300-360 seconds. Particular risk conditions were evident when occupants had no external guidance on the actions to be performed, i.e., the absence of an announcement. In the Göta tunnel experiments [Frantzich & Nilsson, 2009], the time between vehicles stopping and the opening of car doors is included in a range of 1-35 seconds. The sum of the times needed to stop the vehicle and open the door of the vehicles was 20-180 seconds.

4.2.2 Travel time

High occupant densities are generally not common during road tunnel evacuations [Maevski, 2011]. Hence, queuing time is not considered as a crucial factor for the calculation of the travel time. Travel time is therefore mostly affected by distance criteria and the effects of smoke. Two main behavioural factors, namely occupant speeds and the movement patterns of evacuees, have been investigated. In the present work, the analysis is particularly focused on the impact of different way-finding installations on an occupant's exit choice and behaviour.

4.2.2.1 The impact of smoke on movement speeds

Two main data-sets are available for the simulation of the impact of smoke on movement speeds, namely the experiments by Jin [2008] and the experiments by Frantzich and Nilsson [2003]. Current literature includes other data-sets based on laboratory experiments aimed at studying this issue, namely the Wright data-set [Wright et al., 2001] and the Sheba data-sets [Galea et al., 2001], but these are not included in the present work since they are not currently implemented in evacuation models.

To date, there is no definitive interpretation of the available data-sets which can explain people's behaviour when exposed to smoke and there is a need to study the uncertainty related to the type of correlation employed. In addition, considerable variation in the movement speeds of different individuals at different smoke densities is evident in both the data-sets under consideration. This is not reflected in evacuation models, which generally use a simple average correlation. The two data-sets are currently applied as if equivalent, although they were collected in different experimental conditions. Hence, modellers should carefully evaluate the conditions of their scenarios before using a certain data-set and/or the associated behavioural assumptions.

4.2.2.2 The impact of way-finding installations on exit choice

The calculation of travel time is dependent on evacuation routes and distance criteria. The longest is the distance walked in the tunnel, the highest is the time spent by the evacuee in the tunnel before reaching a safe place. Exit/route choice plays a fundamental role during tunnel evacuations given the limited number of egress options available and the potentially rapidly developing hazard. The design of way-finding installations plays an important role in exit selection, especially in road tunnels, where the population is generally not familiar with their surroundings [Nilsson, 2009] and staff is not immediately on hand to provide guidance.

The primary element in this type of analysis relates to the likelihood of the agent seeing the installation, e.g., an emergency exit, a sign, etc. This problem can be studied starting from the analysis of the visibility factors associated with different types of installations. This information is useful to derive one of the components affecting the likelihood of people of receiving and using the information provided. The final probability of using the information provided by the installation is instead affected by several other factors [Nilsson, 2009]. To date, different theoretical frameworks have been applied for predicting the possible responses to the information provided, e.g., the theory of affordances [Hartson, 2003].

4.2.3 Group behaviour

Actual accidents, such as the Tauern [Leitner, 2001] and Mont Blanc tunnel fire [Duffé & Marec, 1999] confirmed that people facing an accident continue their previous actions for quite a long time, i.e., people need confirmation about the danger before deciding to perform actions. An explanation of this behaviour is related to the influence of the actions performed by other evacuees, the so called *social influence* [Latané & Darley, 1970; Nilsson & Johansson, 2009].

S*ocial influence* is divided into normative and informational influence. The first part is the fact that people act in accordance with the expectations of other individuals. The second part is that the action or inaction of others has an influence on people's understanding of the situation. Two examples are the influence of a motorist starting the evacuation influencing others or the inactivity of individuals causing inactivity in others [Boer & Veldhuijzen van Zanten, 2005]. The findings obtained by Nilsson [2009] supported the idea that social influence has a fundamental role during evacuation. The experiments in the Göta tunnel, confirmed that the evacuation behaviours of others strongly affected the individual decision to abandon the vehicle [Nilsson et al., 2009].

An example of social influence is the choice of exit during the tunnel experiments made by Nilsson [2009]. Test participants mentioned that they went towards a certain exit after seeing others walk towards that direction. The most likely explanation for group behaviours is that any individual belongs to a certain population [Norén & Winér, 2003]. Different populations may have different characteristics in terms of the actions performed during the tunnel evacuation. One of the basic findings about group behaviours is that occupants with less information about the situation react earlier than they would if they were alone [Nilsson, 2009]. Although these statements appear reasonable, the lack of data on group behaviour is still evident and further experimental data need to be collected.

4.3 New findings on evacuation modelling in road tunnel fires

The present thesis aims to investigate different problems that evacuation modellers may find when facing the problem of simulating road tunnel evacuation scenarios. Two main aspects have been studied, namely the impact of smoke on movement speeds and the impact of way-finding installations on exit choice.

Data collected during the tunnel experiments presented in paper V showed that neither the inclination nor the tunnel floor materials significantly affected occupant speeds. It is instead argued that the smoke and the reduced visibility conditions were the main limiting factors on movement speed, i.e., smoke was the crucial factor affecting occupants' movement speeds.

The effects of smoke on occupant's movement speeds have been analysed in detail in Paper III. The paper reviews and tests the two main data-sets available for the simulation of the impact of smoke on movement speeds, namely the experiments by Jin [2008] and the experiments by Frantzich and Nilsson [2003].

The two key variables affecting this issue have been investigated, namely 1) the initial occupant movement speeds in clear conditions and 2) the visibility conditions, i.e., generally represented through extinction coefficients. The results deriving from the sensitivity analysis performed in paper III made it possible to investigate the uncertainty related to the use of different assumptions. With regards of the impact of smoke on exit choice, modelling assumptions are dependent on the data-set in use (either the experiments performed by Jin [2008] or Frantzich & Nilsson [2003]) and the interpretation of the data-sets employed. Five types of model interpretations have been identified in Paper III, which are reflected in current evacuation modelling tools.

The results showed that the application of different data-sets or interpretations produced significant differences in the results, given the scenarios examined. An indiscriminate use of default settings may cause consistent differences in the results. Numerical results produced were instead comparable when the same assumptions were employed, i.e., results are not affected by the model employed. This is encouraging because it provides cross-validation among different models.

The analysis provided in Paper III gives evacuation modellers an estimation of the uncertainty linked to these specific aspects and a set of recommendations to be followed to increase the reliability in model results. The main recommendation is to use the most conservative assumptions. Any movement away from this conservative position needs to be justified after a careful analysis of the scenario under consideration.

The second main aspect addressed in the present work is the simulation of the impact of way-finding installations on exit choice. The laboratory experiments described in Paper IV provide information on the visibility factors associated to different types of way-finding installations, e.g., exit signs. This data may represent the input for evacuation models in order to calculate the visibility of the way-finding installation under consideration in a given scenario. Paper IV presents an example of the processes required to represent evacuee behaviours and exit/route choice within evacuation models in relation to different installations.

The results of the tunnel evacuation experiments described in Paper V gave specific information on the impact of different way-finding installations on evacuation. In particular, Paper V provides information on the influence of different tunnel emergency exit designs on exit usage and people's movement patterns. Tunnel experiments in Paper V gave the percentages of emergency exit usage of five different emergency exit layouts. These values allow users to rank different solutions and implement the results within evacuation models, i.e., the probability of using an exit in relation to the installations employed.

Emergency exit layouts were ranked in terms of their effectiveness in attracting people during tunnel evacuations. It was shown that the position of the occupants in the tunnel cross section strongly affect the emergency exit usage, i.e., participants walking in a tunnel on the same side of the emergency exit used it to a greater extent than those on the opposite side. The use of a loudspeaker has been identified as the most effective installation. In contrast, a combination of green and white continuous lights was misinterpreted by many evacuees, causing uncertainty and made the test subjects unsure about the best way to perform. The presented tunnel experiments also confirmed the findings of the previous studies made by Nilsson [2009], where the use of green flashing lights was more effective than standard exit signs and the wall was identified as one of the main aids to evacuation.

One of the main outcomes of the thesis is that the assumptions employed and the data-set assumed by evacuation models should be carefully evaluated in its context of use, i.e. road tunnels. Unfortunately, non-expert users could consider model results as reliable in unique environments as well, and extend their use to applications where no *ad hoc* validation tests have been performed. The use of a model beyond its validation evidence requires then an additional effort by the evacuation modeller to understand the model limitations in representing the evacuation process in that specific environment.

The credibility of evacuation model results is also linked to the availability of experimental data for simulating specific behavioural aspects. This problem is relevant in the case of road tunnel evacuations because of the lack of experimental data [Fridolf et al., 2011]. The application of evacuation modelling tools in road tunnel fires requires several assumptions to be made in order to extrapolate the available data to the context of use. The configuration of the models therefore needs a high degree of modeller's expertise to analyse the resources available and perform a credible calibration of the model input.

4.4 The multi-model approach

The multi-model approach has been presented in Paper VI. This approach consists of a use of different evacuation models at the same time. In a first stage, evacuation models are used individually and the differences among the results of the models are highlighted. The modelling assumptions employed by each model are also investigated, e.g., default settings, modelling methods, etc. Differences may be caused by a lack of a specific sub-algorithm to simulate specific behaviours in a model or the weaknesses of the sub-algorithm itself. Once the sources of these differences are found, one model (or in some cases more than one) may be used as a benchmark for each specific variable/problem. The definition of the benchmark model/s may rely either on the absence of a sub-algorithm in a model or on a comparison with experimental data.

Hence there are two possible methods to apply the multi-model approach (see Figure 4):

A) The input of the models is selected using an iterative process of calibration.
B) Different models are employed to simulate different aspects of the evacuation scenarios.

During the application of Method A, the input of the models is forced to be as similar as possible to the benchmark model/s through an iterative process of input calibration (see Figure 4). In complex cases, there may be a need to perform a sensitivity analysis in order to evaluate the uncertainty linked to that variable.

The application of Method B is performed employing models to simulate different aspects of the evacuation scenarios. For example, model 1 may be used to simulate people movement, i.e., model 1 is the benchmark model for that specific problem, model 2 may be employed for predicting exit choice, model 3 for simulating queuing, etc. Models are therefore used separately for simulating different aspects of the evacuation problems and the results obtained with each models are eventually merged to deterministically calibrate one model. This model should be generally chosen among the ones that gives more control on the calibration of the input and the modelling assumptions, i.e., an open source model.

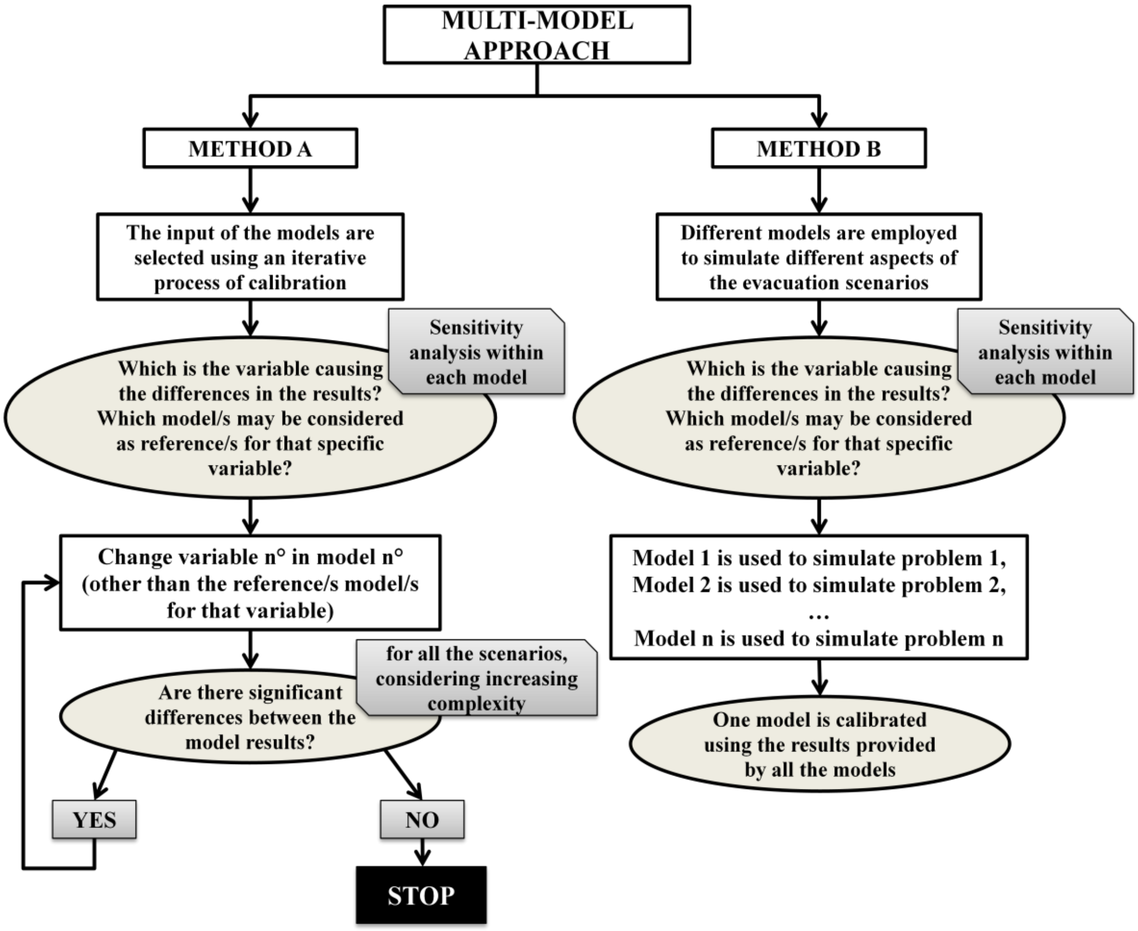

Figure 4. Schematic description of the multi-model approach in the case of 1) iterative process of input calibration and 2) use of different models for simulating different evacuation problems.

The multi-model approach may be used either as a research tool for testing the predictive capabilities of evacuation models (as it has been used in Paper VI) or for assessing road tunnel safety (see next Paragraph 4.5).

4.5 Assessment of the modelling approach

Paper VI provides a description of the three approaches that may be employed to simulate evacuation scenarios, including 1) analytical calculations, 2) individual use of evacuation models, and 3) the multi-model approach.

Analytical calculations represent the simplest approach that can be used. This approach employs the hydraulic method presented in the SFPE handbook by Gwynne and Rosenbaum [2008].

The individual use of evacuation models may be performed in different ways. The first method is the use of model default settings. Default settings are often used for those variables for which the user is not able to find relevant information to calibrate the input. Modellers may also use default settings indiscriminately in order to speed up the process of input calibration, although there is always the need to verify that the default provided by the model developer is in line with the scenario under consideration [Ronchi et al., 2011b]. The second method is the configuration of the models using all the available data/information for the specific scenario under consideration. This approach requires a higher degree of expertise by the modeller in order to choose the appropriate input. Input values are selected among the existing literature/legislations.

The multi-model approach consists of the use of different evacuation models at the same time for the analysis of the evacuation scenarios. This approach was presented in Paper VI and in Sec. 4.4 of the present thesis. The differences between the results obtained during approach 2 are analysed in order to study their causes. The multi-model approach may be used for testing the predictive capabilities of evacuation models and road tunnel safety assessment.

The analysis of the predictive capabilities of the evacuation modelling approaches described in Paper VI made it possible to provide recommendations on the methods to employ in relation to different evacuation scenarios in the case of a road tunnel fire. This is an attempt to provide guidance for evacuation modellers facing the problem of deciding which modelling approach to employ prior to running their scenarios.

Three main characteristics have been used for this classification, including 1) evacuation route, 2) impact of way-finding installations and 3) occupant density. Table 7, Table 8 and Table 9 provide a summary of the possible characteristics of the road tunnel evacuation scenarios under consideration.

Evacuation routes may include a single evacuation route [S], i.e., occupants have only one option to reach a safe place such as going towards one of the entrances or exits of the road tunnel. The scenario may also include emergency exits and occupants may have to choose between multiple evacuation routes and exits [M]. The third case is a very complex evacuation layout with many possible routes [C]. This is the case of underground networks including complex road elements such as roundabouts or intersections.

Way-finding installations, e.g., emergency signage and exit signs, may be in line with the prescription of the European legislation 2004/54/CE [European Council, 2004] [S] or not [NS], e.g., way-finding installations may have a unique design.

Expected occupant densities in the scenarios under consideration may be lower than 1.08 persons/m2 (class A-E in Fruin [1981] or higher than 1.08 persons/m2 [H], i.e., class E and F in Fruin [1981].

Table 7. Characteristics of the evacuation route and layout.

Evacuation route and layout
Single evacuation route [S]
Multiple evacuation routes [M]
Complex layout and evacuation routes [C]

Table 8. Types of way-finding installations.

Way-finding installations
Standard [S]
Not Standard [NS]

Table 9. Characteristics of the occupant density.

Occupant density
Low [L]
High [H]

The previous characteristics of the road tunnel evacuation scenario produces the combinations described in the first column of Table 10.

Table 10. Combination of tunnel evacuation scenario characteristics for the definition of evacuation modelling approaches.

Evacuation routes - way-finding installations – occupant density	Recommended modelling approach
S-S-L	Analytical calculations
S-S-H	Analytical calculations
S-NS-L	Individual use of models
S-NS-H	Individual use of models
M-S-L	Individual use of models
M-NS-L	Individual use of models
M-S-H	Individual use of models
M-NS-H	Individual use of models
C-S-L	Multi-model approach
C-NS-L	Multi-model approach
C-S-H	Multi-model approach
C-NS-H	Multi-model approach

The results coming from the test of the predictive capabilities of different modelling approaches provided in Paper VI make it possible to give recommendations on the modelling approaches and models to employ in relation to the tunnel evacuation scenario under consideration. Table 10 provides a summary of the suggested approaches based on the results and discussion provided in Paper VI.

Analytical calculations may be used if the evacuation scenarios do not include any behavioural aspect, i.e., modellers need to simulate human flows along a single evacuation route (see Table 10).

The individual use of evacuation models may be sufficient for the simulation of scenarios where the layout of the road tunnel is not complex. Hence, evacuees have to choose between multiple exits but the road network is simple, i.e., there are no roundabouts, intersections, etc. In any case, the use of a single evacuation model is sufficient only if the tool employed embeds the features needed to simulate the scenarios under consideration. An example may be the need for a sub-algorithm for simulating exit choice in smoke-filled environment to predict the evacuation route, e.g., the sub-algorithm embedded in buildingEXODUS and FDS+EVAC, or the possibility to simulate the impact of specific way-finding installations, etc. The use of continuous models, e.g., FDS+Evac, Gridflow, Pathfinder, Simulex, etc. is recommended in the case of high occupant densities as may be the case in mixed-use tunnels (vehicles and pedestrian). This is caused by the sensitivity of course/fine network models, e.g., STEPS, buildingEXODUS, to the grid employed in the calculation [Lord et al., 2005]. Modellers should therefore carefully evaluate the characteristics of the model in use prior to using evacuation models individually.

The multi-model approach - presented in Paper VI - is recommended in the case of very complex scenarios and layouts, as in the case of a complex road tunnel network including several way-finding installations, high occupant densities, etc. The application of this approach (either employing method A or method B, see Figure 4) allows the modeller to use the strengths of each model and apply the most suitable algorithms to simulate each specific behavioural variable.

5. CONCLUSIONS

The first objective of the present work was to identify the most common simulation tools and test them in the case of road tunnel evacuations. A survey was performed to identify these tools and a set of applications in the context of road tunnel evacuation was performed. Six models were employed and a wide comparison of modelling approaches was performed. The present work is the first attempt to compare and test such a high number of evacuation models in the context of road tunnel evacuations. The evacuation models included were FDS+Evac 2.3.1 [Korhonen and Hostikka, 2010], Gridflow 3.03 [Bensilum and Purser, 2003], buildingEXODUS 4.1 [Galea et al. 2004], STEPS 4.1 [Mott Macdonald simulation group, 2011], Pathfinder [Thunderhead Engineering, 2011] and Simulex 5.8 [Thompson and Marchant, 1995]. Analytical calculations [Gwynne & Rosenbaum, 2008] were also employed in order to compare the evacuation model results with a hydraulic model.

Two main aspects were investigated, namely the impact of the model and the expertise of model users on results, the *user effect*. The findings suggested that the impact of default settings is crucial on evacuation model results. In particular, the behavioural aspects investigated - the impact of smoke on movement speeds and exit choice - showed that modellers must not rely on default settings, but rather, a careful evaluation of the conditions of the scenario to be simulated is always required. Results showed the importance of the calibration of the model input and its dependence on the expertise of model users, the capabilities of the models and the availability of experimental data.

Different modelling approaches were discussed, including analytical calculations, an individual use of evacuation models and a novel multi-model approach. The new framework of the multi-model approach was presented and the advantages in the case of complex scenarios were analysed. The multi-model approach was identified as being very effective for very complex scenarios in which the features of a single model were not sufficient to perform the analysis. Each model has its strength and weaknesses – which have been discussed in detail - and a joint use of the models permitted to overcome the problems deriving by a single weakness coming from the individual use of one model.

The analysis of the predictive capabilities of evacuation models has been performed through both an analysis of their claimed characteristics – as described by evacuation model developers – as well as different applications of the models in the context of road tunnel evacuation. Among the tests performed, an *a priori* vs *a posteriori* analysis of the models was also made. This analysis was made possible by the results coming from a set of new tunnel evacuation experiments.

The second objective of the present work was the compilation of data from experiments for the calibration of the model input for tunnel evacuation. The present work included the results of a tunnel evacuation experiment performed at the Department of Fire Safety Engineering and Systems Safety of Lund University, Sweden.

The analysis suggested that the lack of lighting and the smoke were the main limiting factors on occupants' movement speed. Other variables such as the surface materials and the inclination of the tunnel slope did not significantly affect the movement speed. Different way-finding installations were tested to study their impact on occupant exit choice. It was possible to rank the effectiveness of different systems. The use of a loudspeaker was found to be the most effective aid to evacuation. The combination of green and white continuous lights and a halogen lamp was instead misinterpreted by a significant percentage of test participants. With regards to the movement pattern observed, the evacuation experiment showed that the majority of participants followed one of the tunnel walls during their evacuation route (91%).

The third and final goal of the present work was to assess the appropriate modelling approach to use in relation to the evacuation scenario under consideration. A key point which was discussed is the assessment of the benefits of a very complex analysis, i.e., including several variables and/or the use of multiple models. Chapter IV included recommendations on the selection of the appropriate approach. Modellers need to perform a case-by-case evaluation of the modelling approach to employ. A classification of the road tunnel evacuation scenario to be simulated has been identified as an effective solution to the problem.

The analytical calculations provided in the SFPE handbook [Gwynne & Rosenbaum, 2008] were useful only when distance criteria was predominant among other behavioural factors, i.e., there was no need to simulate the impact of way-finding installations, only one evacuation route was available and the smoke impact on evacuation was limited, etc. The individual use of evacuation models was effective when the model in use included the features needed to simulate human behaviour in road tunnel fires. The predictive capabilities of six models were tested in Paper VI and models showed different strengths and weaknesses with regards to different behavioural aspects. FDS+Evac and buildingEXODUS were the only models embedding a sub-algorithm which made it possible to directly take into account the influence of smoke on people's exit choice, employing different degrees of modelling sophistication. The six models employed different modelling assumptions with regards to the simulation of the impact of smoke on occupant movement speeds. The uncertainty in the reliability of the assumptions, i.e., default settings and embedded data-sets and their interpretation, was demonstrated by the consistent differences among the model results. Modellers should always take this problem into account when employing a model individually. A recommendation is that evacuation modellers should use the most conservative credible default values, requiring a movement away from this conservative position to be justified.

A novel multi-model approach has been presented and tested. The present work showed that the multi-model approach makes it possible to use each model at its best and to overcome the weaknesses deriving from the use of a single model. Although this approach required high degree of modelling effort and user expertise, the benefits deriving from its application was that the modellers became aware of the sources of uncertainty linked to each single model. In addition, it was shown that this method increased the reliability of model results since it makes use of the strengths of different models and simulates very complex evacuation scenarios.

6. FUTURE RESEARCH

One of the limitations of the present work is that it focuses on two main aspects of road tunnel evacuation, namely the impact of smoke on occupant's movement speed and exit choice. Group interaction is the third crucial aspect in this type of analysis. The current literature on human behaviour in fire does not include a robust predictive theory on this aspect and any modelling efforts would be neglected by the lack of experimental data. It is then recommended that future research will focus on the study of group interactions and the way to embed and validate predictive algorithms to simulate this key aspect of the people performance in road tunnel evacuations.

Another aspect that needs to be further investigated is the analysis of the evacuation performance of people with disabilities whose behaviours may completely differ from the behaviours observed in the other tunnel users. Initial attempts to develop dedicated evacuation modelling tools is under development [Christensen & Sasaki, 2008], but the variability of the possible impairments and the subsequent effects on human behaviour needs dedicated experimental campaigns prior to perform further modelling efforts.

REFERENCES

ANAS (2009). Linee Guida per la Progettazione della sicurezza nelle Gallerie Stradali. Seconda Edizione [National administration of roads and highways, guidelines for the road tunnel safety design], Condirezione Generale Tecnica, Direzione Centrale Progettazione.

Averill JD, Reneke P, Peacock R (2008). Required Safe Egress Time: Data and Modeling. In Proceedings of the 7th International Conference on Performance-Based and Fire Safety Design Methods National Institute of Standards and Technology (NIST).

Banuls Egeda R, Carbonell Vaya E, Casanoves M, Chisvert M (1996). Different Emotional Responses in Novice and Professional Drivers, Traffic and Transport Psychology: Theory and Application, Pergamon, Amsterdam, NL.

Bellamy L & Geyer T (1990). Experimental programme to investigate informative fire warning characteristics for motivating fast evacuation (No. BR172). Building Research Establishment, Garston.

Bensilum M & Purser DA (2003). Gridflow: an object-oriented building evacuation model combining pre-movement and movement behaviours for performance-based design. Fire Safety Science. In Proceedings of the Seventh International Symposium, Worcester, Massachusetts, USA, pp.941-952.

Bernardi M, Macaluso A, Sproviero E, Castellano V, Coratella D, Felici F, Rodio A, Piacentini MF, Marchetti M, Ditunno JF (1999) Cost of walking and locomotor impairment, Journal of Electromyography and Kinesiology 9 pp. 149–157.

Boer L & Veldhuijzen van Zanten D (2005). Behaviour on tunnel fire. In Proceedings of the third International Conference on Pedestrian and Evacuation Dynamics, PED05, Vienna, Austria.

Boyce KE & Shields TJ (1999a) Towards the Characterisation of Building Occupancies for Fire Safety Engineering: Prevalence, Type and Mobility of Disabled People, Fire Technology, 35:1, pp 35-50.

Boyce KE & Shields TJ (1999b) Towards the Characterisation of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and up an Incline, Fire Technology, 35: 1, pp 51-67.

Boyce KE & Shields TJ (1999c). Towards the Characterisation of Building Occupancies for Fire Safety Engineering: Capability of Disabled People to Negotiate Doors, Fire Technology, 35:1, pp 68-78.

Boyce KE, Shields TJ, Silcock GWH (1999) Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capability of People with Disabilities to Read and Locate Exit Signs, Fire Technology, 35:1, pp 79-86.

British Standards Institution PD 7974-6 (2004). The application of fire safety engineering principles to fire safety design of buildings. Human factors. Life safety strategies. Occupant evacuation, behaviour and condition (Sub-system 6)

Canter D, Breaux J, Sime J (1980) Domestic, multiple occupancy, and hospital fires. In: Canter D (ed) Fires and human behaviour Wiley, Chichester, pp. 117–136

Carvel R & Marlair G (2011). A history of fire incidents in tunnels. In A. Beard & R. Carvel (Eds.), Handbook of Tunnel Fire Safety. Second ed London: Thomas Telford, pp. 3-23.

Christensen K & Sasaki Y (2008) Agent-Based Emergency Evacuation Simulation for Individuals with Disabilities in the Population, Journal of Artificial Societies and Social Simulation vol. 11, no. 39.

Christensen K, Collins M, Holt SD, Phillips JM (2006). The relationship between the design of the built environment and the ability to egress of individuals with disabilities, Review of Disability Studies, Volume 2, pp. 24-34.

Christensen LB (2007). Experimental methodology (10th ed.). Boston: Pearson Education.

Council Directive (EC) (2004) 2004/54/EC of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.

Curry GL, Deuermeyer BL, Feldman RM (1989. Discrete Simulation, Holden-Day, Inc., pp. 297.

Deutsch M & Gerard HB (1955). A study of normative and informational social influences upon individual judgment. Journal of Abnormal Social Psychology 51(3) pp. 629-636.

Duffé P & Marec M (1999). Task Force for Technical Investigation of the 24 March 1999 Fire in the Mont Blanc Vehicular Tunnel.: Minister of the Interior - Ministry of Equipment, Transportation and Housing.

Fahy R, Proulx G, Aiman L (2011). Panic or not in fire: Clarifying the misconception, Fire and Materials 2011.

Fahy RF & Proulx G (1996). A study of occupant behavior during the World Trade Center evacuation. In Proceedings of the Seventh International Interflam Conference. Franks C, Grayson S (ed.). Interscience Communications Ltd: London.

Fahy RF (1996). Enhancement of EXIT89 and analysis of World Trade Center data, NIST-GCR-95-684, Fire Analysis and Research Division.

Federal Highway Administration (FHA) (2006). Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response, Report FHWAPL- 06-016, International Technology Scanning Program, Washington, D.C.

Frantzich H, Nilsson D, Eriksson O (2008). Evaluation and validation of evacuation programs. Report 3143. Lund: Dept of Fire Safety Eng. and Systems Safety, Lund University.

Frantzich H & Nilsson D (2003). Utrymning genom tät rök: beteende och förflyttning [Evacuation in dense smoke: behaviour and movement] (No. 3126). Lund: Department of Fire Safety Engineering and Systems Safety.

Fridolf K, Nilsson D, Frantzich H (2011). Fire Evacuation in Underground Transportation Systems: A Review of Accidents and Empirical Research. Fire Technology.

Friedman R (1992). An international survey of computer models for fire and smoke. Journal of Fire Protection Engineering 4 pp. 81-92

Fruin JJ (1971). Pedestrian planning and design (Revised Edition, 1987). Elevator world, INC, USA.

Galea E, Deere S, Sharp G, Filippidis L, Hulse L (2010). Investigating the impact of culture on evacuation behaviour. In Proceedings of Interflam 2010, Interscience Communications Ltd: London, pp. 879-892.

Galea ER, Gwynne SMV, Lawrence PJ, Filippidis L, Blackshields D, Cooney D (2004). buildingEXODUS V4.0 User Guide and Technical Manual. University of Greenwich.

Galea ER, Gwynne SMV, Blackshields D, Lawrence PJ, Filippidis L (2001). Predicting the evacuation performance of passenger ships using computer simulation. In Proceedings of the 9th International Fire Science and Engineering Conference: Interflam 2001, Edinburgh, Scotland, Interscience Communications Ltd: London, Vol. 2, pp.853-864.

Galea ER (1998). A General Approach To Validating Evacuation Models with an Application to EXODUS, Journal of Fire Science, Vol. 16, pp. 414-436.

Gandit M, Kouabenan DR, Caroly S (2009). Road-tunnel fires: Risk perception and management strategies among users. Safety Science, 47(1), pp. 105-114.

Giere RN (1991). Understanding Scientific Reasoning. Harcourt Brace Jovanovich College Publishers, New York, 322 pp.

Gwynne SMV, Au SYZ, Purser D, Boswell D (2011). Accounting for staff response in engineering design. In Capote J (ed) et al: Advanced Research Workshop Evacuation and Human Behaviour in Emergency Situations EVAC11, Santander, Spain.

Gwynne SMV, Purser DA, Boswell DL, (2010). Pre-warning staff delay: a forgotten component in ASET/RSET calculations. In Proceedings for the 5th International Conference on Pedestrian and Evacuation Dynamics, National Institute of Standards and Technology, Gaithersburg, Maryland USA.

Gwynne SMV & Kuligowski E (2010). The faults with default. In Proceedings of the Conference Interflam2010, Interscience Communications Ltd: London. pp. 1473-1478.

Gwynne SMV (2010). Conventions in the collection and use of human performance data, National Institute of Standards and Technology GCR 10-928

Gwynne SMV & Rosenbaum E (2008). Employing the Hydraulic Model in Assessing Emergency Movement. In the SFPE Handbook of Fire Protection Engineering, 4th Edition. National Fire Protection Association, Quincy, MA, pp. 3-396-3-373.

Gwynne SMV, Galea ER, Owen M, Lawrence PJ, Filippidis L (1999). A Review of the methodologies used in the computer simulation of evacuation from the built environment. Building and Environment, 34(6), pp.741-749.

Hartson HR (2003). Cognitive, physical, sensory, and functional affordances in interaction design. Behaviour & Information Technology, 22(5), pp. 315-338.

Hedman G (2009). Stair descent devices: an overview of current devices and proposed framework for standards and testing. PE, CPE University of Illinois at Chicago, Usa. In Proceedings of the fourth International Symposium Human Behaviour in Fire 2009, Cambridge, UK.

International Maritime Organization (2007). Guidelines for Evacuation Analyses for New and Existing Passenger Ships, MSC/Circ.1238, International Maritime Organization, London, UK.

International Standards Organization ISOTR16738 (2009) Fire Safety Engineering. – Technical Information on methods for evaluating behaviour and movement of people. International Standards Organisation, Geneva, 2009

Ingason H & Wickström U (2006) The international FORUM of fire research directors: A position paper on future actions for improving road tunnel fire safety. Fire Safety Journal, 41, pp. 111-114.

International Standards Office, (2007) ISO13571, Life threat of fires, Guidance on the estimation of time available for escape using fire data.

Jin T (2008). Visibility and Human Behavior in Fire Smoke. In the SFPE Handbook of Fire Protection Engineering (fourth edition). National Fire Protection Association, Quincy MA, USA.

Jin T (1976). Visibility through Fire Smoke: Report of Fire Research Institute of Japan 2, 33, pp. 12-18.

Johnson P & Barber D (2007). Burnley tunnel fire—the Arup view. Retrieved 2 November, 2011, from http://www.fpaa.com.au/docs/burnley.pdf

Khoury G, (2003), Common Safety/UPTUN Safety Philosophy Leading to the Global Approach to Tunnel Safety [Online].

Korhonen T & Heliövaara S (2011). FDS+Evac: Herding Behavior and Exit Selection. In Proceedings of the 10th International IAFSS Symposium, 19-23 June 2011, University of Maryland, MD, USA. The International Association for Fire Safety Science, IAFSS.

Korhonen T & Hostikka S (2010). Fire Dynamics Simulator with Evacuation: FDS+Evac Technical Reference and User's Guide. FDS 5.5.3, Evac 2.3.1. VTT working papers.

Kuligowski ED (2011a). Predicting Human Behavior during Fires. Fire Technology, Vol. 48.

Kuligowski ED (2011b). Terror defeated: Occupant sensemaking, decision-making and protective action in the 2001 World Trade Center disaster. University of Colorado.

Kuligowski ED, Peacock RD, Hoskins, BL (2010). A Review of Building Evacuation Models NIST, Fire Research Division. 2nd edition. Technical Note 1680 Washington, US.

Kuligowski, ED & Milke JA (2005). A performance-based egress analysis of a hotel building using two models. Journal of fire Protection Engineering Vol 15.

Larusdottir A, Dederichs A (2010). Evacuation of Children: Movement on Stairs and on Horizontal Plane, Fire Technology, pp. 1-11.

Latané B, Darley JM (1968). The unresponsive bystander: why doesn't he help? Appleton- Century-Crofts, New York.

Leitner A (2001) The fire catastrophe in the Tauern Tunnel: experience and conclusions for the Austrian guidelines. Tunnelling and Underground Space Technology, Vol. 16, pp. 217-223.

Lord J, Meacham B, Moore A, Fahy R, Proulx G (2005). Guide for evaluating the predictive capabilities of computer egress models, NIST Report GCR 06-886.

Maevski IY (2011). Design Fires in Road Tunnels, A synthesis of Highway Practice, Transportation Research Board NCHRP National Cooperative Highway Research Program Synthesis 415.

Maxwell JA (2005). Qualitative Research Design: An interactive approach. Thousand Oaks, CA: Sage Publications.

Mott MacDonald Simulation Group (2011). Simulation of Transient Evacuation and Pedestrian movementS STEPS User Manual 4.1 Version.

Nilsson D (2009). Exit choice in fire emergencies - influencing choice of exit with flashing lights. Phd Dissertaion. Lund University, Lund, Sweden.

Nilsson D, Johansson M, Frantzich H (2009). Evacuation experiments in a road tunnel: A study of Human Behaviour and technical installations, Fire Safety Journal 44, pp. 458-468.

NFPA (2011). NFPA 502 Standard for road tunnels, bridges and other limited access highways, 2011 edition.

Norén A, Winér J (2003). Modelling crown evacuation from road and train tunnels – data and design for faster evacuations, Report 5127, Lund, Department of Fire Safety Engineering, Lund University.

Olenick, SM, Carpenter, DJ, (2003). An updated international survey of computer models for fire and smoke. Journal of Fire Protection Engineering, 13(2), pp.87-110 and online http://www.firemodelsurvey.com/EgressModels.html

Overton S (1977). A strategy of model construction. In: C. Hall and J. Day (Editors), Ecosystem Modeling in Theory and Practice: An Introduction with Histories. John Wiley & Sons, New York. Reprinted 1990, University Press of Colorado, pp. 49-73.

Passenier PO & van Delft JH (1995). The human-machine interface. In J. van Delft and H. Schuffel (Eds), Human factors investigation for future commando centres of the Royal Netherlands Navy [in Dutch], report TNO-TM 1995 A-19, pp. 51-58. Soesterberg (NL): TNO Human Factors.

Purser DA (2009). Application of human behaviour and toxic hazard analysis to the validation of CFD modelling for the Mont Blanc Tunnel fire incident. In Proceedings of the Advanced Research Workshop on Fire Protection and Life Safety in Buildings and Transportation Systems 2009, Santander, Spain, pp 23-57.

Purser D.A., (2008). Assessment of Hazards to Occupants from smoke, toxic gases and heat. In the SFPE Handbook of Fire Protection Engineering (Fourth Edition). National Fire Protection Association, Quincy MA, USA.

Purser DA & Gwynne SMV (2007). Identifying Critical Evacuation Factors and the Application of Egress Models. pp. 203-214 in Proceedings of the 11th International

Interflam Conference, edited by C. A. Franks and S. Grayson. London, England: Interscience Communications Ltd

Purser DA (2003). Behaviour and travel interactions in emergency situations and data for engineering design. In Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics, 20-22August 2003 Greenwich, UK pp. 355-370.

Quarantelli EL (1954). The nature and condition of panic. The American Journal of Sociology, 60(3), pp. 267-275.

Ronchi E, Berloco N, Colonna P, Alvear D, Capote J, Cuesta A (2011a). Sviluppo di un database per la simulazione di persone disabili nei modelli computazionali di evacuazione. (Developing a Database for simulating disabled people within evacuation models), Sicurezza nei Sistemi Complessi 2011, Bari (Italy).

Ronchi E, Gwynne SMV, Purser DA (2011b) The impact of default settings on evacuation model results: a study of visibility conditions vs occupant walking speeds. In Capote J (ed) et al: Advanced Research Workshop Evacuation and Human Behaviour in Emergency Situations EVAC11, Santander, pp 81-95

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2010). Human behaviour in road tunnel fires: Comparison between egress models (FDS+Evac, STEPS, Pathfinder). In Proceedings of the twelfth international Interflam 2010 Conference, Nottingham, UK, pp. 837-848.

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2009). Human Behaviour in case of Fire inside an Urban Tunnel through Computer Modelling. In Proceedings of the Advanced Research Workshop on Fire Protection and Life Safety in Buildings and Transportation Systems 2009, Santander, Spain, pp. 349-361.

Rykiel EJ (1996). Testing ecological models: the meaning of validation, Ecological modelling Vol. 90 No. 3 pp. 229-244.

Saltelli A, Ratto M, Andres T, Campolongo F, Cariboni J, Gatelli D, Saisana M, Tarantola S (2008). Global Sensitivity Analysis. The Primer, John Wiley & Sons.

Santos G & Benigno Aguirre E (2004). A Critical Review of Emergency Evacuation Simulation Models, Proceedings of the NIST Workshop on Building Occupant Movement during Fire Emergencies, Disaster Research Center, University of Delaware.

Shields J (2005) Human behaviour in tunnel fires. In: Beard A, Carvel R (eds) The handbook of tunnel fire safety Thomas Telford Publishing, London

Shields TJ & Boyce KE (2004). Towards Developing an Understanding of Human Behaviour of Fire in Tunnels. In Proceedings of third International Symposium Human Behaviour in Fire 2004, Belfast, 1-3 September 2004, Interscience Communications, pp. 215-228.

Sime JD (1987). Access and Egress for the Handicapped in Public Buildings, in G. Haber and T. Blanks (Eds.) Building Design for Handicapped and Aged Persons: An International Inventory, Portsmouth, UK, 27, 1987.

Sime JD (1984). Escape behaviour in fires: ‘Panic’ or affiliation? PhD thesis, University of Surrey, Guilford.

Sime JD (1980). The concept of panic. In D. Canter (Ed.), Fires and human behaviour. Chichester: John Whiley & Sons, Ltd.

Tavares RM (2009). An analysis of the fire safety codes in Brazil: Is the performance-based approach the best practice? Fire Safety Journal 44:5 pp.749-755

Thompson PA & Marchant EW (1995). A Computer Model for the Evacuation of Large Building Populations, Fire Safety Journal 24, pp. 131-148.

Thunderhead Engineering, 2011. Pathfinder (2011 Version). Technical Reference.

Tong D & Canter D (1985). The decision to evacuate: a study of the motivation which contribute to evacuation in the event of fire. Fire Safety Journal 9, pp. 257–265

Watts JM (1987). Computer models for evacuation analysis, Fire Safety Journal 12 pp. 237-245

Wright MS, Cook GK, Webber GMB (2001). The effects of smoke on people's walking speeds using overhead lighting and way-guidance provision. In proceedings of the second International Symposium on Human Behaviour in Fire 2011, MIT, Boston, USA, Interscience Communications Ltd: London, pp.275-284.

