VERTICAL TRANSPORT EVACUATION MODELLING

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A thesis submitted in partial fulfilment of the
requirements of the University of Greenwich
for the degree of Doctor of Philosophy

September 2011

DECLARATION

I, Michael Kinsey, certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of the Doctor of Philosophy (PhD) being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others.

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ACKNOWLEDGEMENTS

First and foremost I would to thank my supervisors for their guidance and inspiration throughout the course of this thesis. Specifically I would like to thank Prof Ed Galea for allowing me to embark on a PhD (again!), his general advice and patience. I would like to thank Dr Peter Lawrence for his constant support, providing coding assistance for development within buildingEXODUS, and the 'therapy sessions’ when things were not going according to plan.

In addition there are a number of other individuals/groups without which it would not have been possible to complete the presented work, this includes:

- the Engineering and Physical Sciences Research Council (EPSRC) for providing funding for my PhD candidate position,
- the University of Greenwich Research Ethics Committee for approving the human factors surveys,
- Roderic Jones and James Daniel of Kingfell Ltd for organising/assisting with the collection of escalator video footage in the London Underground,
- Dr Jun Chi Ma and Dr Han Xin from the Shanghai Institute of Disaster Prevention and Relief (Tong Ji University, China) for organising/assisting with the collection of escalator video footage in the Shanghai Metro,
- my family and friends for providing support and restraining from asking me "when are you going to get a real job?" too often,
- the 'Lunch Club' (Angus Grandison, John Ewer, Darren Blackshields, Lynn Hulse and Rachel Day) who provided invaluable guidance and midday humour,
- Aoife Hunt for proof reading various sections of the thesis,
- everyone in the Fire Safety Engineering Group (FSEG) at the University of Greenwich who has given advice or general support over the course of this work.

PUBLICATION NOTES

The work produced as part of this thesis has been published in various literature including journals and conference proceedings. The list of these publications along with associated thesis chapters can be seen in Table 1 below. A copy of the papers can be found in Appendix A7.1.

Table 1: Thesis publication list with associated chapters

#	Publications	Chapter(s)
1	Kinsey, M.J, Galea, E.R, Lawrence, P.J, (2008), 'Modelling Pedestrian Escalator Behaviour', Proceedings of the Pedestrian and Evacuation Dynamics Conference, pp689-696.	Chapter 7 Chapter 8
2	Kinsey, M.J, Galea, E.R, Lawrence, P.J, (2009), 'Investigating the Use of Elevators for High rise Building Evacuation through Computer Simulation', Proceedings of the Human Behaviour in Fire Conference, pp85-96.	Chapter 5 Chapter 6
3	Kinsey, M.J, Galea, E.R, Lawrence, P.J, (2009), 'Extended Model of Pedestrian Escalator Behaviour Based on Data Collected within a Chinese Underground Station', Proceedings of the Human Behaviour in Fire Conference, pp173-182.	Chapter 7 Chapter 8
4	Kinsey, M.J, Galea, E.R, Lawrence, P.J, (2010), 'Stairs or Lifts? – A study of Human Factors associated with Lift/Elevator usage during Evacuations using an online Survey', Proceedings of the Pedestrian and Evacuation Dynamics Conference.	Chapter 4
5	Kinsey, M.J, Galea, E.R, Lawrence, P.J, (2010), 'Human Factors Associated with the Selection of Lifts/Elevators or Stairs in Emergency and Normal Usage Conditions', Fire Technology, DOI: 10.1007/s10694-010-0176-7.	Chapter 4
6	Kinsey, M.J, Galea, E.R, Lawrence, P.J, (2011), 'Investigating Evacuation Lift Dispatch Strategies using Computer Modelling', Fire and Materials, DOI: 10.1002/fam.1086.	Chapter 5 Chapter 6

ABSTRACT

Within any high-rise structure or underground/subway station, occupants often heavily rely on vertical transport devices (e.g. escalators, lifts, etc) to travel vertically between levels. Typically such devices provide a faster and more comfortable means to travel than the equivalent stairs. Such devices also provide an additional means for occupant egress. However, the provision for utilising such devices in actual buildings for evacuations is rare. Despite a select number of structures throughout the world allowing the use of vertical transport devices within evacuation scenarios, little is understood with regards to evacuation vertical transport strategies and to what extent such strategies may be influenced by associated human factors. This thesis is intended to address this lack of understanding.

The thesis provides an in depth review of evacuation usage of vertical transport devices in actual evacuations, their provision in building codes, empirical studies analysing human factors, representation within simulated environments, and analysis of previously explored operational strategies. The review provides a broad set of research questions that the thesis is intended to address. Human factors data associated with vertical transport device usage have been collected via an online survey and video analysis. The data analysis has instructed the development of the vertical transport device models and associated agent models within the buildingEXODUS evacuation software. The models include the representation of device selection, the influence of local conditions in close proximity to a device, and the influence of wait time upon device selection. The developed models have been used to demonstrate the influence of different vertical transport strategies and to what extent such strategies are influenced by human factors. Finally, the thesis concludes by summarising the increased understanding achieved through the work presented.

CONTENTS

FIGURES

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Chapter 1 - Introduction

1.1 Introduction

This chapter describes the motivations for the research presented in this thesis along with the subsequent objectives, thesis outline, and contributions to the field in general.

1.2 Research motivations

A 'vertical transport device' within a building can be defined as any device that transports occupants vertically from one level to another. For the purpose of this thesis the term refers specifically to lifts (elevators) and escalators. Whilst both types of device share a number of common characteristics, the nature in which they are used by occupants, employ different operational strategies and provide different levels of service varies considerably.

The increased demand for both residential and commercial space, particularly in central urban areas, coupled with the decreased availability and increased value of land, has caused a proliferation of high-rise building development throughout the world. The rapid growth of some previously relatively less developed economies (e.g. China), has been a catalyst for this trend. This is exemplified in the Council for Tall Building and Urban Habitat's (CTBUH) list of tallest buildings in the world. In 1950 almost all of the 100 tallest completed buildings in the world were located in the US [CTBUH, 2010]. However, 60 years later (2010), the US only accounts for some 28.0% of the 100 tallest completed buildings, with countries such as China (32.0%) and the United Arabs Emirates (18.0%) accounting for an increasing share of the top 100 tallest buildings in the world [CTBUH, 2010]. In addition to the geographical spread of high-rise buildings, the buildings themselves are increasing in height with the average height of the 100 tallest buildings more than doubling between 1930 (160m) to 2010 (350m); representing an average increase of 2.4m per year (see Figure 1) [CTBUH, 2010].

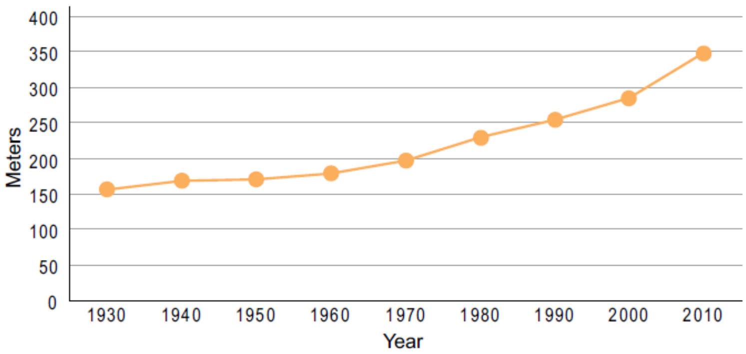


Figure 1: Average height of the 100 tallest buildings in the world [CTBUH, 2010]

This proliferation of high-rise buildings of increasing height throughout the world coupled with the World Trade Center 911 attacks [Averill, et al., 2005], has cast doubt over the capability of such buildings to provide adequate simultaneous full building evacuation using stairs alone. Indeed the introduction of sprinkler systems in high-rise buildings has meant that it is common to find such buildings are only designed to accommodate phased full/partial building evacuation. In such structures the respective emergency stairwell widths prescribed are only designed to accommodate simultaneous evacuation from a select number of floors [Brannigan and Miller-Hooks, 2007] (i.e. not designed for full simultaneous evacuation). Subsequently, the use of lifts during evacuations, whilst not a new concept for the transport of disabled occupants and fire fighter access [British Standards, 2008], has become a serious consideration over the last decade for the general population [Kinsey, et al., 2011]. Ironically, it is only with the use of lifts and the vertical transport capacity that they provide in normal circulation that such high-rise buildings could be designed and built [Barney, 2003]. Several building codes and standards have now begun to consider and include the provision for lift usage for the general population during evacuations [ICC, 2009; NFPA, 2009a; NFPA, 2010; British Standards, 2008].

The increased interest in evacuation lifts requires the examination of the potential merits of evacuation lift strategies and associated human factors. For instance, whether operational strategies can be designed, the impact on performance, the representation within performance-based design, and whether people, in reality, will follow the strategies implemented and use lifts during an emergency. Indeed, current building codes that allow the provision for evacuation lifts do not mention operational strategies for the use of lifts, merely stating when lifts can be used; (e.g. prior to a hazard being detected close to a lift system) [ICC, 2009; NFPA, 2009a; NFPA, 2010]. One method for understanding such issues would be to conduct a full building evacuation of an actual high-rise structure multiple times to assess the impact of different operational strategies and human factors. However, conducting such trials is highly impractical given the time/cost constraints for the people and companies involved. In addition, simultaneously evacuating potentially thousands of occupants using the stairs/lifts, even for a drill, is potentially hazardous. Considering such issues, along with the fact that occupants have traditionally been instructed for the past 40 years to not use lifts during evacuations, very little evacuation lift human factors data has been collected. Consequently, very little is understood regarding such behaviour. This means that if lifts were to be considered for use during an evacuation without due consideration to associated lift human factors, there could potentially be negative consequences. For example, building codes may allow the provision for evacuation lifts to replace the need for additional evacuation stairs (as allowed in certain situations in the ICC, 2009 International Building Code [ICC, 2009]). However, if a disproportionate number of occupants chose to only use the stair during an evacuation, instead of using the available lifts, then this could considerably extend an evacuation.

Further to the need to understand associated human factors, there is also a need to understand the influence of different evacuation lift strategies: identifying how the lift system should be utilised to maximise benefit during an evacuation. Performing multiple evacuation drills within a real building utilising different lift strategies to optimise the results is simply not practical for most high-rise buildings due to the aforementioned costs/reasons. In addition, such drills would not be possible for buildings still in the design phase. A more efficient, cost effective, faster and safer method for exploring the influence of different evacuation lift strategies and the influence of human factors on such strategies is with the use of computational evacuation modelling tools and techniques. Assuming accurate representation, such methods also provide a means to forensically explore past evacuation incidents in order to understand and suggest improvements to training, procedure and operational strategies.

With lift systems themselves being governed by broadly understood laws of physics, modelling lift movement in simulated environments is relatively straightforward [Peters, 1996]. However, as previously mentioned, associated human factors are less well understood with representation within evacuation models either not being possible or very simplistic. At present, with the scarcity of lift human factors data, such behaviour within evacuation models (where existing) either require users to explicitly define the behaviour or is based on optimal behaviour with no empirical basis [Kinsey, et al., 2009a; Kinsey, et al., 2010]. The lack of representation of empirical-based lift human factors within evacuation models has meant that lift evacuation simulation results are considered questionable [Kinsey, et al., 2010].

Similar to high-rise buildings, there has been an increased spread in popularity of underground/subway stations throughout the world in urban city centres in the 20th century [Cudahy, 2004]. The increased usage of cars in such areas and subsequent levels of traffic on the roads has in turn increased the need for alternate methods of public transport within central urban areas, further amplified by imposed environmental regulations [Newman and Kenworthy, 1999; Baum-Snow and Kahn, 2000].

The development and expansion of underground stations, often required to be located deep underground, has only been possible with the introduction of escalators to transport large volumes of occupants through such areas [Strakosch and Caporale, 2010]. Underground stations are therefore already reliant upon on escalators during both circulation and emergency situations. As with lifts, relatively few studies have attempted to quantify escalator human factors, with a large number of past studies focusing on establishing capacity rather than use [Al-Sharif, 1996; Cheung and Lam, 1998; Davis and Dutta, 2002]. Given this, many evacuation models simulate escalators using a flow model; representing homogenous occupant behaviour on the device assuming implicit representation of micro-level behaviour. This means that simulation results using such models are questionable and potentially optimistic [Kinsey, et al., 2009b]. As such there is a need to quantify and understand human factors associated with escalator usage and represent such devices more accurately within evacuation models so that conformance to performance based codes can be reliably demonstrated.

Whilst there are a number potential benefits of using both lifts and escalators during evacuations for fire fighting services [Barker, 1995; Bukowski, 2005a] and individuals with disabilities [Barker, 1995; Fox, 1991; Shields, et al., 2009], the focus of the thesis is evacuation device usage for the general population.

1.3 Research objectives and thesis outline

The objectives of this thesis are to:

- Advance the understanding of human factors associated with the use of lifts/escalators and the influence of associated operational strategies during evacuations.
- Measure the potential extent to which human factors may influence such evacuation lift/escalator strategies.

In Chapter 2 of this thesis an extensive review of literature was conducted to identify the current understanding of lift/escalator usage during evacuations, associated human factors, associated building codes/standards and current modelling tools to represent lifts/escalators. Based on this review a number of research questions have been devised:

Lifts

Questions 1: How would occupants behave given that they have the option to use a lift during an evacuation?

A series of further sub-questions have also been identified:

- What proportion of occupants would actually consider using a lift during an evacuation given they were told that it is safe to do so?
- Does this proportion differ between occupants from different countries, of different gender, BMI and age groups?
- Would the proportion of occupants willing to use a lift during an emergency vary according to floor height?
- What level of crowding in lift waiting areas would cause occupants to redirect from the lift to the stairs during an evacuation?
- How long would occupants be prepared to wait to use a lift before redirecting?
- How would such levels of crowding and lift wait times vary according to floor height during an evacuation?

To address these research questions an online survey was conducted. The nature of the survey and an analysis of the results are presented in Chapter 4.

Question 2: How should human factors associated with evacuation lifts be modelled?

This prompts two sub-questions:

- How should lift/stair selection be modelled?
- How should lift waiting area behaviour be modelled?

The literature reviewed and human factors data collected has been used to help develop a lift model within the buildingEXODUS software. These research questions are addressed in Chapter 5.

Question 3: To what extent would different lift strategies influence an evacuation?

The development of a lift and agent lift model within an existing evacuation modelling software allows the extent to which different lift strategies would influence an evacuation to be investigated. Following from this question, a series of sub-questions need to be answered:

- What influence does decreasing the number of lifts available have upon an evacuation?
- To what extent is it more efficient to use both lifts and stairs compared to stairs or lifts alone?
- Is it efficient to use sky lobbies as staging areas for evacuations?
- Is it efficient to use vertical zoning for evacuations?
- How does lift human behaviour influence different lift strategies?

A series of evacuation scenarios using the developed lift and agent lift model have been performed to address the above research questions. The results from this analysis are presented in Chapter 6.

Escalators

Question 4: How do occupants behave on escalators during evacuations?

A series of further sub-questions have also been identified:

- What proportion of occupants would use an escalator and adjacent stair?
- Would these proportions differ according to different levels of congestion at the entrance to the escalator/stair?
- What proportion of escalator users would walk/ride on an escalator?
- What proportion of riders/walkers would use each side of an escalator?
- What speed would escalator users walk at?
- What is the maximum recorded flow-rate for escalators?

- When such high flow-rates occur are there any determining characteristics of the escalator users?
- Does escalator human factors differ between countries, time period, and direction of travel? If so, to what extent?

To address these research questions escalator human factors data was collected via analysis of video footage of occupants using escalators in normal circulation conditions in three different locations each in a different country. The data collected relates to escalator/stair usage, walker/rider usage, side usage, walker speeds and flow-rates, along with several other factors. The analysis of the results has been presented in Chapter 7.

Question 5: How should human factors associated with evacuation escalators be modelled?

This suggests two sub-questions which are required to be answered:

- How should escalator/stair selection be modelled?
- How should the influence of local conditions be modelled upon escalator/stair selection?
- How should behaviour on escalators be modelled?

The literature review and data collection informed the development of the escalator and agent escalator model within buildingEXODUS. These research questions are addressed in Chapter 8.

Question 6: To what extent would different escalator strategies influence an evacuation?

This prompts a series of sub-questions that are required to be answered:

- To what extent would stopping an escalator moving decrease the efficiency of an evacuation?
- What influence does decreasing the number of escalators available have upon an evacuation?
- How does different escalator strategies influence an evacuation?
- To what extent does different escalator human factors influence each strategy?

A series of evacuation scenarios using the developed escalator and agent escalator model have been performed to address the above research questions. This work is discussed in Chapter 9.

Based on these research questions, the objectives and the subsequent structure of the thesis can be seen in Figure 2.

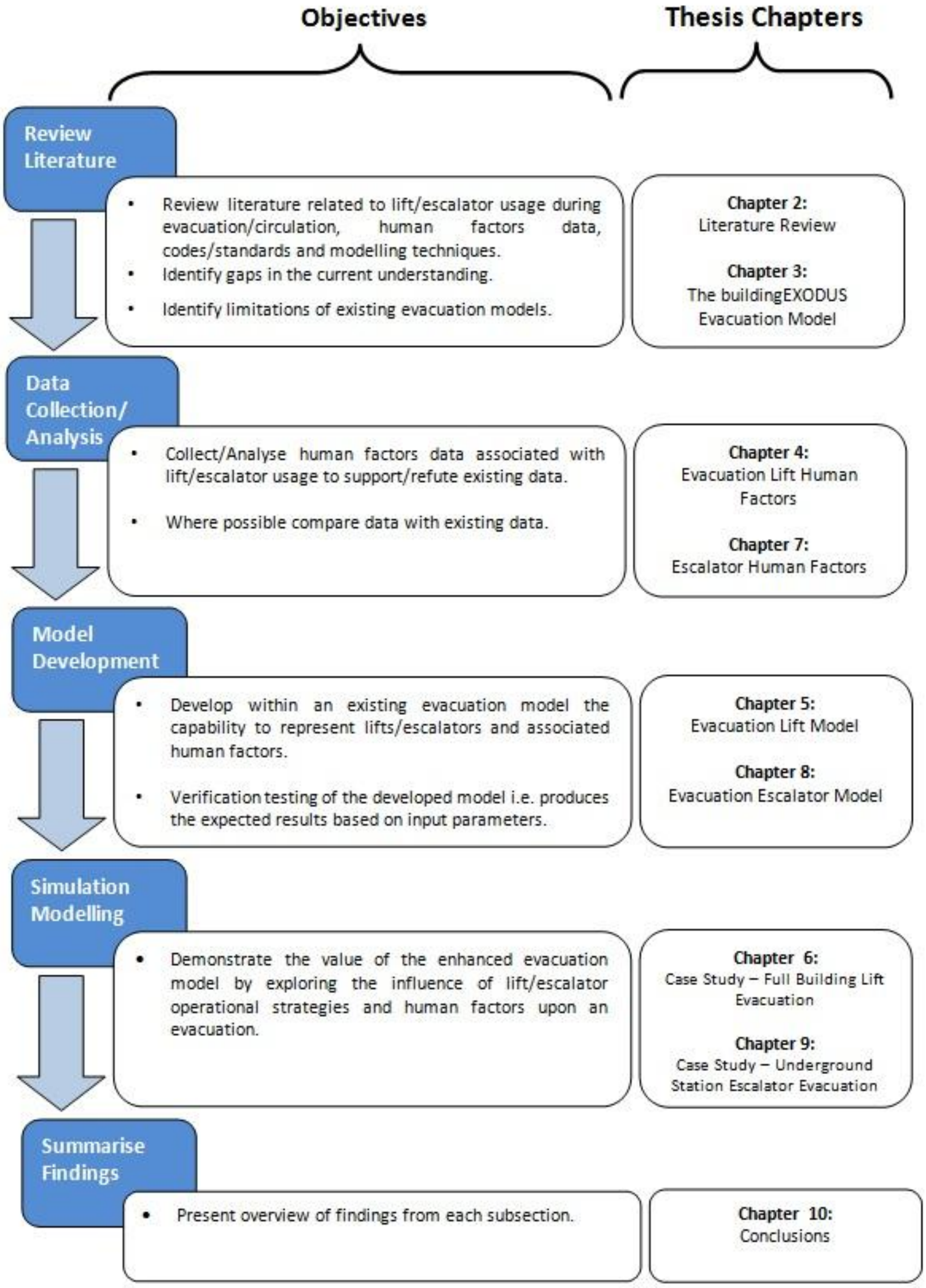


Figure 2: Research objectives and associated thesis chapters

1.4 Research contributions

The research presented in this thesis has provided a number of scientific contributions. The literature review provided an in-depth analysis of actual evacuation incidents that utilised lift/escalator, associated building codes, evacuation lift/escalator strategies, associated human factors data and a review of models that can simulate evacuations using lifts/escalators.

Lift/Escalator human factors data has been collected that has provided an increased level of understanding of how occupants behave on and around such devices. ***For escalator human factors, an increased level of understanding has been obtained regarding escalator/stair selection, flow-rates, walker speeds, walker/rider selection, and side preference selection.*** Data was collected from three different countries which allowed a comparison of how escalator human factors potentially differ between each country. This international study represents one of the most detailed and broadly scoped collection of escalator human factors to date.

For lift human factors, an increased level of understanding has been obtained through data collection relating to human factors consideration to use lifts, the influence of floor height, congestion level redirection, and wait time redirection on the decision to use lifts during evacuations. The data has been analysed overall and for certain criteria according to demographic factors. This includes a cross comparison of participants responses from different countries, BMI (Body Mass Index) groups, age groups, and gender groups. The collected human factors data is considered to represent some of the key facets that influence occupant behaviour during an evacuation. This is first time that a broad range of lift human factors has been collected/quantified using such a demographically diverse sample population. With the current considerations to use evacuation lifts for the general population in a number of countries, the international nature of the data means the findings presented are particularly relevant to a number of countries' current needs within the field.

The representation of lifts/escalators and associated human factors has been developed within an existing evacuation software (buildingEXODUS). Based on published literature, the lift/escalator human factors represented are the first time that such empirical based processes have been explicitly represented on a micro-level within an evacuation model. ***The model has been used to demonstrate the influence of different lift/escalator strategies and to what extent these may be influenced by associated human factors.*** This is the first time that the influence of such a broad variety of human factors has been explicitly represented for such a broad variety of evacuation lift/escalator strategies.

Findings from the evacuation analysis using the developed lift/escalator model can be applied to a range of different evacuation scenarios for other structures beyond those explored in this thesis. Potential benefactors of the research include lift manufacturers, fire safety engineers, building regulators, model developers or indeed any parties interested in the use of evacuation lifts/escalators. Further to this, the development of the lift/escalator model will allow future model users to perform in depth evacuation analysis of both high-rise buildings and underground stations utilising lifts/escalators. In addition the conceptual representative framework of human factors described in the thesis could theoretically be used to instruct similar functionality within other evacuation models.

Chapter 2 - Literature Review

2.1 Introduction

Only a small number of studies have been conducted that have investigated the use of lifts and escalators during evacuations for the general population. The representation of such devices and associated human factors within simulated environments has also been sparse and questionable. This chapter presents a review of the current literature pertaining to this subject.

Both the evacuation lift (section 2.2) and escalator (section 2.3) sections within the chapter have similar structures. After defining a broad context, each section initially gives an overview of some of the past usage of lifts and escalators during both actual and drill evacuations. A broad overview of current building codes, standards and guidelines is then presented. Documented empirical and qualitative human factors data associated with lift and escalator usage is then analysed. A broad description of some of the current evacuation/circulation/lift models is then presented followed by an overview of the emergency operational strategies and simulation results using such devices. Whilst there are a number potential benefits of using lifts and escalators during evacuations for fire fighting services [Barker, 1995] and individuals that are disabled [Proulx, et al., 2009], the focus of this work is device usage for the general population.

2.2 Evacuation lifts

Since the wide-scale adoption of sprinkler systems in high-rise buildings, there has been an expectation that there would rarely, if ever, be a need to undertake full building evacuations. As a result there has been little appetite to seriously explore the use of lift systems for evacuations. However, since the World Trade Centre 911 disaster, there has been a renewed interest in the possible use of lifts for evacuation of high-rise buildings [Bukowski 2008; Koshak, 2003]. Such events have also highlighted the need for high-rise buildings to be able to accommodate full scale evacuations and not simply cater for a defend in place strategy whereby only select floors/areas are evacuated. Indeed, emergency stair widths are often prescribed such that they allow all occupants on a single floor to evacuate in a given amount of time [Boyce, et al., 2009] (i.e. they are not primarily designed for full building egress).

Furthermore, recent computer simulations of high-rise building evacuation suggest that there is a critical floor population density for a given staircase capacity that effectively limits the height of high-rise buildings that can be practically evacuated by stairs alone [Galea, et al., 2008].

Despite the increased interest in using lifts for evacuation, very little literature exists regarding operational and associated human factors. Surprisingly, despite this lack of detailed understanding, a number of high-rise buildings throughout the world allow for the use of lifts during both fire and/or non-fire evacuations for the general population (e.g. Burj Khalifa (UAE) [Evenson and Vanney, 2008], Shanghai World Financial Center (China) [Bukowski, 2008b], Petronas Towers (Malaysia) [Ariff, 2003], Tapei 101 (China) [Hsiung, et al., 2009], Stratosphere tower (US) [Bukowski, 2006], Canary Wharf site (UK) [Charters and Fraser-Mitchell, 2009], Eureka Tower (Australia) [Kuligowski, 2003], etc).

2.2.1 Lift usage during evacuations

In a number of past evacuation situations lifts have been used to good effect to assist in the rapid egress of high-rise buildings [Averill, et al., 2005; Howkins, 2000; Proulx, et al., 2004; Proulx, et al., 1995; Sekizawa, et al., 1999]. In addition, there have been a number of evacuation situations where the use of lifts has resulted in reduced evacuation performance, occupant injury or occupant fatalities [Averill, et al., 2005; Clark, 1981; NFPA, 1998]. In many of these incidents lifts were not intended to form part of the evacuation system but were either used by occupants to egress or occupants were initially located inside them during the initial stages of the emergency evacuation. This section describes a number of such incidents including both actual and drill evacuation situations where occupants used lifts. The incidents analysed include the World Trade Centre 911 evacuation, Cook County Administration Building Fire, Hiroshima Motomachi Fire, Joelma Building Fire and the MGM Grand Fire. In addition a select number of smaller actual and drill evacuations are documented where lifts were utilised.

World Trade Center 911Attack

On September 11th 2001 in the US, terrorists hijacked several commercial airplanes with the intent on flying them into a number of high profile buildings. Two buildings that were hit were World Trade Center Tower 1 (WTC1, North Tower) and World Trade Centre Tower 2 (WTC2, South Tower) in New York. Each tower was identical in height (526.3m, 110 floors) and internal configuration with 99 lifts and an estimated building population of WTC1 and WTC2 of 8,960 and 8,600 respectively at the time of each impact [Averill, et al., 2005]. Lifts serviced a series of 'sky lobbies' where occupants could travel to and from via shuttle lifts before using local lifts to travel to floors between the sky lobbies.

The first airplane struck WTC1 at 8:46:30 AM with an approximate impact zone around floors 93-99. The second airplane struck WTC2 at 9:02:59 AM (approximately 16 minutes and 29 seconds after WTC1) with an approximate impact zone around floors 77-85. Both WTC1 and WTC2 collapsed around 10:28:22 AM (1 hour, 41 minutes, 52 seconds after impact) and 9:58:59 AM (1 hour, 11 minutes, 29 seconds after impact) respectively while occupants were still attempting to evacuate. NIST estimates that between 1,462-1,533 occupants in WTC1 and 630-701 occupants in WTC2 died (the majority of which were on or above the impact zone) with around 7,470 and 7,940 occupants in WTC1 and WTC2 surviving respectively [Averill, et al., 2005].

The NIST report states that in WTC1 there were no operational lifts available for occupants to use as part of their egress. However, Fahy and Proulx [Fahy and Proulx, 2005] state that out of the 202 occupants that they interviewed initially in WTC1 who stated their means of egress, 3 used lifts at some point during their evacuation (not including 22 occupants that were trapped inside lifts). Whilst discrepancies between the exact number of lift users in WTC1 exist it is evident that very few occupants actually used lifts during the evacuation.

Many occupants who were initially in WTC2 observed the aeroplane impacting WTC1 and decided to evacuate the building before the 'official' call to evacuate was made. This should be kept in mind when considering the occupants’ acceptance to use lifts as they may have thought that since they have not been told to evacuate or that there was no fire in WTC2, it was still acceptable to use the lifts to leave the building. Indeed it is mentioned by Galea and Blake [Galea and Blake, 2004] from accounts mentioned in the mass media that there was some confusion as to whether it was acceptable to use lifts, as exemplified by the following statements from two occupant accounts:

"*Shouldn't we be taking the stairs in an emergency like this?" which was replied by her colleague with, "No! Just get in the elevator! C'mon!*" (Experience 1172) [Galea and Blake, 2004]

"*it was okay to take an elevator as they still had power.*" (Experience 1064) [Galea and Blake, 2004]

Other occupants decided that they knew they should not use lifts during an evacuation but due to the long travel distance decided it was acceptable:

"*We got to the 78th floor and Judy said, "Let's see if the elevators are working. I'm thinking I shouldn't be taking an elevator, but I guess the thought of walking down 78th floors in my high heels was not exactly something I wanted to do.*" (Experience 3314) [Galea and Blake, 2004]

Such reports suggest that even though building occupants are often aware of the common practice to not use lifts during evacuations, there are circumstances where they will use their own judgement to decide whether to use lifts or not (i.e. occupants do not merely just do what they are trained/told to do).

The NIST report estimates that approximately 86% of WTC2 occupants begun evacuating prior to WTC2 impact, with 18% of WTC2 occupants using a lift for at least part of their evacuation. From the surveyed occupants, segregating according to floors, occupants were more likely to use a lift higher up in the building, though the precise proportions are hard to determine due to the potentially high number of occupants that were not interviewed and the lack of accurate data regarding the occupancy levels on each floor during the incident.

A number of survivors interviewed, who were physically challenged, were reported to have used lifts to evacuate due to their physical condition.

Some evidence suggests that, when faced with large queues in lift waiting areas, occupants were not prepared to wait for lifts to service their floor. For example, there were reports from survivors who evacuated WTC1 who said:

"*Let me add too that, at the 44th floor there was what they call an inter-zone lift bank, we were led off the stairwell at the 44th floor and shown to that lift where there are hundreds of people milling and I looked at that and I turned around to my team and I said 'no, I am not waiting for a elevator in a building on fire. Let's go' and I walked back to the stairwell and they did too and then we proceeded down*" (WTC1/077/0001 P2, line 22-27) [Galea, et al., 2006a]

"*But he looked into the marble-lined lobby, more than half a city block long, and saw people were standing shoulder to shoulder, waiting for elevators. This is pointless, he thought.*"(Experience 2182) [Galea and Blake, 2004]

The above quotations also highlight that there were quite likely a higher proportion of occupants that would have considered using a lift to evacuate though were deterred due to congestion in the lift waiting areas.

The 9/11 Commission Report [Kean and Hamilton, 2004] states that "Many had attempted but failed to squeeze into packed express elevators" (pp293, reference to WTC2 on the 78th floor sky lobby) which suggests that occupants may exhibit competitive behaviour when attempting to board lifts during an evacuation.

Overall the NIST report states that "Elevator usage by occupants played a significant role in reducing the total loss of life in WTC2 on September 11, 2001" [Averill, et al., 2005] and exemplifies the potential benefit of using lifts during an evacuation.

In addition to those occupants who escaped using lifts, USA Today [Cauchon and Moore, 2002] states that at least 200 occupants died in lifts within WTC1 and WTC2. Whilst some occupants were initially inside lifts at the time of impact and subsequently trapped, a number of them managed to escape. It is appreciated that it is perhaps not always feasible to prevent such incidents occurring considering the nature of certain emergencies, though it does highlight that the lifts can have the potential to considerably inhibit and delay occupant evacuation.

Cook County Administration Building Fire

On October 17th 2003 in the late afternoon the Cook County Administration Building Fire occurred in Chicago, US. The Cook County Administration Building is 36 floors in height (144.78m) with 16 lifts (with groups servicing a given range of floors) and two stairwells which spanned the entire vertical length of the building. Due to the time of the fire there were only around 250 occupants present within the building, many of whom were already leaving or about to the leave the building (44% of those surveyed). The fire started on the 12th floor of the building and was discovered at around 4:57PM (on a Friday). Some occupants who were among the first to initially discover the fire on the 12th floor (prior to the call to evacuate) began evacuating using the lifts, even though they had already seen the smoke/flames. The official call to evacuate the entire building was given at 5:05pm (8 minutes after the initial discovery of the fire) using the P.A system advising occupants to evacuate using the stairs and not the lift. Smoke entered the emergency stairwells which, combined with the automatic locking of stairwell doors (from the outside), meant that certain occupants were not able to leave the stairwells on all floors except on the lobby level. By 6:39PM a report stating the fire was out was made. In total, 6 fatalities occurred on the upper floors (20-24th) and in the stairwell.

Approximately half of the respondents to the survey conducted by Proulx et al [Proulx, et al., 2004] used lifts to evacuate despite warnings (e.g. signage and the P.A system) and previous training telling them that they should not use them during a fire. Indeed only 13.3% (56) of occupants surveyed stated that they understood that they should not use a lift during an evacuation in the building. Analysis of the survey suggested that those occupants who were still working were much more likely to use the stairwells with occupants "tending to continue the activities which they were committed to" [Proulx, et al., 2004] (i.e. those who were already leaving the building (either about to or already using a lift) were more likely to use a lift during the evacuation). Of occupants who stated that they attempted to use a lift and stated their motivations for leaving during the incident, around 50% stated there were leaving for the day, around 35% stated they perceived fire cues and around 10% felt a threat to their safety. The average total evacuation time for surveyed lift users was 5.8 mins which was 61.6% (9.3 min) faster than the average total evacuation time of stair users (15.1mins). Of the occupants that attempted to use a lift, 3 occupants were unsuccessful in using them but no one became trapped or died inside them. Findings from the investigation clearly show lifts have provided significant benefit in reducing total evacuation time.

Hiroshima Motomachi High-rise Apartment Fire

On October 28th 1996 in the mid afternoon the Motmochi Apartment Fire occurred in Hiroshima, Japan [Sekizawa, et al., 1999]. A study group was formed by the JAFSE (Japan Association for Fire Science and Engineering) to investigate occupant behaviour during the fire. The primary publication reporting results was by Sekizawa et al [Sekizawa, et al., 1999] where a survey was conducted of the occupants within the building.

The Motomachi Apartment building is 20 floors in height with four lifts (servicing all floors) and two emergency stairs (with a skip floor design servicing every even floor by direct access). The building contained around 3,000 households. Whilst the survey included data from 164 households, the published paper [Sekizawa, et al., 1999] only relates to the 77 respondents who were at home at the time the fire started. A large proportion (72%) of respondents were elderly (i.e. ≥60 years old) with there being approximately a quarter of them being male and 17% disabled.

At around 2:27PM a fire started on the 9th floor of the building which then spread to the top (20th) floor through the balconies on the outside of the building in less than 20 minutes. The automatic fire alarm was operated at 2:33PM and the fire was suppressed by 5:02PM. No fatalities and only two injuries occurred (one firefighter and one occupant).

Of the respondents surveyed, 54% used a lift either in part or for their entire evacuation through the building. The most common reasons cited for using the lifts related to being more familiar (44%) and the thought that it was more safe (29%) to use, though it was also mentioned in the study that few occupants were aware of the evacuation practice to not use lifts during an evacuation. From Figure 3 it can be seen that as floor height increases the proportion of occupants that used lifts also approximately increases.

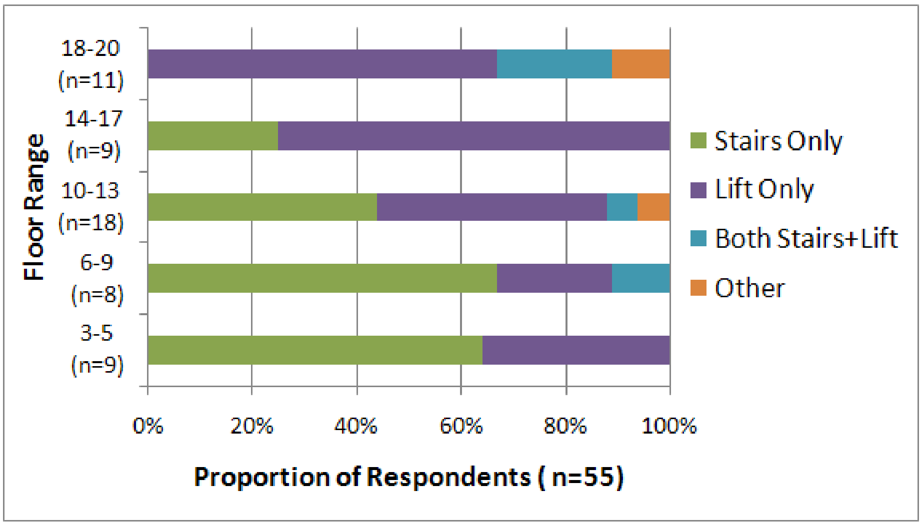


Figure 3: Selected Means of egress by floor [Sekizawa, et al., 1999]

Of all the experiences mentioned during the evacuation, only 1% of occupants stated that they waited for a lift for a long time and only 1% of occupants stated that they could not use a lift due to the crowd. No mention of what occupants defined as being a 'long time' waiting for a lift or what levels of crowding caused them to redirect to the stairs was mentioned.

Joelma Building Fire

On February 1st 1974 in the morning the Joelma Building Fire occurred in San Paulo, Brazil [Craighead, 2009; Howkins, 2000]. The Joelma Building was 25 floors in height. The building housed a single staircase which spanned the entire vertical height of the building. Reports suggest there were at least 4 lifts (each with an operator) which assisted the evacuation. At the time of the fire there were approximately 756 occupants within the building.

The fire started around 8:50AM on the 12th floor. The fire spread up the single stairwell to floor 15 preventing occupants escaping via the stairs. The fire began to subside around 10:30AM and was extinguished at around 1:30PM. In total 179 (23.7%) occupants were killed and 300 (39.7%) injured during the fire. Approximately 300 (39.7%) occupants were reported to have been evacuated using lifts by 4 operators within lift cars.

MGM Grand Fire

On November 21st 1980 in the morning the MGM Grand Fire occurred in Las Vegas, US [Best and Demers, 1982; Bryan, 1981; Clark, 1981]. The MGM Grand building is 23 floors in height with the hotel guest rooms located on floors 3-23 (though the hotel numbering ranges from 5-26 (i.e. there is some contention as to whether the lower levels constitute 2 or 4 floors)). The hotel contained approximately 2,083 guest rooms with the lower floors of the building having a number of entertainment areas including a casino, arcade, restaurants, etc. At the time of the fire there were approximately 3,400 guests registered at the hotel in addition to a number of patrons within the casino. The building contained 6 stairways evenly distributed about the building which spanned the entire vertical height of the building. In addition there were 16 passenger lifts and 8 service lifts, which served a given range of floors. The passenger lifts had no enclosed lift waiting areas whereas the service lifts waiting areas were enclosed.

A fire was discovered on the lower floors of the MGM Grand in the deli between 6:30AM-7:00AM with the fire department being alerted at 7:15AM. The open plan nature of the lower floors and the lack of enclosed lift waiting areas meant that significant smoke spread was reported. This includes smoke spread in all but one of the emergency stairwells and in a number of lift shafts. Many hotel occupants became cut off due to the smoke in the stairwells and evacuated to the roof; approximately 300 people were rescued from the roof via helicopter. The fire was extinguished at approximately 3:00PM (approximately 8 hours after it was initially discovered). In total 85 occupants died and 600 were injured in various locations throughout the building.

Of the 85 fatalities, 61 (71.7%) were located in the hotel with almost all of them being located within close proximity to the lift waiting areas on the respective floors. In total 10 occupants died inside lifts where they were located around the casino level. At floors 20 and 26, 15 occupants died in lift waiting areas.

There was no automatic means of returning lifts to the main lobby area (i.e. hall calls could still be serviced during the fire). Indeed it was reported that some guests boarded lifts during the fire without being aware of the incident and there was at least a single documented case of a survivor (who was initially unaware of the fire) using a lift to evacuate.

Forest Laneway Fire

On January 6th, 1995 in the early morning in North York, Ontario, Canada the Forest Laneway Fire occurred [Proulx, et al., 1995]. Survivor accounts from a total of 219 surveyed respondents from 176 apartments inside the building at the time of the fire were collected. The Forest Laneway building was a 30 floor apartment block which contained 365 apartments, 2 stairwells and 4 lifts. At the time of the fire there were an estimated 545 occupants within the building most of whom were expected to be asleep at that time.

The fire was reported to have started on floor 5 around 5:00AM within an apartment living room. In total 6 occupants died in the fire whose bodies were all located on the upper floors of the stairwell. Only 5% (11) of respondents to the survey reported injuries.

In total 162 (74%) respondents used lifts to evacuate with all but a group of five occupants doing so under the instruction of rescue personnel. There were a number of unsuccessful attempts to use a lift to evacuate which were typically prevented due to smoke spread. With the exception of a few respondents, all appeared to know that they should not use a lift during fire evacuations.

Dusseldorf Airport Terminal Fire

On April 11 1996 in the mid-afternoon the Dusseldorf Airport fire occurred in Germany [NFPA, 1998]. The fire started at 3:31PM in the airport at the east end of the arrivals hall with all airport and external fire fighters arriving at the building by 4:07PM. The fire was under control by 7:20PM (3 hours 49 minutes after the initial report of a problem was made). In total 17 occupants died and 62 were injured. Of the occupants that died, 7 died in a lift when its doors were opened onto the fire level. These occupants were originally on the roof of the airport car park before deciding to evacuate using the lift.

Madingley block on the Cambridge Estate, Kingston upon Thames

In mid-July during the late afternoon in 2010 the Madingley block fire occurred in Kingston, UK [BBC, 2010a; BBC, 2010b]. The Madingley block is a council owned apartment block which has 15 floors with 60 flats housing up to 150 occupants. No details regarding the number of stairs or lifts were mentioned within any of the literature sources.

The fire started around 4:45PM around the top 4 floors of the building. No fatalities or injuries were reported. The fire was brought under control by the fire department at around 8:54PM. Some survivors of the fire reported being forced to use the lifts despite the danger due to the speed at which the fire was spreading. The following is an account of a survivor who was initially on the 14th floor with her grandchildren:

"*We went out of the front door and we had to go down in the lift. I know with the fire they always say 'don't go in the lift', but people (neighbours) were banging on doors and they said you have to go in the lift because it was quite a fierce fire.*" [BBC, 2010b]

Similar accounts of a survivor who needed to evacuate with his baby and pregnant wife, initially on the 10th floor was reported as saying:

"*I took the baby and came out, and (my wife) couldn't walk from the 10th floor so I had to take the lift unfortunately. My wife was screaming inside the lift. But we needed to come out, that was the main thing in my mind.*" [BBC, 2010b]

The above quotes suggests that when faced in imminent danger of a fire, occupants would consider using lifts to evacuate due to increased speed they afford despite knowing that they should not actually use them. The added influence of being required to evacuate with small children, taking longer to evacuate via the stairs, no doubt was also a contributing factor for the occupants to elect to use the lift to evacuate.

Non-Fire Evacuations

In addition to fire evacuations there have been a number of past non-fire evacuations involving the use of lifts. Of those reviewed, the principle cause of evacuation has either been due to a bomb scare or a drill.

Canary Wharf Drill Evacuation

Following the World Trade Center 911 attack, a full building evacuation drill was carried out at 11:00AM on October 30th 2001 of Canary Wharf tower (One Canada Square) in London, UK [BBC, 2001; Treanor, 2001]. Canary Wharf Tower has 50 floors, housing 27 companies that employ around 7,500 occupants within the building. The building contains 4 stairwells and a number of lifts of which different groups service a given range of floors.

Occupants were informed in advance that the drill would take place, and it was stated that the total number of occupants in the building at the time of the drill was much lower than its full capacity with many occupants leaving prior to the call to evacuate. During the drill occupants were given the choice to use either lifts or stairs. The lifts were placed in a special emergency mode that was intended to allow the most people to evacuate in as short a time as possible. The building took approximately 20 minutes to evacuate. Occupants were reported to have said that previous evacuations of the buildings had taken 45 minutes and that the decreased occupancy was probably the main reason for the decrease in total evacuation time.

Petronas Towers Bomb Scare/Drill Evacuation

The day after the World Trade Center 911 attack, the Petronas Towers in Kuala Lumpur, Malaysia was required to fully evacuate both towers due to a bomb alert. This was later followed by a drill evacuation on another day [Ariff, 2003; Bukowski, 2009; Bukowski, 2010].

The Petronas Towers consists of two towers each having 88 floors (451.9m), 3 stairwells, and 39 lifts using a double-decker design for the main lifts with a sky lobby configuration. The lifts include a safety feature whereby if one lift becomes trapped, another lift can move along side it and occupants can transfer between lift cars. The towers are connected via a skybridge between floors 41-42. The evacuation plans for the towers include a procedure that if a single tower is required to be fully evacuated then occupants on the upper floors of the evacuation tower can initially move to the skybridge level via the stairs. Occupants would then move to the adjacent tower via the skybridge where shuttle lifts could be used to evacuate to the ground floor of the adjacent tower. Occupants below the skybridge level in the affected building use the stairs to evacuate to the ground level.

On September 12th a bomb alert prompted a full building evacuation of the Petronas towers. Due to the uncertainty of which tower the threat related to both towers were evacuated. Occupants on the floors above the skybridge in both towers attempted to evacuate to the skybridge level where both groups attempted to cross the skybridge in the opposite direction, creating heavy congestion and contraflow which subsequently resulted in a 'jam'. As a result the evacuation took a number of hours to complete. Bukowski [Bukowski, 2010] reports that following this event the local authorities considered, during a full building evacuation (of both towers) or when the skybridge is rendered inoperable, the use of shuttle lifts servicing the skylobbies in both towers. Occupants travel to the nearest sky lobby below them before boarding a lift which shuttles them to the exit level. A drill was later carried out in October 2002 employing the new strategy and both towers evacuated in 32 minutes. No further details were found regarding the nature or occupancy levels of the towers during the drill, however, it should be kept in mind that the main shuttle lifts were double-decker lifts which would have increased the lift system capacity. As such this is expected to have contributed to further reducing the total evacuation time of the building. The evacuation drill demonstrates the increased benefit of the combined use of both lifts and stairs during an evacuation.

Taipei 101 Drill Evacuation

Prior to officially opening Taipei 101 a number of full building evacuation drills were conducted to explore acceptable evacuation strategies [Bukowski, 2009, 2010; Hsiung, et al., 2009].

Taipei 101 consists of 101 floors (508m in height), contains 2 main stairwells (1.4m in width), and 61 lifts including double-decker shuttle lifts which service a given range of floors using a sky lobby configuration. The original full building evacuation procedure was to only use stairs to evacuate the entire building population.

Prior to the building's completion a full building evacuation drill was conducted using stairs only which took approximately 2 hours 30 minutes to complete. This was considered too long by the local fire department and the inclusion of lifts into the evacuation procedure was explored. A further evacuation drill that used lifts in addition to stairs reduced the total evacuation time to just under one hour (57 minutes), being under half the evacuation time compared to using stairs alone. Similar to the Pretronas Towers incidents, this demonstrates the increased benefit of the combined use of both lifts and stairs during an evacuation compared to stairs alone.

Christchurch Bomb Threat Evacuation

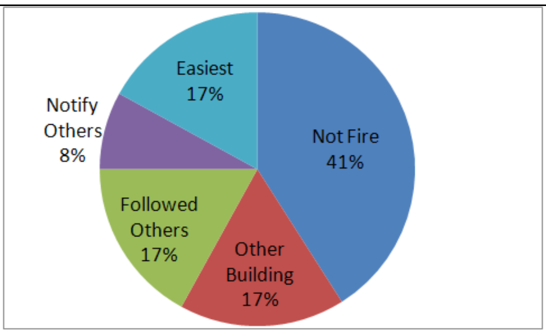
On July 30th 2007 a bomb threat was reported on Kilmore Street, Christchurch, New Zealand and a number of buildings were evacuated. A number of hours later it was determined that there was no bomb. A survey was conducted by Heyes [Heyes, 2009; Heyes and Spearpoint, 2009] that asked respondents from two multi-level buildings involved in the evacuation about their evacuation experience.

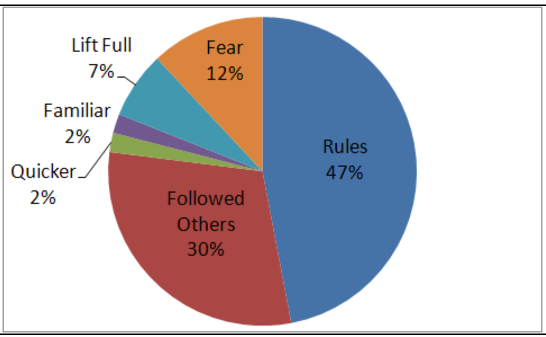
The first building was 5 floors in height and had a single lift. The second building was 6 floors in height and had 2 lifts. Both were office buildings and no details regarding the number of stairwells were reported. In total 45 respondents surveys were collected (13 from the first building and 32 from the second building). In the first building respondents were initially located across 3 floors. In the second building respondents were initially located across 4 floors.

Overall 10 (22.2%) respondents used lifts and 35 (77.8%) respondents used stairs to evacuate. The results presented show that as floor height increases the proportion of occupants that use a lift to evacuate also approximately increases. However, the low response rate/frequency of respondents, the low frequency of respondents that used a lift and only coming from a small number of floors, makes it hard to draw any firm conclusions from the results.

Respondents were also asked about how they felt during the evacuation. Whilst most of the respondents did not think the threat of the event was very high, their levels of urgency were high. Overall, respondents who used a lift perceived there to be a higher level of threat to their personal safety than stair users, however, also had a lower level of urgency to exit the building. This perhaps suggest that either there is little link between threat and urgency or that something else was influencing the respondents decision.

Of the reasons given for evacuation choice by lift respondents (see Figure 4), 41% reported using the lift because they knew it was not a fire event, 17% followed others, 17% reported it was the easiest means of evacuation, 17% said they knew that the situation was in another building and 8% used lifts to go to other floors to notify others. Of the reasons given for evacuation choice by stairs respondents, 47% reported because it was part of their evacuation procedure, 30% followed others, 12 % were afraid of the lift breaking down/being trapped inside the lift, 7% said the lift was full, 2% said stairs were the most familiar route and 2% thought the stairs was the quickest route (see Figure 4).





Lift Users	Stair Users

Figure 4: Reasons given for evacuation choice for those that used the lifts/stairs to evacuate [Heyes, 2009]

Considering 7% of stair users said the lift was full highlights that a higher proportion of occupants would have considered using the lift during the evacuation and also that local conditions in the lift waiting area can cause occupants to redirect to the stairs.

Summary of Lift Usage during Evacuations

A number of actual and drill evacuation incidents that have included the use of lifts have been reviewed. Analysed accounts have shown that occupants will consider using lifts during actual evacuations even if they have been taught/told not to do so; occupants will not necessarily do what they are instructed to do. Such accounts suggest that occupants make their own judgments on whether to use a lift based on local conditions. Occupants have stated that they would not be prepared to wait in highly congested lift waiting areas or for long periods of time for a lift whilst evacuating.

2.2.2 Evacuation lifts for the general population - codes, standards and guidelines

Bukowski [Bukowski, 2009] mentions that the consideration to use lifts during evacuations at a regulatory level can be traced back to almost 100 years ago in 1914 at an NFPA meeting [NFPA, 1914]. At the meeting it was agreed that suitably fire protected lift systems could provide benefit to an evacuation, particularly in high buildings. In 1935 the NBS (National Bureau of Standards) [NBS, 1935] also discussed the potential use of lifts during evacuations. However, in both meetings the use of lifts during evacuations was discounted due to safety concerns and the lack of fire protection measures in existing buildings associated with such usage.

Currently, whilst fire protected lifts are considered a viable means for fire fighting services to fight fire [Barker, 1995] and also assist in the evacuation of disabled occupants [Proulx, et al., 2009], most standards have yet to accept fire protected lifts as a viable means for the general population to evacuate during a fire. Building codes and guidelines from both the US and the UK have been reviewed, including:

- International Code Council International Building Code [ICC, 2009],
- NFPA 101: Life Safety Code [NFPA, 2009a],
- NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems [NFPA, 2010],
- NFPA 5000: Building Construction and Safety Code [NFPA, 2009b],
- BS9999: Code of practice for fire safety in the design, management and use of buildings [British Standards, 2008],
- Guide D: Transportation systems in buildings [CIBSE, 2000].

With certain recent exceptions, building codes typically state that when a fire is detected then lifts should immediately empty the passengers on the nearest viable floor before moving to the fire recall floor (often the ground floor) and open the lift doors (commonly referred to as Phase I Emergency Recall [ASME, 2007]). This allows fire fighting services who enter the building (within close proximity to the lifts) to determine if any of the lifts have not returned and so identify if anyone might be trapped inside. If fire fighters need to use a lift (e.g. in order to rescue occupants or transport equipment) then they can take control of a lift using a key which overrides the automated Phase I Emergency Recall operation (commonly referred to as Phase II mode). In both Phase I and Phase II the lifts should not respond to landing calls within the building.

With the growing usage of performance based codes that state evacuation criteria that can be achieved in a variety of different ways and the increase in high-rise structures, there is a growing trend to allow for the provision of fire protected lifts for the general population during evacuations. Proulx surmises recent progress in the attempts to include lift usage for the general population during fire evacuations within US building codes below:

"*A collaborative effort between ASME, NIST, ICC, NFPA, US Access Board, and the IAFF in March 2004 resulted in task groups developing technical requirements for occupant and firefighter use of elevators during fire emergencies [17]. In the 30+ years of work, the effectiveness of using elevators for reducing overall building evacuation time has been immediately recognized at every workshop; the focus has been on ensuring that the procedures and technology are robust enough to maintain or improve the safety record of using stairs during a fire emergency.*" [Proulx, et al., 2009]

Indeed the International Code Council (ICC) and National Fire Protection Association (NFPA) have already begun to allow the use of evacuation lifts for the general population within a number of their building codes [ICC, 2009; NFPA, 2009a, 2009b, 2010].

The ICC, 2009 International Building Code (Section 1007.4) and NFPA 101 (Annex B) require lift systems meet a given level of protective safety (i.e. equal to that of fire fighting lifts) and that fire/smoke is not detected within close proximity to the lift system for them to be used during an evacuation. If fire/smoke is detected within close proximity to the lift system or any of its components then Phase I recall will be initiated. In NFPA 101 regardless of a building allowing the use of such lifts during an evacuation, the same requirements for the number of means of egress, capacity of means of egress and arrangement (e.g. stair provision) is maintained. However, within the ICC, 2009 International Building Code, if occupant evacuation lifts are present then buildings over 128m in height are not required to have an additional exit stair (in addition to the minimum number of exit stairs as stated in Table 2). As such the ICC, 2009 International Building Code allows the capacity of evacuation lifts to substitute that of an additional stair.

Table 2: ICC, 2009 International Building Code, minimum number of exits per storey

Occupant Load (persons per storey)	Minimum Number of Exits (per storey)
1-500	2
501-1,000	3
>1,000	4

Within NFPA 101, in addition to typical buildings, compliant lifts are permitted as secondary means of escape for certain towers which do not exceed occupancies of 90 persons and are not used by the general public. In NFPA 5000 (Annex E, for building construction) similar requirements as those mentioned in NFPA 101 are stated.

NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems [NFPA, 2010] allows for the use of lifts for the general population providing a similar level of fire safety is achieved for the lift system as in NFPA 101. Unlike NFPA 101, NFPA 130 further stipulates that lifts can be used to substitute other forms of egress (e.g. stairs) but cannot account for more than 50% of the total egress capacity providing one lift is assumed to be out of service.

The British Standard BS 9999:2008 Code of Practice for Fire Safety in the Design, Management and use of Buildings [British Standards, 2008], stipulates that generally lifts should not be used during an evacuation because "it is possible for the occupants using the lift to become trapped due to loss of power; it is possible that lifts could discharge occupants onto the floor containing the fire; people sometimes have to wait for long periods for the lift car to arrive, extending the escape time″ [British Standards, 2008]. However, if lifts provide the same level of safety to that of a fire fighting lift, then they can be used during an evacuation for the general population with priority given to occupants who may have problems escaping via other routes. Such evacuation means would only be considered with a suitable fire risk assessment undertaken. Similarly to NFPA 101, BS9999 also states that in “a building with automatic sprinklers and significant compartmentation or smoke control, a risk assessment might conclude that a non-evacuation lift would be useable in the initial stages" [British Standards, 2008].

The Chartered Institute for Building Service Engineers (CIBSE) in the UK produce a document called Guide D: Transportation systems in buildings [CIBSE, 2000]. The guidelines state recommendations for the use of escalators and lifts in normal circulation situations in addition to a variety of human factors associated. Guidance on the proportion of occupants to use stairs compared to lifts based on collected traffic patterns is also given (see Table 3). The figures suggest that no occupants would be prepared to walk more than 6 floors using the stairs during normal circulation conditions. No further information regarding what influence, if any, the height of a building may have on the proportion stair/lift users is mentioned.

Table 3: Likely proportion of occupants to use lifts and stairs during normal circulation [CIBSE, 2000]

Floors Travelled	Down		Up	
	Stairs (%)	Lift (%)	Stairs (%)	Lift (%)
1	90	10	90	10
2	50	50	80	20
3	20	80	50	50
4	20	80	20	80
5	5	95	5	95
6	0	100	0	100

2.2.3 Evacuation lift human factors - empirical and qualitative data

Despite the interest in utilising lifts during evacuations for the general population, little research has been conducted/published regarding associated human factors. Much of the research into lift usage during evacuations has been based around making the physical components of the lift system resilient to hazardous situations [Klote, 1983; Klote and Tamura, 1991; Bukowski, 2005a, 2005b]. Only a small number of past qualitative studies of actual evacuations where lifts were used have been conducted (see previous sections). Very few have collected empirical/quantitative data. The following section reviews three studies where data was collected regarding evacuation lift human factors. The studies reviewed include Levin and Groner's air traffic control tower lift evacuation interviews [Levin and Groner, 1994], Heyes's lift evacuation surveys [Heyes, 2009], and Zmud's public Perceptions of high-rise building safety and emergency evacuation procedures [Zmud, 2007].

Levin and Groner Air Traffic Control Tower Lift Evacuation Interviews

In 1994 Levin and Groner [Levin and Groner, 1994] produced a study of human factors associated with using lifts to evacuate Federal Aviation Administration (FAA) air traffic control (ATC) towers in the US. The authors visited 13 ATC towers which were used to examine the typical architectural designs, interview ATC managers and at least 2 air traffic controllers per tower. The interviews were intended to gather information on whether occupants would consider using lifts during a fire evacuation. The authors state that prior to evacuating, air traffic controllers are required to notify pilots and arrange for other controllers to assume control of respective aircraft traffic (with estimates for the time taken to complete this task ranging between 1.5-5 minutes). Such pre-evacuation tasks would no doubt potentially increase total evacuation time and the authors were particularly interested in how this may influence queuing for lifts during an evacuation.

The typical structure of ATC towers are tall and narrow buildings with a small footprint. As such they often only have a single lift and single stairway (primarily used for emergencies and when the lift is non-operational). At the time of the study, the use of lifts during fires was prohibited within ATC towers which often meant that only a single route of egress was available during fires (using the stair). Since the survey was conducted the use of lifts as a secondary means of egress for ATC towers is now accepted in the US [Bukowski, 2005a]. Most of the occupants interviewed in the study were aware that they should not use lifts during a fire evacuation.

The authors state that buildings with only a single lift suffer from complaints regarding lifts not being operational, forcing occupants to walk up the stairs. Within the interviews of air traffic controllers the authors state:

"*the perceived reliability of elevators has a strong effect on the controllers expressed willingness to use them during an emergency*" [Levin and Groner, 1994]

A number of comments within interviews stated that lifts regularly broke down in ATC towers and there was a general lack of confidence in lift reliability. A number of air traffic controllers had reservations about using the lifts during a fire evacuation. Indeed interviewees within the study expressed a preference to use the stairs instead of the lifts during a fire evacuation due to not wanting to be reliant on an electrical/mechanical device through fear of becoming trapped. As such the authors highlight that well maintained lifts during normal operations are likely to contribute to reducing such reservations for lift usage during fire evacuations.

As ATC towers typically do not simultaneously contain more than 25 occupants [Levin and Groner, 1994], occupants are not expected to wait very long to use a lift. The authors mention that the main contributing factors to increased lift wait times are the lift capacity and lift speed.

The study conducted provides valuable insights into evacuation lift human factors, however, the general applicability of the results to other building/population types (e.g. commercial (employees), apartments (residents), hospitals (patients), etc), is questionable. Most of these high-rise buildings would quite likely contain more occupants of different types (e.g. coming from multiple companies), with no common social hierarchy (e.g. managers in the same company), having multiple stairwells with a variety of evacuation routes, and a larger building footprint allowing for a greater degree of horizontal movement.

Heyes's Lift Evacuation Surveys

In 2009, Heyes [Heyes, 2009; Heyes and Spearpoint, 2009], as part of a Master thesis, conducted a Post-Evacuation Drill Survey, Evacuation Event Simulation Survey, Online Survey and Bomb Threat Incident survey (previously mentioned) regarding the use of lifts during an evacuation. Heyes states that due to the inherent limitations with each survey, the "triangularisation approach" [Heyes and Spearpoint, 2009] of using different surveys allowed overall trends to be uncovered.

The Post-Evacuation Drill Survey was given to students and staff of the University of Canterbury, New Zealand after evacuating two buildings on campus as part of a drill. None of the buildings included procedures for the use of lifts during evacuations and participants were asked about their evacuation experience and if they would consider using lifts if it were acceptable to do so. In total 91 surveys were completed.

The Evacuation Event Simulation Survey was given to first year engineering students at the University of Canterbury immediately after a lecture. Participants were presented with a hypothetical evacuation situation. Pictures were provided as the event happened that was intended to aid participants in conceptualising the hypothetical situation. Participants were asked what they would do at different stages of the evacuation with regards to a multi-storey evacuation. Participants were divided into two groups; "educated" and "uneducated". In the educated group participants were taught the typical fire safety measures employed in buildings that use lifts as part of their evacuation. The uneducated group participants were not provided with this information. Though it was not mentioned it is believed whilst the participants completed the survey individually, they were located in the same lecture room as other participants whilst doing the survey (i.e. as a class); the extent to which this may have influenced the results is uncertain. In total 229 students participated in the survey.

The Online Survey was given to Arup employees in offices within three different countries/cities: Perth (Australia), San Francisco (US) and Singapore (Republic of Singapore) (the majority of which were engineers). The survey asked participants to judge how imaginary characters would behave within a hypothetical evacuation, their understanding of evacuation procedures in their building, the number of stairs that they would be capable of evacuating down and what concern they would have for using lift/stairs during an evacuation. In total 138 participants were recorded in Perth (27.5% (38)), San Francisco (43.5% (68)), and Singapore (31.9% (44)).

In addition to the experimental surveys, Heyes also surveyed evacuees from a bomb-scare in Christchurch as part of the study which has been reviewed in a previous section.

Across all surveyed locations and occupational groups, the concerns for using lifts during evacuations were the same with the most common concerns relating to being trapped in a lift, having to wait a long time, fire/smoke entering the lift and the lift car free falling.

The percentage of participants that said they would use a lift for different floor heights in each survey is presented in Figure 5. As the floor height increases the proportion of participants that said that they would use a lift also approximately increases.

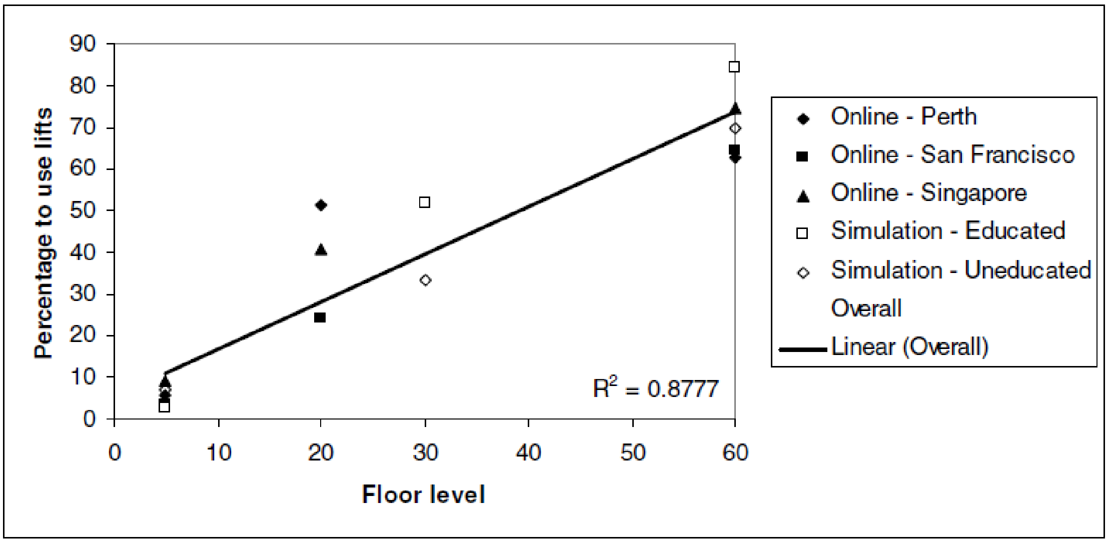


Figure 5: Percentage of occupants to use the lift by floor level [Heyes and Spearpoint, 2009]

A linear regression was performed to obtain a formula (See Equation 1) to predict the proportion of lift users given the floor level:

$$p = 1.14f + 5.3 \quad 5 \leq f \leq 60 \text{ floors}$$

Equation 1

p = Percentage of occupants to use the lift (%)

f = Floor level of the building

A goodness of fit value (R^2) of 0.877 was reported which suggests the regression formula to be a good predictor of the proportion of lift users given a floor level. However, this is surprising considering the proportion of lift users differ between around 3%-25% (from visual inspection of the graph). Indeed this difference appears to increase on the higher floors (Floors ≥20, 20%-25%). It is thought that the linear regression line was constructed and subsequent goodness of fit value calculated using the average proportion of lift users across all surveys for each floor. If so this would reduce the influence of the different proportion of lift users for each floor between surveys and so give an increased R^2 value. In addition, only 4 floor heights were tested for the proportion of lift users in all the surveys (floors 5, 20, 30 and 60). This is also expected to contribute to a smoothing effect and increase the likelihood of a linear correlation emerging. Heyes mentions that the increase in lift users may rise more rapidly after floors 60 and that the relationship between the proportion of lift users and floor height may not be linear. Using the line of best fit suggests that most occupants would use a lift if located above floor 40 within a building.

Heyes compared the proportion of surveyed lift users against those that used lifts in actual incidents. The actual fire evacuation incidents using lifts were the World Trade Centre 911 Attack (WTC2), Chicago Cook County Fire and the Hiroshima Motomachi Apartment Fire. As previously described, each of these fires had unique/different contexts, building structures/heights, populations and situations. Given such differences it may not have been appropriate to compare associated lift usage with the survey results.

Heyes states that participants in the Post Evacuation Survey, Online Survey and the Evacuation Event Simulation Survey were asked questions regarding the length of time they/characters would wait for a lift during an evacuation. This included:

- For the Post Evacuation Survey, participants were asked how long they would be prepared to wait for a lift before they redirected to the stairs, with participants being required to state a given time without any options or prompts from multiple time ranges.

- For the Evacuation Event Simulation Survey, participants who would consider using a lift during the hypothetical evacuation were asked whether they would still wait to use a lift after 5 and 10 minutes.

- For the Online Survey, participants were asked how quickly imaginary characters would take to exit the building using either the lifts or the stairs. For the imaginary characters that used the lift, this included the time waiting for a lift and time travelling in the lift. Participants were then asked, out of the imaginary characters who used the lift and stair, which made the best decision (the stair users or the lift users). A further scenario is presented where the imaginary characters wait for 5 and 10 minutes for the lift on each floor and participants were required to say if they thought waiting for each length of time was the best decision.

Due to the difference between each question (e.g. asking whether it was a good decision for the participant/imaginary character to wait a given time for a lift) and methodology (e.g.

online/lecture based survey), it is uncertain whether the wait times measured in each survey are semantically identical.

Results show the average proportion of lifts users that would continue to wait for a lift at 0, 300, 600 (for the Event Simulation Survey) seconds for each of the floors in each survey (See Figure 6). As expected in all surveys the proportion of people that would use a lift decreases as wait time increases.

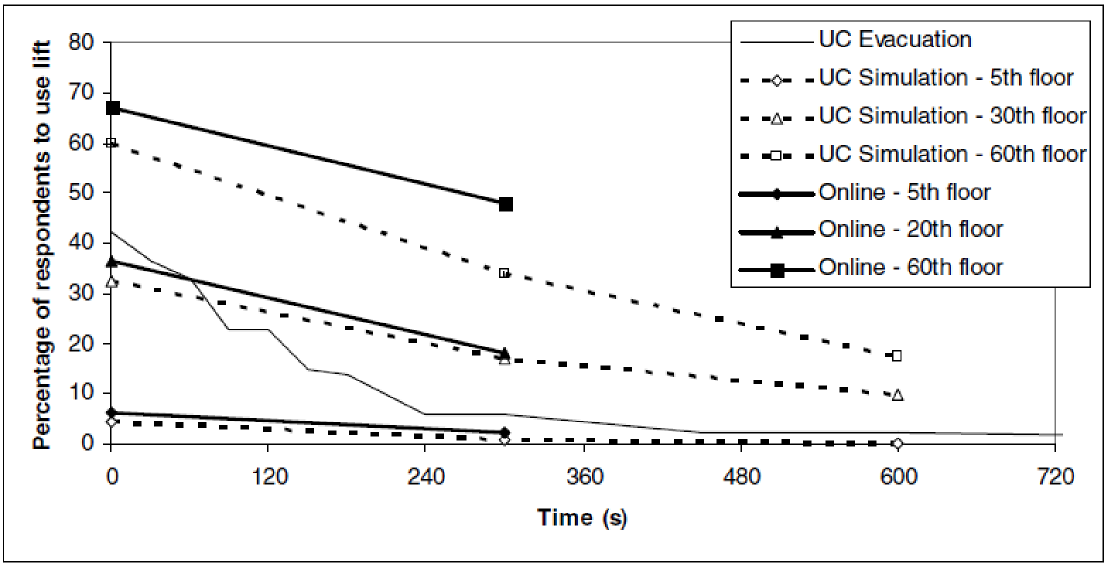


Figure 6: Percentage of people that will use the lift after waiting time [Heyes and Spearpoint, 2009]

Using the proportion of lift users divided by floor number, the corresponding wait times of averaged values were plotted for each survey (see Figure 7 below) to allow a line of best fit along with a subsequent regression formula to be constructed. Heyes states that the responses from the engineer participants had been removed from the plot in order to obtain a better fit curve.

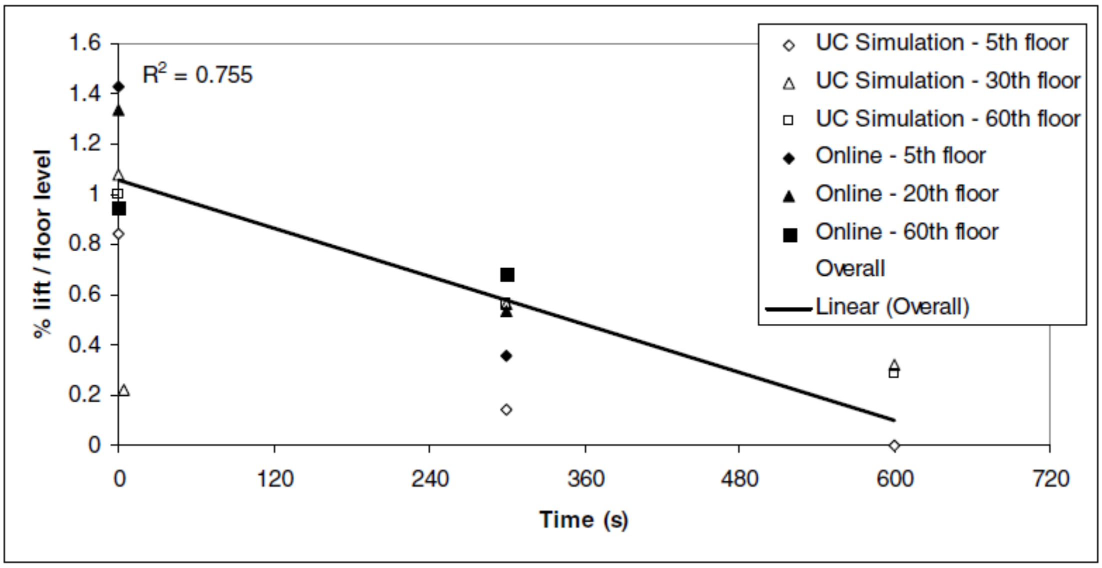


Figure 7: Percentage of respondents that would take the lift over floor level as a function of waiting [Heyes and Spearpoint, 2009]

The following equation (see Equation 2) for the line of best fit was produced:

$$p = (-0.0016t + 1.06).f \quad 5 \leq f \leq 60 \text{ floors} ; 0 \leq t \leq 600 \text{ seconds}$$

Equation 2

p = percentage of occupants to use the lift (%)

f = Floor level of the building

t = waiting time (s)

As with the previous regression, it is believed that the average values of each time period over all surveys was calculated to generate the line of best fit which would subsequently increase the associated R^2 value (reported as 0.755). Indeed even without the engineers responses there appears to be a high degree of variation. Combining the averaged %lift/floor level ratios with the small number of time bins (three bins) is expected to create a smoothing effect increasing the likelihood of a linear correlation.

Heyes hypothesizes that participant's decision to use a lift or stairs would be influenced by which device forms part of the fastest and/or safest evacuation route. Results from the Online Survey and Evacuation Event Simulation showed that participant's primary influence was selecting the device that forms part of their fastest route as opposed to the safest.

Considering different sample populations were used for each survey, it is unclear whether the differences between overall responses in each survey lay in the different samples or in the more general population. Indeed participants came from a narrow occupational range in each survey (i.e. mainly students (small age range) and engineers). This makes it hard to determine if and to what extent the results are generally applicable to a wider population.

Methodological differences exist in how each survey was conducted along with differences between the format of certain questions/answers (e.g. self reported behaviour of what participants would do and reported behaviour of what participants think imaginary characters would do). Comparing responses across surveys may therefore have introduced inconsistencies.

Public Perceptions Of High-Rise Building Safety And Emergency Evacuation Procedures

In 2006 the NFPA commissioned a report by Zmud of NuStats following the World Trade Centre 911 attacks to investigate the current level of fire safety knowledge of high-rise building occupants in the US [Zmud, 2007]. In addition, it was intended to find out if attitudes towards fire safety had changed after of the World Trade Centre 911 attacks. In total 244 occupants from residential buildings (surveyed across 3 cities in the US: Chicago, New York, and San Francisco) and 228 occupants from commercial buildings (surveyed across 7 cities in the US: Boston, Chicago, Detroit, Houston, Los Angeles, Miami, and Philadelphia) were surveyed. Certain questions in the survey related to lift usage during evacuations.

Overall 73% of residential participants and 80% of commercial participants thought that the use of lifts during an evacuation was never safe. In residential buildings on average 2% of participants thought that lifts were "usually safe" and 3% of participants thought lifts were "as safe as using the exit stairs" during an evacuation. Similarly in commercial buildings 3% of participants thought that lifts were "usually safe" and 0% of participants thought that lifts were "as safe as using the exit stairs". It was also reported for the commercial building participants that just over 10% whose office was located on floor 41 or higher reported that they thought that using lifts during evacuations was "usually safe". The findings clearly suggest that the majority of high-rise occupants have reservations about using lifts during evacuations with little difference being recorded between commercial and residential occupancies.

In addition, several respondents mentioned problems with normal lift usage which made them consider what may happen to a lift during a fire. As mentioned in the study by Levin and Groner [Levin and Groner, 1994] of FAA control towers, this highlights that perception of general reliability of the lift system during normal conditions contributes to occupants’ perception of the reliability of using lifts during a fire evacuation.

As part of the survey, participants were given a hypothetical evacuation scenario from their building and a list of possible responses. Less than 5% of participants said that they would use a lift if it was working. Around a quarter of participants believed that going to the roof was a possible alternative to using the stairs to evacuate down.

Considering the general reservations about evacuation lift usage by participants the report concludes that people will need to be retrained in order to generally accept using lifts during fire evacuations.

Summary of evacuation lift human factors- empirical and qualitative data

A series of studies have been reviewed where human factors data was collected regarding evacuation lift usage. In all studies participants were asked how they would behave on/around lifts during an evacuation. In each study participants were recorded as stating that they had reservations about using a lift during an evacuation. Reliability of using lifts in normal circulation situations has been mentioned as an influencing factor. It has also been recorded that as floor height increases the proportion of occupants that would consider using a lift and would wait for a longer to use a lift also increases. In the studies by Levin and Groner [Levin and Groner, 1994] and Heyes [Heyes, 2009; Heyes and Spearpoint, 2009], participants were drawn from narrow demographic groups (e.g. coming from the same occupations) which casts doubt over the general applicability of the findings from such studies. The scarcity of such studies highlights the lack of understanding and, considering the regulatory impetus to consider lift usage, the need to understand associated human factors during evacuations.

2.2.4 Review of software modelling lifts

The first published accounts of lift traffic simulators were in the late 1960's, an example of which was the lift simulation of the World Trade Center for general circulation scenarios [Browne 1968]. Shortly after lift simulators for evacuation were developed in the 1970's when Bazjanac developed a computer simulation tool to conduct both partial and full building evacuation simulations [Bazjanac, 1977]. Since then a variety of numerical and simulation based models have been developed that can represent lifts during evacuations. These can be broadly categorised in to two types: dedicated lift models and circulation/evacuation models.

The primary purpose of dedicated lift models is typically the control and vertical movement of lifts about a building. In such models occupant movement is simplified as a product of distance, occupant speed, flow-rates and arrival rates using numerical calculations. These are typically used by the lift industry to analyse different lift floor dispatch strategies or the influence of different occupant traffic patterns for a given lift system to increase circulation efficiency.

A number of circulation/evacuation models also have the capacity to represent lifts. The focus of such models is based on occupant behaviour (predominantly being agent based); the lift kinematics, lift control and performance metrics within such models is often less developed compared to the dedicated lift models. These models are typically used by engineering companies to simulate occupant behaviour during circulation/evacuation situations in order to demonstrate adequate structural or procedural design for a building.

Within this section a number of lift models and circulation/evacuation models (that contain lifts) has been reviewed. A description of each model and associated components specific to the representation of lifts has been presented.

In 2005 Kuligowski and Peacock produced a review of evacuation models [Kuligowski, 2005] which stated models that could represent lifts: EVACNET, STEPS, Legion and EvacSim. In 2010 a second edition of the review was published [Kuligowski, 2010] which extended the list of models that could represent lifts: SimWalk, PEDFLOW, SpaceSensor, Myriad II, MassMotion, and SGEM. Published details regarding how each model functions is sparse with only a small number of models publishing details regarding lift functionality. The dedicated lift models reviewed were ELVAC, ELEVATE and the Building Traffic Simulator (BTS). The circulation/evacuation models reviewed were STEPS, EvacSim and EVACNET. These were selected to review based on the availability of published literature regarding the lift components of the models.

ELVAC

ELVAC is a numerical based model that computes the total evacuation time, lift round trip time, number of lift trips per floor to evacuate a building using both stairs and lifts. It was developed in QBASIC by Klote and Alvord in 1992 [Klote and Alvord, 1992b] at NIST, US as part of a project to explore the use of evacuation lifts for the US General Services Administration (GSA). The program only has the capability to represent a single group of lifts (a separate simulation for each group of lifts is required where multiple lift groups exist). The following input parameters that are required by ELVAC are: floor heights, total population on each floor, number of lifts, max lift speed, lift acceleration speed, lift capacity, lift door type and width, and lift inefficiency factors. All calculations performed by ELVAC are numerical. Due to the simplified/homogenous human factors represented in the model the total evacuation time and round trip times are considered to be "idealized" (though a trip inefficiency factor can be incorporated). The formula to calculate the total evacuation time by ELVAC can be seen in Equation 3.

$$t_r = t_a + t_o + \frac{(1+n)}{J} \cdot \sum_{j=1}^{m} t_{rj}$$

Equation 3

t_r = total evacuation time

t_{rj} = total round trip time

m = number of round trips

j = number of lifts

n = the trip inefficiency

t_a = lift start up time

t_o = travel time from the lift to outside

The trip inefficiency component in Equation 3 is included to represent additional and/or suboptimal lift time components (i.e. time for trips to empty floors and trips to pick up stragglers). The round trip time for each trip is calculated using the maximum speed and constant acceleration stated by the user. No representation of user-specified jerk (i.e. change in acceleration) is represented.

ELEVATE

ELEVATE is a simulation based model developed by Richard Peters at Peters Research, UK [Peters, 2007, 2002]. This was originally developed in the 1990's in Visual C++. The user manual for the software is publically accessible online [Peters, 2007], in addition to a number of published papers regarding its usage. ELEVATE is a dedicated lift model and its primary purpose is to allow users to explore the influence of different lift floor dispatch strategies and traffic patterns during normal circulation situations. However, ELEVATE has also been used to represent evacuation incidents for consultancy; Howkins [Howkins, 2000] replicated the Hiroshima Motomachi high-rise apartment fire evacuation using stairs/lifts. ELEVATE defines a buildings structure via an abstract representation of a series of nodes (representing lifts, escalators and stairs or any vertical means of traversal) connected via arcs about which occupants move. It is essentially assumed that the main crowd bottlenecks occur around the vertical transfer devices and exits hence the simplification of behaviour representation outside of these areas (though implicitly representation of other bottlenecks through varying arrival rates to those devices could be represented).

ELEVATE has a number of required input parameters (with many having default settings): maximum speed, acceleration rate, jerk, motor start delay, door open/close times, dwell times, lift capacity (number of person or weight) floors served, single/double deck, shut down time, restart time, max door reopening time, etc [Peters, 2002]. Further to this a user can specify different dispatch modes within ELEVATE (e.g. up/down peak modes) in addition to also being allowed to develop their own floor dispatch algorithms and link them into the software. Vertical zoning can be represented where lifts only service specific floors and any number of lift groups can be represented simultaneously. A number of attributes relating to occupants can also be defined including: passenger mass, loading/unloading times, capacity factor (how full occupants will load a lift). The occupant model is not an agent based model where each agent moves about an explicitly defined geometry (as in typical circulation/evacuation model). Instead, occupants' arrival at the lift waiting areas are defined via an arrival time distribution. Arrival rates to the lift waiting areas and stairs can be defined according to default distributions or user-specified arrival data. In addition to lifts and stairs, escalators can also be represented using a flow-rate model. When a lift arrives, those at the front of the queue board the lift first. The concept of different physical wait locations in relation to each lift or occupants influencing each other's behaviour within the lift waiting area whilst waiting is not explicitly represented. The extent to which this may influence occupant lift boarding behaviour is unclear.

Adoption of stairs and escalators by occupants are represented by user-specified proportions. A escalator/stair factor is associated with each floor that defines the proportion of occupants on that floor which will use the stairs/escalators for travelling a given number of floors. The remaining occupants will use the lifts from the given floor.

The simplified representation of occupant behaviour and the extent to which occupant behaviour may influence an evacuation in ELEVATE is limited. Further to this, the behaviour which is represented is based on empirical data collected in normal circulation situations and not evacuation scenarios. Such issues highlight the questionable application to assess evacuation scenarios using such dedicated lift models.

Building Traffic Simulator (BTS)

The Building Traffic Simulator (BTS) was originally developed by Siikonen in the 1980's at KONE, Finland in C++ with a Visual Basic interface [Siikonen, 1993, 1997a, 1997b]. It is a dedicated lift model and is only available to KONE and its clients (i.e. it is not publically available). BTS has also been used to model building evacuation scenarios [Hakonen, 2003a, 2003b; Siikonen and Hakonen, 2003; Siikonen, 2007]. BTS defines a building's structure via a series of nodes (representing lifts, escalators and stairs or any vertical means of traversal) connected via arcs about which occupants move. It essentially assumes that the main bottlenecks and queues of occupant movement only occur around the vertical transfer devices hence the simplification of behaviour representation outside of these devices.

BTS has a number of key input parameters (see Table 4). Occupant behaviour on stairs/escalators is represented using flow to density calculation where the handling capacity of a stair is stated in Equation 4.

$$C_{Stair} = 0.83 \cdot S \cdot D \cdot W$$

Equation 4

C_{Stair} = Handling capacity of the stair (ped/s)

S = Average walker speed (m/s)

D = Occupant density (ped/m^2)

W = Stair width (m)

(where 83% of theoretical actual device handling capacity is used).

Similar to ELEVATE custom lift floor dispatch strategies can be included.

Table 4: Input data required for an BTS simulation [Siikonen, 1997b]

Building	***Lifts***	***Traffic***
• Floor height • Number of floors • Populated floors • Entrance floors	• Number of lifts • Lift sizes • Number of groups • Speeds, acceleration, jerk • Door opening/closing times • Photocell delays • ADO speed and distance • Loading capacity (% of full lift capacity that is filled (usually 80%))	• Passenger arrival rates • Traffic Components • Population distribution • Entrance floor attractions • Transfer times

BTS produces a number of output parameters including occupant lift wait time (time spent waiting for a lift), occupant ride time (time spent riding in a lift), occupant journey time (sum of lift wait time and ride time), and overall averages. BTS assumed that lifts, escalators and stairs are the main bottlenecks in the building.

BTS has the capability to model adults, children and disabled occupants [Susi, et al., 2004]. The default weight of adult occupants is between 68-80kg each occupying around 0.15-0.22m^2 of floor space inside a lift. Such parameters are defined as the capacity of a lift car is limited by the combined weight and space of the occupants inside. Occupants have two types of characteristics: physical and behavioural. Physical characteristics include attributes such as walker speed, lift transfer time, space demand and ability to use each transport device. Behavioural characteristics of occupants determine the decisions occupants make and how they move within the simulated environment e.g. avoiding crowded areas, avoiding walking long distances, etc. Passenger routing is one such key component of the behavioural part of BTS which determines how an occupant decides which transportation devices to use in order to get to their chosen destination. Susi [Susi, et al., 2004] states that by observing transport related behaviour patterns of real passengers the same behaviour can be represented within BTS. An artificial intelligent behavioural model is used to represent how occupants behave. Using the model, occupants exhibit typical occupant behaviour (e.g. avoiding previously visited areas). There are no predefined routes which occupants take; reacting to the local conditions in selecting which transport devices best suit their needs.

The occupant model is composed of two key parts: the router and reactor. The router plans the higher level route within the building using the graph of nodes (transport devices) which essentially ensures that occupants keep travelling in the right direction to reach a desired target. A score is given to each route based on the shortest distance algorithm. The reactor assesses each path based on the individual characteristics of each occupant (e.g. ability to walk long distances), using a sum of weighted values (weighted values are defined according to the occupant type), thereby assigning a score to each route. The values produced by the router and reactor are combined for each route to form a probability distribution from which the occupant has a given likelihood of choosing a specific route (the decision of which route an occupant uses is chosen at random from this probability distribution). No details regarding how the weights for the reactor model have been determined or if they are based on observational data is mentioned. No published accounts of validation or comparison with an actual traffic were found.

When occupants choose to use a lift and arrive in the lift waiting area they can adjust their decision to use a lift based on wait time and the queues for the lift. When a lift arrives those at the front of the queue board the lift first. The concept of different physical wait locations in relation to each lift or occupants influencing each other's behaviour within the lift waiting area whilst waiting is not explicitly represented.

During the evacuation simulations run by Hakonen [Hakonen, 2003b] if a lift car was not filled to capacity on a given floor, then it will move to the next floor in the sequence in order to collect more occupants before taking those occupants to the exit floor. This increases the efficiency of the lift system in better utilising the available space in each lift during an evacuation.

STEPS

The STEPS (Simulation of Transient Evacuation and Pedestrian movementS) circulation/evacuation model was originally developed by Hoffmann and Henson [Hoffman and Henson, 1997] in the 1990s at Mott Macdonald, UK and has since been further developed [Mott, 2003].

STEPS represents floors as continuous planes of discretized space using a Cartesian mesh of a chosen size (typically based on the size of occupied by a single person). Occupants move about the plane based on the underlying mesh. Routes through a structure are defined using a series of checkpoints on a given plane. Occupants interact with the geometry according to their defining attributes which include free walking speed, awareness, patience, association and pre-movement time. Occupants’ fundamental aim is to move through the geometry using the routes defined according to the shortest time selection method at their free walking speed. STEPS has the capability to produce a variety of output data at the individual occupant and overall simulation level.

Lifts in STEPS are defined by a series of attributes which are listed in Table 5. Lift output parameters include averages of round trip time, interval time, wait time, transit time, highest return floor, number of stops, and total population transported.

Table 5: STEPS lift model attributes

Kinematic	Delay times	Physical	Operational
• Speed. • Acceleration rate. • Acceleration jerk. • Deceleration rate. • Deceleration jerk.	• Dwell delay. • Motor delay. • Door opening time. • Door closing time.	• Maximum occupant density. • Lift width/depth/height. • Number of doors.	• Express lift. • Ability to use lift during evacuation. • Floor range specification.

When occupants decide which route to use when traversing multiple planes they will first calculate how long each route is likely to take them to traverse. This calculation considers other occupants speeds (who are on the current plane) in order to determine how long queues are likely to be for each lift, escalator or stair. A patience coefficient is also included which determines the level of acceptance an occupant has to wait in a queue for each route. An overall score for each route is then calculated and the route is selected with the lowest score. Whilst occupants move to their chosen exit they attempt to reduce the travel time. When agents elect to use a lift they attempt to get as close as possible to the chosen lift regardless of whether it is open or in a bank of other lifts. As a result agents do not elect to spread out in a lift waiting area whilst waiting for a lift to arrive. These processes are performed automatically with no explicit user control of how many agents will elect to use a lift on a given floor, how long agents are prepared to wait for a lift, or the influence of congestion in the lift waiting areas being represented.

EVACNET

The EVACNET evacuation model was developed in the 1984 by Francis and Kisko from the University of Florida, US [Kisko, et al., 1998]. EVACNET represents a building as a graph via a series of nodes and arcs. Nodes represent key parts of a building (e.g. rooms, corridors, stairs, escalators, etc), that are connected via arcs. Occupants in the model traverse between nodes via the arcs to evacuate. Nodes are defined by their capacity and initial number of occupants starting in them. Arcs are defined by the time it takes to traverse them, the flow capacity and what nodes they are connected to. Arcs can only connect two nodes. EVACNET is considered to produce optimal evacuation results in the sense that occupants evacuate the building as quickly as possible and decisions are based on minimising the total evacuation time of the entire building.

Lifts are modelled using a special type of node and arc. Each lift opening is represented as a node and is connected via an arc to a corresponding node on the exit floor. Lifts only run a fixed floor service schedule. Lifts are defined by the user via a series of attributes: down time, up time,

time of the first down departure (the time the lift arrives at its first floor), lift capacity, and priority. Occupants are only carried in the down direction. A user manually specifies the frequency of occupants that use each lift and no redirection of occupants to stairs is represented.

EvacSim

EVACSIM was developed by Poon at Victoria University, Australia in the 1990's [Poon 1994]. It is described as a discrete event simulation evacuation model. Occupants are defined via a series of attributes which are grouped into the following categories: occupant response (perceived level of severity of an incident), physical attributes (e.g. walker speeds, occupied space), and building knowledge (familiarity with exits and routes).

Flow to density equations are used to model exits and stairs. Queues (for stairs and lifts) are modelled on a FIFO (First in First Out) principle; they are all linear/single lane. Lifts are modelled using the following states: Call, Ascend, Load, Wait, Descend, Unload, and Free. Occupants exit lifts based on a LIFO (Last in first out) principle; occupants exit lifts in a linear/single lane fashion.

Summary review of software modelling lifts

A series of dedicated lift and evacuation/circulation models have been reviewed. In all models reviewed no representation of empirical based evacuation lift human factors is represented, though some contain circulation lift human factors. Occupants evacuating attempt to reduce their own total evacuation time. Dedicated lift models typically use implicit representation of human factors. Human factors such as lift waiting area behaviour and the influence that local conditions may have are typically not represented.

All models reviewed represent the physical, kinematic, and delay time components of a lift system to varying degrees. The most detailed kinematic components are represented using jerk, acceleration, and maximum speed values. This allows users to represent the movement of lifts within a building based on lift manufacturer kinematic specifications. In contrast, certain models allow users to specify the total lift travel time for a given journey that requires the user to manually calculate these travel times. Whilst both methods have the ability to represent the movement of a lift system, the former is considered more flexible as it allows the user to automatically measure the influence of varying the kinematic attributes of a lift without external calculations by a model user.

2.2.5 Evacuation lift strategies and simulation results

This section addresses literature that describes how lifts could be used during evacuations for the general population. Typically this is demonstrated through the use lift/evacuation model simulations and/or analytical methods. In all cases explored the use of both lifts and stairs is recommended in reducing total evacuation times compared to stairs alone.

Bazjanac [Bazjanac, 1977] states that the total evacuation time of a building using lifts depends on the number and distribution of people, characteristics of lift system, and the design of the building, mentioning the smaller the occupant/lift ratio (i.e. more lifts per person) the faster the evacuation. Bazjanac conducted a series of full building evacuation simulations of a 25 storey building to assess the effectiveness of using lifts during evacuations. Little detail is mentioned regarding the simulation software, simulated scenarios, lift model or how occupant behaviour was represented. In all full building evacuation simulations conducted the buildings were evacuated in less than 30 minutes using downward collective mode where lifts gave priority to occupants on the higher floors. All simulations assumed a constant flow of occupants to the lift lobby and Bazjanac states that the total evacuation time will be considerably extended if this does not occur. Bazjanac further states that to achieve this, occupants should be well trained and wardens should be located in lift waiting areas to facilitate the lift boarding process. Bazjanac mentions that there is little merit in evacuating occupants to other floors compared to evacuating them to the exit floor.

Around a similar time, Pauls [Pauls, 1977] proposed the concept of using shuttle lifts servicing sky lobbies combined with stairs to evacuate a building. Pauls suggested that occupants could initially evacuate to the sky lobbies using stairs and wait for further instructions whilst the best course of action is decided; drawing comparison to a ship evacuation where occupants muster before leaving the ship via lifeboats. If the situation requires, occupants could then board the shuttle lifts from the sky lobbies which would take them to the exit floor. Using numerical calculations, Pauls states that a 41 floor building containing 5,000 occupants could theoretically be evacuated in under 30 minutes. This represents around a 50% decrease in total evacuation time compared to the stairs alone.

In 2005 Wong et al [Wong, et al., 2005] proposed a similar lift evacuation strategy to Pauls with the use of sky lobbies and shuttle lifts. Wong states that because shuttle lifts only typically have two openings (on the ground and sky lobby floor) they require minimal additional pressurisation and water/smoke entry protection measures (for during fires). As such the strategy has a number of cost saving and fire safety protection benefits compared to a standard top-down evacuation strategy using all lifts. Wong used the STEPS evacuation model to run a series of full building evacuations in order to determine the potential benefits of using such a strategy compared to stairs alone.

The hypothetical building used was 100 floors in height with 21,000 occupants. It contained 3 stairwells and 4 refuge floors each serving a maximum of 24 floors. There were 14 shuttle lifts servicing those refuge floors and the exit level. Occupants were given instant pre-movement/response times and required to travel down the stairs to the next refuge floor where they would take the lift to evacuate. STEPS determined the proportion of occupants that would wait for the lift on the refuge floor based on the queuing time and patience of each occupant. No details regarding the proportion of lift/stair users initially starting on each floor, the average lift wait time, or number of occupants that redirected to the stairs after initially choosing the lifts was mentioned. Wong states that a number of simulation scenarios were run until the last stair user evacuated at the same/similar time to the last lift user. This was deemed to produce the fastest total evacuation time. As such the results in Table 6 are considered idealistic.

Table 6: Comparison on percentage of occupants evacuated [Wong, et al., 2005]

Percentage evacuated	Stair	Lift + stair	Difference
25%	26 min	11 min	-58%
50%	53 min	25 min	-53%
75%	80 min	41 min	-49%
90%	96 min	53 min	-45%
100%	110 min	70 min	-36%

As can be seen, the proportion of time saved using both lifts and stairs almost halves compared to stair only case for the first 90% of the population evacuated. The final 10% of the population extended the total evacuation time by 24.3% (17min) towards the end of the evacuation in the lift+stair scenario. This is due to occupants on the upper floors taking longer to evacuate due to having to travel further. Overall the lift+stair evacuation reduced the total evacuation time by 36% compared to the stair only scenario.

Klote et al [Klote, et al., 1992] used the ELVAC lift evacuation model to study the feasibly of using lifts to evacuate 4 General Service Administration (GSA) buildings in the US in the 1990's. For 3 buildings (Hoffman, White Flint, and General Service Buildings) a series of evacuation calculations were run where progressively more floors (starting from the top) used lifts and occupants below used stairs (each stairwell and lift serviced all floors). The study was intended to find the optimal number of upper floors which should use lifts with the remainder of the building using stairs that would produce the shortest total evacuation time.

The fourth building (Jackson Federal Building) was vertically partitioned into 3 zones (low, medium and high-rise) with each zone being serviced by 6 lifts. Calculations were run where different proportions of occupants used the lifts on each floor (with the remaining occupants using the stairs on each floor). The optimal proportion of lift users was found to be 65% of occupants on each floor with the remaining 35% using the stairs. This also included, on the low rise zone, occupants on the top 4 floors all using lifts to evacuate.

A top-down evacuation strategy for lift users was employed in all calculations for all the buildings. Overall results can be seen in Table 7.

Table 7: Overall ELVAC simulation results for the 4 GSA Buildings

Building	Hoffman	White Flint North	Jackson Federal	General Services
Number of Floors	13	18	35	7
Number of Lifts	10	4	18	12
Number of Stairwells	4	2	2	6
Number of Occupants	2,990	1,224	2,660	2,174
Stair Only Evacuation Time	15 min	14 min	26 min	7 min
Lift Only Evacuation Time	24 min	29 min	17 min	17 min
Lift+Stair Optimum Evacuation time	11 min	12 min	13 min	6 min
Approximate % Time Saved Compared to Stair Only	20%	15%	50%	10%

Overall results show that higher buildings would benefit considerably from the use of lifts during an evacuation. Evacuating occupants initially located on the upper floors as a priority was shown to reduce total evacuation time. In the Jackson Federal building calculations, whilst an optimal proportion of lift users was determined for each floor, it is questionable whether it is practical or possible to tell some occupants to evacuate using the lift and others to use the stairs who are initially located on the same floor.

Results presented from the studies by Pauls and Klote et al are based on analytical calculations based on the assumption that people behave in the same way with optimum usage of lifts/stairs assumed/determined. Such homogenous human behaviour and usage of lifts/stairs highlights the optimal nature of the studies.

Galioto et al [Galioto, et al., 2004] developed guidelines for the use of lifts during evacuations; a series of evacuation calculations were performed to ascertain the influence of using lifts and stairs compared to stairs alone. The hypothetical building used was 47 floors in height having 2 stairwells and 19 lifts. The lifts were split into 3 groups each serving a different vertical zone: low-rise (5), medium-rise (6) and high-rise groups (6) (plus one lift servicing all floors in each zone). The building was populated with 3,300 (approximately 70 occupants per floor). Lifts were placed in down peak modes thereby employing a top-down evacuation strategy for each zone. The total time to evacuate the building by stairs alone was calculated (using flow-density equations) to be 25 minutes. The total time to evacuate the building using lifts only was calculated to be 23 minutes. Combining both lifts and stairs (assuming an optimum usage between lifts and stairs) a decrease in total evacuation time to 12 minutes was recorded. This represents a reduction of total evacuation time in excess of 50% compared to the stair only scenario.

Howkins [Howkins, 2000] simulated a similar evacuation scenario to that of the Hiroshima Motomachi apartment fire (mentioned previously). Howkins compared a standard lift collective control mode and a proposed 'fire collective control' using the ELEVATE lift model. Howkin’s 'fire collective control’ method proposes that floors closest to and above the fire floor have priority to use a lift compared to those floors below the fire floor. The simulation results are presented in Table 8. Floors above the fire floor (floor 9) are given priority according to how close they are to the fire so occupants on the floor directly above the fire floor are given priority to use the lifts first. Occupants two floors above the fire floor are then given priority and so on. Howkins states that in a conventional collective control system (a down collective mode/top-down method) occupants closest to the fire floor would have to wait until all occupants on the floors above evacuated first before having priority.

Table 8: Fire evacuation collective control versus conventional collective control[Howkins, 2000]

	Fire Collective Control		Conventional Collective	
Level	**Lift arrives after (sec)**	**Nominal Order**	**Lift arrives after (sec)**	**Nominal Order**
20	226	9	71	1
19	204	8	94	2
18	181	7	116	3
17	159	6	138	4
16	Answered		Answered	
15	132	5	165	5
14	110	4	187	6
13	88	3	209	7
12	66	2	231	8
11	43	1	254	9
10	No Calls / Fire Floor		No Calls / Fire Floor	
9	No Calls / Fire Floor		No Calls / Fire Floor	
8	No Calls / Fire Floor		No Calls / Fire Floor	
7	289	10	288	10
6	Answered		Answered	
5	316	11	315	11
4	Answered		Answered	
3	342	12	342	12
2	Answered		Answered	
1	No Calls		No Calls	

Whilst the 'fire collective control' method offers immediate benefit to occupants closest above the fire floor, overall the total evacuation time of the building is identical to the conventional collective method.

2.2.6 Summary

A review of literature regarding lift usage during actual/drill evacuations, lift evacuation building codes/standards/guidelines, lift evacuation human factors data, software models that include lifts, and evacuation lift strategies has been conducted.

Analysis of actual/drill evacuations using lifts has highlighted that lifts can benefit an evacuation. Despite typical fire safety training of not to use lifts during evacuations many occupants have demonstrated that they are prepared to consider lift usage during an evacuation in certain situations (e.g. not considered a fire, not officially been told to evacuate, told to do so by rescue personnel, in imminent danger). Local conditions in the lift waiting areas (e.g. crowd levels), have been shown to influence occupants' decisions of whether to use a lift or redirect to the stairs. A number of incidents where occupants have either become trapped or died inside lifts has also been mentioned which serve to exemplify that a degree of risk is associated with lift usage. In actual evacuations it has been hard to accurately determine the proportion of occupants that used lifts on each floor due to the uncertainty of each floors total population. Indeed, in all incidents where the proportion of lift users has been calculated, it has been based on just the sample population or an estimate. It is therefore difficult in practice to determine the exact proportion of lift users on each floor in each evacuation. However, results suggest that as floor height increases the proportion of occupants that would consider using a lift also increases.

There is clear drive in recent times by regulatory bodies to incorporate the provision for lift usage for the general population during evacuations. This is particularly the case in the US where a number of guidance/regulatory bodies (e.g. ASME, NFPA, NIST) are coordinating an effort for the use of lifts during evacuations for the general population. Indeed non-mandatory requirements in building codes for such provisions are beginning to already appear. In addition, a number of organisations have developed guidelines using analytical calculations or simulation results to demonstrate the potential benefits of using lifts during evacuations for the general population. However, such results appear to neglect the potential impact of associated human factors.

Despite a number of actual evacuations demonstrating the benefits of lifts and a drive by regulatory bodies to include them for the general population in building codes, very few studies have attempted to understand and quantify human factors associated with evacuation lift usage. It has been shown from the empirical and qualitative studies reviewed that the many occupants have reservations about using lifts during an evacuation. Indeed collected data suggests most occupants know that they should not use lifts during evacuations. Results from past studies suggest that the perception of reliability of lifts during normal circulation appears to influence occupants’ acceptance to consider using lifts during an evacuation.

A review of selected dedicated lift and evacuation models has been conducted. Overall, the evacuation models appear to have greater capacity to represent more detailed/complex human factors compared to the dedicated lift models. This is due to dedicated lift models typically simplifying the movement of occupants as flow based analytical calculations and the lack of explicit modelling of more detailed occupant to occupant interaction that is commonly found in evacuation models. Despite the representation of evacuation lift human factors in a number of models no published material regarding such human factors data (empirical or actual) for any model was found. Indeed the capacity to represent the lift human factors in the models appears to have developed at a faster pace than the understanding of the lift human factors themselves. As such the representation of evacuation lift human factors in such models is considered to be questionable.

A number of studies using software based models and/or analytical calculations have demonstrated how a single lift strategy could potentially influence an evacuation compared to a stair only evacuation given a hypothetical scenario. A number of evacuation lift strategies were explored, including:

- Top-down/downward collective evacuation strategy
- Using refuge floors with shuttle lifts
- Priority for floors above and closest to the fire floor

In all cases explored the combined use of lifts and stairs is recommended in order to reduce total evacuation times by increasing the vertical throughput to the exit level. It appears a common result in the majority of studies for high-rise buildings, assuming optimum use of lifts and stairs, that the total evacuation time can be reduced by as much as 50% compared to stairs alone. The impact of evacuation lift human factors on such results has been neglected in such studies/models. Indeed the primary purpose of such studies appears to be for the demonstration of the potential impact of using lifts during an evacuation (i.e. not the potential influence of associated human factors).

2.3 Evacuation escalators

In certain structures such as deep underground/subway stations, that are well provided for by escalators for normal pedestrian flows, escalators can provide an attractive and efficient alternative to long stairs in evacuation situations. Escalators also offer a larger throughput capacity than a typical single lift for the same number of floors as there is no service wait time for occupants. The inclusion of escalators has made it possible to build ever deeper underground stations. Indeed it is common to find underground stations where there is almost no staircases forming part of the main circulation routes.

Underground stations commonly have a high volume of occupants that simultaneously arrive via incoming trains and traverse out them within short periods of time in normal circulation. As such they should in theory be well catered for getting occupants out of the station during evacuations.

However, the consideration of how to evacuate such structures has largely neglected the potential effect of escalator strategies and escalator human factors. The use of escalators during evacuations has received considerably less attention by comparison to the use of lifts with even less literature readily available. It is believed that this is contributed to by the common assumption that human factors on stairs are similar to that on escalators and that optimal analytical flow calculations for representation of escalator human factors are sufficient for evacuation analysis.

2.3.1 Escalator usage during evacuations

The majority of literature regarding escalator human factors relate to normal circulation conditions. The following section reviews literature regarding two actual evacuation incidents: the World Trade Center 911 attack and the Kings Cross Underground Fire. It is expected that a number of other actual evacuations have occurred in underground stations that have included the use of escalators. However, there is a lack of published literature regarding such events and where it does exists, details regarding escalator usage has not been included or is sparsely mentioned.

World Trade Center 911 Attack

A description of the events the World Trade Center 911 attack has been given in the lift section of this review. Further to the description of the WTC1 and WTC2 towers presented in the lift section, there were two exit levels at the bottom of each tower; mezzanine/plaza level (with an exit only to one side of each tower) and street/concourse level (exiting below the mezzanine/plaza level to both sides of each tower) [Averill, et al., 2005].

Whilst there were a number of escalators within both towers, this review focuses on the most used escalators on the lower levels during the attacks. Occupants evacuating down two of the three emergency stairs would exit onto the mezzanine/plaza level where they could either exit on that level or proceed further down to the street/concourse level via an escalator. Those occupants who did so would then choose to exit on either the street side of the tower or the concourse side. The concourse side would take them into an underground complex of shops where they could reach the street level by going up a level via either stairs or escalators. Both towers were connected via the concourse under the plaza level. The concourse area also connected to an underground station below where a number of occupants were also required to evacuate the station up to the plaza level. A simplified layout of the levels and exits can be seen in Figure 8 below.

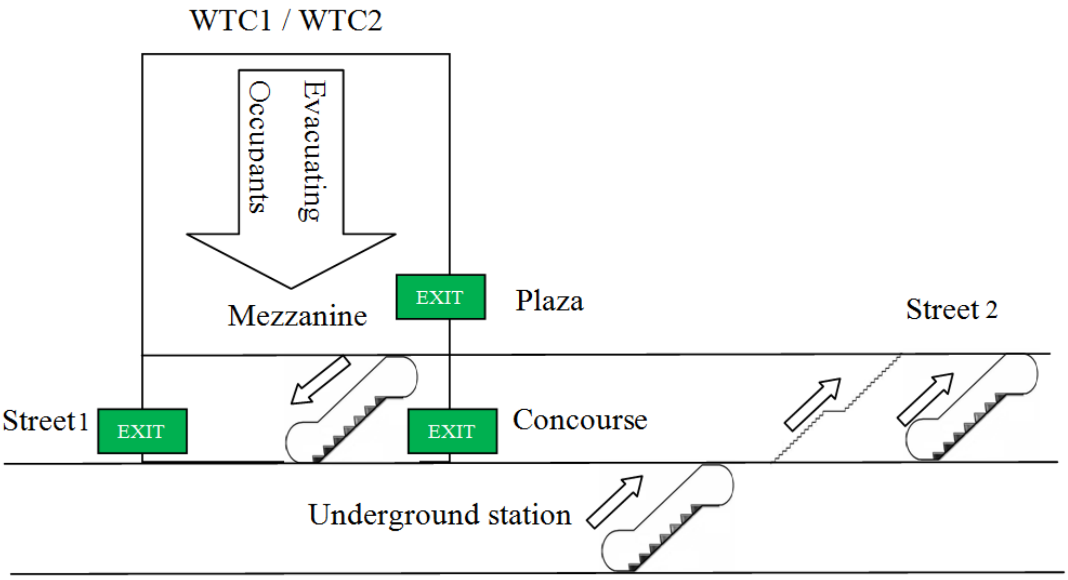


Figure 8: World Trade Center - WTC1/WTC2 simplified exit and lower level layout

It is important to understand the vertical layout of the lower sections of both towers because during the evacuation debris and bodies were falling from both buildings onto the street and plaza level. This posed a danger to occupants evacuating the building and potentially influenced their perception of the severity of the incident. As such it was decided at some point during the evacuation that occupants should evacuate to the concourse level. This meant that the remaining occupants who used two of the emergency stairs from either WTC1/WTC2 were required to use at least one escalator as part of their evacuation route. This included the mezzanine/plaza level escalator to transfer down to the concourse level and either the stairs or escalators from the concourse level to traverse up to the street 2 level.

There were two escalators connecting the mezzanine/plaza level to the street/concourse level; in normal usage one would be moving upwards and the other downwards. Early on during the evacuation, survivor accounts state that these escalators were moving and being used to evacuate occupants. An example of which can be seen below from an occupant initially on floor 36 of WTC2:

"Participant: I ended up on the plaza level …. by then people were kind of jostling to get on the escalator…..…
Interviewer: So, you go to the escalator. Do you have to wait to get on? …
Participant: Yeah… I mean it probably took me you know maybe 30 seconds then to get on. I remember he kind of held some people so that I could just kind of, kind of get on.
Interviewer: And was the escalator moving?
Participant: Yeah, yes. Yes." (WTC2/036/0002) [Galea, et al., 2006a]

However, at some stage during the evacuation both escalators were turned off and certain occupants stated a dislike to walking down static escalators, as highlighted by a survivor who was initially on floor 55 of WTC2:

"Participant: ….And they kept telling us to 'Leave, leave, leave!' And our group was growing. But… and we walked over to where the escalators were, and we just walked down the escalators.
Interviewer: Were there lots of people on the escalator?
Participant: It was just a steady flow. It was like you'd walk out of the stairway and walk down the escalator….
Interviewer: How fast are people moving at this point?
Participant: Just a regular walking pace….
Interviewer: Cos the escalators aren't working. So how fast are people… just walking…
Participant: Slower than on the regular stairs, cos escalators suck to walk down. But, you know, 'Dunk, dunk, dunk, dunk, dunk, dunk…'" (WTC2/055/0001) [Galea, et al., 2006a]

Despite occupants being able to use both escalators, initially, most occupants proceeded to only use one escalator (the normal downward escalator) before eventually using both, as highlighted in the quote below of a survivor initially on floor 13 in WTC1:

"***Participant: …. the only thing I do recall with absolute clarity that was people were only going down the right hand escalator.***

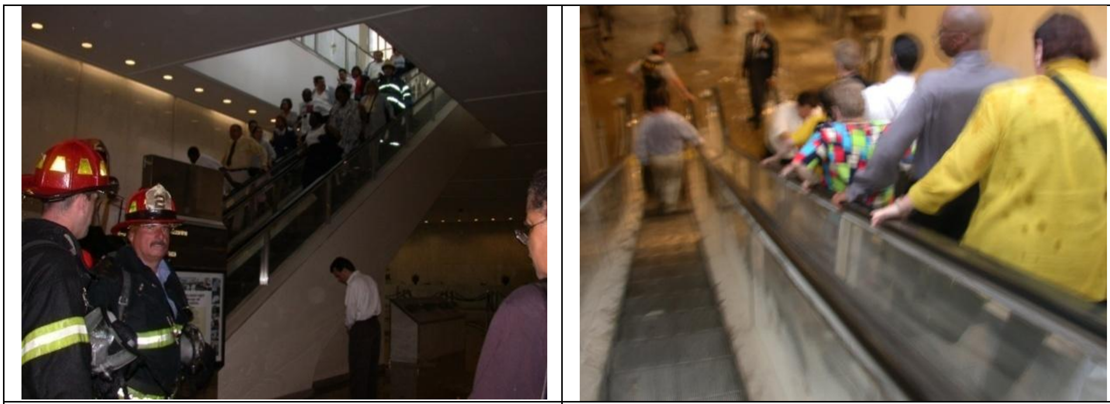
Interviewer: And you said you're about to call something out to someone.

Participant: I was about to say 'hey stupid', you know, 'use both of them' and then somebody else beat me to it.

Interviewer: How fast were they moving down the escalators?

***Participant: I don't recall them moving too quickly but obviously once they went down the second one then traffic opened up quite quickly.*"** (WTC1/013/0001) [Galea, et al., 2006a]

Further evidence to support that only a single escalator was initially being used can be seen in Figure 9 where photographs of mezzanine/plaza escalator users in WTC2 can be seen.



John Labriola	**{Unknown evacuee}**

Figure 9: World Trade Centre (WTC2) - Photo taken by evacuees of mezzanine/plaza escalators

From Figure 9 it can also be seen that the mezzanine/plaza level escalators were narrow with only a single lane being able to form on each escalator. This is confirmed in the following survivor account:

"*Interviewer: So when you reached the escalator, was it a case of having to wait?*

***Participant: Yeah. It really was a small, it was a very narrow… I think it was really only one person, you could squeeze two, but it was a kind of a one-person-at-a-time escalator.*"** (WTC1/044/0002) [Galea, et al., 2006a]

Having a narrow escalator width would have decreased the flow-rate onto the escalators. Due to the escalators being static, forcing all occupants to walk, would have forced increased spacing between escalator users and further contributed to a decreased flow-rate onto the escalators.

In addition to the WTC1 and WTC2 towers, a number of occupants evacuated the underground station connected to the concourse level of the World Trade Center complex. Despite being an evacuation, survivor accounts suggest that normal common side preference behaviour was typically adhered to in the underground station with riders using the right side and walkers using the left side. This is exemplified in the following account of an occupant initially in the underground station:

> **"*Participant: I don't remember anybody having a reaction. Now its kind of hard to have much of a reaction on an escalator. But nobody started to run any more than… there was… you know there was the code on the escalator you stood to the right and you walked to the left so the people who were walking continued to walk and the people on the steps didn't.***
> *Interviewer: That's when the officer… that was when the police officer told you to run for your life?*
> ***Participant: He said literally… actually you know I can't now remember who… at that point there were… voices were starting to be raised. And I can't remember if it was a male or a female officer but he said literally 'Run, run, run for your life.'"***
> (WTC0/PATH/0003) [Galea, et al., 2006a]

Kings Cross Station Fire

On November 18th 1987 in the early evening a fire started on an escalator in London's King's Cross underground station. The escalator was made of wood at that time which contributed to the fire and smoke spreading more rapidly [Fennel, 1988; Donald and Canter, 1990]. A total of 31 people died in the incident.

King's Cross underground station is built over five levels serving multiple tube lines below ground and is connected by passageways, staircases and escalators. It is quoted as being one of the most complex stations in the London Underground [Donald and Canter, 1990]. The Fennel report [Fennel, 1988] states that at the time of the fire London underground had no evacuation plan for the station. The ticket hall of the underground station is connected to a main line station. From the ticket hall level two sets of 3 escalators connect to the passageways that lead to the underground platforms. One set leads to the Victoria line and the other to the Piccadilly and Northern line platforms. Occupants can transfer between tube lines via a series of passageways without having to first travel to the ticket hall level first.

Soon after the fire was discovered at around 7:30PM a passenger pressed the emergency stop button to stop the escalator in question moving (connecting the ticket hall level to the Piccadilly line platform). A ticket inspector cordoned off the static escalator to prevent occupants from using it, shortly after local transport police arrived. Travellers were directed away from using the Piccadilly line escalators to the Victoria line escalators where they could move up to the ticket hall level. Shortly after an official call to evacuate the entire station was made, all occupants coming from the platforms were advised to evacuate via the Victoria line escalators through the ticket hall to the exit/main line station. Fire fighters arrived 13 minutes after the fire had been noticed. Trains continued to stop at the station where occupants alighted despite calls to stop trains arriving. As such rescue personnel were required to continue evacuating occupants from arriving trains.

The top of both the Victoria and Piccadilly line escalators were only a short distance from each other in the main ticket hall. However, the bottom of both escalators was separated by a much longer distance of interconnected passageways. Redirecting occupants to evacuate using the Victoria line escalators from the Piccadilly line escalators severely extended the evacuation route for those occupants. Despite the considerable extension to the route, occupant evacuation via the ticket hall placed many in significant danger. This was due to the fire spread travelling up the Piccadilly line escalator to the ticket hall (i.e. where occupants were alighting the Victoria line escalator). At around 7:45PM flash-over had occurred in the main ticket hall. Occupants on the main escalators were quoted as saying "they saw a fellow passenger descend with his clothes and hair on fire" [Donald and Canter, 1990]. The evacuation route using the 3 Victoria line escalators was then changed and occupants were diverted to take trains in order to evacuate the station.

Donald and Canter [Donald and Canter, 1990] state that occupants within the station only changed their normal behaviour (of passing through the station) when they were either instructed to do so by a figure of authority or "the evidence of their senses was so totally overwhelming that they knew different, extraordinary action was required for survival" [Donald and Canter, 1990]. Many occupants were unaware of the evolving hazard and/or the severity of the situation. Indeed those initially using the Victoria line going to the ticket hall would have not likely experienced any hazard cues until they were near the top of the Victoria line escalator linking to the ticket hall. As such it is likely that many occupants would have adopted normal circulation behaviour on those escalators.

In addition to the escalator human factors, the study serves to demonstrate how reliant underground stations have become on the use of escalators during evacuations. The restricted availability of such devices and associated egress routes is expected to considerably decrease the levels of safety within such structures.

2.3.2 Evacuation escalators - codes, standards and guidelines

The allowance for the use of escalators during evacuations is varied between building codes and standards. Indeed some prohibit the use of escalators during evacuations in certain circumstances. There are many reasons for the restricted use of escalators in emergency situations. These include

- an unexpected shut down during operation possibly causing some escalator users to fall,
- pedestrians may become trapped on the escalator (e.g. disabled) because they cannot physically traverse a static escalator on their own,
- moving escalators may be carrying pedestrians to, rather than away from danger.

In situations where escalators have stopped, the uneven riser height for some of the treads (at the top and bottom of an escalator) increases the likelihood of a miss step resulting in a fall.

Building codes and guidelines from the US and UK have been reviewed with regards to evacuation escalator usage, including:

- International Code Council International Building Code [ICC, 2009],
- NFPA 101: Life Safety Code [NFPA, 2009a],
- NFPA 130: Standard for Fixed Guideway Transit and Passenger Rail Systems [NFPA, 2010],
- NFPA 5000: Building Construction and Safety Code [NFPA, 2009b],
- BS9999: Code of practice for fire safety in the design, management and use of buildings [British Standards, 2008],
- The Buildings Regulation 2000 – Approved Document B – Fire Safety [Communities, 2006]
- Guide D: Transportation systems in buildings [CIBSE, 2000].

The ICC, 2009 International Building Code [ICC, 2009], NFPA 101 [NFPA, 2009a], and NFPA 5000 [NFPA, 2009b] state that escalators should not form part of the required egress capacity of a building.

The NFPA 130 [NFPA, 2010] allows the use of escalators as part of the egress capacity within transit stations providing a series of criteria are met. These include:

- the escalator is not made of combustible materials,
- escalators moving in the direction of egress can carry on moving,
- escalators moving in the opposite direction to egress can be stopped both locally and remotely (including gradual deceleration mechanism),
- provide audible or visual signage to communicate to occupants on or near the escalator.

In addition, escalators that are static are allowed to be started in the direction of egress. Generally, escalators are not permitted to account for more than 50% of the egress capacity of each level in a transit station. However, escalators are permitted to account for more than 50% of the egress capacity providing the escalators can be remotely stopped, the respective level has stair egress access also, and in enclosed stations an exit stair/passageway connects the platforms to a place of safety. Where escalators are used to calculate the egress capacity of a transit station at least one escalator shall be assumed to be out of service (chosen according to which escalator would have the most adverse effect on the egress capacity).

The British Standards BS9999 [British Standards, 2008] stipulate that generally escalators are not considered a means of egress and that occupants should be discouraged from using them during an emergency though it is expected that occupants will use them in certain situations. Escalators should automatically stop moving when a fire alarm is sounded to avoid occupants being taken to rather than away from a hazardous area. Despite this, BS9999 state a number of exceptions to this in which escalators can be used during an evacuation. Escalators can be included as part of the main egress capacity of transit stations providing a fully fire engineered assessment is carried out. Within shops escalators should include drills where, upon the alarm, select staff move to either end of the escalators in order to control the use of the escalator and the people on it.

Approved Document B (ADB) [Communities, 2006] echoes what is mentioned in BS9999 in that escalators should not be consider part of the means of egress though it is expected that occupants will use escalators if they are free from smoke and heat.

CIBSE Guide D: Transportation systems in buildings [CIBSE, 2000] state recommendations for the use of escalators and lifts in normal circulation situations in addition to a variety of associated human factors. Included in the guidelines are theoretical handling capacities (maximum flow-rates) for escalators with different speeds and widths (see Table 9).

Table 9: Theoretical escalator handling capacities according to width (ped/min) [CIBSE, 2000]

Escalator Speed (m/s)	Escalator Tread Width		
	1 m	0.8 m	0.6 m
0.5	150	113	75
0.65	195	146	98
0.75	225	169	113

The guide states that actual escalator handling capacities are likely to be half the theoretical values with the influence of pedestrians leaving tread spacing between each other. On a 0.5m/s escalator it takes just under a second (0.92s) (depending on the tread depth) for each step to appear which the guide states is too fast for the majority of pedestrians to continuously board. The guide recommends that at least two escalators should be placed at each location to handle both up and down flows with each escalator preferably being parallel to each other. The guide states that escalator step risers are typically 21cm in height which is larger than the 18cm maximum recommend step height for stairs. This is why pedestrians typically find walking on escalators more tiring. The guide states that escalators are usually used by pedestrians to travel a small number of floors and when occupants decide when to choose to use an escalator or lift then they will consider travel time, wait time, and walking effort for each device (no justification for this is mentioned). The guide states the proportion of occupants that would likely use an escalator and lift for travelling a different number of floors in Table 10. It is worth noting that no reference of any study or justification for these figures is mentioned or if such figures differ according to direction of travel.

Table 10: Likely proportion of pedestrians to use escalators and lifts [CIBSE, 2000]

Floors Travelled	Escalator (%)	Lift (%)
1	90	10
2	75	25
3	50	50
4	25	75
5	10	90

2.3.3 Escalator human factors - empirical data

The majority of past escalator human factors studies relate to escalator usage during normal circulation conditions. The evacuation related studies reviewed are all experimental with the application being stated/used within an evacuation context. In all literature reviewed the appropriateness and validity of applying the data captured in experimental or normal circulation conditions within an evacuation context is questionable, though the lack of available alternatives based on published literature suggests it is required.

A broad review of literature pertaining to empirical escalator human factors data has been conducted segregating according to escalator/stair choice, escalator flow-rates, proportion of walkers/riders, walker speeds, and escalator side usage.

Escalator/Stair usage

When pedestrians approach an escalator/stair combination they are required to decide which device to use in order to traverse the vertical area. Two major studies that focused on escalator/stair choice based on empirical data were by Cheung and Lam [Cheung and Lam, 1998] and Zeiler et al [Zeiler, et al., 2010]/Knehs [Knehs, 2010], both of which have been reviewed. In both studies a regression analysis of collected data was conducted in order to develop a formula to predict the probability that a pedestrian would use an escalator/ stair using measured attributes (e.g. walker speed, flow-rate, etc).

Route Choices Between Escalator and Stairway in MTR Stations

Cheung and Lam [Cheung and Lam, 1998] recorded the frequency of pedestrians that used escalators/stairs, travel times, and flow-rates in six stations within the Hong Kong Mass Transit Railway (MTR) underground system during peak hours in both the up and down direction. Conditions on the walkways leading to each escalator/stair were also recorded to see how they would influence device selection. This section focuses on escalator/stair selection and the escalator walker speed data is focused on in the escalator walker speed section.

Using the collected data the authors proposed a model to predict if a pedestrian would use an escalator or adjacent stair. The authors suggest that pedestrians make the decision to use an escalator/stair in order to reduce travel time; pedestrians consider expected travel time to and on each device in their selection.

The developed model comprises of a travel time calculation for each device; considering the distance to/on each device, and the current flow of pedestrians onto the device (See Equation 5).

$$t(v) = t_0 + B \, . (\frac{v}{c})^n$$

Equation 5

$t(v)$ = travel time (s) at flow v
t_0 = free flow travel time (s)
v = pedestrian flow (ped/m/min)
c = capacity of pedestrian block (ped/m/min)
B,n = parameters to be estimated

A logit model to predict the probability of a pedestrian using an escalator (P_{esc}) given a relative discomfort measure (X) has then been constructed. The authors defined the relative discomfort measure as the difference between the expected total travel time using the escalator and the stair (See Equation 6).

$$P_{esc} = \frac{1}{1 + \exp X}$$

Equation 6

$X = a + b \, . (t_{esc} + t_{ToEsc} - (t_{stair} + t_{ToStair}))$
t_{esc}= time travelling on the escalator
t_{ToEsc} = time travelling to the escalator
t_{stair} = time travelling on the stair
$t_{ToStair}$= time travelling to the stair
a,b = parameters to be estimated

The data collected within the underground stations was used to estimate the respective parameters in the model through performing a regression analysis. These parameters along with the average free flow walker speeds, walker speeds at capacity (maximum flow-rate), and maximum recorded flow-rates, can be seen in Table 11. The maximum recorded escalator flow-rates for both the up and down escalators was 120 ped/min, which equates to 2 pedestrians boarding the escalator every second. The author states such escalator flow-rates are particularly high and can be partially explained by the smaller physique of oriental pedestrians and the increased motivation of pedestrians to traverse the area (e.g. commuters, etc).

Table 11: Travel Times, Max Flow-rates Functions by Pedestrian Blocks[Cheung and Lam, 1998]

Facility	Number Of Samples	Parameters			Free flow walker speed (m/s)	Walking speed at capacity (m/sec)	Max Flow-rate (ped/min)	R^2
		T_0	B	n				
Escalator Up	611	1.12	0.25	1.07	0.89 [0.88-0.90]	0.73 [0.72-0.75]	120	0.80
Escalator Down	692	0.95	0.41	1.27	1.05 [1.03-1.07]	0.73 [0.71-0.75]	120	0.78
Stair Up	696	1.16	1.18	2.08	0.86 [0.84-0.88]	0.43 [0.42-0.44]	70	0.83
Stair Down	687	1.03	0.63	2.43	0.97 [0.96-0.98]	0.60 [0.59-0.61]	80	0.85
Walkway to Escalator	709	0.87	2.38	2.28	1.15 [1.09-1.21]	0.31 [0.30-0.32]	-	0.86
Walkway to Stair	712	0.87	2.29	3.44	1.14 [1.11-1.18]	0.32 [0.30-0.33]	-	0.83

The logit models used to calculate the probability that a pedestrian will use an escalator (instead of an adjacent stair) was subsequently constructed for the down and up direction (See Equation 7 and Equation 8).

$$P_{esc}^{Down} = \frac{1}{1+\exp(-3.1001-0.1745.xt)} \quad R^2 = 0.84$$

Equation 7

$$P_{esc}^{Up} = \frac{1}{1+\exp(-5.34411-0.2073.xt)} \quad R^2 = 0.87$$

Equation 8

xt = total travel time difference between using the escalator and stair

Using Equation 7 and Equation 8 the predicted proportion of escalator/stair users can be calculated/plotted (see Table 12 and Figure 10). As expected, the regression shows that pedestrians travelling in the up direction have a preference to using the escalator more than pedestrians travelling in the down direction. The regression suggests that there is approximately an even probability that a pedestrian would use the escalator or stair when the stair would take around 26 and 18 seconds longer to traverse than the escalator for the up and down directions respectively.

Table 12: Regression values for given travel time differences between escalator/stair

$Esc_{TravelTime}$-$Stair_{TravelTime}$ (s)	UP		DOWN	
	Escalator	Stair	Escalator	Stair
2	99.3%	0.7%	94.0%	6.0%
4	98.9%	1.1%	91.7%	8.3%
6	98.4%	1.6%	88.6%	11.4%
8	97.6%	2.4%	84.6%	15.4%
10	96.3%	3.7%	79.5%	20.5%
12	94.6%	5.4%	73.2%	26.8%
14	92.0%	8.0%	65.9%	34.1%
16	88.4%	11.6%	57.6%	42.4%
18	83.4%	16.6%	49.0%	51.0%
20	76.8%	23.2%	40.4%	59.6%
22	68.6%	31.4%	32.3%	67.7%
24	59.1%	40.9%	25.2%	74.8%
26	48.9%	51.1%	19.2%	80.8%
28	38.7%	61.3%	14.4%	85.6%

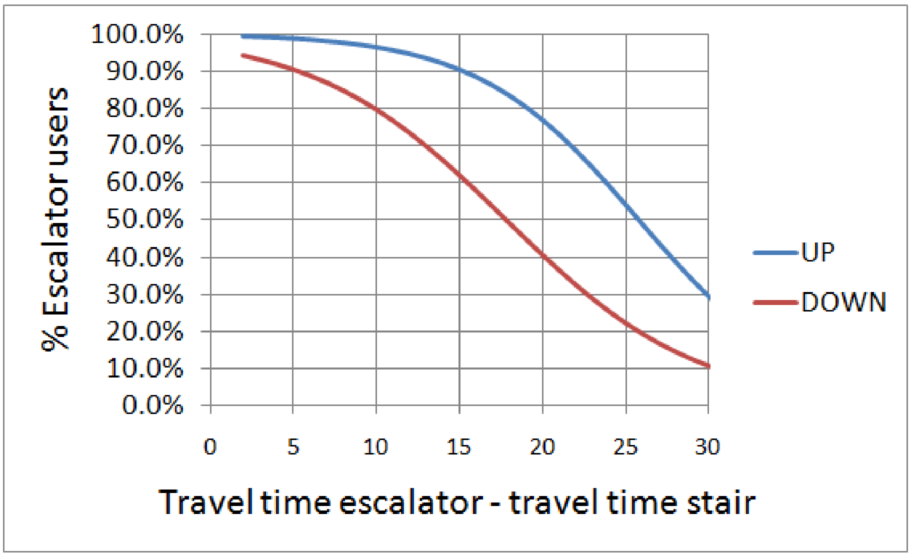


Figure 10: Regression plots for the proportion of escalator users given the travel time differences between escalator/stair

The authors state that pedestrians were more sensitive to delays on the escalator/stair in the down direction compared to the up direction. This is expected as pedestrians would be prepared to wait longer to use an escalator travelling in the up direction due to the increase energy required and slower speeds afforded by an adjacent stair compared to the down direction. The goodness of fit values (R^2) for Equation 7 and Equation 8 were high which suggests that the difference in travel times for using the escalator/stairs is a good predictor of escalator/stair usage.

Within the study data was only collected in peak periods and it is uncertain how this would compare to off peak periods. The assumption that pedestrians are all attempting to minimise their travel time is considered reasonable and in keeping with the theory of Bounded Rationality as mentioned by Simon [Simon, 1957] for the majority of pedestrians. However, the extent to which this occurs is uncertain. Due to the data being collected in a single country it is uncertain whether the data and subsequent model developed is applicable to other countries, particularly western countries where pedestrians are typically of a larger build.

Modelling Random Taste Variations on Level Changes in Passenger Route Choice in a Public Transport Station

Similar to the work by Cheung and Lam [Cheung and Lam, 1998], Zeiler et al [Zeiler, et al., 2010] and Knehs [Knehs, 2010] recorded the number of escalator/stair users in addition to associated flow-rates across three different underground complexes in Austria during normal circulation conditions; locations were referred to as Vienna I, Vienna II and Graz. The height of each escalator was 3.9m for Vienna I and Vienna II, and 4.8m for Graz. A large number of pedestrians were counted using the escalators/stairs across each site; 30,235 in the down direction and 31,630 in the up direction.

In Table 13 the overall aggregated results can be seen including the total average hourly flow-rate for each location (for both escalators and stairs combined). Here it can be seen that in the Vienna II location, despite the similar average total flow-rates recorded in both directions, the proportion of stair users was almost three times as high in the down direction compared to the up direction. However, in the Graz data the average up flow-rate was approximately twice to that recorded in the down direction. It is uncertain why each location’s up and down average flow-rates followed different trends.

Table 13: Number of observations, average flow-rate per hour and proportion of stairs users for each station in each direction [Zeiler, et al., 2010, Knehs, 2010]

	Vienna I	Vienna II	Graz
Up			
Persons	N/A	19105	11130
Average flow /hour	N/A	1273	505
On Stairs (%)	N/A	11.8	21.8
Down			
Persons	3722	16741	11167
Average flow /hour	551	1116	501
On Stairs (%)	13.8	32.0	11.0

The aggregated data was separated according to minutes in the data and flow-rates of 10 ped/min or less were separately analysed. As expected during the periods where less than 10 ped/min were recorded, lower proportions of stair users were recorded (between 7.6%-11.4%). The authors derive from this that the results support the conclusion that during low flow-rates that personal factors are the main influence for device choice.

For the remaining data where higher flow-rates were recorded (>10 ped/min), data points were plotted of the flow-rates against the proportion of stair users at different times (only Vienna II plot was presented). In this Vienna II plot, as the flow-rate increases so does the proportion of stair users, which is expected considering the added width of an adjacent stair compared to the respective escalators. Data from the Vienna II location shows that there was considerable variation between the proportion of stair users for each flow-rate measurement, with this variation decreasing as the flow-rate increases. Again this is expected as the frequency of pedestrians that pass through the area increases so the surrounding structure begins to become the restricting factor for the flow-rate.

A regression analysis was performed in order to develop a formula for predicting the proportion of stair users given the flow-rate. Included within the regression analysis, in addition to the flow-rate, was the counter flow-rate of pedestrians moving in the opposite direction (see Table 14).

Table 14: Dependence of the percentage of persons ascending as a function of the flow-rate (persons per second) and of the rate of the counter flow on the stairs [Zeiler, et al., 2010, Knehs, 2010]

	Vienna I	Vienna II	Graz
Up			
Constant	0.093	0.017	-0.001
Flow-rate	-0.096	0.62	0.32
Flow-rate^2	0.43	-0.16	-0.05
Counter flow	N/A	-0.12	0.20
Down			
Constant	N/A	0.015	-0.001
Flow-rate	N/A	0.17	0.39
Flow-rate^2	N/A	0.11	-0.30
Counter flow	N/A	-0.06	0.08

Flow-rates

Whilst the literature regarding escalator human factors is sparse, the majority of previous studies have focused on escalator flow-rates/handling capacities in normal circulation situations. It is believed this is due to their ease of use to understand/apply for pedestrians dynamic calculations and incorporate such figures into simulation models (many models have the capacity to represent flow based situations). In addition, the most number of pedestrians that can pass through a vertical area in a given amount of time is of prime interest to transport planners and building owners as it defines the upper design limit for occupancy levels of a given area/structure. A selection of five studies have been reviewed which are believed to be representative of the current understanding regarding escalator flow-rates.

Escalator Handling Capacity: Standards Versus Practice

Al-Sharif [Al-Sharif, 1996] states that the theoretical flow-rate of a 1m wide escalator travelling at 0.75 m/s is 225 ped/min which assumes two pedestrians per tread and all pedestrians ride. However, it is widely accepted that this flow-rate is rarely achieved. To demonstrate this and give justification/determine the maximum flow-rate for a typical escalator in the London Underground, pedestrians using a series of seven escalators with varying heights in both the up and down direction were recorded. Pedestrians were counted during 1 minute intervals during peak flow conditions. Results of the study can be seen in Table 15. Here the highest flow-rate recorded was 140 ped/min on Escalator C in the down direction. This represents a considerably lower flow-rate (62.2% (85 ped/min) less) compared to the theoretical maximum flow-rate of 225 ped/min.

Table 15: Escalator heights, direction, day usage, maximum flow-rates recorded for each escalator [Al-Sharif, 1996]

Escalator	A	B	C	D	E	F	G
Height (m)	14.6	14.6	14.6	7.6	7.6	17.2	17.2
Direction	Up	Up	Down	Up	Down	Up	Down
Usage (ped/day)	27,825	27,825	52,622	22,456	24,910	12,179	17,696
Maximum recorded flow-rate (ped/min)	101	104	140	122	123	86	92
% of theoretical maximum flow-rate (225 ped/min)	45%	46.2%	62.2%	54.2%	54.7%	38.2%	40.9%

Al-Sharif states that even during peak conditions it was observed that pedestrians do not occupy every tread. Riders on the right side typically board every other tread and walkers on the left side typically occupy every third tread (i.e. occupy two treads simultaneously whilst moving plus a one tread spacing). Al-Sharif states this is due to pedestrians desire to maintain personal space between themselves and others (termed 'buffer zone'; see Figure 11) which was first proposed by Fruin [Fruin, 1971]. Indeed Fruin first observed the phenomena of escalator pedestrians leaving tread spacing's between each other and the impact this had on the theoretical maximum escalator flow-rates. The buffer zone is defined as an ellipse around the person’s torso. Since the effective depth of an escalator tread is typically less than the depth of this buffer zone means escalator users, unless forced to, typically leave a tread spacing between themselves and the person in front. In addition, for a 1m wide escalator, though it is stated that two pedestrians can stand on each tread, considering the buffer zone, it is unlikely that pedestrians will choose to do so in order to maintain comfort levels. Both of these factors contribute to maximum escalator flow-rates being reduced.

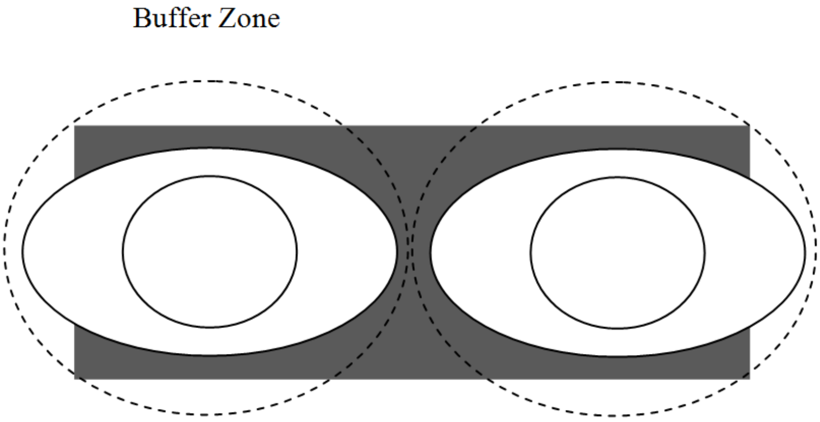


Figure 11: Human ellipse with human buffer zone and escalator tread [Al-Sharif, 1996]

Al-Sharif states that if escalator riders occupy every other tread and escalator walkers occupy every third tread, then the maximum theoretical flow-rate of an escalator is only 50.0% utilised on the rider side and 33.33% utilised on the walker side. Assuming an even number of walkers and riders this translates into a 41.7% (0.5*0.5 + 0.5*0.333) utilisation of the theoretical maximum flow-rate which translates to 93.8 ped/min (41.7% of 225 ped/min). However this does not consider that escalator walkers board the escalator quicker than riders so Al-Sharif proposes a walker factor of 0.7 (i.e. the calculated flow-rate should be increased to 70% of the maximum flow-rate if walker speeds are included). This increases the maximum flow-rate to 134 ped/min (93.8/0.7) which is similar to the maximum flow-rate (140 ped/min) recorded in the field studies.

Pedestrian Planning and Design

Fruin [Fruin, 1971] recorded the times pedestrians took to board escalators based on a photographic survey (i.e. the time it took pedestrians to pass the initial entrance to the section of the escalator to the time pedestrians placed their first foot on the escalator tread). Fruin argues that, in addition to having a preferences to reduce physical contact with other escalator users, the escalator boarding process is a determinant for the pedestrians leaving tread spacings between each other (and thereby influences escalator flow-rates). Average escalator boarding times from the study can be seen in Table 16. The results show that a slight increase in escalator boarding times can be seen when travelling with baggage or travelling during heavy traffic. This would be expected as carrying baggage or travelling in heavy traffic would reduce walker speed. Also males were on average observed to board an escalator faster than females which again is as expected considering male walker speeds are on average faster. No details regarding the definition of 'heavy'/'light traffic or 'baggage' is mentioned.

Table 16: Photographic survey – average escalator boarding times [Fruin, 1971]

	Light Traffic		Heavy Traffic
	No baggage (sec)	**With baggage (sec)**	**No baggage (sec)**
Men	0.95	1.01	1.16
Women	1.06	1.08	1.18
Combined	0.98	1.05	1.17

Despite the boarding time study, Fruin does not record the average spacing between pedestrians or directly link the boarding delay with tread spacing or flow-rate data. As such it not entirely clear to what extent the collected escalator boarding delay times influence flow-rates.

Vertical Transportation - Elevators and Escalator

Maximum theoretical and nominal escalator flow-rates are reported by Strakosch and Caporale [Strakosch and Caporale, 2010] (see Table 17). The normal flow-rates are based on averages over a period of time under normal conditions for different width and speed escalators. No details regarding how the nominal flow-rates were collected or the direction of travel is mentioned.

Table 17: Escalator flow-rates (30 degree incline) [Strakosch and Caporale, 2010]

Width	Incline speed (m/s)	Maximum theoretical capacity (ped/min)	Nominal capacity (ped/min)
0.6 m	**0.45 (90 feet/min)**	84.4	33.6
	0.5 (100 feet/min)	93.8	37.4
	0.61 (120 feet/min)	112.4	45
1m	**0.45 (90 feet/min)**	135	67.4
	0.5 (100 feet/min)	150	75
	0.61 (120 feet/min)	180	90

The nominal flow-rates presented are much lower compared to that presented by Al-Sharif [Al-Sharif, 1996]. This is due to the flow-rates being averaged over normal periods of time (calculated per hour) as opposed to flow-rates just being recorded during peak times (calculated per minute).

Estimation of Capacity of Escalators in London Underground

Similar to Al-Sharif [Al-Sharif, 1996], Davis and Dutta [Davis and Dutta, 2002] collected escalator flow-rates during peak conditions within a number of stations in the London Underground. The authors mention that the London Underground guidelines use 100 ped/min as the assumed maximum flow-rate for escalators. The aim of the study was to determine if this was accurate and determine if escalator height, having two escalators in parallel (double escalator), escalator approach configuration (intersecting contra-flows from downward traffic) and direction of travelled influenced this flow-rate.

On average the highest flow-rates were typically recorded on escalators where pedestrians alighted trains in large batches and large numbers were simultaneously attempting to pass through a given area. Due to escalator users typically forming separate walker and rider lanes in most London Underground stations, the flow-rates were recorded for the walker and rider lanes separately to identify what effect the formation of such lanes had on the flow-rate.

Davis and Dutta state that escalators in the London Underground typically have a tread depth of 0.4m, tread width of 1m and travel at an average speed of 0.72 m/s (43.2 m/min). Using Equation 9 the maximum escalator flow-rate of the rider lane was calculated to be 54 ped/min assuming every other tread is occupied.

$$Cr = Sr \, . \, qr$$

Equation 9

Cr = rider lane flow-rate (ped/min)

Sr = V/D; number of treads passing a point on the escalator each minute

V = 43.2; escalator speed (m/min)

D = 0.4; tread depth (m)

qr = 0.5; proportion of treads occupied

Using Equation 10 the maximum escalator flow-rate for the walker lane was calculated to be 66 ped/min assuming every third tread is occupied (i.e. walkers simultaneously occupy two treads at a time then leave a one tread spacing).

$$Cw = Sw \cdot qw$$

Equation 10

Cw = walker lane flow-rate (ped/min)

Sw = (V+U)/D; effective steps per minute

V = 43.2; escalator speed (m/min)

D = 0.4; tread depth (m)

U = 36; average walker speed (m/min)

qw = 0.33; proportion of treads occupied

Combining the walker and rider lane flow-rates calculates the maximum escalator flow-rate to be 120 ped/min. This is 46.7% (105 ped/min) lower than the maximum theoretical flow-rate stated in CIBSE Guide D of 225 ped/min [CIBSE, 2000]. The maximum flow-rate calculation of Al-Sharif [Al-Sharif, 1996] who also considered tread spacing calculated 134 ped/min as the maximum flow-rate. Though this is similar to that of Davis and Dutta, Al-Sharif's calculation was based on a given proportion of the maximum theoretical flow-rate of 225 ped/min.

The maximum flow-rate (for the walker and rider lanes combined) for each up escalator against escalator height can be seen in Figure 12. Here it can be seen that the maximum up escalator flow-rate recorded was 119 ped/min with all flow-rates recorded being above 100 ped/min. This is similar to the highest flow-rate recorded by Al-Sharif [Al-Sharif, 1996] on an up escalator of 122 ped/min.

Using the walkers and riders flow-rate data combined, a regression analysis using escalator height as a predictor of flow-rate was performed (see Figure 12). However, visual inspection of the graph shows there appear to be little correlation between escalator height and overall flow-rate (highlighted by the low R^2 value of 0.43 for the goodness of fit).

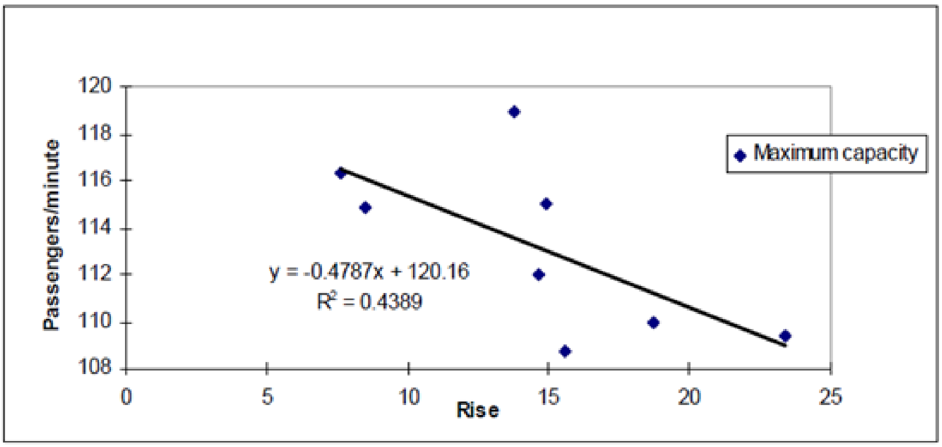


Figure 12: Graph showing maximum up flow-rates (for walkers and riders combined) verses escalator height (rise) [Davis and Dutta, 2002]

The walker and rider data was then separated (see Figure 13) and another regression was performed. Here a stronger correlation between escalator height and flow-rate can be seen. As the escalator height increases the flow-rate for the riders increases but the flow-rate for the walkers decreases which reflects the decreased number of pedestrians being prepared to walk up progressively higher escalators. The increased flow-rate for the riders is explained by people initially in the walker queue moving over to the rider queue/side of the escalator. The graph also shows that as escalator height increases the overall flow-rate approximately decreases. This is due to the number of walkers decreasing so the overall utilisation of each tread also decreases as the walker lanes are used less.