Xie H (2011). Investigation into the Interaction of People with Signage Systems and its Implementation within Evacuation Models. Phd Dissertation, University of Greenwich, UK.

Yin RK (2003). Case study research: Design and methods (3rd ed.). Thousand Oaks: Sage Publications.

Zhang Q (2010). Image based analysis of visibility in smoke laden environments. Dissertation at the University of Hull, UK.

APPENDIX I

Paper I	**Ronchi E** & Kinsey M (2011). *Evacuation models of the future. Insights from an online survey on user's experiences and needs.*
Paper II	**Ronchi E**, Colonna P, Capote J, Alvear D, Berloco N, Cuesta A (2012). *The evaluation of different evacuation models for assessing road tunnel safety analysis.*
Paper III	**Ronchi E,** Gwynne SMV, Purser DA, Colonna P (2012). *Representation of the impact of smoke on agent movement speeds in evacuation models*
Paper IV	**Ronchi E**, Nilsson D, Gwynne SMV (2012). *Modelling the impact of emergency exit signs in tunnels*.
Paper V	Fridolf K, **Ronchi E**, Nilsson D, Frantzich H (2012). *Movement speed and exit choice in smoke-filled rail tunnels.*
Paper VI	**Ronchi E** (2012)**.** *Testing the predictive capabilities of evacuation models for tunnel safety analysis.*

PAPER I

EVACUATION MODELS OF THE FUTURE: INSIGHTS FROM AN ONLINE SURVEY OF USER'S EXPERIENCES AND NEEDS

RONCHI, E.[1] & KINSEY M.J.[2]

[1] *Department of Roads and Transportation. Polytechnic University of Bari, Via Orabona 4, 70100 Bari (BA), Italy*

[2] *Fire Safety Engineering Group (FSEG), University of Greenwich, London SE10 9LS, UK*

Abstract

This paper presents a summary analysis of data regarding evacuation model user's experiences and needs obtained via an online survey. The survey was available in 6 languages: English, German, Chinese, Spanish, Italian and Russian. The different versions allowed the survey to be accessible to an international participant base. The survey was developed by the team at www.Evacmod.net; an evacuation modelling portal for the simulation of human behaviour during emergency situations. Participant responses to the survey in raw data format will be publicly available from the portal to allow model developers/users or any interested parties to analyse the data. In total 198 participants either fully or partially completed the survey. Participants came from some 36 different countries, from a wide range of different education and occupational backgrounds, and used models for a variety of different purposes. The survey consisted of 16 questions addressing issues including perception of importance of model features, usage/awareness of other models, knowledge of model validation/verification, training, and usage of multiple models. The presented analysis provides information for evacuation model developers of user characteristics and subsequent guidance for instructing future model development.

Keywords. Evacuation Models, Human Behaviour in Fire, Emergency scenarios, model survey.

1 Introduction

The understanding of human behaviour in fire has received more research interest during latter half of the 20th century. In parallel, the development of fire safety building codes [Di Nenno et al., 2008] has required engineers to demonstrate buildings conform to an increasing number of fire safety requirements. As part of this, analytical people flow calculations were traditionally adequate to demonstrate a structures evacuation capability. However, the development of ever unique and complex structures has meant it is not always possible to assess certain structures using such calculations [Kuligowski et al., 2010]. This has fuelled the development and usage of computer based evacuation models to explore the potential influence of human factors during unique/complex emergency situations [Thompson & Marchant, 1995, Gwynne et al., 2001].

The use of computers to simulate emergency evacuations can be traced back to the 1970s [Bazjanac, 1977]. Since then a number of evacuation models have been developed with a range of different features [Santos et al., 2004, Gwynne et al., 1999]. Indeed evacuation model capabilities [Lord et al., 2005, Castle, 2007], scrutiny [Ronchi et al., 2010, Tavares, 2008] and validation [Frantzich et al., 2008, Galea, 1998] have been the focus of a large a number of research papers in the last two decades. However, whilst evacuation models are increasing in complexity [Kuligowski & Gwynne, 2005] as understanding of human behaviour in fire progresses, there is a lack of understanding regarding evacuation model user experiences and needs of such models.

To address the above issues and attempt to gain a better understanding of the current uses and desired needs of the evacuation modelling community, an online survey was developed. The survey was developed by the team at www.Evacmod.net; an evacuation modelling portal for the simulation of human behaviour during emergency situations. On the website, students, fire safety engineers, software engineers, behavioural scientists, researchers or any interested parties can communicate and share their knowledge and experience in this field. The use of a publicly accessible online survey was intended to reach as wide as international audience as possible coming from a broad variety of different backgrounds.

The first part of the paper presents a description of the survey and the reason why the questions have been selected. The methods of dissemination have been described in order to demonstrate that the sample population is representative of the general evacuation user modelling community. Participant demographic and characteristics are presented in the following section. These have been described in order to highlight how evacuation models are currently being utilised. Participants were required to provide information about their experiences and degree of knowledge of various aspects regarding evacuation models e.g. model validation, training, model awareness etc. Limitations of the survey have been described together with future possible improvements for data collection. Overall conclusions based on the analysis of participant responses are then presented. Such analysis is intended to assist future development of evacuation models.

2 Survey description

The survey was made available in six languages, English, German, Chinese, Spanish, Italian and Russian. The different versions allowed the survey to be accessible to an international participant base. The methods of dissemination have been various in order to achieve a relevant number of participants belonging to different areas of expertise that use different models. The dissemination of the survey has been conducted in collaboration with a range of model developers. In addition, several online forums have been used that are either dedicated or associated with using such models. These include newsletters, mailing lists, forums, and social networking sites. The call for participation to complete the online survey started in January 2011 and ended in June 2011 over a period of six months.

The survey consisted of 16 questions divided in to two sections and required approximately 15 minutes to complete. The first section (Background and Interests) required information about participants' characteristics and demographics. Information on participant nationality, academic background, position and working area were investigated. Questions regarding types of application, uses and years of experience with the models were included. The second section (Needs and Experiences) addressed several issues including user perception of importance of model features, usage/awareness of other models, knowledge of model validation/verification, model training, and usage of multiple models.

3 Participant characteristics and demographics

In total 198 participants either fully or partially completed the survey. Almost all participants (94% (186)) stated their country of residence. Whilst participants came from some 36 different countries, approximately 40.4% of participants came from three countries including the UK (15.7%), Germany (14.6%) and U.S (10.1%) (see Figure 1).

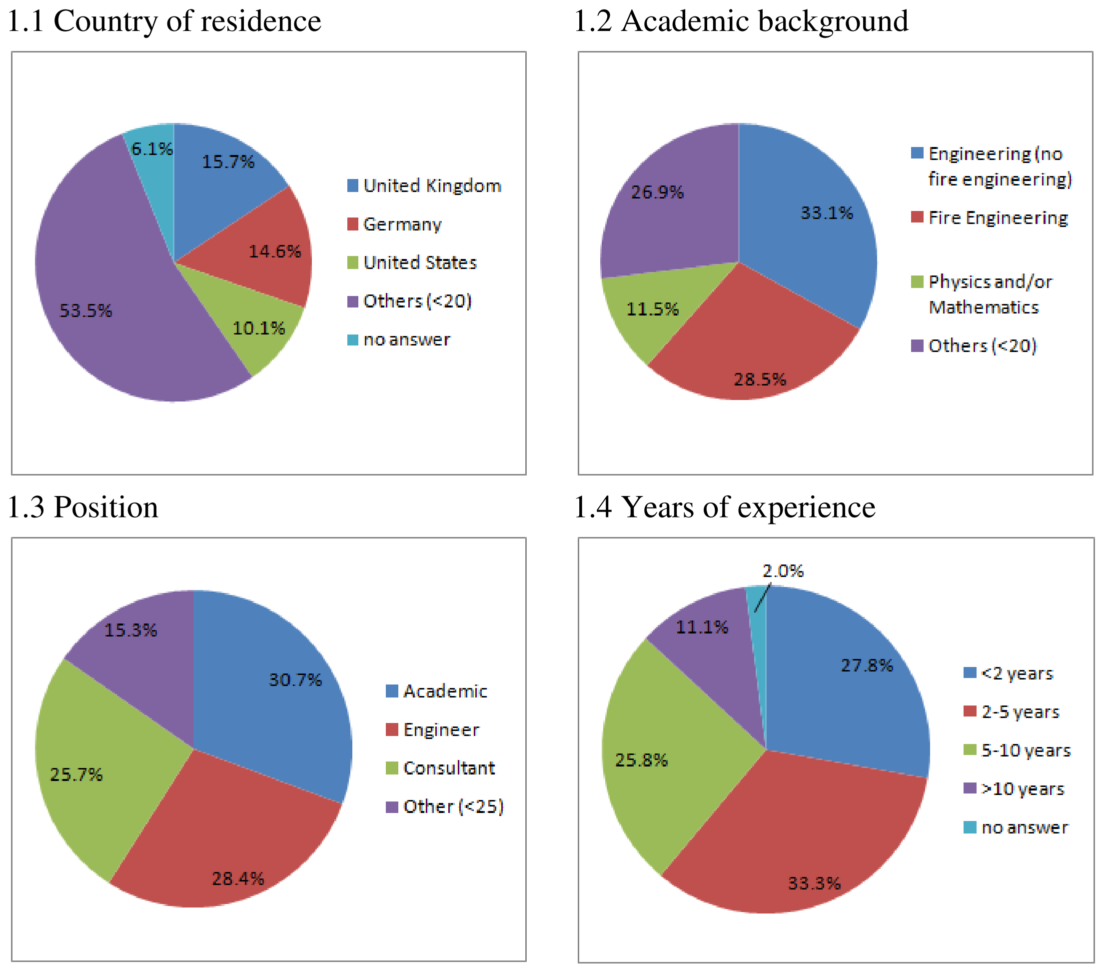

Figure 1: Country of residence (1.1), academic background (1.2), position (1.3 - both considering single and multiple backgrounds), and current working area (1.4) of the survey participants.

Focusing on the academic background of participants, 61.6% came from engineering backgrounds. The majority of participants stated that their current occupation was either in academia (30.7%) or engineering (28.4%) (see Figure 1). From Figure 1 it can also be seen that the majority of participants (61.1%) had less than 5 years experience using evacuation models.

Participants were asked to rate on a 5 point Likert scale the extent to which they use models in different contexts (5 = main context and 1= not at all). Almost two thirds of participants (64.0%) responded that they mainly used models within an evacuation context with just over a third (35.8%) using the models for research/testing (see Table 1).

Table 1: Proportion of responses that stated is of context for using models.

Score	Evacuation (%)	Large-scale events (%)	Pedestrian planning in normal conditions (%)	Research / testing (%)
5 (main context)	64.0	19.1	16.6	35.8
4	13.2	19.7	14.2	16.5
3	10.2	18.5	15.4	13.6
2	6.1	20.2	14.2	15.3
1 (not at all)	6.6	22.5	39.6	18.8

Participants were asked how frequently they used evacuation models. From Table 2 it can be seen that the majority of participants (64.6%) use evacuation models at least once a month. This decreases to approximately a third (33.8%) for participants that use evacuation models at least once a week.

Table 2: Frequency of use of evacuation models.

Frequency	Proportion (%)
Less than once a year	6.1 [12]
At least once a year	93.9 [186]
At least once a month	64.6 [128]
At least once a week	33.8 [67]
Several days a week	17.7 [35]

The data collected represents participants from a wide variety of different countries, backgrounds and experiences with different models. With such a diverse sample of participants it is hoped the general applicability of the results is increased.

4 Results

Participants were presented with a list of factors related to evacuation models. They were asked to state how important they thought each factor was when selecting/using a model based on a 5 point Likert scale (5= very important and 1= not important). The overall frequency of participants that stated the level of importance for each factor can be seen in Figure 2 (N=167). All scores were averaged for each factor then placed in order (the higher the value the more important the factor). A Wilcoxon Signed-Rank test was used to determine if any significant difference existed between factors so that each factor could be given an ordinal value of importance (see blue box values in Figure 2) relative to the other factors.

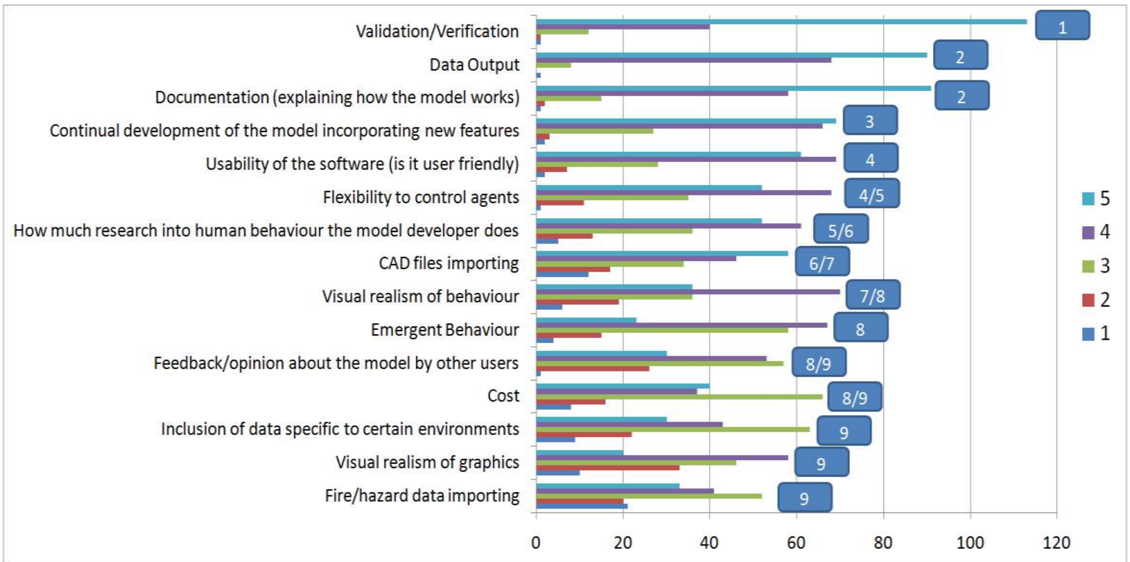

Figure 2: Frequency of participants that stated the level of importance for each factor when selecting/using a model (5= very important, 1= not important). Blue square value indicates overall relative order of importance e.g. 1= most important, 2= second most important, etc.

Overall results show that participants considered validation/verification to be the most important factor when selecting/using a model, closely followed by documentation (explaining how model works) and data output options of the model. Such findings suggest that model users require assurances that a model produces accurate results. Demonstrating a model's predictive capabilities by comparing model results to data collected from actual evacuation/experimental/normal situations is of considerable importance to model users. Similarly, detailed documentation explaining how a model functions with the data used in the model contributes to reducing user uncertainty of how a model functions.

Participants were asked what models they were aware of (N=191). The majority had an awareness of EXODUS (66.5%), FDS+Evac (58.1%), and Simulex (57.6%), with just under half also being aware of STEPS (45.5%) and Pathfinder (40.8%). It is unclear whether model awareness is reflective of the success of a model's marketing, increased number of publications associated with a given model, increased age of a model, the method of survey dissemination favoring certain model users, or general popularity of a model. In addition to stating the models that participants were aware of, participants were also asked what model they mainly used (N=198). Over half of participants mainly used one of six models including Simulex (13.6%), FDS+Evac (12.6%), VISSIM (8.6%), STEPS (7.1%), Pathfinder (6.6%), and EXODUS (5.6%) (see Figure 3).

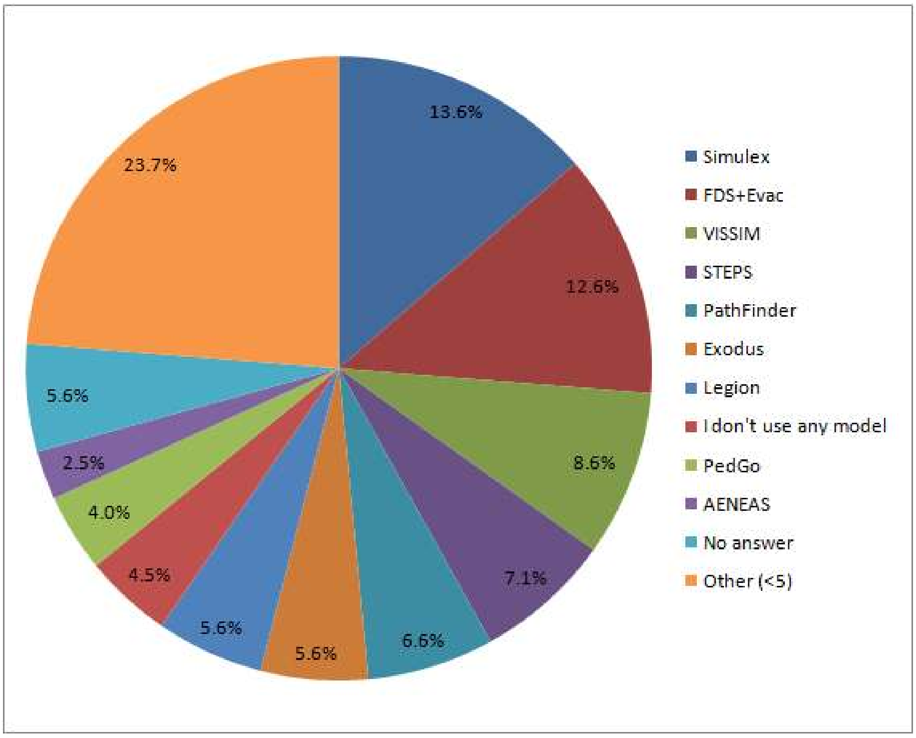

Figure 3: Proportion of participants that mainly use a given model.

Focusing on the top 7 models according to frequency of participants (i.e. ≥10 participants), user responses were separated for the question asking how important different factors were when selecting/using a model (N=170). The scores were averaged for each factor for each model then placed in order. The higher the average score the more important users of a certain model thought a given factor was (see Table 3). It should be highlighted that such results reflect participant perception rather than a models actual success of addressing each factor.

The results highlight that participants believe each model addresses each factor to a different extent. The results also suggest factors that specific model developers might consider advantageous for future model development. It should be kept in mind that such factors may not have been considered by participants when selecting/using their current model. In such incidences, participants may adopt 'confirmation bias' behavior where they state higher importance of certain factors that they know their model addresses i.e. justifying their selection. A similar issue may have occurred with model developers themselves completing the survey. Potential issues like these should be considered when interpreting the results.

Table 3: Ordinal rank of importance for each factor stated by users of each model

	Ordinal Rank (1= more important, 7=less important)						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Cost	F	L	bX	S	P	V	Sim
Validation/Verification	F	L	S	P	bX	Sim	V
Usability of the software (is it user friendly)	bX	P	S	Sim	F	L	V
Emergent Behaviour	bX	F	P	Sim	L	V	S
Fire/hazard data importing	F	bX	P	Sim	S	L	V
CAD files importing	S	L	P	bX	Sim	F	V
Inclusion of data specific to certain environments	L	V	Sim	bX	P	F	S
Visual realism of behaviour	L	S	P	V	bX	F	Sim
Visual realism of graphics	L	P	S	V	Sim	bX	F
Flexibility to control agents	S	bX	L	V	Sim	P	F
Documentation (explaining how the model works)	S	F	P	bX	L	Sim	V
How much research into human behaviour the model developer does	bX	L	F	V	P	S	Sim
Data Output	S	L	bX	Sim	F	P	V
Feedback/opinion about the model by other users	L	F	Sim	P	V	S	bX
Continual development of the model incorporating new features	L	F	P	Sim	V	S	bX

Legenda: bX=buildingEXODUS, F=FDS+Evac, L=Legion, P=Pathfinder, Sim=Simulex, S=STEPS, V=Vissim

Participants were requested to state their level of knowledge regarding validation/verification of the model that they mainly use (N=196). Only 6.1% of participants stated that they had no knowledge of model validation/verification. This means that 93.9% of model users have some knowledge of validation/verification of their model. Indeed 80.1% stated that they had either read literature regarding model validation/verification or both read literature and compared the model with modelled/actual data.

Only 10.6% of participants stated they have an agreement with a model developer for using only one model. This highlights that most model developers actually have a choice of which model to use and are not contractually obliged to use a single model.

Such agreements provide financial benefit to model developers. However, restricting user model choice is considered to have an ultimate negative impact on the field by prohibiting the use of other model's that may better suit a user's needs.

Just over a third (33.7%) of participants stated that they have previously used a different model to the one they currently use. This indicates that most model users have not used more than one model. Though the reasons for this behavior are uncertain, such findings suggest either increased model loyalty, increased model familiarity, lack of awareness of other models, or contractual agreement to use a model.

5 Limitations

The survey has a number of limitations that should be noted. These include:

Dissemination by model developers. As previously mentioned, a small number of model developers have assisted with dissemination of the survey by sending the survey to their users. However, a number of model developers did not respond to the invitation to take part in the survey. This could mean that users of certain models, and their subsequent experiences and needs, are underrepresented in the survey results. Future data collection should perhaps look to address this issue with more collaboration with model developers.

Publicly availability. The survey was publicly accessible. Consequently it was prone to participants perusing through the survey without completing any questions. Another issue was the potential for abuse in the survey (e.g. people completing the survey with malicious intent). Each participant's computer IP address and time stamp were recorded in order to minimise the potential of malicious intent, thus influencing the final analysis. If an IP address occurred multiple times, such responses were analysed to ascertain whether or not the answers provided appeared malicious. Despite this only a single participant response was identified as being malicious.

Likert scale. The use of a Likert scale allows participants to state a finite level of difference between the importance of given factors (i.e. a limited variance). Future data collection could address this by using continuous numerical scale with no bounds to more accurately represent any difference between levels of importance between factors.

Such survey limitations should be considered when interpreting or applying the results in any context. Indeed further investigations should look to address such issues.

6 Conclusions

This paper has presented an analysis of data from an online survey in order to gain an understanding of evacuation model users' experiences and needs. Results have shown that model users consider validation/verification to be the most important factor when selecting/using a model. This is highlighted by 93.9% of participants having some knowledge of validation/verification regarding the model they mainly use. This factor is closely followed in the importance scale by model data output options and documentation explaining how a model works. It is suggested that the results highlight the increased complexity of evacuation models and the subsequent assurances required regarding the accuracy of model results. It is clear that model users require assurances regarding the predictive capabilities and how they are implemented within a model. The authors suggest that this can achieved through greater transparency with regards to algorithms, assumptions, and data incorporated into evacuation models.

The majority of participants only use evacuation models at least once a month. Such infrequent usage suggests the ease of use and familiarity with a model is an important factor. This is highlighted by the usability of software being ranked 4^{th} in terms of importance when selection/using a model. Addressing such factors would decrease the time required to perform evacuation analysis and therefore would likely have cost saving benefits.

Results also suggest that many model users are unaware of other models and subsequently their capabilities. This lack of awareness inhibits informed model selection. To help address this issue the team at www.Evacmod.net has developed a Model Directory in collaboration with Erica Kuligowski at NIST based on a review of evacuation models [2]. This project allows model developers to provide up to date information about models on the site themselves. This provides a central resource for existing and potential future model users to find out more information about each model. Indeed the team at www.Evacmod.net would like to urge any model developers that are not already taking part to join the project.

Both existing and potentially new model users can use the presented analysis for assessing criteria that should be considered when selecting/using an evacuation model.

In addition, the analysis provides model developers with a general insight of users' needs and experiences for a variety of different model users. It is hoped this in turn provides guidance for the focus of future model development. To facilitate such aims, participant responses have been made publicly available on www.Evacmod.net (see http://www.evacmod.net/?q=node/2574) for third party analysis.

Future analysis of the survey results should perhaps seek to segregate the data according to participant specific factors. Of particular interest may be segregation according to the main models participant use, years of experience, and context of model usage.

Acknowledgments

The authors thank the model developers and other individuals that have contributed to the dissemination, including Hubert Klüpfel, Andrey Skochilov, Tobias Kretz, and Steve Gwynne. Furthermore we would like to thank all the survey participants.

References

Bazjanac V (1977). Simulation of elevator performance in high-rise buildings under conditions of emergency, *Human Response to Tall Buildings*, pp. 316-328.

Castle CJE (2007). Guidelines for Assessing Pedestrian Evacuation Software Applications, Centre for Advanced Spatial Analysis University College London. Paper 115.

Di Nenno P (2008). SFPE Handbook of Fire Protection Engineering 3rd edition, 2008, National Fire Protection Association, Quincy, Massachusetts.

Frantzich H, Nilsson D, Eriksson O (2008). Evaluation and validation of evacuation programs. Report 3143. Lund: Dept of Fire Safety Eng. and Systems Safety, Lund University.

Galea ER (1998). A General Approach To Validating Evacuation Models with an Application to EXODUS, Journal of Fire Science, Vol. 16, pp. 414-436.

Gwynne SMV, Galea ER, Lawrence PJ, Filippidis L (2001) Modelling occupant interaction with fire conditions using the buildingEXODUS evacuation model, *Fire Safety Journal*, 36, pp. 327-357.

Gwynne SMV, Galea ER, Owen M, Lawrence PJ, Filippidis L (1999). A Review of the methodologies used in the computer simulation of evacuation from the built environment. Building and Environment, 34(6), pp.741-749.

Kuligowski ED, Peacock RD, Hoskins, BL (2010). A Review of Building Evacuation Models NIST, Fire Research Division. 2nd edition. Technical Note 1680 Washington, US.

Kuligowski ED & Gwynne SMV (2005). What a User Should Know When Selecting an Evacuation Model, *Fire Protection Engineering*, No. 3, pp. 30-40.

Lord J, Meacham B, Moore A, Fahy R, Proulx G (2005). Guide for evaluating the predictive capabilities of computer egress models, NIST Report GCR 06-886.

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2010). Human behaviour in road tunnel fires: Comparison between egress models (FDS+Evac, STEPS, Pathfinder). In Proceedings of the twelfth international Interflam 2010 Conference, Nottingham, UK.

Santos G & Benigno Aguirre E (2004). A Critical Review of Emergency Evacuation Simulation Models, Proceedings of the NIST Workshop on Building Occupant Movement during Fire Emergencies, Disaster Research Center, University of Delaware.

Tavares R (2009). An analysis of the fire safety codes in Brazil: Is the performance-based approach the best practice? Fire Safety Journal

Thompson PA & Marchant EW (1995). A Computer Model for the Evacuation of Large Building Populations, Fire Safety Journal 24, pp. 131-148.

PAPER II

THE EVALUATION OF DIFFERENT EVACUATION MODELS FOR ASSESSING ROAD TUNNEL SAFETY ANALYSIS

RONCHI, E.[1], COLONNA, P.[1], CAPOTE, J.[2], ALVEAR, D.[2], BERLOCO, N.[1], CUESTA, A.[2]

[1] *Department of Roads and Transportation. Polytechnic University of Bari, Via Orabona 4, 70100 Bari, Italy*

[2] *E.T.S. de Ingenieros Industriales y de Telecomunicaciones Grupo GIDAI – Seguridad contra Incendios – Investigación y Tecnología, Universidad of Cantabria, Avda. Los Castros, s/n; 39005 Santander, Spain*

Abstract

The current state-of-the-art presents a multiplicity of evacuation models for simulating emergency scenarios. Each model involves different methodological solutions to represent the same process and each one has its strengths and limitations. In addition, they have their own specific features and often practitioners do not have a thorough understanding of the variables that could be input into the models and how they will affect the results. Thus, there is a need to analyse the differences between the models, why they occur and how they affect the calculations. This study compares three evacuation models (FDS+Evac, STEPS, Pathfinder) and the analytical calculations provided in the SFPE (Society of Fire Protection Engineers) Handbook, each of them using different simulation methods. The case-study is the Lantueno Tunnel in Spain (a two-bore road tunnel with an emergency link tunnel between the two bores). The results initially show that, when considering evacuation scenarios with a single available exit and favourable response times, the obtained evacuation times do not differ significantly between the models. In a second step, the analysis of more complex scenarios has allowed the determination of the main factors of occupant-fire interactions that cause the differences between the models: the use of unfavourable pre-evacuation times and the exit selection process under low visibility conditions. These differences may occur in relation to: 1) modelling method 2) degree of depth of the analysis of the fire conditions during the calibration of the inputs 3) user's experience in applying appropriate safety factors when using only one model.

Keywords. Evacuation Models, Human Behaviour in Fire, Road tunnel fire, Emergency scenarios.

1 Introduction

In recent decades, in Europe alone, tunnel fires have destroyed more than a hundred vehicles causing over 400 deaths and presenting a cost of billions of euro for the European economy [Carvel, 2007]. Disasters like the Mont Blanc Tunnel Fire (Italy-France, 1999) show that these environments should receive particular attention from designers. Consequently, the European Directive 2004/54/EC [Council Directive, 2004] establishes the requirement of a thorough and detailed risk analysis for the tunnels in the trans-European network in order to achieve the appropriate safety levels and reduce the negative consequences of a hypothetical emergency scenario.

In this context, several Computational Modelling software packages have been used in recent years as a tool for analyzing occupant safety conditions in case of emergency. This is the reason why their application, initially almost exclusively for buildings, is currently being extended to a large number of environments such as aircraft, trains, ships, tunnels, etc. Designers often face the problem of performing the safety analysis through the use of a single model, which could lead to errors caused by its weaknesses.

The process of emergency evacuation is a complex phenomenon that requires a holistic approach to the problem. In fact, the factors to be simulated using the evacuation models fall into two categories: physical characteristics and Human Behaviour-related processes. While the first type of factors is deterministic in nature and consequently easy to insert, the variables related to Human Behaviour present difficulties in the input definition step due to their intrinsic randomness.

In addition, road tunnels are unique environments with their own specific characteristics: underground spaces, unknown to users, no natural light, etc. which affect different aspects of Human Behaviour [Boer & Veldhuijzen van Zanten, 2005; Shields & Boyce, 2004; Worm, 2006] such as pre-evacuation times, e.g., people may show vehicle attachment, occupant-occupant and occupant-fire interactions [Bryan, 1977; Jin in Di Nenno, 2002; Frantzich & Nilsson, 2004], herding behaviour, exit selection, etc. The information about these factors can be obtained from data of actual accidents, experiments or drills. The most reliable studies are based on real data, but there is not much experimental literature available. Furthermore, data from experiments and simulations may be accused of lack of realism or be difficult to extrapolate for other analyses. Therefore, designers need a deep knowledge both of the characteristics of the model they use, e.g., the modelling method, as well as of its limitations to represent the above mentioned aspects. A possible solution to this problem is to develop a comparative analysis of different models in order to represent as accurately as possible the emergency scenarios in relation to the model in use. Lord et al. [2005] identify the main objective of this kind of comparative analysis as a process of understanding the causes of uncertainty and variability in the outputs, focusing on variables that "*may have an impact on the results of the egress model that is significant enough to cause a change in an engineer's design of a building*".

This study presents a comparative analysis of three evacuation models: FDS+Evac [Korhonen & Hostikka, 2010], STEPS [Mott Macdonald, 2010] and Pathfinder 2009 [Thunderhead Engineering, 2009]. These three models represent different methodologies to model the evacuation process. Additionally, for some cases of the analysis, they are compared with the analytical calculation of the SFPE (Society of Fire Protection Engineers) Handbook [Gwynne & Rosenbaum in Di Nenno, 2008].

Two approaches for the definition of the inputs have been considered: the deterministic approach and a random approach using distribution functions. Each model is analysed, checking whether the different factors, e.g., movement method, occupant load, fire scenarios, human behaviour, etc. can be implemented: 1) directly or 2) "artificially", using data from other models. The consequence is that if a model is able to reproduce a certain phenomenon accurately, it will be used for adjusting the inputs of the other models through a process of convergence between the different models. For example, this study uses FDS, the Fire Dynamic Simulator within FDS+Evac [Korhonen & Hostikka, 2010] to model fire, smoke, toxic gases, etc. Moreover, there is an analysis of several evacuation scenarios for the Lantueno tunnel in Spain (a two-bore road tunnel with an emergency link tunnel between the two bores). The simulations were carried out under different conditions to obtain a significant range of results. The same input data were considered for all models, taking into account that it was necessary to make some assumptions because of the intrinsic differences between them. The following step is the definition of the crucial parameters, analyzing how they are represented by each model and what their impact is on the simulated process.

This study identified the causes of variability of the results between different models and analyzes the conditions under which the results are similar. The analysis leads to 1) identifying the limitations of each model when simulating specific conditions in road tunnels; 2) comparing the effect of the assumptions set out in the representation of the behavioural parameters of the occupants; 3) establishing safety coefficients to obtain reliable results when considering the effects of the fire-occupant interaction.

2 Material And Methods

The influence that each variable may have on the evacuation process needs to be defined in order to provide an appropriate evaluation of the safety conditions in road tunnels. The literature presents studies on the impact of certain variables and processes. The most frequent behavioural responses to fire could be categorized as evacuation [Worm, 2006], fighting or containing the fire and the notification of other individuals or the fire brigade [Bryan, 1977]. Frantzich & Nilsson [2004] also analysed the possibility to pass by the fire through the smoke; however it is assumed, in most cases, people tend to go in the opposite direction to the fire. Data from surveys confirm this assumption [Gandit et al. 2008, Ronchi et al. 2009].

2.1 The human factor in road tunnel evacuations

Evacuation models simulate factors belonging to two categories, physical features, e.g., tunnel geometry, obstacles, occupant load, vehicles involved in the accident, fire spread, etc. and human behaviour, e.g., pre-movement times, door selection, herding behaviour, etc. This paper mostly focuses on the second category.

2.1.1 Pre-evacuation time

The pre-evacuation time is the time required for each occupant to understand what has happened (detection time) and the time spent to decide what to do (reaction time). This time is influenced by internal and external factors [Colonna et al. 2009]. The internal factors are related to the physical and socio-psychological characteristics of the occupants: their emotional states [Worm, 2006]; cultural background or training [Colonna et al. 2007; Wilde, 2001], past fire-related experience and knowledge of the environment and safety devices [Gandit et al. 2008] i.e. the case of professional drivers [Banuls Egeda et al., 1996]. External factors include social interactions. In fact, people are strongly influenced by the actions of others, i.e., to decide to get out of the vehicle or choose an exit. Other external factors include environmental conditions such as alarm systems, visibility conditions, e.g., emergency lighting system, exit visibility, smoke thickness, road signals, etc. The perception of danger by a selected group of occupants can also be influenced by their position with respect to the fire. Occupants can have a direct perception of the danger, they may only be able to see the smoke or the actions of the alerted people (or a combination of all three) [Ronchi, 2009].

Several behaviours could be observed. Motorists may show vehicle property attachment and/or they can consider their cars as the safest place to be and, after shutting windows and ventilation, will remain seated in their cars [Gandit et al. 2008]. In the experiments performed in the Benelux Tunnel, the results showed that users may remain passive in the interior of their vehicles for between 5 and 6 minutes [Boer & Veldhuijzen van Zanten, 2005].

Boer & Veldhuijzen van Zanten [2005] also described how the passivity of road users can be overcome through the use of an announcement by the tunnel operator. In particular, his study focused on the type of instructions that should be given during a tunnel fire. Only 18% of the drivers left their cars prior to vocal announcement inside the tunnel. Another insight regards the hesitation of the people who left their cars before the announcement compared with those who left after the vocal message. Frantzich & Nilsson [2004] also studied the effectiveness of different types of provided information. They pointed out that an effective message should not contain too much information and the appropriate number of phrases is between 5 and 7. In their experiments, participants opened the door of the vehicle within 35 s. Purser [2009] analyzed the real case of the Mont-Blanc tunnel fire, estimating an average time of 30 s to leave the vehicles. On the other hand, the Italian guidelines for tunnel safety design [ANAS, 2009] provide average values for the time to abandon vehicles (300 s for vehicle users and 90 s for truck drivers). The lack of data leaves the selection of the proper values for pre-movement times to the experience of the designer [Capote et al. 2010]. The use of distribution laws can help the modeller to take into account the above mentioned factors, but it is best practice to model several scenarios (as requested in a risk analysis) with different pre-movement times [Capote et al., 2009; Capote et al. 2011] .

2.1.2 Door selection

This variable depends on the environmental conditions (distance, visibility, etc.), social interactions and the occupants’ knowledge of the tunnel geometry. In general, occupants go towards the nearest exits, but in the case of tunnel fire, emergency exits may similarly be even more deterring and unfamiliar than the tunnel itself [Frantzich & Nilsson, 2004]. Apart from the exit location, occupants also take into account the fire-related conditions, their familiarity with the exits and the exit visibility.

2.1.3 Social interactions

The interactions between occupants are a crucial factor in modelling the evacuation process. Humans tend to be strongly influenced by the behaviour of others, regarding the decision to leave the vehicle as well as for the exit selection [Frantzich & Nilsson, 2004; Ronchi et al., 2010]. There are two main types of interaction between the occupants during an emergency: "emerging groups" and "established groups”, i.e., family, friends, etc. The emerging groups can arise and dissolve during the emergency. The natural behaviour of the established groups is to stay together and ensure that each member has been evacuated safely. In fact, their walking speed will correspond to the slowest user while response times and evacuation routes will be the same for the whole group.

2.1.4 The Influence of Fire

Fire can affect the occupant’s evacuation process. The smoke effects affect the walking speed and may cause incapacitation of the occupants. These effects have been reported in the literature [Frantzich & Nilsson, 2004; Jin in Di Nenno, 2002; ANAS, 2009], including information on individuals with disabilities (the elderly, disabled people, etc.) [Boyce & Shields, 1999]. Unfortunately the scatter of the experimental results is wide and further investigation is still required on this topic. Radiation and temperature effects also may affect the path of the agents.

2.2 Evacuation models

Kuligowski et al. [2010] categorised models due to their modelling method, i.e., the sophistication that each model considers to calculate the evacuation times. The three main categories are Behavioural models, Movement models and Partial Behaviour models. Behavioural models include occupants performing actions, decision-making processes and reactions due to the environmental conditions. Movement models move occupants from one point to another (generally a safe place). Partial Behaviour models primarily calculate occupant's movement, but implicitly reproduce the occupant's behaviour by pre-movement time distributions, overtaking behaviours, the influence of smoke, etc.

The deterministic or the stochastic approach can be used to insert the inputs inside the evacuation models. The complexity of human features and actions during tunnel evacuations could hardly be represented using deterministic parameters, i.e., constant values for walking speed, delay times, etc. Consequently, it is good practice to apply the use of distribution laws.

Simulation methods may differ [Kuligowski et al., 2010], including:

1) Cellular Automata (CA): in which the agents move from one cell of a grid to another one.

2) Agent based modelling (ABD): agents are capable of interacting with the environments and/or other agents following a list of rules that guide their movement; therefore an agent is defined simply as “something that perceives and acts”.

3) Flow based modelling (FBM): occupant density is modelled as a continuous flow. Social factors are not modelled; The inputs employed are walking speeds, physical constraints in walkways, density, and initial position of people. The *flow* of the evacuation process can be then estimated.

The models in this study - FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], STEPS 4.1 [Mott Macdonald, 2010] and Pathfinder 2009 [Thunderhead Engineering, 2009] and the analytical calculations described in the SFPE Handbook by Gwynne & Rosenbaum [in Di Nenno, 2008] - represent a sample of models based on the above described modelling methods.

2.2.1 FDS+Evac

FDS+Evac [Korhonen & Hostikka, 2010] version 2.3.1 is the evacuation module of the Fire Dynamics Simulator (FDS) [McGrattan et al., 2008]. FDS+Evac is a partial behavior model that combines an agent-based model and a Computational Fluid Dynamics (CFD) model where the fire and the egress parts interact. FDS+Evac treats each occupant as a separate agent, using stochastic properties for assigning their main characteristics: walking speed and response times (detection and reaction). The influence of smoke on the movement and behaviour of agents is based on the results of the experiments of Frantzich and Nilsson [2004]. The model gives as results the position, the velocity, and the dose of toxic gases of each human (Fractional Effective Dose FED [Purser in Di Nenno, 2008] inside the computational domain at each discrete time step.

2.2.2 STEPS

Simulation of Transient Evacuation and Pedestrian Movement (STEPS) 4.1 is an agent-based model in which the path to the exit is calculated through a grid (CA). The movement towards the exits is calculated through a potential map. This model allows the user to implement certain random parameters about pre-evacuation times and travel speeds. It permits the import of data from fire models (CFAST and FDS) and their effect on the occupants' movement is calculated according to the values established by Jin [in Di Nenno, 2008].

2.2.3 Pathfinder

Pathfinder 2009.2 is a movement/partial behaviour model. It uses two ways to model the evacuation process. The first is a flow model, the SFPE method by Gwynne & Rosenbaum [in Di Nenno, 2008], based on the calculation of the means of the capacity of the considered environment. The second methodology is an agent-based model i.e. the Reynolds steering behaviour model redefined by Amor [Thunderhead Engineering, 2009]. Occupants are represented as circles moving inside a continuous 2D surface represented by adjacent triangles. The steering system moves passengers along their paths and allows each occupant to interact with the environment and the other occupants. The absence of fire-related features does not permit to directly evaluate the changing conditions due to environmental evolution (smoke density, door visibility, etc.) and the use of a fire model is necessary.

2.2.4 SFPE analytical calculations

The SFPE analytical calculations are based on the flow model described by Gwynne & Rosenbaum in the SFPE Handbook [Di Nenno, 2008]. This analytical calculation permits to obtain the evacuation times through the products of a hydraulic model. It uses a series of expressions that relate data acquired from tests and observation to a hydraulic approximation of human flow based on the calculation of the effective width. The model only provides quantitative results about evacuation times. It does not allow for any input regarding human behaviour. The results provide information on the relationship between speed and density, specific flow, the calculated flow and finally the evacuation time.