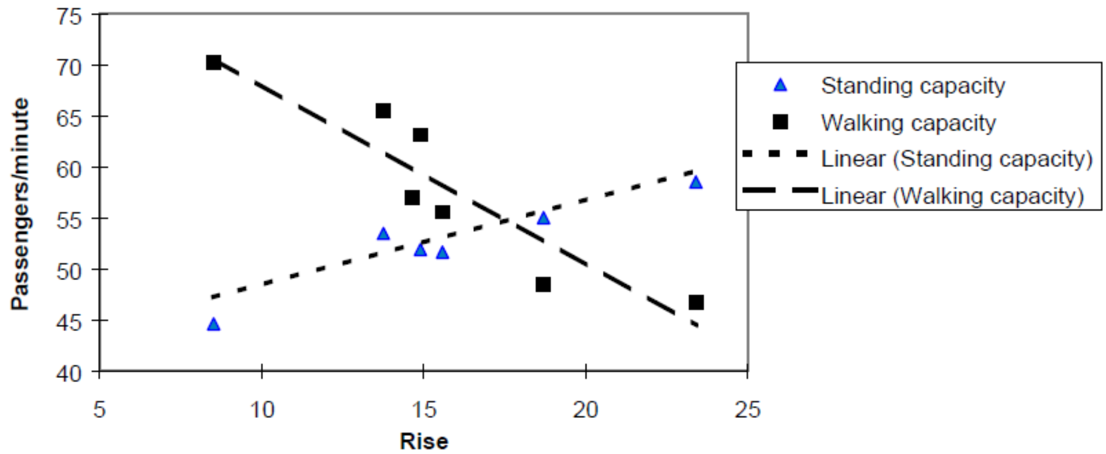


Figure 13: Maximum up flow-rate (for walkers and riders separated) verses escalator height (rise) [Davis and Dutta, 2002]

A regression analysis was performed for both the rider and walker flow-rate data separately analysing whether escalator height, configuration of approach and a double escalator influenced the results. The rider flow-rate data appeared not to be influenced by the escalator approach configuration or there being a double escalator. However, escalator height did appear to influence the results; using escalator height as a predictor gave an R^2 value of 0.81 using the following formula (see Equation 11). This shows that the escalator height is a good predictor of rider lane flow-rates.

$$Cr = 41.27 + 0.73 \cdot Esc_{height}$$

Equation 11

For the walker lane flow-rate data, the escalator height, the presence of a double escalator, and escalator approach configuration (there being a corner of 'Type A' at the foot of the escalator mentioned in the report) all influenced the walker lane flow-rate. Using each of these factors as a predictor in the regression gave a R^2 valued of 0.85 using the following formula (see Equation 12).

$$Cw = 83.49 - 1.20 \cdot Esc_{height} - (8.058.Double_{Esc}) - (6.90.CornerA_{Esc})$$

Equation 12

$Double_{Esc}$= represents either 0 or 1 (1 = there are two parallel escalators going in the same direction from/to the same location, 0 = single escalator).

$Corner_{A}$= represents either 0 or 1 (1 = the approach to the escalator has the same characteristics as corner of type A mentioned in the report, 0 = no corner of type A).

Both rider and walker lane regression formula can be combined to give the overall flow-rate formula for an up escalator (see Equation 13).

$$Cf = 124.76 - 0.47 \cdot Esc_{height} - (8.058.Double_{Esc}) - (6.90.CornerA_{Esc})$$

Equation 13

For the down direction, 15 escalators were recorded though only 7 were included in the analysis as the remaining escalators never appeared to reach peak flow-rates. The overall results are presented in Figure 14. The highest flow-rate recorded was 132.5 ped/min in the Victoria station. This is 5.4% (7.5 ped/min) less than the highest flow-rate recorded by Al-Sharif [Al-Sharif, 1996] of 140 ped/min. In all stations the walker lane had a higher flow-rate than that of the rider lane which is as expected considering walkers move off from the initial escalator tread to allow the proceeding walkers to board the escalator sooner. Unlike the up escalator no relationship between escalator height, being a double escalator, escalator approach configuration, and flow-rate was found. Unlike the up direction data this suggests that escalator height was of little or no influence on the maximum flow-rate on the down escalator data.

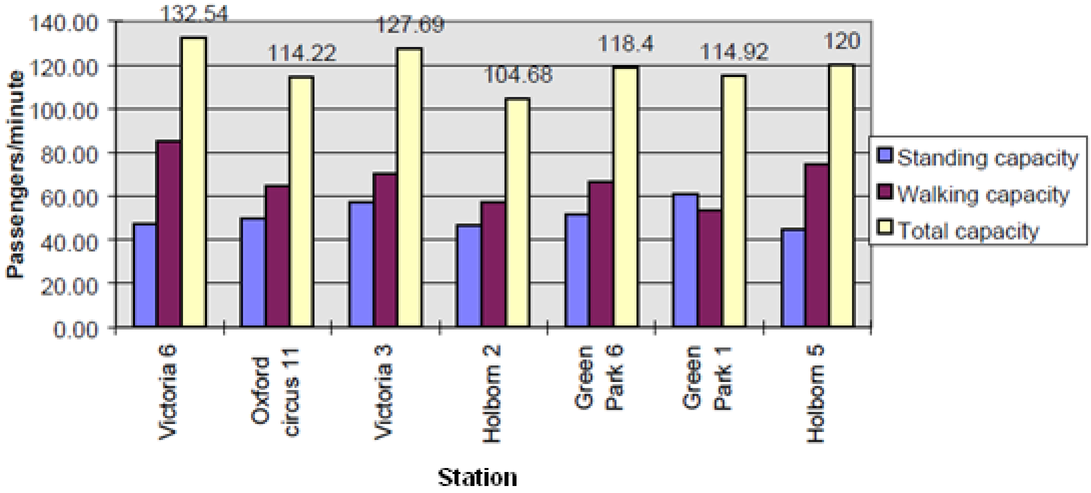


Figure 14: Flow-rate (for walkers, riders and combined) for each station [Davis and Dutta, 2002]

Feasibility of upward evacuation by escalator – An experimental study

Okada et al [Okada, et al., 2009] conducted a series of experiments recording the walker speeds of participants on an upward moving ‘long’ escalator (horizontal length of 49.5m) and ‘short’ escalator (horizontal length of 12.3m) given a series of different conditions. In total 25 experiments were conducted though only the results of 12 were presented [Okada, et al., 2009], using 50 participants of which 70.0% (35) were male and 30.0% (15) were female having an average age of 21 years old all of whom were university students. During the experiments 12 participants wore a special "instant senior" suit which restricted the participants senses and movement to replicate an elderly person (non instant senior participants are referred to as 'healthy'). Within the experiments the average horizontal walker speeds were recorded in addition to the average flow-rate. This section focuses on the flow-rate data within the study.

In the study the static escalator maximum flow-rates varied between 60-66ped/min and the moving escalator maximum flow-rate varied between 90-102 ped/min. As expected the increase in flow-rate for the moving escalator is relative to the speed of the escalator (i.e. an increase of 0.5 m/s caused a 50% increase in flow-rate). This highlights that increased escalator speed also increases the flow-rate with participants being taken away from the escalator entrance at an increased rate. The maximum flow-rate for the moving escalator was 27.1% (38 ped/min) and 23.0% (30.5 ped/min) less than the maximum flow-rates recorded by Al-Sharif [Al-Sharif, 1996]

(140 ped/min) and Davis and Dutta [Davis and Dutta, 2002] (132.5 ped/min) respectively. This is expected considering the escalators in both of these studies were moving approximately 50% faster. The artificial conditions in which the data was collected with participants having no real trip purpose and subsequent motivation to traverse the area may have been a contributing factor. It is also uncertain what influence of all participants being students would have on the flow-rate.

Escalator Walker/Rider usage

Pedestrians that board an escalator, providing they are not blocked by others located in front of them, have the option to walk, ride or both walk and ride along the escalator. A number of studies have mentioned that pedestrians walk and ride on escalators, but hardly any mention the extent to which this occurs. Only two studies were found which present empirical data regarding escalator walker/rider frequencies/proportions.

Pedestrian movement at Victoria Underground station

Al-Sharif [Al-Sharif, 1996] mentions a study by Andrews and Boyes [Andrews and Boyes, 1977] in 1977 where the proportion of walkers and riders was recorded within a London Underground station (Victoria) in both the up/down direction and in peak/off peak times (see Table 18). Here it can be seen that a higher proportion of pedestrians walked when traversing in the down direction or in the peak period. This suggest that time of day and direction of travel influence occupants choice to walk or ride on escalators.

Table 18: Proportion of Walkers during peak/off peak periods as observed by Andrews and Boyes [Andrews and Boyes, 1977]

	Peak		**Off Peak**	
	Walkers	**Riders**	**Walkers**	**Riders**
Up	40%	60%	20%	80%
Down	60%	40%	40%	60%

Estimation of Capacity of Escalators in London Underground

Davis and Dutta [Davis and Dutta, 2002] collected escalator flow-rates within a number of stations in the London Underground with a variety of different height escalators. As part of this study the proportion of walkers was presented for the up escalators against escalator height during peak flow-rate periods (See Figure 15). From visual inspection of the graph the lowest proportion of walkers appears to be around 43% at Green Park station with the highest appearing around 62% at Embankment station. A regression analysis using the escalator height as a predictor gave an R^2 value of 0.83 which suggests that escalator height is a good predictor of the proportion of escalator walkers. It should be noted that in the regression two data points were removed. The Victoria 1 data was removed due to the unusual high number of riders. The authors stated that the high number of riders was possibly due to counting errors or large numbers of groups of pedestrians using the escalator. The Embankment 6 data was also removed due to the high number of riders recorded. The authors state that this was contributed to by the wide staircase near the escalator (i.e. the staircase attracted walkers away from the escalator), making it inappropriate to include. No regression formula was presented in the study though the graph suggests the formula is linear with a negative correlation (i.e. as escalator height increases the proportion of escalator walkers decrease (as expected)). Due to the proportions of walkers only being collected during peak flow-rate conditions it is uncertain how generally applicable the results are to non-peak flow-rate conditions.

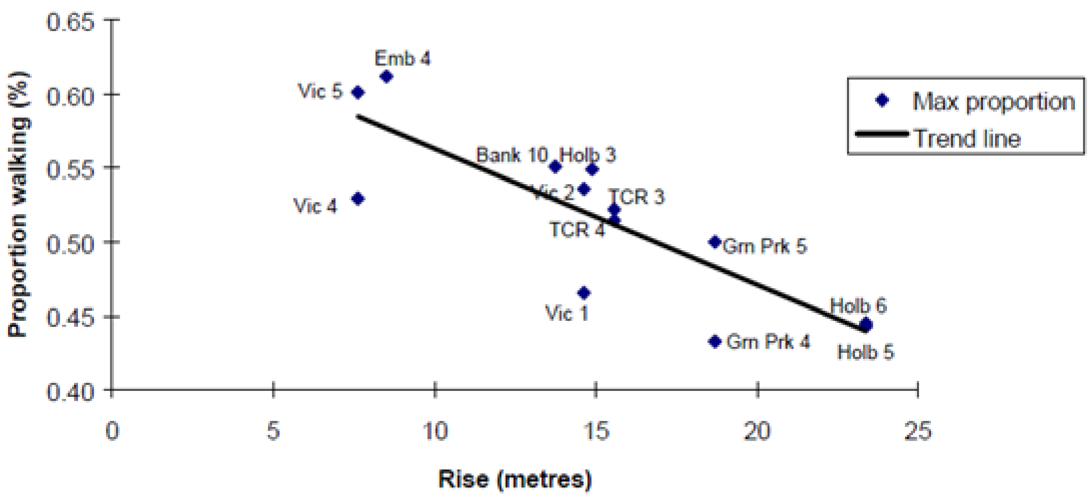


Figure 15: Proportion of walkers using up escalators

Escalator walker speeds

Pedestrians who board an escalator and decide to walk, travel at a given walker speed. The following section presents a review of three empirical studies related to escalator walker speeds.

Feasibility of upward evacuation by escalator – An experimental study

As previously mentioned in the flow-rate section, Okada et al [Okada, et al., 2009] conducted a series of experimental trials recording escalator walker speeds and flow-rates. This section focuses on the walker speed data within the study. Walker speeds were recorded for both a short (5.7m high, 12.3m horizontally long) and long (22.0m high, 49.5m horizontally long) escalator. The speed of both escalators was 0.5m/s.

The walker speed of each participant was recorded for both the short and long escalator and adjacent stair for the short escalator. In addition, a series of group trials were conducted where each participant's walker speed in the group was recorded. Three different group types were defined according to the initial starting location of participants at the foot of the escalators/stair:

- Group A: participants initially randomly organised in a square,
- Group B: formation of two lines with the instant senior participants (those wearing the suit to mimic an elderly person) staggered on either side, and
- Group C: formation of two lines with the instant senior participants spread out on the right side).

For the long escalator 4 cases were run where walker speeds were recorded for individuals travelling alone and then also measured when travelling in Group A. This was repeated for both a moving and static escalator. Walker speeds for Groups B and C were not recorded using the static long escalator. For the short escalator the following cases were run: stair only (individual and Group A), and a series of cases running both a static and moving escalator; individual, and Groups A, B and C. The results are presented in Table 19 and Table 20 below.

Table 19: Average Horizontal Walker Speeds (m/s) (not including the escalator speed)

Escalator	Occupants	Static/ Individual	Moving/ Individual	Static / Group A	Moving/ Group A	Static / Group B	Static / Group C
Long	**Healthy**	0.79	0.76	0.54	0.51	-	-
	Instant senior	0.50	0.43	0.47	0.43	-	-
Short	**Healthy**	0.78	0.71	0.54	0.45	0.55	0.68
	Instant senior	0.53	0.43	0.48	0.40	0.51	0.50

Table 20: Overall Average Horizontal Stair Walker Speeds (ms)

Occupants	Individual	Group A
Healthy	0.75	0.68
Instant senior	0.51	0.54

In addition to the average horizontal walker speeds for the entire length of both the long and short escalator, the average horizontal speed of individual participants at 3 different sections along the long escalator (whilst static) were recorded. This was done as it was expected that walker speeds would reduce as participants travelled further along the escalator due to fatigue.

However, this was not the case in the results and participants' speeds were shown to be reasonably constant with no considerable difference between walker speeds along different sections of each escalator. Whilst this may suggest that fatigue is not a strong influencing factor for escalator walker speeds it should be kept in mind that the participants came from a narrow demographic group who were likely to be relatively fit/young and who were also not required to travel a long distance before/after boarding the escalator (unlike typical pedestrians (e.g. commuters, shoppers, etc)).

The average individual escalator walker speeds (see Table 19) and stair speeds (see Table 20) appear to be similar for both the healthy and instant senior participants. However, the Group A average walker speeds for the healthy participants is 25.9% (0.14 m/s) faster compared to the instant senior participants on the stairs. This may be due to the increased width of the stairs allowing healthy individuals (typically being faster) to more easily overtake the instant senior participants compared to the escalator.

Results suggest that the influence of the escalator length and whether the escalator is moving/static did not have a considerable influence on average escalator walker speeds. The average walker speed of healthy participants (i.e. those not wearing the instant senior suit) in Group A is similar to the average walker speed of the individual instant seniors for both the short and long escalator. This is due to the speed of the group being dictated/strongly influenced by the slowest individuals which would most likely be the instant senior participants blocking the healthy individuals.

The average walker speeds in Group B for healthy participants and instant senior individuals were similar for much the same reason. However, the average walker speeds for Group B were faster than in Group A. This was due to the two lanes being formed by participants prior to boarding the escalator, despite the escalator being static. This suggests that when groups approach an escalator increased speed can be achieved if lanes are formed prior to boarding the escalator; thereby reducing conflicts and subsequent delays at the escalator entrance. The average walker speed in Group C was higher for healthy participants due to the instant elderly all standing to one side thereby allowing the healthy participants to more easily overtake.

Overall static escalator individual walker speeds on the short escalator were similar to the adjacent stair individual walker speeds. However, group walker speeds were notably slower on the static escalator compared to the stairs. The authors note that the increased width of the stairs (being over twice as wide) was likely to contribute to this allowing participants to overtake where possible and so increase the average walker speeds when travelling with other participants on the stairs.

Considering all participants were students within a narrow demographic group it is uncertain how generally applicable the results are. The results suggest that elderly individuals walk slower than non-elderly individuals on escalators. Whilst the author states that the use of the instant senior suit has been verified to produce accurate results, it is believed this is questionable and further work with actual elderly participants is probably required to increase confidence in the walker speed results. Perhaps the most questionable characteristic of the study is the artificial nature, lack of context and motivation for participants to traverse the escalator.

Study on availability and issues of evacuation using stopped escalators in a subway station

Kadokura et al [Kadokura, et al., 2009] carried out a number of experiments where walker speeds were recorded of participants traversing up a static escalator and stair on their own and as part of a group (all participants travelling simultaneously). A total of 39 university students participated in the study. A single escalator (horizontal length of 27.2m and height of 13.2m) and stair was used in the trials. Participant escalator walker speeds were recorded at different points along the escalator.

A graph showing the average individual walker speed and average group/crowd walker speed at different distances along the escalator can be seen in Figure 16. The average walker speed measured was calculated using the actual distance participants travelled on the escalator (i.e. not the horizontal distance).

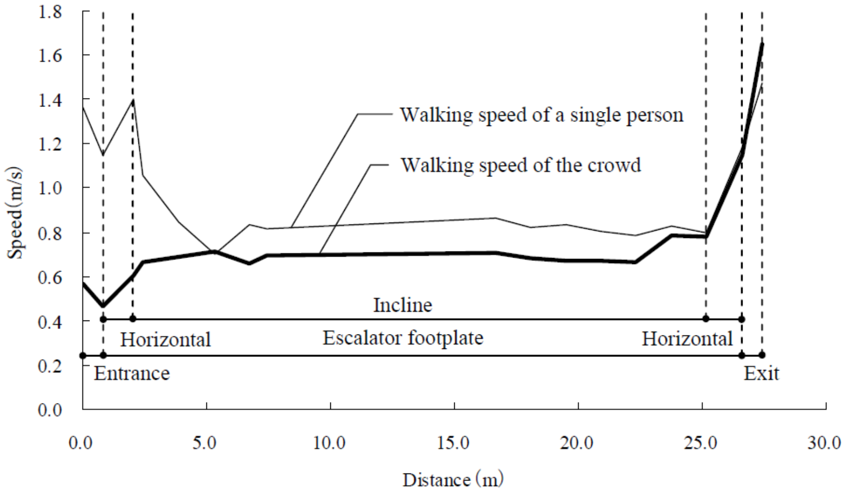


Figure 16: Average walking speed of 39 participants: Single and in a Crowd [Kadokura, et al., 2009]

The average walker speed for individuals along the boarding flat section of the escalator increased from 1.15 to 1.36 m/s whilst moving towards the incline. The average speed along the alighting flat section of the escalator was approximately 1.48 m/s. No explanation as to why the increased walker speed was recorded along the alighting flat section is mentioned by the authors. However, the decrease in effort/energy required compared to the incline section is likely to be a contributing factor. The average walker speed along the incline of the escalator remained approximately constant at 0.8 m/s (horizontal speed 0.7 m/s). The average horizontal walker speed was between 11.4% (0.08 m/s) and 12.9% (0.09 m/s) less than that recorded for the static short and long escalators respectively by Okada et al [Okada, et al., 2009].

The average participant walker speeds when travelling in a group on the boarding flat section of the escalator was slower than that of the equivalent individual walker speeds. This is expected as the crowd density on the escalator boarding flat section can still remain high, hence restricting walker speeds at this time. However, the average walker speed increases on the escalator incline. This is due to each step forcing participants to spread out (decreasing the crowd density) and so walk at a faster speed.

The average group walker speed along the alighting flat section of the escalator was 1.65 m/s. The average walker speeds along the incline of the escalator was 0.7 m/s (horizontal speed 0.61 m/s). As with the experiments by Okada et al [Okada, et al., 2009], average group walker speeds on escalators are expected to be influenced by the slower individuals in the group due to restricted opportunities to overtake those individuals. Further to this, as mentioned in experiments by Okada et al [Okada, et al., 2009], the average walker speeds of groups will be influenced by the position of the slower individuals on the escalator (i.e. blocking or requiring proceeding faster walkers to change sides in order to overtake).

Similar to the study by Okada et al [Okada, et al., 2009], the average walker speeds in both the individual and group experiments along the incline were observed to exhibit little variation along the entire length of the escalator. This may be due to the narrow demographic of participants; all university students and potentially being young/fit individuals so being less likely to experience fatigue (compared to older less fit individuals).

In addition to the static escalator average crowd walker speeds, stair crowd walker speeds were also measured for the same height stairs. The average stair walker speed in the group was 0.77 m/s (horizontal speed of 0.68 m/s). This is similar (7.0% (0.07 m/s)) to the average static escalator walker speed along the incline. This is somewhat surprising considering the stair was approximately twice the width of the escalator. This would be expected to increase the likelihood of participants overtaking each other; higher increased walker speeds would be expected on the stairs. Conversely the small variation between results from the group walker speed experiments on both the escalator incline and stairs may reflect participant’s lack of desire to overtake other participants rather than an imposed condition (i.e. being blocked).

The key findings of the study by Kadokura et al [Kadokura, et al., 2009] are similar to that of Okada et al [Okada, et al., 2009], in addition to suffering some of the same limitations (i.e. questionable general applicability (all student participants)), and artificial nature/ lack of real context/motivation (experimental).

Route Choices Between Escalator and Stairway in MTR Stations (walker speeds)

As previously mentioned in the escalator/stair choice section, Cheung and Lam [Cheung and Lam, 1998] recorded the frequency of pedestrians that used escalators/stairs, travel times, and flow-rates in six stations within the Hong Kong Mass Transit Railway (MTR) underground system during peak hours in both the up and down direction. This section reports on the data presented in the study regarding escalator walker speeds. Overall results are presented in Table 21.

Table 21: Walker speeds by pedestrian blocks [Cheung and Lam, 1998]

Facility	Number Of Samples	Free flow walker speed (m/s)	Walking speed at capacity (m/sec)
Escalator Up	611	0.89 [0.88-0.90]	0.73 [0.72-0.75]
Escalator Down	692	1.05 [1.03-1.07]	0.73 [0.71-0.75]
Stair Up	696	0.86 [0.84-0.88]	0.43 [0.42-0.44]
Stair down	687	0.97 [0.96-0.98]	0.60 [0.59-0.61]
Walkway to Escalator	709	1.15 [1.09-1.21]	0.31 [0.30-0.32]
Walkway to Stair	712	1.14 [1.11-1.18]	0.32 [0.30-0.33]

On average, during free-flow conditions, pedestrian escalator walker speeds were 15.2% (0.16 m/s) faster in the down direction compared to the up direction. This is a slightly larger increase than that observed for the average stair walker speeds (12.8% (0.11 m/s) increase). When the escalators were crowded to capacity the average walker speed on both the up and down escalator was approximately the same at 0.73 m/s. This represents a decrease in average walker speed compared to the free flow conditions between 18.0%-30.5% (0.16m/s - 0.32m/s) for the up and down escalators respectively.

The authors do not state if the escalator walker speeds were based on the horizontal or incline travel distance, though compared to other walker speeds in other studies it is thought the speeds are based on the incline travel distance. If this is correct, converting the average escalator walker speeds to horizontal walker speeds gives the following horizontal walker speeds seen in Table 22.

Table 22: Horizontal escalator walker speeds by pedestrian blocks [Cheung and Lam, 1998]

Facility	Free flow walker speed (m/s)	Walking speed at capacity (m/sec)
Escalator Up	0.77 [0.76-0.78]	0.63 [0.62-0.65]
Escalator Down	0.91 [0.89-0.93]	0.63 [0.61-0.65]

Escalator side usage

As previously mentioned, when pedestrians board an escalator they either walk, ride or both walk and ride. To accommodate each type of behaviour, on escalators wide enough to permit, often separate walker and rider lanes form where those wishing to ride all use one side and walkers use the opposite side. It has been mentioned that some locations request escalator users to ride on both sides of the escalator during peak periods in certain circumstances [Davis and Dutta, 2002].

Based on archived video footage from the 1920's of an escalator in the London Underground, Malvern [Malvern, 2009] observed riders using the right side of the escalator and postulated they did so due to the diagonal finish at the start and end of each escalator. This meant that pedestrians travelling on the left side of the escalator effectively had a longer flat section to travel on at the end of the escalator and so allowed them more time to better adjust their footing when alighting. In the London Underground today, as in a number of countries, it is common to find signage requesting escalator users to "stand on the right side". During off peak periods or during situations where unfamiliar pedestrians traverse an escalator, common side preference behaviour may be disrupted though has negligible influence on the overall flow of pedestrians. As observed by Davis and Dutta [Davis and Dutta, 2002] during peak periods the separation of walker/rider queues for each side of the escalator can influence boarding flow-rates.

Whilst a number of studies make reference to the existence of separate walker and rider lanes on escalators no published literature regarding empirical results could be found regarding the extent to which walkers and riders use each side of escalators.

2.3.4 Review of software modelling escalators

A number of circulation/evacuation models state that they can represent escalators (e.g. Legion, PEDROUTE/PAXPORT, STEPS, SimPED, etc) [Kuligowski, 2005]. However, little information regarding how such models function could be found. The circulation/evacuation models reviewed were STEPS and SimPED which explicitly state the capability to represent escalators in literature along with a broad overview of how pedestrian behaviour is represented.

STEPS

A description of the STEPS circulation/evacuation model has been presented in the lift section (see section 2.2.4). In STEPS escalators are represented in an identical way to stairs using a flow-density based method where users specify the width, angle and speed of the device (the length of which is automatically defined according the floor height). Agent movement onto the device is then governed according to the maximum flow-rate specified, speed of the agent and the density of other agents on the device. This in turn defines the maximum speed that an agent is able to move on the escalator. No details regarding if STEPS has the capacity to represent different agents walking or riding on escalators is mentioned or if/how the speed of the escalator influences this movement. However, setting all a given proportion of agent's escalator walker speeds to 0 would implicitly represent the different proportion of walkers and riders.

As previously mentioned, when agents navigate around a building in STEPS they do so by initially assessing the routes from their current position to their destination and assigning scores to each route. Factors such as estimated travel time and estimated queuing time for each route are calculated with agents attempting to minimise their travel time to their end target. The estimated queuing time for a device is calculated using Equation 14 below.

$$T_{Queue} = N/F$$

Equation 14

N = number of agents that will reach the device/target before that person

F = Flow-rate for the target

In Equation 14, N is predicted considering all other agents on the same floor that are targeting the given device and their walker speeds. No further details regarding how agents consider other agents targeting an escalator/stair is mentioned. In reality, it is uncertain how occupants would be aware of the decision by all other occupants to select an escalator/stair unless they are in close proximity to where other occupants' escalator/stair choice could be anticipated. Such a behavioural model may be appropriate in structures containing a small number of occupants initially located in close proximity in a simple geometry: it could be considered easier to anticipate the movement of other occupants. However, within more complex structures containing large numbers of dispersed occupants this is perhaps unrealistic. In such circumstances, the behavioural model would appear to conflict with the theory of Bounded Rationality [Simon, 1957] where occupants have a limited amount of information, cognitive ability and time to process the information.

Further to this, agents can be assigned a patience value on a scale between 0-1. This relates to how willing an agent is prepared to wait in a queue to use a given device before redirecting to use an alternative device/route. A patience level of 0.5 is considered unbiased (i.e. the patience attribute will not influence their device selection). The higher the patience value, the more patient an agent is assumed to be. The patience value is used to calculate the estimated queuing time which is then used when agents assign scores to each route. As previously mentioned, the route score is then used by the agent to decide which route and subsequent device to use.

SimPED

SimPED is a pedestrian modelling software used to represent pedestrians during normal circulation conditions developed by Daamen [Daamen, 2004]. The model has the capability to represent escalators. Upon the escalators agents can be modelled as either being walkers or riders [Daamen, 2002]. The agent movement speed on an escalator is represented as a product of the agent's walker speed, escalator speed and density of other agents on the escalator. A level of discomfort is also calculated for an escalator according to the crowd density; the more crowded the escalator the higher the associated levels of discomfort (see Equation 15).

$$E = \frac{1}{E_0 + (1 - E_0)(1 - \frac{N_1}{N^{max}})}$$

Equation 15

E_0 = initial comfort value

N_1= number of agents on the escalator

N^{max} = maximum number of agents that can fit on the escalator

When agents approach an escalator/stair combination they select which device to use based on a combination of the shortest perceived travel time calculation and level of discomfort the agent expects to encounter on each device. Each device is given a score and the device with the lowest score is selected by the agent.

2.3.5 Escalator evacuation strategies and simulation results

A series of three evacuation simulation studies have been reviewed in the following sections to demonstrate a variety of different escalator evacuation strategies and simulation results.

Feasibility of upward evacuation by escalator – An experimental study

A description of the experimental escalator trials conducted by Okada et al [Okada, et al., 2009] has been described in previous sections (see section 2.3.3). In addition to the data collected the authors also performed an evacuation analysis using empirical calculations (using the data collected). The analysis was conducted using the plans of an underground station in Tokyo. The station had 2 parallel platforms (B5 and B7 platform) which were located on the 5th and 7th levels respectively below ground. Escalators and stairs were located at either end of each platform. Both platforms had an escalator/stair at either end. A fire was also considered in the calculations at one end of the B7 platform. Agents were required to traverse up a number of escalators/stairs during the evacuation.

All agents initially on the B7 platform used a single escalator/stair at the opposite end to where the fire was located. Agents on the B5 platform split evenly between the escalator/stair at either end of the platform. The stairs adjacent to each escalator were between 1.6m-2.6m wide and all the escalator tread widths were 1m. The initial population on each platform was 1,300 representing the maximum number of passengers on each train (2,600 agents in total).

Evacuation calculations were conducted using the average escalator walker speeds and flow-rates mentioned in the previous sections of the literature review. Here the average walker speeds in groups on a static escalator was 0.47 m/s, on a moving escalator 0.9 m/s, and on a stairway was 0.54m/s. The flow-rate was 1.0 ped/m/s for the stopped escalator and 1.5 ped/m/s for the moving escalator. Evacuation pre-movement/response times were 53s on the fire platform (B7) and 106s on the non-fire platform (B5). Stairs were used in all cases with varying escalator strategies. A description of each case and results can be seen in Table 23.

Table 23: Total Evacuation time Calculation Results [Okada, et al., 2009]

(*All elderly agents use the escalator (other agents use both escalators and stairs))

		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Stairs		X	X	X	X	X	X
Escalators	**Up**	-	Static	Moving	Moving *	Moving	Moving
	Down	-	-	-	-	Static	Moving in Reverse (up)
Total Evacuation Time		24 min 21sec	19 min 10 sec	16min 59sec	16min 30sec	14min 37sec	13min 16sec

Results show that reversing the direction of a moving escalator (to move in the up direction; case 6) compared to the stair only case reduced the total evacuation time by 45.5% representing the fastest total evacuation time. Using both stairs and static up escalators (Case 2) reduced the total evacuation time by 21.3%.

No platform clearance times were presented or details regarding how the evacuation calculations were performed in the study. It is therefore uncertain as to the level of validity or general applicability of the results.

Study on availability and issues of evacuation using stopped escalators in a subway station

A description of the experimental escalator trials conducted by Kadokura et al [Kadokura, et al., 2009] has been described in previous sections (see 2.3.3). In addition to the data collected of participants using a static escalator the authors also performed evacuation simulations (using the data collected) of an underground station. During the evacuation simulation a fire was also modelled on the platform level.

The underground station consisted of three levels with a double-sided platform located on the lowest level. The platform connected to the upper level via 6 pairs of escalators in 4 different locations (12 escalators in total) and two stairs at both ends of the platform. All stairs were 2.5m and all escalators were 1.2m wide. Escalators were assumed to be static during all scenarios. The platform was initially populated with 1,000 agents who were assigned a horizontal stair walker speed of 0.5 m/s and a horizontal static escalator walker speed of 0.45m/s (based on results from the associated experimental study). All agents had instant pre-movement/response times.

The simulated fire on the platform was modelled using the BRI2002 two-layer zone model with both the fire and smoke represented. The fire characteristics were intended to mimic the fire of the Daegu station fire which occurred in South Korea in 2003 [Kadokura, et al., 2009]. The representation of the fire in the evacuation simulations meant that the environmental conditions on the platform became untenable between 2 to 4 minutes after the fire had started. Upon detection of fire/smoke agents moved away from the affected area. However, the influence of the fire/smoke on agents' walker speeds was not represented. In total 6 evacuation scenarios were run which can be seen in Figure 17 and Table 24 below.

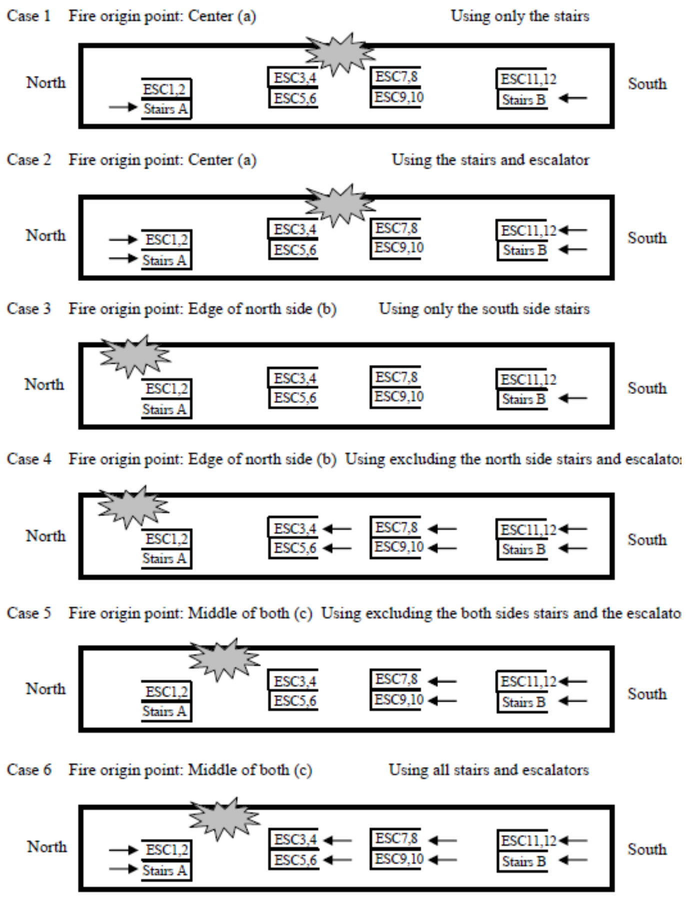


Figure 17: Evacuation Scenarios and fire location [Kadokura, et al., 2009]

Table 24: Number of escalators/stairs available, agents trapped for each case.

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Number of Stairs Available	2	2	1	1	1	2
Number of Escalators Available	0	4	0	10	6	12
Agents trapped	562	423	0	0	331	0

The study focused on the number of trapped agents (i.e. those agents who encountered untenable smoke conditions before evacuating) as opposed to the total or platform evacuation time. The total evacuation time was only stated for Case 3 (422 seconds) and Case 4 (254 seconds). No agents were trapped in Cases 3, 4 and 6 due to the fire not being close enough to the available escalator(s)/stair(s). Most agents became trapped in Case 1 where only a single stair was available and the fire was initially in the middle of the platform (within reasonably close proximity to the available stairs).

The results suggest that the use of escalators can be very effective for aiding an evacuation, especially with the restriction of stair usage caused by fire/smoke spread. The authors state that the introduction of static escalators compared to stairs alone approximately decreased the total evacuation time by a half. This decrease is perhaps less than expected considering the aggregated width of the 12 escalators (14.4m) was almost three times the aggregated width of the 2 stairs (5.0m).

Due to the total and platform evacuation times not being presented along with other simulation parameters (aside from the number of agents trapped) makes it hard to gauge the full extent to which escalators provided benefit in each case.

Study of the human evacuation simulation of metro fire safety analysis in China

Zhong et al [Zhong, et al., 2008] performed an evacuation simulation of a Guangzhou underground station platform for metro line 6 (single platform) in China. Procedures for this underground station state that during an emergency in locations other than the platform, all escalators are turned off and can be used as stairs. If there is an emergency on the platform then up escalators can remain moving and the down escalators can be stopped and reversed in the up direction.

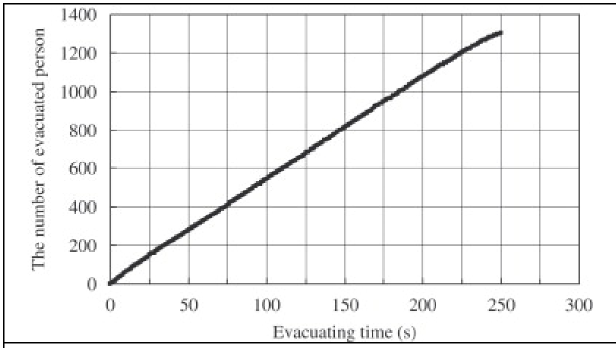
The station has 4 levels with the lowest being the platform level. The platform has 2 escalators and 2 stairs connecting to the level above. The emergency was assumed to occur on the platform so one escalator was made static (used as a stair) and one escalator was kept moving in the up direction (at a speed of 0.65m/s).

The double-sided platform was 72m in length and was initially populated with 1,300 agents. Agent escalator walker speeds were set between 0.60-0.67m/s (it is uncertain how these were distributed or whether these were horizontal walker speeds or incline walker speeds). Instant pre-evacuation/response times were assigned to all agents.

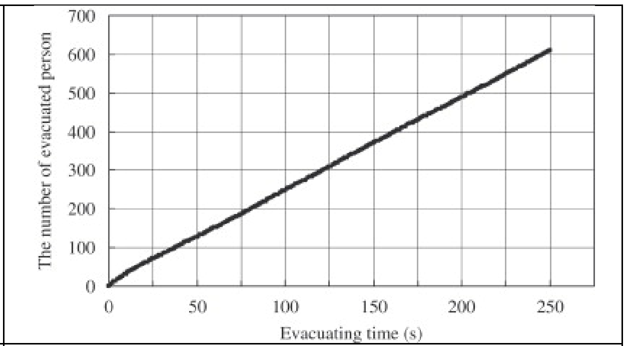
The frequency of agents that evacuated after different periods of time can be seen in Table 25 with evacuation rates presented in Figure 18. The platform took 250 seconds to evacuate with the overall evacuation rate appearing constant for the majority of the evacuation (see Figure 18); the evacuation rate for each escalator/stair was also linear. From Figure 18 it can be seen that the last escalator/stair user alighted at similar times. This suggests that there was no bottleneck or disproportional usage of escalators/stairs (i.e. the frequency of agents that used each device was proportional to the throughput capacity each provided). Indeed, from Figure 18 it can be approximated that 46.2% (600) of agents used the moving escalator, 23.8% (310) of agents used the static escalator and around 30% (390) of agents used the stairs.

Table 25: Simulation Results - Frequency/Proportion of Evacuees against Time

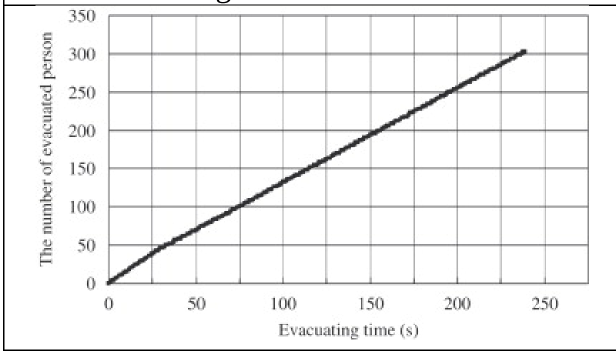
Time	0s	30s	60s	120s	250s
Frequency of Population Evacuated	0	175	330	654	1300
% of Population Evacuated	0%	13.5%	25.4%	50.3%	100.0%



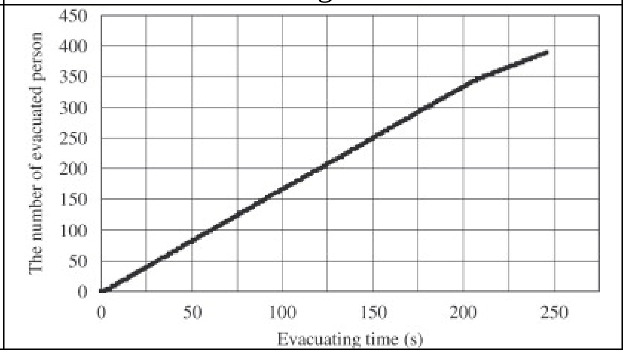
Total number of agents evacuated



Number of agents escaped from moving Escalator



Number of agents escaped from static Escalator



Number of agents escaped from stairs

Figure 18: Simulation Results - Evacuation Rates [Zhong, et al., 2008]

Since none of the escalators and stairs were in close proximity to each other there is expected to be little decision making with regards to device selection (i.e. choosing between escalators and adjacent stairs considering local crowd conditions). In the study no details regarding how agents behaved on the moving escalator is mentioned though it is believed that all agents walked.

2.3.6 Summary

A review of literature regarding escalator usage during actual evacuations, escalator evacuation building codes/standards/guidelines, escalator human factors data, software models that can represent escalators, and evacuation escalator simulation results has been conducted.

It is understood that escalators were likely to have played a key role in a number of actual evacuations; however, little literature regarding the extent to which escalators influenced such evacuations could be found. Indeed it was only due to the severity and nature of the two incidents reviewed (World Trade Center 911 Attacks and the King Cross Fire) that official studies and subsequent reports were produced which mentioned escalator usage. In the incidents analysed for both a high-rise building and an underground station, escalators were shown to have played a key role during each evacuation. The operational strategies employed have demonstrated using escalators in both the moving and static states during an evacuation. In structures such as underground stations there is often little alternative other than using escalators during an evacuation. Within the incidents analysed escalator users were reported to exhibit typical circulation behaviour whilst using the escalators (e.g. orderly queuing, using only the normal downward escalator, common side preference behaviour, etc). This behaviour typically occurred until pedestrians were instructed otherwise or conditions deteriorated to such an extent that caused them to react differently.

Building codes, standards and guidelines in both the US and the UK have been reviewed. In most cases moving escalators can be used during an evacuation in a number of circumstances providing emergency stop provisions are made. However, the guidance differ between the US and UK with regards to the acceptance of considering moving escalators as primary means of egress (i.e. whether they are considered contributing to the evacuation capacity). Theoretical handling capacities of escalators mentioned in guidelines for normal circulation situations are mentioned to be far greater than actual handling capacities recorded.

All escalator human factors data collected was either collected during experimental or normal circulation conditions. Whilst it is questionable if such data is appropriate for use in evacuation situations, the lack of data in actual evacuation conditions suggests it is required. Indeed the review of escalator usage during actual evacuations suggests it may be appropriate for certain emergency conditions to consider escalator users adopting normal circulation behaviour in an evacuation. The majority of data collected in experimental conditions relates to escalator flow-rates and walker speeds. The collection of walker speed data in experimental conditions, where participants have no actual motivation or trip purpose, is considered questionable as walker speeds are expected to be highly influenced by such factors. A number of escalator human factors studies analysed peak flow-rate/handling capacities. These studies typically conducted regression analysis using the flow-rate data collected in order to predict the probability that pedestrians would use an escalator/stair given a certain flow-rate. The analysis of each study appears to suggest such predictive formulas would only be accurate/appropriate during very crowded/busy conditions. In all studies very little information was collected regarding the proportion escalator/stair users, proportion of walkers/riders, or side preference proportions. Indeed no study was found where a broad variety of such escalator human factors was collected and analysed in combination.

A number of pedestrians/evacuation models have the ability to represent escalators though very little published literature regarding how such models function or what data the models use for default settings could be found. The models reviewed typically represent escalators in the same way as stairs with varied attributes (e.g. flow-rates and pedestrian walker speeds). Behaviour such as side preference and walker/rider selection are not explicitly considered in most models. In the models reviewed, device selection (e.g. between escalator/stair), is based on a shortest travel time calculation with agents electing to use a device which they expect will allow them to traverse the area the quickest time. It is uncertain if such a selection method is appropriate for all agents and agents that exhibit suboptimal behaviour appear to not be considered in the models.

A number of studies that conducted evacuation simulations looking at using static and moving escalators have been reviewed. The evacuation simulation studies reviewed demonstrate the potential impact of using moving and static escalators in addition to exploring escalator availability for evacuating a train station/platform. All studies appear to assume that all escalator users walked on escalators and did not consider agents who would ride in addition to separate walker/rider lanes forming. Escalator/stair selection by individual agents and the influence of congestion at the entrance to the escalators/stairs appears to have not been explicitly represented in the simulation results.

Overall analysis of current literature pertaining to escalator evacuation usage suggests that escalators can and have provided benefit during emergency situations. However, whilst some studies have begun to attempt to understand escalator human factors there is still a lack of understanding regarding escalator human factors (e.g. escalator/stair selection, walker/rider proportions, common side preference behaviour, etc). Indeed considering no study has looked at a broad variety of escalator human factors in combination. Further to this, there is a lack of explicit representation of such behaviour in evacuation/circulation models.

2.4 Concluding remarks

A review of literature regarding evacuation lift and escalator usage has been conducted. Lifts have been shown to have assisted a number of actual evacuations in a number of different countries though they were not intended to be used during such incidents. Whilst few accounts exist of escalator usage during actual evacuations, escalators have also been used in both the moving and static states to assist evacuations, often forming part of the only viable egress route.

The usage of lifts/escalators during evacuations for the general population is either already or beginning to be accepted in both UK and US building codes, standards and guidelines. Despite evidence that lifts/escalators have been used to good effect in a number of evacuations there is a scarcity of data related to associated human factors and to what extent they would influence operational strategies.

Many evacuation models state that they can represent escalators and a small number have the capability to represent lifts. Further to this a number of dedicated lift models have also been shown to be able to represent associated human factors during evacuations in a similar fashion. Little information about how evacuation models represent such devices or associated human factors could be found. Of the models reviewed, where a description of how the models represent lifts/escalator and associated agent behaviour could be found, none appear to represent empirically based micro-level human factors.

Chapter 3 - The buildingEXODUS Evacuation Software

3.1 Introduction

The purpose of this thesis is to understand human factors associated with lift/escalator usage and to measure the impact such factors have upon an evacuation. One method to measure the impact such factors have upon an evacuation using lifts/escalators would be to develop a new evacuation model to represent lifts/escalators and associated human factors in order to gauge the effects. However, considering certain evacuation models already exist with a variety of features that could be used in part to represent lifts/escalators during an evacuation, it would be less time consuming and more efficient to develop the functionality within an existing evacuation model.

The buildingEXODUS evacuation software has been chosen as a platform to develop the capabilities to represent lifts/escalators and associated human factors. It is a widely used model that is familiar to the author and contains a number features that would make lift/escalator representation convenient to implement. This chapter gives a brief overview of the buildingEXODUS V4.1 evacuation model including the spatial representation and the agent behaviour. Current limitations with representing lifts/escalators in addition to the associated agent behaviour within the buildingEXODUS evacuation software is then discussed.

3.2 Model overview

The buildingEXODUS evacuation software is designed to simulate the evacuation of people from enclosures. The model has been extensively discussed in literature in the public domain [Galea, et al., 2006b, Galea, et al., 2008] so will only be broadly reviewed.

The software takes into consideration people-people, people-fire and people-structure interactions. The software models the trajectory of each individual person as they make their way out of an enclosure, or are overcome by fire hazards such as heat, smoke and toxic gases. The software was written in C++ using Object Orientated techniques utilising stochastic rule base methods to control people's behaviour. Thus, the behaviour and movement of each individual is determined by a set of heuristics or rules. The software is based on a conceptual framework of five interacting submodels, the **OCCUPANT, MOVEMENT, BEHAVIOUR, TOXICITY** and

HAZARD submodels (see Figure 19). These submodels operate on a region of space defined by the **GEOMETRY** of the enclosure. The software can be used to simulate both evacuation and circulation scenarios.

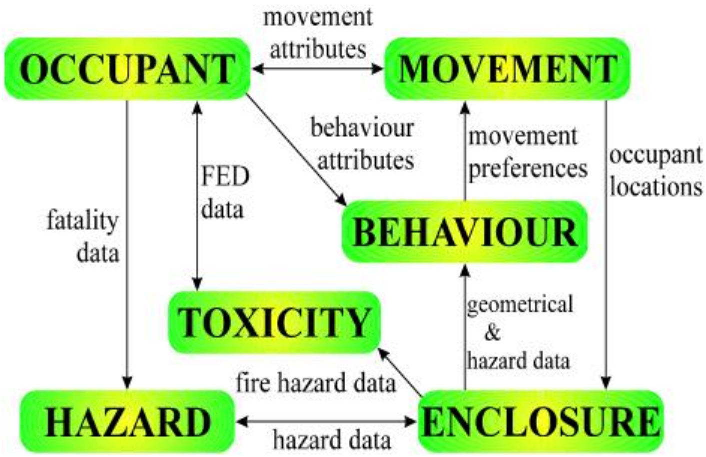


Figure 19: buildingEXODUS Conceptual Framework

3.3 Spatial representation within buildingEXODUS

The spatial representation of a structure/area within buildingEXODUS is represented by a two-dimensional grid of nodes (defining a region of space) that are connected via a series of arcs which determine the distance between each node. The default node represents a 0.5m x 0.5m square region of space. Agents traverse through the geometry by moving between nodes via the arcs. There are a variety of different node types (e.g. free space, exits, internal doors, stairs, obstacles, etc) that allow users to specify different attributes associated with different spatial regions. Geometries with multiple floors can be made up of multiple grids of nodes connected by transit nodes that represent stairs (see Figure 20).

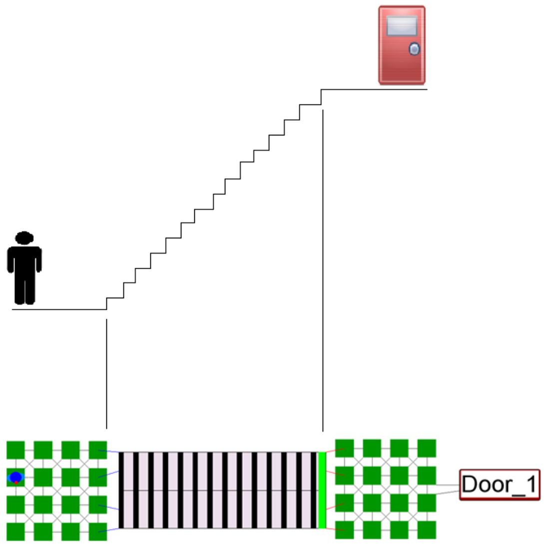


Figure 20: Spatial representation within buildingEXODUS (Nodes, Arcs, Transit nodes, Door)

Stair transit nodes are defined via a series of attributes (see Table 26) that influence how agents behave on the stair during a simulation.

Table 26: buildingEXODUS transit node attribute list

Attribute	Description
Direction (degrees)	Direction the transit node is facing in relation to the other nodes.
Capacity	Maximum number of agents that can simultaneously be on the transit node at any one time.
Lanes	Number of lanes (i.e. number of people that can simultaneously stand side-by-side on the node).
Flow Direction	Direction of travel (bi-direction, up/forward, down/backward).
Drop (m)	Vertical travel distance.
Length (m)	Horizontal travel distance.
Width(m)	Physical width.
Flow-rate (occ/m/m)	Maximum number of agents that can board the stair per minute per meter (used only if flow-rate model is chosen).
Space Required	Number of treads that walkers and riders keep between each other for stair packing or staggered options.
Hand Rail Size (m)	Aggregated width of the handrail.
Effective Width (m)	Width available for agents to occupy.
Number of Risers	Number of risers.
Riser Height (m)	Height of each riser.
Tread Depth (m)	Depth of each tread.

3.4 Occupant behaviour

The Occupant sub-model within buildingEXODUS allows the nature of the occupant population to be specified. A simulated population can consist of a range of people with different movement abilities, reflecting age, gender and physical disabilities as well as different levels of knowledge of the enclosure's layout.

Agents within the model are defined via a set of attributes. These attributes can be broadly categorised into two groups: physical (e.g. gender, weight, height, age, etc), and movement speeds (e.g. run speed, walk speeds, stair up/down walker speeds, crawl speed, etc). The travel speed adopted by agents is dependent on the terrain (defined by the node type) being traversed at any given time. All attributes are configurable by the user and the default attribute values are based on empirical data from a variety of studies. Specifically relevant for this thesis are the stair walker speeds. These represent the incline speeds of agents and are based on the work of Fruin [Fruin, 1971] that is determined by the age and gender of agents (see Table 27).

Table 27: Default stair travel speeds by Fruin [Fruin, 1971] used in buildingEXODUS (maximum recommended values)

Gender	Age (years)	Down avg (m/s)	Up avg (m/s)
Male	<30	1.01	0.67
Female	<30	0.755	0.635
Male	30-50	0.86	0.63
Female	30-50	0.665	0.59
Male	>50	0.67	0.51
Female	>50	0.595	0.485

For transit nodes there are two behavioural regimes that determine the level of spacing agents keep around themselves: Staggered and Packed (see Figure 21). If the Staggered flag is set then agents will attempt to use/maintain treads that are not being used by other agents. If the Packed flag is set then agents will not consider other agents in their tread selection. As previously mentioned different tread spacing values for both staggered and packed behaviour can be defined by the user.

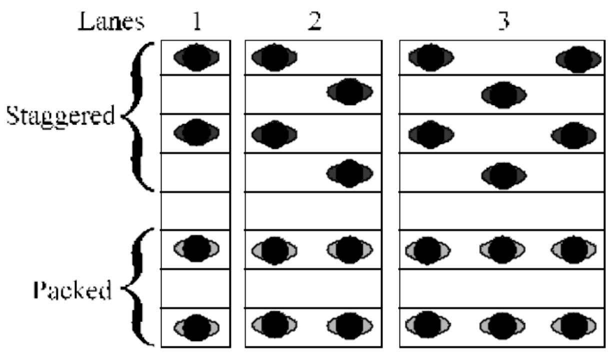


Figure 21: Packed and Staggered occupant behaviour on stairs

Within the software a number of psychological attributes are also associated within each agent including drive, patience and response time. The Drive attribute is used to resolve conflicts for space between competing agents; by default this is determined by the Gender and Age attribute. The Patience attribute defines how likely an agent will wait in a queue before attempting to seek an alternative route for reaching a given target. The Response Time attribute represents the time an agents waits from the beginning of a simulation until the time they begin to either evacuate or instigate a pre-evacuation task.

On the basis of an agent's individual attributes, the Behaviour sub-model determines the agents' response to the current situation, and passes its decision on to the Movement sub-model. The Behaviour sub-model functions on two levels, Global and Local. Global behaviour involves implementing an escape strategy that may lead an agent to exit via their nearest serviceable exit or most familiar exit. The desired global behaviour is set by the user, but may be modified or overridden through local adaptive agent behaviour (i.e. that the agent's rationally assess congestion levels given the information available, albeit in a crude manner), that includes such considerations as determining the agent's initial response, conflict resolution, overtaking, etc. In addition, a number of localized decision-making processes are available to each agent according to the conditions in which they find themselves and the information available to them. This includes the ability to customize their egress route according to the levels of congestion at an internal exit, the environmental conditions and the social relationships within the population.

It is also possible to assign agents with an itinerary of tasks (e.g. visit a pre-defined location) that must be completed prior to the evacuation. To allow for dynamic paths to be adopted by the agents these itinerary points can act as redirection nodes instructing the agents to adopt alternative paths while evacuating or circulating [Gwynne, et al., 1999].

Agents navigate about a geometry based on a potential map; a series of numerical values assigned to each node for each target (e.g. exits, stairs, etc). Agents who are moving towards a given target attempt to move to the next node that has the lowest potential value from all the connecting nodes for a given target. If the node with the lowest potential value is already occupied by another agent, agents will select to use the node with the next lowest potential. Failing this they will elect to use a node with an equal potential value to their currently occupied node. For all targets within a geometry a separate potential map is defined and associated potential values for every node is calculated. This allows agents to navigate to any given target within the simulation. For external exits, an overall potential distance map is defined that calculates the potential map for multiple exits and so defines the nearest exit for each agent. Using this method by default means that agents elect an egress route to an external exit that is closest to their current location.

During a simulation, if agents that are presented with multiple transit nodes connecting the same vertical areas (e.g. adjacent stairs), by default they will elect to use a transit node based on which device forms part of their shortest route to the exit (defined by the potential distance map). This choice is made irrespective of local conditions. As such currently agent device choice is made prior to a simulation starting and does not change during the simulation unless the exit/target selection changes that may potential impact this device selection.

3.5 Current limitations of buildingEXODUS for modelling lifts/escalators

Implicit representation of escalators using a flow-rate system employing transit nodes can currently be achieved in buildingEXODUS, similar to that of other models (e.g. STEPS). Certain representation of micro-level escalator human factors is possible within buildingEXODUS during certain situations using stairs. Escalator/stair selection could be represented as either explicit device assignment to agents by a user or using a redirection node; however, agents would not exhibit adaptive behaviour considering local conditions. Movement speeds could be implicitly represented by agents' stair walker speeds being set to an escalator walker speed plus the speed of the escalator itself. However, if agents were to use both stairs and escalators (or escalators travelling at different speeds) during the evacuation then this method would not be appropriate due to the stair speeds including the speed of the escalator. There are a number of escalator human factors identified in the literature review that could not be explicitly represented within buildingEXODUS. These include adaptive escalator/stair selection, walker/rider selection, rider side preference and walker speed data.

Similarly to escalators, no explicit means for representing lifts and associated occupant behaviour currently exists within buildingEXODUS. Creative means for implicit representation of using lifts in buildingEXODUS could theoretically be achieved with limited functionality. For instance, using internal doors being controlled by user-specified opening/closing times and staging areas (to represent the lifts) is one such method to implicitly represent lifts (See Figure 22). However, this would require a wide breadth of assumptions and require the user to manually calculate the lift transfer/arrival times for each floor. In a building with a large number of floors and complex lift dispatch algorithm this would become very challenging. Such a method would also require the user to explicitly define the number of occupants that use each lift. This task may be further complicated if multiple lifts were located in close proximity in a single lift bank. No explicit representation of lift/stair selection, lift area waiting behaviour, redirection due to location conditions, or open lift selection (for multiple lifts) could be represented. Currently, implicit representation of lifts in buildingEXODUS is impractical, questionable and indeed in complex scenarios not possible.

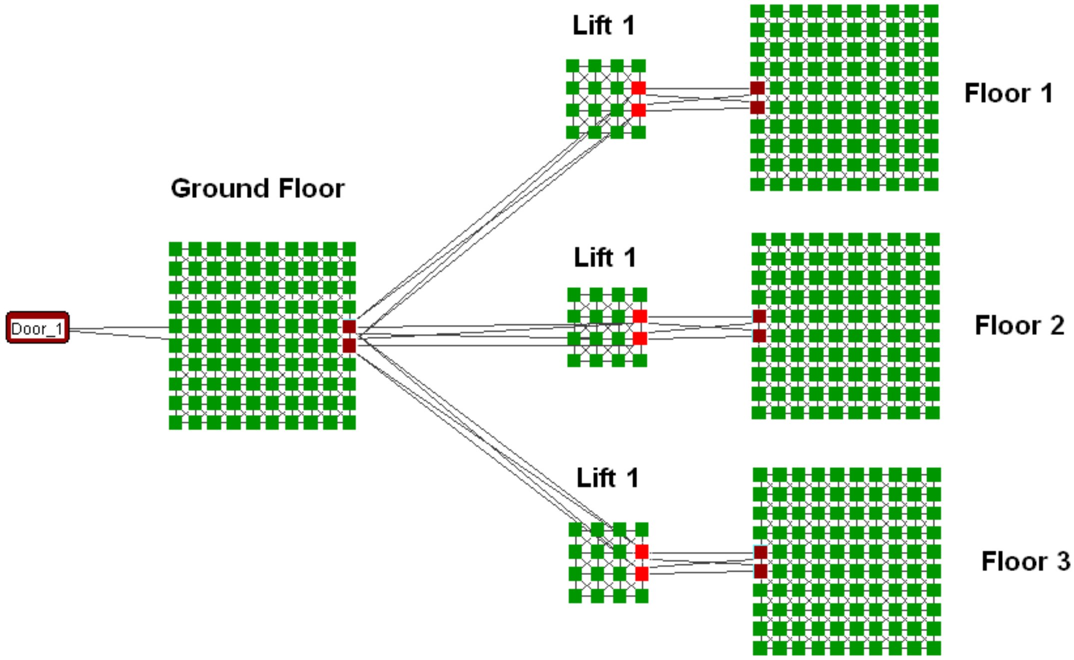


Figure 22: Example of buildingEXODUS implicit lift representation

With the exception of the escalator flow-rate model, it is evident that buildingEXODUS cannot accurately represent lifts/escalators without significant user input and assumptions being made. Indeed, the buildingEXODUS user manual [Galea, et al., 2006a] makes no mention of having the capability to represent such devices or has any associated human factors data.

In contrast, and as previously mentioned, a number of other evacuations models (e.g. STEPS, Legion, etc), have the capability to represent both lifts and escalators with limited associated human factors during an evacuation. Escalators human factors in such models tend to be represented on a macro-level using a flow-rate model. No details regarding any empirical basis for the associated lift human factors for any model could be found. As such this should be considered either a failing in the field of evacuation modelling to understand such factors or a failure in the field to disseminate such work. Further to this, none of the models that represent lifts or escalators are open source. As such development within those models is not possible for third parties.

3.6 Concluding remarks

This chapter has given an overview of the buildingEXODUS evacuation software with specific focus on factors associated with lifts/escalators and associated human behaviour.

The chapter has highlighted that buildingEXODUS has a number of shortcomings with regards to lift/escalator representation that are:

1. Limited capability to represent lifts/escalators,
2. Limited or no capability to represent associated human factors without significant manual intervention by a user,
3. Lack of empirical basis to represent lift/escalator human factors (i.e. device selection, adaptive behaviour according to crowd levels/wait time, boarding/alighting behaviour, and behaviour on each device).

Despite these, buildingEXODUS has a number of existing features that would allow such shortcomings to be addressed in order to represent lifts/escalators and associated human factors. These include the ability to assign agents itineraries of tasks and the use of transit nodes which could be extended to represent other vertical transport devices. The source code and developmental support for buildingEXODUS has also been provided.

The author is only aware of the FDS+Evac evacuation model [Korhonen and Hostikka, 2010] where the source code is publically available. The associated user guide states that it is only suitable for mainly horizontal structures (e.g. sports halls, etc) and that inclined structures have not been validated using the model [Korhonen and Hostikka, 2010]. No explicit method for assigning agents itineraries is provided in the model. Considering such factors, it was deemed less favourable to develop a lift/escalator and associated agent models compared to buildingEXODUS.

The capability of the model to accurately and explicitly represent both lifts and escalators in addition to associated human factors is considered crucial for users requiring to model structures that potentially heavily rely on such devices during evacuations (e.g. high-rise buildings, underground stations, etc).

Chapter 4 - Evacuation Lift Human Factors

4.1 Introduction

Several studies have noted potential human factors associated with lift usage during evacuations [Klote, et al., 1992, Groner and Levin, 1992]. In order to investigate such human factors, interviews with survivors that used lifts in real evacuations or in evacuation drills has been carried out [Sekizawa, et al., 1999, Galea, et al., 2006a, Heyes and Spearpoint, 2009]. Furthermore online/paper based surveys have been conducted posing hypothetical evacuation scenarios where the use of lifts was permitted [Heyes and Spearpoint, 2009]. However, such studies and associated data are scarce. It can also be limited: only involving participants of a particular age or cultural group, those with insufficient experience of lift/stair usage, or those within occupational bias (e.g. participants involved in fire engineering). Subsequently there is a lack of understanding regarding evacuation lift human factors. To address these issues, an online survey was developed (see Appendix A1.1). Participants were asked how they would behave with regards to lift/stair usage given a series of hypothetical situations. This chapter presents the design of the survey and subsequent analysis of participant responses.

4.2 Survey methodology

Permission was granted by the University of Greenwich Research Ethics Committee to conduct a publically accessible online survey (see Appendix A2.1). The call for participation to complete the survey was sent out via several media; website link/leaflet distribution, online forums, university/company emailing lists, friends/family/colleagues, etc. The results presented relate to data collected between July 2008 to July 2009. Utilising the Internet promoted a large and diverse population of participants, however, it also introduced the limitations of an unsupervised survey. This includes participants misinterpreting or giving incomplete responses to questions. For clarity, the subsequent data analysis includes the number of participant responses for each question. False or duplicate participant responses were minimised by recording each participant's computer IP (Internet Protocol) address and time of completion. Despite this no participants responses were identified as being false or duplicate.

4.3 Survey description

To increase the number and cultural diversity of participants, the survey was made available in two languages, English and Chinese (Simplified Chinese). In 2009 China possessed six of the world's ten tallest buildings [CTBUH, 2010]. Furthermore, cities such as Shanghai and Beijing have a large number of high-rise residential and office buildings. As such it was deemed appropriate to have participant responses from such an emerging market for high-rise buildings.

The survey consisted of four sections and required approximately 20 minutes to complete. The first 3 sections addressed the influence of travel distance, queues and groups within a normal circulation setting. Each circulation setting was based around a hypothetical scenario. The scenario description, unless otherwise stated, consisted of the following information:

- You are familiar with the layout of the building.
- The lifts/stairs are located in the same area.
- You are not carrying or wearing anything to restrict your movement.
  A lift is not currently on your floor and you do not know how long you will have to wait for a lift to return.

This description was intended to remove the potential influence of building unfamiliarity, lifts/stairs being located in different areas, current lift floor and luggage/clothing, upon participant responses. In each question participants were requested to state the maximum number of floors they would consider walking on the stairs before redirecting to use the lift. Participants could respond that they would either always use the lift; always consider using the stairs; or state the maximum number of floors that they would consider walking on the stairs before choosing to use a lift.

The fourth section of the survey focused specifically on evacuation usage and informed participants that it was acceptable to use a lift during the presented scenario. Participants were then asked a series of questions related to whether they would consider using a lift during an evacuation. The final questions in the section posed a hypothetical evacuation scenario and asked participants whether they would be prepared to wait for a lift on progressively higher floors. For those participants prepared to wait for a lift, additional questions were asked to determine whether further conditions would influence this decision (e.g. crowding in the lift waiting area and lift wait time).

The following analysis gives an overview of the normal circulation results before focusing on the evacuation section as these results are of primary interest.

4.4 Limitations of the survey

There are number of inherent limitations with any online survey, in particular those posing hypothetical situations and asking participants to quantify their behaviour. Such issues include:

- **Anchoring**: It has been stated in a number of psychological studies that "people's ability to discriminate change in a physical stimulus diminishes as the magnitude of the stimulus increases" [Fetherstonhaugh, et al., 1997]. Thus, in this survey, questions in which participants provide responses representing a large number, may be considered less reliable with anchoring towards certain values (e.g. multiples of 10).

- **Conceptualisation**: In the survey participants are required to predict their decision making process using hypothetical situations. This gives rise to the question as to whether their responses would reflect what they would do in the actual situation i.e. relying on participants' ability to accurately predict their own behaviour, and accurately discriminate between different influences. The more complicated a given hypothetical scenario the increased likelihood that participant responses will become inconsistent with what they would actually do due to their inability to accurately conceptualise the influencing factors. It may also be conjectured that people make such decisions posed in the survey subconsciously and that asking participants to consciously make such decisions could potentially influence their answers.

- **Unsupervised**: Since participants performing the survey were not supervised, this gives rise to the potential for participants misreading, misunderstanding or erroneous answering questions.

- **Survey fatigue**: Since participants were unsupervised and the survey could take up to 20 minutes to complete, some participants may become tired of doing the survey/questions part-way through and begin to give any answer in order to answer as few questions as possible and complete the survey as quickly as possible.

- **Other influencing factors:** The hypothetical situations presented within the survey were intended to present each participant with as simple situation with as little information to process in order to more accurately record the potential influence of different factors.

There may be a variety of other influencing factors and varying degrees with which these influence each other which were not captured/tested within the study.

Such survey limitations should be considered when interpreting or applying the results in other contexts.

4.5 Participant demographic overview

In total, 468 participants either fully or partially completed the survey, of which 424 provided complete demographic information (e.g. gender, age, height and weight). A summary of participant demographic information can be seen in Figure 23. There were slightly more male (60.6% (269)) participants than females (39.4% (175)). Of all participants who provided age data (N=444), the average age was 35.0 years with just 18-30 years being the largest age group (44.6%). The average age of male participants was slightly higher (35.9 years) than females (33.8 years). Considering participants who provided occupational details (N=449) a small proportion were students (18.9%), were from the fire safety/protection profession (7.6%) or came from the lift industry (1.6%). The remaining 71.9% of participant occupations were either classified as coming from other professions or non-specific (e.g. office worker, staff, assistant, etc).

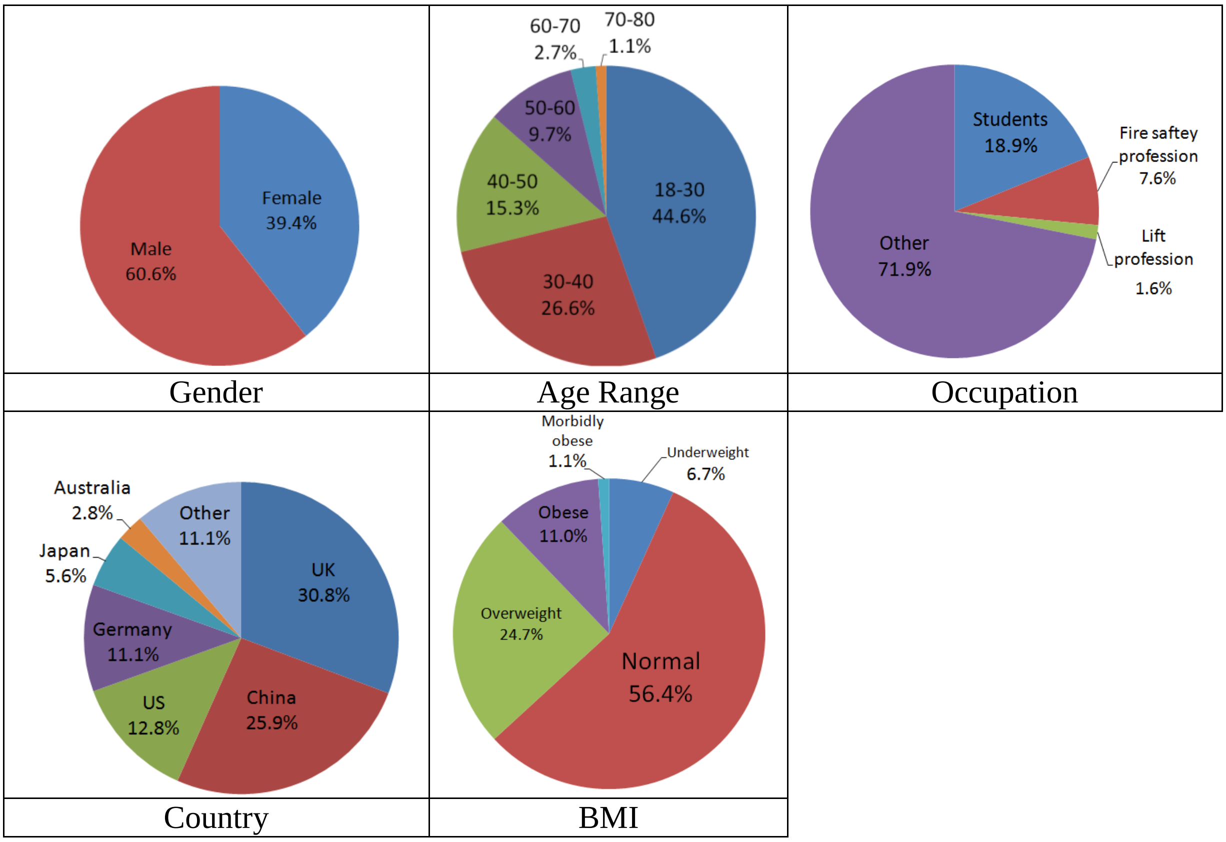


Figure 23: Summary of participant demographic information

Of all the participants, 63.5% confirmed that their place of work/study possessed lifts. These buildings ranged in height between 2 to 78 floors with an average of 10.1 floors. Approximately 15.6% of all participants had at least one lift in their place of residence. These residences varied in height between 3 to 35 floors with an average of 10.8 floors in height.

Participants came from 23 different countries. However, six countries made up approximately 88.9% of all participants: UK (30.8% (144)), China (25.9% (121)), US (12.8% (60)), Germany (11.1% (52)), Japan (5.6% (26) and Australia (2.8% (13)). Using the World Health Organizations classification of body mass indexing (BMI), of all participants who provided plausible height and weight information (N=445), just over half were classified as normal in weight (56.4%). Only 6.7% were considered underweight with just under a half being either overweight (24.7%), obese (11.0%) or morbidly obese (1.1%).

For the initial questions in the evacuation section, an analysis of responses according to gender, age range, country and BMI has been performed (see Appendix A3.1). The countries with the most participants were focused upon. A large sample size was required in order to effectively compare responses between participants from different countries. Therefore, those countries that had greater than 50 participants were used for this comparison (i.e. UK, China, Germany and the US). Responses from these four countries accounted for 80.6% of all participants in the survey.

4.6 Results

4.6.1 Circulation

The first part of the survey, addressing circulation behaviour, explored issues to do with vertical travel distance, queue length in the lift waiting area and group behaviour. Three specific variations of the core scenario, each in separate sections, were presented to the participants: Base case, Queues, and Groups. The additional situational information relating to the nature of these various scenarios is presented in Table 28. Given these specific situations, participants were asked what is the maximum number of floors they would consider travelling on the stairs before electing to use a lift. Participant responses either stated that they would always consider using the stairs, never consider using the stairs (always use the lift), or sometimes consider using the stairs (specifying a finite number of floors they would walk on the stairs). Here, data has been combined for each scenario. Therefore, the analysis includes multiple data-points for each participant.

Table 28: Additional situation information provided for each section.

Base case	Queues	Groups
You are alone in a lift waiting area on your floor.	There are a number of people in the lift waiting area on your floor.	You are travelling with a group of 2-4 people. The people in the group are all of similar physical ability and fitness to yourself. The lift waiting area on your floor is empty.

As previously mentioned, it has been stated in a number of psychological studies that "people's ability to discriminate change in a physical stimulus diminishes as the magnitude of the stimulus increases" [Fetherstonhaugh, et al., 1997]. It is postulated that participants who stated that they would consider walking a finite number of floors that was greater than a given amount could be inaccurate due to potential inability to conceptualise such a large number of floors. In order to minimise the effect of participants overestimating the number of floors they would consider walking on the stairs, responses that stated greater than a given number floors were removed from the analysis. Between 0.2%-1.3% of respondents stated that they lived or worked in a building that contained a lift that had greater than 50 floors. It was therefore thought that very few participants would be familiar with being in a building of such a height, let alone walking down the stairs for that many floors. Consequently participants' responses that stated they would walk a finite number of floors greater than 50 were removed from the analysis. Due to the low number of participant responses specifying greater than 50 floors in any of the questions (ranging between 0.0% (0) -1.7% (8) for each question) such responses are considered outliers and the influence upon the overall analysis is small.

For each question within the circulation section, a Kolmogorov-Sminov test was performed to test whether the frequency distribution fitted a normal curve. Almost all of the frequency distributions followed a positively skewed distribution with a number of outliers typically around multiples of five (participants typically tended towards these numbers when specifying higher numbers of floors). As such the non-parametric Wilcoxon signed-rank test has been used to compare participants paired answers (who would sometimes consider using the stairs; specifying a finite number of floors) in each circulation situation using a 95% confidence interval. An overall summary of the combined average results for the Base case, Queues and Groups circulation section can be seen in Table 29.

Table 29: Overall Combined Average Results Irrespective of Time Pressure or Familiarity for the Base, Queue and Groups cases.