2.3 Case study: the lantueno tunnel

The Lantueno tunnel [Dirección general de Carreteras, 2008] is located in the Cantabria-La Meseta Highway (A-67), between Pesquera and Reinosa (Spain). It is a two-bore uni-directional road tunnel. Its length is about 670 m. Each bore has two lanes and they have sidewalks. (see Figure 1). The tunnel has an emergency tunnel (its length is 18 m and its width is 2.8 m) linking the two tubes. It is located 390 m from the north entrance and it is signposted in each tube by an illuminated panel. There are no restrictions on dangerous goods.

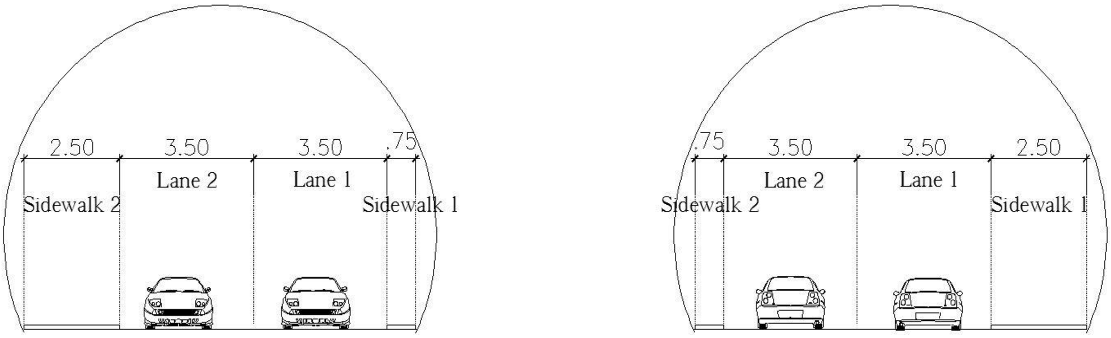

Figure 1. Cross section of the two bores of the case study, the Lantueno Tunnel

2.3.1 Evacuation scenarios

Two cases have been considered:

1) Case A: An accident has occurred in the center of the tube obstructing the emergency tunnel (see Figure 2a).

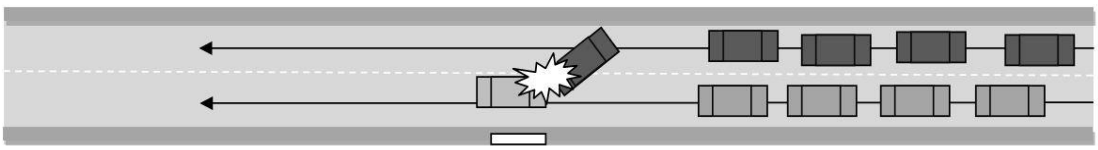

Figure 2a. Position of the accident in scenarios from A1 to A4.

2) Case B: An accident has occurred near the entrance of the tube (see Figure 2b)

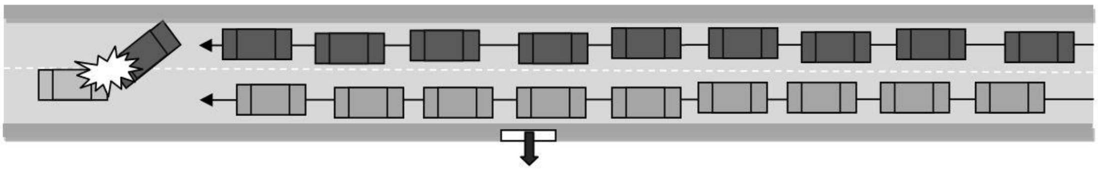

Figure 2b. Position of the accident in scenarios B1.1 and B1.2.

The basic characteristics of the scenarios and the investigated parameters are listed in Table 1.

Table 1. Summary of the inputs about occupant load of the scenarios

Scenario	Considered Variables	Light – Heavy Vehicles (nº)	Occupants (nº)	Fire (Yes/No)
A1.1	Movement Test	120-12	312	No
A1.2		120-12	624	No
A2.1	Random variables: pre-evacuation time and walking speed	120-12	624	No
A2.2		120-12	312	No
A2.3		120-12	624	No
A3.1	Fire influence	120-12	312	Yes
A3.2		120-12	312	Yes
A3.3		120-12	312	Yes
A4.1	FDS+Evac Test. Fire conditions-detection time interaction	120-12	624	Yes
A4.2		120-12	624	Yes
B1.1	Fire influence on exit selection	180-18	936	Yes
B1.2		180-18	936	Yes

The following assumptions have been considered:

• The evacuation is modeled considering the moment at which the vehicles are stationary, queuing behind the vehicles involved in the accident (one in each lane);

• The evacuation is considered complete if the occupants reach the cross connection between the two bores or they leave the tunnel through the entrance.

• Standard dimensions of the vehicles are: 4.5 m x 2 m (cars) and 10 m x 2 m (trucks). The distance between vehicles is 1 m;

• The following occupant load is considered: 2.5-5 occupants/cars and 1-2 occupants/trucks. The assumed percentage of trucks is 10% of the total number of vehicles [Dirección general de Carreteras, 2008);

• Occupants' initial positions are in the vicinity of the vehicles. The pre-evacuation time includes the time required to leave the vehicle;

• The longitudinal slope of 2% of the tunnel is considered in FDS by inserting an inclination of 2 % in the z axis and the smoke is pushed due to this gradient towards the zone where the evacuation takes place. The effects of forced ventilation are not taken into account.

• In the SFPE method, the tunnel is divided into three transversal areas where people are equally distributed and delay times are added after the calculations.

• The CO production (CO_YIELD values in the fire simulation in FDS) was selected by the user following the available literature [Tewarson in Di Nenno, 2008; Ingason, 2001; Bryner et al., 1994]. FED values (and consequently the agents' incapacitation) are strongly influenced by the user's selection of the CO_YIELD i.e. it is strongly influenced by the user's input. The assumption is to use only one reactant considering a certain burner with a pre-defined heat release rate curve. The scope of the paper is to analyze the differences between the models under the same conditions. When performing a risk analysis, a sensitivity analysis considering the variability of the factors affecting the fire and smoke development is required.

• 50 simulations of the scenarios in which there were stochastic parameters were carried out using each model. The samples were processed with fitting methods and the estimations of correspondent normal distributions with a significance level of $\alpha = 0,05$ of the evacuation results were obtained. The statistical treatment of evacuation times provides mean, maximum, minimum and variance.

Case A1: Movement Test

In case A1 two scenarios (A1.1 and A1.2) have been considered in which the inputs are assigned deterministically by the user (see Table 2). The purpose of these scenarios is to investigate whether different movement methods used by the model produce different scenarios with different occupant load.

Table 2. Inputs of scenarios A1.1 and A1.2.

Scenario	**Model***	**People (nº)**	**Fire (Yes/No)**	**Walking speed (m/s)**	**Pre-evacuation time (s)**
A1.1	F, S, P	312	No	1	0
A1.2	F, S, P	624	No	1	0

*F=FDS+Evac, S=STEPS, P=Pathfinder

Case A2: Probability distributions: pre-evacuation time and walking speed

In this case, probability distributions have been considered for the parameters of walking speed and pre-evacuation time (scenarios A2.1 and A2.2). Table 3 shows a summary of the inputs assigned to case A2.

Table 3. Inputs of scenarios A2.1, A2.2 and A2.3

Scenario	**Model***	**People (nº)**	**Fire (Yes/No)**	**Walking speed (m/s)****	**Pre-evacuation time****
A2.1	F, S, P, SFPE	624	No	U: 0.95-1.55	U: 30-210
A2.2	F, S, P, SFPE	312	No	N: $1.25 \pm 3\sigma$, $\sigma=0.1$	N: $120 \pm 3\sigma$, $\sigma=30$
A2.3	F, S, P	624	No	N: $1.25 \pm 3\sigma$, $\sigma=0.1$	Different in each zone

*F=FDS+Evac, S=STEPS, P=Pathfinder, SFPE= analytical calculations; **U= Uniform distribution, N= Standard Normal distribution

The implementation of pre-evacuation times in scenario A2.3 was carried out using the criterion of distance from the accident. In this way a phased response of the occupants was considered.

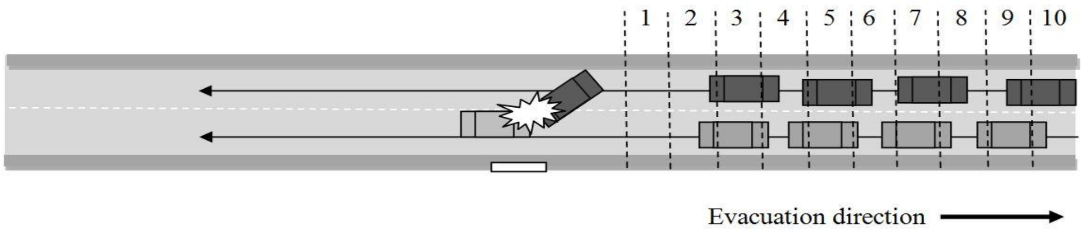

Figure 3. Zones of pre-evacuation time for scenario A2.3

Figure 3 shows how the tube is divided into different areas of response time. In the area closest to the accident (Zone 1), the implemented response time is 30 s. The response time of the occupants of the other zones (zones 2-10) was calculated considering the time needed by the first occupants (from zone 1) to reach different areas with a speed of 1.25 m/s. Then, the values were assigned using normal distribution laws. Mean values from zone 2 to zone 10 are, respectively: 152 s, 184 s, 216 s, 248 s, 280 s, 312 s, 344 s, 376 s, 408 s.

Case A3: Fire influence

The following three scenarios (A3.1, A3.2, A3.3) analyse the influence of fire by varying the values of HRR (Heat Release Rate) using two different values for the hypothetical design of fires. The experimental curves employed (see Figure 4) vary from a minimum of 4 MW – representing a car fire - to a maximum of 30 MW – representing a bus on fire. [Li, 2004, Ingason, 2001, Maevski, 2011]

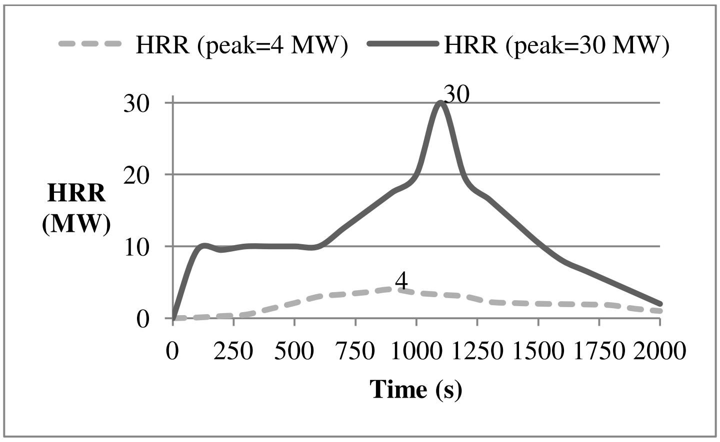

Figure 4. Assumed Heat Release Rate (HRR) curves versus time for the case of HRR peak = 4 MW and HRR peak = 30 MW peak [Ingason, 2001, Li, 2004, Maevski, 2011].

While in scenarios A3.1 and A3.2 the incapacitation caused by CO production is not considered, a Kerosene reactant [Tewarson in Di Nenno, 2008] (R in Table 4) was inserted in scenario A3.3 in order to test the effects of CO production [Bryner et al. 1994]. Table 4 shows a summary of the inputs.

Table 4. Inputs of scenarios A3.1, A3.2 and A3.3.

Scenario	Model*	People (nº)	Fire (Yes/No)	Walking speed (m/s)**	Pre-evacuation time** (s)
A3.1	F, S	312	Yes (4 MW)	N: 1.25±3σ, σ=0.1	N: 120±3σ, σ=30
A3.2	F, S	312	Yes (30 MW)	N: 1.25±3σ, σ=0.1	N: 120±3σ, σ=30
A3.3	F, S	312	Yes (30 MW+R)	N: 1.25±3σ, σ=0.1	N: 120±3σ, σ=30

F=FDS+Evac, S=STEPS; **N= Standard Normal distribution

Case A4: FDS+Evac Test. Fire conditions-detection time interaction

This case aims to understand the impact of the fire development on the evacuation of the tunnel occupants. FDS+Evac can automatically assign a specific response time depending on the smoke spread (see Figure 5) and its proximity to an agent or group of agents. In this case, the use of this feature of the model (scenario A4.2) is compared with a scenario in which unfavourable response times have been considered (scenario A4.1), as shown in Table 5. Lower walking speeds (1 m/s) were selected in order to better evaluate the smoke effects on occupants.

Table 5. Inputs of scenarios A4.1 and A4.2.

Scenario	Model*	People (nº)	Fire (Yes/No)	Walking speed (m/s)	Pre-evacuation time** (s)
A4.1	F	624	Yes (30 MW+R)	1	C: N 600±3σ, σ=140 P: N 180±3σ, σ=40
A4.2	F	624	Yes (30 MW+R)	1	Smoke as a cue for the evacuation

*F=FDS+Evac, **N=Standard normal distribution, C = occupants of light vehicles, P=occupants of heavy vehicles

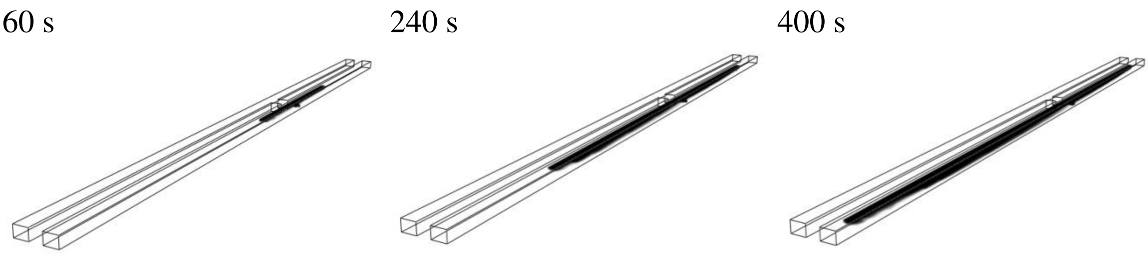

Figure 5. Smoke spread analysis within the tunnel using FDS. It is used in the FDS+Evac model as a cue for the evacuation.

Case B1: Fire influence on exit selection

In case B1.1, the fire influence on exit selection during the evacuation process has been analysed. FDS+Evac takes into account the fire influence on exit selection, while STEPS and Pathfinder do not consider it. For this reason, despite the different features of each model, Pathfinder and STEPS inputs were calibrated using the results of FDS+Evac (scenario B1.2). Pathfinder was calibrated assigning different groups of people in the tunnel in a deterministic way to the emergency exit or the entrance after checking the fire conditions in FDS. In STEPS the calibration was performed by changing the availability of the emergency exit for the evacuation after a certain time (also in this case after checking the fire evolution in the tunnel) Table 6 describes the input data considered in the models.

Table 6. Inputs of scenarios B1.1 and B1.2.

Scenario	Model*	People (nº)	Fire (Yes/No)	Walking speed (m/s)	Pre-evacuation time** (s)
B1.1	F, S, P	936	Yes (30 MW +R)	N: 1.25±3σ, σ=0.1	N: 120±3σ, σ=30
B1.2	F, S_c, P_c	936	Yes (30 MW +R)	N: 1.25±3σ, σ=0.1	N: 120±3σ, σ=30

*F=FDS+Evac, S=STEPS, P=Pathfinder, S_c=STEPS after calibration, P_c=Pathfinder after calibration;
**N= Standard Normal distribution

3 Results and discussion

Case A1: Movement Test

Table 7 shows that the results are very similar between the models and scenarios. Although there is a simultaneous response for all the occupants (i.e. the beginning of the simulation) bottlenecks or congestions do not arise. The increase in the number of occupants (scenario A1.2) had no relevant effects on the evacuation times. Consequently it is possible to state that - despite the different movement methods of the models - the evacuation times did not differ significantly. In this movement test, the evacuation times approximately correspond to the walking speed of the last occupant (the occupant who has the longest evacuation route) multiplied by the distance travelled.

Table 7. Results of case A1. The mean values of evacuation times are shown.

Scenario	Model	Mean (s)	Scenario	Model	Mean (s)
A1.1	FDS+Evac	403	A1.2	FDS+Evac	406
	STEPS	402		STEPS	402
	Pathfinder (Steering/SFPE)	400		Pathfinder (Steering/SFPE)	400

Case A2: Probability distributions: pre-evacuation times and walking speed

The results obtained are similar for the different models, despite the use of different distribution laws of probability for the parameters of occupants' pre-evacuation times and walking speed. The models generate the pre-evacuation time of the occupants at a fixed position (no movement is simulated during this phase) until the evacuation begins.

The use of distribution laws for this parameter implies an overlap of passengers who have already begun moving and those who have not yet responded to the emergency. The implementation of different response groups for scenario A2.3 did not significantly affect the evacuation times. It shows that in this case, the fundamental parameters are the distance travelled and the occupants' walking speed.

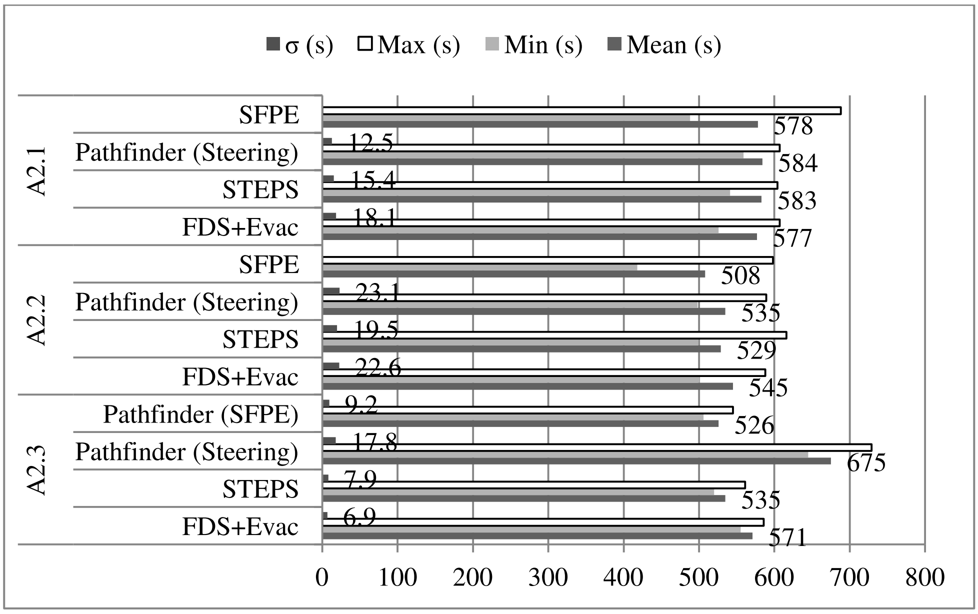

Figure 6. Evacuation times of scenarios A2. The SFPE method is deterministic and standard deviation cannot be calculated.

The Pathfinder model shows differences in the results using the Steering mode. Evacuation times are higher than the other models because occupants who have not yet begun to evacuate, stand in the path of other occupants who are evacuating. They will obstruct their movement until they move from their position. In fact, the SFPE mode in Pathfinder provides lower evacuation times and dispersion (see Figure 6 and Figure 7).

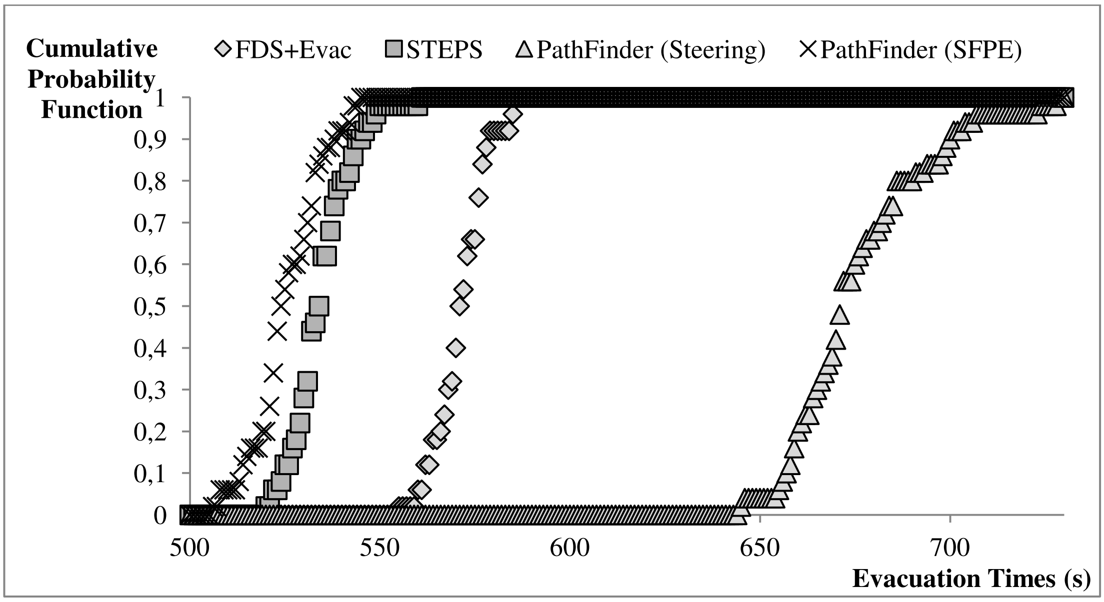

Figure 7. Function of cumulative distribution for scenario A2.3

Case A3: The influence of fire

Scenarios 3.1, 3.2 and 3.3 show no big differences between the models. In FDS+Evac the fire loads do not substantially affect evacuation times. In fact, evacuation times are very similar in the case without fire (scenario 1.4), maybe because of the pre-movement times. They are not high enough for the smoke to consistently affect the evacuation process. In STEPS, the evacuation times grow slightly in scenarios 3.1, 3.2 and 3.3 with respect to scenario 1.4, becoming very similar to the FDS+Evac values.

There are few differences in the same scenario using the parameter smoke “irritant” or “non irritant” as shown in Figure 8. Since in STEPS there is no influence of toxic gas production on humans, the results of scenarios 3.2 and 3.3 are exactly the same (in scenario 3.3, fire produces CO also because of a reactant, using the command CO_YIELD in FDS).

Scenarios A3.1, A3.2 and A3.3 show no big differences between the models (see Figure 8). In FDS+Evac the fire loads do not substantially affect evacuation times. In fact, the results are very similar in the corresponding case without fire (scenario A2.2). This happens because the pre-evacuation times are not high enough to permit the smoke to consistently affect the evacuation process. In STEPS, the evacuation times grow slightly in scenarios A3.1, A3.2 and A3.3, and grow slightly with respect to scenario A2.2, becoming very similar to the FDS+Evac ones. There are few differences in the same scenario using the parameter smoke “irritant” or “no irritant”. Results show that the implementation of favourable pre-evacuation times does not explain the impact of fire within the models. To this end, additional scenarios were carried out, the results of which are described in the following section.

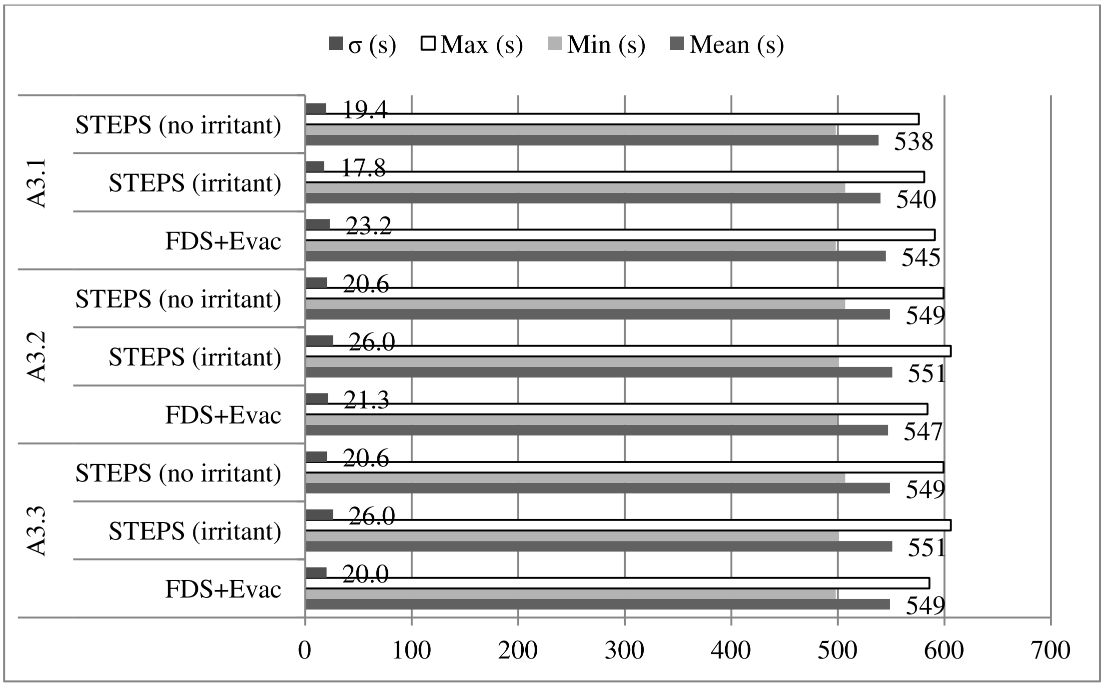

Figure 8. Evacuation times of the A3 scenarios.

Case A4: FDS+Evac Test. Fire conditions-detection time interaction

In case A4, the influence of fire on the pre-evacuation time was analysed. This analysis could only be carried out with FDS+Evac because it is the only model capable of automatically representing this phenomenon. In this case, conservative pre-evacuation times were considered. As shown in Table 8, the times for the tunnel evacuation are higher than the times obtained in the previous cases (nearly three times higher). In scenario A4.2, the smoke development was an additional cue for the start of the evacuation. Consequently, the evacuation times are lower than scenario A4.1. In this scenario the influence of fire is a fundamental parameter for determining the final evacuation time.

Table 8. Evacuation times of scenarios A4.

Scenario	Model	Mean (s)	Min (s)	Max (s)	σ (s)
A4.1	FDS+Evac	1488	1326	1567	29.43
A4.2	FDS+Evac (smoke as an evacuation cue)	1248	1199	1323	28.52

Case B5: Fire influence on exit selection

The analysis of scenarios B1.1 and B1.2 permitted to evaluate the process of exit and evacuation route (way-finding) selection in case of road tunnel fire. In this case, two alternative exits were available (see Figure 9). FDS+Evac is the only model able to directly reproduce the impact of smoke on exit selection. It is mainly based on the individual's visual access of the exit.

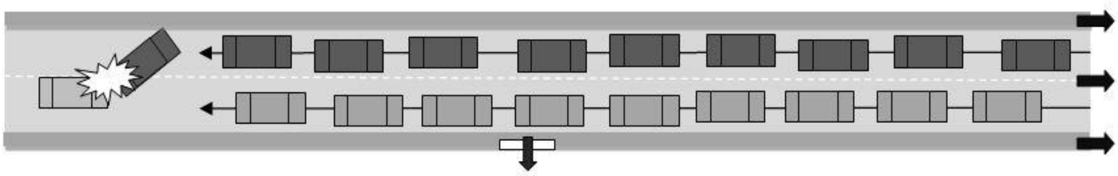

Figure 9. Available exits for the case B

For this reason, the exit at the entrance of the tunnel is the most used by most of the occupants, despite not being the closest exit (see Figure 10a).

This is caused by the presence of smoke in the vicinity of the emergency exit. In the other models (STEPS and Pathfinder) this phenomenon does not arise and the criterion of proximity produces an increase in the number of occupants who use the emergency exit. Consequently, the occupants closest to the fire escape by the emergency exit, produce a significant decrease in the total evacuation times (compared with the FDS+Evac). For this reason, the use of these models causes favourable evacuation times but at the same time is an unrealistic interpretation of the phenomenon.

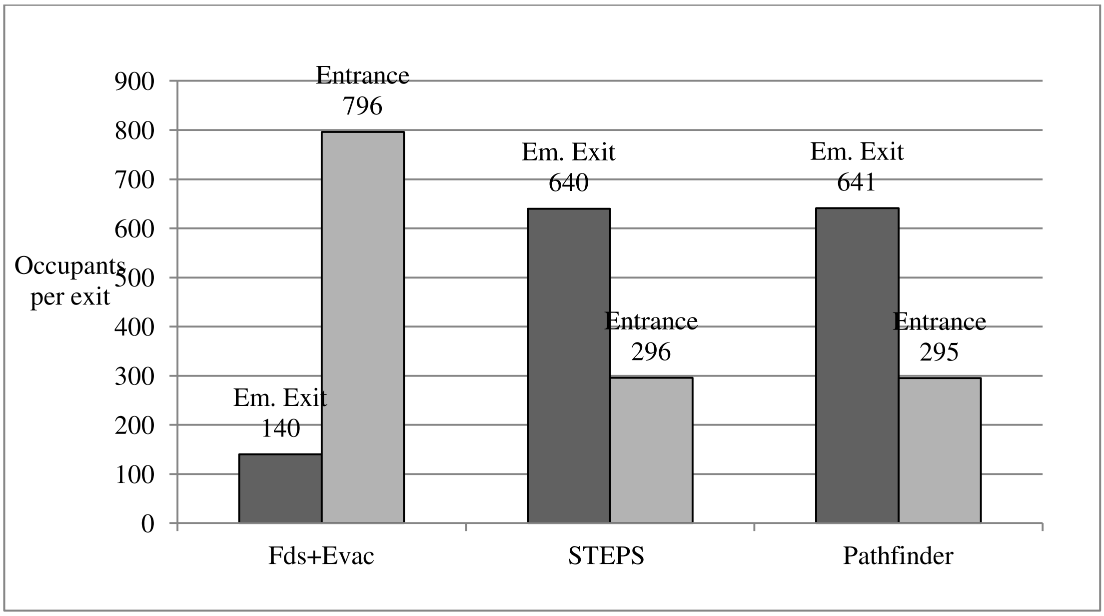

Figure 10a. Exit usage in scenarios B1.1 and B1.2. The Figure shows the mean number of people evacuated through the emergency exit (black) or the entrance (grey) before the input adjustment.

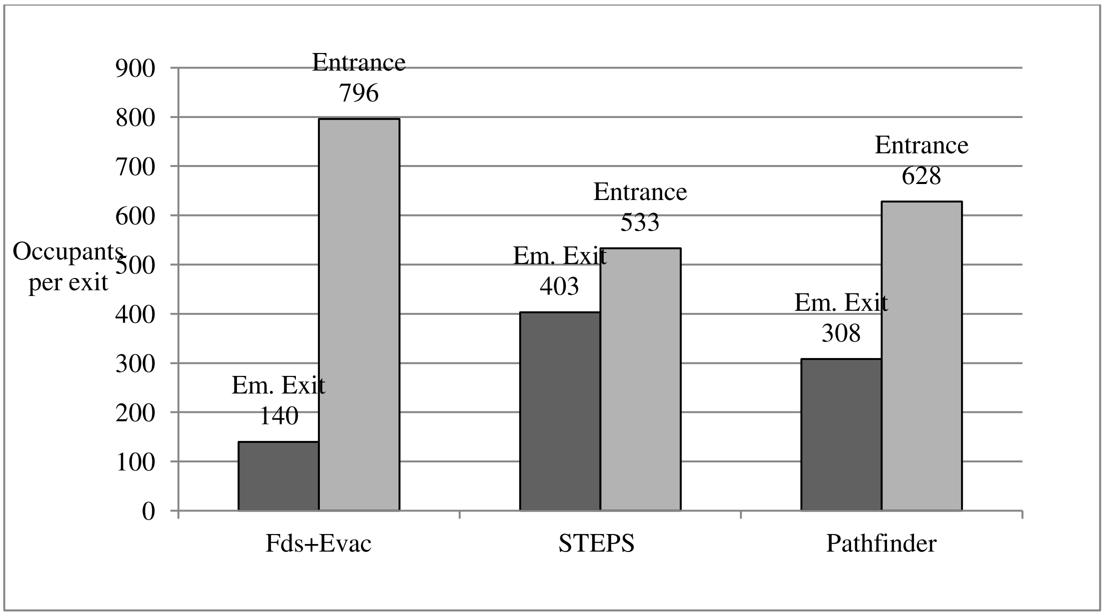

Figure 10b. Exit usage in scenarios B1.1 and B1.2. The Figure shows the mean number of people evacuated through the emergency exit (black) or the entrance (grey) after the input adjustment.

The limitations of the STEPS and Pathfinder models lead us to try a calibration of the exit selection process. It is based on the results obtained with FDS+Evac (Scenario B1.2). In the STEPS model, the user decides whether the emergency exit is available or not assigning a time when it stops to be available for the occupants. The analysis of the fire and smoke spread in FDS lead to consider the emergency exit no longer to be available after 300 s. In the Pathfinder model, the user configures a deterministic distribution of the occupants between each exit. An approximation of this number was estimated by performing the analysis of the fire conditions with FDS.

The number of evacuees through the emergency exit (see Figure 10b) is lower in the STEPS and Pathfinder models. The calibration of the input did not lead to the same proportions between the number of evacuees per exit obtained with FDS+Evac. Nevertheless, the calibration of the inputs in the STEPS and Pathfinder models led to similar results with the FDS+Evac ones, taking into account the influence of fire (see Figure 11).

In these cases, the occupants closer to the fire are forced to evacuate through the entrance instead of using the emergency exit. However, the results obtained with FDS+Evac have a higher degree of dispersion, and slightly higher mean evacuation times are obtained.

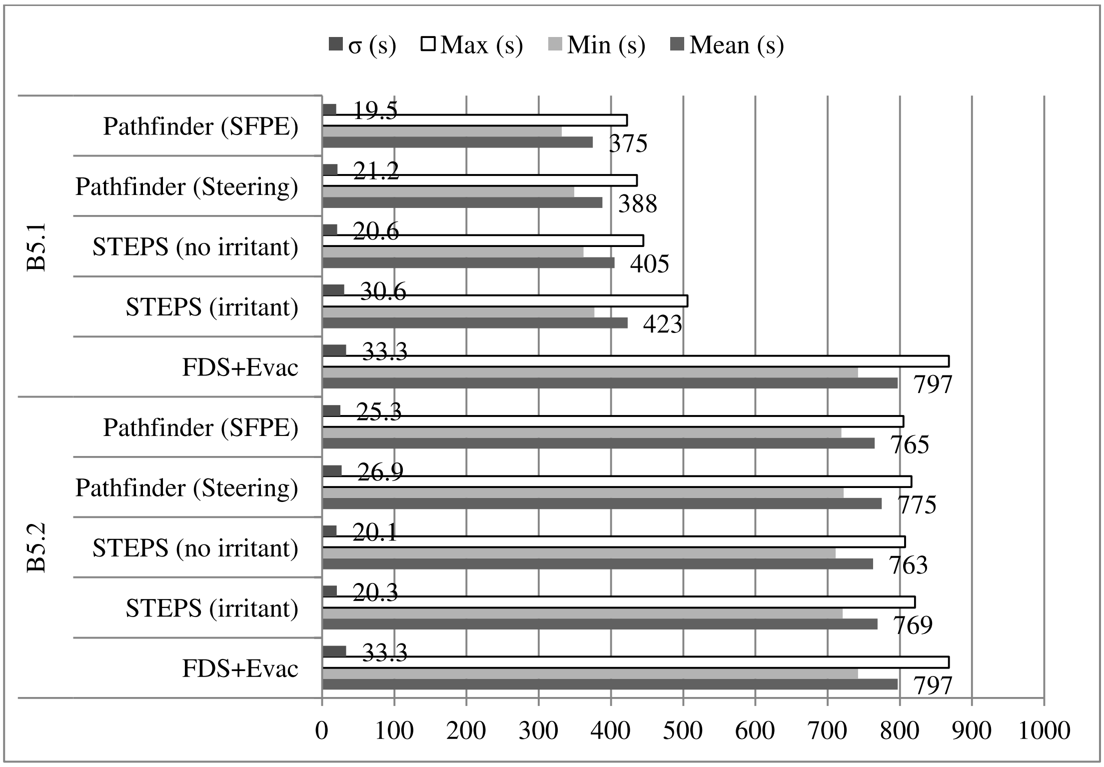

Figure 11. Evacuation times of the case B5.

4 Conclusions

This paper shows a comprehensive analysis of the different methodological solutions for the computer simulation modelling of the road tunnel evacuations. Three different evacuation models were selected (FDS+Evac, STEPS and Pathfinder) in order to have a representative sample of the different available methods. The models were compared by applying them to the case study of a road tunnel, investigating two cases ranging in complexity: 1) Case A (fire in the centre of the bore with only one available escape route through the entrance of the tunnel) and 2) Case B (fire near the entrance of the tube with two available escape routes: the emergency exit and the tunnel entrance). Different approaches were used for the implementation of the fundamental factors in the evacuation process (i.e. pre-evacuation time, social interactions, exit selection and fire influence on occupants' behaviour).

The results of Case A1 (movement test) show no substantial differences between the results of the different models. This means that the movement methods applied provide consistent results. Cases A2 and A3 show that in simple scenarios with a single escape route the evacuation times of the models are very similar. This happens despite having implemented various hypotheses about the pre-evacuation times and, in some cases, fire conditions. The causes are essentially two factors. The first is the importance of the evacuation travel distance as a factor in the calculations of the evacuation time. The second concerns the assumption of assigning favourable pre-evacuation times, in which users are not substantially affected by the fire conditions. For these cases, the designer may use a simpler method by applying the analytical calculations described in the SFPE Handbook in order to obtain a first approximation of the time of evacuation. These results lead us to investigate more unfavourable conditions about pre-evacuation times in order to assess the influence of fire conditions on the evacuation process. The results have shown that, considering more conservative assumptions, the effects of fire in the detection process can be crucial for the calculation of the evacuation times and can produce higher results than in the previous cases. Such scenarios have to be considered in order to achieve optimal safety levels.

The results of Case B5 shows that STEPS and Pathfinder do not take into account the environmental conditions caused by the smoke which can affect the choice of a particular exit. This could be the cause of an underestimation of the evacuation times. For this reason, the user should use appropriate solutions to the problem. The designer needs a deep knowledge of the model he or she is using (i.e. the modelling method and the model features) and the particular characteristics of each scenario to simulate (e.g. Human Behaviour, fire conditions, etc.).

The importance of selecting appropriate values for the main variables affecting evacuation times has been highlighted throughout the paper. Thus, suggestions about the definition of non-obvious data input for tunnel evacuation modelling can be made. The definition of design fires and related smoke and CO yields, illumination, etc. are strictly dependent upon the considered scenarios [Ingason, 2001]; dedicated Literature is available on the topic [Ingason 2001], including an extensive review of the state-of-the-art on the topic [Maevski, 2011]. If no specific information is provided about the design fire to be simulated, it is always best practice to perform sensitivity analysis of the factors affecting the evacuation process (soot and CO yields as well as different materials producing irritant gases). Furthermore, this paper focuses mainly on the variables regarding the evacuation process. Thus, some recommendations on non-obvious human behaviour input data can be provided. According to the available Literature [Jin, 1970, Korhonen & Hostikka, 2010], walking speeds may vary within a range of 0.3 m/s in case of very low visibility conditions and irritant gas up to a normal unimpeded walking speed in clear conditions e.g. 1.25 m/s for adults. Pre-evacuation times are very complicated factors to model due to the intrinsically challenging nature of human behaviour. They depend upon several factors (see Sec. 2.1.1). Nevertheless, real accidents [Purser, 2009] and tunnel experiments [Boer & Veldhuijzen van Zanten, 2005, Frantzich & Nilsson, 2003] show a range of 30-300 s as reasonable values, although even slower occupant's responses may occur [Purser, 2009]. Dedicated studies should be addressed to people with disabilities whose conditions may completely differ from the other tunnel occupants.

However, apart from the user's experience and the ability to tackle individual problems, two possible solutions are suggested. The first can be applied when trying to simulate a scenario using a single model that is not able to simulate the fire and/or its impact on the exit selection process. This solution applies a safety factor (in our case-study it is k=2) in order to have an acceptable safety margin for the evacuation times. The second method has been presented in this article and it is the calibration of a model based on the results of another model capable of reproducing the phenomenon of fire and its impact on the behaviour of the occupants. In this case, satisfactory results have been obtained by modifying the specific parameters of the STEPS and Pathfinder models.

Future developments of the research in this field will be to extend the comparative analysis to a higher number of models and to perform a sensitivity analysis of the variables considered in this paper. In addition, further experimental tests regarding human behaviour during emergencies in tunnels will also help to improve the accuracy of the results of the models.

References

ANAS (2009). Linee Guida per la Progettazione della sicurezza nelle Gallerie Stradali. Seconda Edizione [National administration of roads and highways, guidelines for the road tunnel safety design], Condirezione Generale Tecnica, Direzione Centrale Progettazione.

Banuls Egeda R, Carbonell Vaya E, Casanoves M, Chisvert M (1996). Different Emotional Responses in Novice and Professional Drivers, Traffic and Transport Psychology: Theory and Application, Pergamon, Amsterdam, NL.

Boer L & Veldhuijzen van Zanten D (2005). Behaviour on tunnel fire. In Proceedings of the third International Conference on Pedestrian and Evacuation Dynamics, PED05, Vienna, Austria.

Boyce KE & Shields TJ (1999) Towards the Characterisation of Building Occupancies for Fire Safety Engineering: Prevalence, Type and Mobility of Disabled People, Fire Technology, 35:1, pp 35-50.

Bryan JL (1977). Smoke as a Determinant of Human Behavior in Fire Situations, (Project People). NBS Report NBS-GCR-77-94, University of Maryland, College Park, Washington DC, USA.

Bryner NP, Johnsson LN, Pitts WM (1994). Carbon Monoxide Production in Compartment Fire. Reduced-Scale Enclosure Test Facility, NIST, Report 5568.

Capote J, Alvear D, Abreu O, Lázaro M, Cuesta A (2011). Modelo de Sucesos Infrecuentes en Túneles de Carretera, RIMNI, Vol. 27.

Capote J, Alvear D, Abreu O, Lázaro M, Cuesta A, Alonso V (2010). Infrequent Events Model for Road Tunnels' En Proceedings de International Symposium on Tunnel Safety and Security 2010 March, Frankfurt, Germany.

Capote J, Alvear D, Abreu O, Lázaro M, Cuesta A (2009). Modelado y simulación computacional de evacuación en edificios singulares, RIMNI, Vol. 25, 3, pp227-245.

Carvel R (2007). Tunnel fire safety systems. EuroTransp 5(6) pp. 39–43.

Colonna P, Berloco N, Ronchi E (2009). Optimising fire protection and safety in road tunnels by readjusting risk analysis strategy. In Proceedings of the Fire Protection & Safety in Tunnels Conference, Paris (France).

Colonna P, Pascazio R, Sinatra M, (2007). Road Safety and user behaviour, In Proceedings of the 1st International Congress of Psychotechnics, Bari, Italy.

Council Directive (EC) (2004) 2004/54/EC of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.

Di Nenno (2002) SFPE Handbook of Fire Protection Engineering. 3rd Edition. National Fire Protection Association, Quincy, Maryland, USA.

Dirección general de Carreteras, (2008). Manual de explotación Túnel de Lantueno. Cantabria

Frantzich H & Nilsson D, (2004). Evacuation Experiments in a Smoke Filled Tunnel. Department of Fire Safety Engineering, Lund University. In Human Behaviour in Fire, Proceedings of the Third International Symposium, Belfast, UK, pp. 229–238.

Gandit M, Kouabenan DR, Caroly S (2008). Road-tunnel fires: Risk perception and management strategies among users, Safety Science 47, pp105-114.

Korhonen T & Hostikka S (2010). Fire Dynamics Simulator with Evacuation: FDS+Evac Technical Reference and User's Guide (FDS 5.5.1, Evac 2.2.1).

Kuligowski ED, Peacock RD, Hoskins, BL (2010). A Review of Building Evacuation Models NIST, Fire Research Division. 2nd edition. Technical Note 1680 Washington, US.

Ingason H (2001). Design Fire in Tunnels. Swedish National Testing and Research Institute. Safe and Reliable Tunnels. Innovative European Achievements.

Lord J, Meacham B, Moore A, Fahy R, Proulx G (2005). Guide for evaluating the predictive capabilities of computer egress models, NIST Report GCR 06-886.

Maevski IY (2011). Design Fires in Road Tunnels, A synthesis of Highway Practice, Transportation Research Board NCHRP National Cooperative Highway Research Program Synthesis 415.

McGrattan K, Hostikka S, Floyd J, Baum H, Rehm R, Mell W McDermott R (2008). Fire dynamics simulator (version 5), technical reference guide. National Institute of Standards and Technology Special Publication 1018-5, Department of Commerce, Gaithersburg, MD

Mott MacDonald Simulation Group. Simulation of Transient Evacuation and Pedestrian movementS STEPS (2010) User Manual (4.1 Version).

Purser DA (2009). Application of human behaviour and toxic hazard analysis to the validation of CFD modelling for the Mont Blanc Tunnel fire incident. In Proceedings of the Advanced Research Workshop on Fire Protection and Life Safety in Buildings and Transportation Systems 2009, Santander, Spain, pp 23-57.

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2010). Human behaviour in road tunnel fires: Comparison between egress models (FDS+Evac, STEPS, Pathfinder). In Proceedings of the twelfth international Interflam 2010 Conference, Nottingham, UK.

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2009). Human Behaviour in case of Fire inside an Urban Tunnel through Computer Modelling. In Proceedings of the Advanced Research Workshop on Fire Protection and Life Safety in Buildings and Transportation Systems 2009, Santander, Spain, pp. 349-361.

Shields TJ, Boyce KE, (2004). Towards Developing an Understanding of Human Behaviour of Fire in Tunnels. In Proceedings of third International Symposium Human

Behaviour in Fire 2004, Belfast, 1-3 September 2004, Interscience Communications, pp. 215-228.

Thunderhead Engineering. Pathfinder 2009 (2009.2 Version). Technical Reference.

Wilde GJS (2001). Target Risk 2, PDE Publications, Toronto, CA.

Worm E (2006). Human Behaviour Influencing Tunnel Safety, Dutch Ministry of Transport, Public Works and Water Management, Tunnelling Department, Utrecht, NL. Head of the Centre for Tunnel Safety.

PAPER III

REPRESENTATION OF THE IMPACT OF SMOKE ON AGENT WALKING SPEEDS IN EVACUATION MODELS

RONCHI, E. [1], GWYNNE, S.M.V.[2], PURSER, D.A.[3], COLONNA P.[1]

[1] *Department of Roads and Transportation. Polytechnic University of Bari, Via Orabona 4, 70100 Bari (BA), Italy*

[2] *Hughes Associate, Inc, 52 Jedburgh Road Plaistow E139LG London, United Kingdom*

[3] *Hartford Environmental Research, 1 Lowlands, AL9/5DY Hatfield, United Kingdom*

Abstract. This paper addresses the problem of reproducing the effect of different visibility conditions on people's walking speed when using evacuation models. In particular, different strategies regarding the use of default settings and embedded data-sets are investigated. Currently, the correlation between smoke and walking speed is typically based on two different sets of experimental data provided by 1) Jin and 2) Frantzich and Nilsson. The two data-sets present different experimental conditions, but are often applied as if equivalent. In addition, models may implement the same the data-sets in different ways. To test the impact of this representation within evacuation tools, the authors have employed six evacuation models, making different assumptions and employing different data-sets (FDS+EVAC, Gridflow, buildingEXODUS, STEPS, Pathfinder and Simulex). A case-study of an evacuation scenario is provided in order to investigate the sensitivity of two key variables: 1) initial occupant speeds in clear conditions, 2) extinction coefficients. Results shows that 1) evacuation times appear to be consistent if models use the same data-sets and interpret the smoke vs speed correlation in the same manner 2) the same model may provide different results if applying different data-sets or interpretations for configuring the inputs; i.e. default settings are crucial for the calculation of the model results 3) models using embedded data-sets/assumptions need user expertise, experience and understanding to employ the model appropriately and then to evaluate the results.

Keywords. Evacuation modelling, Human Behaviour in fire, FDS+Evac, Gridflow, buildingEXODUS, STEPS, Pathfinder, Simulex.

1 Introduction

The increasing capabilities of evacuation models [Gwynne et al., 1999, Kuligowski et al., 2010, Santos & Aguirre, 2005, Tavares, 2009] are leading to a high number of new model users. One of the consequences is that the areas of application are becoming more diverse as the community of evacuation model users is growing [Ronchi & Kinsey, 2011, Ronchi et al., 2010]. To increase the number of evacuation model users, model developers are also constantly working on improving the usability of models, making them more accessible and embedding more sophistication. The number of embedded default settings is growing; this has been made to allow users to rapidly obtain results. In fact, default settings often permit the models to be applied without prior configuration of the input [Gwynne & Kuligowski, 2010, Ronchi et al., 2011b].

Evacuation modelling can be a peripheral activity, leading non-expert users to apply these tools. These evacuation modellers may not have a deep understanding of the model capabilities and limitations due to a scarce knowledge on default settings, embedded data-sets employed, range of applicability, Validation and Verification, etc. The situation can be worse, given the multi-disciplinary nature of the field [Kuligowski, 2011]. In brief, the lack of specific academic or professional credentials relating to the use of evacuation models could affect the accuracy and credibility of the simulation results.

The evacuation models market presents simulation packages that can be applied as part of the performance-based approach (i.e. the comparison between ASET - Available Safe Egress Time – and RSET - Required Safe Egress Time) by simulating fire and evacuation processes within the same environment. In this context, one of the main aspects to be reproduced is the simulation of the smoke effects on human performance [Gwynne & Rosenbaum, 2008]. Smoke affects the process of way-finding in a building producing impacts on occupant walking speeds.

This paper presents the application of different data-sets and their subsequent interpretations for reproducing the impact of smoke on occupant walking speeds. The case-study refers to the evacuation of a corridor, providing a sensitivity analysis of the two main variables affecting this issue; i.e. the visibility conditions (often measured by extinction coefficient) and the initial occupant speeds in clear conditions. Many other correlations and constructs are used within evacuation modelling; however in this case-study, a single problem is investigated in order to minimise the influence of any other factors.

The study of the smoke/speed correlation is currently based on two main data-sets. The first is a set of experiments performed by Jin [1976] more than 30 years ago. The experimental data collected has been used for providing the correlation between the extinction coefficient and walking speeds, visibility levels and cognitive abilities when exposed to smoke. The second correlation currently in use is based on the more recent studies conducted by Frantzich and Nilsson [2003] who performed tunnel experiments for studying the influence of different visibility conditions on individual walking speeds. The two data-sets employed different experimental conditions, i.e., types of irritant gases, population characteristics, structural configuration, etc. but are frequently used within evacuation models as if interchangeable. Another issue is the way evacuation models interpret the two data-sets. Currently, there are two main methods to apply the smoke/speed curves to simulate the impact of smoke. The first method to reproduce the impact of smoke on walking speeds simulates a fractional reduction of the initial speed. The speed achieved is affected by two variables, i.e., the visibility conditions and the initial speed in clear conditions. The second option considers an absolute reduction of the speed i.e. agents reduce their speed all in the same way regardless their initial speed in clear conditions. The only variable affecting speed is then the visibility conditions.

There are significant differences between the two data sets and their interpretations, and, this raises a broader question as to how computer models should be designed and presented. Those models with embedded default data sets are particularly susceptible to misuse and misinterpretation of the results, if the user is inexperienced and inexpert.

The authors have selected six models to examine the impact of default settings, embedded data-sets and their interpretation upon results produced. These models have been selected to address two different points: 1) the impact of default embedded data-sets on evacuation results, 2) the impact of different interpretation of the data-sets on results. The following six models – applying different default settings/embedded data – have been used and the results presented: FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], Gridflow 3.03 [Bensilum & Purser, 2003], buildingEXODUS 4.1 [Galea et al.,2004], STEPS 4.1 [Mott MacDonald Simulation Group, 2011], Pathfinder 2011 [Thunderhead Engineering, 2011], Simulex 5.8 [Thompson & Marchant]. They were selected because they present different assumptions with regards to the representation of the impact of smoke on agents; i.e. they may have or not default settings and embed either Jin's or Frantzich and Nilsson's data-set.

Conclusions are presented focussing on the different manners in which these selected evacuation models reproduce the impact of smoke on occupant walking speeds. Considerations on the use of default settings/embedded data are provided as well as suggestions on how to model the impact of smoke on occupant speeds.

2. The impact of smoke on occupant walking speed

The presence of smoke during an emergency may have different impacts on evacuees' behaviours [Bryan, 2002, Wright et al., 2001, Wood, 1972, Xie, 2011]. These impacts could be psychological, physiological or physical. Different occupant behaviours may be caused by contacting with smoke, including: 1) start of the evacuee' response, 2) redirection of people movement, 3) reduction of the efficiency of occupants' movement i.e. the presence of smoke could also lead to an extreme reduction of the occupant movement preventing normal walking behaviour - e.g. causing crawling behaviours [Wood, 1972]. This paper investigates the available literature/data-sets for modelling the impact of smoke on occupant speeds and the manner for interpreting this information within evacuation models.

2.1 Available data-sets

The current literature includes two main experimental data-sets based on Jin [1976] and Frantzich and Nilsson's studies [2003]. The experiments made by Jin [1976] were performed more than 30 years ago and they are currently available in the Society of Fire Protection Engineering Handbook [Jin, 2008], while Frantzich and Nilsson's [2003] experiments were performed more recently. These experiments are often considered (especially in engineering practice) as equivalent data-set to reproduce the impact of smoke on evacuee movement speeds during an evacuation. They both provide a correlation between extinction coefficient, i.e., the visibility conditions within the considered infrastructure, and occupant speeds. Jin's experiments also provide information on the occupants' cognitive abilities when exposed to smoke [1990].

Jin studied the effect of two types of smoke: 1) irritant and 2) non-irritant. Experiments were performed in a 20m-long corridor that was filled with smoke corresponding to an early stage of fire. The experimental population consisted of 17 females and 14 males, ranging from 20 to 51 years in age. Irritant smoke was produced by burning wood cribs, while less irritant black smoke was produced by burning kerosene. Test subjects were instructed to walk into the corridor. In the case of irritant smoke both smoke density and irritation affect the walking speed. The speed decreases rapidly from 1.0 to 0.3 m/s as extinction coefficient increases from 0.1 to 0.5/m (see Figure 1). With relatively dense irritant smoke, the participants were not able to keep their eyes open, causing a zigzag movement or using the wall as an aid to guidance.

The case of non-irritant smoke showed a slower decrease in the walking speed (see Figure 1), with a range of approximately 0.5-1 m/s. The range of extinction coefficient investigated in these experiments was 0.2-1.0/m. In this case, if the smoke concentration is higher than 0.5/m (see Figure 1) the ability to walk at desired speed was seriously affected, although to a lesser degree than with the irritant smoke. They would continue to walk with a minimum speed of approximately 0.3 m/s, behaving as if in darkness and feeling their way along the walls.

Frantzich and Nilsson performed their experiments in a tunnel that was approximately 37 metres long. It was filled with artificial smoke and acetic acid was used to simulate irritation. A total of 46 people took parts in the experiments. A broader range of extinction coefficient was examined than in Jin's experiments (see Figure 1). The range of extinction coefficient was approximately 2.0-8.0 /m. Two different experimental conditions were considered during these trials: participants walked through the tunnel 1) with the tunnel lighting on and 2) with the tunnel lighting turned off (see Figure 1). The analyses were performed separately for the two sets of data and only the data with illumination were used to derive the correlation between extinction coefficient and walking speeds in the analysis performed here. This choice was made because it reflects the current interpretation of this data-set made by the model developers [Korhonen & Hostikka, 2010].

The walking speed range was approximately 0.2-0.8 m/s. The scattering of the collected data was wide and makes it hard to derive a representative occupant walking speed for an assigned extinction coefficient. This is a consequence of the difference in participant characteristics/skills. Another key aspect of the experiments is that occupants seem to walk faster when in close proximity to a wall (the data-set showed in Figure 1 includes both people using the wall or not using it along their path). This finding reproduces observations made by Jin. Also, while Jin's work involved a simple corridor, the Frantzich and Nilsson experimental environment was more complex, involving some way-finding around obstacles. The comparison between the two data-sets can be made by comparing the speed decreasing trend.

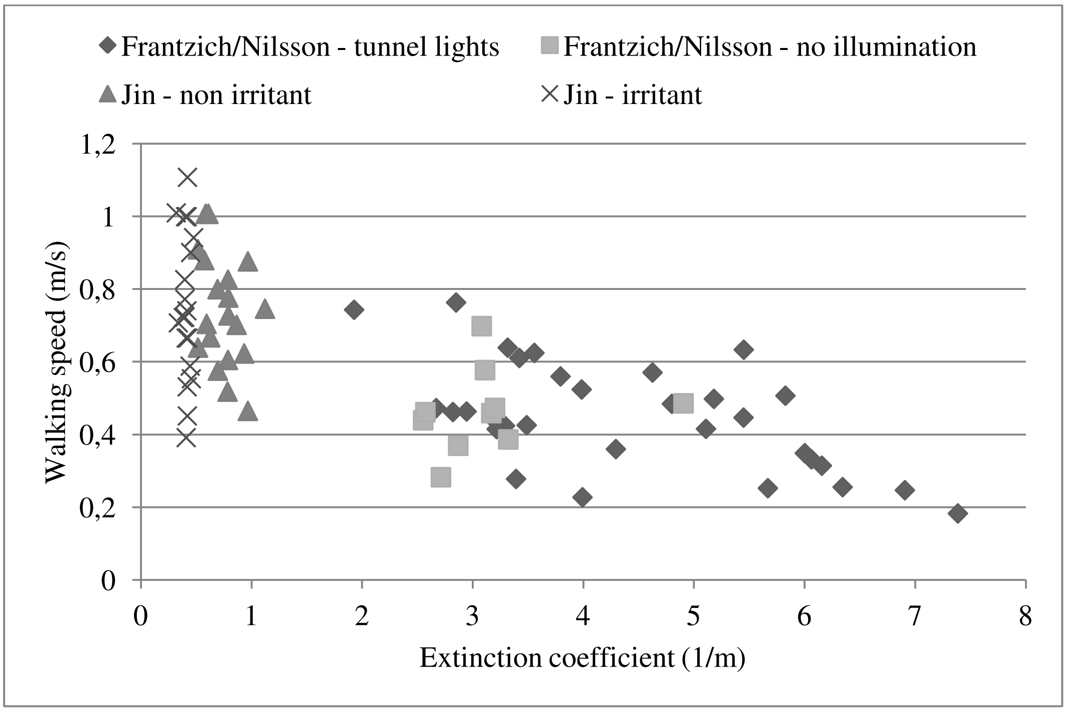

Figure 1. Walking speed as a function of extinction coefficient obtained in Jin's experiments (with irritant and non-irritant smoke) and Frantzich and Nilsson's experiments (with tunnel lights on and no illumination and people using or not using the wall along their path).

With regard to minimum walking speed there are two issues: physical ability to move through dense smoke and behavioural decision-making about whether to continue. For non-irritant smoke Jin found a minimum speed of about 0.3 m/s at high smoke densities where subjects moved as if in darkness, with similar findings in the Frantzich and Nilsson experiments. In fire incidents some people are known to have moved through very dense smoke; however, studies by Bryan have shown that the proportion of people turning back rather than entering smoke increases with the smoke density [Bryan, 2002]. This depends somewhat on the situation (and the options available), so that people in a relatively clear space may turn back rather than attempting to move through dense smoke, while those engulfed in dense smoke in the enclosure of origin may continue to move through very dense smoke. For tunnel fires some people have walked for several hundred metres in dense smoke [Purser, 2009]. For dense, irritant smoke the conditions may become so severe that people are unable to continue walking due to eye pain and breathing difficulties. Possible relationships between walking speed and effluent composition in terms of irritants have been proposed by Purser [2008].

2.2 Data-set interpretations

The current knowledge on occupant behaviour in a smoke-filled environment and the manner in which the available data is interpreted is reflected in the manner in which different evacuation models apply this information to simulate occupant performance in smoke.

Currently, there are two methods adopted within evacuation models when representing reduced movement due to the presence of smoke (see Sec. 2.1):

A) The smoke produces a fractional reduction of the speed i.e. the final speed in smoke is dependent on the individual's walking speed in clear conditions, which is then reduced in accordance with some function relating travel speed to smoke conditions.

B) The smoke effect is interpreted as an absolute reduction of the speed; i.e. the final speed in smoke of each person relies only on the smoke conditions (e.g. extinction coefficient, derived visibility, etc.), regardless of the individual's initial walking speed in clear conditions;

With regards to the minimum speed in smoke, there are three different methods currently adopted to bound the impact of the smoke upon occupant movement:

1) No minimum speed. Each person reduces their speed in relation to the decreasing extinction coefficient.

2) Constant minimum speed. People reduce their speeds in relation to the decreasing extinction coefficient until they reach a constant minimum speed in very dense smoke.

3) Variable minimum speed, based on the individual.

The five combinations of these interpretations (there are not six combinations as an absolute reduction in speed does not include the possibility of not having a minimum speed) are:

(A1) $$v_i^s = v_i^0 c(K_s)$$

(A2) $$v_i^s = Max\left\{v_{i,min}\ , v_i^0 c(K_s)\right\}$$

(A3) $$v_i^s = Max\left\{v_{i,min}\,(i), v_i^0 c(K_s)\right\}$$

(B2) $$v_i^s = Max\{v_{i,min}, v_i(K_s) \pm \Delta\}$$

(B3) $$v_i^s = Max\{v_{i,min}(i), v_i(K_s) \pm \Delta\}$$

A1) Fractional/no minimum speed: the walking speed in smoke v_i^s of occupant i is a fraction $v_i^0 c(K_s)$ (i.e. 0<c≤1) of the speed in clear condition v_i^0 depending on the extinction coefficient K_s;

A2) Fractional/constant minimum speed: the walking speed in smoke v_i^s of occupant i is a fraction $v_i^0 c(K_s)$ (i.e. 0<c≤1) of the speed in clear condition v_i^0 depending on the extinction coefficient K_s; In dense smoke, all occupants end up at the same minimum speed $v_{i,min}$ (approximately 0.3-0.4 m/s)

A3) Fractional/variable minimum speed: the walking speed in smoke v_i^s of occupant i is a fraction $v_i^0 c(K_s)$ (i.e. 0<c≤1) of the speed in clear condition v_i^0 depending on the extinction coefficient K_s; in dense smoke there is a considerable scattering of speeds i.e. $v_{i,min}$ depends on the characteristics of the occupant i.e. $v_{i,min} = v_{i,min}(i)$

B2) Absolute/constant minimum speed: the walking speed in smoke v_i^s depends on the extinction coefficient K_s (absolute reduction), within a certain range Δ of speeds around the average i.e. speed reduction is independent from the occupant speed in clear conditions v_i^0. In dense smoke, all occupants walk at a minimum speed $v_{i,min}$ (approximately 0.3-0.4 m/s);

B3) Absolute/variable minimum speed: the walking speed in smoke v_i^s depends on the extinction coefficient K_s (absolute reduction), within a certain range Δ of speeds around the average i.e. speed reduction is independent from the initial walking speeds v_i^0. In dense smoke, speed reduction is variable among the occupants i.e. $v_{i,min}$ depends on the characteristics of the occupant i.e. $v_{i,min} = v_{i,min}(i)$.

Three interpretations [(A1), (A3) and (B2)] have been identified in existing evacuation models and examples of models applying them are selected and discussed in Section 3.

Another important point to be considered is the lighting conditions during an evacuation. The first consideration is the general illumination conditions enabling occupants to see their surroundings in order to avoid obstacles and navigate towards a desired objective such as an exit or a safe escape route. Models are often based upon the assumption of a generalised diffuse illumination, so that a subjects surroundings are viewed by reflected light [McGrattan et al., 2008], attenuated depending upon the smoke density. In practice the source of illumination is very important. In a situation such as a tunnel, if illumination is by ceiling lighting then it is necessary to consider the extent to which the illumination and contrast of the surroundings is attenuated by the smoke, in addition to the extent to which there is further attenuation of the appearance of illuminated objects to evacuating subjects. In addition it is necessary to consider the effects of systems such as low level emergency lighting and illuminated exit signage. If a subject is in total darkness due to the combined effects of obscuration of general lighting and visual attenuation by smoke, but can see the glow of an illuminated exit sign, this can give purpose and direction to their escape movements, but may not enable them to see other objects in their surroundings in order to walk forward safely and efficiently. The value of extinction coefficient may vary over a wide range according to the combustion environment and illumination conditions, thus causing considerable uncertainty when selecting the extinction coefficient as an input parameter to visibility models [Zhang, 2011]. To some extent these problems can be addressed by gradually incorporating more environmental conditions and/or the individual skills for orientation in smoke into models.

The general lack of theoretical understanding on human performance in smoke makes it difficult to provide a definitive interpretation of the available data-sets. This affects the current evacuation models which use different data-sets and interpretations as if equivalent. This may raise the issue of evaluating the differences among the evacuation model results when applying different default (or pre-defined) settings i.e. different data-sets and interpretations. To explore this problem, this paper provides a case-study where an extensive range of possible scenarios has been investigated varying the two key variables i.e. occupant walking speeds in clear conditions v_i^0 and extinction coefficient K_s.

3. Case study

Six evacuation models have been selected to test their capabilities to reproduce the impact of smoke on occupant walking speeds. Table 1 shows their different strategies about default settings and embedded data-sets.

Table 1. Evacuation models employed and corresponding default settings/embedded data-sets

Model	**Embedded data-set**	**Smoke/Speed curve default interpretation**
FDS+Evac 2.3.1	Frantzich and Nilsson	(A3) Fractional/variable minimum speed
Gridflow 3.03	Any data-set	No default settings
buildingEXODUS 4.1	Jin	(A1) Fractional/no minimum speed
STEPS 4.1	Jin/any data-set	(B2) Absolute/constant minimum speed
Pathfinder 2011	No embedded data-set	No default settings
Simulex 5.8	No embedded data-set*	No default settings*

*The feature of a Smoke/Speed correlation is currently under development i.e. it is available for beta testing but it is not embedded in the model. It is not used in this paper.

3.1 Scenarios

A simple straight corridor (100 m of length and 3.5 m of width) with a single exit located at one end is modelled to test the impact of the different model assumptions on the results produced. The scenarios required a number of further assumptions to be made which were applied across all of the models employed:

- A single agent was simulated to remove agent interaction from influencing the results;
- Smoke was represented (if possible) within the model through a constant extinction coefficient during the simulation. Visibility conditions were therefore considered as constant in each scenario, although different extinction coefficients were examined between scenarios. No influence of external sources of lights is taken into account;
- The toxic effect of smoke was not considered (i.e. FED [Purser, 2008] is always equal to 0);
- Free-flow conditions were assumed at the final exit and no influence of signage is taken into account;
- Two different environmental conditions were considered during the application of the Jin's data-set [1976]: irritant and non-irritant smoke; during the application of the Frantzich and Nilsson's data-set, [2003] the case of irritant and non-irritant smoke is not differentiated i.e. only one correlation to simulate the impact of smoke on speed is provided for both cases. This is based on the fact that the irritant effect in Frantzich and Nilsson's experiment is much less severe than in Jin's experiment [Xie, 2011].
- Jin's data-set is used only within its range of applicability (that is an extinction coefficient within 0.2-1.0/m for non-irritant smoke and 0.2-0-5/m for irritant smoke).
- The smoke influence on speed coming from Frantzich and Nilsson's data-set is derived only from the data where the tunnel lights were on (see Sec. 2.1) in accordance

with model developer's interpretation of the data-set [Korhonen & Hostikka, 2010].
- Initial unimpeded walking speeds in clear conditions were constant values (i.e. distributions are not used);
- Default values about agent's body dimensions were used.
- Hand calculations of the occupant walking speeds in smoke were used for the models which do not permit to directly implement the smoke (Pathfinder and Simulex).

Five different initial walking speeds were considered (ranging from 0.25 m/s to 1.25 m/s). Agents with these initial travel speeds were exposed to five different visibility conditions (i.e. extinction coefficients) for irritant and non-irritant smoke. This produced a total of 50 scenarios. A three place naming convention is used for these scenarios. The first place indicates the assumed initial speed of the agent (either 1.25, 1.0 0.75, 0.5 or 0.25). The second place shows the extinction coefficient (10, 7.5, 3.0, 1.0, or 0.5/m). The final place indicates whether the smoke represented was irritant or non-irritant (either I or NI). Scenarios where there are no differences about irritant and non irritant gas are represented as I/NI. For instance, Scenario [125_10_I] represents an agent with initial speed 1.25m/s, in irritant smoke with extinction coefficient 10/m.

3.1.1 Model input configuration

FDS+Evac

The visibility conditions in FDS+Evac are reproduced using its correspondent fire model FDS, the Fire Dynamics Simulator [McGrattan et al., 2008]. The corridor visibility conditions have been simulated by defining the initial conditions of the environment. This method is based on the assumption of fixed visibility conditions in space and time and no external sources of light. Thus, the calculation of the ratio between the mass of soot and mass of air (Mass fraction – kg/kg) has been provided for obtaining the desired visibility conditions. In FDS, this parameter is the command line &INIT MASS_FRACTION(2) and the input value has been calculated for the 5 different extinction coefficients by simulating a fictitious fuel made of 100% soot. The variables generating toxic gases in FDS are set equal to 0 (i.e. the command line CO_YIELD=0). Initial walking speeds are inserted as a constant value in each scenario. The random fluctuations within the movement model have been set equal to 0. The model by default interprets the Frantzich and Nilsson curve as Fractional/variable minimum speed (Interpretation (A3) in Sec. 2.2). The minimum speed is depending on the characteristics of the single agent i.e. its walking speed in clear conditions.

Gridflow

Default settings in Gridflow provide a minimum value of 0.3 m/s of walking speeds when using a distribution of values. This is not the case of the scenarios considered here, where the model user inserts initial walking speeds as a constant value. Inputs are provided by the user through the use of a spreadsheet. FED values are set equal to 0 in this case (i.e. the toxic effect is not considered in these scenarios). In order to test the models against each other, two different sets of speed factors have been used in Gridflow for simulating the scenarios considered. The first is derived from the FDS+Evac approximation of Frantzich and Nilsson's experimental data (fractional/variable minimum speed - Interpretation (A3) in Sec. 2.2) while the second set of speed factors comes from the Exodus representation of Jin's data-sets (Fractional/no minimum speed – Interpretation (A1) in Sec. 2.2). Hand calculations have been completed for calculating the speed factors according to these two different data-sets and the described interpretations. The speed factors are then inserted into the input spreadsheet for each time step. The susceptibility set for each agent to speed factors was 1, so that every agent will have exactly the selected speed reduction (although it is possible to set varying levels of susceptibility for different individual agents).

buildingEXODUS

The agent was generated with the initial Fast Walk Speed set to the values indicated in Sec. 3.1. The agent was then positioned at the far end of the geometry. An environmental zone was set across the entire geometry and the extinction coefficient within the zone was set to the values of the scenarios examined. In this case, the toxic impact of the gases present is not of interest and was not represented. The model was configured to either use the embedded Jin irritant curve or the Jin non-irritant curve (with no narcotic or irritant gases explicitly modelled in either case). The model interprets these correlations according to the definition provided in Interpretation (A1) (see Sec. 2.2). buildingEXODUS is able to represent the impact that smoke has on the initial response of the agent, the route adopted, the potential for crawling, the presence of agent staggering and boundary use for guidance. The first two behaviours were not relevant in this case study. Crawling behaviour was analysed in some *ad hoc* simulations in which crawling function was enabled. The impact of staggering within the smoke and wall adherence was included (both derived directly from Jin's data-set).

STEPS

The visibility conditions in STEPS have been reproduced by importing the fire data simulated with the FDS tool [Jin, 1990]. The geometry was then directly imported from the FDS input file. The method to simulate the smoke is then the same as employed in FDS+Evac. The model permits the smoke concentrations to be represented at a certain height within the computational domain and then employs Jin's smoke vs speed correlation by default, while customised correlation can be used too. Smoke concentrations were homogenous in the considered scenarios. Consequently the definition of the height of the slice file was not relevant; i.e. the slice file would provide the same information about smoke concentrations at any height. The default Jin's curves are then employed (irritant or non-irritant) to simulate the impact of smoke on occupant walking speeds, applying an absolute reduction with a minimum walking speed; i.e. as described in interpretation (B2) (see Sec. 2.2). No toxic effects of smoke have been introduced in the model.

Pathfinder/Simulex

These models do not permit the impact of smoke on occupant speeds to be directly represented; i.e. no embedded data-sets are provided within the models. Thus, evacuation modellers need to calculate the impact of smoke beforehand, and then reduce the initial occupant speeds in accordance with a pre-defined speed factor to manually represent the impact of the environmental conditions. In order to test the model capabilities and compare models against each other, two different data-sets have been employed by configuring the input as described in interpretation (A3) for Frantzich and Nilsson data-set and interpretation (A1) and interpretation (B2) for Jin's data-set (see Sec. 2.2).

3.2.1 Results

The results produced with the six models are shown in Table 2. The predicted evacuation times are in line with the correlations provided by Jin and Frantzich and Nilsson. As expected, evacuation times increase with higher extinction coefficients and lower initial walking speeds.

Table 2. Evacuation times produced with the six models employed.

Model	***F***	***G***	***G***	***bX***	***bX****	***ST***	***P***	***P***	***P***	***S***	***Sim***	***Sim***
Data-set	***F/N***	***F/N***	***Jin***	***Jin***	***Jin***	***Jin***	***F/N***	***Jin***	***Jin***	***F/N***	***Jin***	***Jin***
Interpretation	**A3**	**A3**	**A1**	**A1**	**A1**	**B2**	**A3**	**A3**	**B2**	**A3**	**A3**	**B2**
Scenario	**Evacuation times (s)**											
125.10.I/NI	419	417	/	/	/	/	416	/	/	417	/	/
125.75.I/NI	203	205	/	/	/	/	204	/	/	205	/	/
125.3.I/NI	107	105	/	/	/	/	105	/	/	103	/	/
125.1.I	87	87	/	/	/	/	87	/	/	88	/	/
125.1.NI	87	87	174	175	178	176	87	176	173	88	174	174
125.05.I	84	83	227	223	226	209	84	228	208	84	227	207
125.05.NI	84	83	96	97	100	98	84	98	99	84	96	97
100.10.I/NI	526	527	/	/	/	/	526	/	/	526	/	/
100.75.I/NI	255	257	/	/	/	/	257	/	/	258	/	/
100.3.I/NI	133	132	/	/	/	/	132	/	/	132	/	/
100.1.I	109	109	/	/	/	/	108	/	/	108	/	/
100.1.NI	109	109	217	218	223	176	108	220	173	108	219	174
100.05.I	105	104	283	279	281	209	103	285	208	105	285	207
100.05.NI	105	104	120	121	122	99	103	121	99	105	121	97
075.10.I/NI	711	713	/	/	/	/	715	/	/	716	/	/
075.75.I/NI	339	332	/	/	/	/	333	/	/	331	/	/
075.3.I/NI	177	175	/	/	/	/	176	/	/	176	/	/
075.1.I	146	145	/	/	/	/	144	/	/	145	/	/
075.1.NI	146	145	289	290	294	176	144	291	173	145	293	174
075.05.I	139	140	377	372	374	209	140	381	208	139	383	207
075.05.NI	139	140	160	162	163	132	140	162	133	139	161	134
05.10.I/NI	998	1000	/	/	/	/	999	/	/	999	/	/
05.75.I/NI	509	500	/	/	/	/	499	/	/	500	/	/
05.3.I/NI	266	263	/	/	/	/	263	/	/	264	/	/
05.1.I	217	217	/	/	/	/	216	/	/	217	/	/
05.1.NI	217	217	435	436	450	199	216	440	201	217	439	199
05.05.1I	208	208	567	557	563	209	208	570	208	207	570	207
05.05.NI	208	208	241	242	245	199	208	242	201	207	243	199
025.10.I/NI	1998	2000	/	/	/	/	1999	/	/	1998	/	/
025.75.I/NI	1005	1000	/	/	/	/	1001	/	/	999	/	/
025.3.I/NI	529	527	/	/	/	/	526	/	/	526	/	/
025.1.I	434	433	/	/	/	/	435	/	/	435	/	/
025.1.NI	434	433	877	872	878	399	435	876	399	435	878	398
025.05.I	415	417	1143	1115	1131	399	417	1142	399	417	1140	398
025.05.NI	415	417	487	484	492	399	417	488	399	417	486	398
125.10.I/NI	419	417	/	/	/	/	416	/	/	417	/	/

Legenda: FDS+Evac= F, Gridflow=G, buildingEXODUS= bX, buildingEXODUS with crawling behaviour function enabled = bX*, STEPS=ST, Pathfinder = P, Simulex = S; F/N= Frantzich and Nilsson data-set employed, Jin= Jin data-set employed; "Interpretation" refers to the type of interpretation of the smoke impact as described in Section 2.2

The evacuation times produced appear to be consistent if the same data-set is employed considering the same assumptions; i.e. the smoke impact on speeds is interpreted in the same manner. An example of the consistency of the results has been provided in Figure 3, where Frantzich and Nilsson's data-set has been applied as in Interpretation (A3) in four different models (where this data-set is applied by default i.e. FDS+Evac or where a default data-set is not available i.e. Gridflow, Pathfinder and Simulex) in the case of four different extinction coefficients - respectively 10 /m, 7.5 /m, 3 /m and 1 /m.

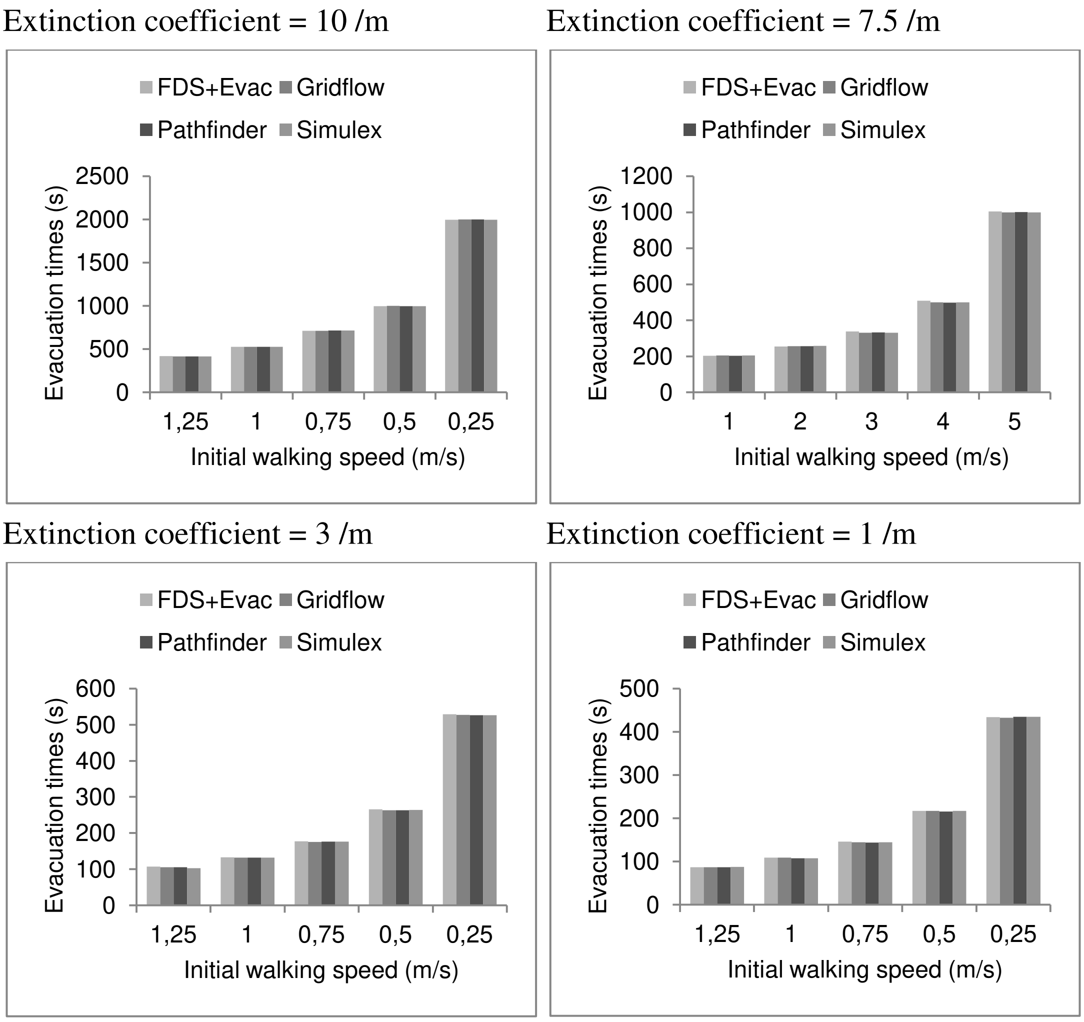

Figure 2. Evacuation times produced by four different models (FDS+Evac, Gridflow, Pathfinder and Simulex) when applying Frantzich and Nilsson's data-set through interpretation (A3).

The analysis of scenarios within the range of applicability of the Jin's curve (that is an extinction coefficient of 0.2-1.0/m for non-irritant smoke and 0.2-0-5/m for irritant smoke) allow us to compare the results of the six models in relation to different default settings employed; i.e. embedded data-set and their interpretation.

Also in this case, results appear to be consistent when applying the same data-set/assumptions. When employing Jin's data-set and interpretation (A1), the Gridflow, buildingEXODUS, Pathfinder and Simulex models provide consistent results. The same consistency appears evident when applying Frantzich and Nilsson's data-set for

FDS+Evac, Gridflow, Pathfinder and Simulex models. STEPS model employs, by default, the absolute interpretation of the Jin's data-set (interpretation (B2)) different from buildingEXODUS (interpretation (A1)). This leads to significant differences among the results. In fact, buildingEXODUS provides by default more conservative results (see Figure 4 and 5) because of the fractional interpretation of the Jin's curve without considering a minimum speed (as happens in STEPS model).

Differences also arise when applying different data-sets. Figure 4 shows the results for the case of irritant smoke and an extinction coefficient = 0.5 /m. The use of Jin's data-set through interpretation (A1) (i.e. fractional/no minimum speed) produces evacuation times that are approximately 170% greater than Frantzich and Nilsson's data-set.

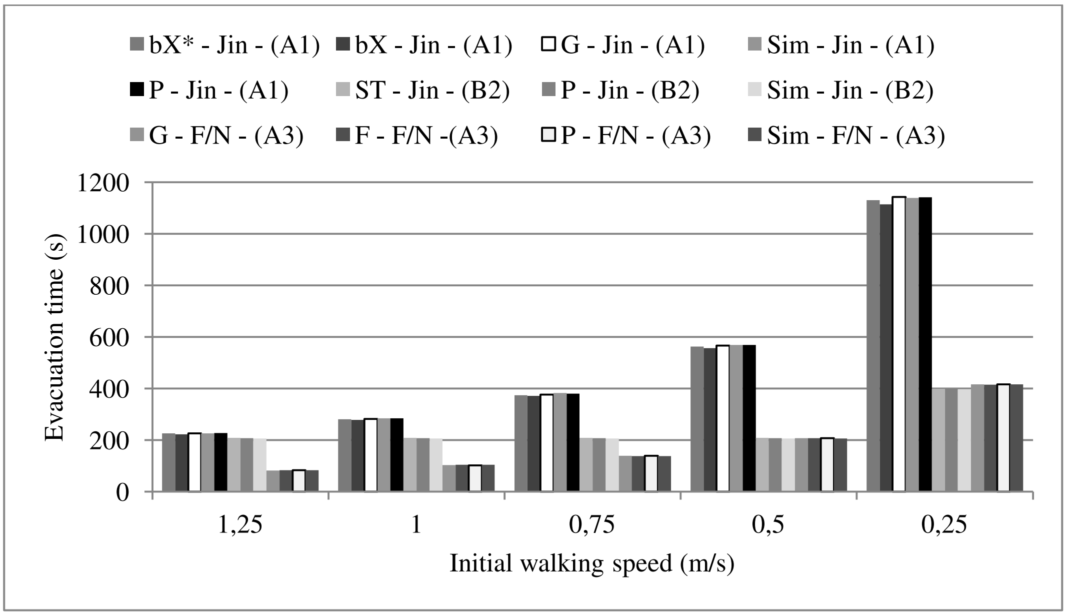

Figure 3. Evacuation times for scenarios with extinction coefficient = 0.5 /m and irritant smoke using six models. Legenda: X – Y – (Z): X is the model employed: [FDS+Evac= F, Gridflow=G, buildingEXODUS= bX, buildingEXODUS with crawling behaviour function enabled = bX, STEPS=ST, Pathfinder = P, Simulex = Sim]; Y is the data-set employed: [F/N= Frantzich and Nilsson is the data-set employed, Jin= Jin is the data-set employed]; (Z) = the type of interpretation of the smoke impact on speeds as described in Section 2.2.*

Next scenarios examine walking speeds when extinction coefficients of 1.0/m (see Figure 4) and 0.5/m are simulated (see Figure 5) for the case of non-irritant smoke.