		Base Case% [#]	Queues% [#]	Groups% [#]
Up	Always use lift	15.8 [592]	12.7 [474]	23.5 [875]
	Always consider using Stairs	3.7 [138]	4.5 [169]	4.3 [161]
	Sometimes consider using Stairs	80.5 [3008]	82.8 [3091]	72.1 [2682]
	Median Stair Travel (floors)	[3.8]	[4.0]	[3.0]
	Mean Stair Travel (floors)	[4.7]	[5.0]	[4.2]
	Total Frequency of Participant Responses	3738	3734	3718
Down	Always use lift	12.2 [450]	10.6 [392]	19.0 [701]
	Always consider using Stairs	5.6 [208]	7.6 [281]	5.0 [184]
	Sometimes consider using Stairs	82.2 [3036]	81.8 [3027]	76.0 [2799]
	Median Stair Travel (floors)	[5.1]	[5.3]	[4.0]
	Mean Stair Travel (floors)	[6.7]	[7.0]	[5.3]
	Total Frequency of Participant Responses	[3694]	[3700]	[3684]

Base case

In the base case, 87.8% of the participants would always or sometimes consider using the stairs to travel down and 84.2% to travel up. On average, participants that would sometimes consider walking on the stairs would walk 42.6% (2 floors) further in the down direction than in the up direction. Significantly more participant responses (67.4% (1928), $p<0.05$) stated they would walk further on the stairs in the down direction compared to the up direction. However, 26.6% (761) of participant responses stated they would not change the number of floors they would consider walking regardless of travel direction. In addition, 5.9% (170) of participant responses actually stated they would consider walking further on the stairs in the up direction compared to the down direction. This highlights that whilst a significant number of participants were recorded as being prepared to walk further in the down direction than in the up direction, this should not be assumed to apply to all participants with approximately 1 in 3 of participant responses stating alternate behaviour.

Queues

When faced with a queue in the lift waiting area, slightly more participants would always or sometimes consider using the stairs compared to the base case, with 89.4% of participants always or sometimes considered using the stairs to travel down (compared with 87.8%) and 87.3% to travel up (compared with 84.2%). This represents a slight decrease in attractiveness of the lift due to the queue in the lift waiting area. On average, the participants that would sometimes consider walking on the stairs would walk 6.4% (0.3 floors) and 4.5% (0.3 floors) further in the up and down direction respectively compared with the base case (i.e. no queue in the lift area). Thus, irrespective of direction of travel, a significant number of participant responses stated they would walk further on the stairs if a queue was present in the lift waiting area (32.1% (1826)), $p<0.05$). However, almost half (49.5% (2813)) of participant responses, stated that they would not change the number of floors they would consider walking on the stairs regardless of there being a queue in the lift waiting area. In addition, 18.4% (1044) of participant responses actually stated they would consider walking fewer floors if there was a queue in the lift waiting area.

Groups

When travelling in a small group, slightly fewer participants would consider using the stairs than in the base case: 81.0% of participants always or sometimes consider using the stairs to travel down (compared with 87.8%) and 76.4% to travel up (compared with 84.2%). This highlights a decrease in attractiveness of the stair when travelling in groups compared to the queue scenario.

On average participants were prepared to walk 5.3 floors down and 4.2 floors up. This represents a decrease of 20.9% (1.4 floors) and 10.6% (0.5 floors) respectively in the down and up direction compared to the base case. Irrespective of direction of travel, a significant number of participant responses stated they would walk further on the stairs if travelling alone than when travelling in a small group (51.5% (2612), $p<0.05$). It should also be kept in mind that 30.2% (1531) of participant responses stated they would not change the number of floors they would consider walking on the stairs regardless of being in a group. In addition, 18.4% (932) of responses actually stated they would consider walking more floors on the stairs if travelling within a small group.

As participants were requested to specify the maximum number of floors they would consider travelling on the stairs in each question, it is possible to determine the minimum proportion of expected lift users for a given travel distance (see Figure 24). Irrespective of the direction of travel or scenario, the majority of participants would not be prepared to walk greater than 5-7 floors on the stairs. Whilst some differences can be seen between each scenario/direction, the curves begin to converge when the travel distance begins to exceed 10 floors. This reflects the small number of participants that are prepared to walk greater than this distance on the stairs. Indeed almost all participants that would sometimes consider using a lift/stairs would elect to use a lift if required to travel more than 20 floors.

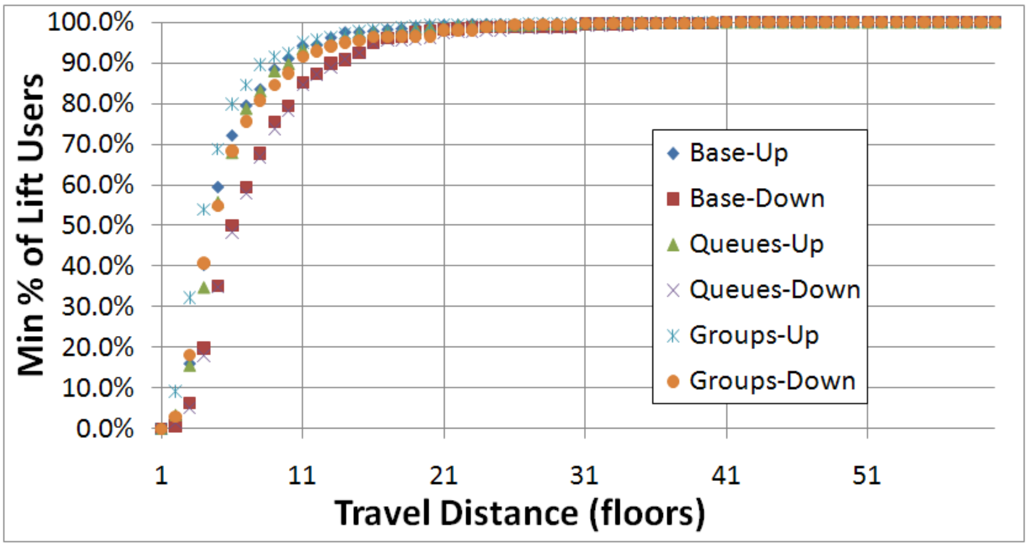


Figure 24: Minimum proportion of lift users for a given travel distance (number of floors) in the up and down direction for the three scenarios

4.6.2 Evacuation

Participants were asked whether they would consider using a lift to evacuate during a hypothetical emergency. Participants were informed:

- They were familiar with the layout of the building.
- The lifts (elevator) and stairs were located in the same area.
- They were travelling alone and were not carrying or wearing anything that would restrict their movement.
- They have been instructed that it is acceptable to use either a lift or stairs to evacuate from the building in emergency situations. During an evacuation they are free to choose to use a lift or stairs.

Of the 467 participants who answered whether they would consider using a lift to evacuate if familiar with a building, approximately a third (33.0% (154))) said that they would consider using a lift to evacuate with a significant proportion (67.0% (313)) answering that they would not (χ^2=54.1, $p<0.05$).

Based on the 98.7% (152) of participants that stated whether they would always use a lift, only a small proportion (7.2% (11)) stated they would. Of the 139 participants who answered whether the height of the floor would influence their decision to use a lift, 87.1% (121) replied that the floor they were on would influence their decision.

Responses suggest that certain participants have reservations about travelling long distances within lifts during an evacuation. Of the 120 participants who specified the maximum number of floors they would consider travelling in a lift, 46.7% (56) answered that there was no maximum number of floors, 22.5% (27) answered 100+ floors, and the remaining 30.8% (37), on average would travel a maximum of 22.0 floors in a lift. Of the 121 participants who specified the minimum number of floors they would consider travelling in a lift, 9.9% (12) answered that there was no minimum number of floors, 0.83% (1) answered 100+, and the remaining 89.3% (108), on average would travel a minimum of 8.5 floors.

Looking at the number of people who answered whether the height of the building would influence their decision to use a lift (N=136), almost two thirds (65.4% (89)) said that the height of the building would influence their decision. Of this group (N=86), 80.2% (69) said that the higher the building the more likely they would be to use a lift. Conversely 19.8% (17) of participants would be less likely to use a lift if the building was taller. Of the participants that would be influenced by the height of the building, 77 cited reasons for their choice (see Table 30). The most common reasons cited by participants that answered 'the taller the building the more likely they would be to use a lift' was to save travel time, reasons of safety or a combination of the two. The most common reasons cited by participants that answered 'the taller the building the less likely they would be to use a lift' was reasons of safety and considering people on the upper floors needing to use the lifts as a priority.

Table 30: Proportion of participants that stated a reason of a given type whether they are more/less likely to use a lift in a taller building.

Reason:	**Overall (%) [frequency]**	**Taller More Likely (%) [frequency]**	**Taller Less Likely (%) [frequency]**
Save travel time	42.9 [33]	40.3 [31]	1.3 [1]
Save wait time	2.6 [2]	1.3 [1]	1.3 [1]
Save personal energy	3.9 [3]	2.6 [2]	0.0 [0]
Safety	13.0 [10]	5.2 [4]	6.5 [5]
Anticipate more/less congestion on stairs	3.9 [3]	3.9 [3]	0.0 [0]
Anticipate lift taking long time (stopping many times or serving other floors)	3.9 [3]	0.0 [0]	3.9 [3]
Consider people on the upper floors	5.2 [4]	0.0 [0]	5.2 [4]
Familiarity	1.3 [1]	1.3 [1]	0.0 [0]
Combinations:			
Save travel time + Safety	13.0 [10]	13.0 [10]	0.0 [0]
Save travel time + Save wait time	3.9 [3]	3.9 [3]	0.0 [0]
Save travel time + Anticipate lift taking long time (stopping many times or serving other floors)	2.6 [2]	0.0 [0]	2.6 [2]
Save energy + Familiarity	1.3 [1]	1.3 [1]	0.0 [0]
Save travel time + Save energy	1.3 [1]	1.3 [1]	0.0 [0]
Save travel time + Anticipate more/less congestion on Stairs	1.3 [1]	1.3 [1]	0.0 [0]

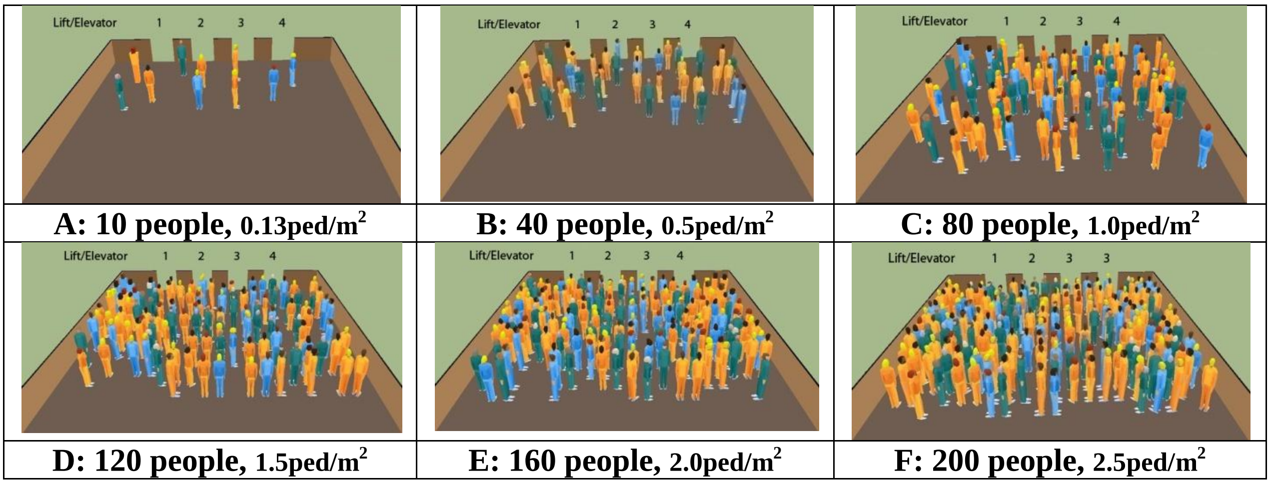
In the proceeding question (Q4F) participants were posed with the following hypothetical situation:

You are instructed to evacuate from a multi-storey building…

- ***You are familiar with the layout of the building.***
- ***It is not a drill but you are not in immediate danger.***
- ***You have a choice to use either one of the 4 lifts servicing your floor or the stairs***
- ***Each lift has a capacity of 10 people.***
- ***A lift waiting area on your floor is crowded with people.***

Participants were then asked if they would consider using a lift:

a) Given that they were located on progressively higher floors in the building,
b) Given a crowd of a specified density was already waiting for the lift (a diagrammatic representation of different crowd densities waiting for lifts was shown to the participants to assist them in selecting the given crowd density (see Figure 25).
c) Given they were required to wait for a specified time to use a lift.



A: 10 people, 0.13ped/m² | **B: 40 people, 0.5ped/m²** | **C: 80 people, 1.0ped/m²**

D: 120 people, 1.5ped/m² | **E: 160 people, 2.0ped/m²** | **F: 200 people, 2.5ped/m²**

Figure 25: Different Crowd Levels in Lift waiting area

In Figure 26 the proportion of participants that would consider using a lift for each floor range can be seen (floor 1 is assumed to be the ground/exit floor). As the floor height increases the proportion of participants that would consider using a lift also increases. This proportion of lift users exponentially increases towards floor range 21-30 then begins to plateau.

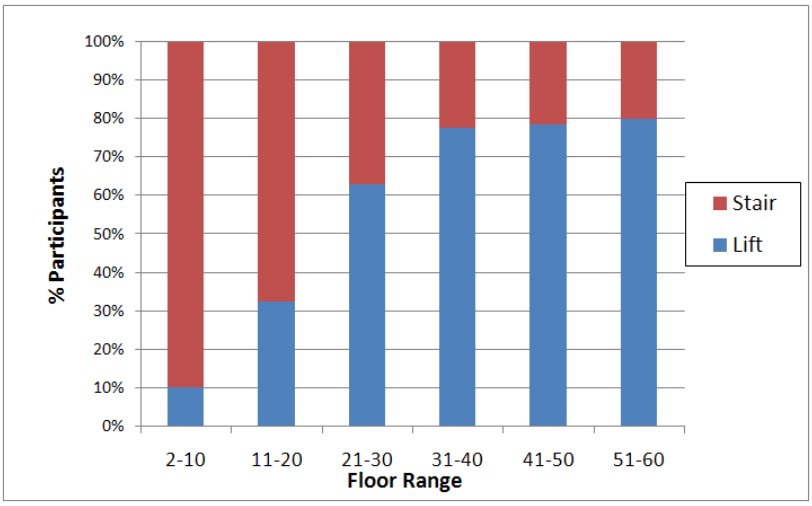


Figure 26: Proportion of Participants that would consider using a lift/stair for each floor range if they were familiar with a building

In Figure 27, the mid-points of each floor range with the respective proportion of participants that would consider using a lift during the evacuation has been plotted. Using the data, a regression analysis can be used to construct a formula that determines the proportion of lift users for a given floor (Equation 16).

$$Y = 0.3207 \ln(x) - 0.4403 \qquad \text{for } 5 \leq x \leq 55$$

Equation 16

Y = proportion of people that would consider using a lift.

X = floor number.

It should be highlighted that this formula is only applicable between floor ranges 5-55 (the lower and upper mid points of the data). The goodness of fit value (R^2) of 0.95 suggests that floor height is a good predictor of the proportion of occupants that would consider using a lift during an evacuation.

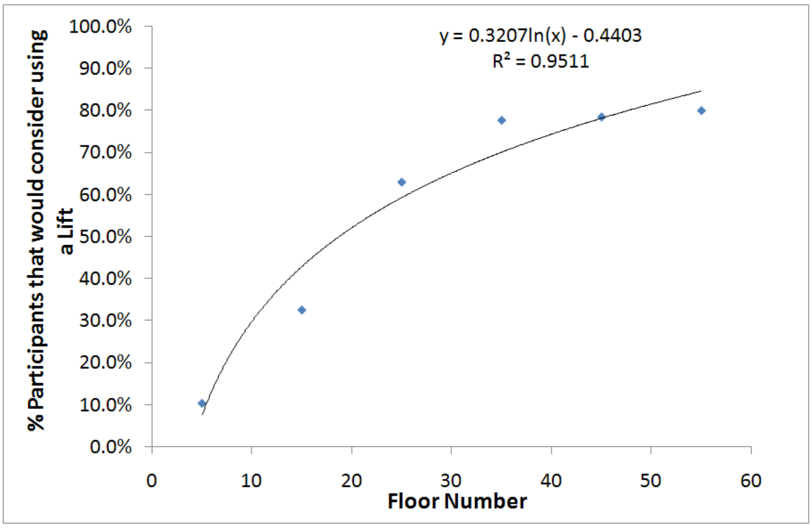


Figure 27: Proportion of Participants that would consider using a lift for each floor if they were familiar with a building

Within Table 31 the proportion/frequency of participants that would consider using a lift to evacuate on each floor range can be seen. In addition, the cumulative proportion/frequency of those participants that would initially consider using a lift, but would choose to redirect to use the stairs if they encountered a crowd of a given density in the lift waiting area can also be seen.

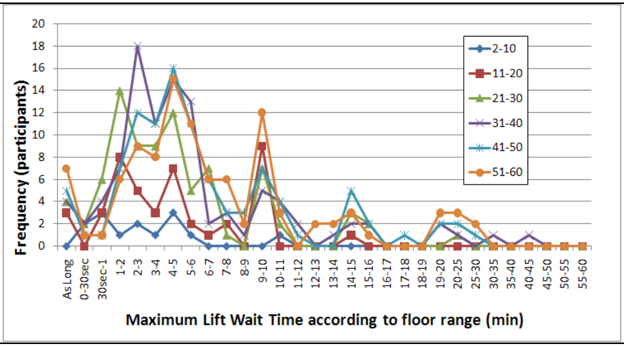
From the results it can be seen that as the floor height increases, the proportion of participants that would wait within a crowd of a higher density also approximately increases (see Table 31). For each floor range this begins to plateau after congestion level E-F (2.0ped/m^2-2.5ped/m^2). This is due to very few participants being prepared to wait in a crowd which is greater than 2.0ped/m^2-2.5ped/m^2. A small proportion of participants (7.1%-14.3%) specified that they would always wait for a lift irrespective of the congestion level.

Table 31: Frequency/Proportion of participants that would consider using a lift and cumulative frequency/proportion of participants who would redirect to use the stairs after encountering a given crowd density

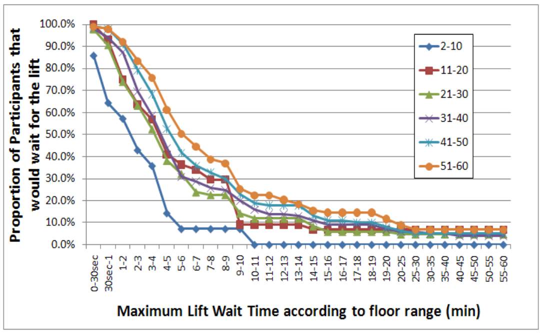
Floor Range Location	Proportion of Participants that would consider waiting to use a lift on a given floor range % [Freq]		Of participants that would initially choose to use a lift, the crowd density in a lift waiting area that would cause a proportion of those participants to redirect to use the stairs. % [Freq]								
	YES	NO	#	Doesn't Matter	A 0.13 ped/m^2	B 0.5 ped/m^2	C 1.0 ped/m^2	D 1.5 ped/m^2	E 2.0 ped/m^2	F 2.5 ped/m^2	F+ 2.5 ped/m^2+
2-10	10.4 [14]	89.6 [121]	14	14.3 [2]	21.4 [3]	42.9 [6]	78.6 [11]	85.7 [12]	85.7 [12]	85.7 [12]	85.7 [12]
11-20	32.6 [44]	67.4 [91]	44	11.4 [5]	15.9 [7]	31.8 [14]	59.1 [26]	86.4% [38]	86.4 [38]	88.6 [39]	88.6 [39]
21-30	63.0 [85]	37.0 [50]	84	7.1 [6]	4.8 [4]	25.0 [21]	63.1 [53]	83.3 [70]	90.5 [76]	92.9 [78]	92.9 [78]
31-40	77.7 [101]	22.3 [29]	99	10.1 [10]	3.0 [3]	19.2 [19]	47.5 [47]	77.8 [77]	86.9 [86]	89.9 [89]	89.9 [89]
41-50	78.5 [102]	21.5 [28]	99	9.1 [9]	3.0 [3]	14.1 [14]	37.4 [37]	65.7 [65]	82.8 [82]	90.9 [90]	90.9 [90]
51-60	80.0 [104]	20.0 [26]	100	11.0 [11]	3.0 [3]	12.0 [12]	32.0 [32]	57.0 [57]	72.0 [72]	84.0 [84]	89.0 [89]

Of participants that would consider using a lift, providing the crowd level did not exceed their stated 'congestion threshold', were asked how long they would be prepared to wait to use a lift. Participants could either respond that they would wait for as long as it takes for a lift to service their floor or state a given finite amount of time.

In Figure 28 the frequency and normalised cumulative frequency distribution of wait times for each floor range can be seen. From Figure 28 (A) in the frequency distribution, it can be seen that the frequency of lift users that would wait for a lift for 'as long as it takes' gradually increases with floor height. It can also be seen that anchoring occurred around multiples of five on and after 10 minutes (e.g. 10 min, 15 min, 20 min), represented by sharp increases in the frequency. This potentially suggests participant's inability to accurately conceptualise wait times of 10 minutes or longer within the scenario. From Figure 28(B), it can be seen that as the floor height increases, the proportion of participants willing to wait a longer amount of time for a lift also approximately increases.



A: Frequency Distribution



B: Cumulative proportion of participants that would wait for a lift for each time range

Figure 28: Frequency distribution and Cumulative frequency distribution of wait times for each floor range if participants were familiar with the building

Participants were asked if they would change any of their previous answers in the evacuation section if they were unfamiliar with the building. Of the 461 participants who responded, approximately a fifth (20.4% (94)) answered that they would behave differently if unfamiliar with the building. From this group, 81.9% (77) would not consider using a lift if they were familiar with the building, however, would consider using a lift if unfamiliar. This means that approximately 1 in 2 (49.5% (228)) of all participants would sometimes consider using a lift to evacuate. This suggests that being unfamiliar with a building increases the likelihood of an occupant considering using a lift during an evacuation.

Figure 29 shows the proportion of participants that would consider using a lift if they were unfamiliar with the building for each floor range. The proportion of participants that would consider using a lift for each floor range is similar to that observed in the familiar situation. This similarity is due to the large proportion of participants that would consider using a lift if familiar but would not change their behaviour if unfamiliar (i.e. the familiar responses dominate the results). Indeed this influenced caused all results for the same questions in the unfamiliar situation to be almost identical.

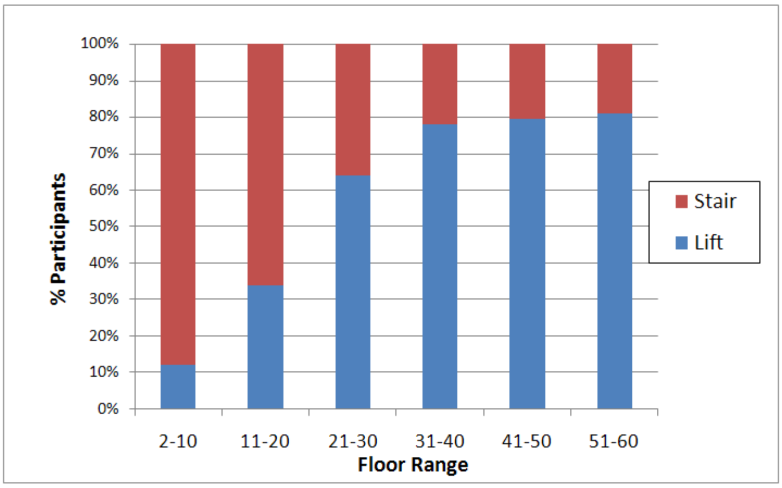


Figure 29: Proportion of Participants that would consider using a lift/stair for each floor range if participants were unfamiliar with a building

4.6.3 Demographic break down

Participant responses for the first five questions in the evacuation section of the survey (Q4A-Q4E) were analysed according to participant demographic groups. The demographic groups explored include gender, age, country and BMI. The purpose of this was to identify if differences existed in responses between participant demographic subgroups. The frequency of responses for certain demographic subgroups became too small (i.e. less than 5) for meaningful statistical analysis for questions Q4G and Q4F. As such these were not included in the analysis. A frequency analysis of cross-demographic subgroups was carried out in order to identify any possible differences between groups (e.g. all males making up a given age range). Results from the analysis of each question for each demographic group can be found in Appendix A3.2.

The only significant difference between any demographic subgroups was with participant country. The hypothetical nature of the survey (i.e. not requiring any physical participation), is thought to have minimised the influence of participant physical characteristics upon the results.

The participant country analysis focused on the top four countries that had the most participant responses: UK (144), China (121), US (60) and Germany (52). Approximately 1 in 2 participants (52.5%) from the US and 1 in 3 participants (36.5%) from Germany would consider using a lift during an evacuation. These decrease for participants coming from both the UK (approx. 1 in 4 (26.4%)) and China (approx. 1 in 5 (21.5%)). A comparison of all countries shows there to be a significant difference between the frequency of participants that would consider using a lift during an evacuation (χ^2=20.3, $p<0.05$). This was caused by the higher number of participants coming from Germany and the US that would consider using a lift compared to participants coming from the UK and China. This suggests that people in the UK and China have more reservations about sometimes using a lift during an evacuation compared to the US and Germany.

4.6.4 Comparison with other studies

A comparison of the survey results with the evacuation lift data presented in the literature review has been carried out. The proportion of surveyed occupants that used lifts during actual evacuation incidents from the literature review is presented in Table 32. The proportion of lift users ranged between 18.0%-74.0% and in all cases lifts were not intended to be used during an evacuation by the general population. From the online survey, irrespective of familiarity, approximately 1 in 2 participants responded that they would sometimes consider using a lift during an evacuation. This is within the range presented in the actual evacuation incidents. However, there were a number of differing characteristics of each incident, including differences in:

- occupant characteristics (e.g. nationality, residents, office workers, elderly),
- structural designs/configurations (e.g. hotels, apartments, office blocks),
- hazard characteristics (e.g. bomb threat, fire, plane impact).

As a consequence the general applicability of such a comparison with the online survey is considered limited.

Table 32: Proportion of surveyed occupants that used lift during actual evacuation incidents

Incident	% Occupants that used lifts (estimated/ of those surveyed)
World Trade Center 911 Attacks	18.0
Cook County Administration Building Fire	50.0
Hiroshima Motomachi High-rise Apartment Fire	54.0
Joelma Building Fire	39.7
Forest Laneway Fire	74.0
Christchurch Bomb Threat Evacuation	22.2

In almost all actual evacuations incidents where information was provided of occupants originating from multiple floors, as expected the higher in the building the more likely occupants were to use a lift. This is identical to that found in the online survey.

The proportion of actual/predicted lift users for different floor heights in the studies presented in the literature reviewed and the online survey can be seen in Figure 30. The CIBSE Guide D [CIBSE, 2000] and online survey circulation data for the down direction increases more rapidly compared to other data as floor height increases. This is expected due to the data relating to normal circulation conditions (i.e. where occupants expect that lift usage is always acceptable and safe to use). The Hiroshima Motomachi High-rise Apartment Fire [Sekizawa, et al., 1999] data also increases sharply with floor height which is expected to be largely influenced by the fact that most occupants were elderly (i.e. physical restrictions of using the stairs encouraged them to use the lift). The data collected in the surveys by Heyes's [Heyes, 2009; Heyes and Spearpoint, 2009] was plotted using the regression formula mentioned in the literature review. The proportion of lift users increases linearly at a more gradual rate compared to the other studies. Much of the survey data from Heyes's study was based on hypothetical situations involving imaginary characters. However, the narrow participant demographic (e.g. many participants were students) is expected to have contributed to causing a higher acceptance to using the stairs on progressively higher floors. This is because such participants are expected to have an increased physical ability compared to studies involving older participants.

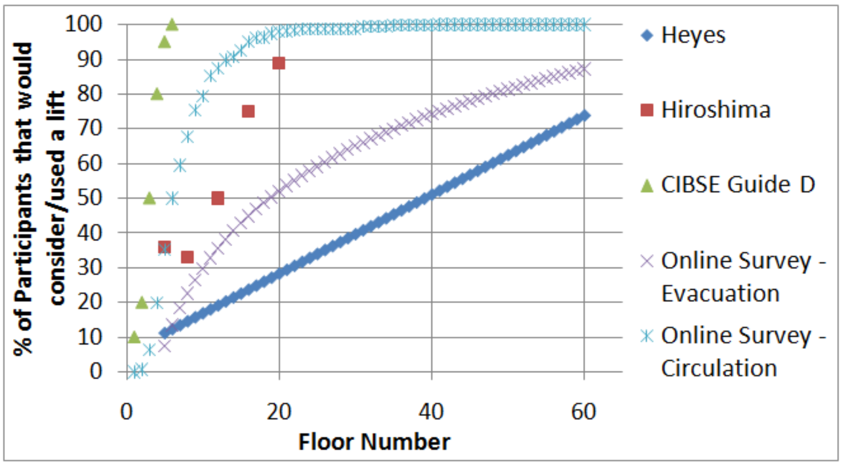


Figure 30: Proportion of participants that would consider/used a lift in the down direction for Heyes's Surveys [Heyes, 2009], Hiroshim Motomachi fire [Sekizawa, et al., 1999], CIBSE Guide D [CIBSE, 2000], the Online Survey –Evacuation/Circulation (base case down)

The online survey data curve presented falls between the study by Heyes and the Hiroshima Motomachi high-rise apartment fire data. This is expected as a broader participant demographic base was used compared to these studies.

The only study in the literature review that considered lift wait time during an evacuation was the surveys conducted by Heyes. Heyes's study showed that during an evacuation the proportion of people that would wait for a lift decreased as wait time increased, and that the higher the floor people were on the longer they would be prepared to wait. This is similar to the findings of the online survey. Heyes suggests that the relationship between lift wait time and the proportion of occupants that would wait for a lift is a negative linear correlation (i.e. as wait time increases the proportion of occupants that choose to wait for a lift linearly decreases). However, the online survey results suggest the trend to be a negative exponential correlation (i.e. as lift wait time increases the proportion of occupants that would wait for a lift exponentially decreases).

Heyes also conducted an online survey of employees of an engineering firm located in three branch offices in different countries: US, Australia and Singapore. Heyes mentions that the participant responses from each country were similar with little variation being observed. However, findings from the online survey presented in this thesis suggest there to be a different level of acceptance to consider using lifts during an evacuation between certain countries. It is uncertain whether difference with the studies by Heyes were due to differences between each participant sample, a more general trend, or caused by differences in the study methodologies.

4.7 Concluding remarks

This section has presented an analysis of data collected from participant responses to an online survey in order to gain an understanding of human factors associated with lift/stair selection in evacuation scenarios.

Despite being informed that the lifts were a safe and acceptable option, irrespective of familiarity, only approximately 1 in 2 participants would consider using a lift during an evacuation. This decreased to approximately 1 in 3 if participants were familiar with the building: increased familiarity with a building decreases the probability that they would consider using a lift. This highlights that there is a degree of reluctance by a large number of individuals to even consider using lifts despite being informed that it is acceptable to do so. Such results underline the need for extensive training in order to convince occupants that it is indeed safe to utilise the lifts during an evacuation.

Within the hypothetical building evacuation, as the floor height increases the proportion of participants that would consider using the lift also increases. Approximately 10% of the population would use a lift even if located below the 10th floor. The proportion of the population that would use a lift increases to approximately 80% up to floor 40 and remains at this level even for higher floors. This suggests that, irrespective of floor height, approximately 20% of the individuals would not wait to use a lift to evacuate. The majority of participants indicated that when considering whether to use a lift or stairs, they would consider crowd density and lift wait time in the lift waiting area. As floor height increases participants tolerance to waiting in a higher crowd density for longer periods increases. Such results suggest that people adapt their behaviour according to changing local conditions in the lift waiting area.

From the analysis of demographic factors, whilst trends were noticeable, no significant differences across the gender, age and BMI demographic groups were found. The lack of differences between such physical demographic factors may be due to the lack of realism afforded by the survey (i.e. not requiring physical participation). There were however, significant differences between the number of participants from certain countries that would consider using a lift during an evacuation. The results suggest that people in the US and Germany are more likely to consider using lifts during an evacuation compared to the UK and China. It is suggested that this may be due to increased general familiarity with high-rise buildings and subsequent lift systems in the US and Germany compared to the UK and China. These findings suggest that the proportion of people that would consider using a lift, even though they were informed that it was safe to do so during an evacuation is not consistent across different countries.

Chapter 5 - Evacuation Lift Model

5.1 Introduction

The previous chapter presented data and analysis of human factors associated with lift usage during evacuations. This chapter presents a lift model along with an agent lift model developed in buildingEXODUS based on the data collected. The lift model represents the physical properties, delay times and kinematical features of a lift system. The agent lift model represents occupants' decision to use a lift or redirect to the stairs at various stages during their egress. For each component of the developed lift and agent lift model a series of verification tests have been performed and results presented (see Appendix A5.1). This is intended to demonstrate that each component behaves as expected and produce appropriate results based on input parameters and simulated conditions.

5.2 Lift model

The following sections describe the lift model within buildingEXODUS representing the lift shaft, car, motion controls, door controls, and kinematics. The lift motion controls, door controls and kinematic components can be defined by the user via a script file within buildingEXODUS (see Figure 31).

```
# Load a Geometry

LoadGem: 32Lift50Floor_advancedLift.exo
alllifts:
startfloor:0
accelerationrate:1.2
jerkrate:1.8
maxspeed:6
dooropeningtimes:0.8
doorclosingtimes:3
dwelldelay:3
sensorbreakdwelldelay:2
motordelay:0.5
capacity:13
maxcapacity:100
shuttlefloorsequence:10 0 9 0 8 0 7 0 6 0 5 0 4 0 3 0 2 0 1 0
exitfloors:0
isonlyforfirefighters:0
```

Figure 31: Sample lift model script file

5.2.1 Lift shaft

The lift model developed within buildingEXODUS is based around using 'transit nodes'. A series of transit nodes span each of the floors within a geometry that in turn define the vertical path and distance a lift moves between each floor (see Figure 32). The dimensions of the shaft in addition to the size of the door on each respective floor can be defined within the model by altering the attributes of each transit node.

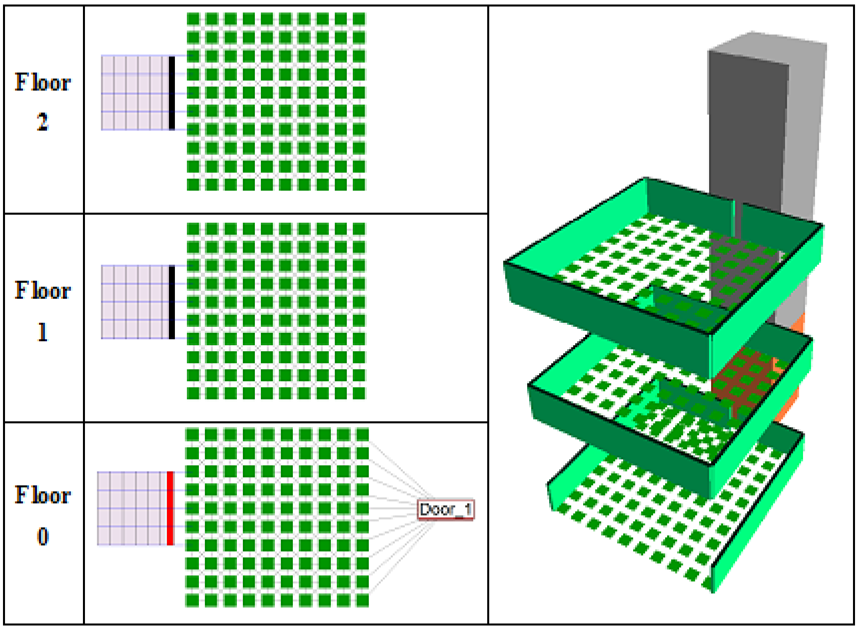


Figure 32: Transit node lift shaft example

5.2.2 Lift car

Once the lift shaft is defined via set of transit nodes, then a lift can be associated with the shaft. There are a number of attributes (see Table 33) that define the movement, delay times and capacity of a lift within the model.

Table 33: buildingEXODUS lift attributes

Attribute	Description
Maximum speed	The maximum rated speed of the lift car (m/s).
Acceleration	The constant rate of acceleration of the lift car (m/s^2).
Jerk	The rate of change in acceleration before and after constantly accelerating (m/s^3).
Start floor	The floor the car will start at the beginning of a simulation.
Door opening time	The time it takes a lift door to open.
Door closing time	The time it takes a lift door to close.
Dwell time	The duration the car doors will stay open after the car doors have fully opened to service a given floor (providing no one enters the lift).
Sensor break adjusted dwell-delay	The adjusted dwell time after the first occupant enters a lift car.
Motor delay	The time, after a lift's doors have closed, before the car starts to move (i.e. the time it takes the motor to start).
Theoretical capacity	The maximum physical number of agents that can enter a car.
Max % of theoretical capacity	The percentage of the 'Capacity' which the car actually reaches.
Serve floor sequence	A sequence of numbers which represent the series of floors the car will serve.
Shuttle floor sequence	A sequence of paired numbers which represent a series of 'pick up' and 'drop off' floors the car will shuttle between.
Exit floors	A list of floor numbers which form the drop off floors for both Shuttle floor and Serve floor sequence. For both sequences, if a lift arrives on an exit floor, everyone currently in the car will exit at the indicated floor.
Start delay	The delay time between when a simulation starts and a lift begins to serve the assigned floor sequence.

5.2.3 Lift motion controls

Within the lift model a mechanism has been developed to control lift cars during a simulation: the floor dispatching. This mechanism allows users to manually define the sequence of floors a lift will service from within a script file. This sequence can be defined in two different ways (floor-sequence or shuttle-floor sequence) along with an exit floor list. Using a floor-sequence, a user specifies the sequence of floors a lift will service during the simulation. The assigned lift will serve each of the floors specified in the sequence. Using a shuttle-floor-sequence, a user specifies a paired-sequence of pick-up/drop-off floors where the lift could pick agents up from and shuttle them to. This shuttle process would repeat until there where no more agents in the pick-up floor transit node catchment area. The process is then repeated for the next pick-up/drop-off floor in the sequence.

An optional feature within the model is for the control algorithm to check if agents are waiting in the next destination floor transit node catchment area. If no agents are waiting then that floor is removed from the sequence list. This process is repeated at the beginning and end of each lift journey so that a lift car does not service a floor where no agents are waiting. This increases the efficiency of the lift system by representing either manual intervention of a lift controller or automated monitoring system in the lift waiting area to determine if a person is still waiting.

For both floor sequence control methods, the exit floor list defines which floor(s) the agents in the car will exit the lift. All simulations presented within this thesis use the shuttle-floor sequence control mechanism. For the shuttle-floor sequence system, using a top-down strategy, if a lift does not fill to its maximum capacity at a pick-up floor, an optional feature is to then move the lift to the next pick-up floor to fill up the remaining spaces in the lift car. An additional optional feature is to keep a lift car's door open whilst it is not filled to capacity whilst there are still agents targeting the lift bank within the lift waiting area. These features reduce the amount of redundant shuttle trips a lift makes when it is not full and so increases the efficiency of the overall evacuation. This assumes that the number of passengers that enter each lift and/or are present within the lift waiting area is detected either via automated means (e.g. weight/motion sensors), or manually via a lift operator/emergency staff/occupants inside the lift.

5.2.4 Lift door controls

Once a lift has opened its doors on a floor, the doors will remain open for the specified dwell time before closing. However, whilst an agent is within a lift waiting area and is targeting one of the lifts in the lift bank, all open lifts that are not full to capacity will keep their doors open. This is in anticipation that another agent might board the lift. This assumes that the lift car doors are kept open either by people already inside the lift or staff controlling the lift. This means that lifts have an increased chance of being filled to their maximum capacity when collecting agents. If a lift is filled to its maximum capacity then the lift doors will close after the sensor break dwell delay expires from the moment the last agent boards the lift.

5.2.5 Lift kinematics

The kinematics of a lift car is defined by its jerk, acceleration and maximum speed. There also are a number of other factors that influence an actual lift’s journey such as friction, ‘wear and tear' of machine parts, etc. However, these are not considered within the current lift model. As such the kinematics of the lift model should be considered "ideal". Specifying the cars jerk, acceleration and maximum speed is sufficient to determine the location of a lift at any point during its journey. The time at which the lift passes each respective floor between its original location and its destination is determined using a series of formulae.

The first significant work in deriving the formulae for the "ideal lift kinematics" was by Motz [Motz, 1991] in 1986. In 1996 Peters [Peters, 1996] derived the necessary time-distance formulae. Given the necessary attributes of a lift, these formulae produce the distance travelled at a given time in a lift's journey. These formulae have been implemented in a modified form within buildingEXODUS to provide the model with the time that a lift passes/arrives at each floor.

With regards to jerk, acceleration and maximum speed, there are three types of journey a lift can make: A) a lift reaches maximum speed, B) a lift reaches its maximum acceleration (but not maximum speed), C) a lift fails to reach its maximum acceleration. Figure 33 below shows each of the three different types of journey that can be made by a lift in terms of the changing values of jerk, acceleration, velocity and distance travelled, over time. A description of the lift kinematic formula used within the lift model can be seen in the Appendix A4.1.

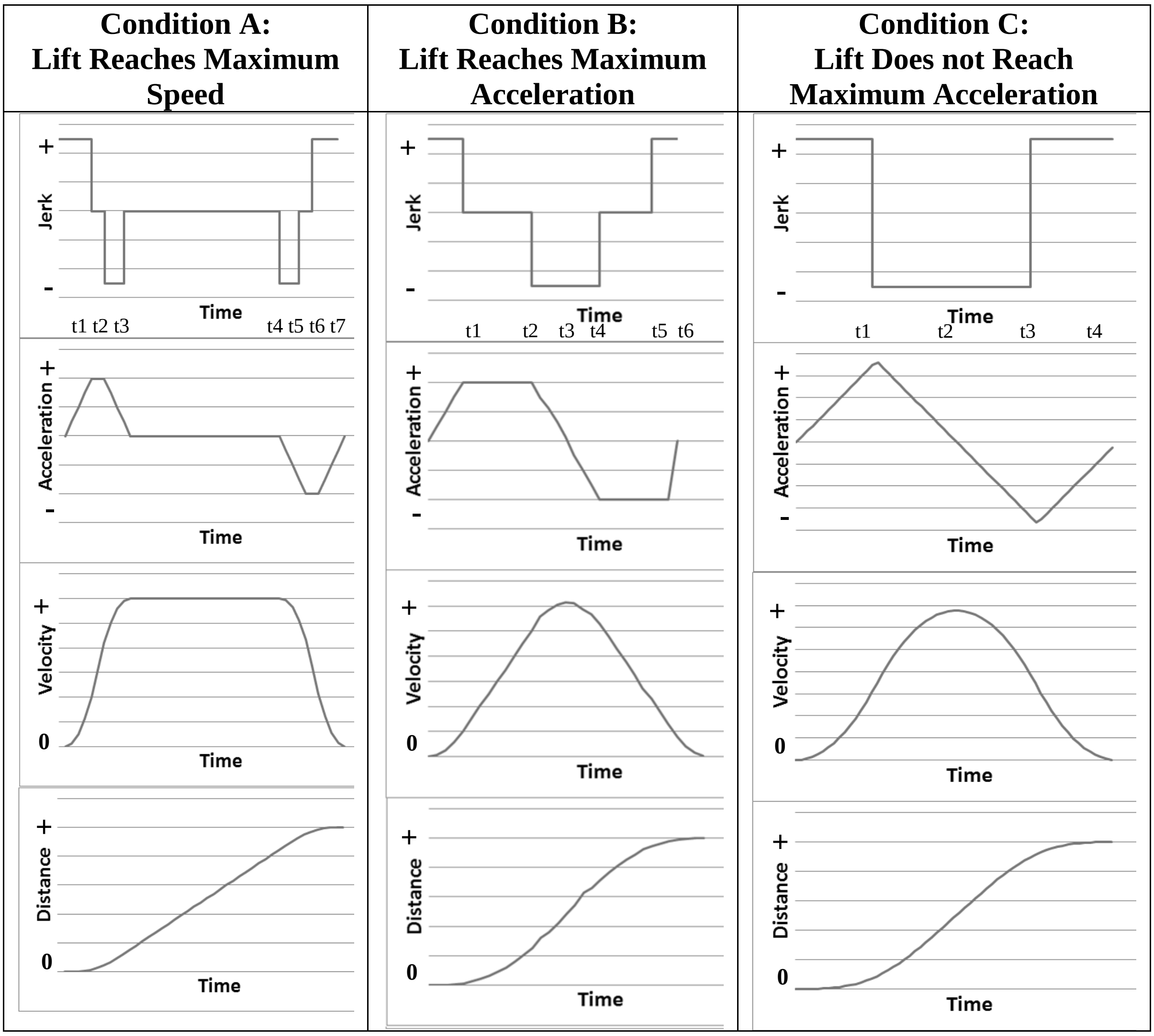


Figure 33: Three types of journey a lift can make with respect to jerk, acceleration and maximum speed [Peters, 1996]

An alternate method for representing the lift kinematics would be to explicitly define the lift journey times (i.e. the user calculates/enters them manually). Whilst this would provide a decrease in computational overhead of having to calculate each journey time for the model, it would increase the evacuation analysis development time through requiring more user intervention. As such, this method was considered less desirable.

5.3 Agent lift model

There are four key decision points within the buildingEXODUS agent lift model: (1) lift/stair choice, (2) initial lift area assessment, (3) lift wait behaviour, and (4) lift redirection (see Figure 34). Each of these is explained in the proceeding sections.

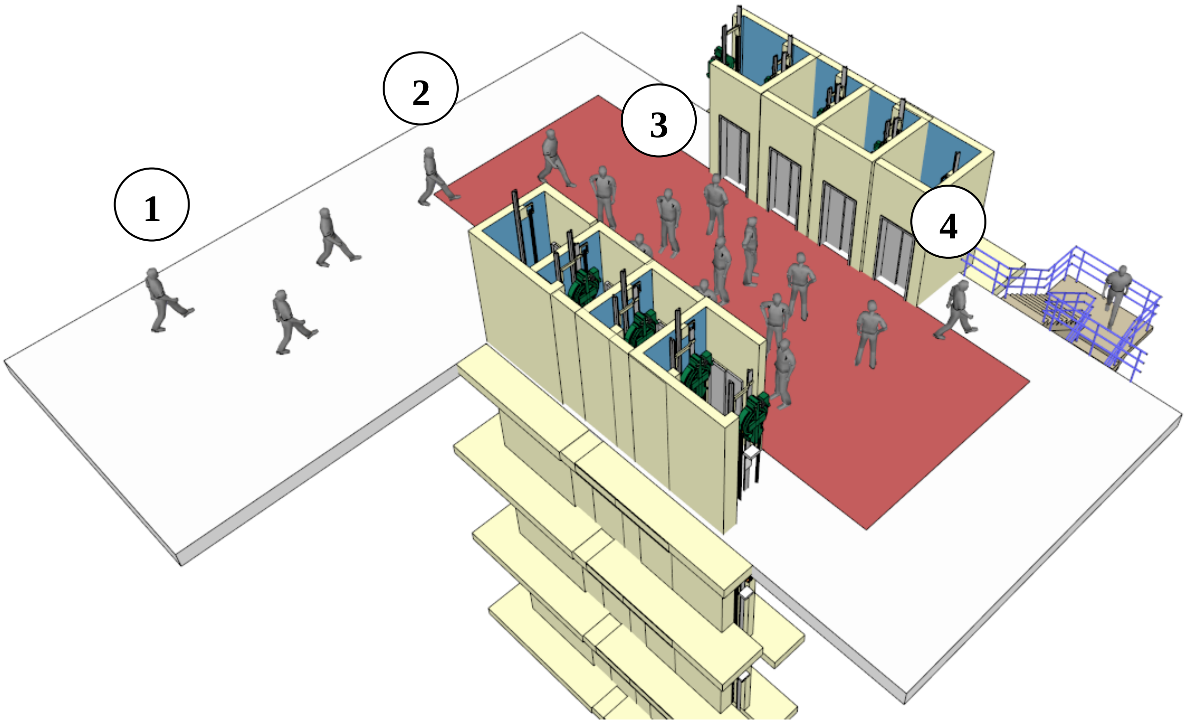


Figure 34: Advanced Agent lift Model - Key Decision Points

The data included in the model is derived from the evacuation section of the online survey in question 4F. This represents the responses of participants in the 'familiar' scenario. The analysis identified that little difference was recorded between participant responses in the 'unfamiliar' scenario compared to the familiar scenario (see Chapter 6). In addition, the majority of high-rise structures are either offices or apartments which contain occupants that are familiar with the structure. As such it was considered appropriate for representing the majority of high-rise buildings to use the data from the 'familiar' scenario.

Despite this, it is possible to alter or use other data within the model should the user require. The characteristics of how agents interact with the lift system during an evacuation (i.e. the distributions used for assignment for the lift model) are set according to the agent's initial floor. This is of particular importance when agents are required to traverse the stairs before potentially using a lift (e.g. a sky lobby scenario). Whilst question 4F in the survey did not pose a sky lobby scenario, the data can be used for sky lobby cases if it is assumed the distribution of lift users, distribution of congestion thresholds and lift wait time distributions of initial occupant starting floor remain the same. Based on the survey data this means that agents on progressively higher floors above a sky lobby are (a) more likely to use a lift, (b) likely to be more tolerant to higher levels of congestion, and (c) are likely to be prepared to wait longer for a lift than those agents on lower floors above a sky lobby.

In Figure 35 a flow chart can be seen showing the main processes and decisions that agents make within the agent lift model. These processes were identified from both the literature review and the online survey results (see Chapter 4) documenting lift human factors.

The agent lift model comprises of a number of key components used to represent occupant interaction with the lifts available. At the beginning of a simulation, agents are required to decide if they will use a lift or stairs using the ***Lift/Stair choice*** component. The agents that elect to use a lift, upon entering their chosen lift bank waiting area, assess whether they would be prepared to wait in the lift waiting area considering the current crowd congestion levels using the ***Lift Congestion Redirection*** component. At this time agents also assess if the lift has already serviced the agent's current floor using the ***Missed Lift*** component. Providing the agent has not missed a lift or redirected due to congestion, they are then required to choose a location to wait for the lift using the ***Lift Wait Location*** component. Whilst within the lift waiting area agents will decide if they are prepared to wait any longer for a lift to service their current floor before redirecting to the stairs using the ***Lift Wait Time*** component. When a lift within the agent's chosen lift bank opens its doors on the agent's floor, the agent decides if they will board the open lift using the ***Open Lift*** component. The agents that initially choose to use a lift but at some stage redirect to the stairs (e.g. due to congestion), use the ***Stair Redirection*** component. A more detailed explanation of each component of the agent lift model can be found in the proceeding sections.

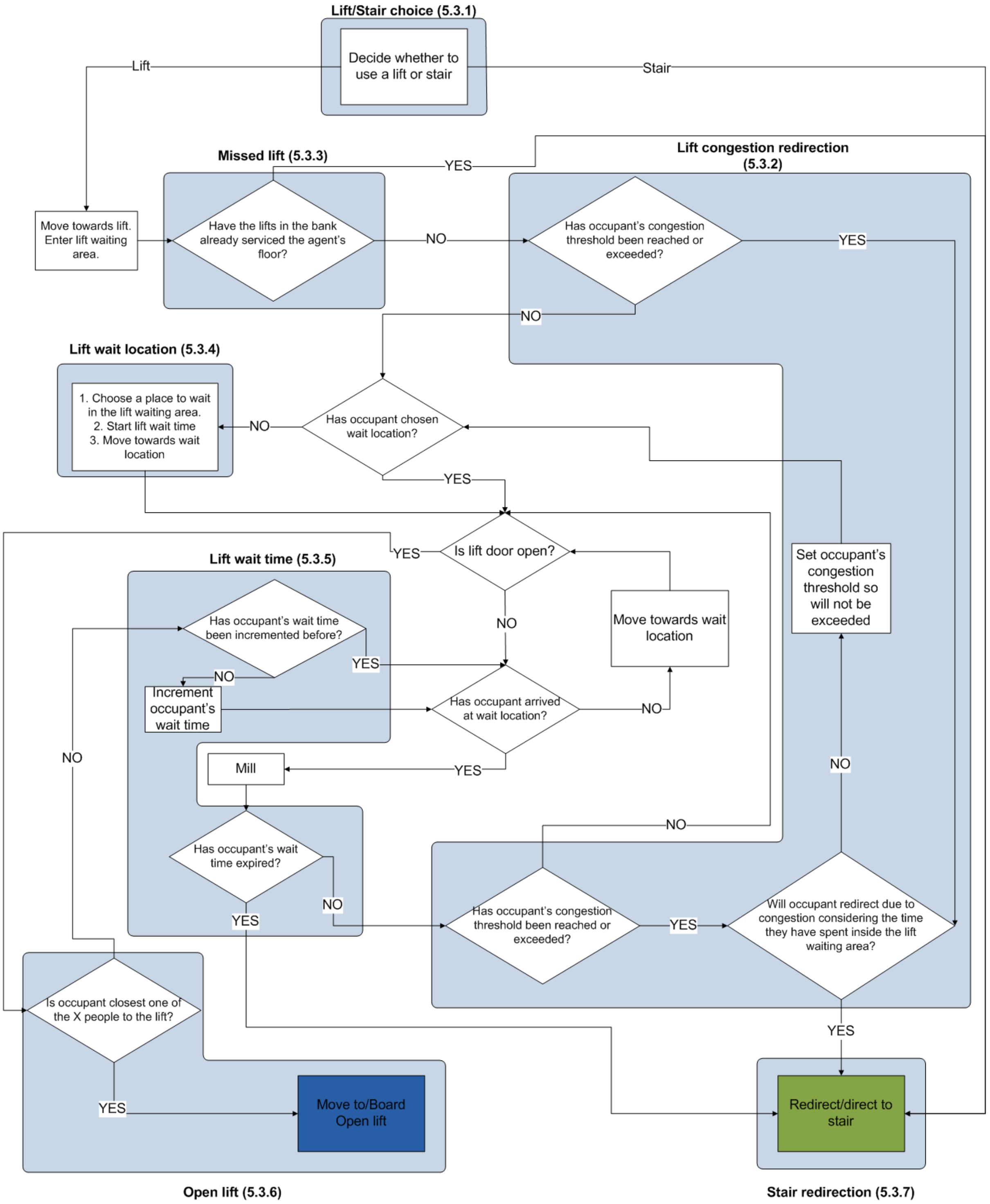


Figure 35: Flow Chart showing key components of the lift agent model and associated chapter sections

5.3.1 Lift/Stair choice

At the beginning of a simulation agents are assigned to use either a lift/stair based on a proportional system according to their initial floor. For the scenarios used in this thesis, either all agents that could use a lift did so, or the proportions of agents for each floor were derived from the online survey data.

Given that an agent has decided to use a lift, there are two possible approaches that the agent can use in selecting which lift bank they will adopt. These are:

- Closest lift bank in service selection (agents select their closest lift bank that is in service).
- Closest serviced lift bank selection with even lift bank usage (agents select their closest lift bank on a given floor that has not already been adopted by a specified number of other agents, so ensuring that each lift bank on a given floor is adopted by approximately the same number of agents).

In addition to these automated approaches, users can explicitly specify which lifts each agent will use.

Once a simulation has started agents do not change their lift/stair selection or redirect to another lift/stair after the initial choice is made. Once the agent's response time has expired they move towards the chosen lift bank. Whilst it is appreciated that actual occupants may indeed change selection to use a lift/stair whilst moving towards their initial choice based on surrounding environmental and social factors, this requires further investigation for future development.

5.3.2 Lift congestion redirection

When agents who have chosen to use a lift enter a lift catchment area, they are assigned a congestion threshold. This is randomly selected from a user-defined distribution according to the floor the agent is on. The default distributions used in the model were derived from the online survey (see Table 31 and Figure 28). If the overall level of congestion (not including the agent making the decision) in the lift catchment area reaches or exceeds that congestion threshold it is assumed that the agent will have a probability that they will either redirect to the stairs or that they will no longer consider crowd congestion. This check is done only once; the first time the agent's congestion threshold is exceeded. This probability that an agent will redirect due to the levels of congestion is described in Equation 17.

$$P\ (RDTC) = LAAT\ /\ CST$$

Equation 17

P(RDTC) = Probability that the agent will redirect due to congestion

LAAT = Lift Area Arrival Time

CST = Current Simulation Time

To demonstrate Equation 17, Table 34 shows the probability of an agent redirecting due to congestion given their LAAT and CST. Here it can be seen that when an agent is initially located in a lift waiting area (i.e. LAAT is equal to 0) the probability of redirecting due to congestion is equal to 0 (agents will not redirect due to congestion). This reflects those agents increased level of commitment to using the lift and will be not be influenced by congestion. This essentially represents agents who have already chosen to use a lift prior to the call to evacuate.

For agents that are initially outside of a lift wait area (i.e. LAAT is greater than 0), if the agents' congestion threshold is reached or exceeded immediately upon entering the lift wait area (i.e. LAAT is equal to CST) 100% will redirect to the stairs. This is based on the assumption that such agents have a decreased level of commitment to using the lift and so are influenced by the congestion more than agents that have already waited in the lift wait area.

With the exception of agents initially in the lift waiting area (i.e. LAAT is greater than 0), as agents spend more time in the lift waiting area (i.e. as CST increases), the probability that they will redirect due to congestion decreases.

Table 34: Calculated probability that an agent will redirect from a lift if congestion threshold is met/exceeded for different lift area arrival times and current simulation times (assuming instant response times)

	Current simulation time (CST) (sec)							
Lift area arrival time (LAAT) (sec)	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	-	1.0	0.5	0.33%	0.25	0.20	0.17	0.14
10	-		1.0	0.67	0.50	0.40	0.33	0.29
15	-		-	1.0	0.75	0.60	0.50	0.43
20	-		-	-	1.0	0.80	0.67	0.57
25	-		-	-	-	1.0	0.83	0.71
30	-		-	-	-	-	1.0	0.86
35	-		-	-	-	-	-	1.0

Further to this, the later an agent arrives in a lift waiting area (i.e. increased LAAT), the more likely it is they will redirect due to congestion if their congestion threshold is reached or exceeded. This is based on the assumption that such agents have a decreased level of commitment to using a lift due to not arriving in the lift wait area earlier. This means that the length of time an agent spends in the lift waiting area in addition to the actual time the agent arrives during the evacuation is considered in the probability. The online survey did not address levels of commitment as a product of time and the resulting influence upon congestion redirection. However, the agent lift model assumes that agents that spend longer and arrive sooner in a lift waiting area have an increased level of commitment to use a lift. This is reflected in the increased likelihood of being less influenced by the local levels of congestion.

If a lift is open in a lift waiting area, an agent who has chosen to redirect to the stairs due to the congestion levels can still elect to use a lift whilst in the lift waiting area. This allows agents who are required to travel through a lift waiting area (i.e. redirecting from the lifts to the stairs) in order to get to the stairs, to still be able to use a lift if they have the opportunity. This is based on the assumption that such agents will not walk past a lift that they have the option to board.

Agents who redirect to the stairs are randomly assigned to use each stair. This is done to reduce the likelihood of any stair being oversubscribed and causing a bottleneck during a scenario.

5.3.3 Missed lift redirection

Agents who initially choose to use a lift but arrive in the lift waiting area after the lift has already serviced the agent's floor will redirect to use the stairs. This represents the influence of either dynamic signage or a communication system informing the agents that the lift has already serviced their floor and that they should use the stairs instead. This system prevents agents from waiting for a lift that will not arrive.

5.3.4 Lift wait location selection

No data has been collected or found to exist in current literature with regards to lift wait location selection in either circulation or evacuation situations. As such the lift wait location selection method developed within the agent lift model is based on a number of assumptions. Agents who decide to wait in the lift catchment area (i.e. do not redirect due to congestion), randomly adopt a location to wait and 'mill' around. The milling process involves agents occasionally randomly moving about their chosen wait location. A default milling distance is set which ensures that milling agents will not travel more than the given distance from their wait location. Whilst milling, agents will not move outside of the lift catchment area.

This regular movement about a chosen wait location helps to ensure that other agents passing through the lift waiting area (who are not going to use a lift in the local area) do not become blocked by other agents waiting for a lift. This means that more agents can fit inside the lift wait area as blocking of new agents entering into the catchment area whilst they move to other locations is reduced. This also means that agents spread out more uniformly within the lift waiting area over time. Without such behaviour blockages by other agents at the entrances of a lift waiting area can occur. This can result in lift boarding delays for agents who have to travel slightly further (through being blocked) in the lift waiting area.

5.3.5 Lift wait time redirection

Agents who choose to wait to use a lift are assigned a wait time which is randomly selected from a user-defined wait time distribution. The default distributions used in the model were derived from the online survey (see Figure 28). The agent's wait time starts upon entering the lift waiting area as agents can choose to use an open lift anytime that they are in the lift waiting area. This allows agents who might be blocked/delayed by other agents from reaching their assigned wait location to consider this added time whilst waiting for a lift. If they are not assigned to use an open lift during this wait time, agents will redirect to use the stairs.

If a lift opens whilst agents are waiting, but they do not board (e.g. the lift is full), the agents' wait times are increased further by half of their original wait time. The wait time is only increased once and does not affect agents who would 'wait for as long as it takes'. This is intended to represent agents willing to wait longer for a lift in anticipation that they will be able to board a lift soon. This assumption is not based on empirical data. Further investigation is required to understand the influence of how lifts servicing a floor would affect occupant lift wait time. If an agent has redirected to use the stairs when a lift opens, and the agent is still in the lift catchment area, the agent can still choose to board the lift if there is enough space inside. However, the agent will continue to redirect to the stairs if no space is available (i.e. they will not wait any longer).

5.3.6 Open lift selection

When a lift door opens in a lift bank, the nearest agents who are waiting in the catchment area move to use the lift. Only the number of agents that can fit inside the lift (derived from the lift maximum capacity) attempt to board the lift. As a result there is no competition for lift boarding and the boarding process is orderly. If multiple lifts open their doors simultaneously at a given floor, the agents select the nearest open lift that is not oversubscribed. Where the nearest lift and nearest agents are paired (i.e. an agent is one of the nearest to the lift and the lift is the nearest to the agent) those agents will choose to use that open lift. Agents who could not board their nearest lift, will assess if they can board their second nearest lift using the same process, and so on. This process is repeated until all spaces in all open lifts have been allocated to waiting agents.

5.3.7 Stair redirection

Agents who redirect to the stairs after initially choosing to use a lift are distributed such that each of the stairs are adopted by approximately an even number of agents. This is done so that any single stair is not oversubscribed to produce a bottleneck. Within the model it is possible to disable this behaviour with redirecting agents only following the potential map: the shortest route to their next exit/target. Typically this would result in agents moving to the stairs that forms part of this route. No data was collected with regards to stair selection and further investigation is required regarding this type of behaviour.

5.3.8 Additional agent attributes

For all agents who initially choose to use a lift, the time they enter into the lift catchment area (Lift Wait Start time (LWS)) and the time they either choose to use an open lift or redirect to use the stairs (Lift Wait End time (LWE)) is recorded. For agents that use a lift, their 'Lift Wait Time' (LWT) is calculated by subtracting the LWS from the LWE. These additional attributes are stored for each agent and is included in the output to the main buildingEXODUS results table within a simulation file.

In addition, all agents have a lift flag status that is used to identify how agents have interacted with the lift system during a simulation (see Table 35). This can either signify that agents used a lift during a simulation (Lift User), redirected due to congestion (LCR), redirected due to wait time expiration (LTW), missed the lift (ML), or did not consider using a lift (N/A).

Table 35: Agent lift attributes

Code	Type	Lift Catchment Area Wait Time	
		Start Time	**End Time**
Lift User	Lift User	Enter catchment area	Assigned to use a lift
LCR	Redirected due to congestion	Enter catchment area	Decision to redirect time
LTW	Redirected due to wait time expiration	Enter catchment area	Decision to redirect time
ML	Missed lift	Enter catchment area	Decision to redirect time
N/A	Stair user	-	-

5.4 Concluding remarks

This chapter has described the development of a lift model and agent lift model within the buildingEXODUS evacuation software. The lift model represents the movement of a lift car given a set of kinematic attributes along with various delay times, in addition to a control mechanism that allows a variety of evacuation floor dispatch strategies to be employed. The development of the agent lift model was instructed by and uses the empirical data presented in the previous chapter. The agent lift model represents an occupant’s initial choice to consider using a lift, the influence of congestion in the lift wait area and wait time upon an occupant’s decision to redirect to the stairs during an evacuation. A number of assumptions have been made in the agent lift model. These were required to be included in order to represent human factors where no associated empirical data was collected or available. A number of agent attributes have also been included within the model to allow analysis of how each agent interacted with the lift system during a simulation. For each component of the lift model and agent lift model the results from a series of verification tests are presented (see Appendix A5.1) to demonstrate that the model behaves as intended given a range of input parameters and simulated conditions.

Chapter 6 - Case Study: Full Building Lift Evacuation

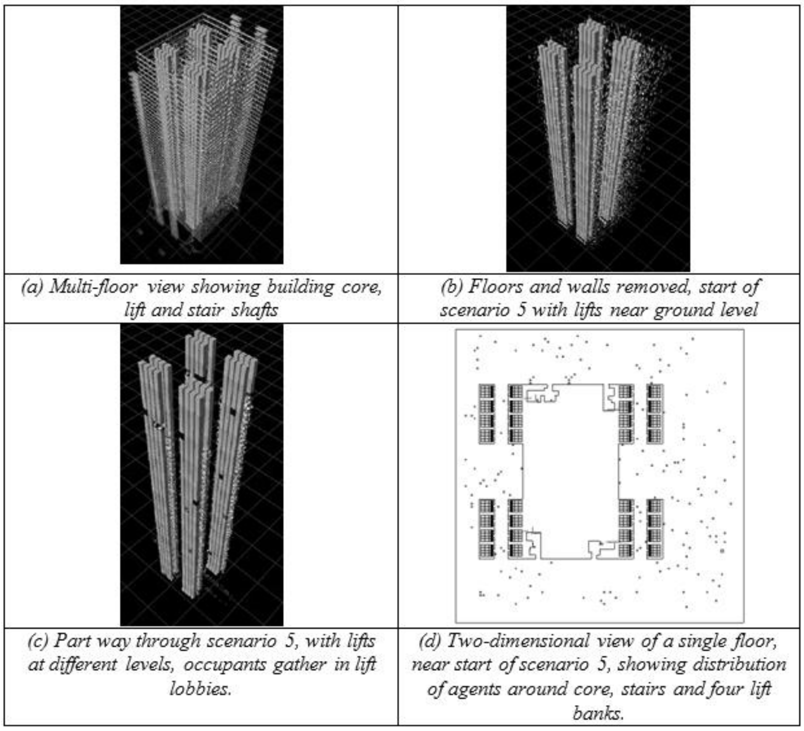
6.1 Introduction

A series of full building evacuation scenarios have been performed using the developed lift and agent lift model presented in the previous chapter. A description of the geometry, lift attributes, population and scenarios using a variety of evacuation lift strategies is presented followed by the results. The purpose of the evacuation scenarios is to compare the relative merits of different evacuation lift strategies and to what extent they may be influenced by associated human factors.

6.2 Geometry

A hypothetical building was developed within buildingEXODUS to perform the evacuation analysis. The building has 50 floors which is comparable to the current tallest completed building in the UK (One Canada Square) [CTBUH, 2010], with a floor-to-floor height of 3m (the total height of the building was 150m in height). CBISE Guide D [CIBSE, 2000] states that, as a rule of thumb, a building should provide at least one lift for every three floors within a building to provide excellent service. In addition, the guide also recommends that eight is the maximum number of lifts that can be presented to occupants within a single lift waiting area to allow occupants to monitor the arrival of lifts easily. Considering this, the hypothetical building contains four stairwell cores and four lift banks each having eight lifts, providing approximately 1.56 lifts per three floors (see Figure 36). Such a configuration conforms to the guidance stated in CIBSE Guide D [CIBSE, 2000].

With the exception of the ground floor all levels in the building have the same layout and configuration. In certain scenarios specific floors were designated as sky lobbies where agents from multiple floors move to and wait to use the lifts during the evacuation. In such buildings, it is common to find that sky lobbies are intended to be refuge areas with sufficient occupant capacity and fire/smoke/water protective measures in place to protect the enclosed population. However, the influence of such configuration factors upon evacuation dynamics is considered beyond the scope of the study. Each stair allowed two agents to stand abreast side-by-side with agents preferring to stagger their locations (i.e. prefer not to stand side by-side) and maintain at least one tread spacing between themselves and the agent in front. Each stair is doglegged design where an intermittent landing (1m×3.2m) connects the two legs; each leg being 1.5m in width and 4.6m in horizontal length allowing a maximum of 16 agents to simultaneously occupy each leg of the stairs at a time.



(a) Multi-floor view showing building core, lift and stair shafts

(b) Floors and walls removed, start of scenario 5 with lifts near ground level

(c) Part way through scenario 5, with lifts at different levels, occupants gather in lift lobbies.

(d) Two-dimensional view of a single floor, near start of scenario 5, showing distribution of agents around core, stairs and four lift banks.

Figure 36: Sequence of views from buildingEXODUS of high-rise building lift evacuation, (a), (b) and (c) depicting 3D virtual reality view and (c) depicting two dimensional view

6.3 Lift attributes

The defining attributes for the lift kinematics and physical characteristics in each scenario were based on the Chartered Institution for Building Service Engineers (CIBSE) Guide D: Transportation Systems in buildings [CIBSE, 2000]. Each lift had a maximum capacity of 13 agents, a maximum speed of 6m/s, acceleration rate of 1.2m/s^2 and a jerk rate of 1.8m/s^3. In addition, each lift had a door opening time of 0.8s, door closing time of 3.0s, a dwell delay of 3.0s and a motor delay time of 0.5s. Using these parameters approximately 31.5s are required for a lift to travel from the ground floor to the top floor and fully open its doors. At the beginning of each simulation each lift started at the ground floor. For each lift simulation not involving stairs, where lifts serviced multiple floors (i.e. non-sky lobby scenarios), a top–down shuttle evacuation strategy was employed by each of the lifts. Here all the lifts evacuate the agents on the top floor first and shuttle them to the ground floor until all people have evacuated that floor. The lifts then proceed to the floor below this and the process is repeated.

6.4 Population

With the exception of the ground floor, there were 160 agents located on each floor (7,840 agents in total). Agents were modelled as non-connected individuals and were not constrained by groups. The demographics of the agent were assigned according to the default population within buildingEXODUS, representing a broad cross-section of attributes and capabilities [Galea, et al., 2006b]. All agents were assumed to react instantly at the beginning of each scenario so response time is not considered a parameter within the analysis.

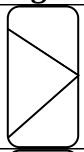
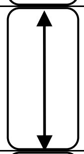
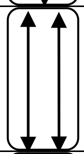
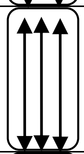
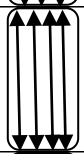
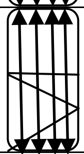
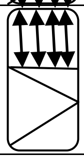
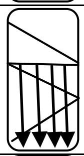
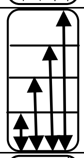
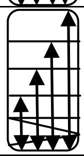
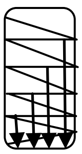
6.5 Scenarios

For each scenario, different combinations of lifts and stairs were used to evacuate the entire building population. In each case, the priority of the lifts was to service the upper floors first, sequentially working down to the lower floors. Several scenarios examined the use of shuttle zones and sky lobby arrangements. The full list of scenarios is summarised in Table 36. These scenarios were selected as many existing high-rise buildings already use shuttle zones and sky lobbies. As such, the results from the evacuation analysis are intended to be more generally applicable to both design-phase and existing high-rise buildings.

Lift frequency is varied in some scenarios. This is intended to explore the impact of the number of lifts on evacuation efficiency and to explore the effect of lift banks being rendered inoperable during an evacuation (e.g. due to fire, technical fault, etc). For each scenario all lifts initially started on the ground floor. Due to the hypothetical nature of the building, aside from the external walls and the lift/stair cores, no furniture or internal obstructions were represented within each scenario.

In each scenario, agents that initially elected to use the available lifts approximately evenly distributed among each lift bank. Similarly, of the agents that initially elected to use the stairs, would approximately evenly distribute between them. This was to minimise the influence of uneven lift/stair usage. Uneven lift/stair usage would likely decrease the evacuation efficiency of each scenario. However, the main focus of this study to measure the extent to which different lift strategies and associated human factors influence an evacuation.

Table 36: Overview of evacuation scenarios

Scenario	Diagram	Description
1		Stairs only
2		8 lifts (1 lift bank)
3		16 lifts (2 lift banks)
4		24 lifts (3 lift banks)
5		32 lifts (4 lift banks)
6		32 lifts, with the lower half of the building (floors 0-25) population using the stairs and the upper half (26-49) using the lifts to shuttle to the ground floor.
7		32 lifts, with the lower-half of the building (floors 0-25) population using the stairs and the upper half (26-49) using the lifts to shuttle to the middle floor (floor 25) from the agents floor of origin, then continue their evacuation via the stairs.
8		32 lifts, with the lower-half of the building (floors 0-25) population using the stairs and the upper half (26-49) initially using the stairs to walk to a sky lobby on floor 25 where agents would be shuttled via lifts to the ground floor.
9		32 lifts, 4 shuttle zones - each lift bank servicing a series of 12 floors of agents, with each zone being evacuated from the top-down of the zone to the ground floor.
10		32 lifts, 4 shuttle zones + 1 Stair zone - each lift bank servicing a series of 10 floors of agents, with each zone being evacuated from the top-down of the zone to the ground floor. Agents below floor 10 only use the stairs to evacuate.
11		32 lifts, 4 Sky lobbies – there is a sky lobby every 10 floors in the building (4 sky lobbies in total) with each lift bank servicing one of the sky lobbies. Agents travel down the stairs to the next sky lobby below where the lifts shuttle them to the ground floor. Agents below floor 10 only use the stairs to evacuate.

6.6 Results

Each of the lift evacuation scenarios was simulated using a simplified version of the Lift Agent Model (SLAM) and an advanced version of the Lift Agent Model (ALAM). The SLAM assumes all agents that can use a lift do so during a simulation with no redirection from lift waiting areas. In these scenarios agents exhibit deterministic and non-adaptive behaviour. The ALAM incorporates the online survey data mentioned in Chapter 4. To iterate, this includes the following data for each floor range:

- the proportion of occupants that would initially choose to use a lift (see Table 31),
- what levels of congestion in the lift waiting area would cause them to redirect to the stairs (see Table 31),
- how long they would be prepared to wait to use a lift (see Figure 28).

The data used in the ALAM scenarios assume that all agents have the capability to use the stairs. In addition, all occupants would at least consider using a lift given the option and that they are sufficiently assured/convinced/trained that the lifts are safe to use during an evacuation. During scenarios using the ALAM agents exhibit probabilistic adaptive behaviour based on the attributes assigned.