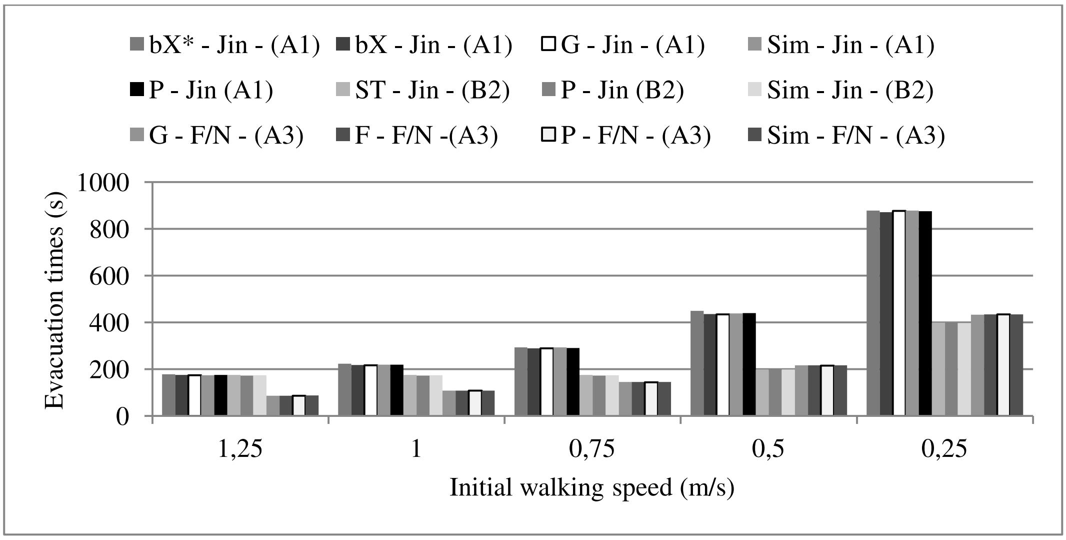

Figure 4. Evacuation times for scenarios with extinction coefficient = 1 /m and irritant smoke using six models. Legenda: X – Y – (Z) is following the same representation of Figure 4.

Results show that the use of Jin's correlation through interpretation (A1) leads to an increase of evacuation times; it consists in approximately a 97-107% when the extinction coefficient is 1.0/m and 14-19% when the extinction coefficient is 0.5 /m. As expected, the differences in the evacuation times are again higher where lower walking speeds are initially assumed. As in the previous scenarios (extinction coefficient =0.5 /m and irritant smoke), different interpretation of the data-set employed provide significant differences in the results (e.g. STEPS and BuildingEXODUS results applying the default).

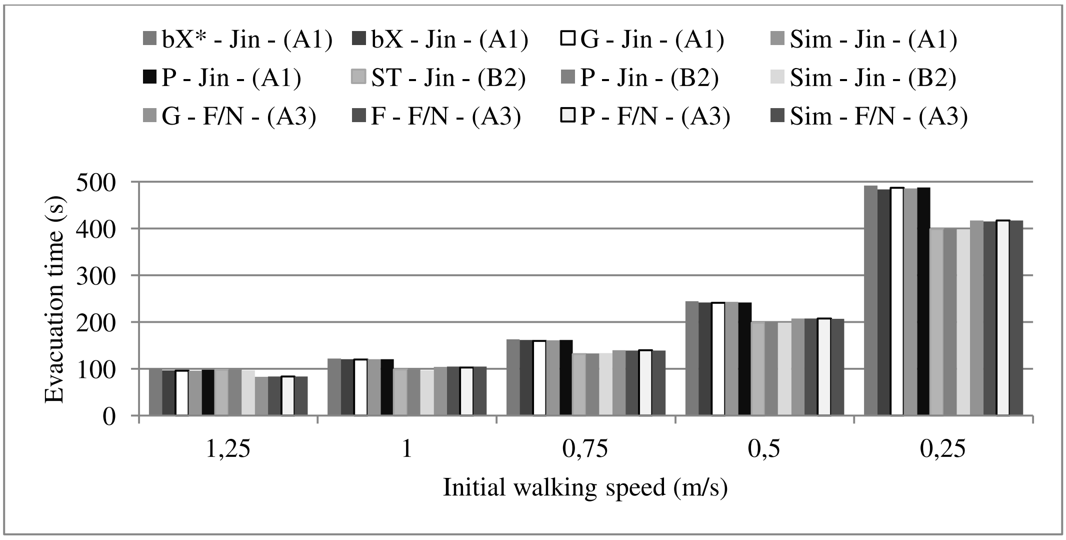

Figure 5. Evacuation times for scenarios with extinction coefficient = 0.5 /m and irritant smoke using six models. Legenda:. X – Y – (Z) is following the same representation of Figure 4.

4. Conclusions and discussion

This paper focused on the modelling issues that arise when employing evacuation models to simulate the impact of smoke on occupant walking speeds. The impact of default settings, embedded data and user/model interpretations on evacuation modelling results were also investigated. The case-study presented covers the key variables affecting this issue i.e. initial occupant walking speeds in clear conditions and different extinction coefficients. Two data-sets have been analysed in detail for this purpose: Jin's and Frantzich/Nilsson's experimental data. A description of the typical interpretations of the smoke data-sets has been provided. Five different categories of model interpretations have been identified (see Sec. 2.2) in order to describe the manner models interpret the data. Six models using different strategies about empirical data-set have been compared: 1) FDS+Evac, 2) Gridflow, 3) buildingEXODUS, 4) STEPS, 5) Pathfinder and 6) Simulex. A total of 50 scenarios have been examined to test the sensitivity of the results, given the embedded relationship between the smoke conditions (i.e. extinction coefficient) and the speed reduction.

The results presented show that (1) the application of different data-sets or interpretations produced different results - when the same or different models are used, given the scenarios examined; (2) the numerical results produced are comparable when the same assumptions are employed i.e. data-sets/interpretations are the same among different models. This is encouraging in that it provides some cross-validation between the models, such that the all provide similar results for agent movement under these conditions and for the effects of smoke density on velocity (when using the same assumptions for smoke effects).

Both of the original data-sets show considerable variation in the walking speeds of different individuals at different smoke densities. In contrast, the models tend to use a simple average correlation. A more realistic outcome might be obtained by varying both the unrestricted walking speeds and the sensitivity of speed to smoke density among an evacuating occupant population.

Both data-sets are often considered to be equivalent; instead, modellers should carefully evaluate the conditions of the scenario of interest before selecting the data-set and/or the associated behavioural assumptions. Different populations and smoke concentrations were involved in the scenarios that produced these data-sets. Modellers should be aware of these differences and the potential implications that they might have on the analysis at hand.

Model developers frequently use default or library settings to provide suggested values and/or to enable the model to produce results without significant user intervention. This provides a valuable aid to the user. However, it requires that the user understands the assumed settings and their impact, to ensure that the settings are credible and appropriate for the application at hand.

Omission in the available data and supporting information on the conditions under which the data were obtained, along with limited user expertise, contributes to the likelihood that default/pre-determined settings might be applied inappropriately. This may have serious consequences for model developers (i.e., their models may look less credible, especially where the underlying assumptions of the defaults settings are not well documented), the user (they may look inexpert) and the safety levels of associated designs (they may be based on inaccurate results produced using inappropriate assumptions). It may therefore be safer for model developers to either:

- Not include model defaults at all - therefore always requiring the values used to be justified by the user, or
- Assume the most conservative credible default values possible - requiring a movement away from this conservative position to be justified in the knowledge that a less expert user employing the default settings would not be using overly optimistic values.

It is recognised that the potential for problems with default settings can be reduced through detailed and comprehensive model documentation. However, this alone does not combat all instances where the model can be misunderstood and/or misapplied. The two suggestions, although potentially making a model more difficult to initially use, provide an additional safeguard against an unsophisticated use of default settings when adopted in conjunction with the necessary model documentation

Further consideration also needs to be given to the interactions between smoke and the lighting in occupied enclosures in addition to the effects of attenuation between objects and evacuating occupants.

Acknowledgments
The authors wish to thank Daniel Nilsson for providing the data-set of the tunnel experiments made by the Department of Fire Safety Engineering and Systems Safety at Lund University and for his valuable help in their interpretation.

References

Bensilum M, Purser DA (2003) Gridflow: An Object-oriented Building Evacuation Model Combining Pre-movement And Movement Behaviours For Performance-based Design. Fire Safety Science 7, pp. 941-952.

Bryan JL (2002) Behavioral response to fire and smoke. In DiNenno PJ (ed) et al: the SFPE handbook of fire protection engineering, third edition, National Fire Protection Association, Quincy, pp. 3-315-341.

Frantzich H & Nilsson D (2003). Utrymning genom tät rök: beteende och förflyttning [Evacuation in dense smoke: behaviour and movement] (No. 3126). Lund: Department of Fire Safety Engineering and Systems Safety.

Galea ER, Gwynne SMV, Lawrence PJ, Filippidis L, Blackshields D, Cooney D (2004). buildingEXODUS V4.0 User Guide and Technical Manual. University of Greenwich.

Gwynne SMV & Rosenbaum E (2008). Employing the Hydraulic Model in Assessing Emergency Movement. In the SFPE Handbook of Fire Protection Engineering, 4th Edition. National Fire Protection Association, Quincy, MA, pp. 3-396-3-373.

Gwynne SMV & Kuligowski E (2010). The faults with default. In Proceedings of the Conference Interflam2010, Interscience Communications Ltd: London. pp. 1473-1478.

Gwynne SMV, Galea ER, Owen M, Lawrence PJ, Filippidis L (1999). A Review of the methodologies used in the computer simulation of evacuation from the built environment. Building and Environment, 34(6), pp.741-749.

Korhonen T & Hostikka S (2010). Fire Dynamics Simulator with Evacuation: FDS+Evac Technical Reference and User's Guide. FDS 5.5.3, Evac 2.3.1. VTT working papers.

Jin T (2008). Visibility and Human Behavior in Fire Smoke. In the SFPE Handbook of Fire Protection Engineering (fourth edition). National Fire Protection Association, Quincy MA, USA.

Jin T & Yamada T (1990). Experimental study on human emotional instability in smoke filled corridor: part 2. Journal of Fire Sciences 1990 8:124

Jin T (1976). Visibility through Fire Smoke: Report of Fire Research Institute of Japan 2, 33, pp. 12-18.

Kuligowski ED (2011a). Predicting Human Behavior during Fires. Fire Technology, Vol. 48.

Kuligowski ED, Peacock RD, Hoskins, BL (2010). A Review of Building Evacuation Models NIST, Fire Research Division. 2nd edition. Technical Note 1680 Washington, US.

McGrattan K, Hostikka S, Floyd J, Baum H, Rehm R, Mell W, McDermott R (2008) Fire dynamics simulator (version 5), technical reference guide. National Institute of Standards and Technology Special Publication 1018-5, Department of Commerce, Gaithersburg, MD

Mott MacDonald Simulation Group (2011) Simulation of Transient Evacuation and Pedestrian movementS STEPS User Manual (4.1 Version).

Purser DA (2009). Application of human behaviour and toxic hazard analysis to the validation of CFD modelling for the Mont Blanc Tunnel fire incident. In Proceedings of the Advanced Research Workshop on Fire Protection and Life Safety in Buildings and Transportation Systems 2009, Santander, Spain, pp 23-57.

Purser D.A., (2008). Assessment of Hazards to Occupants from smoke, toxic gases and heat. In the SFPE Handbook of Fire Protection Engineering (Fourth Edition). National Fire Protection Association, Quincy MA, USA.

Ronchi E, Kinsey M, (2011) Evacuation models of the future. Insights from an online survey on user's experiences and needs. In Capote J (ed) et al: Advanced Research Workshop Evacuation and Human Behaviour in Emergency Situations EVAC11, Santander, pp 145-155

Ronchi E, Gwynne SMV, Purser DA (2011) The impact of default settings on evacuation model results: a study of visibility conditions vs occupant walking speeds. In Capote J (ed) et al: Advanced Research Workshop Evacuation and Human Behaviour in Emergency Situations EVAC11, Santander, pp 81-95

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2010). Human behaviour in road tunnel fires: Comparison between egress models (FDS+Evac, STEPS, Pathfinder). In Proceedings of the twelfth international Interflam 2010 Conference, Nottingham, UK, pp- 837-848.

Santos G, Aguirre BE (2005) Critical review of emergency evacuation simulation models. In: RD Peacock, ED Kuligowski (eds) Workshop on building occupant movement during fire emergencies. National Institute of Standards and Technology, Gaithersburg, pp 27–52

Tavares RM (2009) Evacuation processes versus evacuation models: "Quo Vadimus?", Fire Technology No. 45 pp 419-430. DOI: 10.1007/s10694-008-0063-7

Thompson PA & Marchant EW (1995). A Computer Model for the Evacuation of Large Building Populations, Fire Safety Journal 24, pp. 131-148.

Thunderhead Engineering (2011) Pathfinder 2011. Technical Reference.

Wood P (1972). The Behaviour of People in Fires. Fire Research Note No.953, Fire Research Station.

Wright MS, Cook GK, Webber GMB (2001). The effects of smoke on people's walking speeds using overhead lighting and way-guidance provision. In proceedings of the second International Symposium on Human Behaviour in Fire 2011, MIT, Boston, USA, Interscience Communications Ltd: London, pp.275-284.

Xie H. (2011) Investigation into the interaction of people with signage systems and its implementation within evacuation models. Dissertation. University of Greenwich

Zhang Q, Rubini, PA (2011) Modelling of light extinction by soot particles. Fire Saf J vol. 46 pp 96–103 doi:10.1016/ j.firesaf.2010.11.00

PAPER IV

MODELLING THE IMPACT OF EMERGENCY EXIT SIGNS IN TUNNELS

RONCHI, E.[1], NILSSON, D.[2], GWYNNE, S.M.V.[3]

[1] *Department of Roads and Transportation, Polytechnic University of Bari, Italy, Via Orabona 4, 70100 Bari, (Italy)*

[2] *Department of Fire Safety Engineering and Systems Safety, Lund University, Box 118, 221 00 Lund, (Sweden)*

[3] *Hughes Associates (UK), London, United Kingdom*

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 ---- 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 [Sime, 1985 occupants may consider the 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 [Gandit et al., 2008]). The quick development of untenable conditions during tunnel fires [Fridolf et al., 2011, Shields, 2005] 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 [Purser, 2009] 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 [Nilsson, 2009] and staff may be not immediately on hand to provide assistance [Carvel & Marlair, 2011]. To address these issues, tunnel safety regulations provide information on the types of signs to be used for indicating emergency exits [Council Directive, 2004, NFPA, 2011, UN, 1968].

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.) [Beeson & Mayer]; whether the sign is noticed when visible; whether the information in the sign is understood when noticed [Nilsson, 2009, Gibson, 1978, Hartson, 2003]; and whether this is information is acted upon when understood. This process is described in details elsewhere [Kuligowski, 2011, Xie, 2011, Lindell & Perry, 2004].

The visibility of exit signs under smoke conditions has been investigated since the 1950s [Rasbash, 1951]. However, this research does not fully describe the visibility levels reached in different environmental conditions, given different sign designs, colour schemes and individual attributes [Zhang & Rubini, 2011, Zhang, 2010]. Relatively little research has been completed on the impact of different emergency exit designs on people's exit choice [Nilsson, 2009, Xie, 2011, Xie et al., 2007]. 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 a*gent* 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 present 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.

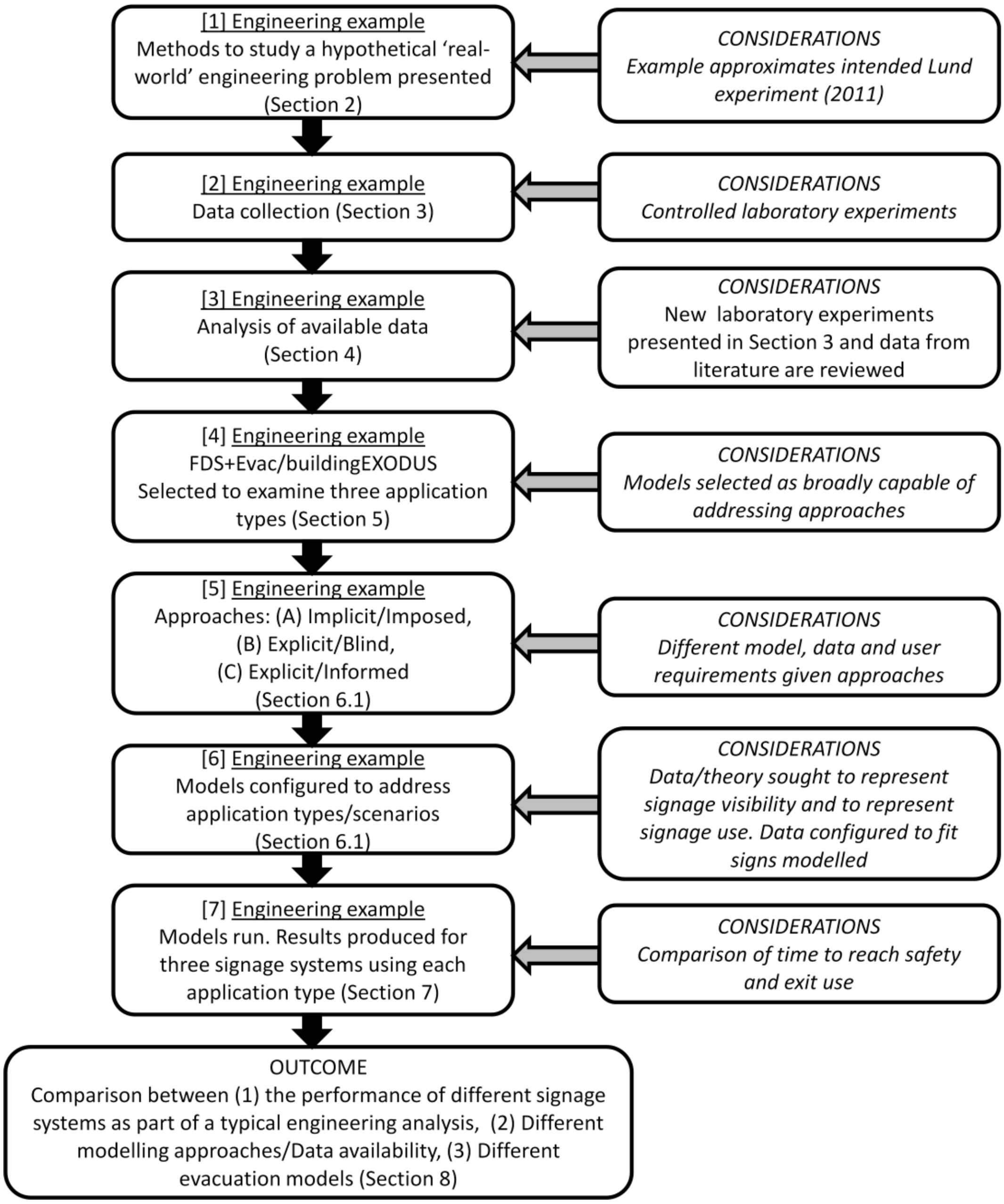

Figure 1. Overview of the methods adopted

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) [Nilsson, 2009, Beeson & Mayer, 2008, Krishnan et al., 2001, Cleary, 2004]. 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 [Korhonen & Hostikka, 2010], and 2) buildingEXODUS [Galea, 2004, Filippidis et al., 2008]. 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 [Filippidis et al., 2008, Kuligowski et al., 2010, Gwynne & Kuligowski, 2010, Gwynne et al., 1999, Gwynne et al., 2001, Ronchi et al., 2010, Xie et al., 2009, Xie et al., 2009].

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 [Gwynne & Kuligowski, 2010], as applied to typical engineering applications ([8] in Figure 1).

3. Lund 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 led, 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).

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]

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 [Jin, 1976]:

$$S = \frac{KS}{K_S} \qquad \text{[Eq. 1]}$$

where S is the visibility in m, K_s is the extinction coefficient in m^{-1} and *KS* is a constant.

According to Jin [1976], 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 [Jin, 1976, Mulholland, 2008]. 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.

Table 2. The average value and the standard deviation for KS

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

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 [Beeson & Mayer, 2008]. 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 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 [Krishnan et al., 2001].

In reality, the likelihood of a person understanding and using information provided by a sign (given that it is seen) is dependent upon a number of factors [Wickens & Hollands, 2000]. In the case study, the key design difference between the signs is their colour. Therefore these are factors examined. Nilsson's previous experimental works [Nilsson, 2009] 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 [2009]. Different way-finding installations were installed in a corridor, including emergency exits equipped with signs of different colours. The experiments consisted in 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.

Figure 2. Standard design of European emergency exit sign

These are only approximations, but are derived from previous estimates [Nilsson, 2009]. 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 [2009] consisted in participants facing the choice between 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*.

Table 3. Associations collected from the Nilsson's experiments [Nilsson, 2009].

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

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 [Nilsson, 2009].

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 %

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 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 [Xie, 2011]. 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 2.3.1 [Korhonen & Hostikka, 2008], developed by VTT Technical Research Centre of Finland together with NIST, the National Institute of Standards and Technology and 2) buildingEXODUS 4.1 [Galea, 2004, Filippidis et al., 2008] 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 [1995] 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 [Frantzich & Nilsson, 2003]. The incapacitation model is a simplified version of the FED concept introduced by Purser [2008].

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 [Purser, 2008]. 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 [1976]. 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 Trädskolevägen tunnel

The Trädskolevägen 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, 80m in length and 2) a horizontal section, also 80 m in length.

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

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 $1m^{-1}$. 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 emergency exit. The agent is assumed to move off immediately;

i.e. there is no pre-evacuation time.

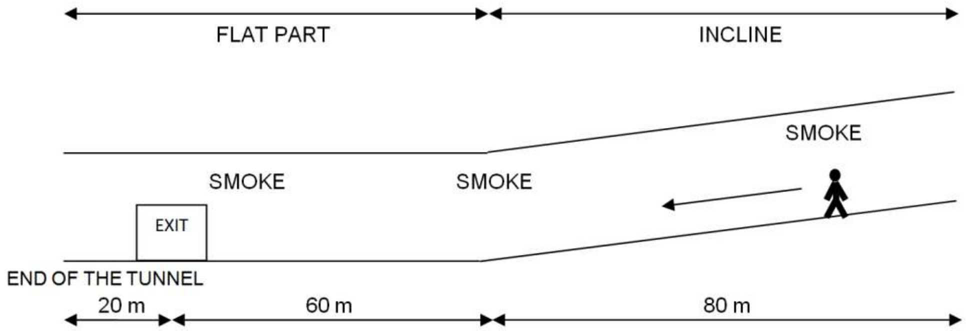

Figure 3. Schematic representation of the evacuation process. The agent has to evacuate through either the emergency exit or through the end of the tunnel.

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.

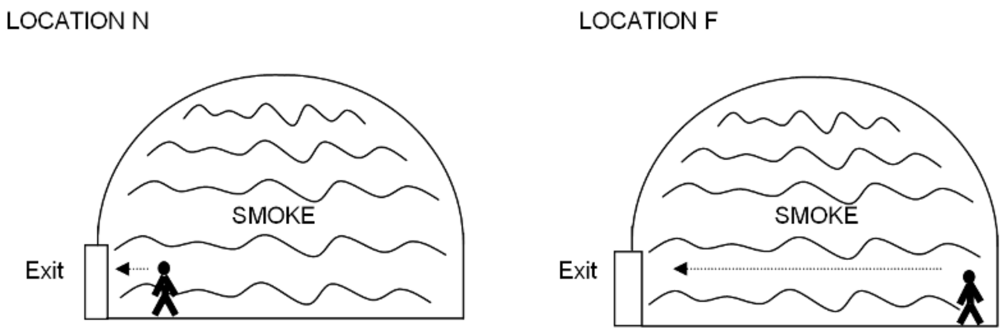

Figure 4. Initial Position of the agents in the cross section of the tunnel.

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.

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

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

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

Table 7. Imposed values of emergency exit use for the Approach A both for FDS+Evac and buildingEXODUS.

Scenario	Likelihood of People Using Signage Information.
1.N	50 %
1.F	0 %
2.N	90 %
2.F	70 %
3.N	90 %
3.F	60 %

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 [1976] and Mulholland, [2008]). 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 Table 4 and Table 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 [Korhonen & Hostikka, 2010]). The agent’s speed is automatically modified by the model when they encounter smoke, based on the Frantzich and Nilsson's experimental data-set [Frantzich & Nilsson, 2003].

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 1.5m/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 [Kumm, 2010]. 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 [Jin, 1976]. 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 [Gwynne et al., 2001]. Crawling is also represented within buildingEXODUS [Galea, 2004]. However, this was disabled during this analysis.

6.1.2 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.

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 [Sime, 1985, Frantzich & Nilsson, 2003]. The individual walking speeds and the smoke influence was assumed to be same as that adopted in Approach A.

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 [BS, 1999, BS, 2000, NFPA, 2010], producing visibility ranges of 13.2m, 6.6m and 30m 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 [Xie, 2007, Xie et al., 2009].

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 1.35m/s.

6.1.3 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.

FDS+Evac. This approach uses the experimental data described in Section 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 /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:

$$V_g = \frac{KS_n}{K} - \frac{KS_{ls}}{K} \quad \text{[Eq. 2]}$$

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 15m 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).

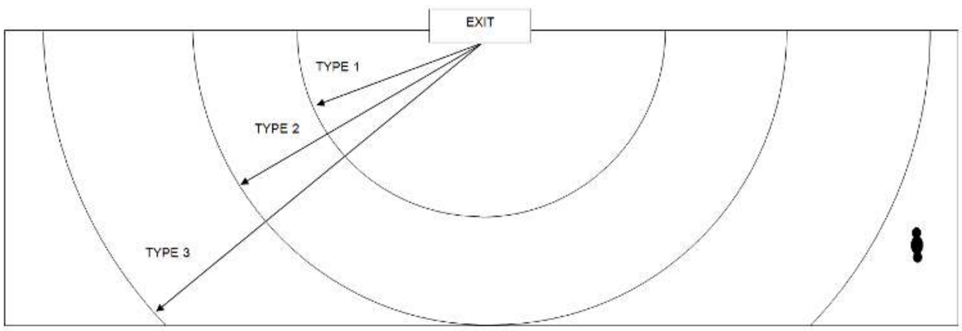

Figure 5. Approximation of the visibility catchment areas inserted in FDS+Evac by scaling soot densities for the three types of sign.

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 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 [Frantzich & Nilsson, 2003]) employed within FDS+Evac. Walking speeds are increased in the incline by 10% accordingly with Kumm [2010].

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 Table 4 and Table 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 Table 4 and Table 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

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.

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

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 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.

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

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

7.2 Approach B

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 Table 4 and Table 7.

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

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 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).

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

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

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 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.

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

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.

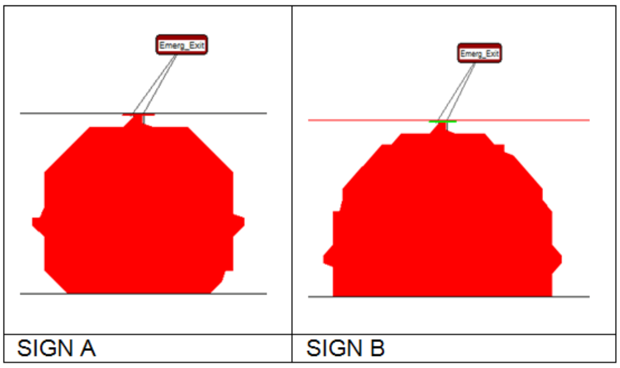

Figure 6. Example visibility catchment areas calculated by buildingEXODUS.

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 determined 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.

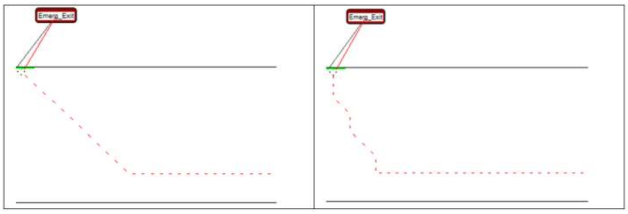

Figure 7. Routes adopted given starting location.

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 [Gwynne et al., 2001, Jin, 1976]).

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

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 configured 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 produced permitted to identify the impact of the modeller's expertise on model results, i.e., whether he/she uses default settings or an implicit or explicit calibration of the model input. Results will also permit to compare the embedded sub-algorithms in 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.

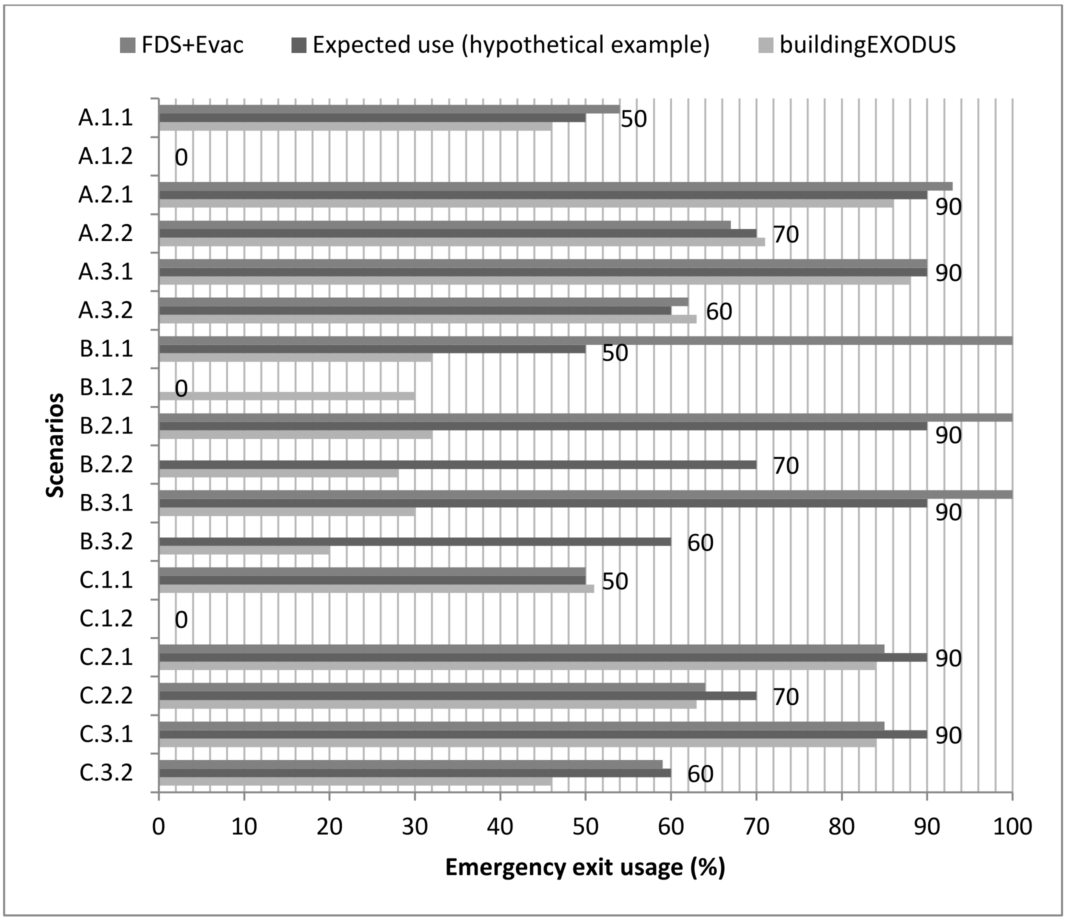

Figure 8. Summary of emergency exit usage. The labels show the expected use.

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 different types of emergency exit signs. 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) data-sets 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 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.

Table 14. Summary of Simulated Evacuation Times.

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

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 produced comparable results when suitably configured. However, the configurations of the models when explicitly represent agent-sign interaction for the benchmark case examined took time, detailed information and user expertise. These resources may not always be available in all cases, although where they were 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 model 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 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 configuration of the two models input will be useful for future engineering applications in tunnels.

This work 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.

Acknowledgments
Enrico Ronchi thanks the Lerici foundation as his grant-giving institution during this research work at Lund University. Enrico Ronchi also thanks Timo Korhonen from VTT for his valuable help in the use of FDS+Evac.

References

Beeson S & Mayer JW (2008). Patterns of light - Chasing the spectrum from Aristotle to LEDs. Springer, New York.

BS 5499-4:2000, Safety signs, including fire safety signs. Code of practice for escape route signing.

BS 5266-7:1999, Lighting applications. Emergency lighting.

Carvel R & Marlair G (2011). A history of fire incidents in tunnels. In A. Beard & R. Carvel (Eds.), Handbook of Tunnel Fire Safety (Second ed., pp. 3-23). London: Thomas Telford.

Cleary TG. (2004). Video detection and Monitornig of Smoke Conditions. In International Conference on Automatic Fire Detection "AUBE '04", 13th Proceedings.

University of Duisburg. [Internationale Konferenz uber Automatischen Brandentdeckung.] September 14-16, 2004, Duisburg, Germany, Luck, H.; Laws, P.; Willms, I., Editor(s), pp 681-690,.

Convention on Road Signs And Signals (1968), done At Vienna On 8 November, United Nations.

Council Directive (EC) (2004) 2004/54/EC of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.

Filippidis L, Lawrence P, Galea ER, Blackshields D (2009) Simulating the Interaction of Occupants with Signage systems. In Proceedings of 9th IAFSS Symposium Karlsruhe, Germany, 2008, pp. 389-400.

Filippidis L, Galea ER, Gwynne SMV, Lawrence PJ (2008). Representing the Influence of Signage on Evacuation Behavior within an Evacuation Model. Journal of Fire Protection Engineering vol. 16 no. 1 pp. 37-73

Frantzich H & Nilsson D (2003). Utrymning genom tät rök: beteende och förflyttning [Evacuation in dense smoke: behaviour and movement] (No. 3126). Lund: Department of Fire Safety Engineering and Systems Safety.

Fridolf K, Nilsson D, Frantzich H (2011). Fire Evacuation in Underground Transportation Systems: A Review of Accidents and Empirical Research. Fire Technology.

Galea ER, Gwynne SMV, Lawrence PJ, Filippidis L, Blackshields D, Cooney D (2004). buildingEXODUS V4.0 User Guide and Technical Manual. University of Greenwich.

Gandit M, Kouabenan DR, Caroly S (2009). Road-tunnel fires: Risk perception and management strategies among users. Safety Science, 47(1), pp. 105-114.

Gibson JJ (1978). The ecological approach to visual perception. Boston: Houghton Mifflin Company.

Gwynne SMV, Galea, ER, Lawrence PJ, Filippidis, L, (2001) Simulating occupant interaction with smoke using buildingEXODUS. Proceedings of the 2nd International Symposium Human Behaviour in Fire, Boston, USA, 2001, pp 101-110.

Gwynne SMV & Kuligowski E (2010). The faults with default. In Proceedings of the Conference Interflam2010, Interscience Communications Ltd: London. pp. 1473-1478.

Gwynne SMV, Galea ER, Owen M, Lawrence PJ, Filippidis L (1999). A Review of the methodologies used in the computer simulation of evacuation from the built environment. Building and Environment, 34(6), pp.741-749.

Hartson, HR (2003). Cognitive, physical, sensory, and functional affordances in interaction design. Behav. & Inf. Technology, 22(5), 315-338.

Helbing D, Molnar P (1995). Social force model for pedestrian dynamics, Physical Review E 51, pp. 4282–4286.

Jin T (1976). Visibility through Fire Smoke: Report of Fire Research Institute of Japan 2, 33, pp. 12-18.

Korhonen T & Hostikka S (2010). Fire Dynamics Simulator with Evacuation: FDS+Evac Technical Reference and User's Guide. FDS 5.5.3, Evac 2.3.1. VTT working papers.

Krishnan SS, Lin KC, Faeth GM (2001). Extinction and scattering properties of soot emitted from buoyant turbulent diffusion flames. Journal of Heat Transfer, 123(2), pp. 331-339.

Kuligowski E. (2011) Terror defeated: Occupant sensemaking, decision-making and protective action in the 2001 World Trade Center Disaster. Dissertation, University of Colorado, US.

Kuligowski ED, Peacock RD, Hoskins BL, (2010) A Review of Building Evacuation Models NIST, Fire Research Division. 2nd edition. Technical Note 1680 Washington, US.

Kumm M (2010). Räddningstjänstens förflyttningshastighet under mark: – en förstudie om slangdragning i olika undermarksmiljöer, [Emergency services movement speed - a preliminary study in various underground environments – in Swedish] Mälardalen University.

Lindell M, Perry R (2004), Risk Communication In Multiethnic Communities. Thousand Oaks, CA: Sage Publications, Inc.

NFPA 502 (2011) Standard for Road Tunnels, Bridges and Other Limited Access Highways.

NFPA101 Life Safety Code (2012)

Nilsson D (2009) Exit Choice In Fire Emergencies - Influencing Choice Of Exit With Flashing Lights. Dissertation, Lund University.

Purser D, (2009) Application of human behaviour and toxic hazard analysis to the validation of CFD modelling for the Mont Blanc Tunnel fire incident, In Proceedings of the Fire Protection and Life Safety In Buildings and Transportation Systems Workshop, Santander pp 23-57.

Purser D.A., (2008). Assessment of Hazards to Occupants from smoke, toxic gases and heat. In the SFPE Handbook of Fire Protection Engineering (Fourth Edition). National Fire Protection Association, Quincy MA, USA.

Rasbash, D. J. (1951). The Efficience of Hand Lamps in Smoke. IFE Journal , 11 (1), p. 46.

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2010). Human behaviour in road tunnel fires: Comparison between egress models (FDS+Evac, STEPS, Pathfinder). In Proceedings of the twelfth international Interflam 2010 Conference, Nottingham, UK, pp- 837-848.

Shields J (2005) Human behaviour in tunnel fires. In: Beard A, Carvel R (eds) The handbook of tunnel fire safety Thomas Telford Publishing, London

Sime J (1985) Movement toward the familiar—person and place affiliation in a fire entrapment setting. Environmental Behaviour

Xie Hui (2011) Investigation into the Interaction of People with Signage Systems and its Implementation within Evacuation Models. Phd Dissertation, University of Greenwich, UK.

Xie H, Filippidis L, Galea ER, Blackshields D, Lawrence PJ. Experimental Study of the Effectiveness of Emergency Signage. In Proceedings of the 4th International Symposium on Human Behaviour in Fire, Robinson College, Cambridge, UK, 13-15 July 2009, pp. 289-300.

Xie H, Filippidis L, Gwynne SMV, Galea ER, Blackshields D, Lawrence P (2007) Signage legibility distances as a function of observation angle. Journal of Fire Protection Engineering, vol. 17.

Zhang Q, Rubini, PA (2011) Modelling of light extinction by soot particles. Fire Safety Journal vol. 46

Zhang Q, (2010) Image based analysis of visibility in smoke laden environments. Dissertation at the University of Hull, UK.

Mulholland GW (2008) Smoke Production and Properties. In the SFPE Handbook of Fire Protection Engineering (Fourth Edition). National Fire Protection Association, Quincy MA, USA.

Wickens CD & Hollands JG (2000). Engineering psychology and human performance (3rd ed.). Upper Saddle River: Prentice Hall.

PAPER V

MOVEMENT SPEED AND EXIT CHOICE IN SMOKE-FILLED RAIL TUNNELS

FRIDOLF, K.[1], RONCHI, E.[2], NILSSON, D.[1], FRANTZICH, H.[1]

[1] *Department of Roads and Transportation. Polytechnic University of Bari, Via Orabona 4, 70100 Bari (BA), Italy*
[2] *Department of Fire Safety Engineering and Systems Safety Lund University Box 118, S-221 00 Lund, Sweden*

ABSTRACT

An evacuation experiment including 100 individuals was performed inside a tunnel in order to study the effectiveness of different way-finding installations and to collect data on movement speeds and human behaviour. The participants took part in the experiment individually, and no group interactions were studied. The experiment tunnel was 200 meters long and an emergency exit was located 180 meters into the tunnel. In addition, emergency signs including distances to nearest exits were located every eight meters on both sides of the tunnel. The tunnel was filled with artificial smoke and acetic acid, which produced a mean light extinction coefficient of 2.2 m^{-1}. Participants had been told that they would participate in an evacuation experiment, but they had not been informed about the layout of the tunnel or the technical installations. The average movement speed was found to be approximately 0.9 m/s, independent of tunnel floor material. The experiment also demonstrated the importance of the emergency exit design. A loudspeaker, which provided people with an alarm signal and a pre-recorded voice message, was found to perform particular well in terms of attracting people to the exit, independent of which side of the tunnel the participants were following.

Keywords. evacuation experiment, smoke filled tunnel, underground rail transportation systems, movement speed, modelling speed, movement pattern, walking path, exit choice, emergency sign, human behaviour.

Introduction

The severe consequences of fires in underground rail transportation systems, such as the Baku subway fire of 1995 [Carvel & Marlair, 2011, Rohlén & Wahlström, 1996] and the Kaprun funicular fire of 2000 [Carvel & Marlair, 2011, Larsson, 2004, Schupfer, 2001], have led the scientific community to investigate people's behaviours and evaluate the best design solutions in order to reduce the time to reach a safe place. Tunnels represent an environment that is not familiar to most people, and staff is not immediately on site to provide help. For these reasons, more and more studies are focusing on improving the means of egress and on learning more about the behaviour of tunnel users in evacuation situations [Nilsson, 2009, Purser, 2009, Ronchi et al., 2010, Galea & Gwynne, 2000, Oswald et al., 2005, Oswald et al., 2008, Oswald et al., 2011, Proulx & Sime, 1991, Fridolf et al., 2011]. In the present paper, the main focus is evacuation in underground rail transportation systems. However, much of what is presented can also be applied to other underground transportation systems, e.g., road tunnels.

A key aspect during evacuation in underground rail transportation systems is the impact of the smoke on human behaviour and performance; people may need to change their initial choice of exit and/or perform different types of behaviour, e.g., reduce their speed or crawl. The current literature on movement speeds includes two main experimental data sets based on experiments by Jin [1976, 1978] and Frantzich and Nilsson [2003, 2004], which provide two different correlations on the relation between visibility, i.e., extinction coefficient, and movement speed. The results illustrate that the movement speed decreases with increasing extinction coefficient. Jin's [1976, 1978] study included investigations of both irritant and non irritant smoke, providing speeds between 0.3-1 m/s for irritant smoke and 0.5-1 m/s for non-irritant smoke. In case of irritant smoke, people were not able to keep their eyes open, which caused them to walk in zigzag paths or use the wall as an aid. The minimum observed movement speed of 0.3 m/s corresponds to the walking speed in complete darkness. Movement during conditions with a broader range of extinction coefficients was investigated in experiments by Frantzich and Nilsson [2003, 2004], and the obtained movement speed range was approximately 0.2-0.8 m/s. In both experiments the wall was found to be of great importance to the participants, who used it as an aid during the evacuation.

In accordance with the affiliative theory [Sime, 1984], people tend to evacuate towards places or people of familiarity. In the case of rail tunnels, this is reflected in the likelihood of people that will try to evacuate via a familiar place, e.g., the tunnel entrance or exit, even if they are in the middle of the tunnel. A questionnaire study by Gandit et al. [2009] highlights that although many users know about emergency exits, many of the same people will not use them, i.e., emergency exits may be considered even more deterring than the tunnel itself [Nilsson et al., 2009]. Accident reports [Duffé & Marec, 1999, Fridolf et al. 2011] also confirm this statement. The ineffective use of emergency exits may cause prolonged evacuation times and could lead to tragic consequences due to the rapid development of untenable conditions in these types of facilities [Gandit et al., 2009].

In order to improve people's ability to orient themselves in smoke-filled environments different solutions can be applied [Hartson, 2003, Kuligowski, 2011]. Signage can for example be used to impact exit choice [Nilsson, 2009, Filippidis et al., 2008, Xie et al., 2009]. The influence of signage on exit choice is dependent on different factors [Nilsson, 2009], which includes whether the sign is visible or not, given the visibility conditions and the sign design, and the cognitive processes that affect the evacuees' to notice, understand and use the information provided by the signage [Xie, 2011].

Way-finding systems are an alternative measure to make evacuation from underground rail transportation systems easier, and many experiments have been performed to test the performance of different systems [Nilsson, 2009, Proulx & Sime, 1991, Heskestad, 1999, Jin & Yamada, 1994, Paulsen, 1994, Rasbash, 1951]. For example, Nilsson [2009] performed evacuation experiments on the use of green flashing lights, demonstrating the effectiveness of green to attract attention to the sign which informs people about the exit. Furthermore, Boer and Veldhuijzen van Zanten [2005], Nilsson [2009], and Proulx & Sime [1991] describe how the passivity of tunnel users can be overcome through the use of vocal messages by the tunnel operator. In particular, their studies focused on the type of instructions that should be given to evacuees. They concluded that people reacting to a clear announcement spent less time hesitating than those reacting before the announcement was made. Also, if an informative message were given rapidly, the evacuation process was faster.

The discussion above demonstrates that a fire in an underground rail transportation system can result in devastating consequences in terms of loss of life. But the experimental studies discussed above also show that there are means of reducing the total evacuation time in underground rail transportation systems. However, much of the data are associated with great uncertainties, which evidently is due to the intrinsic variability in human responses. Further experimental data appear then necessary in order to increase the knowledge on evacuation behaviours and responses in underground rail transportation systems. In addition, there is a need to explore variables that were only partially investigated in previous studies, e.g., the influence of different floor surfaces on occupants' movement speed, the impact of different inclinations on movement speeds and different emergency exit designs.

In order to address the above-mentioned issues an evacuation experiment was performed in a smoke-filled tunnel. The choice of research strategy was dictated by the main objectives of the experiment, which were:

1. To study the effectiveness of different way-finding systems in a smoke-filled tunnel
2. To collect data on human performance and movement speeds in a smoke-filled tunnel, focusing on the different variables affecting the movement, e.g., floor inclination and surface materials

Method

On May 30-31 and June 1 2011 an evacuation experiment was performed in Stockholm, Sweden. The experiment was performed in a single bore tunnel that previously had been used in the construction of a road tunnel in Stockholm, namely the Southern link (Södra länken). The tunnel was provided with technical installations typical for rail tunnels. However, there were no rail tracks inside the tunnel. In the following sections the participants, the layout of the experiment, the procedure, the scenarios, the data collection and the analysis of the experiment are described.

Participants

A total of one hundred participants were recruited among the general public and among employees at the Traffic Administration Office in Stockholm. The means of recruitment and participants' characteristics are presented in the following sections.

Recruitment

Two months before the experiment, information about the study was published on an online portal, used by researchers who want to get in contact with potential test participants for their studies. Anyone that was interested in participated in the experiment could apply online. The information included a description of the experiment, i.e., that the participants were going to walk through a realistic tunnel in dense artificial smoke, that acetic acid would be used to create an irritating environment, that the participants would undergo a questionnaire study related to the experiment, and that some of the participants would be interviewed. The information also included formal details on the location and the dates of the experiment, compensation for participation and the duration of the experiment. No information was given on the tunnel features, e.g., the tunnel layout, emergency exits or other technical installations.

Participants were recruited from the general public and among employees at the Traffic Administration Office in Stockholm. Both groups received the exact same information about the experiment, but the employees at the Traffic Administration Office in Stockholm applied by sending an email to the researcher in charge of the experiment instead of applying online. In order to exclude sensitive individuals, each person that had applied for the experiment had to undergo a so-called Hospital Anxiety and Depression (HAD) test [Zigmond & Snaith, 1983]. This was done 2-3 weeks before the experiment and only persons that received a score of less than eight for both anxiety and depression were included in the experiment. In addition, persons who were younger than 18 years, had asthmatic health problems or were active within the field of fire safety, e.g., as fire protection engineers or fire fighters, were not allowed to take part in the experiment. The persons that were selected for the experiment received additional information after having passed the HAD test, which was distributed at latest a week before their participation. The information included details on the procedure, risks, benefits, treatment of data, publication of results, casualty insurance and the researcher in charge of the experiment.

The terms of insurance during, and compensation after, the experiment varied between the members of the general public and the employees at the Traffic Administration Office in Stockholm. Employees at the Traffic Administration Office in Stockholm participated during working hours as a part of their fire safety training and were therefore insured and compensated by their employer. In contrast, participants from the general public were covered by a casualty insurance administered by Lund University and were compensated with 300 SEK (approximately €34) for their participation.

Participant characteristics

A total of one hundred persons participated in the experiment, namely 56 men and 44 women. The age ranged from 18 to 66 years, with an average age of 29.4 years. The height of the participants varied from 153 to 198 cm, with an average of 175 cm. See Table 1 for a detailed summary. Eighty-three of the participants reported that they were right-handed and consequently 17 of the test participants were left-handed.

Table 1. A summary of the participants' age and height.

	Mean	Min	Max	Std.
Age [years]	29.4	18	66	10.3
Height [cm]	175.1	153	198	9.4

The majority of the participants, namely 89 persons, said that they used the Metro once, or more than once, every week, see Table 2. Thus, it was concluded that the majority of the participants had knowledge and experience of travelling with the Metro. Thirteen of the participants reported that they had received information on what to do in a fire in the Stockholm Metro on at least one occasion. Most of them had read the emergency information posters in the trains or at the Metro stations, some reported having seen the emergency evacuation signs above the train doors in the trains and one person even reported having seen "emergency stuff" inside the tunnel at one occasion when the train he was travelling in had been moving slowly.

Table 2. A summary of the participants' travelling frequency.

Travel frequency	Participants [no.]
Several times per week	78
About one time per week	11
About one time per month	10
Less than one time per month	1
	100

A rather high proportion of the participants, namely 22 persons, stated that they had walked on the tracks inside a Metro or a rail tunnel on at least one occasion. The most common reason was work or education related, some mentioned it had been to obtain dropped belongings, e.g., a cell phone, and some said they had been "young and stupid" when they had done so. Considering the answers it seemed as only a few had been walking longer distances on the tracks, and also that the time elapsed since they had done so was long. Two persons reported that they had participated in a real evacuation in the Stockholm Metro before the evacuation experiment. Both persons had evacuated from a station platform due to fire, thus not from a train inside a tunnel similar to the evacuation experiment, but neither of the persons had actually seen the fire or the smoke.

Experiment setup

The experiment was carried out in a single bore tunnel in Stockholm. The tunnel was equipped with emergency signs and an emergency exit, and during the experiments the tunnel was filled with artificial smoke and acetic acid fumes. In the following sections the tunnel layout, the technical installations and the smoke properties in terms of visibility and concentration levels are presented.

Tunnel layout

The evacuation experiment was carried out in a single bore tunnel in Stockholm previously used in the construction of a road tunnel in Stockholm, namely the Southern link (Södra länken). Due to the fact that the end of the tunnel was closed when the Southern link was taken into operation, the only way in and out of the experiment tunnel was the tunnel entrance, see Figure 1. The experiment tunnel was at the time of the experiment not used for traffic, but occasionally the Greater Stockholm Fire Brigade used the tunnel for fire-fighting exercises. The total length of the tunnel was approximately 300 meters, but during the experiments only the first part of 200 meters was used.

The tunnel included two segments: one part (a) of 122 meters with an inclination of 10%, and one part (b) of 76 meters with no inclination, see Figure 1. Generally, the floor surface was smooth and consisted of compact gravel. However, in order to enable an analysis of movement speeds on different materials, one part (c) measuring approximately 32 meters long and 1.5 meters wide, was covered with macadam of size 32-64 millimetres about 150 meters into the tunnel, commonly used in rail tunnels. The tunnel width was about 8 meters.

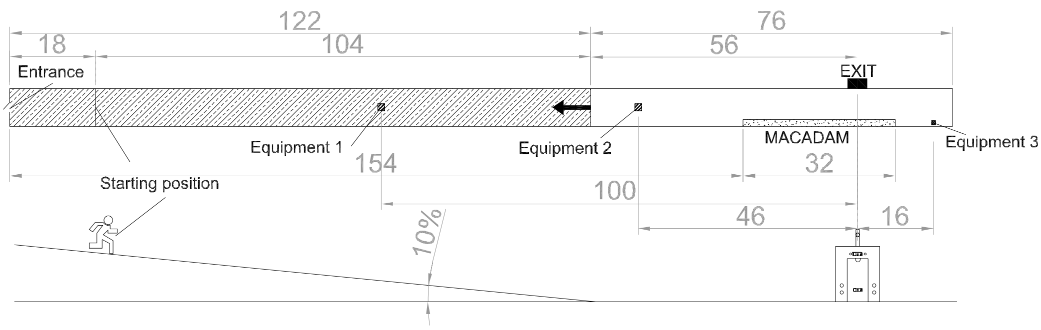

Figure 1. A schematic top (above) and side view (below) of the tunnel geometry.

Technical installations

Emergency signs were installed every eight meters on both sides of the tunnel at a height of about one meter, see Figure 2. The signs were models of the emergency signage used in the Stockholm Metro and provided information on distances to the nearest exits as well as a source of light. During normal conditions, i.e., without the presence of smoke and other light sources, the light intensity from the emergency signs corresponded to 1 lux, measured at ground level at equal distance between two signs

[European Commission, 2008]. Apart from the emergency signs, no other illumination was provided inside the tunnel during the experiment.

Figure 2. A picture of the emergency sign installed every eight meters inside the tunnel.

One hundred eighty meters into the tunnel, an emergency exit was installed on the left side of the direction of travel, marked EXIT in Figure 1. The emergency exit design is shown in Figure 3 and Figure 4. The door represented the only exit inside the tunnel and was equipped with a number of way-finding installations, which were combined in order to study their effectiveness in terms of attracting people to the door. The six types of installations are numbered in Figure 3 and are described in Table 3.

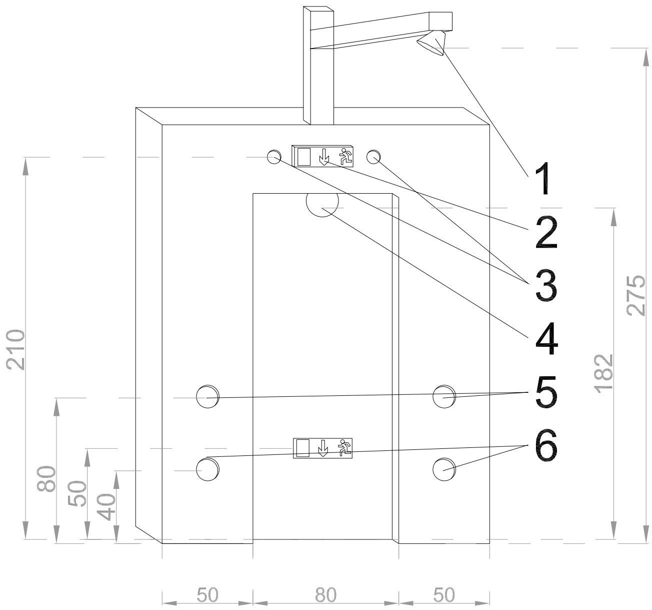

Figure 3. A schematic drawing of the emergency exit inside the tunnel (measurements in centimetres).

Figure 4. A picture of the emergency exit inside the tunnel.

Table 3. A description of the different way-finding installations on the emergency exit.

Installation	Description
1. Halogen lamp	A white halogen lamp of 500 W installed above and directed towards the door. Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 556 lux, measured 22 cm from the lamp.
2. Emergency exit sign	Standard backlit European emergency exit sign.
3. Green flashing lights	Green flashing lights, which consisted of two green light bulbs, installed on each side of the emergency exit sign above the door. The lights flashed with a frequency of approximately 1 Hz, i.e., one flash per second.
4. Loudspeaker	Loudspeaker installed on the upper centre part of the door enabling an alarm signal and a pre-recorded voice message to be broadcasted. The alarm signal consisted of an increasing signal, which was repeated three times within 1.5 seconds [ISO, 1987]. The frequency range was 800-970 Hz. The alarm signal was repeated twice before the pre-recorded voice message; a computer generated female voice that said (translated from Swedish): *The sound is coming from an exit. Follow the sound in order to get out.* The alarm signal and voice message could be heard approximately 25 meters from the door.
5. Green lights	Green light bulbs installed on each side of the door on the lower part of the frame. Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 11 lux, measured 20 cm from the bulb.
6. White lights	White light bulbs installed on each side of the door on the lower part of the frame. Light intensity during normal conditions without the presence of smoke and other light sources corresponded to 63 lux, measured 20 cm from the bulb.

Artificial smoke and acetic acid

In order to create an environment that was as realistic as possible, but without putting the participants' health into danger, the tunnel was filled with both artificial cold smoke and acetic acid during the experiment. Two smoke machines, which were located at the end of the tunnel (equipment 3 in Figure 1), produced the smoke using a mixture of polyglycole and distilled water. In addition, acetic acid was boiled in pots located in the beginning and the end of the tunnel. The smoke and the acetic acid were evenly distributed inside the tunnel during the experiment by a fan, which was turned off when there was a participant inside the tunnel.

Measurements of the light extinction coefficient were made with a device that consisted of a light source and a receiver, which were fixed 1 meter apart in a steel frame. The light source was a laser diode and emitted light with the mean wavelength of 670 nm, and the receiver was a photodiode with a peak sensitivity wavelength of 710 nm. The measurements were made at two locations inside the tunnel, namely equipment 1 and 2 in Figure 1, at a height of about 1.5 meters. In the present study the light extinction coefficient was calculated according to Equation 1, where I was the intensity of the light as it had passed through path length L of smoke and I_0 was the intensity without any smoke present. Measurements of the acetic acid were made manually with an accuro Gas Detection Pump, manufactured by Dräger. As for the smoke density measurements the gas measurements were made at different locations inside the tunnel.

$$D_L = -\frac{1}{L}\ln\left(\frac{I}{I_0}\right) \qquad \text{[Eq. 1]}$$

The mean light extinction coefficient during the experiments was 2.2 m^{-1}, with a standard deviation of 0.54 m^{-1}. This can be translated into a mean visibility of about 1.4 meters for reflecting signs, and 3.4 meters for light-emitting signs [Jin, 2008]. The mean gas concentration of acetic acid was 4 ppm during the experiments, thus, well below the Swedish Work Environment Authority's recommended level of short time exposure, i.e., 10 ppm for 15 minutes [Swedish Work Environment Authority, 2005].

Procedure

At the days of the experiment the participants arrived in groups of about ten people. The actual evacuation inside the tunnel was, however, performed individually and the evacuation scenario was determined by the activated way-finding installations on the emergency exit, described above, and the initial starting position inside the tunnel. In the following sections the sequence of events at the days of the experiment, the scenarios, the data collection, and the analysis are presented.

Sequence of events

The experiment was carried out on May 30-31 and June 1 2011. It was divided into three-hour periods, and at the beginning each period a group of about ten people arrived at the site of the experiment. At their arrival the participants were led into a parked bus in close vicinity to the tunnel entrance, which served as a gathering point during the whole experiment. The responsible researcher began by welcoming the participants and briefed them about the experiment and the safety procedures. The same information had been mailed to the participants a couple of weeks before the experiment and was merely a repetition.

The experiment was carried out with one participant at a time, and no group interactions were studied. Having received the instructions inside the bus the participants were selected one by one for the experiment, which began with the participant being led out of the bus and provided with protective clothes, more specifically, an overall, boots, gloves and a helmet. The participant was then led to the tunnel entrance where he or she was shown a short video film from the Stockholm Metro. The film, which was shown in a first person perspective, illustrated a person travelling in a train that eventually came to a stop inside a tunnel. When the film ended the participant was led into the tunnel and told to imagine that it was he or she in the video, and that he or she should find a way to safety.

A fire fighter was always present inside the tunnel to film the evacuation or to assist the participant if he or she signalled for help. However, due to the dense smoke inside the tunnel the fire fighter could not be seen by the participant during the experiment. When the participant entered the tunnel the fire fighter led him or her to the first emergency sign of the tunnel. The participant was left approximately 2-3 meters in front of the sign, and then told to initiate evacuation. Whether the participant was left on the right or left side of the tunnel was dependent on the scenario, see Table 4. On the first sign the distances 160 and 268 meters to the closest exit was printed, see Figure 2. Note that the distance of 268 meters, which pointed towards the tunnel entrance, was hypothetical, and only a way of encouraging participants to move into the tunnel.

The experiment ended when the participant either had found the emergency exit located inside the tunnel, or when the participant had walked past the emergency exit and reached the end of the tunnel. When the experiment had ended, the participant was led out of the tunnel by a fire fighter and returned to the bus where he or she answered a questionnaire about the experiment. Some participants also took part in an interview about the experiment after the questionnaire study. Note that each participant only participated in the experiment once, i.e., each participant only took part in one evacuation. The reason was to avoid learning effects in terms of familiarity with the environment, location of exits and walking in smoke.

Scenarios

The way-finding installations on the emergency exit were combined to give five experiment scenarios. In addition, the initial position of the participants inside the tunnel was varied for each scenario, i.e., the participants either started the evacuation on the same side of the tunnel as the emergency exit (A) or on the opposite side (B), see Figure 5. A summary of the number of participants in each scenario is presented in Table 4, and the number describing the way-finding installations in each scenario is referring to Figure 5 and Table 3.

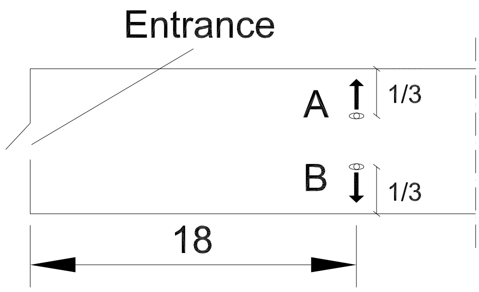

Figure 5. Initial location of the participants inside the tunnel.

Table 4. The experiment scenarios and number of participants for each scenario.

Scenario	Way-finding installations	Initial location	Number of participants
1	2	A	12
		B	12
2	2, 3	A	10
		B	10
3	1, 2, 5, 6	A	10
		B	16
4	2, 4	A	10
		B	14
5	1, 2, 3, 5, 6	A	1
		B	5

Data collection

In order to enable an analysis of movement speeds, walking strategies, exit choice and other human behaviour activities, each evacuation was documented with a thermal imaging camera, namely a MSA Evolution 5600. The videos were recorded onto a memory card and transferred to a computer after each evacuation. A fire fighter managed the documentation by following the participants at a distance of 5-10 meters throughout the evacuation, enough not to be seen in the dark and smoke filled tunnel.

As a complement to the video recordings each participant had to fill out a questionnaire after the experiment. The questionnaire consisted of 26 questions, some of which were divided into sub questions, and included both closed ended questions, i.e., yes/no, multiple choice or scaled questions, and open ended questions, i.e., questions were the participants were asked to write freely. The questionnaire was divided into four parts and the first part included questions related to general information about the participant, e.g., gender, age and previous experience. The second part included questions related to the experiment and the participant's behaviour during the experiment, e.g., the degree of realism and the method used for orientation. The third part of the questionnaire included questions about technical installations and the perceived benefit of different installations. Finally, the fourth part of the questionnaire included questions related to the participant's feelings during the experiment, e.g., physical and psychological feelings. Care was taken during the formulation of the questions to make sure that the topic had been clearly defined, that the questions were relevant for the purpose of the study, that the questions were not biased and that the risk of misinterpretation was minimal. For this purpose, the framework suggested by Foddy [1993] was adopted.

To furthermore strengthen the reliability of the study, some participants were also asked to take part in an interview study. The interviews were semi-structured, meaning that the questions could be changed or adapted to the participant. Furthermore, the order of the questions was not fixed. In the interviews the participants were shown the video recording of their evacuation and asked to explain their behaviour and thoughts during different sequences of the evacuation. The interviews were recorded and were always performed after the participant had handed in the questionnaire.

Analysis

The video recordings were analysed with the aim to reconstruct the evacuation paths of each participant, and finally to calculate the movement speed and document the exit choice of each participant. This was made by taking into consideration different factors contributing to the estimation of each participant's position during the passage of time, including (1) the position of the fire fighter filming each evacuation, i.e., the recording angle, and (2) the position of the participants in relation to the emergency signs, which could be seen on the thermal imaging camera due to the heat being generated by the lamps. In addition, if a participant changed his or her direction of travel, the position inside the tunnel was estimated by counting the number of steps made. The distance between a participant and the tunnel wall was used as additional information to estimate the participant's position inside the tunnel.

The above listed factors were used to draw the walking path of each participant in a CAD format. The CAD drawings were then used to reconstruct the movement pattern of each participant, i.e., the position of the participant inside the tunnel during the evacuation. Furthermore, the drawings included information of every change of walking direction, behaviour, type of floor material and tunnel inclination. This information was coupled with the participant's behaviour, i.e., the CAD drawings also included information on when and where inside the tunnel the participant performed a certain action. Hence, the final drawing enabled a derivation of information about each participant's movement speed and position inside the tunnel as a function of time.

The video recordings were also used to document the behaviour of each participant, e.g., walking and way-finding behaviour, use of visual and tactile information, and positioning of the hands. The type of walking posture was derived by analysing the position of the body in comparison with the emergency signs. As the height of the emergency signs was known to be approximately one meter, it was possible to estimate the position of the different parts of each participant's body in comparison with the reference of one meter from the ground.

The questionnaire answers were reproduced in a large matrix and information relevant to the paper were statistically processed. Interviews were transcribed and read in order to find general trends.

Results

Data on experiences of the evacuation, movement speeds, movement patterns, and exit choice are presented in the following sections. The data is based on a combination of video observations, questionnaire answers and interview answers. Included quotes have been translated from Swedish. Due to an error, which occurred during one of the evacuations, only 99 of the 100 participants were included in the analysis of the video recordings. Furthermore, a technical problem that occurred in another of the evacuations permitted only half of the video recording to be analysed. All of the 100 participants took part in the questionnaire study, and 65 took part in the interview study.

Experiment experiences

In the questionnaire study the participants were asked about their experiences during the experiment. The majority of the questions were scaled, and the participants were for example instructed to express the perceived degree of realism in the experiment on a scale between 1 and 10. It is not believed that the participants answered the questions believing that "2" was twice as much as "1", and it is therefore argued that the scale of the questions is ordinal. Hence, the results presented in this section are presented in box-plots rather than with mean values plus/minus a standard deviation.

The boxplots included in the presentation below should be interpreted in the following way:

- The tops and bottoms of each box are the 25th and the 75th percentiles of the samples.
- The line inside each box is the sample median, i.e., the 50th percentile of each sample.
- The lines extending above and below each box are the whiskers, and represent the sample minimum and maximum, excluding the extreme values, i.e., the outliers.
- The distances between the tops and the bottoms of each box are the interquartile ranges.
- The "+" are the outliers, i.e., sample values more than 1.5 times the interquartile range away from the top or bottom of each box. In order to make duplicate "+" available, the points have been uniformly randomized along the factor axis for each group.

The participants were asked to describe the degree of realism of the experiment by comparing the experiment to a real fire in a similar environment, see the left boxplot in Figure 6. Alternative "1" corresponded to "not realistic" and alternative "10" corresponded to "very realistic". Seventy-five percent of the participants graded the experiment "5" or higher, which strengthens the validity of the results. Some of the participants who were interviewed gave recommendations for future studies in order to raise the degree of realism. The recommendations included adding dummies to simulate unconscious evacuees, and increase the concentration of acetic acid in the air to make the environment more irritating.

The greater majority of the participants were not worried that they would get hurt in the experiment, which is illustrated by the answers to the question "Were you worried that you would get hurt during the experiment?" in the questionnaire study. Alternative "1" corresponded to "No, not at all" and alternative "10" corresponded to "Yes, very much", and 91% of the participants answered "3" or lower, see Figure 6. However, some of the interviewed participants mentioned being afraid of stumbling or falling inside the tunnel, some of whom also related this to getting hurt.

Most participants believed that they would have been able to evacuate the tunnel successfully if it had been a real fire when they answered the question "Had this been a real fire, what would the chance be of you evacuating the tunnel successfully?". Alternative "1" corresponded to "very small and alternative "10" corresponded to "very high", and 80% answered "6" or higher, see Figure 6. Note that one participant failed to answer the question and was therefore not included in the analysis.

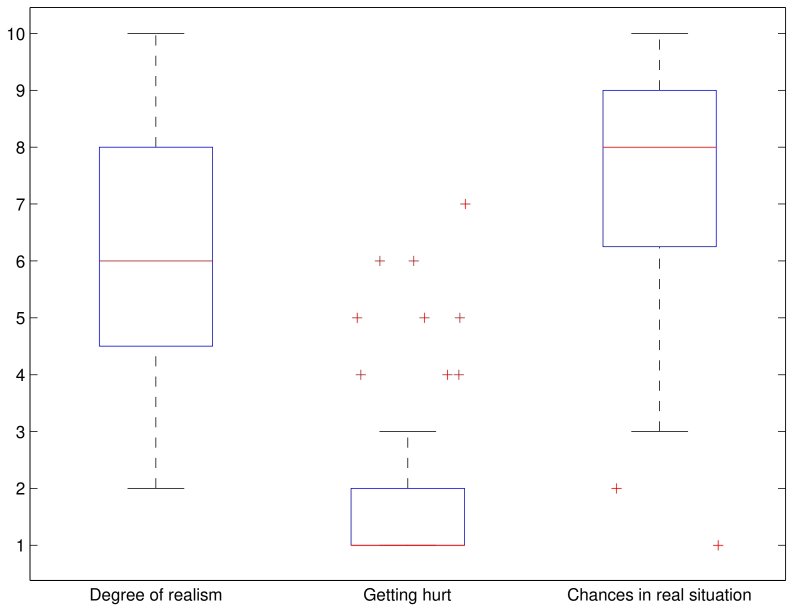

Figure 6. Answers to scaled questions in the questionnaire study.

The participants were in the questionnaire study also asked to estimate the perceived level of (1) uncertainty, (2) stress, (3) fear, (4) orientation problems, (5) physical discomfort in terms of nausea and (6) physical discomfort in terms of eye irritation during the experiment. Alternative "1" corresponded to "None" and alternative "10" corresponded to "High", and the result is presented in Figure 7. Considering the boxplots, the overall impression is that most participants felt neither uncertain, stressed, were afraid, had orientation problems or experienced a high level physical discomfort. Statements made by the participants in the interview study furthermore reinforce this interpretation. Some interview answers also suggest that the perception of these types of feelings decreased with the increased time spent inside the tunnel.

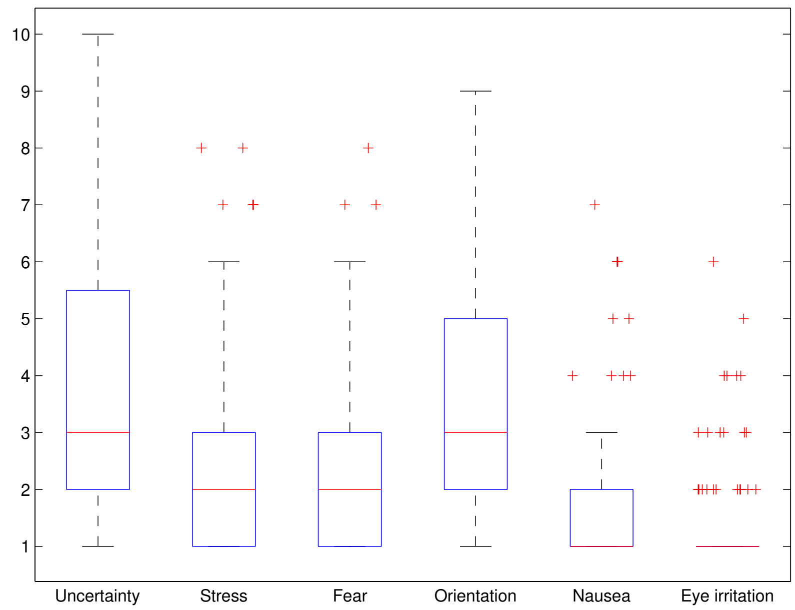

Figure 7. Answers to scaled questions in the questionnaire study.

Movement speeds

The video recordings of the evacuations were used to determine the movement speeds inside the smoke filled tunnel. A distinction has been made between movement speed and modelling speed. The movement speed was calculated for each participant by dividing the total distance walked in the tunnel by the time employed, i.e., the stops made by the participants were excluded in the analysis of the movement speed. The total distance walked is explained in Figure 8 as A-a1-a2-a3-a4-B. In contrast, the modelling speed was calculated for each participant by dividing the distance between two points inside the tunnel, i.e., A-B in Figure 8, by the total time, including the duration of the stops made during the evacuation.

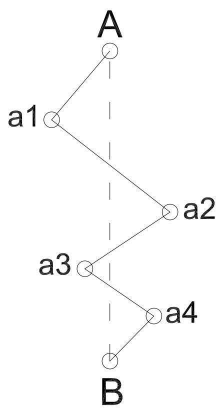

Figure 8. Difference between total distance walked by a participant (A-a1-a2-a3-a4-B), and the distance between two points inside the tunnel (A-B).

The movement and modelling speeds are presented in Table 5 and Table 6. The speeds are presented for the respectively parts of the tunnel, which are illustrated in Figure 1. All participants walked in the first part (a) of the tunnel, represented by a smooth floor material and an inclination of 10%. Also, all participants walked in the second part (b) of the tunnel, which consisted of a smooth floor material and no inclination. However, whether or not a participant walked on the third part (c) of the tunnel, which consisted of macadam and no inclination, depended on the initial position inside the tunnel at the beginning of the evacuation, and the participant's walking route.

Table 5. Movement speeds in different parts of the tunnel.

	Sample of participants [no.]	Movement speed [m/s]			
		Min	Max	Mean	Std.
Part A	99	0.42	1.42	0.91	0.23
Part B	98	0.51	1.45	0.91	0.22
Part C	52	0.50	1.82	0.94	0.29

Table 6. Modelling speeds in different parts of the tunnel.

	Sample of participants [no.]	Modelling speed [m/s]			
		Min	Max	Mean	Std.
Part A	99	0.41	1.42	0.90	0.24
Part B	98	0.50	1.45	0.91	0.22
Part C	51	0.45	1.82	0.92	0.29

The results presented in Table 5 and Table 6 imply that neither an inclination of 10% or an uneven floor material consisting of macadam have an impact on the movement speed. In fact, the movement speed was actually a bit higher on the macadam. Due to the small differences in the different parts of the tunnel it is hard to draw any far-reaching conclusions as to why. However, one possible explanation could be that learning effects may have been present, i.e., that the participants got used to the environment the longer they stayed inside the tunnel. Another explanation could be that the neither floor material nor inclination will determine the movement speed in a dark and smoke filled tunnel. The results also illustrate the small differences between movement and modelling speeds. This can be explained by the fact that only 25% participants actually stopped at some time during their evacuation, and that the average time stopped by a participant was short; 14 seconds (std. 14 seconds).

Movement patterns

The video recordings also enabled an analysis of the participants' movement patterns inside the tunnel. Previous studies have demonstrated the importance of the walls during evacuation in smoke filled tunnels [Fratzcih & Nilsson, 2004, Jin, 2008], and the same type of observations was made in the present study. Ninety-one percent of the participants followed one of the tunnel walls at least 75% of the total distance walked during the evacuation. One possible explanation of this behaviour could be to facilitate orientation inside the dark and smoke filled tunnel. This was mentioned by many of the interviewed participants, for example Participant 61, who in the interview said:

> *Yes, the visibility was minimal. You could at best see one to one and a half light forward [8-12 meter, author's comment]. And... My strategy was to stick to a wall, in order to be able to orient myself.*
>
> *Participant 61, 1 min 12 sec into the interview*

Another possible explanation for the participants' tendency to follow the tunnel walls is the emergency signs, see Figure 2, which were installed every eight meters. Ninety-six percent of the participants reported in the questionnaire study that they had seen the signs sometime during their evacuation, 82% said that they had seen the signs already in the beginning of the evacuation. Not only did the signs help the participants to orient themselves in the tunnel by showing the distances to the closest exits, but participants in the interview study also expressed that it was comforting to see the signs inside the tunnel. This is illustrated by a statement made by Participant 81 in one of the interviews:

[...] And I felt relieved to have something like that [the signs, author's comment]. Not to think about my situation, but to think "Alright, I should follow these signs, I should check how many metres they have counted down, and when I have passed it I should start looking for the next one".

Participant 81, 1 min 43 sec into the interview

The emergency signs seem to have been very important to a large proportion of the participants. Especially the lamps installed on each sign, which provided the participants with orientation points inside the otherwise dark and smoke filled tunnel, were appreciated. Many of the participants adopted a technique where they moved close to one of the walls, looked for and walked towards a lamp, and then started to look for the next. The importance of the emergency signs and the lamps was shared by many of the interviewed participants, and can be summarized with this statement made by Participant 3:

I trusted... I just focused on the lamps with my eyes, did not look for anything else at all. The lamp, and the signs with the lamps, was the only thing that I was looking for.

Participant 3, 2 min 19 sec into the interview

In addition to the analysis of the participants' walking paths, an analysis was also made of the most frequent walking behaviours inside the tunnel. A classification was made with regard to the walking posture and the participants' position of the hands during the evacuation. Note that many of the participants changed walking posture and the position of their hands during the evacuation. The term most frequent walking behaviour therefore refers to the behaviour that a participant adopted the longest distance walked inside the tunnel.

The analysis revealed that the most frequent walking posture was upright; 79% of the participants adopted this behaviour. In other words, of all the filmed participants, 79% walked the longest distance in an upright posture during their evacuation. The second most frequent walking posture was a crouched posture, which was adopted by 20%. Examples of the upright and the crouched posture are shown in Figure 9 and Figure 10. One participant, i.e., 1% of all the participants, walked very carefully and off balance during the whole evacuation and a preferred walking posture could not be determined. Some of the participants that adopted a crouched posture during their evacuation were asked about this behaviour in the interview. However, it seemed as there was no consensus among the participants as to why they walked with a crouched posture. Among the mentioned reasons were that the participants wanted to keep the same level as the emergency lamps, that there was an uncertainty about the tunnel height that it was done to check if the smoke was less dense closer to the ground, and that it was done to improve the walking balance.

The video recordings also showed that many participants used their hands to prevent themselves from walking into an obstacle and to find their way out of the tunnel. In fact, 52% of the participants walked with their hands in front of the body at some time during their evacuation, and 43% put one or two hands on the wall at some time. In terms of the most frequent position of the participants' hands, i.e., the longest distance walked by each participant with his or her hands in a certain position, most participants preferred to position their hands normally alongside their body, namely 38%. Thirty-one percent of the participants preferred to have their hands in front of their body, and 30% kept at least one hand on the tunnel wall during the major part of the walked distance. The normal position with hands alongside the body is illustrated in Figure 9, with hands in front of the body in Figure 11, and with at least one hand on the wall in Figure 12.

The interview study gave some explanations as to why the participants choose to walk with their hands either in front of their body or on the wall. The most common used explanation was related to orientation, i.e., a large proportion of the interviewed participants answered that they used their hands to orient themselves inside the tunnel. Some of the interviewed participants also expressed that they kept their hands in front of themselves or on the tunnel wall in order to protect themselves. The uncertainty related to the tunnel wall design, and the need to reduce the risk of getting hit by an obstacle is for example illustrated in the following statement by Participant 57:

> *I held out my right hand so that I wouldn't walk into the wall, but I did not want to walk too close, because... I thought that there maybe was something... Something projecting, sort of.*
>
> *Participant 57, 1 min 19 sec into the interview*

Other reasons that were mentioned for walking with the hands in front of the body or on the wall were related to balance and safety. Some participants said that they kept one or two hands on the wall in order to support their walking balance. Others said that it was simply something that increased the perceived level of safety inside the tunnel.

Figure 9. A participant walking with an upright posture, with hands in a normal position alongside the body.

Figure 10. A participant walking with a crouched posture.

Figure 11. A participant walking with the hands in front of the body.

Figure 12. A participant walking with both hands on the tunnel wall.

Exit choice

The video recordings of the evacuations were, in addition to the analysis of movement and modelling speeds and movement patterns, also used to document the exit choice of each participant, i.e., if a participant chose the emergency exit or not. The results are presented in Table 7. A total of six participants had moved across the tunnel section when they reached the emergency exit. Note that location in Table 7 therefore refers to the participant's position inside the tunnel before they reached the emergency exit, see Figure 13, in contrast to their initial position when the evacuation started, see Figure 5.

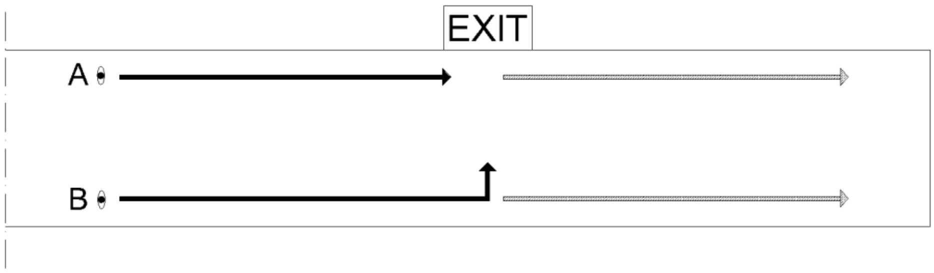

Figure 13. The position of a participant inside the tunnel shortly before the emergency exit, i.e., the end location.

Table 7. The participants' exit choice in the different scenarios.

Scenario	End location	Number of participants	Number of participants that choose emergency exit
1	A	12	12 (100%)
	B	12	8 (67%)
2	A	11	11 (100%)
	B	9	7 (78%)
3	A	8	5 (63%)
	B	18	12 (67%)
4	A	10	10 (100%)
	B	14	14 (100%)
5	A	1	1 (100%)
	B	4	4 (100%)

As can be seen in Table 7, the probability of a participant choosing the emergency exit was generally higher for the participants that were walking on the same side as the exit in contrast to the participants that were walking on the opposite side. In fact, for all scenarios except scenario 3, 100% of the participants on the same side as the emergency exit used it. It could therefore be argued that the type of way-finding installations on the emergency exit inside a tunnel is most beneficial for people on the opposite side of the emergency exit, in this experiment end location B, see Figure 13.

It seems as if the introduction of green flashing lights, i.e., scenario 2, contributed to the usage of the emergency exit if compared with the standard design in scenario 1. This conforms to previous studies [McClintock et al. 2001, Nilsson et al., 2005], and has been explained with the fact that flashing lights direct evacuees' attention and make them notice the emergency exit. In addition, it has been argued that the colour green is associated with safety and emergency exit [Nilsson, 2009].