The SLAM evacuation analysis identifies the influence of different lift strategies upon an evacuation. The ALAM evacuation analysis identifies to what extent each lift strategy is influenced by human factors. The following sections present results of the evacuation analysis using both the SLAM and ALAM. A comparison of the scenario results from the two models has then been performed.

6.6.1 Simplified Lift Agent Model (SLAM)

The results for the various simulations using the SLAM are presented in Table 37.

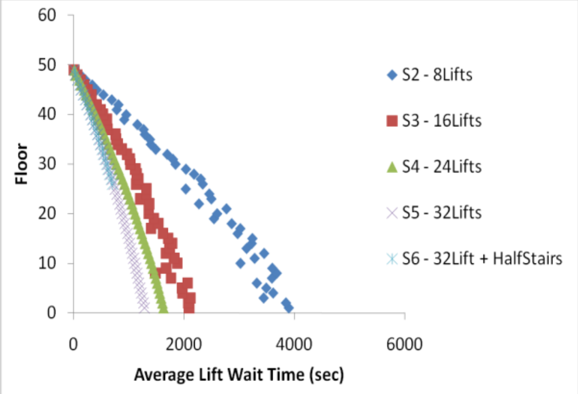
Table 37: Simplified lift agent model simulation results - Summary

Scenario	Number of lifts	Evacuation time of last lift user (min)	Evacuation time of last stair user (min)	% Time saved (compared to stairs only)	Time to evacuate top half of building (floor ≥26)	Avg PET (min)	Avg LWT (min)	Time taken to evacuate proportion of the population (min)		
								25%	50%	75%
1	**0**	-	35.9	-	20.3	17.6	-	9.3	17.5	25.8
2	**8**	71.1	-	-100.0	41.2	40.8	36.1	24.1	43.0	58.9
3	**16**	39.1	-	-8.9	22.2	22.5	19.5	13.5	23.6	32.3
4	**24**	29.0	-	19.2	16.2	16.6	15.1	10.0	17.3	23.7
5	**32**	23.2	-	35.4	12.9	13.3	12.0	8.1	13.9	18.8
6	**32 + half stairs top-down**	13.4	18.6	48.2	12.3	8.6	6.2	5.0	8.5	11.9
7	**32 + half stairs top middle**	35.4	33.1	1.4	12.3	17.6	4.8	9.3	17.6	25.8
8	**32 + half stairs, 1 x Sky Lobby**	18.8	18.7	47.6	17.7	9.6	0.0	5.5	9.7	13.8
9	**32 + 4 Shuttle Zones**	23.5	-	34.5	22.4	10.2	10.2	5.7	9.9	13.9
10	**32 + 4 Shuttle Zones + 10 Stairs**	20.0	7.3	44.3	18.7	8.1	6.8	4.2	7.2	11.7
11	**32 + 4 x Sky Lobbies**	18.3	7.3	49.0	17.1	7.2	0.8	3.8	6.4	9.9

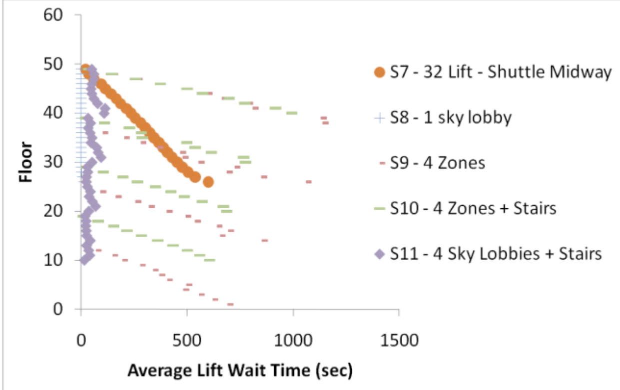
The base line comparison for all the cases is the stair only evacuation (scenario 1) as this is representative of typical evacuation practice where the lifts are not used. This produced a Total Evacuation Time (TET) of 35.9 min with 20.3 min required to clear the top half of the building. The average Personal Evacuation Time (PET) for the scenario was 17.6 min. This indicates that on average, a person required 17.6 min to exit the building. The TET for Scenarios 2 (8 lifts) and 3 (16 lifts) were 71.1 min and 39.1 min respectively, both being longer than the stair only case. The average Lift Wait Time (LWT) represents the overall average time agents spent waiting for a lift. The 8 lift scenario (scenario 2) produced the longest LWT of all cases at 36.1 min which was some 46.0% longer than the 16 lift scenario (Scenario 3). Indeed the longest LWTs were in Scenarios 2-5. In these scenarios only lifts were used and agents on the lower floors waited the longest due to the top-down lift strategy employed (see Figure 37).

For Scenarios 2-5 the evacuation rate increased towards the later stages of each evacuation unlike in the stair only case which decreased towards the later stages of the evacuation (see

Figure 38). The increase in evacuation rate was due to the lifts having to travel a shorter distance towards the end of the evacuation as the remaining agents were located on the lower floors, given the top-down lift strategy. This can be seen in Figure 39 where the difference between the floor clearance times in these scenarios decreases on progressively lower floors in the building.



Scenarios 2-6



Scenarios 7-11

Figure 37: Simplified lift agent model simulation results - Average Lift Wait Time (LWT) of agents who initially start on each floor and use a lift

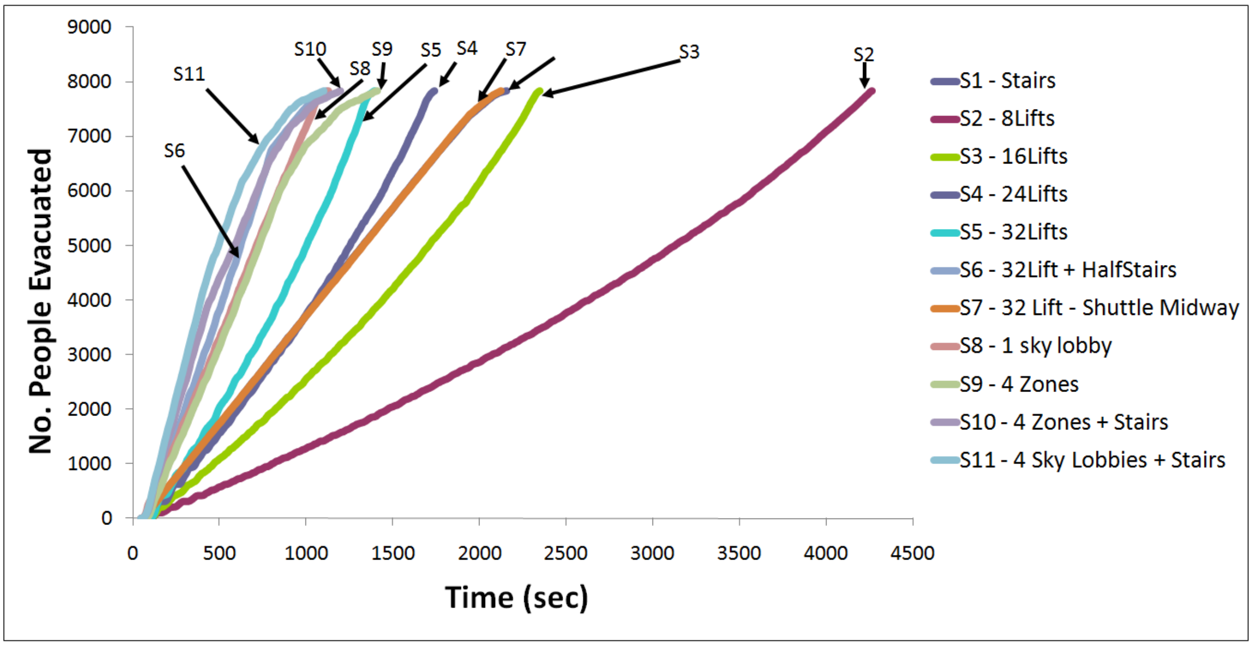
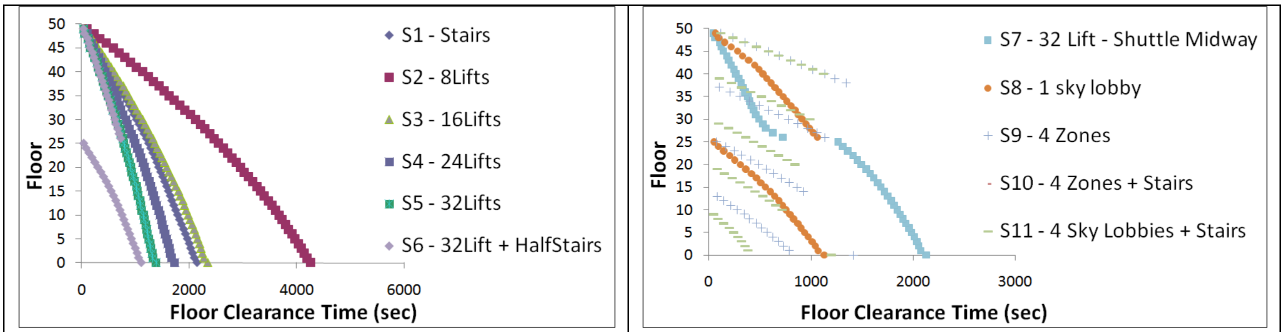


Figure 38: Simplified lift agent model simulation results - Number of people evacuated against time (sec) for each scenario



Scenarios 1 - 6	Scenarios 7-11

Figure 39: Simplified lift agent model simulation results - Floor Clearance Times for each scenario

It is not until 24 lifts were used (Scenario 4) that the TET decreased in relation to the stair only case by 19.2% (6.9 min). However, even with 24 lifts the average PET (16.6 min) was still only marginally less than the stair only case. From Figure 38, it can be seen that the stair only curve outperformed the 24 lift case for the first 16.3 min (45.4% of the stair evacuation and 56.2% of the 24 lift case) where some 46.2% (3,620) agents evacuated. However, from Table 37 it can be seen that the 24 lift case (Scenario 4) cleared the upper half of the building marginally faster (20.2%) than the stair only case (Scenario 1). Overall the majority of floor clearance times were only marginally improved compared to those observed in the stair only scenario.

When 32 lifts were used (Scenario 5) a further reduction in TET of 35.4% and reduction of overall average PET of 24.4% compared with the stair only case was recorded. The use of lifts provided a substantial benefit to agents initially located in the top half of the building with the upper half of the building being cleared substantially faster (36.4% (7.4min)) than the stair only case. Comparing the 8 lift scenario with the other lift only scenarios, it can be seen that there was an approximate 1.8, 2.5 and 3.1 times reduction in TET for the 16, 24 and 32 lift scenarios respectively. This suggests that for a given population distribution and number of floors, the speed up in evacuation performance does not necessarily linearly increase with the number of lifts used.

In Scenario 6 an evacuation strategy in which the bottom half of the building used the stairs to evacuate while the top half used 32 lifts to evacuate to the ground was explored. This strategy produced the second shortest TET of 18.6 min; almost 50% faster than the stair only case. For the first 9.3 min during the stair only scenario only 25% of all agents evacuated. However, during the same period of time in Scenario 6, over twice as many agents had evacuated. As is to be expected, the time to clear the top half of the building was similar to that of Scenario 5 at 12.9 min. In addition, the time to clear each floor was also similar (see Figure 37) but the average

PET decreased to 8.6 min. The parallel usage of both the stairs and lift system allowed the lower floors to be cleared in a shorter amount of time (see Figure 39) compared to Scenarios 2-5. In this scenario, the last agents out of the building were the stair users, resulting in a decrease in the evacuation rate towards the very end of the evacuation (see Figure 38). Considering this scenario only contained half the number of lift users compared Scenario 5, all of which were located in the top half of the building, it is not surprising that the LWT decreased by almost 50%.

Scenario 7 is similar to Scenario 6, however, instead of agents on the upper floors being taken to the ground, they were taken to the central floor from where they used the stairs to continue their evacuation. The TET for this scenario increased to 35.4 min (only marginally faster than the stair only case) and the average PET, at 17.6 min, is identical to that of the stair only case. It took approximately the same length of time to evacuate the same proportion of agents throughout the entire duration of the stair only case. However, we note that the time to clear the upper half of the building was one of the quickest (along with Scenario 6), requiring only 12.3 min. While the time to evacuate the entire building was equivalent to the stair only case, using this strategy does provide one of the quickest ways to clear the upper half of the building. Due to the lifts shuttling agents a shorter distance to the middle floor instead of the ground floor (as in Scenario 6), a notable decrease in the average LWT was recorded (22.6% (1.4 min)). It should be kept in mind that the lifts discharged agents onto the central floor faster than the stairs discharged agents away. This caused large crowds to form around the stair entrance and eventually began to spill over into the respective lift waiting areas where agents alighted the lifts. Towards the end of the upper half of the building's evacuation this caused some agents to be delayed from alighting the lift due to being blocked by queuing agents for the stairs (see slight tailing off of floor clearance times for floors 27 and 26 for Scenario 7 in Figure 39). This highlights that when considering employing such a lift evacuation strategy, the discharge capacities of the lifts and the connecting stairs should be considered in order to minimise the levels of congestion and possibility of blocking of alighting lift users.

In Scenario 8 the concept of a sky lobby is introduced. Here the agents in the upper part of the building were required to descend to the central floor, evenly distributing among each stair, from where they took a lift to descend to the ground. The agents below the central floor all used the stairs to evacuate to the ground. As in Scenario 6, the parallel use of the stairs and lifts increased the vertical throughput, reflected in the decreased floor clearance times (see Figure 39). This is also reflected in the fact that the evacuation time of the last lift and stair user was approximately the same. In this case the TET was 18.8 min, some 47.6% faster than the stair only case.

However, it required approximately the same period of time (17.7 min) to clear the top half of the building as agents initially in this part of the building were required to walk down the stairs to the central floor. The LWT for this scenario was the shortest recorded of all scenarios with the majority of lift users (initially located above the middle floor) able to board an open lift immediately after entering the lift waiting areas. This is contributed to by the fact that lifts in the model will keep their doors open in the lift waiting areas while the lift is not full to capacity and there is still an agent targeting the lift bank in the lift waiting area. This effectively means that agents may end up waiting inside a lift until no other agents are targeting the lift bank (i.e. agents wait inside a lift). The staggered arrival of agents to the lift waiting area (having to initially travel on the stairs) increased the likelihood of this occurring. As a consequence this meant that when the large majority of agents arrived in the lift waiting areas on the central floor a lift was waiting for them already.

In Scenario 9 four shuttle zones were introduced with each group of eight lifts servicing the 12 floors within their allocated zone (the bottom zone had 13 floors). In each zone the lifts serviced the floors from the top-down. In this case the TET decreased to 23.5 min which is some 34.5% faster than the stair only case, but slower than Scenario 6, with the last agents to evacuate coming from the top zone (see Figure 39) where the lifts had a longer journey. Using this approach required 22.4 min to clear the upper half of the building, some 2.1 min slower than the stair only case. Clearly this is a very inefficient strategy for clearing the upper half of the building. In Scenario 10 this concept is extended by making all agents below the 10th floor use the stairs rather than the lifts. In this case four shuttle zones were used with each group of eight lifts servicing 10 floors. While this case represents an improvement over Scenario 9, being 44.3% quicker than the stair only case, the time required to clear the upper half of the building was only 1.6 min faster than the stair only case. The LWT for Scenario 9 decreased considerably by a third in Scenario 10. This represents the effects of there being fewer lift users (on the lower 10 floors) and fewer floors in each shuttle zone allowing lifts to service each floor quicker.

In Scenario 11 four sky lobbies were introduced, one on every 10th floor with each sky lobby being serviced by eight lifts (a single lift bank). Within each zone, agents descended using stairs, to a sky lobby where they boarded a lift that took them directly to the ground. Below the 10th floor, all agents used the stairs to evacuate. This case produced a TET of 18.3 min which is almost 50% faster than the stair only case. The upper half of the building was cleared in a marginally shorter amount of time at 17.1 min compared to the stair only scenario. This scenario produced a comparable TET to Scenario 6 but took 39.0% (4.8 min) longer to clear the upper half of the building (see Table 37). However, the average PET was lower than any other scenario (7.2 min). From Figure 38 it can be seen that this scenario produced the best evacuation rate of all the scenarios. The first 75% of agents evacuated some 2 min sooner than the next quickest scenario (Scenario 6). Indeed in the same time that it took 25% of agents to evacuate in the stair only case, almost three times as many agents (75%) had already evacuated in Scenario 11. The LWT for this scenario was the second shortest at less than a minute and this was caused by much the same reason as Scenario 6. Due to the sky lobbies servicing less floors than Scenario 6, meant that agents on average typically had a shorter distance to travel to a sky lobby. This meant that the arrival rate of agents to the lift waiting areas was less staggered compared to Scenario 6, hence the slightly increased average LWT. Lift users initially located on floors closer to the sky lobbies typically waited longer than those further away (see Figure 37). Results from this scenario indicate that the introduction of multiple sky lobbies (with the lower levels only using the stairs) makes it possible to evacuate a greater number of people in the same amount of time for the majority of the evacuation than in any other scenario examined.

The performance of Scenario 11 could potentially be further improved through the introduction of local lifts that take agents to the sky lobby rather than use the stairs. It can be seen in Figure 38 that scenarios involving zoning/multiple sky lobbies (Scenarios 9, 10, 11) produce increasingly inefficient evacuation performance towards the end of the evacuation sequence. This is because the lifts servicing the zones/sky lobbies on the lower levels are left idle whilst the lifts servicing the upper levels are still in operation. The performance of such scenarios could potentially be increased by using the idle lifts from the lower floors to assist in shuttling the remaining agents on the upper floors/zones to the exit level.

6.6.2 Advanced Lift Agent Model (ALAM)

A summary of results for the various simulations using the Advanced Lift Agent Model (ALAM) are presented in Table 38. The overall average LWT for all agents that used a lift and those that initially consider using a lift but redirected to the stairs is presented in Table 39. The proportion of agents that performed a given action regarding the lift system is presented in Figure 40. This shows the proportion of agents who:

- did not consider using a lift (Stair only),
- used a lift (Lift User),
- initially considered using a lift but redirected due to congestion (Congestion Redirection),
- initially considered using a lift but redirected due to lift wait time expiration (Wait time Redirection).

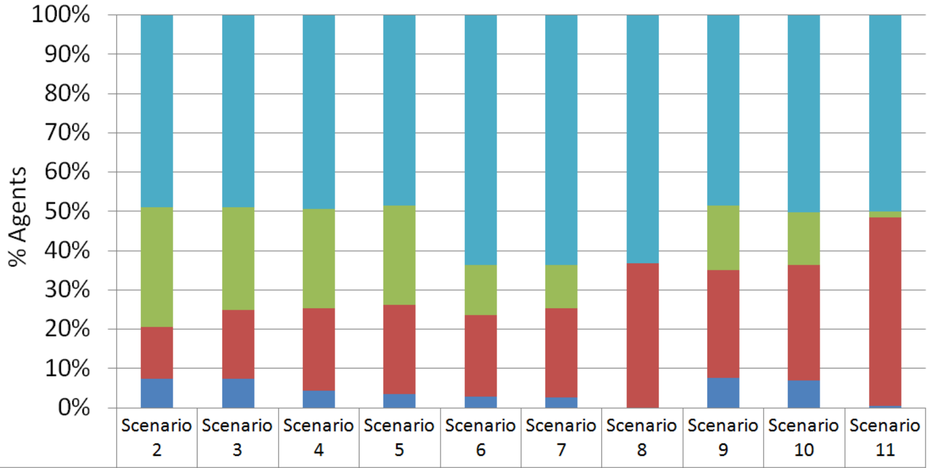
These proportions are segregated according to agent's initial floor in each scenario in Figure 41. Egress curves, the time it took the last agent to traverse pass through the stairs or board a lift (floor clearance time) and the average LWT for lift users for each floor can be seen in Figure 42.

Table 38: Advanced lift agent model simulation results - Summary

Scenario	**Number of lifts**	**Evacuation time of last lift user (min)**	**Evacuation time of last stair user (min)**	**% Time saved (compared to stairs only)**	**Time to evacuate top half of building (floor ≥26) (min)**	**Avg PET (min)**	**Time taken to evacuate proportion of the population (min)**		
							25%	**50%**	**75%**
1	**0**	-	35.9	-	20.3	17.6	9.3	17.5	25.8
2	**8**	18.1	32.4	9.7	14.9	14.4	7.4	13.6	21.3
3	**16**	14.8	31.0	13.6	13.1	13.3	6.4	14.2	20.1
4	**24**	12.4	29.6	17.5	13.2	12.5	5.7	11.2	19.0
5	**32**	12.0	29.1	18.9	10.9	12.0	5.2	10.9	18.3
6	**32 + half stairs top-down**	8.9	29.4	18.1	12.9	12.3	5.3	10.8	19.0
7	**32 + half stairs top middle**	35.7	35.7	0.6	22.0	17.6	9.4	17.6	25.9
8	**32 + half stairs, 1 x Sky Lobby**	18.5	24.9	30.6	17.4	10.9	6.1	10.9	15.4
9	**32 + 4 Shuttle Zones**	11.7	27.5	23.4	13.3	10.7	4.6	9.2	16.7
10	**32 + 4 Shuttle Zones + 10 Stairs**	11.3	26.6	25.9	13.5	10.5	4.6	8.7	16.3
11	**32 + 4 x Sky Lobbies**	14.0	24.0	33.1	16.5	8.2	4.4	7.4	11.3

Focusing on the 8 lift scenario (Scenario 2), the last agent to evacuate came from the stairs 14.3 min after the last lift user. From Figure 40 it can be seen that only 13.3% of agents actually used a lift. Indeed no agents on floor 10 and below used a lift to evacuate (see Figure 41). This indicates that the lift system was heavily underutilised during the evacuation. This scenario cleared the top half of the building in 14.7 min representing a 26.6% decrease compared to the stair only scenario. A majority of lift users were located on the top ten floors of the building (see

Figure 41). The majority of agents who initially considered using a lift redirected to the stairs. Most of these agents (30.3%) were not prepared to wait longer to use a lift, though a small proportion (7.3%) redirected due to congestion in the lift waiting area (see Figure 40). Those who did redirect to the stairs waited on average 3.4 min in the lift waiting area. This was almost half as long as the average time that agents who used a lift waited (6.3 min) (see Table 39). Agents initially in the upper part of the building were serviced first by the lifts. In the lower part of the building there were only a small proportion of agents who considered using a lift. This explains why a lower proportion of agents redirected due to wait time expiration in both the upper and lower parts of the building (see Figure 41).



	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11
Stairs Only	49.0%	49.0%	49.3%	48.5%	63.6%	63.6%	63.1%	48.5%	50.3%	50.1%
Wait time Redirection	30.3%	26.1%	25.3%	25.3%	12.9%	11.2%	0.01%	16.4%	13.4%	1.4%
Lift User	13.3%	17.7%	20.9%	22.8%	20.7%	22.6%	36.8%	27.7%	29.2%	48.1%
Congestion Redirection	7.3%	7.3%	4.5%	3.5%	2.8%	2.6%	0.1%	7.5%	7.1%	0.4%

Figure 40: Advanced lift agent model simulation results - Overall Proportion of agent that used the stairs, lifts and redirected from the lifts to the stairs due to wait time expiration or congestion in the lift waiting area

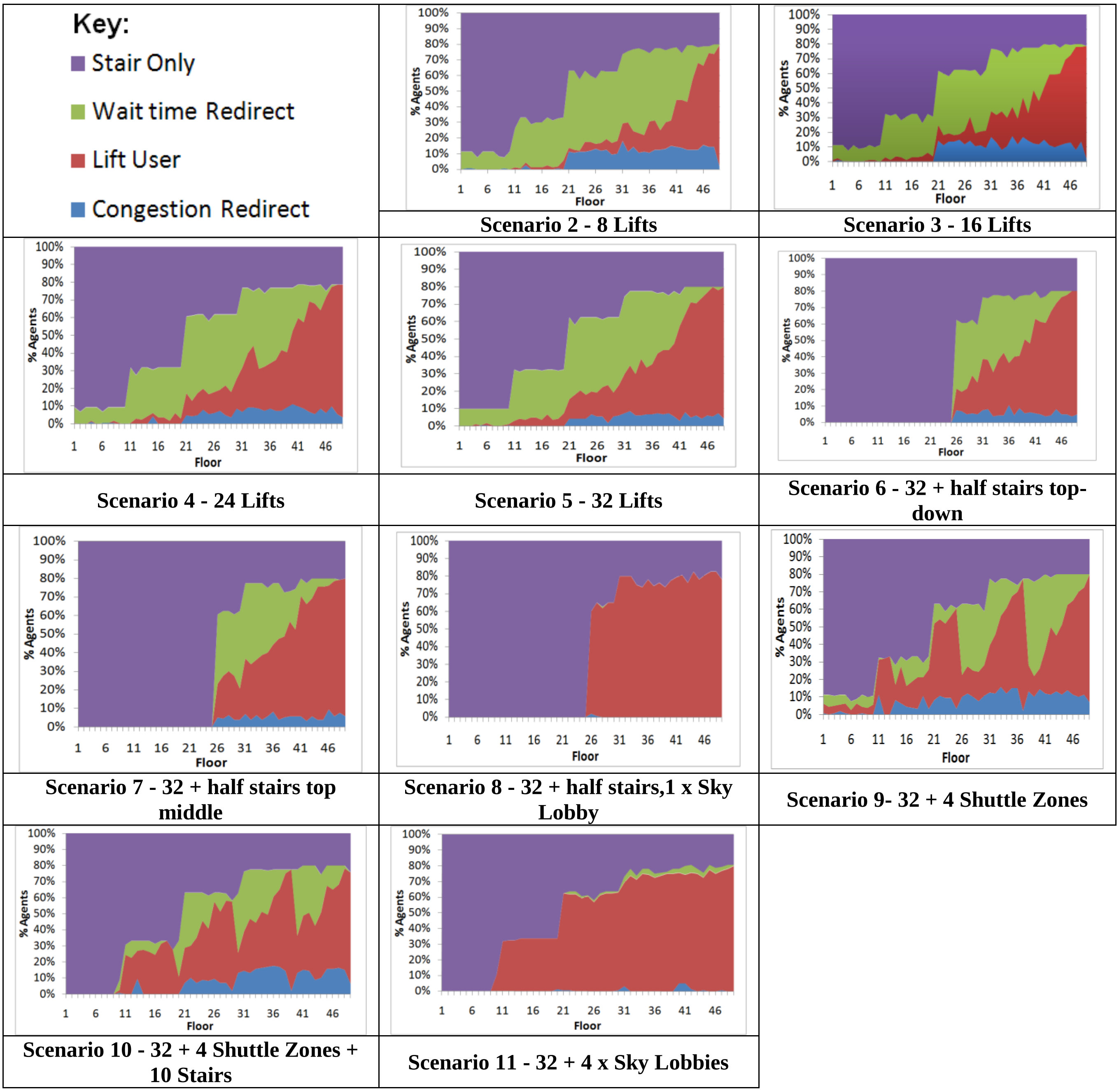


Figure 41: Advanced lift agent model simulation results - Proportion of lift agent types according to floor height

When further lift banks were included (Scenarios 3-5) only a marginal decrease in the time saved compared to the stair only scenario was recorded. In these scenarios, the decrease in TET ranged from 9.7%-17.5% compared to the stair only scenario. The time to evacuate the top half of the building was 26.6%-35.5% (5.4 min-7.2 min) shorter than the stair only scenario. The floor clearance times and evacuation rates for Scenarios 3-5 were comparable for each scenario (see Figure 42). Even though the number of available lifts increased in each scenario, the proportion of agents that used a lift only increased by 17.7%-22.8% (see Figure 40). This suggests that irrespective of the number of lifts available, using a top-down evacuation strategy for the entire building is not very effective. This is because agents are not prepared to wait long periods of time for the lift to service the majority of floors. Further to this, as the number of lifts increased, only a marginal decrease in LWT was recorded (see Table 39). In addition, agents arrived in the lift waiting areas sooner when more lift banks were used due to the decreased travel distance. This led to more agents redirecting due to wait time expiration. As expected, due to the top-down lift strategy, agents initially located on higher floors typically had shorter LWTs (see Figure 42).

Table 39: Advanced lift agent model simulation results - Average Lift Wait Time (LWT) of all agents that considered using a lift, lift users and non-lift users (agents who initially chose to use a lift but then redirected to the stairs)

Scenario	Number of lifts	Avg Lift User LWT (min)	Avg Non Lift User LWT (min)	Avg Overall LWT (min)
2	**8**	6.3	3.4	4.2
3	**16**	4.7	2.8	3.5
4	**24**	4.1	2.8	3.3
5	**32**	3.8	2.7	3.2
6	**32 + half stairs top-down**	3.2	2.1	2.7
7	**32 + half stairs top middle**	2.9	2.1	2.6
8	**32 + half stairs, 1 x Sky Lobby**	0.0	0.1	0.0
9	**32 + 4 Shuttle Zones**	3.2	2.0	2.7
10	**32 + 4 Shuttle Zones + 10 Stairs**	3.2	1.8	2.6
11	**32 + 4 x Sky Lobbies**	0.5	1.3	0.5

In Scenario 6 all agents initially in the lower half of the building used the stairs to evacuate and agents in the upper half had the option to use a lift to take them to the ground floor. Consequently an increased proportion (63.6%) of stair users were recorded compared to Scenario 5 (see Figure 40). The TET for this scenario was comparable to the 32 lift scenario (Scenario 5) at 29.4 min. In addition, the floor clearance times and evacuation rate were also similar for both scenarios (see Figure 42). Looking at Figure 41, it can be seen that very few agents in the lower half of the building used a lift in Scenario 5. As such forcing those agents to use the stairs in Scenario 6 had little impact on the TET. The time to clear the upper half of the building took 2 min longer in Scenario 6 than in Scenario 5. This reflects the increased crowding on the stairs in the lower half of the building in Scenario 6. This increased crowding was caused by agents all directly going to the stairs in the lower half of the building (in Scenario 6). Whereas in Scenario 5, almost a third of agents (28.8%) in the lower half of the building initially went to use a lift before redirecting to the stairs. This staggered their arrival time to the stairs. A comparable average LWT for lift users was recorded in Scenario 6 (3.2 min) compared to Scenario 5 (3.8 min) (see Table 39). In addition, the average LWT per floor for lift users followed a similar trend for the upper floors (see Figure 42).

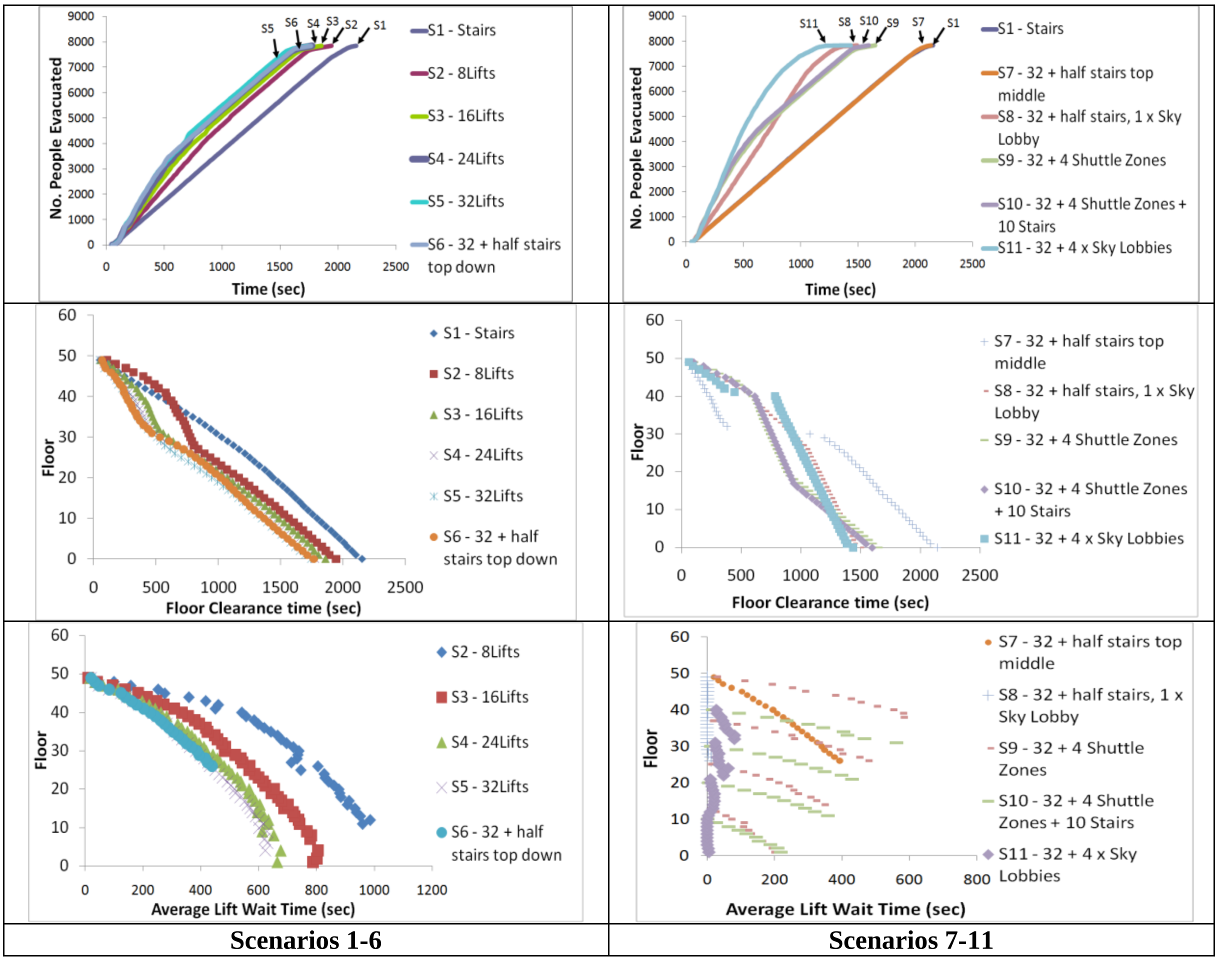


Figure 42: Advanced lift agent model simulation results for each scenario- Number of people evacuated against time (sec), floor clearance times, and average lift wait time (LWT) of agents who initially start on each floor and use a lift

Similar to Scenario 6, in Scenario 7 agents in the lower half of the building used the stairs to evacuate with agents in the upper half of the building having the option to use a lift to take them to the central floor before using the stairs to evacuate. The TET for this scenario was comparable to the stair only scenario as all agents were required to use the stairs to traverse the lower half of the building. As in Scenario 6, the impact of restricting lift usage to agents in the top half of the building had little effect on the proportion of agents that used a lift (see Figure 40). The increased number of agents entering the stairs on the central floor (from using a lift) restricted the flow of agents on the stairs coming from the upper floors. This resulted in the time to clear the upper part of the building taking marginally longer (1.7 min (8.4%)) than the stair only scenario. Due to all agents using the stairs during Scenario 7 meant that the overall evacuation rate was comparable to the stair only scenario (see Figure 42).

The single sky lobby scenario (Scenario 8) where agents in the top half of the building had the option to use a lift on the central floor, produced the second quickest evacuation with a decrease in TET of 30.6% (11 min) compared to the stair only scenario. Despite this, the time to clear the upper half of the building was only marginally less (2.9min (14.3%)) than the stair only scenario at 17.4 min. The majority of agents that considered using a lift to evacuate did so (36.8%) with a small proportion redirecting to the stairs due to congestion (7.5%) or lift wait time expiration (16.4%) (see Figure 40 and Figure 41). This was caused by the staggered arrival of agents to the sky lobby as they were required to initially traverse the stairs. This meant that very few agents experienced high levels of congestion in the lift waiting area. This was further contributed to by there being four lift banks available on the sky lobby floor about which agents on the floors above could spread. In addition, due to the lifts only servicing two floors (sky lobby floor and the ground floor), agents did not have to wait a long time for the lifts (see Table 39). As such this scenario produced one the shortest average LWTs. Lift users initially located on or near the sky lobby floor had to wait the longest as they were among the first to arrive in the lift waiting areas (see Figure 42).

In Scenario 9, four shuttle zones were employed and each agent had the option to use a lift on their current floor. The TET for this scenario reduced to 26.6 min, some 25.9% faster than the stair only scenario. It took a similar period of time (13.3 min) to evacuate the top half of the building compared to the 24 and 16 lift scenarios. However, this strategy was the third quickest scenario to evacuate 50% of agents before decreasing to the fourth quickest scenario overall (see Table 38 and Figure 42). This signifies that the initial evacuation efficiency using this strategy is reasonable but becomes increasingly inefficient towards the end of the evacuation with the last stair user evacuating some 15.8 min (59.4% longer) than the last lift user. Again this highlights that the lifts were underutilised towards the end of the evacuation with just over a quarter (27.7%) of agents using a lift to evacuate with 23.9% redirecting to the stairs (see Figure 40). From Figure 41 it can be seen that more agents initially located on higher floors within a shuttle zone used lifts. This was because agents initially located on lower floors within each shuttle zone had to wait longer for a lift to service their floor and so were more likely to redirect to the stairs due to wait time expiration. The overall proportion of agents that redirected due to congestion whilst not being very high (7.5%) was the highest recorded for all scenarios. This was contributed by the fact that there was only a single lift bank available on each floor which caused the increased levels of congestion in each lift waiting area. Comparable LWTs with Scenario 6 for both the lift users and non-lift users were also recorded.

Scenario 10 extended the concept employed in Scenario 9 by requiring agents on the bottom 10 floors to use the stairs with the remaining floors being partitioned into four shuttle zones. Very few agents elected to use a lift to evacuate on the bottom 10 floors in Scenario 9 (see Figure 41). As such forcing them to use the stairs in Scenario 10 was of little consequence to those agents (see Table 41). However, this did mean that the remaining shuttle zones had fewer floors; only having 10 instead of 12 floors. Despite this, only a marginal decrease in TET by 3.3% (0.9 min) (see Table 38) was observed compared to Scenario 9.

The four sky lobby scenario (Scenario 11) produced the shortest TET (24.0 min) of all scenarios, representing a 33.1% decrease compared to the stair only scenario (see Table 38). Almost all agents who considered using a lift did so (see Figure 40). The time to evacuate the top half of the building was only 18.7% (3.8 min) shorter than the stair only case. The overall evacuation efficiency had more agents evacuated at any point than in any other scenario (see Table 38 and Figure 42). However, the efficiency decreased considerably towards the end of the evacuation. As with the SLAM scenarios, this was contributed to by agents being evacuated faster on the lower sky lobbies due to the decreased lift travel distance. As such those lifts were unused towards the end of the evacuation. In addition, contraflow occurred on the sky lobby floors around the stair entrances. In these locations one flow of agents were attempting to enter the sky lobby (intending to board a lift) whilst others were redirecting to the stairs. Both of these factors caused a decrease in evacuation efficiency.

In all scenarios, agents using the stairs were the last to evacuate with differences between the last lift user and stair user evacuation time ranging between 0.1 min (Scenario 7) to 20.5 min (Scenario 6). This suggests that the lifts were underutilised and that if more agents used the lifts then further decreases in TET could be achieved.

6.6.3 Comparison of the SLAM and ALAM scenarios

The summary results for each scenario using the SLAM and ALAM have been reproduced in Table 40.

Table 40: Comparison of SLAM (S) and ALAM (A) scenario summary results

Scenario	Number of lifts	Agent Model	Evacuation time of last lift user (min)	Evacuation time of last stair user (min)	% Time saved (compared to stairs only)	Time to evacuate top half of building (floor ≥26)	Avg PET (min)	Time taken to evacuate proportion of the population (min)		
								25%	50%	75%
1	0	S/A	-	35.9	-	20.3	17.6	9.3	17.5	25.8
2	8	A	18.1	32.4	9.7	14.9	14.4	7.4	13.6	21.3
		S	71.1	-	-100.0	41.2	40.8	24.1	43.0	58.9
3	16	A	14.8	31.0	13.6	13.1	13.3	6.4	14.2	20.1
		S	39.1	-	-8.9	22.2	22.5	13.5	23.6	32.3
4	24	A	12.4	29.6	17.5	13.2	12.5	5.7	11.2	19.0
		S	29.0	-	19.2	16.2	16.6	10.0	17.3	23.7
5	32	A	12.0	29.1	18.9	10.9	12.0	5.2	10.9	18.3
		S	23.2	-	35.4	12.9	13.3	8.1	13.9	18.8
6	32 + half stairs top-down	A	8.9	29.4	18.1	12.9	12.3	5.3	10.8	19.0
		S	13.4	18.6	48.2	12.3	8.6	5.0	8.5	11.9
7	32 + half stairs top middle	A	35.7	35.7	0.6	22.0	17.6	9.4	17.6	25.9
		S	35.4	33.1	1.4	12.3	17.6	9.3	17.6	25.8
8	32 + half stairs, 1 x Sky Lobby	A	18.5	24.9	30.6	17.4	10.9	6.1	10.9	15.4
		S	18.8	18.7	47.6	17.7	9.6	5.5	9.7	13.8
9	32 + 4 Shuttle Zones	A	11.7	27.5	23.4	13.3	10.7	4.6	9.2	16.7
		S	23.5	-	34.5	22.4	10.2	5.7	9.9	13.9
10	32 + 4 Shuttle Zones + 10 Stairs	A	11.3	26.6	25.9	13.5	10.5	4.6	8.7	16.3
		S	20.0	7.3	44.3	18.7	8.1	4.2	7.2	11.7
11	32 + 4 x Sky Lobbies	A	14.0	24.0	33.1	16.5	8.2	4.4	7.4	11.3
		S	18.3	7.3	49.0	17.1	7.2	3.8	6.4	9.9

The TETs produced by the ALAM were 54.4% (38.7 min) and 20.7% (8.1 min) shorter for Scenarios 2 and 3 than produced by the SLAM respectively. However, the TETs produced by the ALAM in Scenarios 4 and 5 were 2.1% (0.6 min) and 25.4% (5.9 min) longer than those produced by the SLAM respectively. Closer inspection of Scenarios 4 and 5 shows the ALAM to evacuate the first 75% of agents quicker than the SLAM. The decrease in performance towards the end of these scenarios using the ALAM was due to the decreased evacuation rate by stair users. However, the SLAM scenarios increased evacuation efficiency towards the end of the evacuation due to the shorter distance the lifts were required to travel whilst servicing the lower floors.

In Scenario 6, there was a 58.1% (10.8 min) increase in the TET using the ALAM compared to using the SLAM. This increase in TET using the ALAM was caused by agents using the stairs with the last lift user evacuating some 20.5 min before the last stair user. Closer inspection of the floor clearance curves shows the top half of the building was cleared in approximately the same length of time using the ALAM and SLAM. However, the time to clear the lower half of the building in the ALAM took considerably longer. This was because as an increased number of agents elected to use the stairs from the upper half of the building. Agents that used a lift in the ALAM scenarios, on average waited almost half the time (48.5% (3.2 min)) for a lift compared to those agents in the SLAM scenarios (6.2 min) (see Figure 40).

Similar to Scenario 6, Scenario 7 employed lifts to evacuate agents to the central floor of the building. Results produced by both the ALAM and SLAM were similar in terms of TET, evacuation rate and proportion of time saved compared to the stair only scenario. However, the upper half of the building took 44.1% (9.7 min) less time to clear using the SLAM compared to using the ALAM. This was caused by some agents using the stairs instead of the lift in the upper part of the building in the ALAM scenarios. Due to agents having the option to redirect from the lifts in the ALAM, meant the average LWT for lift users was considerably less (1.9 min (39.5%)) compared to the average LWT using the SLAM (see Table 41).

Table 41: Comparison of SLAM and ALAM - Average Lift Wait Time (LWT) of all lift users

Scenario	Number of lifts	AVG Lift User LWT (min)	
		ALAM	SLAM
2	**8**	6.3	36.1
3	**16**	4.7	19.5
4	**24**	4.1	15.1
5	**32**	3.8	12.0
6	**32 + half stairs top-down**	3.2	6.2
7	**32 + half stairs top middle**	2.9	4.8
8	**32 + half stairs, 1 x Sky Lobby**	0.0	0.0
9	**32 + 4 Shuttle Zones**	3.2	10.2
10	**32 + 4 Shuttle Zones + 10 Stairs**	3.2	6.8
11	**32 + 4 x Sky Lobbies**	0.5	0.8

Results produced by the single sky lobby case (Scenario 8) show the TET to decrease by almost a quarter (6.1 min (24.5%)) using the SLAM compared to the ALAM. The last lift user in both models evacuated at approximately the same time with the top half of the building also taking approximately the same amount of time to evacuate with both models. The evacuation rate remained almost linear for the majority of the evacuation in both models. However, as with other scenarios, the decreased performance caused by stair users initially on the upper floors of the building using the ALAM extended this overall evacuation time. The average LWT of lift users in both models was approximately the same due to very few agents redirecting to the stairs from the lifts on the sky lobby floor using the ALAM (see Table 41).

Scenario 9 introduced the concept of shuttle zones where each lift bank serviced a given set of floors or zone. The overall TET for the ALAM was marginally longer (17.0% (4 min)) than the SLAM. However, the first 50% of agents that evacuated did so in a similar amount of time (Table 40). The evacuation rate in both models decreased towards the end of the evacuation though the causes are different for each model. The SLAM inefficiency was caused by the lifts having to travel further whilst servicing the agents in the top zone. The ALAM inefficiency was caused by stair users initially located in the upper parts of the building having to travel further. The time to clear the upper half of the building was 40.6% (9.1 min) shorter using the ALAM due to both the stairs and lifts being utilised in the upper part of the building. The average LWT for lift users was 68.6% (7 min) shorter using the ALAM. This is reflective of the decreased proportion of agents using the lifts (27.7%) and the adaptive behaviour represented (see Table 41).

Similar to Scenario 9, Scenario 10 employed 4 shuttle zones with agents in the bottom 10 floors being required to use the stairs to evacuate. As previously mentioned, using the ALAM there was little difference between Scenarios 9 and 10. This was because very few agents elected to use a lift on the bottom 10 floors. In contrast, using the SLAM a decrease in TET compared to Scenario 9 was recorded. This was due to each shuttle zone containing less floors and all agents being forced to use the lifts on those floors. The last agent to evacuate using the SLAM was a lift user coming from the last floor served (floor 40) in the upper zone. As previously mentioned in Scenario 9, in both the ALAM and SLAM the evacuation rate decreased towards the end of the evacuation for different reasons. For the ALAM this was caused by stair users. For the SLAM this was caused by lift users. The average LWT for lift users in the SLAM scenario was over twice as long (52.9% (3.6 min)) to that of lift users in the ALAM scenario.

In the final scenario four sky lobbies were used with the bottom 10 floors using the stairs (Scenario 11). The TET using the SLAM was 23.8% (5.7 min) shorter than using the ALAM. However, the evacuation rate for the first 75% of agents was similar for both models. In addition, the time to evacuate the upper half of the building, the average LWT for lift users, and average

PET were similar for both models. For both models, Scenario 11 produced the quickest and most efficient evacuation rate compared to all other scenarios.

With the exception of the 8 and 16 lift scenario (Scenarios 2 and 3), the results show that the SLAM produced shorter TETs than the ALAM. Using the ALAM, the lifts were underutilised with the last evacuee in all scenarios coming from the stairs. This imbalance in lift/stair usage decreased both the TET and the evacuation rate towards the end of each scenario. Such results highlight the potential inefficiency caused by human factors upon lift evacuation strategies. Findings also suggest that certain evacuation lift strategies may be less susceptible to inefficiencies caused by human factors. Results suggest that the combined use of stairs and sky lobbies/zoning, that stagger the arrival of occupants to the lift waiting areas and/or reduce lift wait times, produce higher evacuation rates by comparison to top-down strategies.

The comparison of scenarios results using each model has demonstrated that lift human factors can have a considerable effect upon overall evacuation dynamics. The extent to which this influence occurs is highly dependent upon the evacuation lift strategy employed. The results suggest that using lifts can offer potential benefits of speeding up an evacuation by as much as half assuming non-adaptive occupant behaviour. However, factoring in adaptive occupant behaviour suggests a decrease by around a third is more realistic. It is proposed that with suitable orchestration of building occupants (e.g. by fire safety personnel, training, etc), further reductions in total evacuation times may be possible.

6.7 Concluding remarks

The aim of this chapter was to demonstrate the potential influence of different evacuation lift strategies and how such strategies may be influenced by human factors. Results pertaining to a series of full building lift evacuation scenarios employing a variety of evacuation lift strategies have been presented. Each scenario was run using a Simplified Lift Agent Model (SLAM); assuming all agents that could use a lift did so, and also using an Advance Lift Agent Model (ALAM); including lift human factors data collected from the online survey presented in Chapter 4.

Results using the SLAM, suggest that the speed-up in evacuation performance is not necessarily linear with increasing number of lifts. Using a lift only strategy in which each lift visits each floor, the total evacuation time can be reduced by 35.4% and the time to clear the top half of the building reduced by 36.4% using 32 lifts compared to a stair only strategy. A more efficient evacuation strategy involves using lifts in conjunction with stairs. If 32 lifts are used to clear the top half of the building while the agents in the lower half of the building utilise the stairs, the building can be emptied 48.2% faster compared to a stair only strategy. The time to empty the top half of the building is reduced by 39.4% compared to the stair only case. ***The most efficient overall strategy (in terms of evacuating the most agents at any given time) involved using all lifts arranged into four sky lobbies where agents on the lower floors used the stairs. Within each sky lobby zone agents initially use the stairs to descend to the sky lobby where they board a lift that takes them directly to the exit level. In this case the building could be evacuated approximately 50% faster than the stair only case and the upper half of the building could be emptied 15.8% faster than the stair only case***. While the upper half of the building took 39.0% longer to clear than in the case where the lifts were used to evacuate only the top half of the building, this case produced the highest egress rate. Due to the lower sky lobby lifts having less further to travel, meant that those lifts finished evacuating the lower floor agents much sooner than the upper floor sky lobby lifts. This meant that the efficiency of the evacuation rate during this scenario decreased towards the end of the evacuation. Once the lower floor sky lobby lifts have finished servicing their floors, if they were utilised to assist evacuating agents from the upper floor sky lobbies, this could reduce the influence of this inefficiency.

As shown in the literature review, previous studies have shown that the combination of both lifts and stairs can reduce total evacuation times by as much as a half compared to stairs alone [Pauls, 1977; Klote, et al., 1992; Wong, et al., 2005; Bukowski, 2010]. This is similar to that found by the SLAM results employing different evacuation lift strategies combined with stair usage. In the cases presented in the literature review and the SLAM results, deterministic and non-adaptive agent behaviour was used. ***Considering the ALAM results, where agent behaviour was adaptive and empirically based, suggest that the approximate 50% reduction in evacuation time with the combined use of stairs and lifts is optimistic. Considering adaptive lift human factors, the greatest decrease in evacuation time recorded was by approximately a third using both lifts and stairs compared to the stairs only. Results suggest the human factors can considerably decrease the efficiency of a lift evacuation and alter underlying evacuation dynamics. The extent of this influence is dependent on the lift strategy employed.*** The predominant cause of the inefficiency was by the underutilisation of the lift system. In the majority of scenarios using the ALAM, the predominant cause of agents redirecting to the stairs from the lift was due to wait time expiration. The results suggests that if more occupants would consider waiting in crowds for longer in the lift waiting area, the efficiency of the evacuation could be improved with more agents using the lifts. ***Certain lift evacuation strategies have been shown to be less susceptible to decreases in efficiency due to the simulated human factors. These include lift evacuation strategies where sky lobbies and shuttle zones were employed that either disperses the arrival time of agents to the lift waiting areas and/or decrease the levels of congestion in the lift waiting areas.***

The presented evacuation analysis has demonstrated the ability of the developed model to represent a variety of lift evacuation strategies and associated human factors. This model might be used as part of an engineering analysis, comparing procedural variants that include lift use. Based on the analysis presented here, a number of operational and human factors affecting an evacuation using lifts have been suggested. Further investigation is required to assess the extent to which the results are generally applicable. Indeed the presented analysis can be used to guide such future investigation.

Chapter 7 - Escalator Human Factors

7.1 Introduction

A number of studies have collected escalator human factors data [Fruin, 1971; Cheung and Lam, 1998; Davis and Dutta, 2002; Okada, et al., 2009; Kadokura, et al., 2009; Zeiler, et al., 2010; Knehs, 2010]. Typically such studies have focused on individual characteristics of specific behaviours (e.g. walker speeds, flow-rates, etc). Indeed no studies were found where a variety of escalator human factors were analysed. As such it is uncertain how different escalator human factors interact or influence other types of behaviour. It is also uncertain whether such escalator human factors are unique to the countries where the studies were conducted.

To address these issues, escalator human factors data within three underground stations were collected. Each station was located in a different country; Spain, China and England. The data was collected during normal circulation conditions using personal video cameras and existing CCTV (Closed Circuit Television) systems already in each location. The data has been used to instruct the development of the evacuation agent escalator model presented in the proceeding chapter. As mentioned in the literature review, previous studies [Galea, et al., 2006a; Donald and Canter, 1990] have noted that pedestrians have exhibited typical circulation behaviour on escalators during actual evacuations. As such it is suggested that escalator human factors are broadly comparable between circulation and evacuation situations.

The data collected relates to escalator/stair usage, walker/rider usage, side usage, walker speeds and flow-rates. The chapter presents definitions and methodology of each data item along with a description and analysis of each dataset. A comparison between each dataset and data presented in previous studies has also been conducted.

7.2 Definitions and methodology

The following sections describe the methodology of how each data item was collected from the video footage. All video footage was collected by third party groups/companies under the guidance of the Fire Safety Engineering Group (FSEG) at the University of Greenwich. The Spanish footage was collected by Autoritat del Transport Metropolità (ATM) and Ferrocarrils de la Generalitat de Catalunya (FGC) (located in Barcelona). The Chinese footage was collected by the Shanghai Institute of Disaster Prevention and Relief (SIDPR) at Tong Ji University (located in Shanghai). The English footage was collected by Kingfell Ltd (located in London).

7.2.1 Escalator/Stair usage

When pedestrians approach a combination of escalators and stairs, they are required to make a choice as to which device they will use to traverse to the next level. To better understand this process, the number of pedestrians that used each escalator/stair has been recorded for each of the datasets collected.

It was relatively simple to count pedestrians using each escalator given their limited capacity (i.e. the width of each escalator typically only accommodated 2 pedestrians at any one time). For wide stairways (e.g. in the Chinese dataset), keeping track of each pedestrian during busy periods became more challenging. This increased the likelihood of counting pedestrians multiple times. To minimise this inaccuracy, pedestrians were only counted just before they moved out of view of the camera. Frame by frame analysis of the video footage was also performed in order to further minimise this inaccuracy. Despite such mitigating techniques, it is accepted that there may be some error in the counting process.

7.2.2 Walker/Rider usage

When pedestrians board an escalator, they either ride, walk or ‘ride and walk’ on the escalator. The frequencies of pedestrians who rode or walked the entire length of the escalator were recorded. Pedestrians who walked and rode have not been included in the analysis given that they were relatively rare (e.g. less than 1.0% were observed). As such it was considered not to be required to be represented within a simulated environment due to its expected minimal influence.

7.2.3 Side usage

When pedestrians board an escalator, they adopt a side/position of the escalator to use: left, right, centre or sometimes pedestrians change sides as they move along an escalator. As observed in previous studies, in certain locations escalator users adopt a ‘common side preference’ whereby walkers and riders use opposite sides of an escalator. The side/position that each escalator users adopted was recorded.

7.2.4 Walker speeds

The walker speeds of the pedestrians that walked the entire length of the escalator and who were unimpeded were recorded. Here, ‘unimpeded‘ means that no other pedestrians were immediately in front of the chosen pedestrian (at least approximately 5 steps) for the entire length of the escalator journey and they did not appear to stop/pause whilst on the escalator.

The walker speed was recorded from the time the walker placed their first foot on an escalator tread until the time they placed their first foot on the ground when alighting the escalator. In some circumstances due to restricted visibility the feet of pedestrians could not be seen. Here, an approximation was carried out based on the upper body position and gait of the pedestrian when they walked on/off the escalator. For each dataset, examples of pedestrians boarding/alighting escalators can be seen in Figure 43. Walker speeds were calculated using the horizontal distance of each escalator less the speed of the escalator (i.e. the horizontal walker speeds of the pedestrians were recorded).

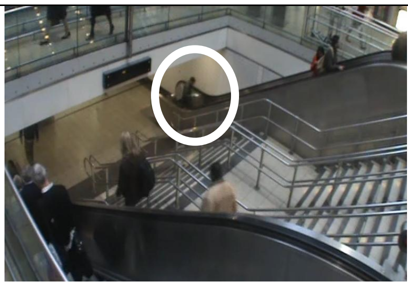
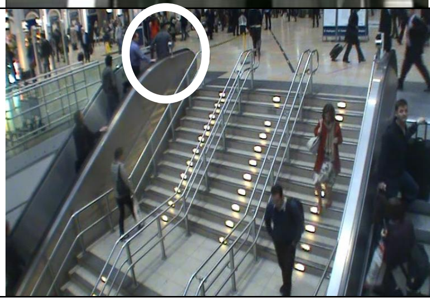
	Boarding	Alighting
Spain		
China		
England		

Figure 43: Boarding/Alighting time examples

7.2.5 Flow-rates

The time at which all escalator users boarded/alighted an escalator was recorded. There are two types of flow-rates associated with escalator usage. The entry flow-rate represents the number pedestrians that board an escalator over a period of time. The exit flow-rate represents the number of pedestrians that alight an escalator over a period of time. With regards to restricted pedestrian visibility, the same principles apply as with recording walker travel speeds where an approximation of escalator users boarding/alighting times were made.

The measured flow-rates included all pedestrians who walked or rode the entire length of each escalator. It should be reiterated that the small number of pedestrians that both walked and rode on an escalator were not included in the analysis. Since a small number of pedestrians exhibited this behaviour it is expected to have a very little influence upon the results.

7.3 Analysis of Spanish data

The Spanish data was collected in the Provença station, Barcelona, Spain. The station itself is located in the very centre of the city and consequently it is used by a large number of people every day for travelling about the city. The station currently services two tube lines (Line 6 and Line 7) that run on the same track from East to West of the city. In addition the station is linked to another station called Diagonal which services a further track, namely Line 3 (though this station was not analysed in this investigation).

The footage of two separate escalators was collected: an up and down escalator. The CCTV (Closed Circuit Television) security camera system already in place at the station was used to capture the video footage. The cameras were located at the top of each escalator, providing for an elevated, frontal, full-length view of each escalator (see Figure 44). This provided a means to observe the full-length of each escalator. However, when people traversing the escalator were at the top, this obstructed the view of the rest of the escalator. This meant the alighting/boarding times of pedestrians behind the obstructing pedestrians could not be recorded.

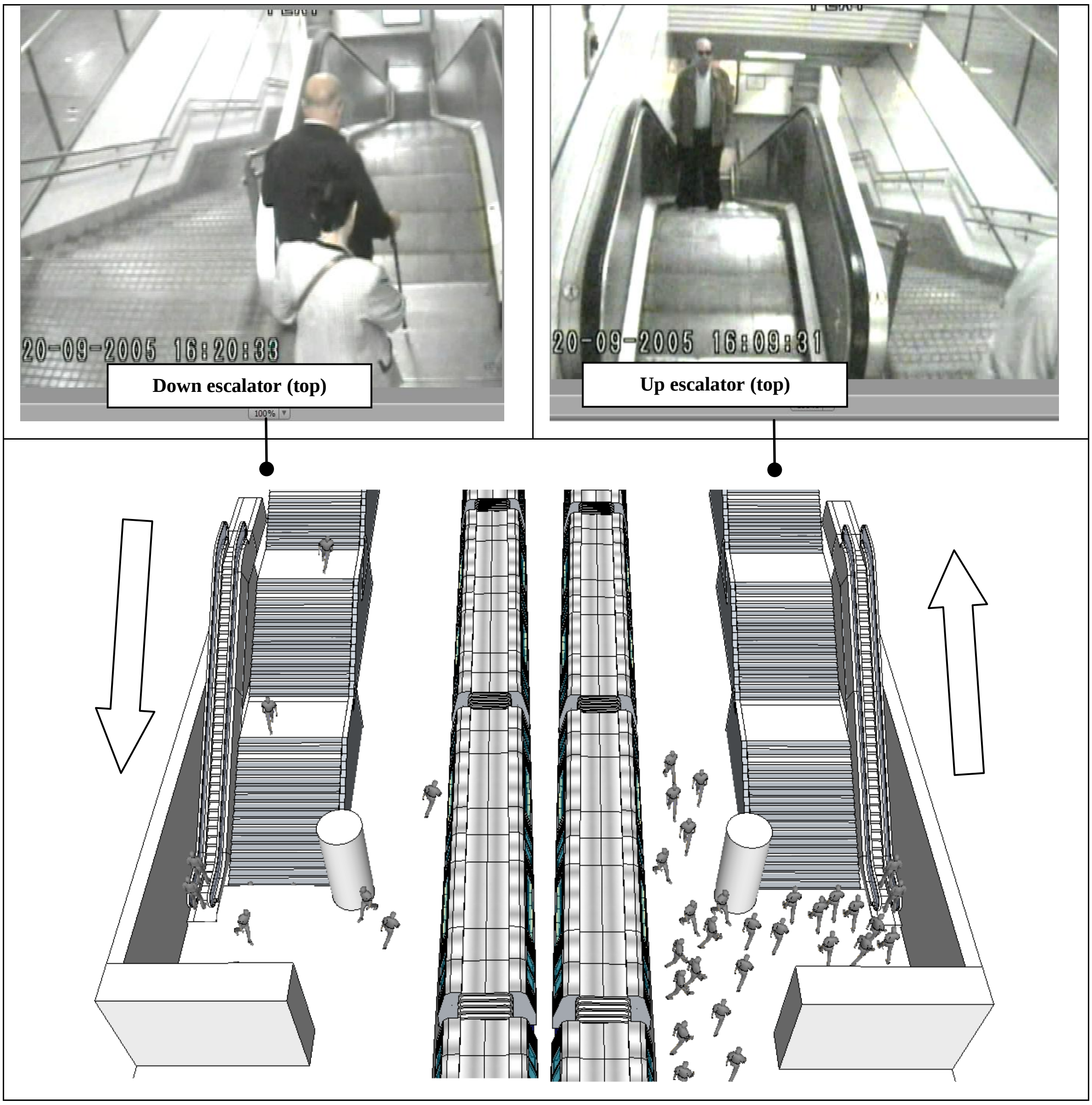
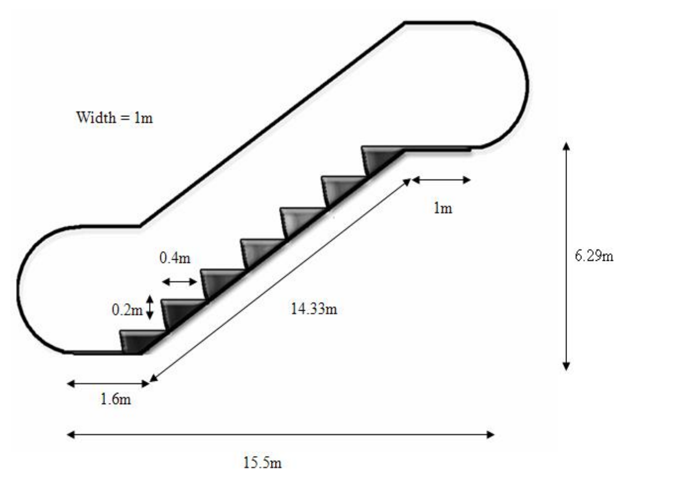
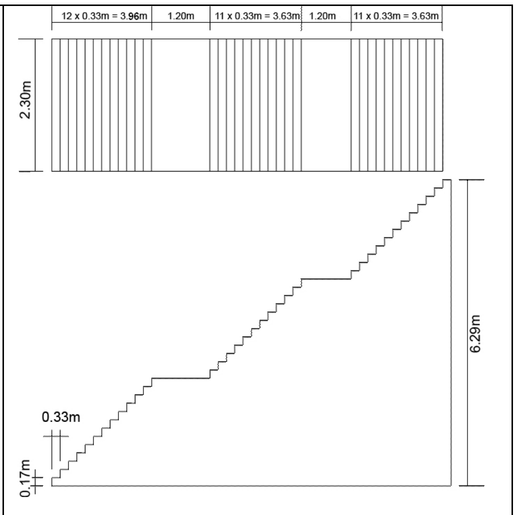


Figure 44: Spanish Data - The location of the two escalators and camera positions (diagram not to scale)

Each escalator had a horizontal speed of 0.5 m/s and the total length of each escalator was calculated at 17.0m (horizontal length 15.5m, height 6.29m) (see Figure 45). The up escalator links the platform level to the lobby level of the underground station. It provides a means for pedestrians who arrive on incoming trains to traverse to the lobby level. The platform is single sided with trains only arriving on one side of the platform. Subsequently pedestrians on the platform level can only approach the escalator/stair from the stair side. The down escalator links the lobby level to the platform level of the underground station. It provides a means for pedestrians arriving from outside the station to traverse to the platform level to board incoming trains. As with the up escalator, pedestrians could only approach the down escalator from the stair side. The stairs that run parallel with both escalators provide an alternate means to traverse the vertical area. Each escalator was recorded during a rush-hour and non-rush hour period. One camera was used for each escalator (at the top of the escalator) and recorded for 30 minutes each (the total amount of footage collected was 4 x 30min = 120 min/2 hours).



A: Escalator dimensions



B: Stairway dimensions

Figure 45: Spanish Data - Escalator (a) and Staircase (b) dimensions

In total, 590 escalator users were recorded using the up escalator: 404 during the rush-hour and 186 during the non-rush hour (see Table 42). In addition, 92 pedestrians using the adjacent stair were recorded. Irrespective of time period a similar proportion of males and females were recorded (see Table 42). Pedestrians were categorised according to a given age range based on appearance. Of all pedestrians, 0.51% (3) appeared to be children (i.e. appeared to be below 12 years old) and 4.58% (27) appeared to be over 60 years old. The remaining 94.92% (560) appeared to be aged between 12-60 years old (see Table 42).

Table 42: Spanish Data - Frequency/proportion of participants according to gender, age group, and time period for the up escalator

		Age Ranges			**Totals**	
		<12 yrs % [Freq]	**U60 yrs % [Freq]**	**>60 yrs % [Freq]**	**Gender Total % [Freq]**	**Period Total [Freq]**
Rush-hour	**Males**	0.5 [1]	44.8 [181]	1.6 [3]	45.8 [185]	404
	Females	0.9 [2]	53.0 [214]	1.4 [3]	54.2 [219]	
Non-rush hour	**Males**	0.0 [0]	41.4 [77]	12.5 [10]	47.3 [88]	186
	Females	0.0 [0]	47.3 [88]	10.2 [9]	52.7 [98]	
Total		0.5 [3]	94.9 [560]	4.6 [27]	590	

In total, 366 escalator users were recorded using the down escalator: 252 during the rush-hour and 114 during the non-rush hour (see Table 43). In addition, 169 pedestrians using the adjacent stair were recorded. There were slightly more females than males recorded during both periods (the rush-hour and non-rush hour) on the down escalator (see Table 43). Of all pedestrians recorded, 11.2% (41) appeared to be children (i.e. appeared to be below 12 years old) and 3.01% (11) appeared to be over 60 years old. The remaining 85.8% (560) appeared to be aged between 12-60 years old (see Table 42).

Table 43: Spanish Data - Frequency/proportion of participants according to gender, age group, and time period for the down escalator

		Age Ranges			Totals	
		<12 yrs % [Freq]	U60 yrs % [Freq]	>60 yrs % [Freq]	Gender Total % [Freq]	Period Total [Freq]
Rush-hour	Males	9.9 [25]	36.9 [93]	0.0 [0]	46.8 [118]	252
	Females	6.4 [16]	45.6 [115]	1.2 [3]	53.2 [134]	
Non-rush hour	Males	0.0 [0]	32.5 [37]	3.5 [4]	36.0 [41]	114
	Females	0.0 [0]	60.5 [69]	3.5 [4]	64.0 [73]	
Total		11.2 [41]	85.8 [314]	3.0 [11]	366	

7.3.1 Escalator/Stair usage

The number of pedestrians that used each escalator and adjacent stair was recorded for both the up and down direction in both rush-hour and non-rush hour periods (see Table 44).

In total, 535 pedestrians were recorded descending to the lower level using either the down escalator or adjacent stair. Of these, significantly more (68.4% (366)) were escalator users than stair users (31.6% (252)) (χ^2=20.7, p<0.05). Little difference can be seen between the number of pedestrians using the escalator/stair during the rush-hour and non-rush hour. (χ^2=0.05, p>0.05). This suggests that that time period has little influence upon escalator/stair usage in the down direction.

In total, 682 device users were recorded ascending to the higher level using the up escalator or adjacent stair. As in the down direction significantly more (86.5% (590)) used the escalator than the stairs (13.4% (92)) (χ^2=362.2, p<0.05). Unlike the down direction, significantly more escalator users (94.4% (186)) were recorded in the non-rush hour compared to the rush-hour period (χ^2=13.9, p<0.05). It is thought that this is influenced by the higher number of pedestrians simultaneously traversing the area during the rush-hour. This typically resulted in an increased queue length for the escalator and so a higher proportion of stair users was recorded.

Comparing each direction, overall there were significantly more escalator users (86.5% (590) in the up direction than in the down direction (68.4% (366)) (χ^2=57.2, p<0.05). This is expected considering the further benefit the up escalator provides compared to the down escalator in terms of increased speed and decreased energy expenditure.

Overall the results suggest that, irrespective of direction of travel, the majority of pedestrians strongly preferred to use the escalator rather than the stair. However, the escalator is more favoured in the up direction compared to the down direction.

Table 44: Spanish Data - Breakdown of escalator to stair users in the up and down directions during rush and non-rush hour periods

		Escalator User Frequency % [Freq]	**Stairs User Frequency % [Freq]**
Up Escalator	**Rush-hour**	83.3 [404]	16.7 [81]
	Non-rush hour	94.4 [186]	5.6 [11]
	Total	86.5 [590]	13.5 [92]
Down Escalator	**Rush-hour**	68.9 [252]	31.1 [114]
	Non-rush hour	67.5 [114]	32.5 [55]
	Total	68.4 [366]	31.6 [169]
Overall	**Rush-hour**	77.1 [656]	22.9 [195]
	Non-rush hour	82.0 [300]	18.0 [66]
	Total	78.6 [956]	21.4 [261]

7.3.2 Walker/Rider usage

In total, 956 escalator users were recorded either walking or riding for both the up and down directions during both rush and non-rush hour periods (see Table 45). From these results it can be seen that irrespective of time of day or direction of travel the most preferred method for traversing an escalator was by riding (χ^2=244.0, p<0.05). No significant difference between the number of walkers/riders in each period could be found (up (χ^2=3.3, p>0.05) or down (χ^2=0.0, p>0.05)). Similar to the escalator/stair usage data, this suggests that time of day and subsequent levels of motivation have little influence upon walker/rider choice.

Significantly more walkers were observed in the up direction compared to down direction (χ^2=45.0, $p<0.05$). It is suggested this is because pedestrians travelling up were about to leave the station. Pedestrians travelling on the down escalator only derived benefit to their journey from walking on the escalator if a train was about to arrive; otherwise they would have to wait after traversing the escalator. Such results potentially suggest that 'post-escalator action' influences escalator walker/rider choice.

Table 45: Spanish Data - Breakdown of walkers to riders in the up and down directions during rush and non-rush hour periods

		Walker Frequency % [Freq]	Rider Frequency % [Freq]
Up Escalator	**Rush-hour**	29.2 [118]	70.8 [286]
	Non-rush hour	22.0 [41]	78.0 [145]
	Total	27.0 [159]	73.0 [431]
Down Escalator	**Rush-hour**	21.0 [53]	79.0 [199]
	Non-rush hour	21.1 [24]	78.9 [90]
	Total	21.0 [77]	79.0 [289]
Overall	**Rush-hour**	26.1 [171]	73.9 [485]
	Non-rush hour	21.7 [65]	78.3 [235]
	Total	24.7 [236]	75.3 [720]

7.3.3 Side usage

In total, 956 escalator users were recorded using different positions for both the up and down directions during the rush and non-rush hour periods (see Table 46). The data suggest that there is a clear common side preference for riders to use the right side and walkers to use the left side of an escalator.

Irrespective of direction, a similar proportion of riders used the right side of the escalator in both the rush-hour (80.0%) and non-rush hour (81.4%) periods (χ^2=0.18, p>0.05). During both the rush-hour periods the side preference of 404 up escalator users was noted, of whom 70.8% (286) were riders. The majority of these riders (89.5% (256)) adopted the right side. During the non-rush hour period the side preference of 186 up escalator users were noted, of whom 78.5% (146) were riders. Of these, 87.7% (128) of the riders adopted the right position. There is no significant difference between the frequency of riders that used each position in each period on the up escalator (χ^2=0.15, p>0.05).

Table 46: Spanish Data - Breakdown of side preference for escalator users in the up and down directions during rush and non-rush hour periods

Direction	Period	Walker/Rider	Left % [Freq]	Right % [Freq]	Centre % [Freq]	Varied % [Freq]	Period Total % [Freq]	Total % [Freq]
Up	Rush-hour	Walkers	47.5 [56]	30.5 [36]	12.7 [15]	9.3 [11]	68.5 [404]	61.7 [590]
		Riders	10.5 [30]	89.5 [256]	0.0 [0]	0.0 [0]		
	Non-rush hour	Walkers	45.0 [18]	25.0 [10]	7.5 [3]	22.5 [9]	31.5 [186]	
		Riders	11.6 [17]	87.7 [128]	0.7 [1]	0.0 [0]		
	Total	Walkers	46.8 [74]	29.1 [46]	11.4 [18]	12.7 [20]	590	
		Riders	10.9 [47]	88.9 [384]	0.2 [1]	0.0 [0]		
Down	Rush-hour	Walkers	37.7 [20]	35.8 [19]	11.3 [6]	15.1 [8]	69.6 [252]	38.3 [366]
		Riders	26.1 [52]	66.3 [132]	4.0 [8]	3.5 [7]		
	Non-rush hour	Walkers	33.3 [8]	33.3 [8]	4.2 [1]	29.2 [7]	30.4 [114]	
		Riders	22.2 [20]	71.1 [64]	6.7 [6]	0.0 [0]		
	Total	Walkers	36.4 [28]	35.1 [27]	9.1 [7]	19.5 [15]	366	
		Riders	24.9 [72]	67.8 [196]	4.8 [14]	2.4 [7]		
Overall	Rush-hour	Walkers	44.4 [76]	32.2 [55]	12.3 [21]	11.1 [19]	68.6 [656]	956
		Riders	16.9 [82]	80.0 [388]	1.6 [8]	1.4 [7]		
	Non-rush hour	Walkers	40.6 [26]	28.1 [18]	6.3 [4]	25.0 [16]	31.4 [300]	
		Riders	15.7 [37]	81.4 [192]	3.0 [7]	0.0 [0]		
	Overall	Walkers	43.4 [102]	31.1 [73]	10.6 [25]	14.9 [35]	956	
		Riders	16.5 [119]	80.4 [580]	2.1 [15]	1.0 [7]		

The majority of escalator riders adopted the right position in both the rush-hour (71.1% (64)) and non-rush hour (66.3% (132)) periods in the down direction (χ^2=0.58, p>0.05). This is similar to that recorded for the up direction. This suggests that time period has little influence for up escalator side usage.