The introduction of the strong halogen lamp above the emergency exit, and the continuous lights at each side of the exit, i.e., scenario 3, does not seem to increase the usage of the emergency exit. In fact, the design did not only avert participants walking on the opposite side of the tunnel, but also three persons that were walking on the same side as the exit. The reason for this cannot be expressed with certainty, but interview statements by some of the participants provide clues as to why the design was inadequate. Many participants actually interpreted the door as a train when they first identified it inside the tunnel. Consequently, this introduced an uncertainty in the decision making to choose the door or stick to the participants' already chosen walking path. The misinterpretation of the exit for a door is illustrated by a statement made by Participant 43, where he explains that he initially chose to continue to follow the opposite side of the tunnel because he thought it was a train on the other side:

> *Yes, I thought it was supposed to be a train. So I did not go there. Otherwise I would have done that directly [gone to the exit, author's comment].*
>
> *Participant 43, 3 min 43 sec into the interview*

Studying Table 7 reveals that the exit design in scenario 4, with a standard backlit European emergency exit sign and a loudspeaker, was very efficient in terms of getting the participants to use the exit. All 24 participants, independent on location inside the tunnel, used the door. An analysis of the walking paths of the participants in scenario 4 also reveals that the participants located on the opposite side of the emergency exit seem to have changed their walking direction, i.e., started to move towards the other side of the tunnel, earlier inside the tunnel than in the other scenarios. This behaviour, typical for scenario 4, is illustrated in Figure 14. Furthermore, the perceived rating of the combined alarm signal and voice message was rated high in the questionnaire study by the 24 participants included in the scenario, and received a median score of 8.5 of 10.

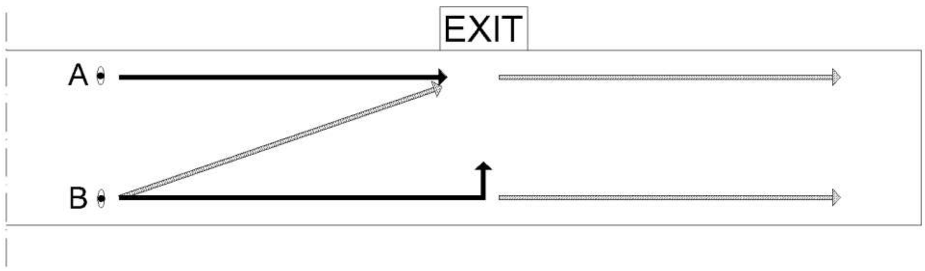

Figure 14. An illustration of the walking path typical for participants that were walking on the opposite side (B) of the emergency exit in scenario 4.

In addition to the exit design in scenario 4, the design in scenario 5, which included all installations but the loudspeaker, was also effective in terms of attracting participants to the exit. Before the experiment it was hypothesized that the door would repel the participants by providing too much information, but this does not seem to have been the case. However, the number of participants in the scenario was low and the results should therefore be treated carefully.

A statistical test, namely Fisher's exact test [Fisher, 1934], was used in order to investigate the significance of differences between the observed frequencies in each scenario where the participants had been walking on the opposite side of the emergency exit inside the tunnel. One test was carried out for each combination of scenarios, and the exact p-values (one-sided) are presented in Table 8. Note that Scenario 5 was excluded in the analysis due to the low number of observations, i.e., participants, and the fact that all participants used the emergency exit.

Table 8. Exact p-values of Fisher's exact test for consistency when comparing the scenarios pair wise.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Scenario 1	-	0.477	0.656	0.033
Scenario 2	0.477	-	0.450	0.142
Scenario 3	0.656	0.450	-	0.020
Scenario 4	0.033	0.142	0.020	-

In terms of emergency exit usage, Table 8 shows that the emergency exit design used in scenario 4 was significantly better ($p < .05$) than the designs used in scenario 1 and 3. The same conclusion can be drawn if scenario 4 is instead compared with a combination of scenarios 1, 2, 3 and 5. The calculated one-sided p-value then becomes 0.022 ($p < 0.05$).

Discussion

The results of the evacuation experiment provide detailed data on movement speeds and movement patterns inside a dark and smoke filled tunnel. In addition, the study illustrates the importance of technical installations along the evacuation route, and how an exit design may affect the usage of the exit during evacuation in underground rail transportation systems. The results presented in the paper may not be generalized for a situation with for example no smoke. However, it is argued that the results are of great importance in the fire safety design of underground rail transportation systems as they represent a worst credible fire scenario in this type of facility.

The movement speeds presented in the paper are in line with the data that has been presented in previous studies [Frantzich & Nilsson, 2003, Frantzich & Nilsson, 2004]. The analysis suggests that neither inclination nor tunnel floor material significantly affects the movement speed, and this is illustrated by the small differences in movement speeds in the different parts of the tunnel. It is instead hypothesized that the smoke and the lack of lighting will be the limiting factors on the movement speed in a fire evacuation in underground rail transportation systems. A modelling speed has also been presented in the paper, in which the duration of the stops of a participant has been included. It is suggested that this so called modelling speed should be employed when using evacuation models that do not take into account stops made by the agents during the simulation of their evacuation paths.

Evacuation experiments in this type of environment, in which the participants have had to walk for as far as 160-180 meters, are rare. In for example the study by Jin [1976, 1978] the distance walked by the participants was only 20 meters, and in the experiment by Frantzich and Nilsson [2003, 2004] the tunnel length was 37 meters. Walking in a dark and smoke filled tunnel for over 160 meters could mean that participants are subject to fatigue, affecting the movement speed negatively, or that participants adopt to the environment, which could affect the movement speed positively. However, no significant differences were identified in terms of movement speeds related to the distance walked inside the tunnel. This observation is particularly important as it suggest that the movement speeds presented in the article can be generalized for a real situation, thus improving the external validity of the results.

The importance of the tunnel walls was demonstrated in the evacuation experiment. The video recordings revealed that 91% of the participants followed one of the tunnel walls at least 75% of the total distance walked during the evacuation. The primary reason was that it facilitated orientation inside the otherwise dark and smoke filled tunnel. Many of the participants also kept one or two hands on the wall in order to not lose their orientation. To provide tunnels with handrails, which have been suggested in previous studies [Frantzich & Nilsson, 2004], therefore appears to be a good solution that may improve the ability to orient during an evacuation inside a rail tunnel.

Another reason as to why the participants choose to follow one of the walls was the emergency signs, which were installed on the tunnel walls every eight meters. The signs were very appreciated by the participants as they included information on the distance to the closest exits. This information confirmed that the participants were walking in the right direction, and also gave them clear and detailed information on how much further they had to walk, which could be related to the remaining time they had to stay in the tunnel. Furthermore, the lamps installed on each sign provided the participants with orientation points inside the otherwise dark and smoke filled tunnel. It is argued that these signs are very important in a real evacuation, and future research should study if the design could be further improved.

The evacuation experiment also demonstrated that certain emergency exit designs are better than others in terms of attracting people during an evacuation inside a tunnel. Furthermore, it was shown that the usage of the emergency exit depended on the position of the participants inside the tunnel. Participants that walked on the same side of the tunnel as the emergency exit used it to a greater extent than those who walked on the opposite side. It could therefore be argued that the type of way-finding installations on the emergency exit inside a tunnel is most beneficial for evacuees on the opposite side of the emergency exit inside the tunnel.

A door equipped with a loudspeaker, thus enabling an alarm signal and a voice message to be broadcasted to evacuees, was found to perform very well in the experiment and attracted all participants to the exit. In contrast, a combination of green and white continuous lights and a strong halogen lamp was misinterpreted as a train by many of the participants. Although the lights got noticed through the dense smoke, this introduced an uncertainty and made the participants unsure of how to respond, i.e., to continue follow the wall or to walk towards the door. These observations clearly demonstrates the importance of not only coming up with an exit design, but also to test it in an environment similar to the one it is intended to be used in.

It is not obvious that an emergency exit equipped with a loudspeaker will increase usage of it in a building. The number of walking routes may be many, as may the number of exits. However, inside a rail tunnel where evacuees generally only have two options, either to walk in the tunnel direction or to choose an exit in the wall, the loudspeaker may be essential if the evacuees are to notice the emergency exit at all. The loudspeaker is deemed especially important for those walking on the opposite side of the exit. As the distances between two emergency exits may sometimes exceed many hundred meters in underground rail transportation systems, the consequences of an evacuee missing an exit could be devastating. It is therefore suggested that future research should study the effects of loudspeakers on exit choice in underground rail transportation systems further, and also test the performance of different combinations of alarm signals and voice messages.

In the present study, a combination of data collection techniques has been used in order to improve the reliability of the results that has been presented above. Video recordings were used in order to enable the analysis of the participants' movement speed, behaviour and exit choice inside the tunnel. The great benefit of video recordings is that they permit an analysis of the material several times, with a subsequent increase in the reliability of the results. In addition, a questionnaire study that included all participants and an interview study that included 65 of the participants have been used in order to find explanations as to why the participants moved and behaved the way they did. The questionnaire and interview answers are believed to hold invaluable information, and have provided information on for example why certain exit designs were more appreciated than others. In relation to the purpose of the experiment it is therefore argued that the reliability of the results is high.

The evacuation experiment that has been described in the paper has been an attempt to describe a real world phenomenon. As it is an attempt, the evacuation experiment is intimately associated with both uncertainties and limitations, which evidently affects the validity of the results. One limitation of the experiment is for example that people may behave differently in a real situation in which they would be subject to a real fire, toxic smoke and higher stress levels. Another limitation of the experiment is related to the social influence [Deutsch & Gerard, 1955, Latané & Darley, 1968, Nilsson & Johansson, 2009], which will affect the reactions and actions of people in a real fire evacuation. No such observations have been made in the present study as the experiment was carried out individually. Future research should therefore try to verify the results in the present study with results from evacuation experiments in which participants evacuate together.

Conclusions

The analysis of the evacuation experiment showed that the average movement speed inside a smoke filled rail tunnel can be expected to be approximately 0.9 m/s, and that neither macadam or tunnel inclination of 10% have a great affect on the movement speed. The experiment also demonstrated the importance of both tunnel walls and emergency signs, which had been installed every eight meters inside the experiment tunnel. Both of these features can be expected to facilitate orientation during an evacuation in a rail tunnel. Furthermore, the experiment illustrated the importance of the emergency exit design. Smoke produced by a fire in an underground rail transportation system may obscure way-finding light installations, especially for people walking on the opposite side of an emergency exit inside a tunnel. For this reason, the installation of a loudspeaker on the emergency exit, which can provide evacuees with a combined alarm signal and a pre-recorded voice message, may be particularly effective in terms of attracting people to an exit inside a rail tunnel, independent on which side of the tunnel they are walking.

Ethical considerations

According to the Swedish ethics act [Lag, 2003] all research that involves procedures that may be psychologically invasive to the participants must be subject to a review by a regional ethics board. The present study was reviewed and consequently approved [Kellner, 2011a, Kellner, 2011b]. The important ethical issues discussed below were identified and addressed within the project.

Preparation and precautions

A number of precautions were taken to avoid both psychological and physical injury in the experiment. The risk of psychological injury was minimised by preventing individuals who received a high score for both anxiety and/or depression according to the HAD questionnaire. Recruitment, from taking part. The HAD questionnaire was administered to everyone who responded to the advertisements about the experiment. Those participants who passed, i.e., who received a low score for both anxiety and depression, were then given a consent form and written information about the experiment.

The written information explained the background and aim, and also provided the participants with a description of the experiment. The description included information about the procedure, risks and benefits for the participants, handling of data and insurance. It was emphasized in the document that the experiment was voluntary and that it could be terminated at any time. Information about how to terminate the experiment was also included.

In addition to the written information, participants were also given oral information before the experiment was started. The oral information was given to each group of participants arriving at the experiment site. Written informed consent was then collected. Before each participant entered the tunnel, the most important safety information was repeated. More specifically, it was emphasized that the experiment was voluntary and it was pointed out again how they should act if they wanted to terminate their participation. The procedure for terminating the experiment was to give a signal to the fire fighter inside the tunnel by waving your arms.

A number of precautions were taken to minimize the risk of physical injury and to reduce the consequences of these injuries. During the preparation and installation of equipment the tunnel was checked several times to ensure that there were no spikes or other obstacles in the walls that people could bump into or get entangled in. The concentration acetic acid was also checked during test runs to make sure that it was below the threshold for short-term exposure specified in the Swedish legislation [37]. Checks of the concentration of acetic acid were also made several times during the experiments.

Before the participants entered the tunnel they were given protective clothes, namely an overall, boots, gloves and a helmet, in order to reduce the consequence of a fall or collision. In addition, all participants were followed by a fire fighter inside the tunnel. The fire fighter used a thermal imaging infrared camera that allowed him to see participants through the smoke. The task of the fire fighter was to intervene if he observed a potentially dangerous situation or signs of anxiety, and to help the participant out of the tunnel if he or she gave the termination signal. Finally, all participants were insured so that they would receive financial compensation and reimbursement of medical costs in case they got injured.

Follow-up

Two months after the experiment, the participants were contacted to determine if they had suffered any injury or discomfort as a result of the study. Telephone calls were made to all participants and approximately 90% were possible to get hold of. The participants were asked if they had experienced any discomfort as a result of the experiment and they were also given the opportunity to freely point out other things related to the study. None of the contacted participants reported any injury or discomfort in the follow-up telephone interviews.

Acknowledgements

The authors wish to acknowledge the funding from the METRO project. METRO is a multidisciplinary project where researchers from different disciplines cooperate with practitioners with the common goal to make underground rail mass transportation systems safer in the future. The following nine partners participate in METRO:

Mälardalen University, SP Technical Research Institute of Sweden, Lund University, Swedish National Defence College, Swedish Fortifications Agency, Greater Stockholm Fire Brigade and Stockholm Public Transport (SL). METRO is funded by five organizations, namely *Stockholm Public Transport (SL), Swedish Civil Contingencies Agency (MSB), the Swedish Transport Administration (Trafikverket), the Swedish Fortifications Agency (Fortifikationsverket), and the Swedish Fire Research Board (Brandforsk).* More information about METRO can be found at the following web page: http://www.metroproject.se. The authors also wish to thank Dr. Stefan Svensson, Dr. Rita Fahy and Mr. Sam Grindrod for their help during the experiment. Furthermore, the authors wish to thank MSA Nordic AB, and especially Stefan Berglund, who made the documentation of the experiment possible by lending their thermal imaging cameras. Finally, Enrico Ronchi wishes to acknowledge the Swedish Institute (SI) as his grant giving authority during this research work at Lund University.

References

Boer L & Veldhuijzen van Zanten D (2005). Behaviour on tunnel fire. In Proceedings of the third International Conference on Pedestrian and Evacuation Dynamics, PED05, Vienna, Austria.

Carvel R & Marlair G (2011). A history of fire incidents in tunnels. In A. Beard & R. Carvel (Second edition), Handbook of Tunnel Fire Safety. Second ed London: Thomas Telford, pp. 3-23.

Deutsch M & Gerard HB (1955). A study of normative and informational social influences upon individual judgment. Journal of Abnormal Social Psychology 51(3) pp. 629-636.

Duffé P & Marec M (1999). Task Force for Technical Investigation of the 24 March 1999 Fire in the Mont Blanc Vehicular Tunnel.: Minister of the Interior - Ministry of Equipment, Transportation and Housing.

European Commission, (2008). 2008/163/EC: Commission Decision of 20 December 2007 concerning the technical specification of interoperability relating to safety in railway tunnels in the trans-European conventional and high-speed rail system (notified under document number C(2007) 6450).

Filippidis L, Lawrence P, Galea ER (2008). Simulating the Interaction of Occupants with Signage systems. In proceedings of the ninth International Symposium on Fire Safety Science, IAFSS 2008, Karlsruhe, Germany.

Fisher RA, (1934) Statistical Methods for Research Workers, fifth ed. Edinburgh: Oliver & Boyd.

Foddy W (1993). Constructing questions for interviews and questionnaires: theory and practice in social research. Cambridge: Cambridge University Press.

Frantzich H & Nilsson D (2003). Utrymning genom tät rök: beteende och förflyttning [Evacuation in dense smoke: behaviour and movement] (No. 3126). Lund: Department of Fire Safety Engineering and Systems Safety.

Frantzich H & Nilsson D (2004). Evacuation Experiments in a Smoke Filled Tunnel, presented at the third International Symposium on Human Behaviour in Fire, London.

Fridolf K, Nilsson D, Frantzich H (2012) The effects of different train exit configurations on the flow rate of people during evacuation in underground rail transportation systems, Manuscript submitted for publication.

Fridolf K, Nilsson D, Frantzich H (2011). Fire Evacuation in Underground Transportation Systems: A Review of Accidents and Empirical Research. Fire Technology.

Galea ER & Gwynne SMV (2000). Estimating the Flow Rate Capacity of an Overturned Rail Carriage End Exit in the Presence of Smoke, Fire and Materials, vol. 24, pp. 291-302.

Gandit M, Kouabenan DR, Caroly S (2009). Road-tunnel fires: Risk perception and management strategies among users. Safety Science, 47(1), pp. 105-114.

Hartson HR (2003). Cognitive, physical, sensory, and functional affordances in interaction design. Behaviour & Information Technology, 22(5), pp. 315-338.

Heskestad AW (1999) Performance in Smoke of Wayguidance Systems, Fire and Materials, vol. 23, pp. 375-381.

International Standards Organization (1987) ISO 8201:1987 - Acoustics - audible emergency evacuation signal", International Organization for Standardization, Genéve.

Jin T (2008). Visibility and Human Behavior in Fire Smoke. In the SFPE Handbook of Fire Protection Engineering (fourth edition). National Fire Protection Association, Quincy MA, USA.

Jin T & Yamada T (1994). Experimental Study On Effect Of Escape Guidance In Fire Smoke By Travelling Flashing Of Light Sources. In Proceedings of the fourth International Symposium on Fire Safety Science, IAFSS 1994, Ottawa, Canada.

Jin T (1978) Visibility through Fire Smoke, Journal of Fire & Flammability, vol. 9, pp. 135-157.

Jin T (1976). Visibility through Fire Smoke: Report of Fire Research Institute of Japan 2, 33, pp. 12-18.

Kellner AM (2011a) Excerpt from the record of the proceedings 2011/4 - Item 11 (in Swedish), Regional Ethics Board in Lund, Lund (Sweden).

Kellner AM (2011b) Excerpt from the record of the proceedings 2011/5 - Item 11 (in Swedish), Regional Ethics Board in Lund, Lund (Sweden).

Kuligowski ED (2011). Terror defeated: Occupant sensemaking, decision-making and protective action in the 2001 World Trade Center disaster. University of Colorado.

Lag (2003). 2003:460 om etikprövning av forskning som avser människor [The Act concerning the Ethical Review of Research Involving Humans (2003:460)], Utbildnings departementet [The Ministry of Education and Cultural Affairs].

Latané B & Darley JM (1968). The unresponsive bystander: why doesn't he help? Appleton- Century-Crofts, New York.

Larsson S (2004) Tunnelolyckan i Kaprun 2000 [Tunnel Accident in Kaprun 2000], Försvarshögskolan [Swedish National Defence College], Stockholm, 2004.

McClintock T, Shields T, Reinhardt-Rutland A, Leslie J (2001). A Behavioural Solution to the Learned Irrelevance of Emergency Exit Signage. In Proceedings of the second International Symposium on Human Behaviour in Fire, University of Ulster, Belfast.

Nilsson D (2009). Exit choice in fire emergencies - influencing choice of exit with flashing lights. Phd Dissertaion. Lund University, Lund, Sweden.

Nilsson D & Johansson A (2009) Social influence during the initial phase of a fire evacuation-Analysis of evacuation experiments in a cinema theatre, Fire Safety Journal, vol. 44, pp. 71-79.

Nilsson D, Johansson M, Frantzich H (2009) Evacuation experiment in a road tunnel: A study of human behaviour and technical installations, Fire Safety Journal, vol. 44, pp. 458-468.

Nilsson D, Frantzich H, Saunder W (2005) Coloured Flashing Lights to Mark Emergency Exits - Experiences From Evacuation Experiments. In Proceedings of at the eight International Symposium of Fire Safety Science, IAFSS 2005, Tsinghua University, Beijing, China.

Oswald M, Kirchberger H, Lebeda C (2008) Evacuation of a High Floor Metro Train in a Tunnel Situation: Experimental Findings. In Proceedings of the fourth International Conference on Pedestrian and Evacuation Dynamics, PED 2008, University of Wuppertal, Germany.

Oswald M, Lebeda C, Schneider U, Kirchberger H (2005) Full-Scale Evacuation Experiments in a smoke filled Rail Carriage - a detailed study of passenger behaviour under reduced visibility. In Proceedings of the third International Conference on Pedestrian and Evacuation Dynamics, PED 2005, Vienna, Austria.

Oswald M, Schjerve N, Lebeda C (2011) Carriage Evacuation in local, public rail transportation systems in case of fire Experiments, Findings and Human Behavior. In Proceedings of the Advanced Research Workshop on Evacuation and Human Behavior in Emergency Situations, Santander, Spain.

Paulsen T (1994) The Effect of Escape Route Information on Mobility and Way Finding Under Smoke Logged Conditions. In Proceedings of the fourth International Symposium on Fire Safety Science, IAFSS 1994, Ottawa, Canada.

Proulx G, Sime J (1991) To Prevent 'Panic' in an Underground Emergency: Why Not Tell People the Truth?. In Proceedings of the third International Symposium on Fire Safety Science, London.

Purser DA (2009). Application of human behaviour and toxic hazard analysis to the validation of CFD modelling for the Mont Blanc Tunnel fire incident. In Proceedings of the Advanced Research Workshop on Fire Protection and Life Safety in Buildings and Transportation Systems 2009, Santander, Spain, pp 23-57.

Rasbash DJ (1951) The Efficiency of Hand Lamps in Smoke, Institute of Fire Engineers Quarterly, vol. 11, pp. 46-52.

Rohlén P & Wahlström B (1996) Tunnelbaneolyckan i Baku, Azerbaijan 28 oktober 1995 [The Subway Accident in Baku, Azerbaijan, 28 October 1995], Statens räddningsverk [Swedish Rescue Services Agency], Karlstad.

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2010). Human behaviour in road tunnel fires: Comparison between egress models (FDS+Evac, STEPS, Pathfinder). In Proceedings of the twelfth international Interflam 2010 Conference, Nottingham, UK, pp. 837-848.

H. Schupfer, Fire disaster in the tunnel of the Kitzsteinhorn funicular in Kaprun on 11 Nov. 2000, presented at the fourth International Conference on Safety in Road and Rail tunnels, Madrid, Spain, 2001.

Sime JD (1984). Escape behaviour in fires: 'Panic' or affiliation? PhD thesis, University of Surrey, Guilford.

Swedish Work Environment Authority (2005) Occupational Exposure Limit Values and Measures against Air Contaminants, AFS 2005:17.

H. Xie, L. Filippidis, E. Galea, D. Blackshields, and P. Lawrence, "Experimental study of the effectiveness of emergency signage", presented at the fourth International Symposium on Human Behaviour in Fire, Cambridge, UK, 2009.

Xie H (2011). Investigation into the Interaction of People with Signage Systems and its Implementation within Evacuation Models. Phd Dissertation, University of Greenwich, UK.

Zigmond AS Snaith RP (1983) The hospital anxiety and depression scale, Acta psychiatrica Scandinavica, vol. 67, pp. 361-70.

PAPER VI

TESTING THE PREDICTIVE CAPABILITIES OF EVACUATION MODELS FOR TUNNEL FIRE SAFETY ANALYSIS

RONCHI, E.[1]

[1] *Department of Roads and Transportation. Polytechnic University of Bari, Via Orabona 4, 70100 Bari (BA), Italy*

ABSTRACT

The scope of this paper is to test the predictive capabilities of different evacuation modelling approaches to simulate tunnel fire evacuations. The study is based on the *a priori* modelling (prior to the experiments) vs *a posteriori* modelling (after the data collection stage) of a set of tunnel evacuation experiments performed in a tunnel in Stockholm, Sweden. Different degrees of modelling sophistication were employed: A) the analytical calculations provided by the Society of Fire Protection Engineers (SFPE) handbook, B) an individual use of evacuation models and C) a novel approach, namely the multi-model approach. Six evacuation models were employed, namely FDS+Evac, BuildingEXODUS, STEPS, Pathfinder, Gridflow and Simulex. The author has *a priori* simulated the experiments with the three modelling approaches. The experimental results were used to simulate *a posteriori* the same scenarios. Results showed that: 1) the use of model default settings produced significant differences in the results, 2) the calibration of models input required different degrees of effort in relation to the sophistication embedded in the model, i.e., whether it used deterministic assumptions or not, 3) analytical calculations were not a sufficient method to simulate complex tunnel evacuation processes, i.e., exit choice in smoke, 4) the use of a single model was not sufficient if the modellers had not information to calibrate the input, 5) the novel multi-model approach was a useful tool to test the sensitivity of the results to the model employed and the model sub-algorithms.

Keywords. Tunnel Safety, Evacuation modelling, Multi-model approach, Human behaviour in fire, Exit choice, emergency evacuation.

1. Introduction

The number of tunnels through-out the road networks all over the world is in the order of several thousand [Maevski, 2011]. They may differ by type, length, width, type of traffic, etc. Tunnels may show unique characteristics which make it difficult to identify a standard method to study their safety. Public awareness of the consequences of fire in tunnels was raised by the recent series of major incidents involving significant losses in terms of human lives [Shields, 2011]. This has been demonstrated by the recent tragic events such as the Mont Blanc Tunnel Fire in 1999 [Duffé and Marec 1999], the Tauern tunnel fire in 1999 [Leitner, 2001] and the St. Gotthard fire in 2001 [Carvel and Marlair, 2005, Maevski, 2011].

These events have led to changes in the international legislations, e.g., EC/2004/54, [Council Directive, 2004] through the introduction of a set of requirements aimed to help tunnel safety designers to minimize the risk of casualties during emergency events. The general objective was to ensure an adequate level of safety in tunnels in the case of fire. On the other hand, technical solutions are evolving rapidly, thus leading legislators of different countries to introduce an alternative method to the traditional prescriptive code such as in Italy [ANAS, 2009] and the United States [NFPA502, 2011], i.e. the Performance Based Design approach. This approach is based on the tools of Fire Safety Engineering. Prescriptive codes simply provide a set of measures to be applied by designers in a systematic way. Performance-Based design methods are based on the concept that infrastructure must have an adequate level of safety, allowing the use of every possible technological solution. The method to perform this analysis is to compare the RSET (Required Safe Egress Time) and ASET (Available Safe Egress Time) in order to verify the achievement of the desired performance. The RSET is generally calculated using two different methods 1) analytical calculations – provided in the SFPE Handbook [Gwynne & Rosenbaum, 2008] and 2) Evacuation modelling.

Evacuation modelling is a new and immature field [Ronchi & Kinsey, 2011, Kuligowski, 2010] and tools are continuously under development. The difficulties in producing reliable results are exaggerated by the challenging nature of modelling the RSET. The prediction of the RSET is affected by the capabilities of models to reproduce behavioural factors and the assumptions made by modellers [Ronchi et al. 2011]. In addition, the absence of a robust predictive conceptual model of occupant behaviours in fire [Kuligowski, 2011] requires a high degree of user's expertise to calibrate the evacuation models input and perform safety analyses. In particular, the analysis of the current literature on road tunnel evacuations [Boer, L., & Veldhuijzen van Zanten, D., 2005, Nilsson et al., 2009, Fridolf et al., 2011, Purser, 2009, Ronchi et al. 2010, Shields, 2005] highlights the lack of information on the human performances in the event of a fire.

The need for a broad analysis of the current methods to calculate the RSET in road tunnel evacuation is therefore evident, leading to look for the optimal manner to use the current available tools and evaluating their limitations. The aim of the paper is to provide a vast comparison between different models and methods and assess the best approach to be used in relation to the complexity of the tunnel evacuation scenario under consideration. In addition, a new approach is proposed, namely the multi-model approach, designed in order to use together several models in the case of very complex evacuation scenarios.

The selection of the tools employed has been made with the purpose to analyse models based on different modelling methods, data-sets and assumptions. They employ a variety of different methods for representing both the structure as well as human behaviours, e.g., different movement models, sub-algorithms for representing the impact of smoke on human behaviour, etc. The application of a broad range of different evacuation models, i.e., six models, namely FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], Gridflow 3.03 [Bensilum & Purser, 2003], buildingEXODUS 4.1 [Galea et al. 2004], STEPS 4.1 [Mott Macdonald simulation group, 2011], Pathfinder 2011 [Thunderhead Engineering, 2011], Simulex 5.8 [Thompson & Marchant, 1995] and the analytical calculations provided by the SFPE handbook [Gwynne & Rosenbaum, 2008] enables to make general considerations on the approaches to apply for safety analyses. These models have been tested through the comparison between the *a priori* and *a posteriori* simulations of a tunnel evacuation experiment. This method permits to evaluate the strengths and the weaknesses of each model and identify the needed degree of modelling sophistication in relation to the scenario to be simulated.

The overall objective of this research is testing the effects of the use of different approaches in the evacuation results, i.e. to study the differences among the methods employed in term of result comparison.

The main purposes are three:

1) *Testing the predictive capabilities of evacuation models:* a set of models are tested by the comparison of *a priori* and *a posteriori* simulations of tunnel

evacuation experiments, exploring different factors, such as the impact of default settings on results, use of sub-algorithms, etc.

2) *Presenting different modelling approaches:* the same evacuation scenarios are simulated applying different degrees of modelling sophistication. A novel approach is also presented, the multi-model approach.

3) *Assessment of the best approach*: the analysis of the differences in the results leads to assess the cases in which a deep analysis is required and the cases in which a simple analytical calculation is sufficient. This evaluation is performed taking into account the different scenarios/purposes of the safety analysis.

2. Methodology

The definition of the possible methods to compare evacuation model results is still under discussion in the scientific community. Lord et al. [2005] provided the definition of three different levels to perform the evaluation and comparison of evacuation model results:

1) Blind Calculation – This type of calculation is based on a basic description of the scenario to be modelled, including the information on the geometry of the infrastructure. The model user has the freedom to decide the additional details needed to run the simulations. The benefits coming from this type of analysis are the possibility to verify different input calibrations.

2) Specified calculation – A detailed description of model inputs is provided here. This includes the geometry of the infrastructure as well as the occupant characteristics, the range of numerical constants to be used in each model.

3) Open calculation – All information about the scenario to be simulated is provided here. Two possible references may be used, i.e., actual evacuation data or benchmark model runs completed from other models that were validated for that scenario.

In the present work, blind calculations represent the process of *a priori modelling* where the evacuation modeller has no benchmark to evaluate the results produced by models. Open calculations are instead based on the availability of all the required information to calibrate the input, i.e., the *a posteriori* modelling is based on the collected experimental results. The comparison of the *a priori* and *a posteriori* results permits to evaluate different information in relation to the type of calculation performed (blind and open calculation). The analysis of the blind calculations permit to evaluate the impact of default settings on model results and the data employed for the input configuration. The comparison between blind and open calculations has been found as appropriate to compare the algorithms embedded within the models. The cross comparison between blind, open simulations and experimental results permitted to evaluate the sources of the differences among model results and the actual people performance.

Starting from the above described scopes of the paper, three approaches may be considered to simulate the evacuation scenarios, namely 1) analytical calculations, 2) individual use of evacuation models and 3) the multi-model approach.

1) The simplest approach is the hydraulic method described in the SFPE handbook by Gwynne and Rosenbaum [2008] in which analytical calculations are used to calculate the RSET.

2) The calculation is made using evacuation models individually. There are two manners to simulate the different scenarios using this approach. The first method is the use of model default settings. Evacuation models generally include data-sets and default settings in order to facilitate users and increase the speed of model input configuration. Default settings are often used for that variables for which the user is not able to find relevant information to calibrate the input. Modellers may also use default settings indiscriminately in order to speed up the process of input calibration, although there is always the need to verify that the default provided by the model developer is in line with the scenario under consideration [Ronchi et al., 2011]. Previous studies have highlighted that consistent differences may appear in the results if the process of input calibration is based on default settings [Ronchi et al., 2011]. For this reason, this approach has been included in the present work, i.e., the scope is to evaluate the differences among different model results when using default settings/embedded data-sets and warm modellers on the possible inaccuracy deriving from their indiscriminate application. The second method is an attempt to configure the models using all the available data/information for the specific scenario under consideration (see Figure 1). This approach requires a higher degree of expertise by the modeller in order to choose the appropriate input. Input values are selected among the existing literature/legislations. As pointed out by Gwynne [2010], modellers need to evaluate several aspects of the available data including

uncertainty in the provided input, experimental/environmental conditions of the data, data collection techniques, etc.

3) The last approach consists of a multi-model approach for the analysis of the evacuation scenarios. The differences among the results obtained during the approach 2 are analysed in order to check their causes. In the simplest cases, these sources are easily found because a certain model is not able to reproduce all problems. An example may be a model which does not embed a sub-algorithm to simulate the impact of smoke on exit choice. One model (or in some cases more than one) may be used as reference for that specific variable and the input of the other models is forced to be as similar as possible to it/them in order to match the model/s. In complex cases, there may be a need to perform a sensitivity analysis in order to evaluate the impact of a certain variable on the model results, i.e., the uncertainty linked to that variable. The second method to determine the reference model/s for each specific problem is the comparison with experimental data, i.e., if there is evidence of the correspondence between the numerical results produced by a single model and the actual people's performance. Also in this case, the input of the models is calibrated starting from the model/s that better represented a specific variable, i.e., the results produced by a single model are in line with the observed phenomenon. The multi-model approach can be also used to simulate different aspects of the evacuation process by using individually a single model at the time for different aspects of the evacuation, e.g., one model may be used for simulating exit choice and then the output obtained is implemented in another model to simulate human flows. Once the reference model(s) or benchmark experimental data are identified, an iterative process of input calibration is performed in order to check the impact of the changes on the final results. The process ends when the results of different models become consistent.

The multi-model approach may be then used in both stages of the simulation process. In the first case it may be used for the *a priori* simulation of the evacuation scenarios. This is possible when the sources of the differences among model results derive from the embedded features of the models, i.e., a model is able to reproduce behaviours that another model is not able to simulate. The second possibility is its application during the *a posteriori* simulation. When there is no *a priori* evidence of a model that better represents a certain aspect/behaviour of the evacuation, the use of benchmark experimental data allows the modeller to identify the model(s) results that match with the actual people performance.

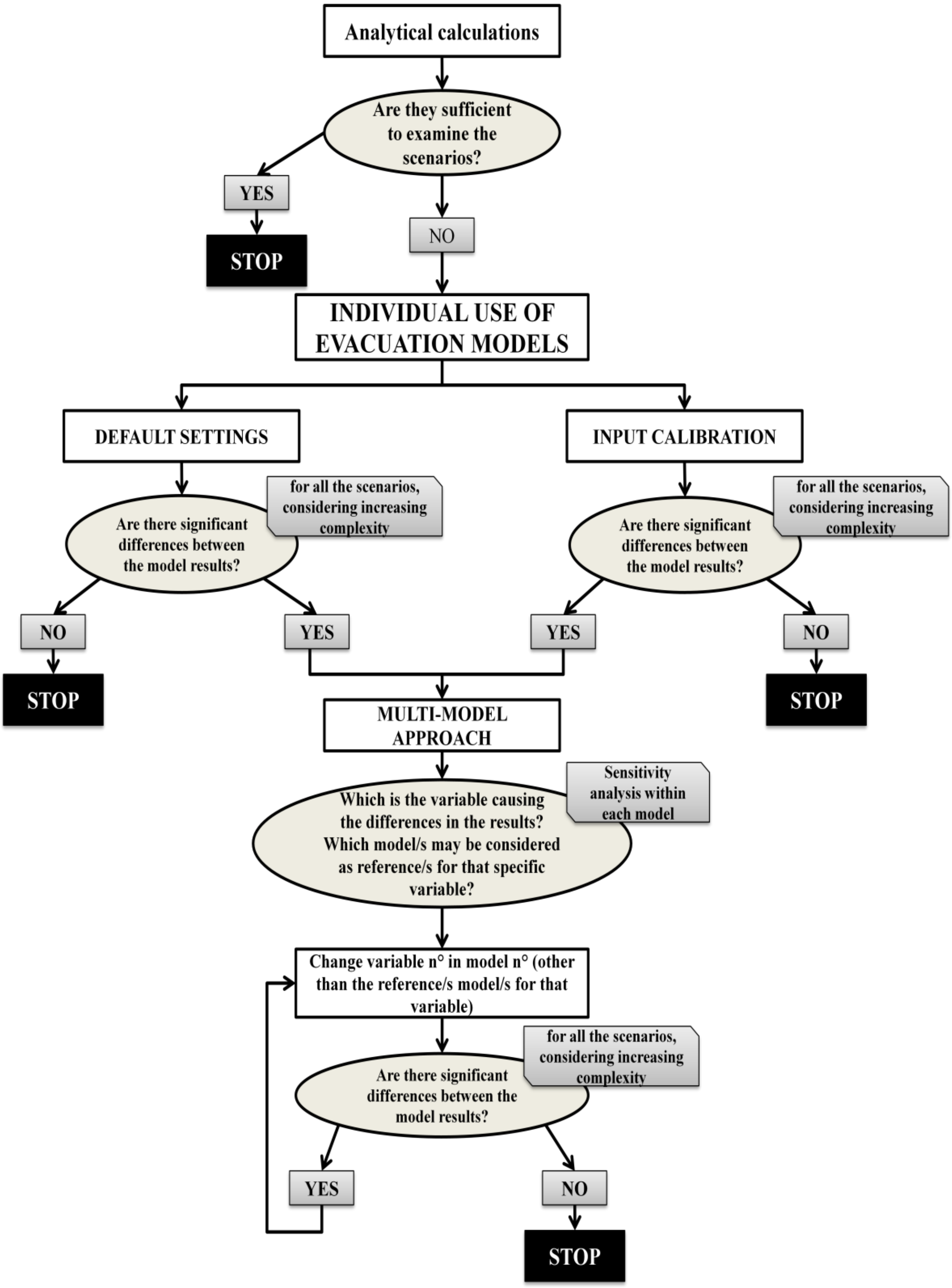

Figure 1. Scheme of the methodology used to test the predictive capabilities of evacuation models

The benefits coming from the use of the multi-model approach are diverse. The first advantage is that the practitioners become aware of the possible sources of uncertainty in the most used models and novice users are led to pay more attention when using certain default variables. An example is the different correlation currently employed to represent the impact of smoke on agent speeds, i.e., the reduction of agent speeds for a given extinction coefficient may vary among models [Ronchi et al., 2012a]. Modellers may be then lead to assume the most conservative credible assumptions. The second benefit is related to the fact that the multi-model approach permits to better represent the actual performances, because it uses each model at its best, i.e., one model may be the reference for a specific variable while another one may be the reference for another variable. This technique may be particular effective for reconstruction analysis, i.e., forensic analysis, where highest degree of precision is required in the analysis. Another possible field of application is the case of a very complex tunnel layout, including underground roundabouts, intersections, etc., e.g. the tunnel network in the city of Tromsø, Norway. Modellers can then evaluate if the uncertainty is related to a certain modelling method, sub-algorithm or default setting and apply models at their best. The assessment of the best approach relies then on the scale of the problem and the complexity of the scenario (see Figure 1).

In Figure 1 the definition of significant differences between the model results, i.e., in terms of evacuation times, levels of congestions, etc. is based on the hypothesis that differences are considered as relevant if their impact is "*significant enough to cause a change in an engineer's design*" [Lord et al. 2005].

In order to evaluate the effectiveness of the different approaches for tunnel evacuation applications, a case study - for which experimental results are available - has been analysed in detail. The possibility to compare the *a priori* and *a posteriori* simulations permits to define the differences of the results with an actual evacuation scenario and the subsequent assessment of the best approach to use.

3. Case Study: The Trädskolevägen tunnel

In order to test the predictive capabilities of the chosen evacuation models, the Trädskolevägen tunnel in Stockholm, Sweden, has been chosen as a case study in this paper. The tunnel has been selected as it is currently used by the Department of Fire Safety Engineering and Systems Safety of Lund University, Sweden, to perform evacuation experiments. This allowed obtaining information for the *a posteriori* simulations of the evacuation scenarios, based on the experimental results presented in the paper “Movement speed and exit choice in smoke-filled rail tunnels” [Fridolf et al., 2012].

Two main aspects were analysed during the evacuation experiments: 1) the impact of way-finding installations on exit choice given the presence of smoke, 2) the impact of smoke on evacuee's behaviours, i.e., movement speeds in a smoke-filled environment.

The Trädskolevägen tunnel is a single bore tunnel that previously had been used in the construction of a road tunnel in Stockholm. During the experiments, 200 metres of tunnel length were used. The tunnel includes two different parts: 1) an inclined section, 104 m in length and 2) a horizontal section, 72 m in length (56 m + 16 m in Figure 2). The slope factor in the inclined section is about 10%. The cross section width of the tunnel is 8 m. Different surface materials were investigated in the experiments.

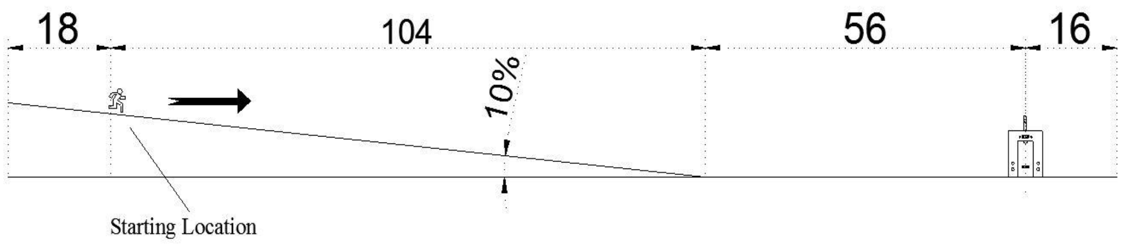

Figure 2 . Side view of the Trädskolevägen tunnel.

Standard emergency signage was installed in the tunnel in accordance with the Stockholm metro layout. Approximately one hundred and eighty metres into the tunnel a mock-up door was installed in one side of the tunnel. This door was equipped with a number of different way-finding installations, e.g., exit signs, etc. that were used or not according to the different scenarios.