During both periods on the down escalator, it can be seen that walkers did not adopt a common side preference. An even proportion of walkers elected to use both the right and left side of the escalator. In addition, compared to the up escalator users, a lower proportion of riders were observed to adopt the common side preference of standing on the right side. The difference in side usage is perhaps caused by the smaller number of pedestrians simultaneously using the escalator in the down direction compared to the up direction. In the down direction pedestrian arrival to the escalator was more sporadic, coming from various locations. In the up direction pedestrians arrive at the escalator from single trains in higher concentrations. As such, for the down direction, many walkers and riders may not have felt it was necessary to keep to a certain side of the escalator as it perhaps did not inconvenience many other escalator users. This suggests that pedestrian behaviour on escalators may take into consideration the experience of other escalator users.

7.3.4 Walker speeds

Given that the camera views were occasionally obstructed by escalator users it was not possible to measure the speeds of all escalator walkers. In total, 52 walker speeds were recorded: 34 in the up direction and 18 in the down direction. The frequency distribution for all walker speeds can be seen Figure 46. Analysis of the walker speed frequency distributions, regardless of segregating according to sub-categories (e.g. direction of travel, time period, etc), showed each distribution not to be normal (using a Kolmogorov-Smirnov test). As such the non-parametric 2 sample Mann-Whitney U- test was used to determine if there were any significant differences between walker speeds in each category. The breakdown of average walker speeds is summarised in Table 47.

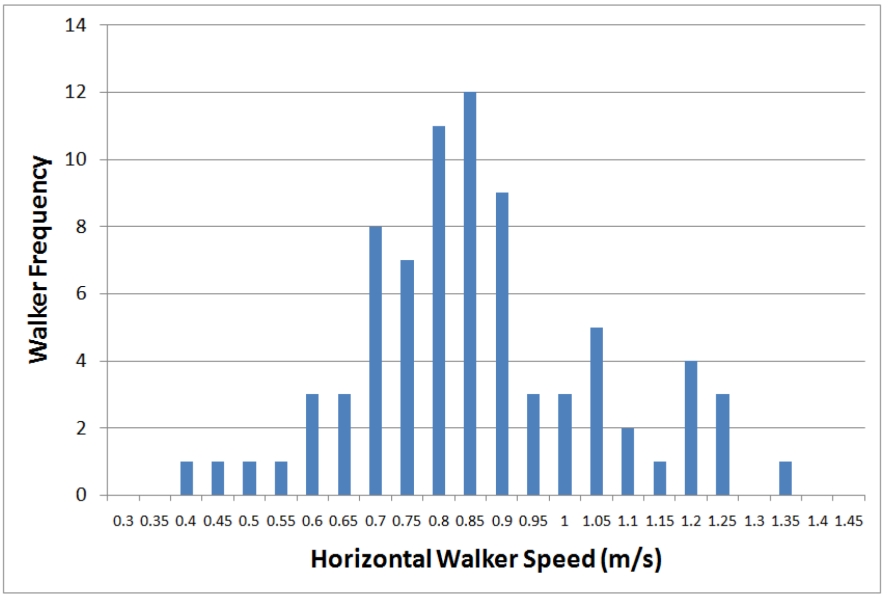


Figure 46: Spanish Data - Horizontal escalator walker speed frequency distribution (combined for direction, time period and gender)

Table 47: Spanish Data - Average horizontal walker speeds

		Down (m/s)			Up (m/s)		
	Gender	**Rush-hour**	**Non-rush**	**Overall**	**Rush-hour**	**Non-rush**	**Overall**
Average	**Males**	0.84 [0.72-1.04]	1.30 [1.16-1.51]	1.1 [0.72-1.51]	0.77 [0.51-1.39]	0.83 [0.80-0.86]	0.78 [0.51-1.39]
	Females	0.82 [0.68-1.09]	0.74 [0.59-1.00]	0.76 [0.59-1.09]	0.74 [0.50-1.19]	0.69 [0.51-0.83]	0.71 [0.50-1.19]
	Overall	0.83 [0.68-1.09]	0.89 [0.59-1.51]	0.86 [0.59-1.51]	0.76 [0.50-1.39]	0.71 [0.51-0.86]	0.74 [0.50-1.39]
Frequency	**Males**	4	3	7	13	2	15
	Females	3	8	11	9	10	19
	Overall	7	11	18	22	12	34

On average escalator users walked 16.2% (0.12 m/s) faster in the down direction than in the up direction, though this did not represent a significant difference ($p>0.05$). Segregating according to time period escalator walkers were on average observed to walk 7.2% (0.06 m/s) faster in the non-rush hour in the down direction and 7.0% (0.05 m/s) faster in the rush hour period in the up direction. No significant difference was found between walker speeds in the rush-hour and non-rush hour periods ($p>0.05$). On average males walked 44.7% (0.34 m/s) and 9.9% (0.07 m/s) faster in both the down and up direction respectively. Both were significantly faster than females ($p<0.05$).

7.3.5 Flow-rates

The entry flow-rate was recorded for the down escalator and the exit flow-rate was recorded for the up escalator. The breakdown of average, maximum and minimum flow-rates is summarised in Table 48.

Table 48: Spanish Data – Minimum, average and maximum escalator flow-rates

Period	Direction	Min (ped/min)	Avg (ped/min)	Max (ped/min)
Rush-hour flow-rate	Down (entry)	4.0	9.0	19.0
	Up (exit)	2.0	15.3	41.0
Non-rush hour flow-rate	Down (entry)	1.0	4.5	9.0
	Up (exit)	1.0	6.7	19.0
Overall	Down (entry)	1.0	6.8	19.0
	Up (exit)	1.0	11.0	41.0

Irrespective of time period, the up escalator flow-rate was on average higher than the down escalator. This would be expected as more people were typically observed simultaneously arriving (from underground trains) at any given time on the up escalator. The arrival of pedestrians to the down escalator was typically more sporadic as they were not all simultaneously coming from the same location. As such the maximum down escalator flow-rates are reflective of the dispersed arrival times to the escalator rather than the maximum achievable flow-rates being imposed by the structural dimensions of the escalator. Indeed the maximum down escalator flow-rates are considerably lower than that recorded in other studies mentioned in the literature review. In total, 10 pedestrians were observed to carry items of luggage (e.g. bags, etc) upon both escalators. The scarcity with which this occurred meant that it is expected to have little influence upon the recorded escalator flow-rates. As such analysis of escalator flow-rates according to user luggage has not been included.

The average flow-rate was 128.4% and 50.0% higher for the up and down escalators respectively in the rush-hour period than in the non-rush hour period. The highest flow-rate recorded was on the up escalator during the rush-hour at a rate of 41.0 ped/min in the twenty-sixth minute (1560-1620 seconds) (see Table 48 & Figure 47). During this period there was a high proportion of riders (95.1%) with the majority of pedestrians using the right side (82.9%). This highlights that the width of the escalator was not being fully utilised even during this period. There were a slightly higher proportion of females (56.1%) than males (43.9%).

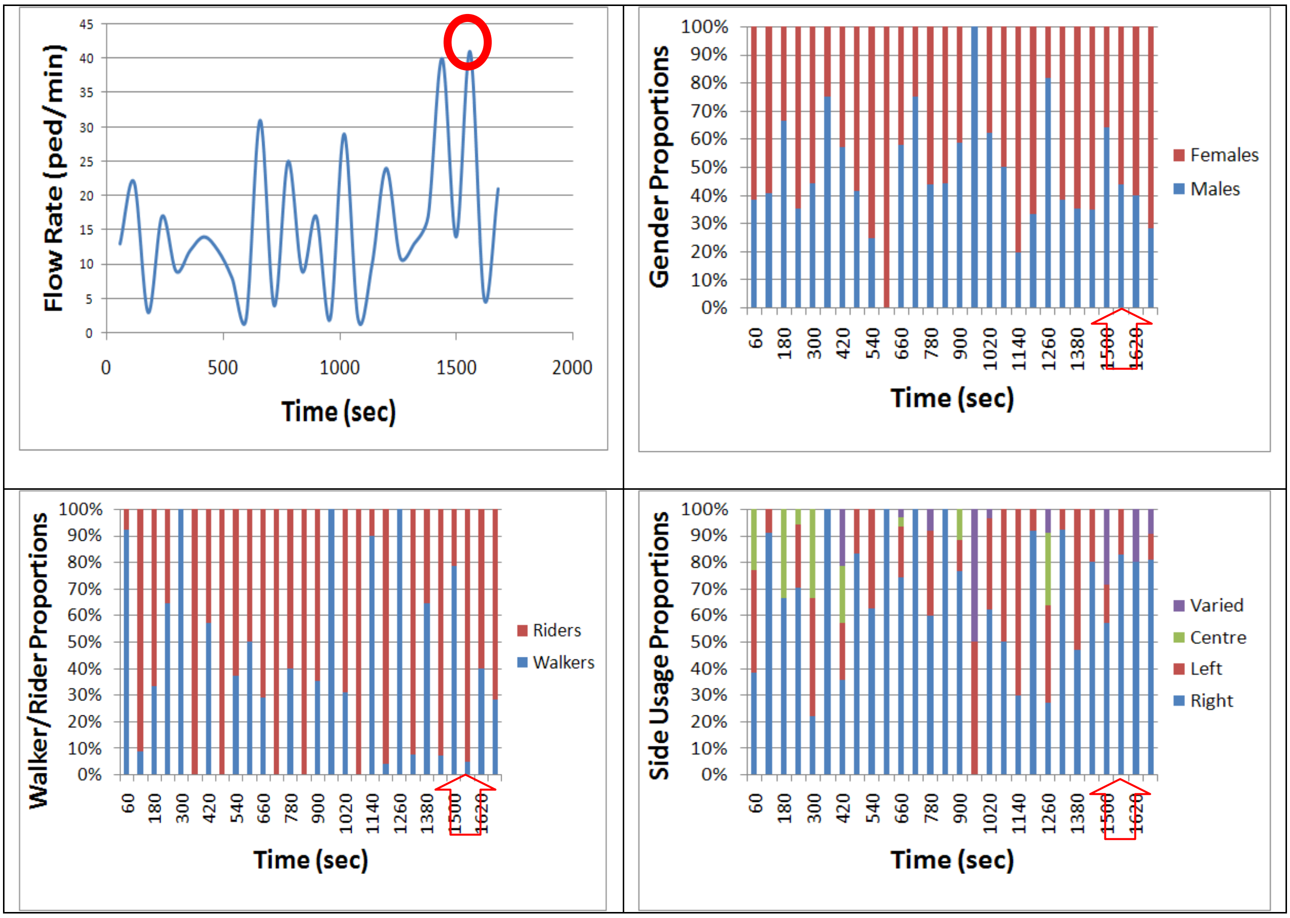


Figure 47: Spanish Data - Rush-hour up: peak flow-rate (highlighted by the red circle) with corresponding proportion of males/females, walkers/riders, and side usage (highlighted by the red arrows)

The highest entry flow-rate for the down escalator was during the rush-hour period when a flow-rate of 19 ped/min was recorded in the twenty-eighth minute (see Table 48 & Figure 48). During this period there were a high proportion of riders (89.5%) with a slightly higher proportion of participants using the right side than the left (63.2%). A similar proportion of males (52.6%) and females (47.4%) were recorded.

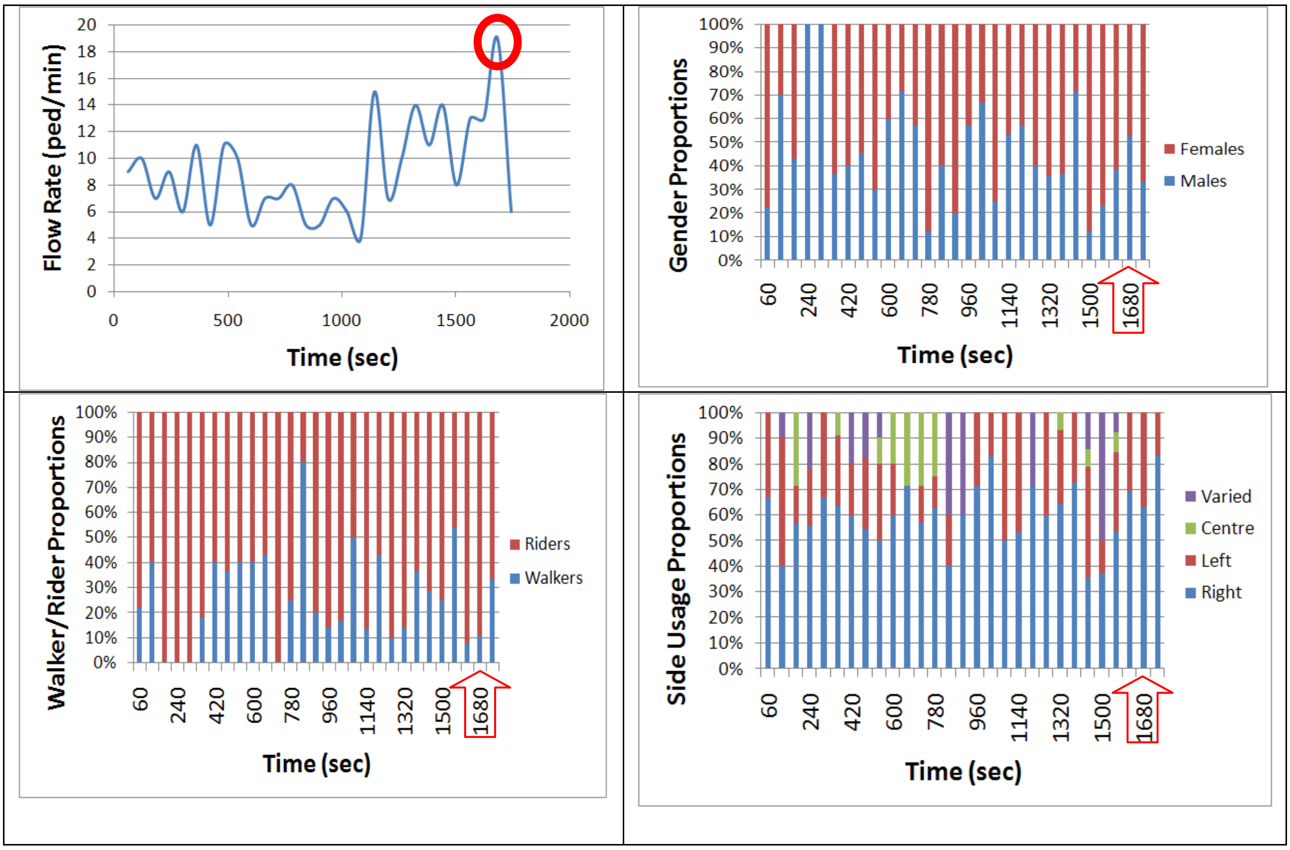


Figure 48: Spanish Data - Rush-hour down: peak flow-rate (highlighted by the red circle) with corresponding proportion of males/females, walkers/riders, and side usage (highlighted by the red arrows)

Analysis of the highest flow-rate curves suggests that the flow-rates recorded were not physically constrained by the escalators but determined by the pedestrians themselves with most pedestrians not using all available space on the escalators (i.e. using both sides and all available treads).

7.4 Analysis of Chinese data

The Chinese video footage was collected in the People's Square underground station, Shanghai, China. The station itself is located in the centre of the city and as such is located near a number of large office buildings, shopping centres and tourist attractions. Consequently it is used by a large number of pedestrians every day for travelling about the city. During peak rush-hour periods high crowd densities on the platform areas can be observed. These can exceed 1.08 ped/m² which represents Fruin's Level of Service D, described as "representing only the most crowded public areas" [Fruin, 1971]. At the time of the data collection the station serviced two tube lines (Line 1 and Line 2). Within this study, data from two identical escalators was collected at different times. Both were up escalators identified as Escalator A (recorded during the rush-hour) and Escalator D (recorded during the non-rush hour). Both escalators linked the same platform level to the above lobby level of Line 1. Local restrictions meant that data collection from equivalent down escalators was not possible.

Each escalator had an adjacent stair that provided pedestrians with an alternate means of traversal. The platform is double-sided, which means that trains arrive on both sides of the platform (going in opposite directions). Subsequently pedestrians on the platform level can approach the escalator/stair from either the stair or escalator side. This is typically dictated by which side of the platform a train arrives on. For each escalator, two personal digital video cameras were used to record the footage. Both of the escalator entrances (on the platform level) and exits (on the lobby level) were recorded (from different angles for each escalator in order to assist in obtaining different types of data (see Figure 49)). Each camera recorded footage for 1 hour for each escalator/stair (a total of 2 hours of footage for both escalators/stairs).

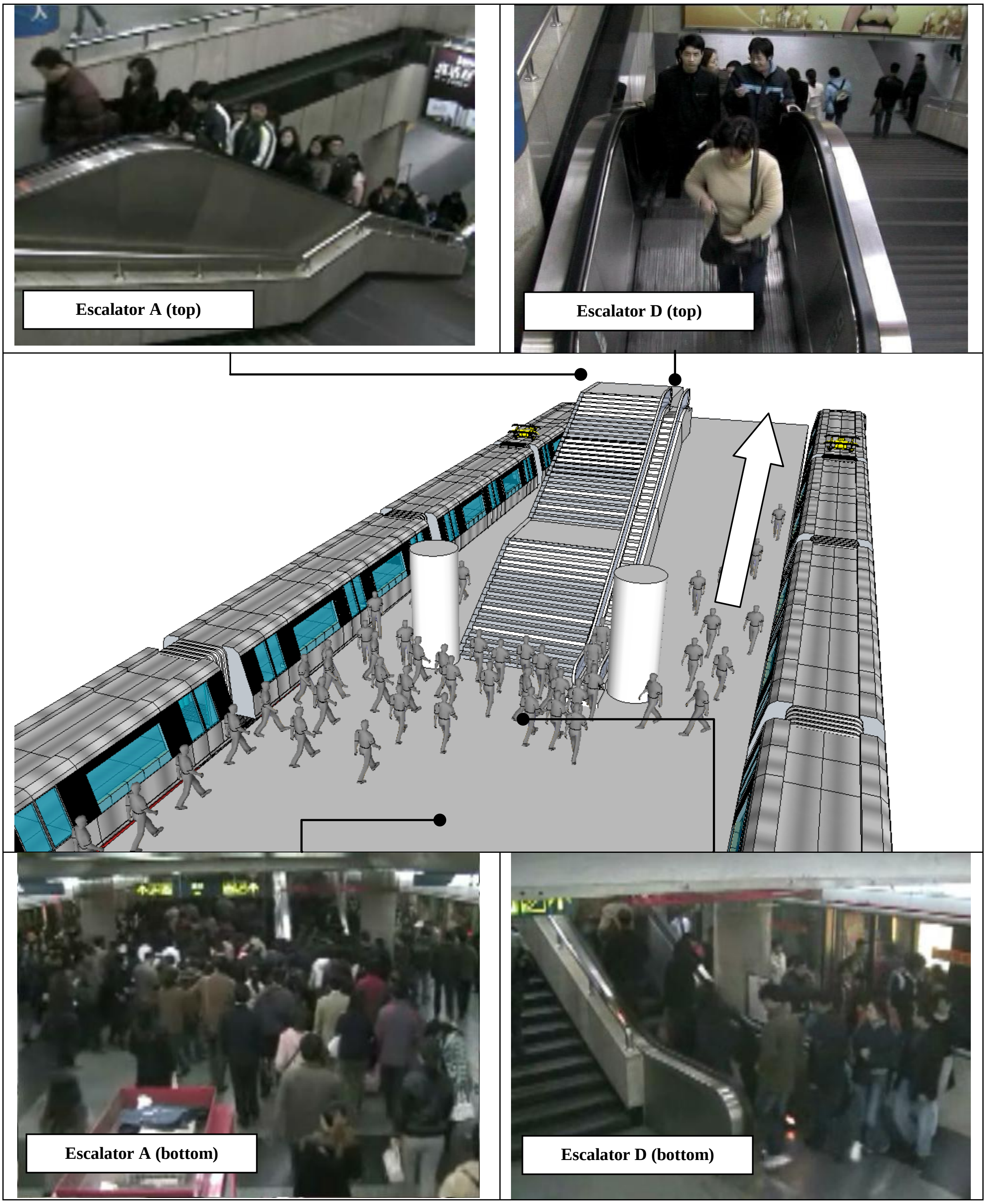
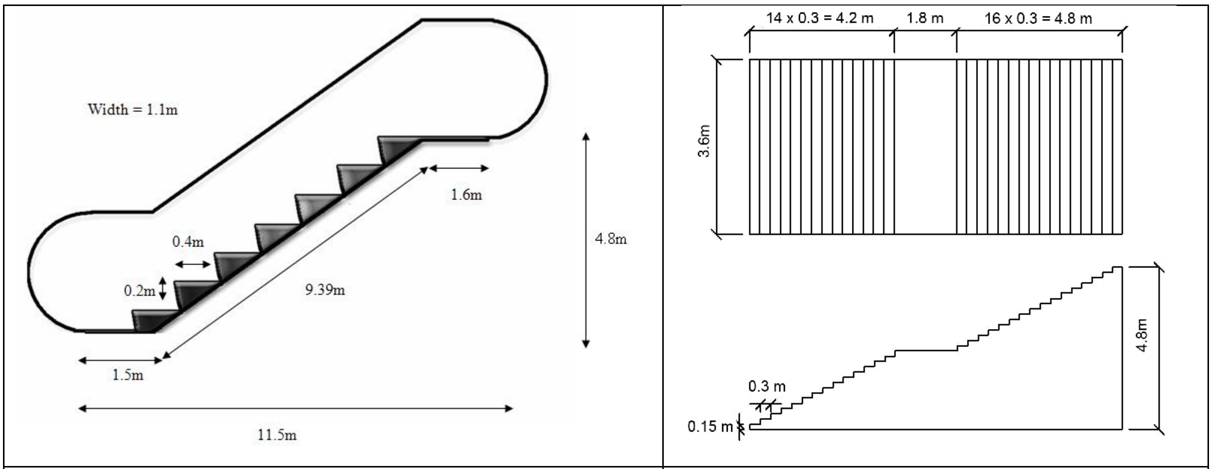


Figure 49: Chinese Data - The location of each camera for each escalator (each escalator/stair configuration was identical) (diagram not to scale)

Each escalator had a horizontal speed of 0.5 m/s. The dimensions of each escalator and adjacent stair can be seen in Figure 50.



A: Escalator dimensions	**B: Stairway dimensions**

Figure 50: Chinese Data - Escalator (a) and Staircase (b) dimensions

Due to certain camera angles and permission restrictions, it was not possible to collect the same items of data for each escalator/stair. The breakdown of data collected for each escalator can be seen in Table 49.

Table 49: Chinese Data - Analysis performed according to period

	Escalator A (Rush-hour)	Escalator D (Non-rush hour)
Escalator/Stair usage	x	
Side usage Frequencies		x
Walkers/Rider usage	x	x
Walker Speeds	x	x
Flow-rates		x

In total, around 4,787 pedestrians were recorded using each escalator; 2,752 during the rush-hour (Escalator A) and 2,035 during the non-rush hour (Escalator D). In addition, some 2,451 stair users during the rush-hour period were also recorded. Due to the camera angles used, data relating to pedestrian age and gender was not collected during the rush-hour. However, pedestrian age and gender information was collected during the non-rush hour (see Table 50). During the non-rush hour a similar proportion of males and females were recorded. A small proportion of pedestrians appeared to be below 12 years old (3.0%) or older than 60 years old (2.5%). The remaining 94.4% (1,922) of pedestrians appeared to be aged between 12-60 years old.

Table 50: Chinese Data - Frequency/proportion of participants according to gender and age group for the up non-rush hour escalator

		Age Ranges			Totals	
		<12 yrs % [Freq]	**U60 yrs % [Freq]**	**O60 yrs % [Freq]**	**Gender Total % [Freq]**	**Period Total [Freq]**
Non-rush hour	**Males**	3.1 [33]	94.6 [993]	2.3 [24]	51.6 [1050]	2035
	Females	2.9 [29]	94.3 [929]	2.7 [27]	48.4 [985]	
Overall		3.0 [62]	94.4 [1922]	2.5 [51]	100.0 [2035]	

7.4.1 Escalator/Stair usage

Pedestrians arrived at the escalator/stair from arriving trains. It was possible to identify from the footage when trains arrived/departed on each side of the platform. As such the escalator/stair usage analysis has been segregated according to train arrival side. This is intended to explore whether side of approach influences escalator/stair usage. In addition, increases in pedestrian traffic have been associated with increased stair usage by Zeiler et al [Zeiler, et al., 2010] and Knehs [Knehs, 2010]. This is because as escalators become oversubscribed more pedestrians elect to use adjacent stairs. As such the analysis has been further segregated according to batches of pedestrians from arriving trains: each train arrival was classed as a separate batch. Since each train had different numbers of pedestrians alighting at any one time, has allowed the influence of pedestrian traffic upon escalator/stair usage to be measured.

During the non-rush hour period, the camera angles did not offer a full view of the exit or entrance of the adjacent stair. As such the escalator/stair usage frequencies were only collected during the rush-hour. There was a wide variation in the number of pedestrians per batch and the subsequent levels of congestion observed at the foot of the escalator/stair during the rush-hour. It was therefore deemed necessary to segregate each batch according to the levels of congestion at the foot of the escalator/stair; defined as either being “congested” or a “non-congested”. Due to the high levels of congestion within the “congested period”, it was not possible to record individual pedestrian details. As such during these periods only the number of pedestrians that used the escalator/stair was collected.

To quantitatively distinguish between congested and non-congested periods for each batch, the level of congestion needed to be measured. To facilitate a consistent method of measuring the approximate congestion levels, a region measuring approximately 3m x 6m in front of the escalator/stair (including the escalator flat section) was defined. This region was then considered crowded when the number of pedestrians in the area approximately reached or exceeded 18 pedestrians. This represented an average of 1+ ped/m^2 (see Figure 51). This corresponds to Fruin's level of service D and above (i.e. 0.72+ ped/m^2) [Fruin, 1971]. Fruin states that at level of service D "the majority of persons would have their normal walking speeds restricted...this would only represent the most crowded public areas" [Fruin, 1971]. In addition to this, during levels of congestion much higher than this, it became increasingly difficult to count pedestrians given the camera angle.

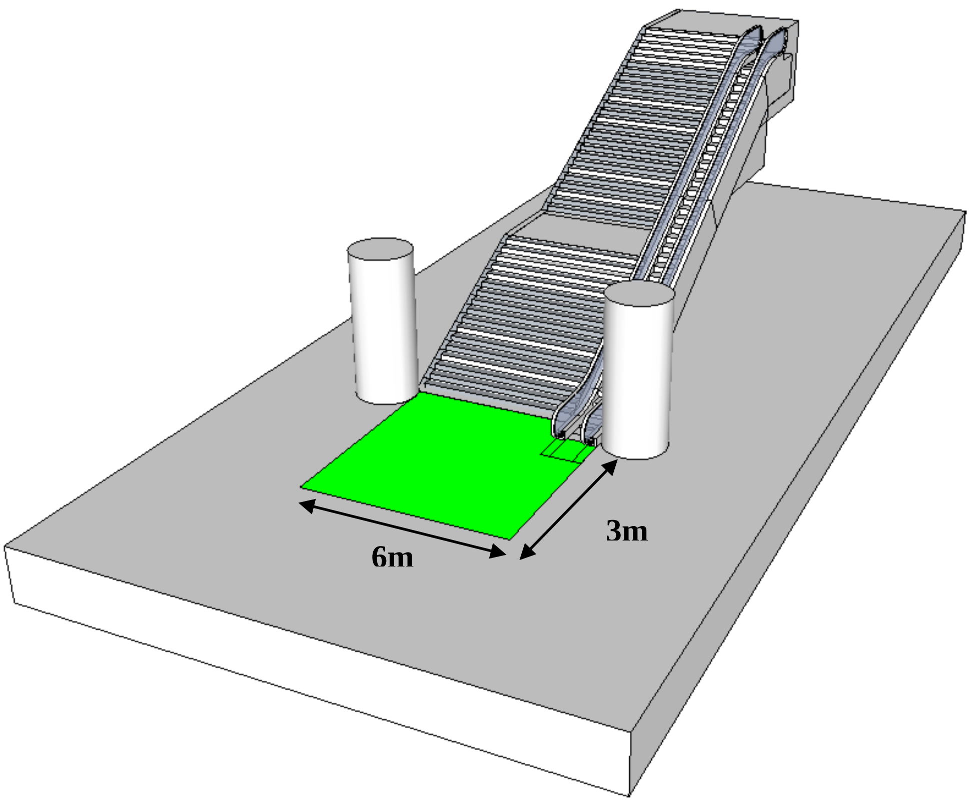


Figure 51: Chinese Data - Measured area of where congestion is defined (diagram not to scale)

To assist in counting the number of pedestrians in this area, an approximate 3m x 6m x 1.6m 3D box, represented by white lines in Figure 52, was overlaid onto the video footage. A pedestrian was defined as being inside the 3D box in front of the escalator/stair if their feet were above Line A and their head was below Line B.

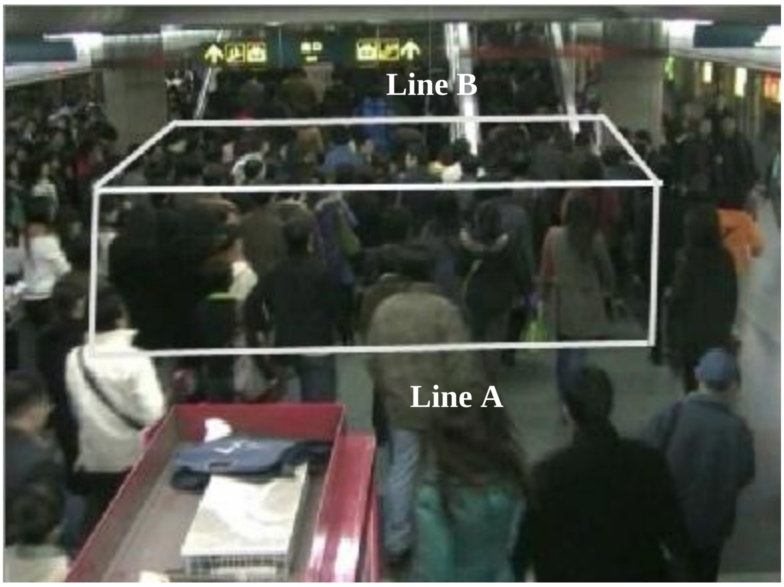


Figure 52: Chinese Data – Rush-hour, platform level: Video screen grab of area where congestion is defined

Using this approach there are two instances relating to extremes of a person's height that can result in an inaccuracy during the counting process. The first instance occurs with very small pedestrians: it is possible that a small pedestrian leaves the given area and enters onto the stair but their head remains below Line B. This would effectively mean that pedestrian would still be counted as being in the area (see Figure 53, Instance 1). The second instance occurs with very tall pedestrians present in the area: it is possible that a very tall pedestrian is never counted as their head moves above Line B before their feet move above Line A. This would effectively mean they are never counted (see Figure 53, Instance 2). The height a pedestrian would need to be to fit each instance can be approximated to 1.5m or less for Instance 1 and 2.5m or greater for Instance 2. Despite the possibility of such instances occurring, neither was observed during the data collection process.

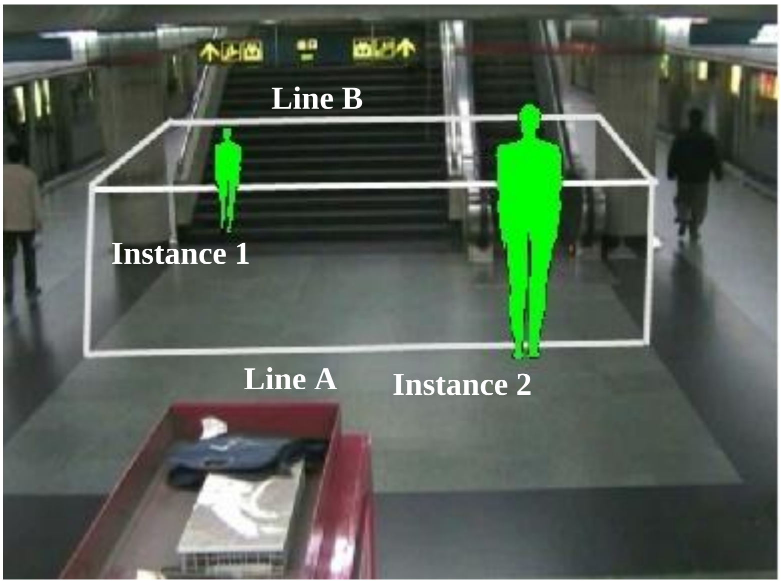


Figure 53: Chinese Data - Instances of peoples' height which cause problems when counting people in the given area

Three views of the region showing three different crowd densities are presented in Figure 54. To highlight each person within the catchment area a white circle has been placed on each pedestrian's head. The congested period threshold (1 ped/m^2) is presented in Figure 54B. This density is intended to represent the lowest level of congestion during the congested periods. The difference in the level of congestion can be seen by comparing the heavily congested period shown in Figure 54c with the low congestion period shown in Figure 54A.

		
A: Approximately 12 people (0.67 ped/m^2 average)	**B: Approximately 18 people (1 ped/m^2 average)**	**C: Approximately 31 people (1.7 ped/m^2 average)**

Figure 54: Chinese Data - Different levels of congestion

For the analysis of the congested periods, the number of pedestrians was only recorded when the levels of congestion reached or exceeded 18 people in the 3m x 6m area. This ensured that all pedestrians recorded in the batch used either the escalator or stair during a period of sufficient congestion.

The catchment area where congestion is measured took some time for the specified levels of congestion to build up once a train had arrived. The first pedestrians to enter the escalator/stair area were typically the first to leave the train and were also positioned close to the escalator/stair. Towards the end of each congested period, the levels of congestion gradually decreased as no new pedestrians entered the area. The last pedestrians to enter the escalator/stair area were typically the last to leave the train and/or were also positioned furthest away from the escalator/stair. During both of these periods, despite being part of a congested period, pedestrians about to traverse the escalator/stair would have made their device choice during a non-congested period. These pedestrians made their escalator/stair choice when large crowds of other pedestrians were in front or behind them. As such for consistency with the non-congested data, these pedestrians were excluded from the analysis.

It should be highlighted that even with such methods to assist the counting process, a number of factors contributed to potential counting errors. These include human error in counting large numbers of people, the restricted camera angles provided and pedestrians obstructing views. Consequently the method of counting provides an approximation of the number of pedestrians in the area. The extent to which such errors occur is uncertain and requires further investigation.

In total, 4,531 pedestrians were recorded ascending to the upper level using the escalator or the adjacent stair; 1,182 during non-congested periods (20 train arrivals) and 3,349 during congested periods (8 train arrivals) (see Table 51). During the non-congested periods 76.7% (907) of all pedestrians used the escalator (χ^2=336.9, $p<0.05$). Irrespective of which device pedestrians were initially closest (i.e. train arrival side), the escalator was the preferred device with similar proportion of escalator users (74.5%-81.7%) recorded in all non-congested periods (χ^2=5.8, $p>0.05$). This suggests that the side of approach to the escalator/stair does not exert a considerable influence upon device selection during non-congested periods.

Table 51: Chinese Data - Non-congested escalator/stair users

Train Arrival Side	Arrival Frequency	Escalator User Frequency	Stair Users Frequency	% Escalator Users
Escalator	7	532	172	75.6
Stair	9	184	63	74.5
Both (2 trains)	4	191	40	82.7
Overall	20	907	275	76.7

During the congested periods over twice (64.7% (2,167)) as many pedestrians were observed compared to the non-congested periods. During these periods, trains were recorded as either arriving on the stair side or two trains arriving simultaneously on both sides (i.e. no instance of a single train arriving on the escalator side was observed). Approximately the same proportion of pedestrians (35.0%-35.1%) were observed using the escalator when trains arrived from either the stair or both sides simultaneously (χ^2=0.001, p>0.05). As with the non-congested periods this suggests that during congested periods the side of approach has little influence upon escalator/stair usage.

During the congested periods, crowds formed around the entrance of the escalator/stair, the base of the stair and along the platform. In these circumstances some pedestrians were likely heavily influenced by the crowd into using a particular device simply based on proximity and ease of accessibility to the device. The relative width of the escalator/stair is expected to have some influence on the proportion of pedestrians using each device during such periods. Given that the stair is some 3.3 times wider than the escalator, if there were an equal preference to use the stair and the escalator based on width alone then we would expect the stair to attract around 330% times as many users. However, we find that the stair attracts some 190% more users. Thus, while the relative widths of the devices may be influencing pedestrians' choice, pedestrians are also exercising some discretion concerning device usage (e.g. assessing local conditions, influenced by personal factors, etc).

Table 52: Chinese Data - Congested escalator/stair users

Train Arrival Side	Arrival Frequency	Escalator User Frequency	Stair Users Frequency	% Escalator Users
Stair	3	250	463	35.1
Both (2 trains)	5	923	1713	35.
Overall	8	1173	2176	35.0

7.4.2 Walker/Rider usage

In total, 4,787 pedestrians were recorded either walking or riding on each escalator during both the rush-hour and non-rush hour periods (Table 53). It was observed for most train arrivals that riders who typically were among the first to board the escalator stood on both sides of the escalator. This meant they blocked pedestrians behind them from having a choice to walk up the escalator. This resulted in almost all pedestrians (96.7%-98.7%) riding both escalators in both the rush-hour and non-rush hour periods. As such it is unclear whether the proportion of walkers/riders is a reflection of pedestrian choice or a by-product of behaviour imposed by other pedestrians. Almost all walkers recorded were among those pedestrians who boarded each escalator first for a given train arrival and so were not blocked by riders.

Table 53: Chinese Data - Walker/Rider frequencies during rush-hour and non-rush hour periods

	Train Arrival Frequency	Walkers % [Freq]	Riders % [Freq]
Rush-hour	**28**	3.3 [92]	96.7 [2,660]
Non-rush hour	**25**	1.3 [27]	98.7 [2,008]
Overall	**53**	2.4 [119]	97.6 [4,668]

7.4.3 Side usage

In total, 2,035 pedestrians' side usage was recorded (see Table 54). Almost all pedestrians adopted either the left (49.0%) or right (48.8%) side of the escalator (χ^2=0.43, p>0.05). There appears to be no common side preference whereby walkers and riders elect to use opposite sides of the escalator. As such, high congestion levels were observed on the escalator with riders typically leaving fewer treads between other riders compared to walkers.

Table 54: Chinese Data - Side preference for escalator users during the non-rush hour period

Period	Walker/Rider	Left % [Freq]	Right % [Freq]	Centre % [Freq]	Varied % [Freq]	Total % [Freq]
Non-rush hour	Walkers	33.33 [9]	29.93 [8]	7.41 [2]	29.63 [8]	1.3 [27]
	Riders	49.00 [984]	47.61 [956]	3.29 [66]	0.10 [2]	98.7 [2,008]
	All	47.37 [993]	48.80 [964]	3.34 [68]	0.49 [10]	2,035

7.4.4 Walker speeds

Given that the camera views were occasionally obstructed by escalator users it was not possible to measure the speeds of all escalator walkers. In total, 79 escalator walker speeds were recorded. Over twice as many walker speeds were recorded during the rush-hour (72.2% (57)) than the non-rush hour (27.8% (22)). This is however, expected considering over twice as many escalator users were recorded in the rush-hour period. Similar proportions of males and females were recorded in both periods (rush-hour: 57.9% (33) male/42.1% (24) females, non-rush hour: 45.5% (10) males, 54.5% (12) females). Due to most escalator users riding on both sides resulting in blocking, the walker speeds recorded were typically of those who were among the first to board the escalator from an arriving train.

The frequency distribution of all walker speeds can be seen in Figure 55. Analysis of the walker speed frequency distributions, regardless of segregating according to sub-categories (e.g. gender , time period, etc), showed each distribution not to be normal (using a Kolmogorov-Smirnov test). As such the non-parametric 2 sample Mann-Whitney U- test was used to determine if there were any significant differences between walker speeds in each category.

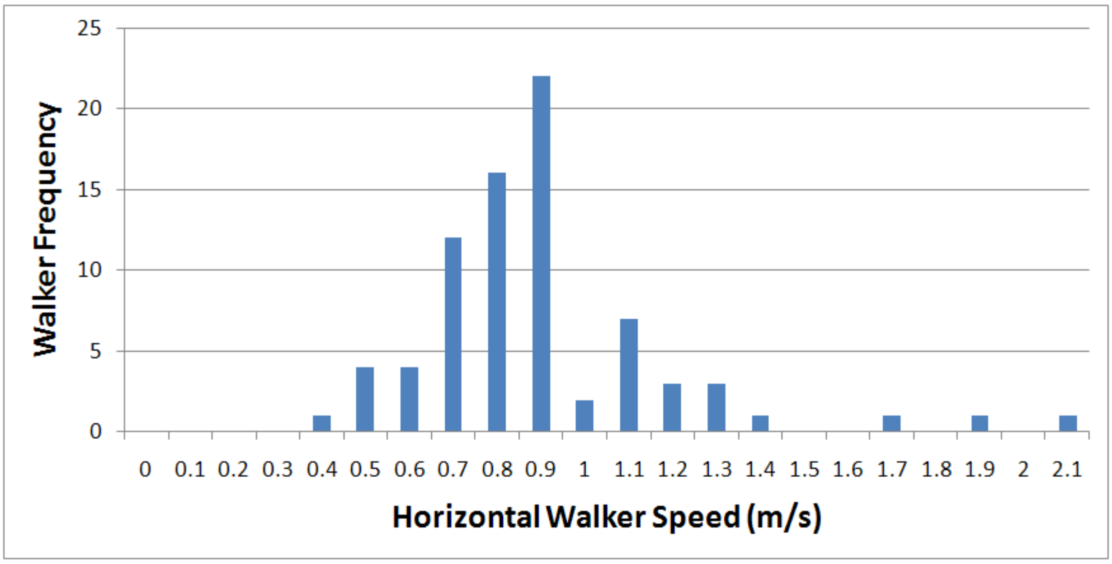


Figure 55: Chinese Data - Horizontal escalator walker speed frequency distribution (combined gender and time period)

The breakdown of average horizontal escalator walker speeds is summarised in Table 55. As expected, overall walker speeds were significantly faster (34.3% (0.23 m/s)) during the rush-hour compared to the non-rush hour period ($p<0.05$).

Males walked significantly faster (8.8%(0.07)) than females ($p<0.05$). However, this was due to the greater variation between male and female walker speeds during the non-rush hour period. Indeed there was no significant difference between the male/female speeds during the rush-hour ($p>0.05$). These findings suggest that male and female walker speeds are similar during the rush-hour. However, whilst both males and females reduce their walker speeds during the non-rush hour, females do so more than males.

Table 55: Chinese Data - Average Horizontal Walker Speeds

	Gender	Rush-hour (m/s)	Frequency	Non-rush (m/s)	Frequency	Overall	Frequency
Average	Males	0.91 [0.69-1.32]	33	0.75 [0.39-0.95]	10	0.87 [0.39-1.32]	43
	Females	0.89 [0.59-1.25]	24	0.61 [0.42-0.78]	12	0.80 [0.42-1.25]	36
	Overall	0.9 [0.59-1.32]	57	0.67 [0.39-0.95]	22	0.83 [0.39-1.3]	79

7.4.5 Flow-rates

Due to camera viewing restrictions only the exit flow-rate was recorded during the non-rush hour period in the Chinese data. The flow-rate for each minute can be seen in Figure 56. The highest flow-rate recorded was 102 ped/min in the twenty-first minute (1200-1260 seconds) (see Figure 56 instance ‘A’). A similarly high flow-rate of 100ped/min was also recorded in the fifty seventh minute (3360-3420 seconds) (see Figure 56 instance ‘B’). During both of these periods there was approximately a similar proportion of males (49.0%/52.0%) and females (48.0%/51.0%), with all pedestrians riding and a similar proportion of pedestrians using both the right (48.0%/49.0%) and left side (48.0%/49.0%) of the escalator.

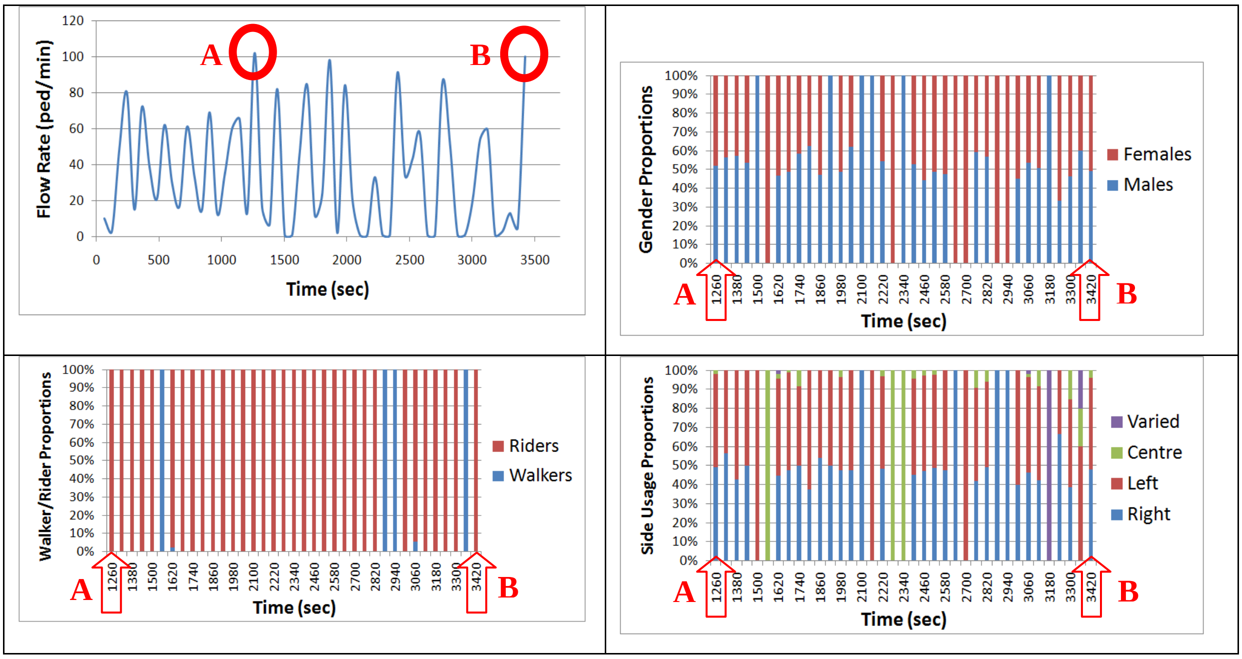


Figure 56: Chinese Data - Non-rush hour up: peak flow-rates (highlighted by the red circles) with corresponding proportion of males/females, walkers/riders, side usage (highlighted by the red arrows)

The flow-rate exceeded 60 ped/min a number of times during the non-rush hour which represents greater than 1 person exiting the escalator every second. This is reflective of the high crowd densities observed on the escalator where almost all pedestrians rode the escalator with typically two pedestrians occupying most escalator treads. The average overall flow-rate was 35ped/min with a minimum of 1 ped/min recorded in any minute. In total, 13 pedestrians were observed to carry items of luggage. As with the Spanish data, the scarcity with which this occurred meant that it is expected to have had little influence upon the recorded escalator flow-rates. As such analysis of escalator flow-rates according to user luggage has not been included.

7.5 Analysis of English data

The English data was collected in Paddington underground station in London, England. The station links the underground train network to the mainline national rail services and also forms part of the Heathrow airport express/connect coach service [Transport, 2010b]. In addition, it links 4 underground tube lines (Bakerloo, Circle, District, and ‘Hammersmith & City’ lines). As such many commuters and international travellers pass through the station every day. It is therefore common to find many pedestrians carrying various types of luggage in the station.

The footage of two adjacent escalators and an adjacent stair was collected over a period of two days. The escalators were moving in opposite directions (see Figure 57). The escalators/stair linked the ticket hall level of the underground station to the adjoining mainline railway station platform level.

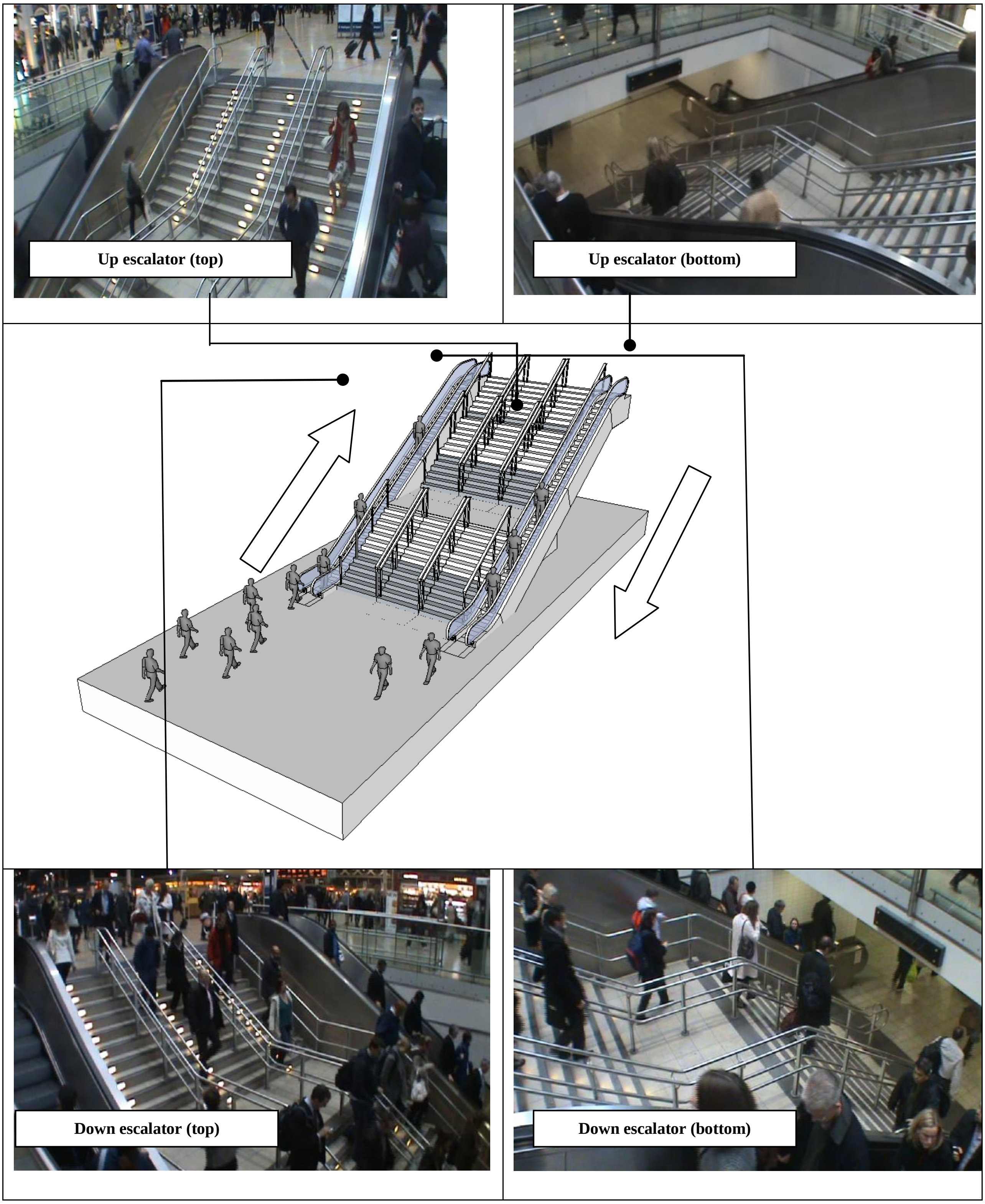
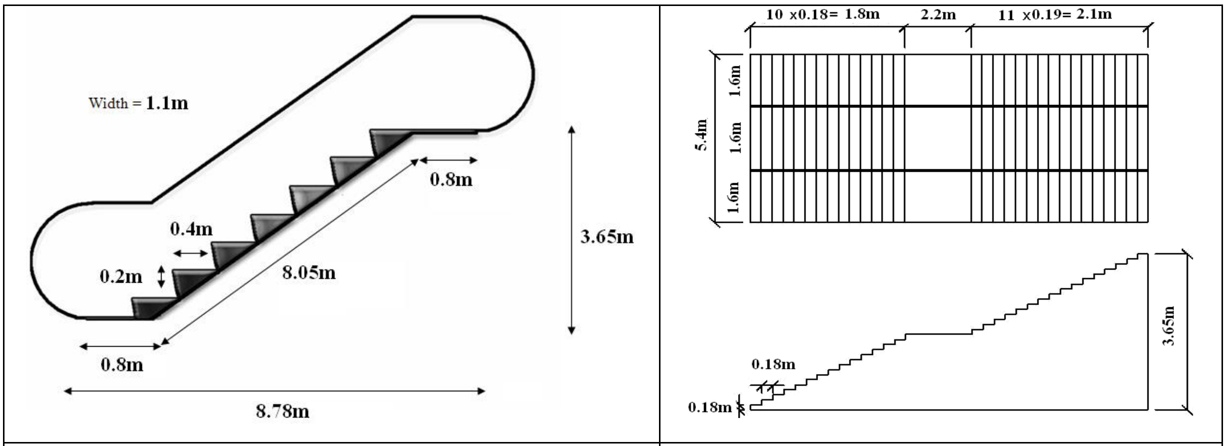


Figure 57: English Data - The location of each camera for each escalator/stair (diagram not to scale)

Each escalator had a vertical drop of 3.65m with a horizontal length of 8.78m and horizontal speed of 0.5 m/s (see Figure 58). The adjacent three lane stair (separated by two hand rails) comprised of two flights connected via a single landing.



A: Escalator dimensions	B: Stairway dimensions

Figure 58: English Data - Escalator and Stair dimensions

Data was collected via video footage in approximate 20 minute segments during the morning rush-hour, afternoon non-rush hour and evening rush-hour for both days (2 x 3 x 20 = 120 min of footage). A technical fault occurred on Day 2 whilst filming the morning rush-hour on the down escalator. This produced a small time delay of 6.8 minutes in recording. This delay meant the recording was extended for the same period of time to ensure that a comparable length of footage was obtained.

In total, 11,019 pedestrians were recorded: 6,123 on the escalators and 4,896 on the stair. Slightly more males (59.3% (3,629)) were recorded than females (40.7% (2,494)) using each escalator.

Of all 2,958 escalator users recorded on Day 1, 59.2% (1,752) were males and 40.8% (1,206) females. Very few escalator users appeared to be under 12 (0.44% (13)) or over 60 years old (1.7% (51)) (see Table 56). Approximately 22.2% (296) more escalator users were recorded on the up escalator than on the down escalator. On the up escalator approximately twice as many pedestrians were recorded during the morning and evening rush-hour compared to the afternoon non-rush hour period, representing the increased usage during peak times. On the down escalator there were 36.5% (127) and 46.0% (160) more escalator users recorded in the morning and evening respectively compared to the afternoon.

Table 56: English Data -Day 1 frequency/proportion of participants according to gender, age group, time period and direction

			Age Ranges			Totals		
			<12 yrs % [Freq]	U60 yrs % [Freq]	>60 yrs % [Freq]	Gender Total % [Freq]	Period Total % [Freq]	Day Total [Freq]
Up	Morning	Male	0.0 [0]	61.5 [378]	0.2 [1]	61.6 [379]	37.8 [615]	1627
		Female	0.0 [0]	37.9 [233]	0.5 [3]	38.4 [236]		
	Afternoon	Male	0.3 [1]	60.4 [201]	1.5 [5]	62.2 [207]	20.5 [333]	
		Female	0.6 [2]	36.3 [121]	0.9 [3]	37.8 [126]		
	Evening	Male	0.4 [3]	56.6 [384]	1.2 [8]	58.2 [395]	41.7 [679]	
		Female	0.0 [0]	40.8 [277]	1.0 [7]	41.8 [284]		
Down	Morning	Male	0.2 [1]	60.6 [288]	0.6 [3]	61.5 [292]	35.7 [475]	1331
		Female	0.2 [1]	38.3 [182]	0.0 [0]	38.5 [183]		
	Afternoon	Male	1.1 [4]	52.9 [184]	2.6 [9]	56.6 [197]	26.1 [348]	
		Female	0.0 [0]	42.0 [146]	1.4 [5]	43.4 [151]		
	Evening	Male	0.2 [1]	54.3 [276]	0.6 [3]	55.1 [280]	38.2 [508]	
		Female	0.0 [0]	44.1 [224]	0.8 [4]	44.9 [228]		
Total			0.4 [13]	97.8 [2894]	1.72 [51]	2958		

Approximately the same number of escalator users were recorded on Day 2 and Day 1 with a higher proportion of males (59.3%) than females (40.7%) (see Table 57). Considerably more escalator users (64.4% (771)) were recorded on the up escalator than the down escalator.

Table 57: English Data -Day 2 frequency/proportion of participants according to gender, age group, time period and direction

			Age Ranges			Totals		
			<12 yrs % [Freq]	U60 yrs % [Freq]	>60 yrs % [Freq]	Gender Total yrs % [Freq]	Period Total yrs % [Freq]	Day Total [Freq]
Up	**Morning**	**Male**	0.3 [3]	58.0 [564]	0.8 [8]	59.2 [575]	49.4 [972]	1968
		Female	0. [2]	40.0 [389]	0.6 [6]	40.8 [397]		
	Afternoon	**Male**	0.8 [3]	57.6 [227]	0.8 [3]	59.1 [233]	20.0 [394]	
		Female	0.5 [2]	38.8 [153]	1.5 [6]	40.9 [161]		
	Evening	**Male**	0.0 [0]	55.5 [334]	2.5 [15]	58.0 [349]	30.6 [602]	
		Female	0.3 [2]	40.0 [241]	1.7 [10]	42.0 [253]		
Down	**Morning**	**Male**	0.0 [0]	61.8 [342]	0.7 [4]	62.6 [346]	46.2 [553]	1197
		Female	0.0 [0]	36.7 [203]	0.7 [4]	37.4 [207]		
	Afternoon	**Male**	0.0 [0]	58.6 [184]	2.5 [8]	61.1 [192]	26.2 [314]	
		Female	0.3 [1]	36.6 [115]	1.9 [6]	38.9 [122]		
	Evening	**Male**	0.0 [0]	54.5 [180]	0.6 [2]	55.2 [182]	27.6 [330]	
		Female	0.3 [1]	43.9 [145]	0.6 [2]	44.8 [148]		
Total			0.44 [14]	97.2 [3077]	2.34 [74]	3165		

7.5.1 Escalator/Stair usage

The frequency/proportion of all escalator/stair users according to day, period, and direction can be seen in Table 58.

Overall, there were significant differences between the proportion of escalator/stair users in the up and down direction (χ^2= 553.3, p<0.05). In the up direction the escalator was the most used device (67.0%) (χ^2= 620.0, p<0.05). However, in the down direction the stair was the most used device (55.3%) (χ^2= 63.0, p<0.05). This suggests that escalators are more attractive for those ascending than those descending. This is expected considering the added effort and time required in travelling in the up direction.

Looking at each period, for the up direction significantly more escalator users were recorded during the morning (χ^2=539.1, p<0.05). However, in the down direction there were significantly more stair users (64.0%) (χ^2=63.0, p<0.05). During the afternoon there were significantly more escalator users irrespective of direction (χ^2=105.2, p<0.05). Similarly during the evening period there were also significantly more escalator users than stair users in both directions (χ^2=4.6, p<0.05). However, this was a weaker correlation than that observed in the other periods. This suggests that during the evening, whilst the escalator is the most used device, the direction of travel appears to have less of an influence upon escalator/stair usage compared to the morning and afternoon periods. Overall, the results highlight that the escalator was the most used device in all time periods for both directions with the exception of the morning down direction.

Table 58: English Data -Frequencies and proportion of escalator/stair users

		Up % [Freq]			Down % [Freq]		
		Day 1	**Day 2**	**Overall**	**Day 1**	**Day 2**	**Overall**
Morning	**Stair**	28.5 [245]	22.1 [276]	24.7 [521]	64.8 [873]	63.4 [958]	64.0 [1831]
	Escalator	71.5 [615]	77.9 [972]	75.3 [1587]	35.2 [475]	36.6 [553]	36.0 [1028]
Afternoon	**Stair**	8.4 [75]	25.2 [133]	22.2 [208]	41.6 [248]	45.6 [263]	43.6 [511]
	Escalator	81.6 [333]	74.8 [394]	77.8 [727]	58.4 [348]	54.4 [314]	56.4 [662]
Evening	**Stair**	46.3 [586]	43.1 [456]	44.9 [1042]	49.6 [500]	46.2 [283]	48.3 [783]
	Escalator	53.7 [679]	56.9 [602]	55.1 [1281]	50.4 [508]	53.8 [330]	51.7 [838]
Overall	**Stair**	35.8 [906]	30.5 [865]	33.0 [1771]	54.9 [1621]	55.7 [1504]	55.3 [3125]
	Escalator	64.2 [1627]	69.5 [1968]	67.0 [3595]	45.1 [1331]	44.3 [1197]	44.7 [2528]
	Stair	33.0 [1771]			55.3 [3125]		
	Escalator	67.0 [3595]			44.7 [2528]		

7.5.2 Walker/Rider usage

The frequency and proportion of all escalator walkers/riders according to day, period, and direction can be seen in Table 59. Of the 6,123 escalator users recorded the majority rode (74.9%). There was no significant difference between the proportion of walkers/riders between each day (χ^2= 3.787, p>0.05).

Table 59: English Data - Frequencies and proportion of walkers/riders

		Up % [Freq]			Down % [Freq]		
		Day 1	**Day 2**	**Overall**	**Day 1**	**Day 2**	**Overall**
Morning	**Riders**	65.5 [403]	64.4 [636]	65.5 [1039]	65.3 [310]	70.3 [389]	68.0 [699]
	Walkers	34.5 [212]	34.6 [336]	34.5 [548]	34.7 [165]	29.7 [164]	32.0 [329]
Afternoon	**Riders**	88.9 [296]	81.2 [320]	84.7 [616]	87.1 [303]	80.9 [254]	84.1 [557]
	Walkers	11.1 [37]	18.8 [74]	15.3 [111]	12.9 [45]	19.1 [60]	15.9 [105]
Evening	**Riders**	78.2 [531]	83.6 [503]	80.7 [1034]	79.7 [405]	71.2 [235]	76.4 [640]
	Walkers	21.8 [148]	16.4 [99]	19.3 [247]	20.3 [103]	28.8 [95]	23.6 [198]
Overall	**Riders**	74.8 [2689]			74.9 [1896]		
	Walkers	25.2 [906]			25.1 [632]		
	Riders	74.9 [4585]					
	Walkers	25.1 [1538]					

Overall, significantly more males (29.2%) elected to walk compared to females (19.3%) (χ^2= 77.0, p<0.05). There was a significant difference between the number of walker/riders in each period (χ^2= 1.8, p<0.05). Regardless of direction, in the evening periods there were significantly more walkers (21.0%) than in the afternoon periods (15.6%) (χ^2= 16.3, p<0.05). In the morning periods there were significantly more walkers (33.5%) than in the afternoon (χ^2= 147.9, p<0.05) and evening periods (χ^2= 91.404, p<0.05).

Overall there were approximately the same proportion of walkers for both the up (25.2%) and down (25.1%) directions (χ^2=0.03, p>0.05). During the morning periods there were a similar proportion of walkers for both the up (34.5%) and down escalator (32%) (χ^2= 1.8, p>0.05). Similarly for the afternoon periods there was a comparable proportion of walkers for both the up (15.3%) and down escalator (15.9%) (χ^2= 0.09, p>0.05). However, during the evening significantly more walkers were observed on the down escalator (23.6%) than on the up escalator (19.1%) (χ^2= 5.8, p<0.05).

The results show that time period influences the proportion of walkers/riders. Pedestrians during the rush-hour periods appear more motivated (reflected in the higher proportion of walkers) than during the non-rush hour periods. The combination of time period and direction of travel only appeared to influence the proportion of walkers/riders in the evening. Here significantly more walkers were recorded in the down direction. It is unclear the reasons for this however, this may indicate that direction and period influence pedestrians' decision to walk/ride on an escalator.

7.5.3 Side usage

The proportion of escalator users according to side preference can be seen in Table 60 (Day 1), Table 61 (Day 2) and Table 62 (Overall). During both days there was a common side preference for riders to use the right side and walkers to use the left side of each escalator regardless of direction, day or period. Indeed a significant number of walkers used the left side (78.2%) and riders used the right side (88.4%) (χ^2= 5,853.6, $p<0.05$). There was a more significant difference in the up direction (χ^2= 4284.5, $p<0.05$) (91.6% riders right / 82.9% walkers left) than in the down direction (χ^2= 1699.9, $p<0.05$) (83.7% riders, right / 71.4% walkers left). This suggests that those on the up escalator conformed more to the common side preference behaviour than those on the down escalator. This may be due to more pedestrians typically simultaneously using the escalator in the up direction. In turn this may have prompted more pedestrians to conform to either riding on the right side or walking on the left side through not wanting to inconvenience other escalator users.

Overall the centre (1.3%) and varied (1.6%) positions were adopted by a small proportion of escalator users over all periods. The majority of escalator users who varied their side whilst on the escalator were walkers, commonly having to walk around riders whilst traversing the escalator.

Table 60: English Data - Proportion of walkers/riders that used each side on the escalator (Day 1)

Day	Period	Direction	Type	Left %	Right %	Centre %	Varied %
Day1	Morning	Down	**All**	31.2	65.3	1.1	2.5
			Rider	7.7	91.3	0.6	0.3
			Walker	75.2	16.4	1.8	6.7
		Up	**All**	32.0	65.9	1.5	0.7
			Rider	1.0	98.8	0.2	0.0
			Walker	91.0	3.3	3.8	1.9
	Afternoon	Down	**All**	30.2	63.2	4.0	2.6
			Rider	28.7	68.0	1.7	1.7
			Walker	40.0	31.1	20.0	8.9
		Up	**All**	12.6	83.8	1.8	1.8
			Rider	7.1	91.9	0.3	0.7
			Walker	56.8	18.9	13.5	10.8
	Evening	Down	**All**	23.6	72.4	1.6	2.4
			Rider	7.9	88.6	2.0	1.5
			Walker	85.4	8.7	0.0	5.8
		Up	**All**	22.1	75.6	1.2	1.2
			Rider	7.2	91.9	0.4	0.6
			Walker	75.7	16.9	4.1	3.4
	Overall	Down	**All**	28.0	67.5	2.0	2.5
			Rider	14.0	83.3	1.5	1.2
			Walker	73.5	16.0	3.8	6.7
		Up	**All**	23.9	73.6	1.4	1.1
			Rider	5.1	94.1	0.3	0.4
			Walker	82.1	9.8	4.8	3.3

Table 61: English Data - Proportion of walkers/riders that used each side on the escalator (Day 2)

Day	Period	Direction	Type	Left %	Right %	Centre %	Varied %
Day2	Morning	Down	All	30.4	66.5	0.2	2.9
			Rider	11.1	87.9	0.0	1.0
			Walker	76.2	15.9	0.6	7.3
		Up	All	36.1	62.7	0.6	0.6
			Rider	8.2	91.5	0.0	0.3
			Walker	89.0	8.0	1.8	1.2
	Afternoon	Down	All	26.4	72.0	0.3	1.3
			Rider	18.9	80.3	0.0	0.8
			Walker	58.3	36.7	1.7	3.3
		Up	All	20.6	77.2	1.0	1.3
			Rider	9.1	90.3	0.3	0.3
			Walker	70.3	20.3	4.1	5.4
	Evening	Down	All	30.3	67.0	1.2	1.5
			Rider	16.6	82.1	1.3	0.0
			Walker	64.2	29.5	1.1	5.3
		Up	All	21.3	75.1	2.3	1.3
			Rider	10.7	86.5	2.2	0.6
			Walker	74.7	17.2	3.0	5.1
	Overall	Down	All	29.3	68.1	0.5	2.1
			Rider	14.8	84.2	0.3	0.7
			Walker	69.3	23.8	0.9	6.0
		Up	All	28.5	69.4	1.2	1.0
			Rider	9.3	89.5	0.8	0.4
			Walker	83.5	11.6	2.4	2.6

Table 62: English Data - Proportion of walkers/riders that used each side on the escalator (Overall)

Day	Period	Direction	Type	Left %	Right %	Centre %	Varied %
Overall		Down	All	28.6	67.8	1.3	2.3
			Rider	14.4	83.7	0.9	0.9
			Walker	71.4	19.9	2.4	6.3
		Up	All	26.4	71.3	1.3	1.0
			Rider	7.4	91.6	0.6	0.4
			Walker	82.9	10.8	3.4	2.9
		Overall	All	27.3	69.8	1.3	1.6
			Rider	10.3	88.4	0.7	0.6
			Walker	78.2	14.6	3.0	4.3

Irrespective of direction of travel, significantly more riders used the right side in the rush-hour (92.3%) compared to the non-rush hour (82.8%) (χ^2=57.3, $p<0.05$).

Significantly more escalator users adhered to the common side preference behaviour in the down direction for the morning period compared to the up direction (χ^2=513.4, $p<0.05$). Similarly, significantly more escalator users adhered to common side preference behaviour in the up direction for the evening period compared to the down direction (χ^2=563.8, $p<0.05$). It is expected that the majority of pedestrians who used the escalators during these periods were commuters. In the morning period, commuters typically arrived at the station from the mainline trains so a greater number of down escalator users were observed. In the evening period, commuters typically arrived at the station on underground trains so a greater number of up escalator users was observed. During the afternoon periods, fewer pedestrians were observed simultaneously traversing the escalator. Indeed during these periods a larger variation in the proportion of walkers/riders using each side can be seen.

As observed in the Spanish data, such results suggest that the likelihood of a pedestrian conforming to common side preference is influenced by the number of other escalator users. During periods where many escalator users are present, escalator users may prefer not to inconvenience other escalator users behind them by blocking them (i.e. riding on the walker side). During periods where a small number of escalator users are present, adherence to common side preference has less impact on other escalator users behind them. As such adherence to common side preference was observed less during periods where less escalator users were observed.

It should be highlighted that whilst there were no signs on either of these escalators requesting pedestrians to stand on the right side, there were signs on other escalators in the London Underground asking pedestrians to "Stand on the right side". Since pedestrians on the up escalator would have probably traversed at least one escalator with these signs on, these may have influenced a pedestrian's side choice on the up escalator. The influence of such signage upon escalator side selection would likely increase the adherence to the common side preference.

7.5.4 Walker speeds

In total, 810 escalator walker speeds were recorded: 52.1% (422) on Day 1 and 47.9% (388) on Day 2 with 359 on the down escalator and 451 on the up escalator. A large majority of these were male (70.7% (572)). More walkers were observed in the morning (54.3% (441)) and evening (32.2% (261)) than in the afternoon (13.4% (108)).

The frequency distribution of walker speeds can be seen in Figure 59. Analysis of the walker speed frequency distributions, regardless of segregating according to sub-categories (e.g. direction of travel, time period, etc), showed each distribution not to be normal (using a Kolmogorov-Smirnov test). As such the non-parametric 2 sample Mann-Whitney U- test was used to determine if there were any significant differences between walker speeds in each category.

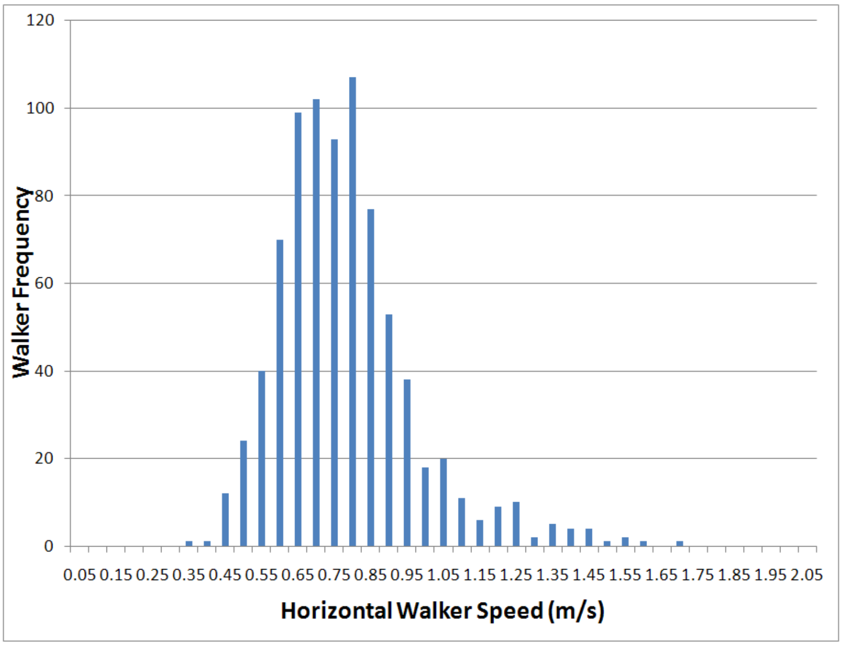


Figure 59: English Data - Horizontal escalator walker speed frequency distribution (combined for direction and gender)

The average walker speeds according to day, gender, period, and direction can be seen in Table 63. The overall average walker speed of pedestrians on the down and up escalator was 0.82 m/s and 0.70 m/s respectively. Overall escalator walkers were 17.1% (0.12 m/s) faster on the down escalator than on the up escalator ($p<0.05$). Males walked 13.33% (0.10 m/s) and 7.5% (0.05 m/s) faster than females in the down and up direction respectively ($p<0.05$). Comparison of overall walkers speeds for both days showed there to be no significant difference between each day ($p>0.05$). In addition there was no significant difference between walker speeds between each period ($p>0.05$). The results suggest that gender and direction of travel influence escalator walker speeds; however, time period does not.

Table 63: English Data - Average, minimum and maximum horizontal walker speeds on the up and down escalator during each period on each day according to gender

Direction	Period	Gender	Day 1		Day 2		Overall	
			Average Speed (m/s)	Frequency	Average Speed (m/s)	Frequency	Average Speed (m/s)	Frequency
Down	Afternoon	Female	0.66 [0.57-0.81]	10	0.73 [0.46-1.09]	12	0.70 [0.46-1.09]	22
		Male	0.78 [0.38-1.38]	21	0.82 [0.58-1.34]	21	0.80 [0.38-1.38]	42
		Average /Total	0.74 [0.38-1.38]	31	0.79 [0.46-1.34]	33	0.76 [0.38-1.38]	64
	Evening	Female	0.82 [0.55-1.44]	19	0.77 [0.52-1.20]	27	0.79 [0.52-1.44]	46
		Male	0.87 [0.49-1.46]	45	0.91 [0.47-1.44]	35	0.89 [0.47-1.46]	80
		Average /Total	0.86 [0.49-1.46]	64	0.85 [0.47-1.44]	62	0.85 [0.47-1.46]	126
	Morning	Female	0.73 [0.40-1.10]	26	0.76 [0.50-0.96]	18	0.74 [0.40-1.10]	44
		Male	0.89 [0.48-1.55]	60	0.80 [0.56-1.67]	65	0.84 [0.48-1.67]	125
		Average /Total	0.84 [0.40-1.55]	86	0.79 [0.50-1.67]	83	0.81 [0.40-1.67]	169
	Overall	Female	0.75 [0.40-1.44]	55	0.76 [0.46-1.20]	57	0.75 [0.40-1.44]	112
		Male	0.86 [0.38-1.55]	126	0.83 [0.47-1.67]	121	0.84 [0.38-1.67]	247
		Average/Total	0.83 [0.38-1.55]	181	0.81 [0.46-1.67]	178	0.82 [0.38-1.67]	359
Up	Afternoon	Female	0.63 [0.41-0.79]	6	0.69 [0.57-0.87]	5	0.65 [0.41-0.87]	11
		Male	0.67 [0.44-1.09]	19	0.76 [0.48-1.31]	14	0.71 [0.44-1.31]	33
		Average/Total	0.66 [0.41-1.09]	25	0.74 [0.48-1.31]	20	0.70 [0.41-1.31]	45
	Evening	Female	0.63 [0.45-0.87]	24	0.66 [0.42-0.85]	12	0.64 [0.42-0.87]	36
		Male	0.72 [0.41-1.51]	57	0.70 [0.43-1.23]	42	0.71 [0.41-1.51]	99
		Average/Total	0.69 [0.41-1.51]	81	0.69 [0.42-1.23]	54	0.69 [0.41-1.51]	135
	Morning	Female	0.69 [0.44-0.86]	36	0.69 [0.48-1.02]	43	0.69 [0.44-1.02]	79
		Male	0.70 [0.32-1.23]	99	0.74 [0.46-1.20]	94	0.72 [0.32-1.22]	193
		Average/Total	0.70 [0.32-1.23]	135	0.72 [0.46-1.20]	137	0.71 [0.32-1.23]	272
	Overall	Female	0.66 [0.41-0.87]	66	0.68 [0.42-1.02]	60	0.67 [0.41-1.02]	126
		Male	0.70 [0.32-1.51]	175	0.72 [0.43-1.31]	150	0.72 [0.32-1.51]	325
		Average/Total	0.69 [0.32-1.51]	241	0.72 [0.42-1.31]	210	0.71 [0.32-1.51]	451

7.5.5 Flow-rates

The entry flow-rate was recorded for all footage collected. With the exception of the afternoon period on Day 1, the average flow-rate for the up escalator was higher in each period than for the down escalator (see Table 64). This would be expected as more people were typically observed simultaneously arriving (from underground trains) at any given time on the up escalator than on the down escalator. As with the Spanish data, these maximum recorded down escalator flow-rates are thought to be more reflective of the dispersed arrival times to the escalator rather than the maximum achievable flow-rates.

Table 64: English Data - Minimum, average and maximum flow-rates

		Day 1 (ped/min)			Day 2 (ped/min)			Overall (ped/min)		
Period	**Direction**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**
Morning	**Down**	7.0	23.0	45.0	11.0	28.9	47.0	7.0	26.0	47.0
	Up	4.0	29.1	45.0	6.0	37.5	75.0	4.0	33.3	75.0
Afternoon	**Down**	3.0	16.5	36.0	5.0	15.7	29.0	3.0	16.1	36.0
	Up	0.0	16.5	30.0	3.0	19.4	38.0	0.0	18.0	38.0
Evening	**Down**	12.0	25.4	39.0	9.0	16.5	28.0	9.0	21.0	39.0
	Up	15.0	33.6	47.0	9.0	31.2	46.0	9.0	32.4	47.0
Overall	**Down**	3.0	21.6	45.0	11.0	20.4	47.0	3.0	21.0	47.0
	Up	0.0	26.7	47.0	3.0	29.4	75.0	0.0	28.1	75.0

The highest escalator flow-rate recorded was 75 ped/min on the up escalator during the morning of Day 2 of the eleventh minute (600-660 seconds) (see Table 64 and Figure 60). During this period pedestrians moving in the up direction were funnelled into using the escalator due to the adjacent stairs being crowded with pedestrians moving down. As such, pedestrians moving in the up direction had little choice to use the adjacent stair.

During this peak-flow rate period there were a higher proportion of riders (68%) with approximately even usage of both the left and right side of the escalator: each side was fully utilised. A slightly higher proportion of males (62.8%) were also recorded. The majority of pedestrians (60.7%) carried items of luggage. However, most were small items (i.e. only a rucksack (26.0%) or only a handbag (20.8%)). As such it is expected that this had little influence upon the flow-rate.

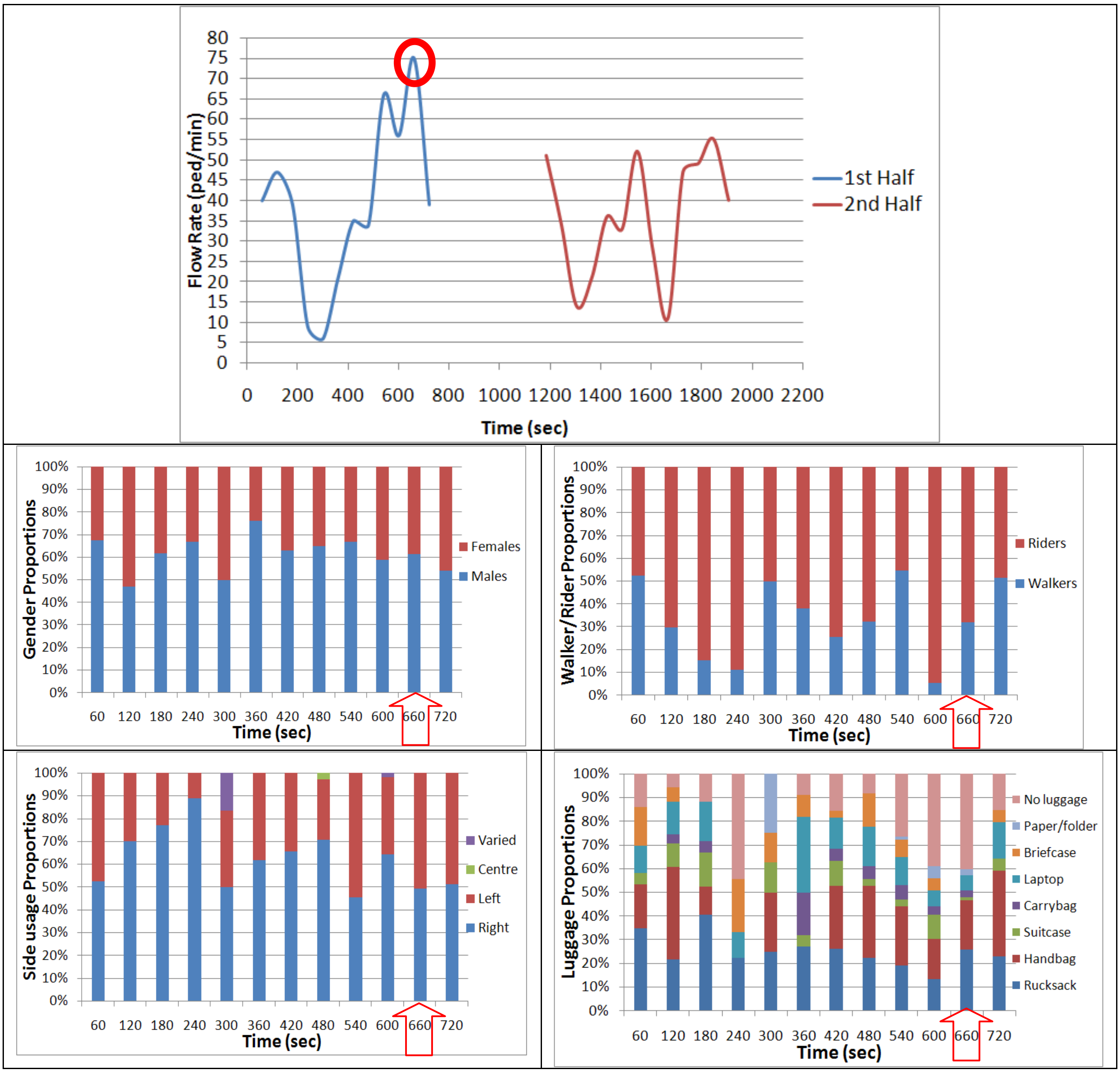


Figure 60: English Data - Day 2, Morning up: peak flow-rate (highlighted by the red circle) with corresponding proportion of males/females, walkers/riders, side usage, and luggage types (highlighted by the red arrows)

The highest escalator entry flow-rate on the down escalator was 47 ped/min during the morning on Day 2 in the first minute (0-60 seconds) (see Table 64 and Figure 61). During this period there was a higher proportion of riders (66%) with approximately two thirds (66.0%) using the right side of the escalator. Similar to the up direction a slightly higher proportion of males (61.7%) were recorded. Approximately three quarters (75%) of escalator users carried items of luggage. However, similar to the up direction, most only carried small items (i.e. only a rucksack (27.7%) or a handbag (25.5%)).

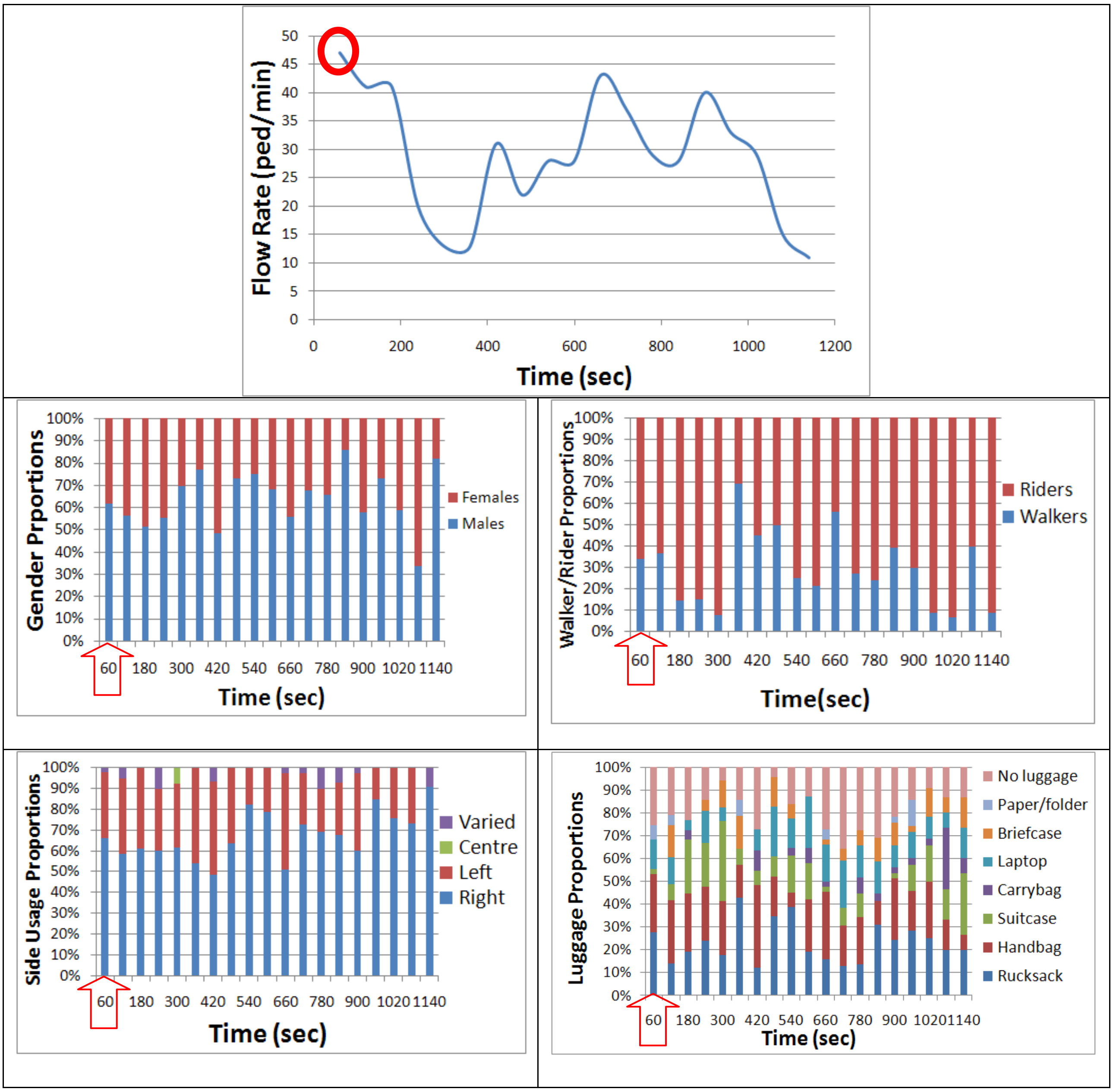


Figure 61: English Data - Day 2, morning, down: peak flow-rate (highlighted by the red circle) with corresponding proportion of males/females, walkers/riders, side usage, and luggage types (highlighted by the red arrows)

7.6 Comparison of Spanish, Chinese and English data

This following section compares each of the escalator datasets collected in each country. Though it is uncertain whether each dataset is representative of typical escalator human factors of each country, the purpose of such a comparison is to suggest potential cultural differences in escalator human factors where further investigation maybe of worth. In addition, there may be unidentified differences between the datasets. These may include situational, location, demographic and contextual differences. As such further investigation is required to support/refute such findings.

The configuration and dimensions of each escalator/stair for each dataset were not identical. Because it is uncertain what effects such differences have on escalator human factors, a brief description of the main structural/configuration escalator/stair differences is provided. The dimensions of each escalator/stair within each dataset is reproduced in Figure 62 for clarity.

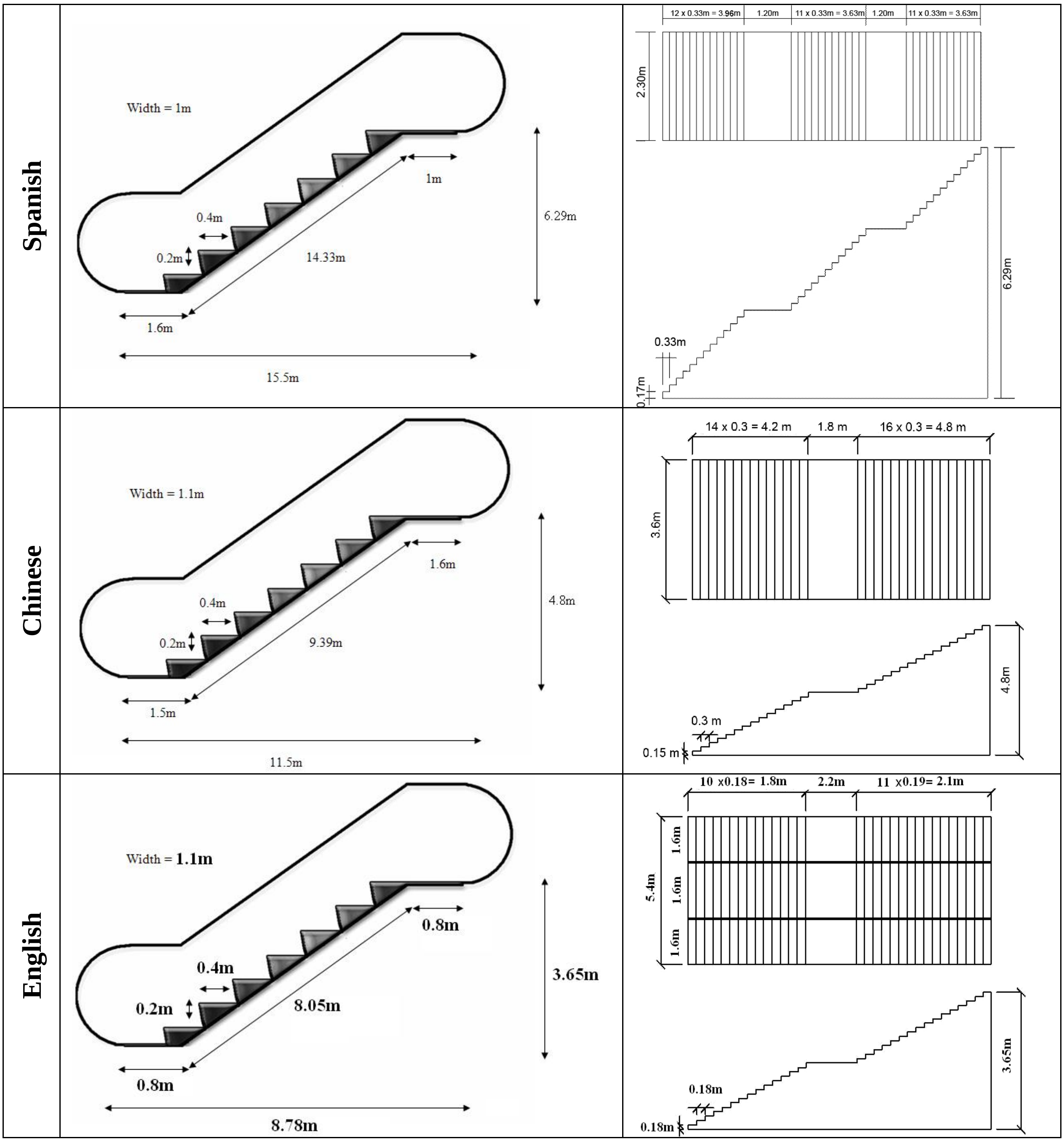


Figure 62: Escalator/Stair dimensions for each dataset

The Spanish escalators were the longest of all datasets being almost twice the height (6.29m) of the lowest escalator in the English dataset (3.65m). Despite this the riser height and tread depth, in addition to the escalator width were approximately the same for all escalators in each dataset. This increase in height of the Spanish escalator/stair meant the adjacent stair had two landings connecting three flights of stairs compared to a single landing connecting two flights of stairs in both the Chinese and English stairs. Increased travel distance may influence pedestrian's escalator/stair choice (e.g. longer travel distances encourage escalator usage). Also this may cause further fatigue to pedestrians that may influence walker/rider choice and subsequent side selection.

The adjacent stair to the escalator in the English dataset was partitioned by two handrails spanning the entire length of the stair and connected landings. The adjacent stairs in both the Spanish and Chinese datasets did not contain partitioning handrails. In addition, the stairs in the English dataset were over twice the width (5.40m) compared to the Spanish dataset stairs (2.30m) and 1.5 times the width of the Chinese dataset stairs. Increased stair width may increase the proportion of stair users, particularly during peak periods.

The direction of approach for the Spanish escalators was restricted to the left (stair) side for both the up and down escalators. The Chinese escalators/stairs could be approached from either side though train arrival side typically dictated the nearest device. The English escalators/stairs could only be approached from the front in the up direction (there was no side approach) and from any direction for the down escalator/stair. Pedestrian direction of approach may influence device selection, especially in crowded situations, with pedestrians potentially electing to use their closest device.

The English dataset escalator/stair configuration included two escalators moving in opposite directions with bidirectional flows on the adjacent stairs in between. Both the Spanish and Chinese dataset escalator/stair configuration included a single escalator and adjacent stair where bidirectional flows of pedestrians moving in opposite directions was infrequent. Such differences in pedestrian flows on the stairs may influence pedestrian escalator/stair usage (e.g. increased pedestrian flows in the opposite direction on the stairs may increase escalator usage).

In both the Spanish and Chinese datasets the escalator/stair connected the train platform to the above lobby area. This meant that the majority of up escalator/stair users had immediately alighted an underground train. In the English datasets the escalator/stair connected an intermediary ticket office level (located above the platform level, at the bottom of the escalator/stair) and the above lobby level. This meant that the majority of up escalator/stair users had just alighted an underground train and then used an escalator to get to the ticket hall level before using the observed escalator. Recent usage of escalators, particularly covering long distances, may influence walker/rider choice and walker speeds due to the potential increased fatigue.

In all datasets where age and gender were recorded the majority of pedestrians appeared to be aged between 12-60 years old with approximately even proportions of males and females: no considerable differences between pedestrians age and gender were found in each dataset.

The total amount of video footage and real-time footage collected for each dataset can be seen in Table 65. Approximately twice the length of real-time footage was collected in the English dataset due to being collected over two days compared to the Spanish and Chinese datasets being collected on a single day. In addition, there appeared to be more pedestrians per train in the Chinese dataset compared to the Spanish dataset. Subsequently the overall frequency of pedestrians observed for the Spanish (1,217), Chinese (6,566) and English (6,123) datasets varied considerably.

Table 65: Total length of video/real-time footage collected for each dataset

Dataset	Video footage (min)	Real time footage (min)
Spanish	120	120
Chinese	120	120
English	480	240

All of the Chinese dataset was collected for up escalators so comparison of the Chinese dataset according to direction of travel has not been performed. For both the Spanish and Chinese datasets, the rush-hour data was collected in the morning. For consistency the English morning rush-hour period data will be used for comparison instead of the evening rush-hour period data.

Findings from the following analysis assume that each dataset it representative of pedestrians in each country and that the escalator/stair structural/configuration differences have little or no influence upon associated human factors.

7.6.1 Escalator/Stair usage

For consistency, the Chinese non-congested rush hour up escalator/stair usage data has been used to compare with the Spanish and English data with regards to escalator/stair usage. This was because the high levels of congestion at the entrance to the escalator/stair in the congested Chinese data was never reached in the Spanish and English escalator/stair data (i.e. there were no incidents when such a higher number of pedestrians simultaneously arrived at the foot of the escalator/stair).

Overall, more escalator users were recorded than stair users in all datasets for the up direction. However, a higher proportion of escalator users were recorded in the up direction in the Spanish data (86.5% (590)) compared to both the Chinese data (76.7% (907)) and English data (67.0% (3,595)). This represents a significant difference between the number of escalator/stair users in the up direction for each country (χ^2=137.6, $p<0.05$).

Segregating each period (rush-hour/non-rush hour) in the up direction, in the Spanish data a significantly higher proportion of escalator users were recorded for the non-rush hour (94.4% (186)) compared to the rush-hour (83.3% (404)) period (χ^2=14.8, $p<0.05$). Within the English data in the up direction overall a similar proportion of escalator users were recorded in both the rush-hour (75.3% (1,587)) and non-rush hour periods (77.8% (727)) (χ^2=2.2, $p>0.05$).

A higher proportion of escalator users were recorded in the down direction in the Spanish data (68.4% (366)) compared to the English data (44.7% (2,528)) (no down data was collected in the Chinese dataset). Indeed, in the down direction the majority of pedestrians elected to use the stairs over the escalator in the English data (55.3% (3,125)). This represents a significant difference between the proportion of escalator/stair users in the down direction between the Spanish and English datasets (χ^2=110.2, $p<0.05$).

Segregating each period (rush-hour/non-rush hour) in the down direction, in the Spanish data a similar proportion of escalator users was recorded in both the rush-hour (68.9% (252)) and non-rush hour (67.5% (114)) (χ^2=0.1, $p>0.05$). However, within the English data in the down direction a significantly higher proportion of escalator users were recorded in the non-rush hour (56.4% (662)) compared to the rush-hour period (36.0% (1,831)) (χ^2=143.3, $p<0.05$).

Results suggest that most pedestrians in all countries would have a preference to use an escalator (compared to adjacent stair) to travel up. However, the extent of this preference varies between countries. Findings also suggest that escalator/stair usage in Spain and England is influenced to a different extent by time period (rush-hour/non-rush hour) and direction of travel. In the down direction, pedestrians in Spain appear to have a greater preference for using an escalator. In the up direction, pedestrians in England appear to have greater preference for using an escalator.

Further investigation is required to ascertain whether the observed differences are due to the stated factors (i.e. time period, direction of travel), or by-products of such factors (e.g. higher levels of congestion during the rush-hour periods).

7.6.2 Walker/Rider usage

As previously mentioned, the Chinese walker/rider usage data perhaps does not accurately represent the proportion of escalator users who would like to walk on the escalators. This is due to the observed blocking behaviour with a high proportion of riders typically occupying both sides of the escalators. It cannot therefore be determined whether the walker/rider behaviour was a true reflection of pedestrian personal choice or imposed due to other pedestrian behaviour. As such only the Spanish and English walker/rider frequencies have been compared.

Irrespective of time period there were a similar proportion of walkers in both the Spanish and English data in both the up (27.0% and 25.2% respectively) and down (21.0% and 25.1% respectively) directions ($\chi^2=4.3$, $p>0.05$). Little variation in the proportion of walkers during the rush-hour and non-rush hour periods (21.0%-29.2%) was observed in the Spanish data ($\chi^2=7.8$, $p>0.05$). However, in the English data significantly more walkers were recorded in the rush-hour (32.0%-34.5%) compared to the non-rush hour (15.3%-15.9%).

Results suggest that direction of travel does not greatly influence walker/rider usage in both England and Spain. In Spain the time period also does not appear to influence walker/rider usage. However, time period does appear to influence walker/rider usage in England where the proportion of walkers increases considerably during the rush-hour.

7.6.3 Side usage

Due to the blocking behaviour in the Chinese data, it cannot be determined whether the side usage behaviour was a true reflection of pedestrian personal choice or imposed due to other pedestrian behaviour. As such only the Spanish and English side usage data have been compared.

Common side preference behaviour was observed in both the Spanish and English data with a majority of riders electing to use the right side (80.4% and 88.4% respectively) and walkers using the left side (43.4% and 78.2% respectively) of the escalators.

In both the Spanish and English data a higher proportion of riders adhered to the common side preference behaviour (using the right side) in the up direction compared to the down direction (88.9% and 91.6% respectively). This suggests that direction of travel influences escalator side preference in both Spain and England in a similar way. Pedestrians are more likely adhere to common side preference when travelling up in both countries.

Within the Spanish data, no significant difference was recorded between the proportion of riders that used each side during the rush-hour and on-rush hour periods (χ^2=0.18, p>0.05). However, within the English data, overall significantly more riders used the right side during the rush-hour (92.3%) compared to the non-rush hour (82.8%) (χ^2=57.3, p<0.05).

Irrespective of time period, segregating according to direction of travel, a similar proportion of riders used the right side of the escalator in the up direction in the English data (91.1%-94.3%). However, in the down direction, significantly more riders (89.4%) used the right side during the rush-hour compared to the non-rush hour (73.6%).

The results suggest that escalator side usage is not influenced by time period in Spain. However, in England time period appears to cause more pedestrians to conform to the common side preference during the rush-hour period. It is postulated that this may be caused by the increased number of pedestrians simultaneously using the escalators during the rush-hour periods within the English data compared to the Spanish data.

7.6.4 Walker speeds

Due to each of the walker speed distribution in each dataset not being normally distributed the non-parametric Mann-Whitney U-test was used to test for significant differences between the distributions.

On average the Chinese walker speeds were 12.2% (0.09 m/s) and 16.9% (0.12 m/s) faster than the average Spanish and English walker speeds respectively (p<0.5). This was largely contributed to by the faster walking speeds during the rush-hour period in the Chinese data compared to the other datasets.

In the up direction, the male Chinese walker speeds (0.87 m/s) were on average 11.5% (0.09 m/s) and 20.8% (0.15 m/s) respectively faster than the male Spanish (0.78 m/s) and English walker speeds (0.72 m/s) ($p<0.05$). Similarly, the female Chinese walker speeds (0.80 m/s) were on average 12.7% (0.09 m/s) and 17.6% (0.12 m/s) respectively faster than the female Spanish (0.71 m/s) and English walker speeds (0.68 m/s)($p<0.05$).

In the up direction, the Chinese rush-hour walker speeds (0.9 m/s) were on average 18.4% (0.14 m/s) and 26.8%(0.19 m/s) respectively faster than the Spanish and English rush-hour walker speeds ($p<0.05$).

No significant difference was recorded between the Spanish and English walker speeds in any of the subgroups ($p>0.5$). The results suggest that escalator walker speeds are similar in Spain and England. However, both male and female walker speeds are considerably faster in China for the up direction.

7.6.5 Flow-rates

The highest flow-rate recorded in all datasets was the up exit flow-rate in the Chinese data where 102 ped/min was recorded. This was 148.8% and 36.0% respectively higher than the highest flow-rates recorded in the Spanish (41 ped/min, exit) and English (75 ped/min, entry) datasets. All of the highest flow-rates in each dataset were recorded on the up escalators. As previously mentioned this was expected as more pedestrians were typically observed simultaneously arriving (from underground trains) at any given time on the up escalators than on the down escalator.

The highest flow-rate recorded in all datasets for a down escalator was in the English dataset where 47 ped/min was recorded. This was 147.4% higher than the Spanish dataset's highest down flow-rate (19 ped/min). As previously mentioned, none of the down flow-rates are expected to be representative of the maximal achievable flow-rates. Indeed the down flow-rates are expected to be reflective of the sporadic arrival of pedestrians to the down escalators rather than behaviour imposed by the dimensions of the escalators.

7.7 Comparison with other studies

This following section compares each of the escalator datasets with escalator data presented in the literature review. This includes a comparison of the data relating to escalator/stair usage, walker/rider usage, walker speeds, and escalator flow-rates. As mentioned in the literature review, no past empirical data regarding escalator side usage could be found. Therefore a comparison of escalator side usage could not be performed.

7.7.1 Escalator/Stair usage

The regression formula developed by Cheung and Lam [Cheung and Lam, 1998] (reproduced in Equation 18 and Equation 19 for clarity) can be used to calculate the probability that an individual pedestrian would use an escalator given the difference between expected travel times to/on an escalator and adjacent stair.

$$P_{esc}^{Down} = \frac{1}{1 + \exp(-3.1001 - 0.1745.xt)}$$

Equation 18

$$P_{esc}^{Up} = \frac{1}{1 + \exp(-5.34411 - 0.2073.xt)}$$

Equation 19

xt = total travel time difference between using the escalator and stair

Using Equation 18 and Equation 19 the probability of an occupant electing to use an escalator can be calculated with the average escalator walker speeds collected for each dataset and the stair/normal walker speeds collected by Fruin [Fruin, 1971] (stair speeds (up; 0.57 m/s, down;0.77 m/s)/normal walker speed (1.35 m/s)). Using these parameters, irrespective of dataset or direction used, the regression formulae predicts that almost all pedestrians (95.7%-99.9%) would elect to use an escalator (see Table 66).

No details regarding escalator height or length were mentioned in the study by Cheung and Lam. However, it is clear that the small height of the escalators/stairs (3.65m-6.29m) in each dataset meant that the travel time difference between walking on the escalators/stairs was small (with 'xt' being calculated between 1.2s-9.0s for each dataset). As such this resulted in a high proportion of escalator users when using Cheung and Lam's regression.

Table 66: Overall proportion of escalator/stair users: Spanish data, Chinese data, English data, Cheung and Lam's regression prediction (given escalator data) [Cheung and Lam, 1998], Zeiler et al [Zeiler, et al., 2010] and Knehs [Knehs, 2010] data

Datasets	Up: % Device Users		Down: % Device Users	
	Escalator	Stairs	Escalator	Stairs
Spanish	86.5	13.5	68.4	31.6
Chinese (non-congested/congested)	76.7 / 35.0	23.3 / 65.0	-	-
English	67.0	33.0	44.7	55.3
Cheung and Lam: Spanish (xt=9.0s)	99.9	0.1	98.1	1.9
Cheung and Lam: Chinese (xt=8.5s)	99.9	0.1	-	-
Cheung and Lam: English(xt=1.2s)	99.6	0.4	95.7	4.3
Zeiler et al and Knehs: Vienna I	N/A	N/A	86.2	13.8
Zeiler et al and Knehs: Vienna II	88.2	11.8	68.0	32.0
Zeiler et al and Knehs: Graz	78.2	21.8	89.0	11.0

Comparing the overall proportion of escalator users in each dataset to that recorded by Zeiler et al [Zeiler, et al., 2010] and Knehs [Knehs, 2010] for the up direction, ranged between 67.0%-88.2% (excluding the Chinese congested periods). In the down direction, with the exception of the English data, a similar range of values were recorded between 68.0%-89.0%. The English dataset represents the only instance where the overall proportion of stair users was greater than the proportion of escalator users.

7.7.2 Walker/Rider usage

As previously mentioned, in the Chinese data almost all escalator users rode adopting both sides which restricted the option of proceeding escalator users to walk. As such only the Spanish and English datasets (i.e. where escalator users had a choice to walk/ride), have been compared with data found in the literature.

From Table 67 it can be seen that the overall proportion of up walkers for the Spanish and English datasets were comparable to Andrews and Boyes [Andrews and Boyes, 1977] off peak data, ranging between 20.0%-27.0%. However, in the down direction the proportion of walkers in each dataset varied considerably (21.0%-60.0%) compared to that recorded by Andrews and Boyes. A large contribution to this difference was the high proportion of walkers recorded by Andrews and Boyes in the peak data.

Table 67: Overall proportion of walkers/riders: Spanish data, English data, and Andrews and Boyes [Andrews and Boyes, 1977]

Datasets	Up %		Down %	
	Walkers	Riders	Walkers	Riders
Spanish	27.0	73.0	21.0	79.0
English	25.2	74.8	25.1	74.9
Andrews and Boyes: Peak	40.0	60.0	60.0	40.0
Andrews and Boyes: Off Peak	20.0	80.0	40.0	60.0

Included within the study by Davis and Dutta [Davis and Dutta, 2002] was a graph presenting the proportion of walkers in the up direction for different escalator heights (see Figure 63). Though no table of values was presented in the study for the graph, the values can be approximated. The lowest proportion of walkers was around 43% at Green Park 4 station with the highest around 62% at Embankment 4 station. This suggests that the proportion of walkers varies at different locations with a maximum range around 19%. The proportion of walkers for the Spanish (27.0%) and English (25.2%) datasets for the up direction were considerably lower than the lowest proportion observed by Davis and Dutta.

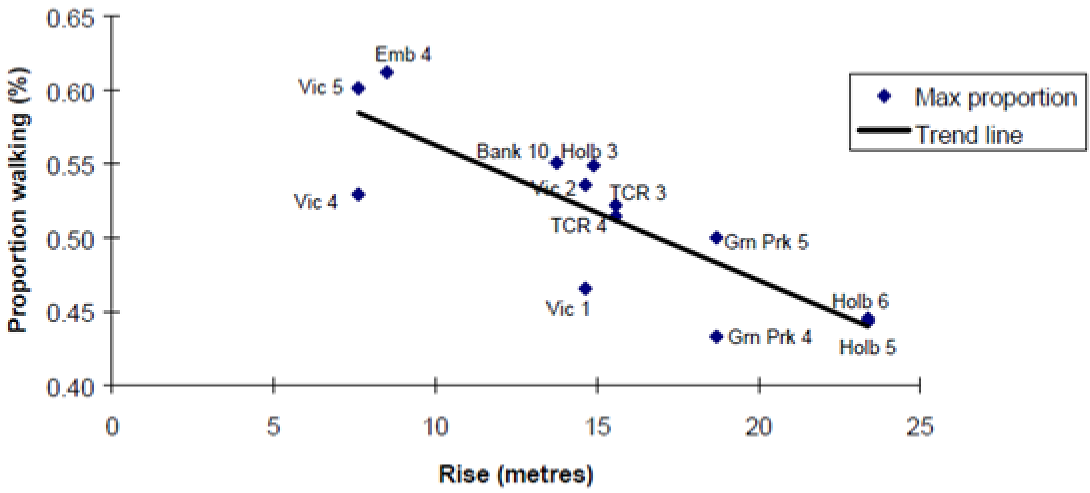


Figure 63: Proportion of walkers using up escalators by Davis and Dutta [Davis and Dutta, 2002]

Considering the escalator heights of both the Spanish (6.29m) and the English (3.65m) datasets, Davis's and Dutta's linear regression suggests that there would be approximately 60% and 62% walkers respectively. These estimated proportions of walkers are considerably higher compared to the observed proportion of walkers in the Spanish (33.0%) and English (36.8%) datasets. It is expected that this can be partially explained by Davis and Dutta only recording the proportion of escalator walkers during peak flow-rate conditions. As such, the proportion of walkers is expected to be inflated due to requiring full tread utilisation in order for peak conditions to be reached (i.e. more walkers using the walker lane). In contrast the proportion of walkers in the Spanish and English datasets were recorded over longer periods of time including non-peak conditions. As such this may explain why such differences in the proportion of walkers was observed.

7.7.3 Walker speeds

Overall average escalator walker speeds from the Spanish, English and Chinese datasets along with results from studies mentioned in the literature review can be seen in Table 68.

Table 68: Escalator characteristics and average horizontal walker speeds (m/s) - Spanish data, Chinese data, English data, Okada et al [Okada, et al., 2009], Kadokura et al[Kadokura, et al., 2009], Cheung and Lam [Cheung and Lam, 1998]

Dataset	Escalator State	Escalator Speed (m/s)	Escalator Height (m)	Escalator Horizontal Length (m)	Up: Walker Speed (m/s)	Down: Walker Speed (m/s)
Spanish	Moving	0.5	6.3	15.5	0.74	0.86
Chinese	Moving	0.5	4.8	11.5	0.83	-
English	Moving	0.5	3.7	8.8	0.71	0.82
Okada1: Healthy	Moving	0.5	5.7	12.3	0.71	-
Okada2: Healthy	Static	0.0	5.7	12.3	0.78	-
Okada3: Healthy	Moving	0.5	22.0	49.5	0.76	-
Okada4: Healthy	Static	0.0	22.0	49.5	0.79	-
Okada5: Instant Senior	Moving	0.5	5.7	12.3	0.43	-
Okada6: Instant Senior	Static	0.0	5.7	12.3	0.53	-
Okada7: Instant Senior	Moving	0.5	22.0	49.5	0.43	-
Okada8: Instant Senior	Static	0.0	22.0	49.5	0.50	-
Kadokura: Incline Speed	Static	0.0	13.2	27.2	0.70	
Cheung and Lam	Moving	0.75	-	-	0.77	0.91

The escalator heights in each study ranged between 3.7m-22.0m, representing a wide range of vertical travel distances. With the exception of the study by Okada et al [Okada, et al., 2009] where participants donned a special suit to mimic an elderly person (instant senior), irrespective of escalator height or state (being static or moving), all the average walker speeds were similar ranging between 0.70-0.83 m/s. This suggests that average up escalator walker speeds are influenced very little by escalator height, motion state or country.

The study by Kadokura et al [Kadokura, et al., 2009] showed that walker speeds on the incline of an escalator remained approximately constant. This suggests that, irrespective of escalator length, fatigue has little influence upon up walker speeds. The instant senior average walker speeds collected by Okada et al [Okada, et al., 2009] were all considerably lower (0.43m/s-0.53 m/s) than that recorded in the other trials/studies (0.70m/s-0.83m/s)). This is expected as the intention of the instant senior was to replicate elderly pedestrians which would likely walk slower.

The study by Cheung and Lam [Cheung and Lam, 1998] was the only study that recorded down escalator walker speeds. The average down walker speeds recorded by Cheung and Lam (0.91 m/s) was similar to both the Spanish (0.86 m/s) and English (0.82 m/s) data. Indeed a similar increase in walker speeds compared to the respective average up walker speeds can also be seen (15.5%-18.2% faster). As with the up direction, this suggests that there is little variation between overall average escalator walker speeds in the down direction between different countries.

7.7.4 Flow-rates

Both CIBSE Guide D [CIBSE, 2000] and Strakosch [Strakosch and Caporale, 2010] state that for an escalator travelling at 0.5m/s that is 1m wide, the maximum theoretical flow-rate is 150 ped/min (irrespective of direction). This can be calculated using Equation 20.

$$Ce = \frac{K.60.Ev}{Sd}$$

Equation 20

Ce = theoretical maximum flow-rate (ped/min)
K = maximum number of people per tread (ped)
Ev = escalator speed (m/s)
Sd = escalator tread depth (m)

For Equation 20 to reach the maximum theoretical flow-rate it is assumed that 2 people per tread with tread depth of 0.4 m is used. However, both CIBSE Guide D and Strakosch state that such theoretical flow-rates are rarely achieved in practice.

The highest flow-rate recorded in the current study was in the Chinese dataset (102.0 ped/min) which is identical to the maximum flow-rate recorded in the experimental trials by Okada et al [Okada, et al., 2009] (102.0 ped/m) (see Table 69). All escalator users rode the escalator in the Chinese data (utilising both sides of the escalator); however, in the trials conducted by Okada et al all escalator users walked. This highlights that different escalator behaviour can result in identical flow-rates. Both of these studies were predominantly made up of individuals from Asian demographics. It has been stated in past studies that Asian pedestrians are typically of smaller physique, require less personal space and are more tolerant to invasion of this space compared to typical Western pedestrians [Tanaboriboon, 1986]. This may have contributed to the higher escalator flow-rates in these Asian escalator datasets due to the subsequent increased crowd density at the entrance to the escalators compared to the Spanish and English datasets.

Table 69: Maximum recorded escalator flow-rates: Spanish data, Chinese data, English data, Al-Sharif [Al-Sharif, 1996], Davis and Dutta [Davis and Dutta, 2002], and Okada et al [Okada, et al., 2009]

Dataset	Speed (m/s)	Width (m)	Up (ped/min)	Down (ped/min)
Spanish	0.5	1	41.0	19.0
Chinese	0.5	1	102.0	-
English	0.5	1	75.0	47.0
Al-Sharif	0.75	1	122.0	140.0
Davis and Dutta	0.72	1	119.0	132.54
Okada: Static Escalator	0	1	66.0	-
Okada: Moving Escalator	0.5	1	102.0	-

The highest flow-rates recorded in the literature reviewed were by Al-Sharif [Al-Sharif, 1996] for both the up (122 ped/min) and down (140.0 ped/min) directions. This represent between 2.0-2.33 pedestrians boarding an escalator every second. These flow-rates were higher for the up and down direction than all of the datasets in the current study. It should be highlighted that the speed of the escalators in the study by Al-Sharif were 0.75 m/s: 50% faster than that of the moving escalators in the other studies. As Equation 20 suggests, increased escalator speed is likely to contribute to increased escalator flow-rates. This would have allowed boarding pedestrians to be transported away from the escalator entrance more quickly, so allow proceeding pedestrians to board sooner.

7.8 Concluding remarks

Human factors data related to escalator usage has been collected in three underground stations each in a different country. The data and subsequent analysis relate to escalator/stair usage, walker/rider usage, side usage, walker speeds and flow-rates. The majority of escalator users across all datasets appeared to be aged between 12-60 years old with very few children or elderly pedestrians being recorded.

Key findings from the analysis are:

- There is a clear preference for pedestrians to use an escalator compared to an adjacent stair. The extent of this preference varies according to country, time period and direction of travel. As expected, pedestrians have a greater preference for using an escalator in the up direction than in the down direction. As crowd congestion levels increase along with subsequent queues for the escalator, the attractiveness of using the escalator decreases.
- Irrespective of country or direction of travel, the majority of pedestrians prefer to ride instead of walk on escalators. The extent to which this occurs can be influenced by time period, with more pedestrians electing to walk during rush-hour periods. It is suggested that this reflects increased levels of pedestrian motivation to traverse the area more quickly due to time restrictions (e.g. getting to work on time). Considering time restrictions imposed by an evacuation, findings suggest escalator users maybe more inclined to walk instead of ride during such situations.
- In both the Spanish and English datasets escalator users exhibited common side preference behaviour whereby the majority of riders used the right side and the majority of walkers used the left side of the escalator. The extent to which escalator users conform to this common side preference varies according to country. In certain countries, escalator users typically conform more to the common side preference behaviour in the up direction during the rush-hour periods. It is suggested that this is due to the increased number of pedestrians using the escalator during these periods. This suggests that escalator users exhibit side preference behaviour in relation to other escalator users. In the Chinese dataset the majority of pedestrians were observed to ride the escalators evenly on both sides. This prevented other escalator users from walking on the escalators. Whilst such behaviour inhibits personal walker/rider choice, it does facilitate an increased flow-rate onto the escalator due to higher crowd densities achieved through increased tread utilisation.
- Overall, escalator users walk faster in the down direction than in the up direction, and males walk faster than females. Time period has been shown to have little influence upon escalator walker speeds. The Spanish and English escalator walker speeds were similar. However, the Chinese walker speeds were significantly faster than both the Spanish and English walker speeds. Comparisons with data presented in the literature review suggest that average escalator walker speeds do not vary a great deal between countries or with escalator height.

- The highest flow-rate recorded in the up direction was in the Chinese dataset (102 ped/min). This was greater than the highest flow-rates recorded in either the Spanish (41 ped/min) or English (75 ped/min) datasets. All of the maximum flow-rates recorded were lower than the theoretical maximum flow-rates (150 ped/min) or the maximum recorded in the literature review (140 ped/min). In all datasets the maximum flow-rates were recorded for up escalators. This was because they were typically used by more pedestrians simultaneously attempting to traverse the area.

There were similarities and differences in the Spanish, English and Chinese datasets. However, it should be kept in mind that there were some differences between the escalator/stair configurations and dimensions in each dataset. The extent to which this influences escalator human factors requires further investigation.

The analysis has highlighted the extent to which a variety of escalator human factors occur. It has also has suggested how certain escalator human factors are influenced by time period, direction of travel and local conditions. Further to this, potential cultural differences have been highlighted.

Chapter 8 - Evacuation Escalator Model

8.1 Introduction

The previous chapter presented data and subsequent analysis of how pedestrians behave on/around escalators during normal circulation situations. During a number of evacuations, evidence suggests that escalator users behave in a similar way as they do in normal circulation conditions [Galea, et al., 2006a; Donald and Canter, 1990]. Combined with the scarcity of empirical evacuation escalator human factors data, suggests that the use of escalator circulation data for the application within an evacuation context is appropriate. The collected data has been used as a basis to develop an evacuation escalator and agent escalator model within buildingEXODUS. The escalator model represents the physical properties and movement speed of an escalator. Components of the agent escalator model relate to escalator human factors analysed in the previous chapter. These include escalator/stair usage, walker/rider usage, side usage, walker speeds and flow-rates. The following chapter presents a description of the developed escalator and agent escalator model. A series of component verification tests have been performed and results presented (see Appendix A6.1) for the developed escalator and agent escalator model. This was to demonstrate the model behaves as intended given a series of input parameters and simulated conditions.

8.2 Physical escalator

The escalator model developed within buildingEXODUS is based around using ‘transit nodes’ to represent escalators. Reiterating what is mentioned in the Chapter 5, a transit node represents a device that allows agents to move between two areas/levels (e.g. stairway, escalator, lift, etc). Further to this, transit nodes provide a set of defining attributes unique to each device (e.g. stair, corridor, etc). This allows users to alter the physical representation of a device within the model. Such attributes provide a mechanism for a user to alter the agent behaviour associated with a given transit node.

Using transit nodes the physical dimensions of stairs can already be represented within buildingEXODUS. These include the number of risers/treads, width, height, horizontal length, and number of lanes. The existing stair model within buildingEXODUS was extended to represent the additional physical and kinematic characteristics of an escalator. This includes the speed of an escalator (m/s), direction of movement (up/down) and the level run distance (m) (the length of the flat sections at the top and bottom of an escalators) (see Figure 64).

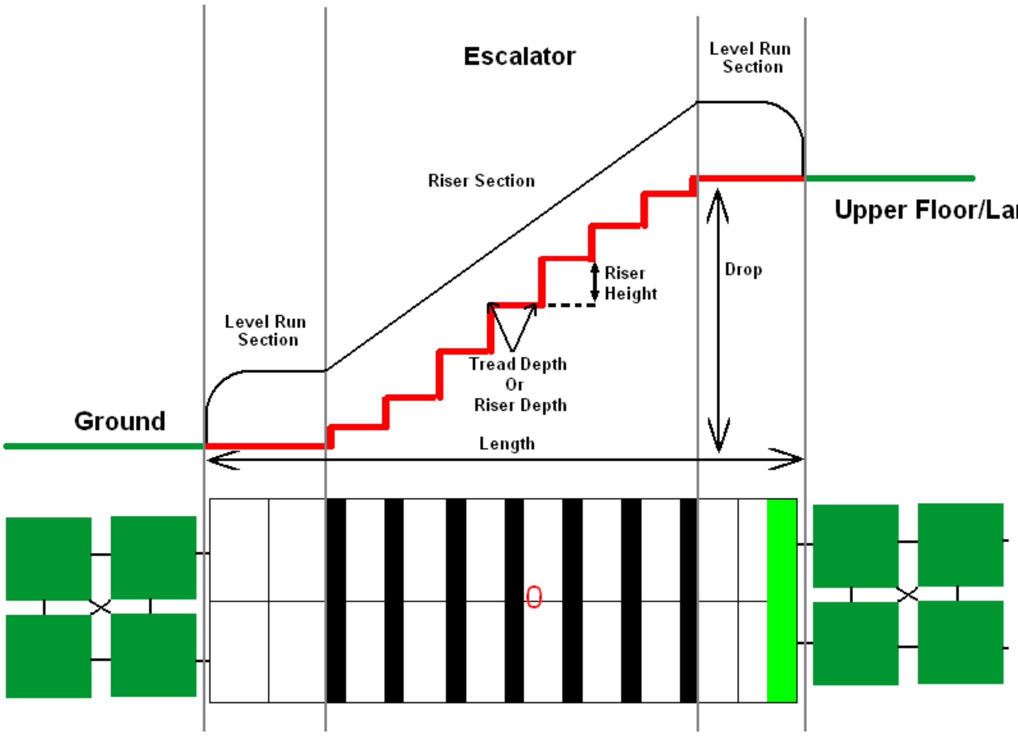


Figure 64: Escalator transit node within buildingEXODUS [Galea, et al., 2006b]

8.3 Escalator agent model

There are two key decision points within the developed agent escalator model: (1) device choice (e.g. escalator/stair selection), (2) escalator behaviour: rider side choice, walker/rider choice, and walker speed selection (see Figure 65).

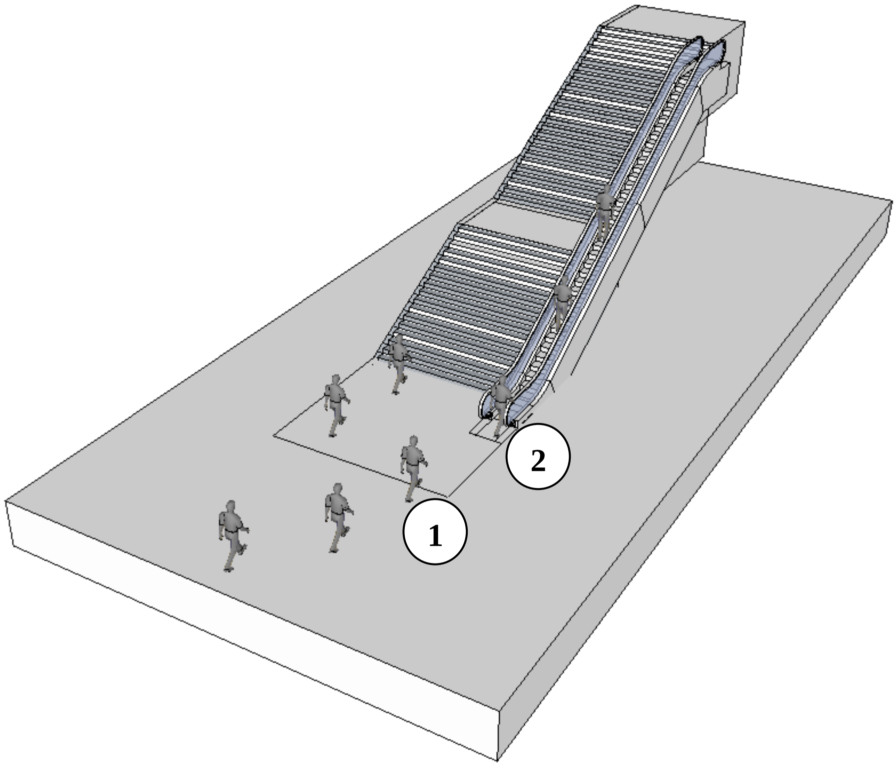


Figure 65: Escalator Agent Model - Key Decision Points: 1- Device Choice, 2- Escalator behaviour

Based on the key decision points, a flow chart showing the main processes that agents make within the escalator agent model can be seen in Figure 66. The model comprises of a series of key components that direct escalator agent behaviour. When an agent enters into a transit node catchment area and needs to vertically traverse the area, they are required to make a decision which transit node they will use. This action is performed using the ***Device choice*** component of the escalator agent model. If an agent has selected to use an escalator transit node, they move towards the escalator. Immediately prior to boarding the escalator, the escalator model checks if the flow-rate or micro-agent system is being employed for the given escalator. If the flow-rate system is employed then agents will be assigned a boarding delay time before boarding the escalator using the ***Flow-rate*** component. If the micro-agent system is employed then the agent will be assigned to be a walker or a rider using the ***Walker/Rider choice*** component. Agents that are assigned to be walkers board the escalator on the nearest available side on the escalator and walk along the escalator using the ***Walker speed*** component. Agents that are assigned to be riders select which side of the escalator they will ride upon using the ***Side preference*** component; only electing to board the escalator on that side.

The default data included in the agent escalator model for each component is based on the London datasets presented in the previous chapter. However, it is possible to alter or use other data within the model. A more detailed explanation of each component of the escalator agent model can be found in the following sections. The section title and corresponding section number have been highlighted for each component in Figure 66.

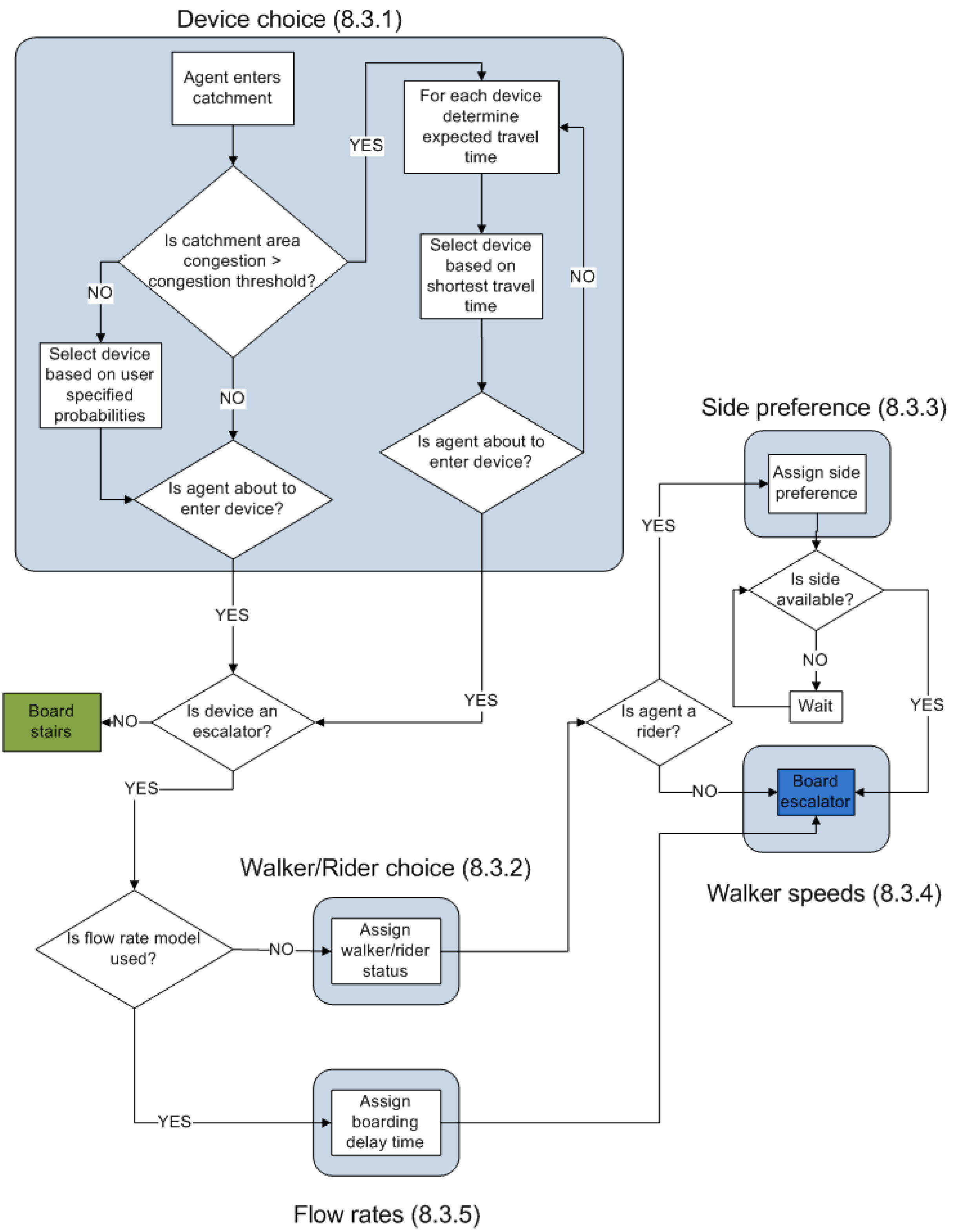


Figure 66: Flow chart showing key components of the escalator agent model and associated chapter sections

8.3.1 Device choice

When an escalator and stair link the same two floors, approaching pedestrians are required make a decision which device they will use. It is suggested that this choice is made within close proximity to the devices so that pedestrians can judge which device to use based on local conditions (e.g. congestion levels, etc). To represent this decision making in the escalator agent model, each transit node within close proximity that links the same levels are clustered together within a 'transit node group'. Each transit node group has an adjustable user-defined catchment area at the top and bottom of the transit node group which defines the spatial boundaries where pedestrians make the decision of which transit node to use within the group (see Figure 67). If transit nodes are not grouped then agents will elect to use a transit node according to which one forms part of their shortest path to the given destination.

For agents that have entered a transit node catchment area there are three separate systems that can determine which transit node they will use in the transit node group (the system employed is specified by the user). These are the proportion system, the shortest time system, and the hybrid system.

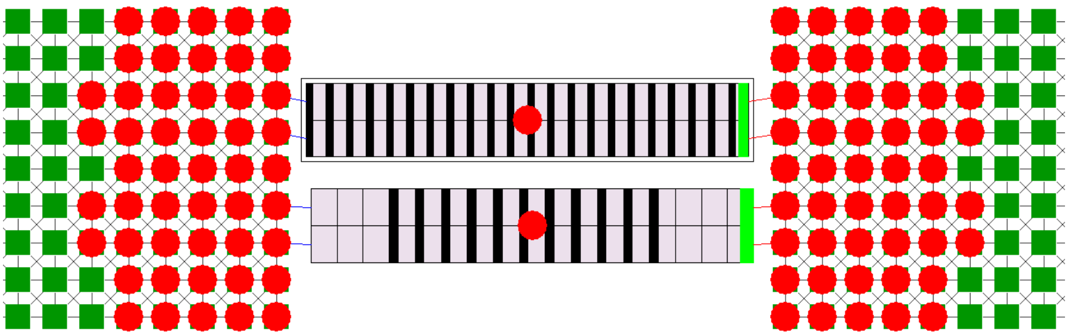


Figure 67: Escalator and stair transit node group with catchment area displayed (red circles).

Proportional System

The proportion system requires the user to explicitly state the proportion of agents that will use each device within a transit node group. Using this system, when an agent enters the catchment area they are assigned a device to use based on the user-specified proportion that are static throughout a simulation. The user-specified proportions are used within buildingEXODUS to form boundaries on a scale between 0-1. When agents enter a transit node catchment area a random number is generated (from a uniform distribution between 0-1). The random number is then compared with the boundaries in order to determine which transit node the agent will elect to use. After this initial device selection agents do not change their choice. This system is most appropriate for scenarios where lower levels of crowding occur at the entrance to the escalator/stair and relies on data that is representative of the type of scenarios being considered. Such a system allows a user to incorporate collected data regarding the proportion of device users, as presented in the previous chapter.

Shortest Time System

The shortest time system relies on each individual agent making a decision as to which device to use based on local conditions. The decision is based on the assumption that the main motivation of the agent is to reduce their overall travel time whilst traversing through the area.

The shortest time system is a theoretical framework which ensures that agents select the device which they expect will allow them to traverse the vertical area in the shortest period of time. This is determined by the agent initially estimating the time it would take to travel to each device based on the distance from their current position and their speed. In addition, agents take into consideration the wait time of other agents between them and the device. These combined wait times are added to the travel time calculation. Further to the travel time to each device, the expected travel time incurred on each device is also estimated. This considers the travel distance on the device, device speed (if any), and the agent's device walker speed. A summary of the travel times calculated for the shortest time system can be seen in Figure 68.

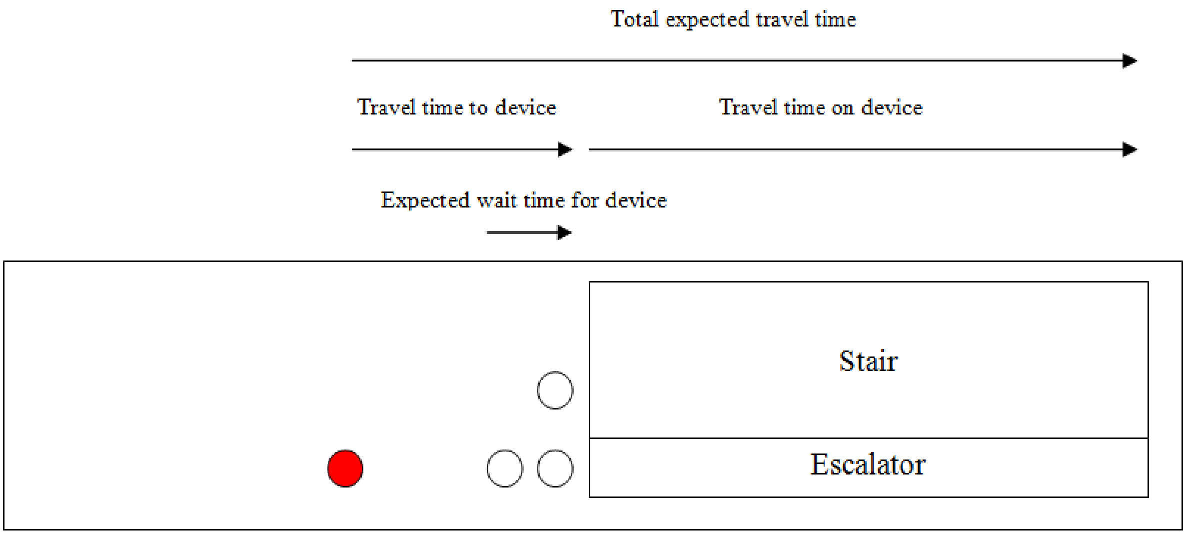


Figure 68: Shortest time system diagram

The total expected travel time for each device is calculated using Equation 21.

$$T(D) = \frac{\mathrm{Dist_{td}}}{\mathrm{WS}} + \sum_{i=0}^{n} \mathrm{WT_i} + \frac{\mathrm{Dist_{od}}}{\mathrm{WS_d} + \mathrm{D_s}}$$

Equation 21

T(D) = total expected travel time (sec)

$Dist_{td}$= distance to device (m)

WS = walker speed on the ground (m/s)

n = number of agents in a straight line path towards the given device

WT_i = current wait time of agent i (sec)

$Dist_{od}$= travel distance on the device (m)

WS_d = walker speed on the device (m/s)

D_s = device movement speed (m/s)

The agent selects the device within the transit node group that provides the shortest expected travel time and moves towards the selected device. Whilst in the catchment area and prior to boarding the desired device, the agent reassesses their device choice and may select another device based on the shortest time system. This reassessment is performed every 2 seconds prior to boarding the device. This reassessment delay is intended to minimise agents 'rebounding' between transit nodes when choosing which device to use (i.e. keep changing their transit node choice in line with the changing number of agents in front of them). This reassessment time of 2 seconds was derived through sensitivity analysis with minimal rebounding occurring for a single escalator/stair. For certain other escalator/stair configurations or scenarios a decreased or increased reassessment time maybe more suitable. Consequently the reassessment time is configurable by the user within the model.

Using the shortest time system agents adapt their device choice in response to other agent behaviour. The shortest time system is most appropriate for scenarios involving motivated pedestrians where high levels of congestion occur at the entrance to the escalator/stair area.

Hybrid System

The hybrid system incorporates both the proportion system and the shortest time system. It decides which of the two systems to use according to the levels of congestion in the transit node catchment area. The selection system requires the user to specify a congestion threshold value for the transit node catchment area. This congestion threshold value can be set between 0-1. It represents the proportion of nodes in the transit node catchment area that are occupied by agents targeting the transit node group. For example, a congestion threshold value of 0.5 represents 50% of nodes in the transit node catchment area that are occupied by agents targeting the transit node group. Using the default 0.5m node/arc representation this represents a congestion density of 2 ped/m^2. When the levels of congestion in a catchment area are below the congestion threshold, agents entering into the catchment area select the device to use based on the proportion system. When the levels of congestion reach or exceed the congestion threshold, agents select which device to use based on the shortest time system. This hybrid system allows suboptimal device selection behaviour to be represented at low levels of congestion and adaptive device selection at higher levels of congestion. As such the device selection system is appropriate to use when both low and high levels of congestion are experienced at the entrance to a transit node group over the course of a simulation.

Within buildingEXODUS all three device selection systems can be accessed through altering the congestion threshold value set by the user: 0 (shortest time system), 1 (proportional system), 0-1 (hybrid system).

Whilst each dataset in the previous chapter only analyzed pedestrian choice between a single escalator and adjacent stair, the developed model will allow users to incorporate as many escalators/stairs as is required.

8.3.2 Walker/Rider choice

Agents that elect to use an escalator, immediately prior to boarding the escalator, are required to choose whether they will ride or walk on the escalator. This is determined by user-specified proportions associated with the escalator. The user specifies the proportion of agents that will walker on the escalator. As with the proportion device selection system, this is then used to form boundaries on a scale between 0-1 associated with walking/riding. When agents are about to board an escalator a random number is generated (from a uniform distribution between 0-1). The random number is then compared with the boundaries to that defined by the user-specified proportions in order to determine whether the agent will walk or ride on the escalator. Very few pedestrians were observed to both walk and ride on the escalators in the data (see previous chapter). As such the model assumes that agents do not alter their decision to be a walker or rider whilst on the escalator.

8.3.3 Side preference

Agents that elect to use an escalator and choose to be a rider are required to decide which side of the escalator to use. This is defined by user-specified proportions. The remaining agents that walk on an escalator utilise any available side in order to keep walking and are not constrained by which side to use in the model. From the data in the previous chapter, few riders typically used the centre position or varied their position as they traversed the escalator. As such riders in the model can only opt to use either the left or right side of an escalator. As with the proportion device selection system, the user-specified proportions are used to form boundaries on a scale between 0-1 associated with riders using the left/right side. When agents are about to board an escalator and elect to be a rider, a random number is generated (from a uniform distribution between 0-1). The random number is then compared with the boundaries to that defined by the user-specified proportions in order to determine whether the agent will use the left or right side of the escalator. If an agent is blocked from boarding their chosen side by an agent in front, they will delay boarding until that side becomes available. This ensures the specified proportion of riders that use each side of the escalator is maintained.

8.3.4 Walker speeds

Agents that elect to use an escalator and choose to be a walker, will attempt to move along the length of the escalator at their assigned escalator walker speed for the given direction. This is represented by calculating the horizontal distance an agent would move along the escalator considering their horizontal escalator walker speed and the horizontal speed of the escalator for each time step of the simulation. The agent's location on the escalator is then updated each time step. If a walking agent is blocked by another agent in front then they will attempt to move around the agent using the opposite side of the escalator. As such the actual speed that agents walk along an escalator can be restricted by other preceding slower moving agents on the escalator.

8.3.5 Flow-rates

An alternate method to the previously presented micro-level escalator model is to use the flow-rate model that sets a capping flow-rate upon agents boarding the escalator. The specified flow-rate, stated in pedestrians per second, is used to define a minimum delay time between any two agents boarding the escalator (i.e. a proceeding agent has to wait a minimum amount of time before they can board the escalator). The calculation for this can be seen in Equation 22 below.

$$t_{MinDelay} = \frac{1}{F}$$

Equation 22

$t_{MinDelay}$ = minimum escalator delay time (min)

F = user-specified flow-rate (ped/min)

The flow-rate specified is a capping value to ensure that the number of agents boarding an escalator over a period of time is not exceeded. Once agents board an escalator they are assigned a travel speed from a uniform distribution defined by a user specifying a maximum and minimum value. The time each agent takes to traverse the escalator is then calculated according to length of the escalator, their assigned walker speed (assigned from the max/min distribution) and the escalator speed. As such either all agents can be assigned to be riders (all assigned a walker speed of 0 m/s) or all agents are assigned to be walkers (all assigned a random speed between the maximum and minimum range specified). No inter-agent or micro-level behaviour on the escalator (e.g. side preference, etc), blocking, queuing, etc is explicitly represented in the flow-rate model. After an agent's traversal time on the escalator has expired they will alight at the opposite end of the escalator. The flow-rate model is considered a simplified representation of escalator human factors with limited implicit representation of such factors. It is considered appropriate for users who wish to reduce computational overhead (e.g. using large geometries), only have/require maximum flow-rates to be represented, or wish to compare results with empirical calculations (that typically use flow-rates).

8.4 Concluding remarks

This chapter has described the developed escalator and agent escalator model within the buildingEXODUS software. The escalator model represents both the physical and kinematic features of an escalator. The agent escalator model represents the occupant interaction with an escalator. Escalator human factors represented include device choice, walker/rider choice, side preference, and walker speeds. In addition, an escalator flow-rate model has also been developed. The escalator agent model is controlled via a series of user-specified values that define how agents in a simulation interact with an escalator. The developed model allows the escalator human factors data presented in Chapter 7 to be represented. Further to this, the model allows users to measure how different escalator human factors may influence an evacuation. The developed model permits users to explicitly represent different micro-level escalator human factors. Results from Chapter 7 suggest that escalator human factors vary between different countries. The developed model provides a mechanism to explicitly represent such differences. Results from component verification testing of the model have been presented (see Appendix A6.1) which show the model to produce expected results based on given input parameters and simulated conditions.

Chapter 9 - Case Study: Underground Station Escalator Evacuation

9.1 Introduction

A series of evacuation scenarios have been performed using the developed escalator model and escalator agent model presented in the previous chapter. A description of the geometry, escalator attributes, population and scenarios is presented followed by the results. The purpose of the evacuation scenarios is to demonstrate the extent to which different escalator strategies and escalator human factors influence an evacuation.

9.2 Geometry

The building used for the simulations was a hypothetical underground station. The geometry consisted of 2 levels. The lower level contained a double-sided platform below ground connected via 5 escalators, each with adjacent stairs, to a ticket hall level above. The ticket hall level is where the exits of the station are located. In addition, an emergency stair was positioned at either end of the platform (see Figure 70). The platform was 18m wide and approximately 140m long. Each escalator/stair enclosure linking the platform to the ticket level was approximately 7.5m in width and 15m in length. The total area of the platform was 2,520m^2-112.5m^2 = 2,407.5m^2. Each escalator/stair had identical dimensions to the escalators/stairs observed in the Spanish data (see Figure 69) with the escalator travelling at 0.5m/s. The Spanish escalator/stair dimensions were chosen as they were the longest escalator/stairs in all three studies presented in Chapter 7. As such is expected that escalator human factors would have greater influence for longer vertical distances.

The emergency stairs located at either end of the platform level had the identical dimensions to the adjacent stairs to the escalators. However, the emergency stair at the south end of the platform had a slight variation with the top flight being of a dog legged configuration connecting to the ticket hall level above.

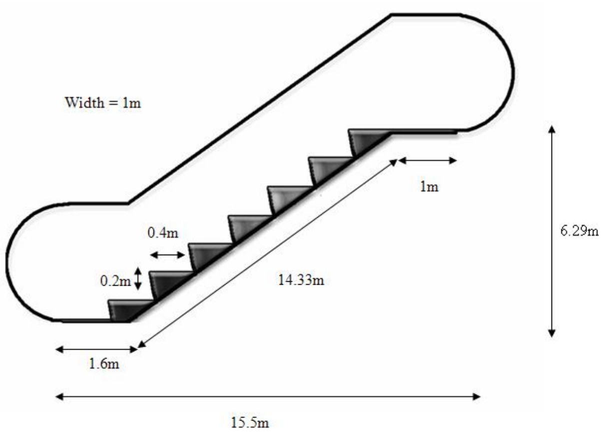
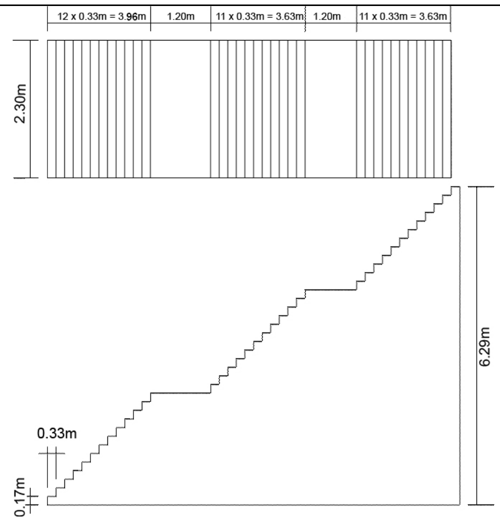
	
A: Escalator dimensions	**B: Stairway dimensions**

Figure 69: Case study escalator (a) and stair (b) dimensions

Each escalator/stair was arranged into transit node groups. Each transit node group had a catchment area size of 4m from the escalator/stair transit nodes. This was determined as a suitable size considering the initial level of congestion on the platform. It allowed agents to change their device selection without being over committed to using a given device considering the layout of the geometry and the number of agents already on the platform.

The geometry had two exits (Exit 1 and Exit 2) both located on the ticket hall level (see Figure 70). Exit 1 was 18m in width and Exit 2 was 7m in width, both representing an open plan exit without doors. The maximum travel distance to Exit 1 and 2 was 67.3m and 68.3m respectively from the platform level.