Three different layouts, i.e. combination of installations, are considered in this study:
Type 1) Standard European emergency exit sign (backlit sign)
Type 2) Standard European emergency exit sign (backlit sign) + Green flashing lights
Type 3) Standard European emergency exit sign (backlit sign) + Spotlight above the door + continuous white and green lights.

The participants walked through the tunnel one at a time and no group interactions were investigated. During the experiments, the tunnel was filled with artificial cold smoke containing acetic acid. The purpose was to make the fire scenario as realistic as possible, without putting the participants' health into jeopardy. An average extinction coefficient of approximately 2.2 /m was measured in the tunnel during the experiments.

Two initial locations of the participants were considered during the experiments. The first initial location was in the inner side of the tunnel cross section (Location A in Figure 3), and the second one is on the outer side of the cross section (Location B in Figure 3).

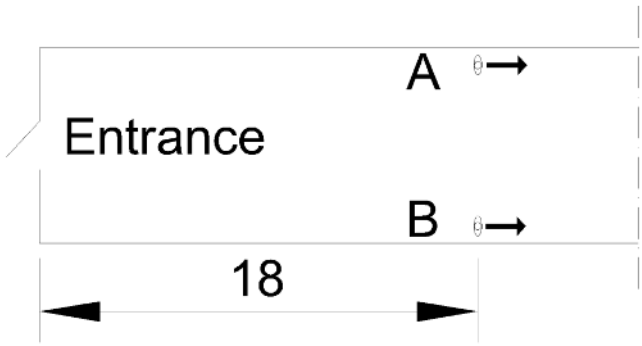

Figure 3. Initial locations in the tunnel cross section.

Table 1 provides a list of the scenarios. They are a combination of the initial location of test participants and the type of emergency exit design in use.

Table 1. Summary of the scenarios.

Scenario	Emergency exit design	Initial position of the occupant
1A	Type 1	Location A
1B	Type 1	Location B
2A	Type 2	Location A
2B	Type 2	Location B
3A	Type 3	Location A
3B	Type 3	Location B

Further information on the experimental procedures employed, installations in use, data collection techniques, etc. can be found in the paper by Fridolf et al. [2012].

3.1 Results of the experiments

The experimental results are presented in Table 2 and Table 3 [Fridolf et al., 2012]. Two main aspects were investigated, namely 1) exit choice in different scenarios, i.e. whether the participants use the emergency exit or they reached the end of the tunnel without using it and 2) occupant walking speeds (considering the total time spent by every participant divided for the total walked distance) in the different combinations of surface material/inclination.

Table 2. Summary of experimental results for exit choice in the different scenarios.

Scenarios	Emergency exit use (%)	Evacuation times (s)
1A	100	176
1B	67	205
2A	100	218
2B	78	208
3A	62	187
3B	67	214

Table 3. Summary of the experimental results about modelling speeds

Surface material/ inclination	Modelling speed (m/s)
Asphalt/slope	Mean=0.9, σ=0.2
Asphalt/flat	Mean=0.9, σ=0.2
Ballast/flat	Mean=0.9, σ=0.3

Three type of combination surface material/inclination were investigated, namely asphalt/incline, asphalt flat, and ballast/flat. No significant differences were found in the values of walking speeds along the different materials/inclination. Two different movement speeds were derived from the analysis of the experimental data, namely movement speed and modelling speed. The movement speed was calculated for each participant by dividing the total distance walked by the time employed, i.e., the stops made by the evacuees were excluded from the calculation of the movement speed. In contrast, the modelling speed was calculated for each participant by dividing the total distance walked in the different parts of the tunnel by the total time, i.e., the stops made during the evacuation were included.

The modelling speed is used in the present work, corresponding to approximately 0.9 m/s for each combination (see Table 3). The differences in terms of evacuation times in the scenarios derive from the different paths made by the test participants, i.e., different walking distances were recorded during the experiments. It also needs to be noted that the calculated speeds do not include the case of participants walking zigzag along different surface materials. This information was excluded from the calculation of the speeds because it was not possible to assign a specific surface material to those patterns.

3.2 A priori modelling

Actual tunnel fire scenarios showed that the possibility to notice and use emergency exits has been found as a crucial factor for people safety [Gandit, 2009, Nilsson, 2009, Xie, 2009]. Some models do not embed a predictive algorithm to take this problem into account. The lack of human behaviour data often do not permit to easily obtain information to calibrate models [Ronchi et al., 2012]. In addition, visibility conditions may become rapidly untenable, thus leading to a quick reduction of the occupants way-finding abilities due to the impact of the smoke [Xie, 2011]. For these reasons, the presented *a priori* predictions are focussed on two main aspects of the evacuation process:

1) The simulation of the impact of smoke on agent movement speeds.
2) The simulation of the impact of way-finding installations on exit choice in smoke-filled environments.

The third aspect that is not addressed in this paper is group behaviours. The presented tunnel experiments include only one person at a time for each trial, therefore this aspect can be omitted. During engineering analyses, this factor should be instead taken into account, although the lack of experimental data make very difficult to predict group behaviours [Korhonen & Heliövaara, 2011].

Different *a priori* approaches are used in the following sections. Analytical calculations provided by the SFPE Handbook [Gwynne and Rosenbaum, 2008] were used in approach A. Six models were employed individually to simulate the tunnel evacuation scenarios in approach B (default settings application) and approach C (model input configuration), namely FDS+Evac 2.3.1 [Korhonen & Hostikka, 2010], Gridflow 3.03 [Bensilum & Purser, 2003], buildingEXODUS 4.1 [Galea et al. 2004], STEPS 4.1 [Mott Macdonald simulation group, 2011], Pathfinder 2011 [Thunderhead Engineering, 2011], Simulex 5.8 [Thompson & Marchant, 1995]. The multi-model approach is used in approach D. During the application of approach B, C and D fifty simulations of each scenario have been simulated in evacuation models in order to evaluate the average evacuation times and the percentage of emergency exit usage.

3.2.1 Approach A: analytical calculations

Gwynne & Rosenbaum [2008] provided a methodology to apply a hydraulic method to calculate the RSET based on the work made by Nelson & Mowrer [2002]. This method permits to model evacuation times by a series of expressions that approximate human movements to a hydraulic flow. Since the tunnel under consideration has a simple geometry, the hydraulic model can be easily applied for the whole structure, i.e., the second-order hydraulic model has been employed [Gwynne & Rosenbaum, 2008].

This method does not permit to simulate any behavioural aspect, i.e., time for decision making, exit choice process, etc. The consequence is the lack of predictions about the exit usage in the case of multiple available exits. In the presented case study, results showed the evacuation time needed to reach the two possible exits, but the method did not provide any predictive algorithm to consider the fact occupant may use or not the emergency exit. For this reason, the six scenarios produced all the same results, i.e., the emergency exit layout and the initial location of occupants was not affecting the evacuation results.

The formulas employed were:

(1) $F_s = SD$ (2) $F_c = F_s W_e$ (3) $t_p = \frac{p}{F_c}$

Where:

S is the occupant's speed (m/s);

p is the number of persons (p);

D is the density of people (p/m2);

F_s is the specific flow, i.e., the flow of evacuating persons past a point in the exit route per unit of time per unit of effective width (p/s/m);

F_c is the calculated flow, i.e., the predicted flow rate of persons passing a point in an exit route (p/s);

W_e is the effective width, that indicates the boundary layer clearance from walls needed by persons moving through exit routes (cm);

t_p is the time for passage, that is the time for a group of persons to pass a point in an exit route (s)

According to the considered scenarios, i.e., only one person for each trial, the method prescribes that - in the case of densities lower than 0.54 person/m^2 - occupants move at their own pace. The reduction of the speed due to the reduced visibility conditions is based on the studies made by Jin [Jin, 2008, Nelson & Mowrer, 2002]. For the analysed scenarios - where the smoke is very thick and irritant gas is considered - Jin's data suggests a lower speed of 0.3 m/s. Two different walking distances may be walked by the occupants in relation to the fact they use or not the emergency exit, i.e., 160 metres in the case they use the emergency exit and 176 metres if they reach the end of the tunnel. Evacuation results obtained by applying Equation (1), (2) and (3) are resumed in Table 4.

Table 4. Summary of the results obtained by the application of approach A.

Scenarios	**Emergency exit usage (%)**	**Evacuation times (s)**
1A	No prediction	536-589
1B	No prediction	536-589
2A	No prediction	536-589
2B	No prediction	536-589
3A	No prediction	536-589
3B	No prediction	536-589

The method employed produced evacuation times equal to 536-589 seconds. The range of evacuation results would be higher if the distance between the emergency exit and the final end of the tunnel is longer or in the case of a more complicated layout, i.e., several available emergency exits.

3.2.2 Approach B: individual use of models

The six models employed present different assumptions and different degrees of modelling sophistication. The use of default settings does not permit to directly insert information on the different layout of the emergency exit (exit signs, flashing lights, etc.) when applying evacuation models. The consequence is that the results coming from the scenario with the same initial location of the agents will produce the same results, i.e., scenarios 1.A=2.A=3.A and 1.B=2.B=3.B. The modelling techniques and assumptions used to run the simulations are the same described in a previous paper presented by the author [Ronchi et al., 2012], although the scenarios represented here have some differences. At the time of the *a priori* simulations, no information was available on the visibility conditions during the tunnel experiments and the exact position of the mock-up emergency exit in the tunnel. For this reason the *a priori* simulations were re-made applying the same methods/assumptions but considering these modifications about the scenarios to be modelled.

With regards to the simulation of the impact of emergency exit layout on exit choice, models present different assumptions and degrees of people interaction with the smoke conditions. These interactions range from a simple deterministic evaluation made by the evacuation modeller prior to run the simulations to complex algorithms to simulate the agent's process of gathering and processing exit sign information. Kuligowski [2010] described the possible options available for route and exit choice as 1) occupants travel the fastest route (optimal), 2) occupants choose the shortest route (shortest), 3) route choice is defined by user (user defined) and 4) occupants choose the route in relation to the conditions in the building, e.g., smoke, queuing, etc. (conditional). Table 5 provides a list of the methods and factors available in the models employed. A fundamental aspect is whether a model is able or not to reproduce a change of the selected exit during the course of the evacuation in relation to the evolving fire conditions of the environment, e.g., changing visibility conditions. Key factors in the representation of the smoke impact on agent's exit choice is the possibility to represent the emergency exit layout and the agent's familiarity with the exits, i.e., emergency exits may be considered by tunnel evacuees even less familiar than the tunnel itself [Gandit, 2009].

There is also the possibility that a model does not present an embedded algorithm to simulate a specific variable In this case, the box in Table 5 shows "NO". Evacuation modellers should then calculate the possible impact of this variable beforehand.

Table 5. Summary of default settings/embedded data-set for the representation of smoke impact on agent's exit choice.

Models	**Route choice sub-algorithm**	**Exit choice default**	**Familiarity with the exits**	**Emergency exit design**	**Smoke Impact**
FDS+Evac 2.3.1	Optimal, conditional, user defined	Conditional	YES	YES	YES
Gridflow 3.03	Shortest, Random, user defined	Shortest	NO	NO	NO
buildingEXODUS 4.1	Optimal, conditional, shortest, user defined	Conditional	YES	YES	YES
STEPS 4.1	Conditional	Conditional	YES	NO	NO
Pathfinder 2011	Optimal, Shortest, User defined	Shortest	NO	NO	NO
Simulex 5.8	Shortest or altered distance map	Shortest	NO	NO	NO

The emergency exit usage simulated according to the default assumptions made by the models is shown in Table 6. FDS+Evac has a sub-algorithm to calculate route choice. The model takes into account several factors such as the smoke conditions, the familiarity of the agents with the exits and the emergency exit design itself (although the modeller needs to calibrate this input after a prior configuration of the smoke conditions [Ronchi et al., 2012]). According to the scenarios, agents were either able or unable to use the exit in relation to their location in the cross section (0 % or 100 % of emergency exit usage by default). The default exit choice algorithms of Gridflow, Simulex and Pathfinder are essentially based on distance criteria, i.e., distance maps in Gridflow and Simulex or steering behaviours in Pathfinder for the case where queuing is not a predominant factor. The consequence is that a single evacuee by default uses the closest exit, i.e., the emergency exit in the considered scenarios, i.e., 100% of emergency exit usage in all the scenarios. BuildingEXODUS provides three default libraries based on guidance derived from British [BS5266-7, 1999 and BS5499-4, 2000] and US standards [NFPA101, 2012]. By default, no specific information on the nature of the signs is given. The results produced (see Table 6) can only be indicative of those that might occur, i.e., any similarity with the actual behaviour is largely coincidental. STEPS default exit choice algorithm is based on exits potential, i.e., distance from each cell to the closest exit. The model calculates the distance from each free cell to the exit by using a recursive algorithm. Also in this case, for a single evacuee, the closest exit, i.e., the emergency exit, is used by the agent.

Table 6. Emergency exit usage using approach B in six evacuation models.

Models	**Scenarios (Emergency exit usage %)**	
	1A, 2A,3A	**1B, 2B, 3B**
FDS+Evac 2.3.1	100	0
Gridflow 3.03	100	100
buildingEXODUS 4.1	28-32	22-28
STEPS 4.1	100	100
Pathfinder 2011	100	100
Simulex 5.8	100	100

As pointed out by Ronchi et al. [2011a], two main data-sets are currently available for the simulation of the impact of the smoke on agent walking speeds. These data-sets – Jin's data-set [Jin, 2008] and Frantzich and Nilsson's data-set [Frantzich & Nilsson, 2003]. Both are employed by evacuation models as if equivalent although they represent different experimental conditions [Ronchi et al., 2012] (see Table 7).

Table 7. Summary of default settings/embedded data-set for the representation of smoke impact on agent walking speed.

Models	Default settings	Smoke/speed embedded data-set
FDS+Evac 2.3.1	pre-defined	Frantzich and Nilsson
Gridflow 3.03	NO	Any data-set
buildingEXODUS 4.1	pre-defined	Jin
STEPS 4.1	pre-defined	Jin
Pathfinder 2011	NO	/
Simulex 5.8	NO	/

Evacuation times were then calculated accordingly to the default correlation smoke vs movement speeds provided by each model developers. Further discussions on the assumptions made by the model developers to interpret the data-sets and obtain the correlations were provided by Ronchi et al. [2012], i.e., models may use different interpretation of the same data-set. An example is that the data-set provided by Jin is translated in two different correlations by STEPS and buildingEXODUS. Gridflow, Pathfinder and Simulex models do not provide for default settings on this issue (Gridflow permits to implement any data-set without a default correlation, while Pathfinder and Simulex do not permit to directly implement the influence of smoke on agent speeds). For this reason they are not included in this step of the analysis.

The other three models, FDS+Evac, buildingEXODUS and STEPS provide results accordingly to their assumed default setting/embedded data-set (see Table 8). Results produced by FDS+Evac are the lowest because the default settings are based on the data-set provided by Frantzich and Nilsson.

Table 8. Summary of the evacuation times obtained using approach B.

Models	Scenarios	Evacuation times
FDS+Evac 2.3.1	1A, 2A,3A	155
FDS+Evac 2.3.1	1B, 2B, 3B	171
buildingEXODUS 4.1	1A, 2A,3A	301
buildingEXODUS 4.1	1B, 2B, 3B	304
STEPS 4.1	1A, 2A,3A	533
STEPS 4.1	1B, 2B, 3B	557

3.2.3 Approach C - model configuration

A set of assumptions have been made for configuring each model's input through the available literature.

Walking speeds may be either configured using Jin's data-set or the Frantzich and Nilsson's data-set. Jin's data-set was used in STEPS and buildingEXODUS because it is embedded within the two models. FDS+Evac employed instead the Frantzich and Nilsson's data-set. Gridflow, Pathfinder and Simulex have no default settings about this aspect. They have been configured using a fractional reduction in the speed in accordance with the Frantzich and Nilsson's correlation because it was thought that it was more appropriate for the scenarios under consideration, i.e., the experimental conditions to be simulated were more similar to that data-set than Jin's experiment where the extinction coefficients investigated were always lower than 1 /m.

The probability of using an exit is essentially dependent on two factors, namely 1) visibility, if the sign is visible or not and 2) the probability of using the exit once the sign is seen.

Visibility of exit signs can be calculated only in FDS+Evac and buildingEXODUS. These models were then calibrated in accordance with the assumptions presented by the author in a previous work [Ronchi et al., 2012]. No information may be derived on the visibility of the emergency exit signs in the other four models. The percentage of likelihood of using the exit was then applied. This was derived from previous literature [Ronchi et al., 2012]. The emergency exit usage in Gridflow, STEPS, Pathfinder and Simulex was calibrated using a set of imposed values (see Table 9). Evacuation times were then calculated accordingly (see Table 10).

Table 9. Emergency exit usage using approach C in six evacuation models.

Scenario	**Emergency exit usage in models (%)**		
	FDS+Evac	**buildingEXODUS**	**Gridflow, STEPS, Pathfinder, Simulex**
1A	50	41	50
1B	0	2	0
2A	82	72	90
2B	62	53	70
3A	82	76	90
3B	56	37	60

Table 10. Summary of evacuation times obtained using approach C.

Scenario	Evacuation times in models (s)					
	FDS+Evac	Gridflow	buildingEXODUS	STEPS	Pathfinder	Simulex
1A	164	163	296	560	163	162
1B	171	170	313	587	171	171
2A	158	157	286	540	156	158
2B	165	165	294	567	164	164
3A	158	157	284	538	157	157
3B	166	166	299	569	166	167

3.2.4Approach D – Multi-model approach

Evacuation models were calibrated starting from the analysis of the available features within models. The correlation employed by FDS+Evac about the impact of smoke on movement speeds was the most similar to the experimental conditions. The fractional reduction of the movement speed produced by the model is in accordance with the Frantzich and Nilsson's data-set. The similarities in the observed walking speed are mainly due to the fact that the experiments were employing a similar type of smoke of the data-set employed by FDS+Evac [Frantzich &Nilsson, 2003], i.e. cold artificial smoke and acetic acid. In line with this data-set, for the given visibility conditions, i.e., extinction coefficient equal to 2.2. /m, agent speeds are approximately 1 m/s. The value is obtained considering the speed reduction of the default value of initial speed in clear condition of the agents, i.e., 1.25 m/s for the adult category. Applying the Jin's data-set that is used by buildingEXODUS and STEPS, the calculated final speed for the given visibility is lower (respectively 0.54 m/s in buildingEXODUS and 0.3 m/s in STEPS). FDS+Evac has been considered in this case as the reference model for this aspect during the *a priori* application of the multi-model approach.

With regards to exit choice, several considerations may be performed on the predictive algorithms used by models. BuildingEXODUS and FDS+Evac are the only models able to directly simulate the environmental conditions among the six models employed. The benchmark model was then selected among them. The predictions made by FDS+Evac were affected in this case by the fact that an exit is assumed to be not visible in the model if the distance of the agent to the exit is more than twice the visibility distance. The consequence is that an agent may use the emergency exit if its position in the cross section permits him to notice the exit. This is confirmed by the fact that scenario 1B - where the exit is not visible - produced a 0 % of emergency exit usage in both approach B and approach C. BuildingEXODUS presents a detailed and complex sub-algorithm that permits to achieve a high degree of sophistication during the simulation of the impact of signage on exit choice. Four elements may be simulated, including (1) the physical area from which a sign can be seen, (2) the likelihood of an agent actually seeing the sign given the angle at which they approach it, (3) the likelihood of them paying attention to the sign and absorbing the information and (4) the likelihood of them using the information provided to them. This algorithm permits to simulate not only the visibility of exit signs but also the detailed interaction between the agents and the environment, i.e., the configuration of the scenario under consideration, e.g., emergency exit layout, emergency signage, etc. For this reason, buildingEXODUS has been employed as a benchmark model in this case and the derived percentages of emergency exit usage have been employed to calibrate the other models.

The iterative process of input calibration of the six models using the two reference models - buildingEXODUS for the simulation of exit choice and FDS+Evac for simulating the impact of smoke on agent walking speeds - produced the following results (see Table 11 and Table 12).

Table 11. Emergency exit usage in six evacuation models obtained using approach D.

Scenario	Emergency exit usage in models (%)		
	FDS+Evac	buildingEXODUS	Gridflow, STEPS, Pathfinder, Simulex
1A	36	39	39
1B	0	1	1
2A	70	74	74
2B	46	49	49
3A	66	71	71
3B	34	33	33

Table 12. Summary of the evacuation times obtained using approach D.

Scenario	Evacuation times in models (s)					
	FDS+Evac	Gridflow	buildingEXODUS	STEPS	Pathfinder	Simulex
1A	165	165	177	166	165	165
1B	171	171	185	171	172	170
2A	160	161	169	160	161	161
2B	167	166	175	165	167	167
3A	161	160	170	160	161	160
3B	168	167	179	168	167	167

3.3 A posteriori modelling

The *a posteriori* modelling of the tunnel evacuation experiments have been made through the use of experimental results for enhancing the predictive capabilities of the models. Data about movement speeds were then inserted deterministically within the 6 models i.e. open calculations were performed. With regards to exit choice, an attempt has been made to calibrate the model input starting from an analysis of the experimental results obtained. The approach employed (approach E) is the individual use of evacuation models.

3.3.1 Approach E – individual use of models

In FDS+Evac and buildingEXODUS, the experimental data were matched with the predictive algorithm of the models by modifying the underlying experimental percentage of usage associated with different emergency exit layout. The visibility of exit signs is instead reproduced through the application of the sub-algorithms embedded within the models.

Gridflow and Pathfinder have both the possibility to directly assign the exit to be used by each specific agent, i.e., the emergency exit usage is deterministic. STEPS was used in this case by assigning specific path to agents in order to match the two main experimental path observed (towards the emergency exit or the end of the tunnel). Simulex permitted to assign altered distance maps to each agent and then affect the exit choice accordingly.

Results about emergency exit usage are presented in Table 13. Gridflow, STEPS, Pathfinder and Simulex results reproduced exactly the experimental results observed since the algorithm employed is deterministic. In FDS+Evac and buildingEXODUS the experimental results were matched with the predictive capabilities of the models. This is reflected in the way the models simulated the visibility of the different emergency exit layouts. An example is the results for scenario 1B in FDS+Evac. The model produced no emergency exit usage by the agents, in line with the modelling assumption that an exit is usable as long as the agent is situated at less than twice the visibility distance to the exit.

Table 13. Emergency exit usage using approach E in six evacuation models.

Scenario	Emergency exit usage (%)		
	FDS+Evac	buildingEXODUS	Gridflow, STEPS, Pathfinder, Simulex
1A	100	87	100
1B	0	54	67
2A	100	75	100
2B	76	64	78
3A	60	58	62
3B	66	50	67

Agent speeds have been inserted in the model input in accordance with the results collected from the experiments, i.e. 0.9 m/s. The evacuation times produced by the six models are presented in Table 14.

Table 14. Summary of the evacuation times obtained using approach E.

Scenario	Evacuation times in models (s)					
	FDS+Evac	Gridflow	buildingEXODUS	STEPS	Pathfinder	Simulex
1A	178	177	184	178	178	177
1B	196	189	190	188	189	188
2A	178	177	186	178	178	177
2B	188	188	190	188	188	187
3A	185	185	189	186	185	184
3B	189	189	193	188	189	188

3.4 Result Comparison

Evacuation models have been evaluated starting from the analysis of their features and the comparison between the *a priori* simulation of the scenarios, the experimental results and the *a posteriori* simulations performed.

The comparison between the *a posteriori* modelling results and the observed experimental performance highlighted the cause of the differences among model results. They derived mainly from 1) the embedded sub-algorithms in the model and 2) the process of input calibration. The differences among evacuation times were related to the actual distance walked by the participants during the trials, i.e. the modelling speeds observed were referred to the average speeds in different surfaces, not in different scenarios. It is then argued that results should be evaluated in terms of the predicted emergency exit usage and the walking speeds, rather than a direct comparison of the evacuation times.

As expected, in the present study, the correlation employed by FDS+Evac about the representation of the impact of smoke on movement speeds produced values similar to the experimental results. The fractional reduction of the agent speeds produced by FDS+Evac for the given visibility conditions – an extinction coefficient equal to 2.2. /m - was approximately 1 m/s. Applying the Jin's data-set (used by default in the analytical calculation, buildingEXODUS and STEPS), the calculated final speeds for the given visibility conditions are instead respectively equal to 0.54 m/s and 0.3 m/s. The value produced by FDS+Evac is then comparable with the observed experimental value of 0.9 m/s. When the model input was configured applying the FDS+Evac correlation in Gridflow, Pathfinder and Simulex, the four models produced comparable results (see Table 10).

Results produced employing the multi-model approach shows the benefits from its use. The application of approach A, B and C for the given scenarios shows that the application of the data-set provided by Jin showed an increased evacuation times. The a priori capabilities of the models were instead enhanced by the application of the multi-model approach, i.e., model results become comparable in approach D because of the iterative process of calibration of the agent speeds.

The *a posteriori* modelling step (approach E) is an attempt to use the experimental data not only to deterministically calibrate the input, but coupling the information coming from the behaviour observed with the predictive capabilities of models in terms of visibility and usage of the exits (if available). This is reflected in the results obtained with FDS+Evac and buildingEXODUS in approach E, i.e., they do not exactly match the experimental data (the average differences in terms of emergency exit usage are respectively 12% and 14%), but represent an attempt to provide reasonable values of emergency exit usage based on experimental data.

Several considerations may be performed on the predictive algorithms of the models employed. Analytical calculations (approach A) did not permit to predict the emergency exit usage. For this reason, this method should be avoided if the scenarios under consideration include predicting the choice among different exits along the evacuation route. STEPS, Gridflow, Pathfinder and Simulex do not include a sub-algorithm able to predict the impact of different way-finding installations on agent exit choice. This is reflected in the fact that their calibration should be based only on experimental data or other model results.

As expected, results provided using the *a priori* modelling approach B (the application of default settings) showed that the approach was not sufficient to simulate the impact of different emergency exit layout and rank the effectiveness of the installations employed in the different scenarios. The predicted usage of emergency exit should then rely on a higher degree of modelling sophistication.

Results provided by approach C (model configuration) are dependent on the models employed. BuildingEXODUS and FDS+Evac were able to rank qualitatively the different emergency exit layouts and the results produced are qualitatively in line with the collected experimental data i.e., layout 2 is the more effective system. The other models rely only on a deterministic calibration of the model input. The lack of empirical information was instead the cause of the inaccurate prediction of specific behavioural aspects. An example is the observed percentage of the emergency exit usage with layout 3 in the case of participants in the proximity of the exit, i.e., location A (see scenarios 3A in Table 15). As described by Fridolf et al. [2012], the actual behaviour of some occupants was to choose to continue to go towards the opposite side of the tunnel although they noticed the emergency exit. This was because they thought the exit was a train. This was reflected in the results obtained with all the *a priori* modelling techniques employed, where all models provided higher emergency exit usage for agents placed in the proximity of the exit (location A and scenario 3A) than the behaviours observed during the experiments. The use of the experimental results in the *a posteriori* simulations (approach E) was instead useful to reproduce this problem, i.e. the percentage of usage in Scenario 3A became similar to the experimental data observed (62 %).

Results about exit choice produced by buildingEXODUS and FDS+Evac were affected by their embedded exit selection algorithm. Results confirmed that models were able to qualitatively predict the effectiveness of different emergency exit layout when the input was adequately calibrated (approach C, D and E). In FDS+Evac, the predictive capabilities are affected by the fact that an exit is usable as long as the exit is placed at a distance less more than twice the visibility distance. This basic hypothesis used by the model is not justified by experimental data and it may be not in line with the observed behaviours. An example is the result obtained for scenario 1B where the model in all the approaches provides an emergency exit usage of 0 %. For this reason, buildingEXODUS was considered as the reference model for the problem of exit choice in the multi-model approach.

Table 15. Summary of emergency exit usage (%) for approaches A-E and experimental results.

Experimental results			
Scenario	Emergency exit usage (%)		
1A	100		
1B	67		
2A	100		
2B	78		
3A	62		
3B	67		
Approach A: No predictions of emergency exit usage			
Approach B			
Scenario	FDS+Evac	buildingEXODUS	Gridflow, STEPS, Pathfinder, Simulex
1A, 2A, 3A	100	28-32	100
1B, 2B, 3B	0	22-28	100
Approach C			
Scenario	FDS+Evac	buildingEXODUS	Gridflow, STEPS, Pathfinder, Simulex
1A	50	41	50
1B	0	2	0
2A	82	72	90
2B	62	53	70
3A	82	76	90
3B	56	37	60
Approach D			
Scenario	FDS+Evac	buildingEXODUS	Gridflow, STEPS, Pathfinder, Simulex
1A	36	39	39
1B	0	1	1
2A	70	74	74
2B	46	49	49
3A	66	71	71
3B	34	33	33
Approach E			
Scenario	FDS+Evac	buildingEXODUS	Gridflow, STEPS, Pathfinder, Simulex
1A	100	87	100
1B	0	54	67
2A	100	75	100
2B	76	64	78
3A	60	58	62
3B	66	50	67

In the multi-model approach, the *a priori* capabilities of the models are used together. Qualitatively valid predictions of emergency exit usage and agent speeds were obtained, i.e., the effectiveness of the different emergency exit layout produced was in line with the observed experimental data. From a quantitative point of view, model predictions shows problems in predicting "unexpected" behaviour in the case of lack of experimental data, such as the occupants interpreting the exit as a train in scenario 3A.

4. Assessment of the modelling approach

Different modelling approaches have been tested in this paper, in line with the description made in Section 2. Six evacuation models have been employed and the comparison between the results obtained permits to derive recommendations on the approaches to use in relation to the scenarios to be simulated.

Analytical calculations (approach A) may be used if the evacuation scenarios to be simulated include homogeneous behavioural aspects, i.e., the predominant need is the calculations of human flows along a single path. This approach is not recommended if the tunnel is equipped with way-finding installations, which impact can't be implemented with this approach and people have to choose their evacuation path among different possibilities, i.e. several exits are available. Such calculations provide a simplistic prediction of evacuation and movement times with human behaviour being defined by the user rather than being predicted.

The individual use of evacuation models through the use of default settings (approach B) is recommended only if the modeller has verified that the embedded data-sets/default configuration of the model in use is in line with the scenario to be simulated. This can be achieved by the comparison with the documentation provided with the model, which should include detailed information on the data-sets/default settings employed. In the present work, the use of default settings was not sufficient, i.e. the emergency exit usage was dependent on the exit layout in use which should instead be modelled within the models after the analysis of the relevant literature.

The individual use of evacuation models through the process of input calibration (approach C) may be used in tunnel scenarios if the scenarios under consideration are not extremely complex, i.e., the geometry of the tunnel is simple and the user is able to identify one model which capabilities permit to simulate the key behavioural aspects. In addition, sufficient experimental data are required to correctly calibrate the evacuee's behaviours.

The analysis of the case study showed that the only two models able to directly represent the impact of different emergency layout on exit choice in smoke-filled environment were buildingEXODUS and FDS+Evac. It was therefore possible to derive from them *a priori* qualitative information on the effectiveness of the different systems. In contrast, the quantitative evaluation of the results shows the need of experimental data to calibrate the model input, because no quantitative data was available to calibrate the exact percentages of emergency exit usage of the layout studied during the experiments. The experimental data described in Section 3.1 and in the paper by Fridolf et al [2012] permitted to calibrate this variable in the a *posteriori* simulation step (approach E) and increase the reliability of the results. The *a posteriori* simulations performed showed that once the models are calibrated deterministically with experimental data, the results produced are in line with the expected performance, i.e., results were less influenced by the modelling assumptions employed.

In the case of very complex scenarios e.g. a complex tunnel geometry, several way-finding installations, high occupant densities, interaction smoke-occupants, etc. the multi-model approach is recommended. This approach enables the modeller to simulate different behavioural aspects applying together the models that are most suitable for different specific variables , i.e., one model(s) may be the reference model for one problem, while another model(s) is the benchmark for another problem. Results are therefore merged in an iterative process of input calibration which permits to use together the best sub-algorithms included in each model and increase the accuracy of the results produced.

5. Discussion and Conclusion

This paper presented different approaches to simulate tunnel evacuation scenarios and provided a test of the capabilities of six models, namely FDS+Evac, buildingEXODUS, STEPS, Pathfinder, Gridflow and Simulex. Different modelling approaches have been described and a novel multi-model approach has been presented. The predictive capabilities of the models have been tested against a set of experimental data given the tunnel evacuation scenarios.

The analysis permitted the exploration of the capabilities of the models employed in relation to two main aspects of the evacuation process in tunnels, namely 1) the impact of smoke on agent walking speeds and 2) the impact of different way-finding installations on exit choice.

FDS+Evac has been the model that best represented the impact of smoke on agent walking speeds given the similarities between the scenario under consideration - an evacuation experiment - and the data-set embedded in the model - the Frantzich and Nilsson's data-set [Frantzich and Nilsson, 2003]. Models including the possibility to implement any data-set, e.g., Gridflow, were identified as effective tools as well but required a higher degree of modeller's expertise to configure the input. Models without an embedded correlation about the impact of smoke on agent speeds, e.g., Pathfinder, Simulex, did not permit to reproduce the effect of changing visibility conditions. Modellers need then to perform an evaluation of the possible agent speeds, given the visibility conditions, prior to run the simulations.

FDS+Evac and buildingEXODUS are the only models, among the six models employed, embedding a sub-algorithm that permitted to directly take into account the influence of smoke on people exit choice [Ronchi et al. 2012]. BuildingEXODUS was identified as a model with an effective predictive sub-algorithm to study the impact of way-finding installations on exit choice, given the embedded sophistication of the sub-algorithm to simulate the interaction between the agents and the signage.

It should also be noted that evacuation models generally simulate approximately direct evacuation paths, i.e. they do not take into account the actual patterns made by people during the evacuation. Modelling speeds, i.e., speeds including stops, may be introduced in models to take into account of these differences in the actual behavioural process. One problem is that even if the stops during the evacuation are taken into account in the modelling speeds, the actual evacuation paths made by the evacuees are not simulated. This modelling assumption may be overcome if the model is able to reproduce specific patterns, as it may be necessary in the case of reconstruction analysis (forensic). In fact, buildingEXODUS, STEPS and Pathfinder are able to reproduce assigned itineraries and reproduce the desired pattern of the agents.

With regards of general applicability of evacuation models, continuous models, e.g. FDS+Evac, Pathfinder, Simulex, Gridflow, are generally more effective in simulating people movement, in particular in the case of high occupant densities as it may be the case of pedestrian tunnels. This is essentially due to the sensitivity of fine/course network models, e.g., STEPS, buildingEXODUS, to the grid employed in the calculation. This was shown in previous studies [Lord et al., 2005] and it is then recommended to perform dedicated analysis aimed to test the sensitivity to the grid employed when using this type of models for evacuation scenarios including high people densities.

Analytical calculations are useful only in the case that the distance criteria is predominant among the other evacuation aspects, e.g., there are no available way-finding installations, only one evacuation path/exit is available, etc. The individual use of evacuation models may be effective if the model in use is selected after a review of its characteristics in relation to the scenarios to be simulated and modellers have sufficient information to calibrate their input. The six models presented different characteristics which make them useful for different types of tunnel applications. The presented new framework of the multi-model approach permits to use each model at its best and enables the simulation of very complex scenarios using one or more models as reference for the behaviours to be simulated. This method requires high degree of modelling effort and user's expertise. In the case of very complex scenarios, the individual capabilities of one model may be not sufficient and the multi-model approach permits to use together different models and obtain accurate results in term of prediction of people performance.

Acknowledgments
The author wish to acknowledge Steve Gwynne for his contribute in the application of the buildingEXODUS model. The author also thanks Daniel Nilsson for his valuable suggestions.

References

ANAS (2009). Linee Guida per la Progettazione della sicurezza nelle Gallerie Stradali. Seconda Edizione [In Italian, National administration of roads and highways, Guidelines for the road tunnel safety design], Condirezione Generale Tecnica, Direzione Centrale Progettazione.

Bensilum M & Purser DA (2003). Gridflow: an object-oriented building evacuation model combining pre-movement and movement behaviours for performance-based design. Fire Safety Science. In Proceedings of the Seventh International Symposium, Worcester, Massachusetts, USA, pp.941-952.

British Standards Institution 5266-7:1999, Lighting applications. Emergency lighting.

British Standards Institution 5499-4:2000, Safety signs, including fire safety signs. Code of practice for escape route signing.

Carvel R & Marlair G (2011). A history of fire incidents in tunnels. In A. Beard & R. Carvel (Eds.), Handbook of Tunnel Fire Safety. Second ed London: Thomas Telford, pp. 3-23.

Council Directive (EC) (2004) 2004/54/EC of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network.

Duffé P & Marec M (1999). Task Force for Technical Investigation of the 24 March 1999 Fire in the Mont Blanc Vehicular Tunnel.: Minister of the Interior - Ministry of Equipment, Transportation and Housing.

Frantzich H & Nilsson D (2003). Utrymning genom tät rök: beteende och förflyttning [Evacuation in dense smoke: behaviour and movement] (No. 3126). Lund: Department of Fire Safety Engineering and Systems Safety.

Fridolf K, Nilsson D, Frantzich H (2011). Fire Evacuation in Underground Transportation Systems: A Review of Accidents and Empirical Research. Fire Technology.

Fridolf K, Ronchi E, Nilsson D, Frantzich H (2012) Movement speed and exit choice in a smoke-filled rail tunnel (Manuscript submitted for publication).

Galea ER, Gwynne SMV, Lawrence PJ, Filippidis L, Blackshields D, Cooney D (2004). buildingEXODUS V4.0 User Guide and Technical Manual. University of Greenwich.

Gandit M, Kouabenan DR, Caroly S (2009). Road-tunnel fires: Risk perception and management strategies among users. Safety Science, 47(1), pp. 105-114.

Gwynne SMV & Rosenbaum E (2008). Employing the Hydraulic Model in Assessing Emergency Movement. In the SFPE Handbook of Fire Protection Engineering, 4th Edition. National Fire Protection Association, Quincy, MA, pp. 3-396-3-373.

Gwynne SMV (2010). Conventions in the collection and use of human performance data, National Institute of Standards and Technology GCR 10-928.

Jin T (2008). Visibility and Human Behavior in Fire Smoke. In the SFPE Handbook of Fire Protection Engineering (fourth edition). National Fire Protection Association, Quincy MA, USA.

Korhonen T & Hostikka S (2010). Fire Dynamics Simulator with Evacuation: FDS+Evac Technical Reference and User's Guide. FDS 5.5.3, Evac 2.3.1. VTT working papers.

Korhonen T & Heliövaara S (2011). FDS+Evac: Herding Behavior and Exit Selection. In Proceedings of the 10th International IAFSS Symposium, 19-23 June 2011, University of Maryland, MD, USA. The International Association for Fire Safety Science, IAFSS.

Kuligowski ED, Peacock RD, Hoskins, BL (2010). A Review of Building Evacuation Models NIST, Fire Research Division. 2nd edition. Technical Note 1680 Washington, US.

Kuligowski ED (2011). Predicting Human Behavior during Fires. Fire Technology, Vol. 48.

Leitner A (2001) The fire catastrophe in the Tauern Tunnel: experience and conclusions for the Austrian guidelines. Tunnelling and Underground Space Technology, Vol. 16, pp. 217-223.

Lord J, Meacham B, Moore A, Fahy R, Proulx G (2005). Guide for evaluating the predictive capabilities of computer egress models, NIST Report GCR 06-886.

Maevski IY (2011). Design Fires in Road Tunnels, A synthesis of Highway Practice, Transportation Research Board NCHRP National Cooperative Highway Research Program Synthesis 415.

Mott MacDonald Simulation Group (2011). Simulation of Transient Evacuation and Pedestrian movementS STEPS User Manual 4.1 Version.

Nilsson D (2009). Exit choice in fire emergencies - influencing choice of exit with flashing lights. Phd Dissertation. Lund University, Lund, Sweden.

Nilsson D, Johansson M, Frantzich H (2009). Evacuation experiments in a road tunnel: A study of Human Behaviour and technical installations, Fire Safety Journal 44, pp. 458-468.

NFPA (2011). NFPA 502 Standard for road tunnels, bridges and other limited access highways, 2011 edition.

NFPA101 Life Safety Code (2012)

Purser DA (2009). Application of human behaviour and toxic hazard analysis to the validation of CFD modelling for the Mont Blanc Tunnel fire incident. In Proceedings of the Advanced Research Workshop on Fire Protection and Life Safety in Buildings and Transportation Systems 2009, Santander, Spain, pp 23-57.

Ronchi E, Alvear D, Berloco N, Capote J, Colonna P, Cuesta A (2010). Human behaviour in road tunnel fires: Comparison between egress models (FDS+Evac, STEPS, Pathfinder). In Proceedings of the twelfth international Interflam 2010 Conference, Nottingham, UK, pp. 837-848.

Ronchi E, Nilsson D, Gwynne SMV (2012), Modelling the impact of emergency exit signs (Manuscript submitted for publication).

Ronchi E, Gwynne SMV, Purser DA, Colonna P (2011a). Representing the impact of smoke on agent walking speeds in evacuation models (Manuscript submitted for publication).

Ronchi E, Gwynne SMV, Purser DA, (2011b). The impact of default settings on evacuation model results: a study of visibility conditions vs occupant walking speeds. In Proceedings of EVAC11, Santander (Spain)

Ronchi E & Kinsey M (2011). Evacuation models of the future. Insights from an online survey on user’s experiences and needs. In Proceedings of EVAC11, Santander (Spain)

Shields J (2005) Human behaviour in tunnel fires. In: Beard A, Carvel R (eds) The handbook of tunnel fire safety Thomas Telford Publishing, London

Thompson PA & Marchant EW (1995). A Computer Model for the Evacuation of Large Building Populations, Fire Safety Journal 24, pp. 131-148.

Thunderhead Engineering (2011). Pathfinder (2011 Version). Technical Reference.