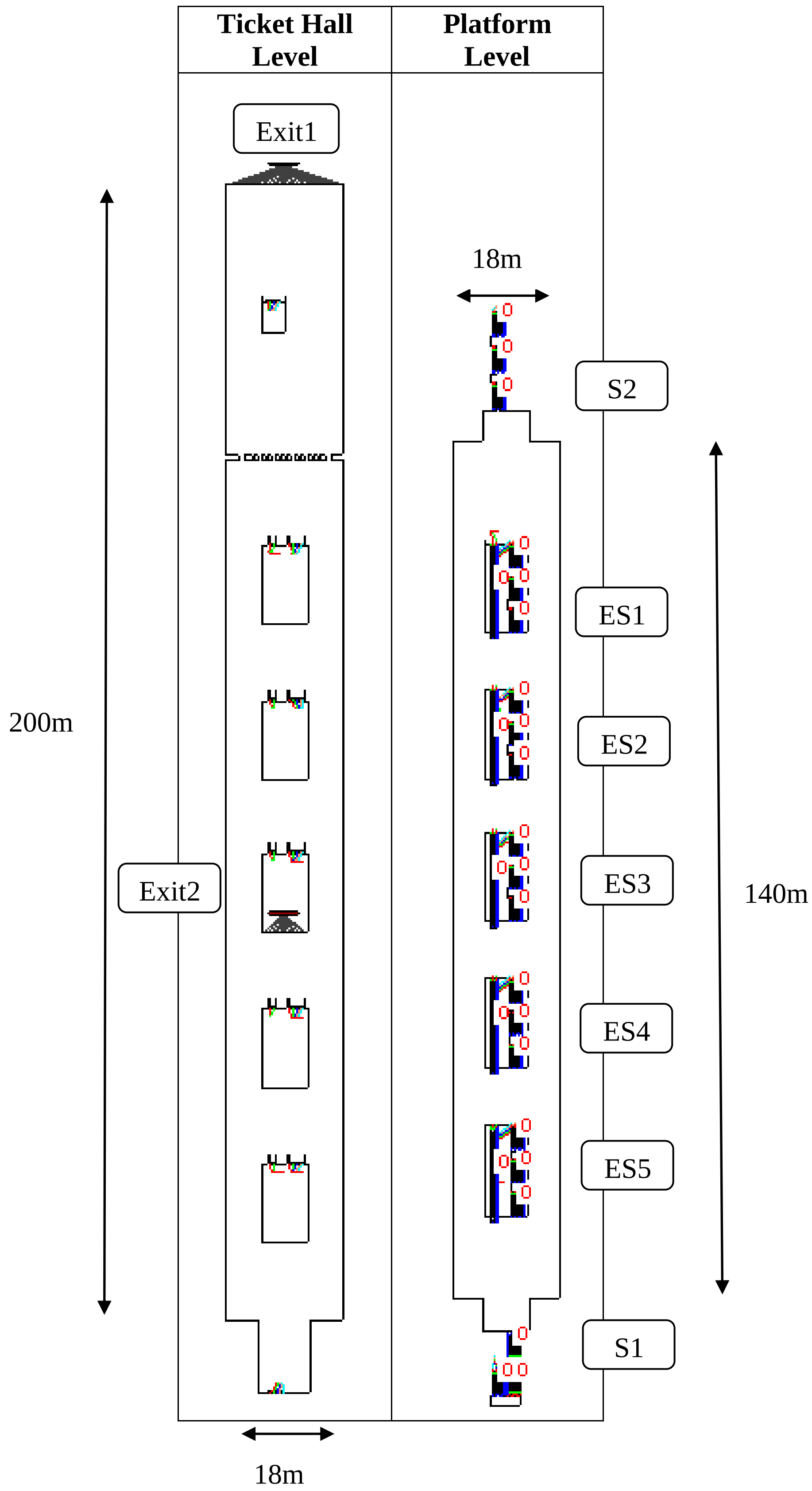


Figure 70: Hypothetical underground station geometry (ES=Escalator/Stair, S=Stair)

9.3 Population

Within each scenario agents were modelled as non-connected individuals and were not constrained by groups. The demographics of the agent were assigned according to the default population within buildingEXODUS, representing a broad cross-section of attributes and capabilities [Galea, et al., 2006b].

The NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems 2010 [NFPA, 2010] includes recommendations for maximum occupancy levels within train stations. It states that the maximum agent load for a train station shall be based on trains simultaneously arriving at each platform within a station plus the simultaneous arrival of agents entering the station for each train during peak times. The 1996 Rolling Stock 7 car design (currently used on the Jubilee line in the London Underground, UK) spans a length of approximately 124 metres which is similar to the platform length in the hypothetical geometry. Such trains allow a maximum train capacity of 964 passengers (234 sitting, 730 standing) [Transport, 2010a].

In addition to representing occupants simultaneously arriving on trains at each platform, those occupants that would already be waiting on each platform was also required to be represented. The platform waiting occupancy has been proposed to be 50% of the maximum train capacity. In the given geometry this equates to 2x482=964 agents (for two trains on either side of the platform). This waiting occupancy frequency is considered to be the upper limit of the maximum platform occupancy. All occupants initially on the platform level were assumed to be located on the platform itself and no representation of occupants disembarking trains is represented. This assumes that escalators/stairs and associated human factors were considered the main constricting factor upon the platform evacuation. Combined with the maximum capacity for a train on each platform gives a total platform level occupancy of 2,892 agents. The total level of occupancy on the platform is considered maximal and meant that on average the platform effectively had approximately 1.2 ped/m² which corresponds to Fruin's level of service E described as "Standing in physical contact with others is unavoidable" [Fruin, 1971].

Within each scenario approximately an even number of agents initially on the platform level elect to use each escalator/stair to traverse to the ticket hall above as part of their egress (see Table 70). The initial agent starting locations on the platform were specified such that these frequencies for device usage were achieved with agents using their nearest escalator/stair. This was to ensure that any single escalator/stair component was not disproportionally oversubscribed (so extending the evacuation). Though uneven escalator/stair loading would decrease the efficiency of an evacuation the focus on the investigation is how escalator strategies and human factors influence an evacuation. Approximately 10% (388) of all platform agents were assumed to use the emergency stairs at either end of the platform. This represents the decreased usage (compared to the main escalator/stair) due to the expected lack of familiarity with stairs due to not being used during normal circulation situations.

The ticket hall level above was assumed to be initially occupied by the same number of waiting agents on a single platform (964). This was intended to represent both entering and exiting agents to the station. The frequency of agents initially on the ticket level were assigned to use each exit according to the proportion of the aggregated width each exit provided; with 28.0% (270) assigned to Exit 1 and 72.0% (694) assigned to Exit 2. As with the escalator/stair assignment on the platform level, this was to minimise the influence of uneven usage of exits and the potential decreases in evacuation efficiency caused. Combining the total platform and ticket level occupancy, the entire occupancy of the station was 3,856 agents.

Table 70: Device frequency usage

Device(s)	**% Throughput Provision for level**	**Approximate Agent Frequency Usage in each Simulation**
ES1	18.0	521
ES2	18.0	521
ES3	18.0	521
ES4	18.0	521
ES5	18.0	520
S1	5.0	144
S2	5.0	144
Platform Total		2,892
Exit 2	51.2	270+ 1706 (S2+ES3+ES4+ES5) = 1,976
Exit 1	48.8	694 + 1186 (S1+ES1+ES2) = 1,880
Total	100	3,856

The Chinese Design Code for Subway platforms [Planning, 2003] specify an average evacuation response/pre-movement time of 60 seconds for agents on a transit station. Such specifications have been typically used to assess upper limit design requirements. With this in mind, agents within the modelled scenarios were randomly uniformly assigned a response/pre-movement time range between 0-120 seconds (0-2 minutes) with an average of 60 seconds.

For Scenarios 9,10 and 11, where a different number of escalators/stairs were available during the evacuation, Table 71 shows the agent frequency distribution that were used for each escalator/stair/exit with approximate even usage of the escalator/stair pairs. When an escalator/stair is unavailable in a given scenario the agents that would have used the unavailable escalator/stair were evenly redistributed among the other escalators/stairs.

Table 71: Scenario 9, 10 and 11 escalator/stair/exit frequency usage

	Scenario 9		**Scenario 10**		**Scenario 11**	
Device(s)	**% Of Agent Usage**	**Agent Frequency Usage**	**% Of Agent Usage**	**Agent Frequency Usage**	**% Of Agent Usage**	**Agent Frequency Usage**
ES1	-	-	-	-	-	-
ES2	22.5	651	30.0	868	45.0	1302
ES3	22.5	651	30.0	868	-	-
ES4	22.5	651	30.0	868	45.0	1302
ES5	22.5	651	-	-	-	-
S1	5.0	144	5.0	144	5.0	144
S2	5.0	144	5.0	144	5.0	144
Platform Total		2,892		2,892		2,892
Exit 2	61.4	270+ 2,097 (S2+ES3+ES4+ES5) = 2,367	55.8	270+1,880 (S2+ES3+ES4) = 2,150	44.5	270+1,446 (S2+ES4) = 1,716
Exit 1	38.6	694 + 795 (S1+ES2) = 1,489	44.2	694 + 1,012 (S1+ES2) = 1,706	55.5	694 +1,446 (S1+ES2) = 2,140
Total	100	3,856	100	3,856	100	3,856

Agents were assigned escalator walker speeds derived from the English walker speed distribution (see Chapter 7). This is with the exception of scenarios where agents did not walk on the escalators, the escalators were static or where specific walker speed datasets were used. The English walker speed distributions were used as they were the largest and most complete walker speed distributions out of the three studies (see Chapter 7). The walker speeds were also considered appropriate considering the hypothetical station occupancy levels were based around the English London Underground rolling stock capacities for a specific carriage type. The walker speed distributions were defined according to gender and direction of travel.

Whilst data pertaining to agent tread spacing on escalators was not collected in the previously presented studies, Al-Sharif [Al-Sharif, 1996] has stated that escalator users rarely occupy every available tread. Considering this, the transit node packing option within buildingEXODUS was employed in each simulation for both escalators and stairs. Using the default settings, this meant that on stairs agents were required to maintain at least a 2 tread spacing between them and any agent in front of them (i.e. agents can occupy every other tread). For escalators this meant that riders were required to keep at least a 1 tread spacing and walkers a 3 tread spacing between them and any agent in front of them (based on observations by Al-Sharif [Al-Sharif, 1996]).

9.4 Scenarios

A series of 14 evacuation scenarios have been performed exploring the influence of different escalator strategies and escalator human factors upon an evacuation (see Figure 73). In Scenario 2, each escalator was static though agents could still walk up the escalators if they chose to. No data was collected with regards to static escalator walker speeds in each of the studies. As such agents assessed whether to use a static escalator based on their stair walker speed. If agents elected to use the static escalator they would use their stair walker speed to traverse the escalator.

Scenarios 3-8 explored the impact of different human factors upon an evacuation. This included analysing the influence of the number of escalator/stair users, number of walkers/riders, ride side usage, and different congestion threshold values. Scenarios 9, 10 and 11 focused on the influence of escalators/stairs being unavailable. The final three scenarios (Scenarios 12-14) employed the escalator human factors data analysed within Chapter 7 each relating to a different country. Due to the escalator model representing two lanes of an escalator, the rider side usage data from each dataset was normalised to only include the right and left side for these scenarios. Considering the low proportion of riders that elected to use the centre position or varied their position on the escalator, this was considered to have little influence upon the results. Whilst congestion level data at the entrance to each escalator/stair was not collected in the Spanish and English data, a congestion threshold value (CT) of 1ped/m^2 was used in each of these scenarios (i.e. the same as that used in the Chinese data). This was to allow agents in these scenarios to adapt their behaviour according to the congestion at the base of the escalator/stair for these scenarios.

Table 72: Overview of evacuation scenarios - Attribute Settings

Scenario	Escalator Motion (Moving/ Static)	Escalator/Stair (%)		Walker/Rider (%)		Rider Side Usage (%)		Escalator Walker Speeds (S/C/E)	Congestion Threshold (CT) (ped/m^2)	Description
		Escalator	Stair	Walker	Rider	Left	Right			
1	-	0	100	-	-	-	-	-	-	Stair only
2	Static	-	-	-	-	-	-	{stair walker speeds}	0	Stairs + Static Escalator (stair-walker speeds on escalator)
3	Moving	50	50	0	100	-	100	-	-	50/50 Stairs/Esc + 100 Riders (100 Right)
4	Moving	-	-	100	0	-	-	English	0	Stairs/Esc + Shortest time + 100 Walkers
5	Moving	-	-	0	100	50	50	-	0	Stairs/Esc + Shortest time + 100 Riders (50/50)
6	Moving	-	-	0	100	0	100	-	0	Stairs/Esc + Shortest time + 100 Riders (100 Right)
7	Moving	50	50	100	0	0	0	English	1	50/50 Stairs/Esc + Shortest time/CT 1ped/m^2 + 100 Walkers
8	Moving	50	50	100	0	0	0	English	2	50/50 Stairs/Esc + Shortest time/CT 2ped/m^2 + 100 Walkers
9	Moving	-	-	100	0	-	-	English	0	Stairs/Esc + Shortest time + 100 Walkers +No Stair/Esc 1
10	Moving	-	-	100	0	-	-	English	0	Stairs/Esc + Shortest time + 100 Walkers + No Stair/Esc 1/5
11	Moving	-	-	100	0	-	-	English	0	Stairs/Esc + Shortest time + 100 Walkers + No Stair/Esc 1/3/5
12	Moving	83.3	16.7	29.2	70.8	3.5	96.5	Spanish	1	Spanish Data (up rush-hour/normalised side%)
13	Moving	75.6	24.4	3.3	96.7	50.7	49.3	Chinese	1	Chinese Data (up rush-hour/normalised side%)
14	Moving	75.3	24.7	34.5	65.5	5.4	94.6	English	1	English Data (morning up rush-hour/normalised side %)

9.5 Results

A summary of results for each scenario is presented in Table 73 with evacuation curves shown in Figure 71. The average frequencies/proportions of escalator/stair users are presented in Table 74. Due to the short times involved in evacuating a relative small structure compared to the high-rise lift evacuation analysis, results have been presented in seconds rather than minutes.

Table 73: Average TET, PET, CWT, Platform Clearance Time, Door 1 and 2 Exit times for each scenario (average of 5 simulations)

Scenario	Avg TET (sec)	Avg PET (sec)	Avg CWT (sec)	Platform Clearance Time (sec)	Overall: % Time Saved Compared to Stairs Only	Overall: % Time Saved Compared to Stair+Static Escalator	Platform: % Time Saved Compared to Stairs Only	Platform: % Time Saved Compared to Stair+Static Escalator
1	429.1	67.4	67.6	336.6	-	-21.6	-	-23.4
2	352.9	66.0	40.5	272.8	17.8	-	19.0	-
3	379.9	66.0	42.7	307.1	11.5	-7.7	8.8	-12.6
4	324.8	67.6	36.3	245.6	24.3	8.0	27.0	10.0
5	338.7	67.3	36.6	268.1	21.1	4.0	20.4	1.7
6	361.3	67.6	40.9	291.3	15.8	-2.4	13.5	-6.8
7	321.3	67.3	32.6	246.7	25.1	9.0	26.7	9.6
8	314.7	67.3	31.5	229.3	26.7	10.8	31.9	15.9
9	367.2	67.2	46.2	269.7	14.4	-4.1	19.9	1.1
10	421.0	66.6	56.9	327.0	1.9	-19.3	2.9	-19.9
11	563.8	73.7	95.7	468.0	-31.4	-59.8	-39.0	-71.6
12	343.4	67.4	36.1	255.6	20.0	2.7	24.1	6.3
13	332.0	67.3	32.4	245.9	22.6	5.9	26.9	9.9
14	336.3	67.4	35.1	254.1	21.6	4.7	24.5	6.9

Scenario 1 represents a situation representative of common practice in an actual evacuation [British Standards, 2008; Communities, 2006] whereby the escalators are not used and agents were required to use only the stairs. This scenario produced the second longest Total Evacuation Time (TET) of 429.1s with the platform taking 336.6s to clear. On average agents spent just over one minute waiting in congestion with the average Cumulative Wait Time (CWT) being 67.6s. Another common practice during an evacuation is to turn the escalators off, but allow agents to walk on the device. If it is assumed that agents elect to use a device based on the shortest time system (Scenario 2), the TET reduces to 352.9s, a decrease of 17.8% (76.2s). In addition, the platform clearance time also reduces to 272.8s, a decrease of 19.0% (63.8s). On average approximately a quarter of agents (26.1%) who made an escalator/stair choice, used an escalator. This reflects the influence of the increased width of the stairs compared to the static escalator.

In Scenario 3 the escalators were turned on, agents were evenly assigned to use both the escalators/stairs and all escalator users rode on the right side. During this scenario a small increase (7.7% (27.0s)) in TET to 379.9s was observed compared to the static escalator case

(Scenario 2). If it is now assumed that agents elect to use a device based on the shortest time system with all escalator users walking (Scenario 4), the TET reduces even further to 324.8s. This represents a decrease of 24.3% (104.3s) compared to the stair only scenario and was one of the fastest scenario recorded. Similarly the platform clearance time also decreased by 27.0% (91s) to 245.6s compared to the stair only scenario. A reduction in average CWT by almost a half (46.3% (31.3s)) to 36.3s was also recorded compared to the stair only scenario. On average a higher proportion of agents elected to use the escalator (59.5%) compared to the stairs (40.5%). An increased overall average flow-rate of agents onto the escalators (87.7 ped/min) was observed compared to Scenario 3 (68.3 ped/min) where agents were only allowed to board the right side and ride the escalator.

Table 74: Average Proportions/Frequencies of escalator/stair users (per escalator/stair pair)

Scenario	ES1 % [Freq]		ES2 % [Freq]		ES3 % [Freq]		ES4 % [Freq]		ES5 % [Freq]		Overall Avg. % [Freq]	
	Esc	**Stair**	**Esc**	**Stair**	**Esc**	**Stair**	**Esc**	**Stair**	**Esc**	**Stair**	**Esc**	**Stair**
1	0.0 [0]	100 [521]	0.0 [0]	100 [521]	0.0 [0]	100 [521]	0.0 [0]	100 [521]	0.0 [0]	100 [520]	0.0 [0]	100 [2604]
2	28.4 [147.8]	71.6 [373.2]	27.1 [141]	72.9 [380]	25.3 [131.8]	74.7 [389.2]	23.9 [124.6]	76.1 [396.4]	25.8 [134]	74.2 [386]	26.1 [679.2]	73.9 [1924.8]
3	48.8 [254.2]	51.2 [266.8]	51.7 [269.6]	48.3 [251.4]	51 [265.6]	49 [255.4]	49.7 [258.8]	50.3 [262.2]	49.3 [256.4]	50.7 [263.6]	50.1 [1304.6]	49.9 [1299.4]
4	62.5 [325.6]	37.5 [195.4]	58.1 [302.6]	41.9 [218.4]	58.7 [305.8]	41.3 [215.2]	58.5 [304.8]	41.5 [216.2]	59.7 [310.6]	40.3 [209.4]	59.5 [1549.4]	40.5 [1054.6]
5	57.7 [300.4]	42.3 [220.6]	58.4 [304.2]	41.6 [216.8]	58.4 [304.4]	41.6 [216.6]	58.6 [305.4]	41.4 [215.6]	59.1 [307.2]	40.9 [212.8]	58.4 [1521.6]	41.6 [1082.4]
6	45.1 [235.2]	54.9 [285.8]	50.6 [263.4]	49.4 [257.6]	52.6 [273.8]	47.4 [247.2]	51.4 [267.6]	48.6 [253.4]	52.4 [272.6]	47.6 [247.4]	50.4 [1312.6]	49.6 [1291.4]
7	51.3 [267.2]	48.7 [253.8]	53.9 [280.8]	46.1 [240.2]	47.3 [246.4]	52.7 [274.6]	47.7 [248.6]	52.3 [272.6]	47.9 [249.2]	52.1 [270.8]	49.6 [1292.2]	50.4 [1312]
8	46 [239.6]	54 [281.4]	49.9 [260]	50.1 [261]	45.3 [236.2]	54.7 [284.8]	44.9 [234]	55.1 [287]	46.2 [240.2]	53.8 [279.8]	46.5 [1210]	53.5 [1394]
9	0.0 [0]	0.0 [0]	55.2 [359.4]	44.8 [291.6]	54.4 [354.2]	45.6 [296.8]	52.6 [342.4]	47.4 [308.8]	56 [364.6]	44 [286.4]	54.6 [1420.6]	45.4 [1183.6]
10	0.0 [0]	0.0 [0]	52.8 [458.2]	47.2 [409.8]	52.4 [455.2]	47.6 [412.8]	49.3 [428]	50.7 [440]	0.0 [0]	0.0 [0]	51.5 [1341.4]	48.5 [1262.6]
11	0.0 [0]	0.0 [0]	52.0 [676.6]	48.0 [625.4]	0.0 [0]	0.0 [0]	48.6 [633.2]	51.4 [669]	0.0 [0]	0.0 [0]	50.3 [1309.8]	49.7 [1294.4]
12	41.9 [218.2]	58.1 [302.8]	52 [271]	48 [250]	46.8 [243.8]	53.2 [277.2]	44.3 [231]	55.7 [290.2]	46.5 [241.6]	53.5 [278.4]	46.3 [1205.6]	53.7 [1398.6]
13	51.7 [269.4]	48.3 [251.6]	55 [286.4]	45 [234.6]	52.3 [272.4]	47.7 [248.6]	50.6 [263.6]	49.4 [257.4]	49.8 [259]	50.2 [260.8]	51.9 [1350.8]	48.1 [1253]
14	42.4 [221]	57.6 [300]	51.9 [270.4]	48.1 [250.6]	47.8 [249]	52.2 [272]	44.9 [233.8]	55.1 [287.2]	46.5 [241.8]	53.5 [278.2]	46.7 [1216]	53.3 [1388]

In Scenario 5 all escalator users were assumed to ride with an even number adopting each side. In this scenario an average decrease in TET of 10.8% (41.2s) and 12.7% (38.9s) in platform clearance time can be seen compared to when escalator users all rode on the right side (Scenario 3). Compared to when all escalator users walked (Scenario 4), only a slight increase in TET (5.2% (16.9s)) and platform clearance time (9.2% (22.5s)) was recorded.

Scenario 6 is identical to Scenario 3 where all escalator users rode on the right side, except that agents used the shortest time system for device selection instead of evenly being assigned. A slight decrease in TET by 4.7% (17.7s) was observed compared to Scenario 3 with a similar reduction (5.1% (15.8s)) in platform clearance times. Approximately an even number of agents used each escalator/stair with the average PET/CWT being similar in both scenarios. Indeed each escalator/stair was adopted by approximately an even number of agents through the use of the shortest time system (see Table 74) in Scenario 6 which would account for the similarities with Scenario 3.

Scenario 7 extended Scenario 4 by using the hybrid device selection system. In this scenario a Congestion Threshold (CT) value of 1ped/m^2 was set with even usage of each escalator/stair imposed before the CT was reached. The scenario produced one of the shortest TETs (321.3s) and platform clearance times (246.7s). It was comparable to Scenario 4 where all agents used the shortest time system when choosing to use an escalator/stair. In Scenario 4 approximately an even number of agents used each escalator/stair. As such assigning an even proportion of agents to use each device before a given level of congestion was reached in Scenario 7 had little effect. A similar phenomenon occurred in Scenario 8 where the altered CT of 2ped/m^2 had little influence upon the overall evacuation compared to Scenario 4.

The concept of reducing escalator/stair availability is introduced in Scenario 9. In this scenario ES1 was unavailable with agents who would have used ES1 evenly using the remaining escalators/stairs. In addition, the shortest time system was used with all escalator users walking. Both the TET and platform clearance times were marginally longer by 13.3% (42.4s) and 9.8% (24.1s) respectively compared to when all escalators/stairs were available (Scenario 4). Scenario 10 extends the escalator/stair unavailability concept to two escalator/stairs (ES1 and ES5) being unavailable at either end of the platform. Here an average TET of 421.0s and platform clearance time of 327.0s was recorded which is similar to the time taken to evacuate the station in the stair only scenario (Scenario 1). Despite this, the evacuation rate was notably higher than the stair only case for a large proportion of the TET: between approximately 42.8% (180s) - 87.9% (370s) of the TET (see Figure 71). This was due to the added vertical throughput afforded by the available escalators and escalator users all walking. The TET from Scenario 10 increased by 29.6% (96.2s) compared to Scenario 4 where all escalators/stairs were available. The final scenario involving escalator/stair unavailability was Scenario 11 where 3 escalators/stairs were unavailable. This scenario produced the longest TET of all scenarios at 563.8s, representing a 73.6% (239.0s) increase compared to Scenario 4 where all escalator/stairs were available. In all scenarios involving escalators/stairs being unavailable approximately an even number of agents used each device. The escalator/stair availability results suggests that there may not be a linear increase in time with linear decrease of escalators/stairs availability. Escalator human factors have been shown to impact the extent to which platform clearance times are increased when escalators/stairs are unavailable.

The final three scenarios (Scenarios 12, 13 and 14) used the escalator human factors data analysed in Chapter 7. As previously mentioned there are a number of similarities between each dataset relating to escalator/stair usage (all datasets), rider usage (Spanish and English datasets), rider side usage (Spanish and English datasets) and walker speeds (Spanish and English datasets).

Whilst there were significant difference between the Chinese and both the Spanish and English walker speed distributions, almost all escalator users rode the escalator in the Chinese data. This meant the impact of the increased walker speeds had little influence upon the overall scenarios involving those datasets. The most prominent difference with the Chinese dataset scenario (Scenario 13) compared to both the Spanish (Scenario 12) and English (Scenario 14) dataset scenarios was the high proportion of riders using both sides of the escalator. In this scenario a slight decrease in TET of 332.0s was recorded, representing a marginal reduction of 3.3% (11.4s) and 1.3% (4.3s) respectively compared to the Spanish and English dataset scenarios. The platform clearance time similarly was marginally reduced by 3.8% (9.7s) and 3.2% (8.2s) respectively compared to the Spanish and English dataset scenarios. These results suggest that having separate walker/rider lanes with a decreased proportion of walkers compared to riders (Spanish/English dataset scenarios) is similar to having most/all escalator users ride using both sides and not forming separate walker/rider lanes (Chinese dataset scenario). This is exemplified in Scenario 4 (where all agents walked) and Scenario 5 (where all agents rode on both sides) where little variation was also observed.

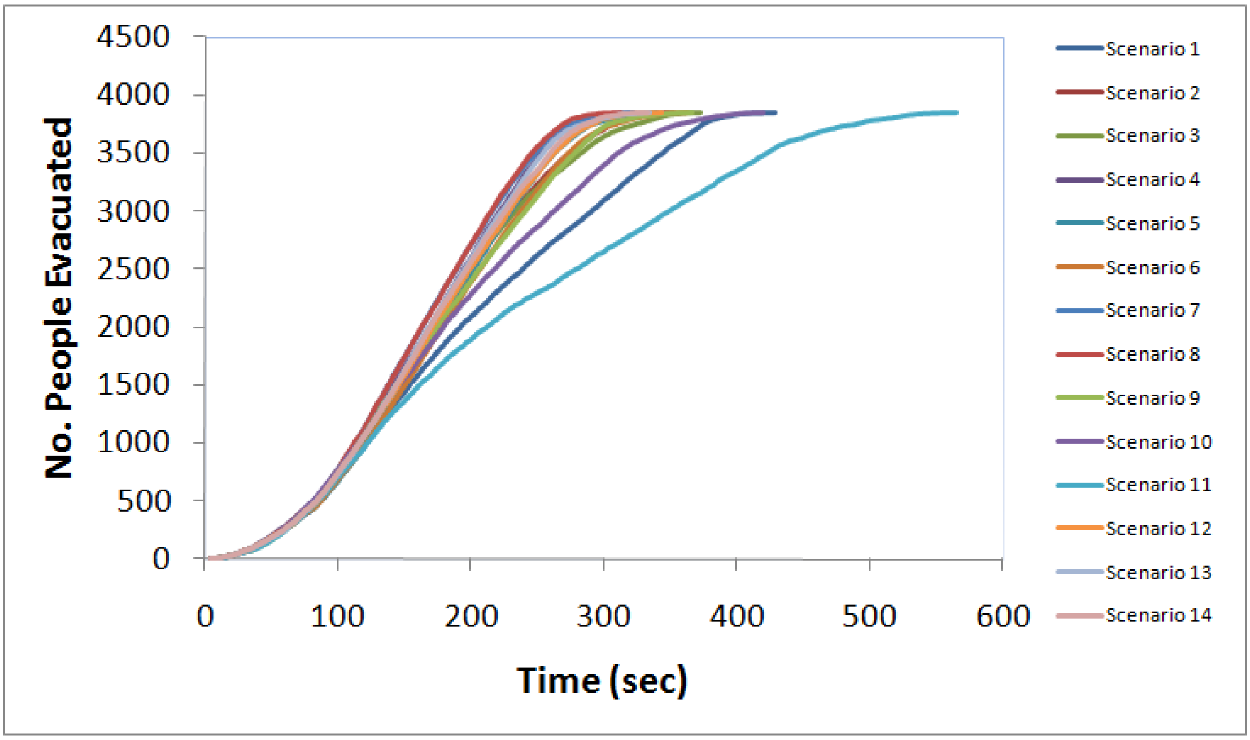


Figure 71: Evacuation curves for each scenario

In all scenarios agents initially on the ticket hall level were among the first to evacuate the station so varying escalator strategies or associated human factors had little influence on those agents. Consequently the evacuation curves for all scenarios (see Figure 71) are similar for the first 964 agents in each scenario (i.e. the total ticket hall population). The remaining agents evacuated from the platform level below so were influenced by the different escalator strategies and varying human factors.

9.6 Concluding remarks

This chapter has presented the results of a series of evacuation scenarios using the developed escalator and agent escalator model to explore the potential influence of escalator strategies and human factors upon an evacuation.

The simulation results have shown that escalator human factors can have a considerable influence upon a full underground station evacuation. Whilst a variety of escalator human factors have been explicitly represented and explored within the scenarios, the inter-influencing nature of certain escalator human factors has been shown to be more dominant than others. This is exemplified in the final three scenarios (Scenarios 12, 13, 14) that incorporated each dataset. Whilst significant differences existed between the Chinese datasets and the Spanish/English datasets, the influence of the high proportion of riders (approximately evenly using both sides of the escalator) in the Chinese dataset scenario negated the influence of the increased Chinese walker speeds. As a result, little variation was observed between the scenarios that incorporated each dataset.

The evacuation analysis has demonstrated that even the provision of static escalators can have a considerable influence upon an evacuation compared to using stairs alone. ***Furthermore, the provision of a moving escalator has been shown to decrease overall evacuation times by up to approximately 25% compared to using stairs alone and around 10% compared to using static escalators.*** Results have shown that little decrease in TET was observed when all escalator users walked compared to if they all rode. As such, ***urging escalator users to ride on both sides of an escalator, maximising tread utilisation, may be advantageous during an evacuation considering the reduced likelihood of escalator users tripping compared to walking.*** During scenarios where escalators/stairs were rendered unavailable, as expected, had a considerable impact upon the evacuation. In those scenarios, increases in TET of up to 59.8% and platform clearance times of up to 71.6% compared to stairs alone were recorded. Such findings highlight the severity caused by the unavailability of escalators/stairs (e.g. due to fire/smoke, code stipulations, etc), and the need to consider additional provision of vertical egress capacity.

The presented evacuation analysis has demonstrated the developed model can represent a variety of escalator evacuation strategies and associated human factors. This capability could be employed within an engineering analysis, where the performance of different procedural variants are compared. Based on the analysis, a number of operational and human factors affecting an evacuation using escalators have been suggested. Further investigation is required to assess the extent to which the results are generally applicable. Indeed the presented analysis can be used to guide such future investigation.

Chapter 10 - Conclusions

The objective of this thesis has been to advance understanding of human factors associated with the use of vertical transport devices (lifts/escalators) and the influence of associated operational strategies during evacuations. As part of this study the buildingEXODUS evacuation software has been developed to include the representation of lifts/escalators and associated human factors during an evacuation. The software was chosen as access to the source code along with development support was made available. In addition, the software incorporates a number of existing agent control features that could be utilised in the development of the vertical transport agent models. Using the developed vertical transport and associated agent models, a series of evacuation scenarios have been performed. These scenarios explored the influence of different vertical transport strategies and how human factors influence each strategy.

The main research questions posed in Chapter 1 and general overview of the findings that address each question in the thesis have been described in the following sections. Such questions represent the lack of understanding in the field of vertical transport evacuation modelling based on the literature reviewed.

Question 1: How would occupants behave given that they have the option to use a lift during an evacuation?

Issues associated with this question were addressed in Chapter 4 where results and analysis from an online lift survey were presented. The analysis identified that ***irrespective of familiarity with a building, approximately half of all participants stated that they would sometimes consider using a lift during an evacuation.*** This decreased to approximately a third if participants were familiar with the building. This suggests that ***increased familiarity with a building decreases the likelihood of considering using a lift during an evacuation.***

Of participants that would consider using a lift during an evacuation, as expected and demonstrated by Heyes [Heyes, 2009], results have ***shown as floor height increases the proportion of those occupants that would actually choose to use a lift also increases.*** The majority of occupants would consider the floor they were initially located on, the levels of congestion in a lift waiting area, and the amount of time they were waiting for a lift in the decision to use a lift during an evacuation. ***In addition, occupants' tolerance to waiting in more crowded lift waiting areas for longer periods of time to use a lift also increases with floor***

height. ***Results suggest that occupant gender, age, and BMI do not significantly influence their decision to consider using a lift during an evacuation. However, the country that occupants are located does appear to be an influencing factor in this decision.*** Significantly higher level of acceptance to consider using lifts during evacuations in the US and Germany compared to the UK and China was recorded.

Question 2: How should human factors associated with evacuation lifts be modelled?

This question has been addressed in Chapter 5 where the development of a lift model and agent lift model has been presented. The agent lift model developed was based upon data from the survey presented in Chapter 4. This represents the first time that dedicated evacuation lift human factors data has been used as a basis for developing an associated agent model within evacuation software. Verification testing has demonstrated that the lift model and agent lift model behaves as intended given input parameters and simulated conditions. Whilst this does not confirm the model predictive capabilities, it does provide a level of confidence in its application to represent the stated lift/agent behaviour.

Question 3: To what extent would different lift strategies influence an evacuation?

This question has been addressed in Chapter 6 where the developed lift and agent lift model was used to perform a series of lift evacuation simulations. A series of full building lift evacuation scenarios utilising different lift strategies were simulated. These were run once where agents exhibited deterministic and non-adaptive behaviour (Simplified Lift Agent Model (SLAM)) and once where agents exhibited probabilistic and adaptive behaviour (Advanced Lift Agent Model (ALAM)). The ALAM employed the survey data presented in Chapter 4 and represents more realistic behaviour compared to the SLAM. For all lift strategies the inclusion of this realistic agent behaviour caused a decrease in overall evacuation performance. This was because the lift system was typically underutilised due to agents not being prepared to wait in given levels of congestion or for certain periods of time whilst in the lift waiting area.

Analysis of each scenario results show that ***the most efficient lift evacuation strategies employed both stairs and lifts, where the building used sky lobbies and lifts shuttled agents to the ground floor. Using such strategies with non-adaptive agent behaviour, a maximum reduction in total evacuation time compared to stairs alone of approximately a half was found***. However, ***using such strategies and adaptive agent behaviour, produced a maximum reduction***

in total evacuation time of approximately a third. Such strategies were less susceptible to decreases in efficiency caused by human factors. This was because most agents' arrival to the lift waiting areas was staggered due to initially having to use the stairs. Subsequently this decreased the overall levels of congestion in the lift waiting areas. Since most high-rise buildings are vertically partitioned into zones (with different lifts servicing a given range of floors) and/or include sky lobbies, such strategies have a practical benefit of being able to be employed in most existing high-rise buildings. Sky lobbies in high-rise buildings are also typically designed as refuge areas that provide further benefits in terms of fire protection. Using sky lobby lift strategies also requires little or no input from an operator or automated means of person detection in the lift waiting areas (e.g. determining if any evacuees are still waiting in a lift waiting area). This is because the lifts shuttle between the same floors for the entire duration of the evacuation. Consequently there is no risk of an occupant being left behind and potentially waiting for a lift that may have already serviced their floor. Further to this, such a strategy could make use of existing shuttle lifts that are typically housed in blind shafts (i.e. not servicing other floors between the ground and the sky lobby). This would negate the need for further pressurisation measures and decrease the likelihood of smoke or fire entering the lift shaft [Wong and Luo, 2005]. Such findings highlight the need to consider lift strategies and associated human factors when devising evacuation strategies of high-rise building that heavily rely on lifts. ***The results demonstrate that not only can lifts provide general benefit to evacuation performance, but evacuation lift human factors can influence different lift strategies in different ways***. Such influences should be considered when determining the extent to which lifts can provide benefit to an evacuation.

Question 4: How do occupants behave on escalators during an evacuation?

This question has been addressed in Chapter 7 where results and analysis of data collection of human factors associated with escalator usage during normal circulation conditions is presented. Whilst the data was not collected under emergency or evacuation conditions, based on previous literature reviewed, evidence suggests that escalator human factors during normal circulation and evacuation conditions are comparable [Galea, et al., 2006a; Donald and Canter, 1990].

The data analysis has shown that direction of travel (up/down), time period (rush-hour/non rush hour) and country have varying influences upon escalator human factors. The results suggest that pedestrian choice to use an escalator/stair is influenced differently by time period and direction of travel in England and Spain. The escalator was the most popular device choice in the up direction in both countries but the stairs were more popular in the down direction in England (the influence of direction of travel in the Chinese dataset was not captured). In the Chinese dataset the influence of high levels of congestion has been shown to considerably influence the proportion of escalator/stair users. As the levels of congestion increased at the entrance to the escalator/stair, the proportion of stair users also increased. This is expected to reflect the increased width and subsequent throughput provided by the wider stair compared to the adjacent escalator.

Results suggest that ***escalator walker speeds were similar in England and Spain but, despite being significantly fewer walkers in China, walker speeds were significantly faster***. In the English and Spanish datasets, there is a common side preference where riders typically use the right side and walkers use the left side. Conversely, analysis of the Chinese dataset showed the majority of escalator users to ride on both sides of escalators. Indeed, a number of significant differences were recorded between escalator human factors compared to both the Spanish and English datasets. The highest escalator flow-rate recorded was in the Chinese dataset (102 ped/min) though this was less than the maximum flow-rate in the literature reviewed (140.0 ped/min [Al-Sharif, 1996]). ***The high number of riders approximately evenly using both the left and right side of the escalator contributed to such high flow-rates being achieved***. This typically meant that each tread of the escalator was fully utilised more of the time compared to when separate walker/rider lanes formed in the Spanish and English datasets. Indeed the highest flow-rates occurred in all datasets when the majority of escalator users rode the escalator with a similar proportion electing to use both the right and left side. The analysis has highlighted that pedestrians behaviour on escalators is influenced by country, direction of travel, and time period.

Question 5: How should human factors associated with evacuation escalators be modelled?

This question has been addressed in Chapter 8 where the development of an escalator model and agent escalator model has been presented. The agent escalator model developed was based on the data presented in Chapter 7. Verification testing has demonstrated the escalator model and agent escalator model behave as intended given input parameters and simulated conditions. As with the agent lift model, whilst this does not confirm the model predictive capabilities it does provide a level of confidence in its application to represent the stated escalator/agent behaviour.

Question 6: To what extent would escalator strategies influence an evacuation?

This question has been addressed in Chapter 9 where the developed escalator model and agent escalator model were used to perform a series of evacuation scenarios. A series of underground station escalator evacuation scenarios utilising different escalator strategies with varying human factors were simulated. Results from the simulations have shown that a static escalator can provide benefit to an evacuation compared to scenarios where only stairs are used. ***Using moving escalators was shown to decrease total evacuation time by up to 25% compared to stairs alone and around 10% compared to using a static escalator***. During scenarios that included human factors data from different countries (see Chapter 7), little variation between each scenario was observed. This was due to the similarities between datasets from each country and counter influencing escalator human factors (e.g. blocking behaviour reducing the influence of increased walker speeds). Similar total evacuation times were recorded in scenarios when all escalator users walked and in scenarios when all escalators rode on both sides. As such, ***urging escalator users to ride on both sides of an escalator, maximising tread utilisation, maybe advantageous during an evacuation considering the reduced likelihood of escalator users tripping compared to walking. Overall the simulation results have shown that escalator strategies and human factors can considerably influence an evacuation***. Such findings highlight the need to consider such factors when devising evacuation strategies of buildings that heavily rely on escalators (e.g. underground stations).

In conclusion, each of the research questions have been addressed within the thesis. As such the thesis has advanced current understanding and associated technology related to vertical transport evacuation modelling through:

- Providing greater understanding of human factors associated with vertical transport device usage during evacuations. This has been achieved through the collection and extensive analysis of a broad variety of lift/escalator human factors.

- Developing improved empirical based modelling capabilities for simulating occupant behaviour on and around vertical transport devices during evacuations. This has been achieved through the model developed within existing evacuation software based on novel research into lift/escalator human factors.

- Demonstrating the relative merits of using different vertical transport strategies during evacuations and gauging to what extent human factors influence each strategy. This has been achieved through a series of original simulated evacuation scenarios and comparisons with scenarios that include a variety of different associated human factors.

10.1 Future work

All research questions outlined have been addressed. However, invariably the nature of the subject matter, involving human factors, means the findings support a given hypothesis as opposed to being absolute. As such further work and evidence to support/refute the existing findings are required. This section proposes a selection of such future work. The recommended future work has been segregated into separate sections related to future data collection, lift/escalator model development, and evacuation scenarios.

Future data collection/analysis

The online lift survey and escalator video footage used to collect human factors data both had a number of limitations (e.g. conceptualisation, being unsupervised, survey fatigue, camera viewing angles, etc). As such further data should be collected in either experimental and/or actual evacuations using lifts/escalators to address such limitations. Comparisons of such evacuation data with the survey and video data would provide a means to suggest the level of variability and subsequent suitability of applying such data to an evacuation scenario.

The questions in the online lift survey were intended to provide information in an uncomplicated manner such that participants would not be confused. This was so that participants would be more likely to make accurate predictions as to how they would behave according to a given influence (e.g. floor height). It is possible that there are a number of additional aspects that influence human factors associated with evacuation lift usage. This may include the influence of training, response/pre-evacuation times, lift waiting behaviour, group dynamics, etc. Further investigation is required to measure to what extent other influencing human factors associated with evacuation lift usage might have upon an evacuation.

The online lift survey presented participants with a single decision to use a lift and what threshold of a given criteria (e.g. wait time) would cause them to redirect to the stairs. Further to this decision of lift usage, occupants may adapt their behaviour whilst on a stair and possibly choose to redirect to a lift bank under certain conditions (e.g. waiting in a queue for a long time on a stair). As such another area of interest would be to identify if and to what extent occupants adapt their behaviour on stairs given that they have the option to use a lift (i.e. what factors would cause them to redirect from using the stairs to use a lift).

The video analysis of pedestrians using escalators also had a number of limitations. Each piece of video footage was collected in normal circulation conditions. Evidence in past literature of actual evacuations suggests that pedestrians exhibit similar behaviour during evacuations as they do in normal circulation situations [Galea, et al., 2006a; Donald and Canter, 1990]. However, further investigation is required to ascertain, if and to what extent escalator human factors may vary during evacuations.

Local restrictions in each underground station meant that only a limited amount of video footage could be collected. Coupled with the labour intensive method by which the video footage was analysed, meant that only a limited amount of data could be extrapolated for each item of footage. Future investigations should perhaps seek to collect data over a longer period of time with a decreased number of variables, possibly with the use of automated counting tools. This should allow more data to be collected and general escalator human factors trends to be more easily identified.

From the video analysis it could not be ascertained whether the observed escalator human factors were products of habitual behaviour, cultural norms and/or conscious behaviour. One method to address such issues would be to collect data via a combination of video footage and post escalator usage participant surveys. These could be used to identify pedestrians' motivations and reasoning for their behaviour.

The video analysis focused on escalator usage within underground stations. Further data collection involving other types of structure that also heavily rely on escalators (e.g. shopping centres, airports, etc) would be of interest. This allow a comparisons with the presented study to identify if escalator users behave in a similar way to that in the observed underground stations.

Future lift/escalator model development

Both the lift survey data and escalator video data were used as a basis for the development of the agent lift/escalator models. In addition to the empirically based components of each model, further components were included based on a number of assumptions. Such agent behaviour was implemented in order to allow agents to be more flexible in adapting to their local conditions. Experimental/actual escalator evacuation data could be used to provide an empirical basis for such model components. In addition, such data would also allow for validation of the agent lift/escalator models. Indeed the limited number of empirical studies analysing evacuation lift/escalator human factors suggest further data collection is necessary to conduct such model validation.

A number of additional model components could be added to improve the level of flexibility and representation of lifts/escalators and associate human factors. For the lift model, the represented kinematics attributes of a lift are the jerk, acceleration and maximum speed. Using these attributes the jerk and acceleration are assumed to be the same for the increase towards the maximum speed and decrease from maximum speed. As mentioned in the literature review, this is similar to a number of lift modelling simulation tools. However, the acceleration/jerk to and from the maximum speed may potentially vary. An extension to the existing kinematic attributes would be to allow users to define separate rates of acceleration/jerk to and from the maximum speed to represent any variation.

The overall kinematics of the lift model are considered “ideal” in the sense that they do not consider the influence of factors that decrease the efficiency of the lift movement (e.g. friction, ware of machine parts, etc). Though manufactures include methods to limit the extent to which they may influence a lift’s movement, invariably over time they emerge. To represent such aspects within the lift model, a kinematic inefficiency factor could be included. This could be represented as a proportion of time increase for a lift journey due to such inefficiencies of the machine parts. To ascertain what level of inefficiency should be prescribed according to which lift factor requires further investigation.

The floor dispatch control system in the lift model allows users to explicitly define which floors and in what order a lift will service during an evacuation. Using the floor sequence method, a lift will service each floor in the sequence once in the specified order irrespective of occupants waiting in the lift waiting areas. Using the shuttle floor sequence method, the lift system will monitor the number of agents waiting in the lift waiting area of the next floor in the sequence to determine if a lift is still required to service that floor. An extension to these static floor sequences would be to allow the lift system to dynamically decide which floors to service in which order based on occupant factors (e.g. floor requests, wait time, number of occupants waiting, etc). Such dynamic evacuation lift dispatch strategies could be developed as a programmed module that could plug into the existing lift model. This would in turn allow users to develop and test their own dynamic evacuation lift dispatch strategies within buildingEXODUS. This could be used to gauge how existing circulation floor dispatch strategies may provide benefit during an evacuation scenario.

Future evacuation scenarios

The developed lift/escalator and associated agent models were used to demonstrate the influence of a variety of different evacuation strategies. In addition, the models were used to identify how human factors might influence each strategy. For the lift scenarios, all strategies were static in the sense that once a lift had serviced the floors in its assigned floor sequence, they would stop. Further development of the model whereby stopped lifts are utilised to service another lift’s floor sequence could be of interest. This would allow the gauging of how much increased efficiency could be achieved from utilising stopped lifts.

In all scenarios, full building simultaneous evacuations were explored. However, it is common to adopt either partial or phased evacuations in certain situations. Exploring the extent to which different lift strategies and human factors influence both partial and phased evacuations would be of interest. This would provide particular benefit to large high-rise buildings where such procedures are more likely.

For the agent lift/escalator model, agents who initially chose to use a lift/escalator only had the option to maintain their initial choice of lift/escalator bank or redirect to the stairs to evacuate. Further evacuation scenarios that explore agents moving between other lift/escalator banks may be of interest to identify if any further improvements or degradations in evacuation efficiency might arise from such behaviour.

In all of the evacuation lift scenarios a hypothetical 50 storey structure was used and in all of the evacuation escalator scenarios a hypothetical 2 level underground station was used. To extend the findings derived from these scenarios, the same scenarios, incorporating the same lift/escalator strategies and human factors components could be reproduced for structures with different configurations. This would allow the gauging of how much the findings from the presented simulations are generally applicable to other structures.

Finally, each lift/escalator evacuation scenario included the option for agents to use either lifts/stairs or escalators/stairs at a single instance to vertically traversing a given area. In complex multilevel geometries, occupants may be presented with multiple instances of choosing between using lifts, escalators and stairs. In such scenarios, complex vertical wayfinding strategies may be employed by occupants to evacuate a building. The developed lift/escalator model has the capability to represent the decision of occupants to use lifts, escalators and stairs at various stages within an evacuation. However, further data collection regarding vertical wayfinding human factors is required to configure the model and reliably represent such behaviour.

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Appendix

A1.1 Online Survey

A summary of the questions posed in the on-line survey is presented in this Appendix, the full survey can be found at http://fseg.gre.ac.uk/elevator/. Presented in Appendix A1.1-A1.6 is the full text of each of the participant consent form, hypothetical scenarios posed in the section dealing with circulation and the questions posed for each of the scenarios.

A1.1.1 Participant Consent Form

Participant Information Sheet

Thank you for agreeing to participate in this study. This study is being conducted by the University of Greenwich and your participation in this study is helping to improve evacuation safety.

THE QUESTIONNAIRE:

- As part of this study, you will be asked to fill out a questionnaire.
- While you are under no obligation to answer any of the questions we would appreciate if you could provide an answer to all of the questions.
- If you have any problems in completing the questionnaire please ask the research assistant and they will explain the question.
- There are no right or wrong answers.
- The entire process should take about 10 minutes of your time.

YOUR ANSWERS:

- The answers you provide to the questionnaire will be analysed and the data stored.
- We will keep the data for research purposes and some of the analysed data may be published and shown in public fora.
- Your name and any unique identifying personal details will not be associated with your questionnaire.
- The questions have been designed to collect information which will help us in our understanding of human behaviour during normal and evacuation scenarios.

RIGHT TO WITHDRAW:

- The public survey in which you are about to participate involves simple questions and answers and should present no difficulties to you.

- However, if at any time you wish to withdraw from the questionnaire, please inform the member of staff and you will be free to leave, no reasons need to be provided.

CONFIDENTIALITY:

- We request that you do not discuss the detailed nature of the questionnaire with any one likely to participate in the survey.

For further information about this survey please contact:

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A1.1.2 Circulation Section – The Scenarios

1. Base Case

Situation:

You are in a multi-storey building and....

- You are familiar with the layout of the building.
- The lifts/elevators and stairs are located in the same area.
- You are travelling alone and are not carrying or wearing anything which would restrict your movement.
- **You are alone in the lift/elevator lobby.**
- **The lift/elevator is not currently on your floor and you do not know how long you will have to wait for the lift/elevator to return**.

2.Queues

Situation:
You are in a multi-storey building and....
• You are familiar with the layout of the building. • The lifts/elevator and stairs are located in the same area. • You are travelling alone and are not carrying or wearing anything which would restrict your movement. • **There are a number of people in the lift/elevator lobby.** • **The lift/elevator is not currently on your floor and you do not know how long you will have to wait for the lift/elevator to return**.

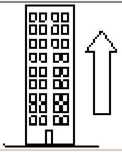
3.Groups

Situation:
You are in a multi-storey building and....
• You are familiar with the layout of the building. • The lifts/elevator and stairs are located in the same area. • **You are travelling with a group of 2-4 people.** • **The people in the group are all of similar physical ability and fitness to yourself.** • The lift/elevator lobby is empty. • The lift/elevator is not currently on your floor and you do not know how long you will have to wait for the lift/elevator to return.

A1.1.3 Circulation Section – The Questions

a) You need to travel UP a number of floors.

For each situation identified below, please state the maximum number of floors you would consider taking the **STAIRS** to travel **UP** (state '-' if you would always use the stairs and 0 if you would always use the lift/elevator).

	You are on a			
	(a) leisure activity with no time pressure.	(b) leisure activity with some time pressure.	(c) business activity with no time pressure.	(d) business activity with some time pressure.
I would use the stairs if I had to travel UP...	__________ **floors**	__________ **floors**	__________ **floors**	__________ **floors**

b) If you were unfamiliar with the building but all the other conditions were the same, would you change your answers to the above questions?

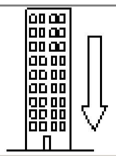
☐YES ☐NO

If YES, how many floors would you now travel:

(a) **_______floors** (b) **_______floors** (c) **_______floors** (d) **_______floors**

c) You need to travel DOWN a number of floors.

For each situation identified below, please state the maximum number of floors you would consider taking the **STAIRS** to travel **DOWN** (state '-' if you would always use the stairs and 0 if you would always use the lift/elevator).

	You are on a			
	(a) leisure activity with no time pressure.	(b) leisure activity with some time pressure.	(c) business activity with no time pressure.	(d) business activity with some time pressure.
I would use the stairs if I had to travel DOWN...	__________ **floors**	__________ **floors**	__________ **floors**	__________ **floors**

d) If you were unfamiliar with the building but all the other conditions were the same, would you change your answers to the above questions?

☐YES ☐NO

If YES, how many floors would you now travel:

(a) **_______floors** (b) **_______floors** (c) **_______floors** (d) **_______floors**

A1.3 Evacuation Section – The main scenario (and variations) and associated questions

A1.1.4 Evacuation Section – The Scenario

Situation:

You are in a multi-storey building and....

- You are familiar with the layout of the building.
- The lifts/elevator and stairs are located in the same area.
- You are travelling alone and are not carrying or wearing anything which would restrict your movement.
- **You have been instructed that it is acceptable to use either the lifts/elevators or stairs to evacuate from your building in emergency situations. During an evacuation you are free to choose to use with the lifts/elevators or stairs.**

A1.1.5 Evacuation Section – The Questions

a) Would you consider using the lift/elevator to evacuate?

☐YES ☐NO

If YES go to **4b**. If NO go to **4g**.

b) Would you <u>always</u> use the lift/elevator to evacuate in preference to the stairs?

☐YES ☐NO

If YES go to **4g**. If NO go to **4c**.

c) Would the height of the floor you were on influence your decision?

☐YES ☐NO

If YES go to **4d**. If NO go to **4e**.

d) What is the maximum AND minimum number of floors you would consider travelling in a lift/elevator to an exit floor?

- The maximum number of floors I would consider travelling in a lift would be _______ floors (state '-' if there is no maximum).
- The minimum number of floors I would consider travelling in a lift would be _______ floors (state '-' if there is no minimum).

e) <u>Irrespective of the floor your are on</u> (i.e. regardless of how far you need to vertically travel), would the height of the building influence your decision?

☐YES ☐NO

If YES, select which statement is most appropriate:

☐ The higher the building, the more likely I would want to use the lift/elevator.

☐ The higher the building, the less likely I would want to use the lift/elevator.

Please explain your answer:

____

____

____

____

____

f) You are instructed to evacuate from a multi-storey building…

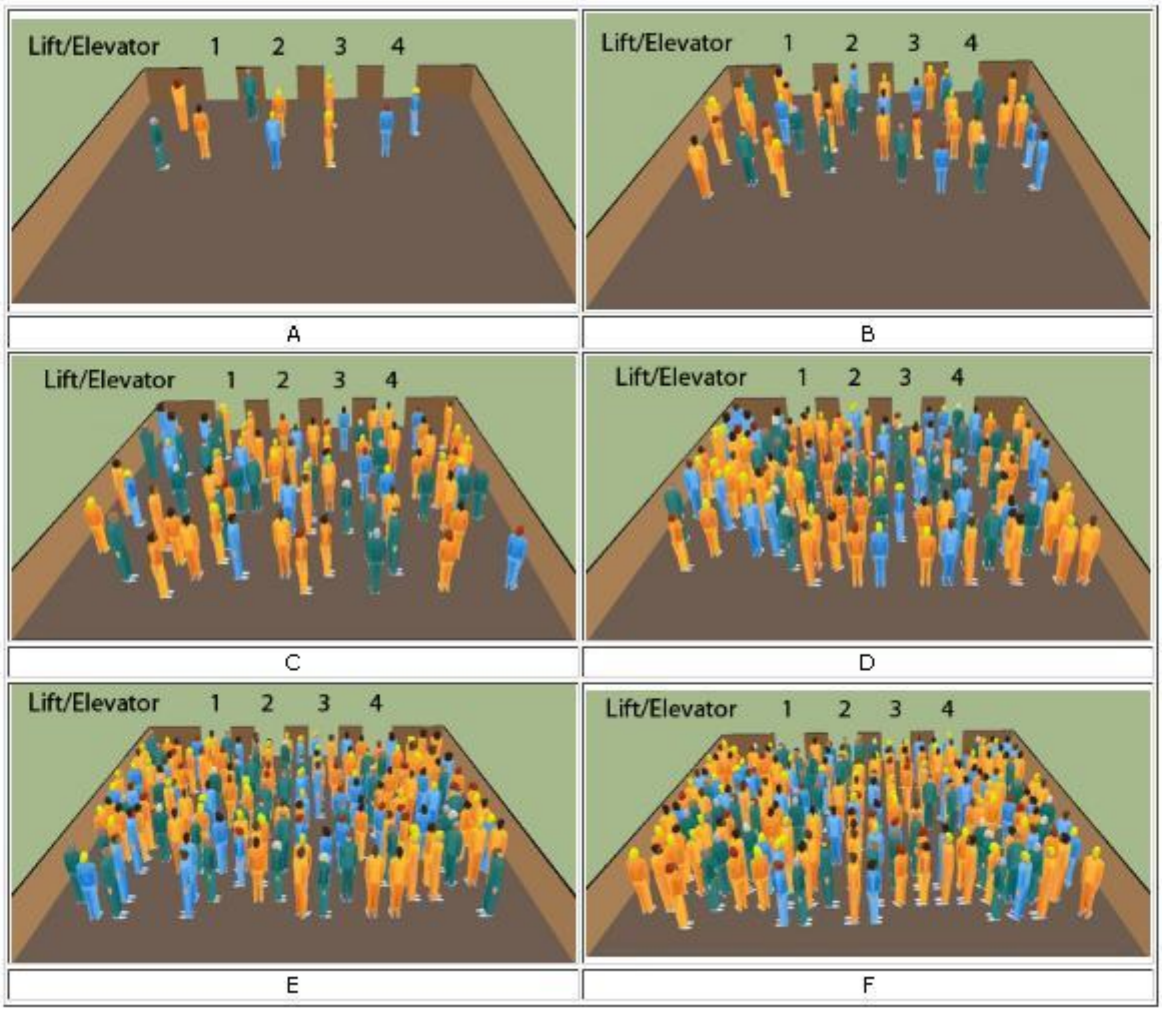
- It is an emergency but you are not in immediate danger.
- You have a choice to use either <u>one of 4 lifts/elevators servicing your floor</u> OR <u>the stairs.</u>
- Each lift/elevator has a capacity of 10 people.
- The lift/elevator lobby is crowded with people.

In the table below please indicate if you would wait to use a lift/elevator given that you are located in each of the indicated floor regions. If you would consider waiting

to use a lift/elevator for a given floor region, please fill in the remaining two columns.

You are located between floors...	**Due to the crowd you will have to wait to use the lift/elevator, are you prepared to wait to use the lift/elevator?**	**If YES…** **Based on the Crowd level key, select the crowd level that would deter you from waiting for the lift/elevator.**	**If YES….** **Given that the crowd is below the indicated size/density, what is the maximum time that you would consider waiting for the lift/elevator before using the stairs?**
2-10	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn't matter	
11-20	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn't matter	
21-30	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn't matter	
31-40	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn't matter	
41-50	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn't matter	
51-60	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn't matter	

Crowd level Key:



g) Would you change your above answer(s) if you were UNFAMILIAR with the building BUT knew that it was OK to use the lifts to evacuate?

☐YES ☐NO If NO go to 5.

If YES, please complete the table below as if you were **<u>UNFAMILIAR</u>** with the building:

You are instructed to evacuate from a multi-storey building…

- It is an emergency but you are not in immediate danger.
- You have a choice to use either <u>one of 4 lifts/elevators servicing your floor</u> OR <u>the stairs.</u>
- Each lift/elevator has a capacity of 10 people.
- The lift/elevator lobby is crowded with people.

You are located between floors...	Due to the crowd you will have to wait to use the lift/elevator, are you prepared to wait to use the lift/elevator?	If YES… Based on the Crowd level key, select the crowd level that would deter you from waiting for the lift/elevator.	If YES…. Given that the crowd is below the indicated size/density, what is the maximum time that you would consider waiting for the lift/elevator before using the stairs?
2-10	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn’t matter	
11-20	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn’t matter	
21-30	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn’t matter	
31-40	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn’t matter	
41-50	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn’t matter	
51-60	☐YES ☐NO	☐<A ☐A-B ☐B-C ☐C-D ☐D-E ☐E-F ☐>F ☐ Crowd size doesn’t matter	

A1.1.6 Person Details Section - The Questions

a) What is your Gender?

○ MALE ○ FEMALE

b) What is your date of birth?

[MONTH ▾] [DAY ▾] [YEAR ▾]

c) Approximately how much do you weigh? (select a value AND select one of the metrics)

[VALUE ▾] [METRIC ▾]

d) Approximately how tall are you? (select a value AND select one of the metrics)

[VALUE ▾] [METRIC ▾]

e) Usually, how many days a week do you engage in greater than 30 minutes of moderate exercise?

[SELECT ▾] days a week.

If you selected more than '0' days a week, please tick which moderate activity you take part in:

☐ Walking	☐ Tennis	☐ Football / Soccer
☐ Cycling	☐ Aerobics	☐ Rugby / American Football
☐ Jogging	☐ Gym	☐ Cricket/Baseball
☐ Swimming	☐ Badminton	☐ Hockey
Other. Please Specify: ____		

f) Do you smoke?

○ YES ○ NO

If YES, how many cigarettes a day do you usually smoke?

[SELECT ▾] cigarettes a day.

g) Do you have any physical conditions which would inhibit you participating in physical exercise? E.g. pregnant, asthma.

○ YES ○ NO

If YES, please specify: ____

h) Do you have any physical/psychological condition which would influence your choice to use a lift/elevator? E.g. claustrophobia, vertigo, wheelchair bound, etc

○ YES ○ NO

If YES, please specify: ____

Place of Work/Study & Occupation

i)What is your occupation?

j) **Does your place of work/study have a lift/elevator(s)?**

YES NO

If YES....

- How many floors does the building have?	SELECT floors.
- What floor do you most commonly work/study on?	SELECT
- Do you usually use the lift/elevator to travel to that floor?	YES NO
- Approximately how many times a day, in your place of work/study, do you use the lift/elevator to **go UP** ?	SELECT times a day.
- Approximately how many times a day, in your place of work/study, do you use the lift/elevator to **go DOWN** ?	SELECT times a day.
- Do you use the stairs in your place of work/study?	YES NO
If YES...	

	How many times a day do you use the stairs?	How many floors do you usually travel on the stairs?
Travelling UP	SELECT times a day.	between SELECT and SELECT floors
Travelling DOWN	SELECT times a day.	between SELECT and SELECT floors

Place of Residence

k)Does your place of residence have a lift/elevator(s)?

YES NO

If YES....

- How many floors does the building have?	SELECT floors.
- What floor do you live on?	SELECT
- Do you usually use the lift/elevator to travel to that floor?	YES NO
- Approximately how many times a day,in the building you live, do you use the lift/elevator to **go UP** ?	SELECT times a day.
- Approximately how many times a day, in the building you live, do you use the lift/elevator to **go DOWN** ?	SELECT times a day.
- Do you use the stairs in the building you live?	YES NO

If YES...

	How many <u>times a day</u> do you use the stairs?	How many <u>floors</u> do you usually travel on the stairs?
Travelling UP	SELECT times a day.	between SELECT and SELECT floors
Travelling DOWN	SELECT times a day.	between SELECT and SELECT floors

Past Evacuation Experience

l)Have you ever been involved in an actual (not a drill) building evacuation?

YES NO

If YES, for the most recent evacuation that you were involved in…

What date was the evacuation?	MONTH ▾ DAY ▾ YEAR ▾
How many floors did the building have?	Select ▾
What floor where you located on?	Select ▾
Did you use the Lift/Elevator, Stairs or neither to evacuate?	○ Lift/Elevator ○ Stairs ○ Neither
Please give any further details you think might be useful: (**200** characters remaining on your input limit)	

A2.1 Online survey - University of Greenwich Research Ethics Committee Acceptance Letter

the UNIVERSITY of GREENWICH

Mr Michael Kinsey

Direct Line 01634 883870
Direct Fax 01634 883738
Email R.J.Odle@gre.ac.uk
Our Ref RSAO/REC/08/3.4.6
Date: 19 July 2008

Dear Mr Kinsey,

University Research Ethics Committee – Minute 08/3.4.6 – Modelling Vertical Transport and Associated Pedestrian Behaviour

I am writing to confirm that your application has been approved by Chair's Action as authorised by the Committee and you have permission to proceed:

I am advised by the Committee to remind you of the following points:

- Your responsibility to monitor the project and notify the UREC immediately of any information received by you, or of which you become aware, which would cast doubt upon, or alter, any information contained in the original application, or a later amendment, submitted to the UREC and/or which would raise questions about the safety and/or continued conduct of the research.
- The need to comply with the Data Protection Act
- The need to comply, throughout the conduct of the study, with good research practice standards
- The need to refer proposed amendments to the protocol to the UREC for further review and to obtain UREC approval thereto prior to implementation (except only in cases of emergency when the welfare of the subject is paramount).
- You are authorised to present this University of Greenwich Research Ethics Committee letter of approval to outside bodies, e.g. LRECs, in support of any application for further research clearance.
- The requirement to furnish the UREC with details of the conclusion and outcome of the project and to inform the UREC should the research be discontinued. The Committee would prefer a concise summary of the conclusion and outcome of the project, which would fit no more than one side of A4 paper, please.
- The desirability of including full details of the consent form in an appendix to your research, and of addressing specifically ethical issues in your methodological discussion.

On behalf of the Committee may I wish you success in your project.

Yours sincerely

pp Lynne Spencer

Dr Bob Odle
Secretary, University Research Ethics Committee

cc Prof Ed Galea

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A3.1 Online Survey – Participant cross-demographic analysis

Country + Age

In Table 75, for participants that provided their country and age information, a frequency break down of participant's country location and age range can be seen. It can be seen that the majority of participants in the UK and China were aged between 18-40. Of participants from China there were significantly more aged between 18-30 (χ^2=140.3, $p<0.05$) than any other age range and only 2.6% of participants from China were over the age of 40. Participants from Germany and the US came from a more evenly distributed age range; there was no significant differences between the frequency of participants in each age range (Germany: χ^2=4.5, $p>0.05$ and US: χ^2=3.7, $p>0.05$).

Table 75: Participant Demographics - Country and Age Range

Country	**Age Range % [Freq]**			
	18-30	**31-40**	**41-50**	**50+**
UK	39.9 [55]	26.8 [37]	15.2 [21]	18.1 [25]
China	68.7 [79]	28.7 [33]	2.6 [3]	0.0 [0]
Germany	38.6 [17]	18.2 [8]	20.5 [9]	22.7 [10]
US	14.0 [8]	28.1 [16]	28.1 [16]	29.8 [17]

Country + BMI

In Table 76, for participants that provided their country and height/weight information, a frequency break down of participant's country location and BMI category can be seen. With the exception of participants in the UK, the majority of participants were considered normal in weight in each country. Approximately half of all participants from the UK (50.0%) and the US (44.7%) were considered either overweight or obese.

Table 76: Participant Demographics - Country and BMI (Body Mass Index)

Country	BMI Category % [Freq]			
	Underweight	Normal weight	Overweight	Obese
UK	8.2 [11]	41.8 [56]	34.3 [46]	15.7 [21]
China	10.3 [12]	69.2 [81]	15.4 [18]	5.1 [6]
Germany	2.0 [1]	62.0 [31]	28.0 [14]	8.0 [4]
US	1.8 [1]	53.6 [30]	21.4 [12]	23.2 [13]

Country + Gender

In Table 77, for participants that provided their country and gender information, a frequency break down of participant's country location and gender can be seen. Both the UK and Germany had approximately even numbers of males and females. However significantly more males than females were recorded in both China (χ^2=7.9, $p<0.05$) and the US (χ^2=4.3, $p<0.05$) accounting for over 60% of participants from each country.

Table 77: Participant Demographics - Country and Gender

Country	Gender % [Freq]	
	Male	Female
UK	54.9 [79]	45.1 [65]
China	62.8 [76]	37.2 [45]
Germany	46.2 [24]	53.8 [28]
US	63.3 [38]	36.7 [22]

Age + BMI

In Table 78, for participants that provided their age and height/weight information, a frequency break down of participant's country location and BMI can be seen.. With the exception of the 50+ age range, the majority of participants in each age range were normal weight. In the 50+ age range 61.0% of participants were either overweight or obese. As the age ranges increase the proportion of participants that were either overweight or obese also increases. This is perhaps reflective of the increased sedentary lifestyles of older participants.

Table 78: Participant Demographics - Age Range and BMI (Body Mass Index)

Age Range	BMI Category % [Freq]			
	Underweight	Normal weight	Overweight	Obese
18-30	12.6 [24]	66.0 [126]	14.7 [28]	6.8 [13]
31-40	4.4 [5]	53.5 [61]	29.8 [34]	12.3 [14]
41-50	0.0 [0]	53.3 [32]	35.0 [21]	11.7 [7]
50+	0.0 [0]	39.0 [23]	32.2 [19]	28.8 [17]

Age + Gender

In Table 79, for participants that provided their age and gender information, a frequency break down of participant's age and gender can be seen. The 18-30 age range was the only age group where a similar proportion of males and females were recorded. In the remaining age groups a significant ($p<0.05$) higher number of males was recorded, with over 60.0% males being recorded in those age groups.

Table 79: Participant Demographics - Age Range and Gender

Age Range	Gender % [Freq]	
	Male	Female
18-30	55.6 [110]	44.4 [88]
31-40	63.6 [75]	36.4 [43]
41-50	61.8 [42]	38.2 [26]
50+	70.0 [42]	30.0 [18]

BMI + Gender

In Table 80, for participants that provided their gender and height/weight information, a frequency break down of participant's gender and BMI can be seen. A slightly higher proportion of females than males were consider normal in weight. Almost twice the proportion of overweight male participants were recorded compared to females. Almost four times the proportion of underweight females were recorded compared to males. A similar proportion of both males and females were considered overweight.

Table 80: Participant Demographics - Gender and BMI (Body Mass Index)

Gender	BMI Category % [Freq]			
	Underweight	Normal weight	Overweight	Obese
Male	3.3 [9]	53.6 [147]	30.3 [83]	12.8 [35]
Female	12.3 [21]	60.8 [104]	15.8 [27]	11.1 [19]

A3.2 Online Survey – Evacuation questions Q4A-Q4E – demographic analysis

Where categorical frequency data has been compared between demographic subgroups a Chi Square test has been used to test for significant difference between each group and associated χ^2 and p-values have been stated. In certain instances where the cell frequencies have been below 5 or a two by two table has been used, then a Yates' Chi Square test has been used to correct potential anomalies caused by such data in the standard Chi Square calculation.

Certain questions required participants to state the minimum and maximum number of floors that they would consider travelling within a lift during an evacuation. Collating the values for the participant responses for all of these questions in each demographic subgroups showed the responses to not be normally distributed. For questions where there were only two demographic subgroups (e.g. male/female), the non parametric Mann-Whitney test was used to identify significant differences between those demographic subgroups (used for two unpaired groups). For questions that involved more than two demographic subgroups the non-parametric Kruskal-Wallis significance test was employed (used for three or more unpaired groups).

Cross-demographic frequencies

In Table 78 and Table 79 the frequency of participants in each demographic group that answered Q4A of the online survey can be seen.

More males were recorded than females in each country with the proportion of males ranging between 57.9%-69.2%. The largest subgroup were males aged between 18-30 in both the UK (26.3% (10)) and China (38.5% (10)), with the largest subgroup in the US being males aged between 41-50 (63.6% (7)). The largest subgroup from Germany were males who did not specify their age (26.3% (5)). Indeed with the exception of the US, the majority of participants from each country were aged below 40 years of age. The majority of participants from the US (61.3% (19)) were above 40 years of age. Approximately 65.4% (17) of Chinese participants were aged between 18-30 which is well above the overall average of 40.3% (62) of participants across all countries within the 18-30 age range. Focusing on the BMI subgroups in Table 82, all underweight participants were aged between 18-30. Over half participants (51.3% (39)) who were normal weight were aged between 18-30 with the majority (64.5% (49)) being males. There was an even spread of participants across each age range among the obese group though the large majority of them (80.0% (32)) were males.

Varying frequencies of participants in each demographic have been shown to exists across demographic subgroups. Such differences between subgroups may influence the demographic group analysis and so should be considered in the following comparison.

Table 81: Participants who would consider using a lift to evacuate according to Country, Gender and Age group

		Age Range					
Country	**Gender**	**18-30**	**31-40**	**41-50**	**50+**	**Unspecified**	**TOTAL Gender**
UK	**Male**	10	5	2	5	0	22
	Female	5	3	4	3	1	16
	Unspecified	0	0	0	0	0	0
	TOTAL	15	8	6	8	1	38
China	**Male**	10	4	2	0	2	18
	Female	7	1	0	0	0	8
	Unspecified	0	0	0	0	0	0
	TOTAL	17	5	2	0	2	26
US	**Male**	4	4	7	5	0	20
	Female	1	2	2	5	1	11
	Unspecified	0	0	0	0	0	0
	TOTAL	5	6	9	10	1	31
Germany	**Male**	3	0	1	2	5	11
	Female	2	3	2	1	0	8
	Unspecified	0	0	0	0	0	0
	TOTAL	5	3	3	3	5	19
Other	**Male**	16	10	5	1	0	32
	Female	4	1	3	0	0	8
	Unspecified	0	0	0	0	0	0
	TOTAL	20	11	8	1	0	40
TOTAL	**Male**	43	23	17	13	7	103
	Female	19	10	11	9	2	51
	Unspecified	0	0	0	0	0	0
	TOTAL	62	33	28	22	9	154

Table 82: Participants who would consider using a lift to evacuate according to BMI, Gender and Age group

		Age Range					
BMI	**Gender**	**18-30**	**31-40**	**41-50**	**50+**	**Unspecified**	**TOTAL Gender**
Underweight	**Male**	3	0	0	0	0	3
	Female	4	0	0	0	0	4
	Unspecified	0	0	0	0	0	0
	TOTAL	7	0	0	0	0	7
Normal weight	**Male**	27	10	4	5	3	49
	Female	12	5	6	3	1	27
	Unspecified	0	0	0	0	0	0
	TOTAL	39	15	10	8	4	76
Overweight	**Male**	9	8	9	4	2	32
	Female	1	3	2	1	1	8
	Unspecified	0	0	0	0	0	0
	TOTAL	10	11	11	5	3	40
Obese	**Male**	3	4	2	4	1	14
	Female	2	1	2	4	0	9
	Unspecified	0	0	0	0	0	0
	TOTAL	5	5	4	8	1	23
TOTAL	**Male**	43	23	17	13	7	103
	Female	19	10	11	9	2	51
	Unspecified	0	0	0	0	0	0
	TOTAL	62	33	28	22	9	154

Results – Gender

Of all participants that answered whether they would consider using the lift during an evacuation and specified their gender (N=467); 60.8% (284) were males and 39.2% (183) were females. Of these participants, a higher proportion of males (36.3% (103)) would consider using a lift during an evacuation than females (27.9% (51)) (see Table 83). Whilst this suggests that females are more likely to have reservations about using a lift during an evacuation, this does not represent a significant difference between each gender (Yates'-χ^2=3.2, p>0.05).

Table 83: Frequency/Proportion of males/females that would and wouldn't consider using a lift during an evacuation

	Gender % [Freq]		**All Participants % [Freq]**
Would you consider using a lift during an evacuation?	**Males**	**Females**	
YES	36.3 [103]	27.9 [51]	33.0 [154]
NO	63.7 [181]	72.1 [132]	67.0 [313]

A small proportion of both males (8.8% (9)) and females (4.0% (2)) would always consider using the lift during the evacuation (Yates'-χ^2=0.6, p>0.05) (see Table 84).

Table 84: Frequency/Proportion of males/females that would and wouldn't always use a lift during an evacuation

	Gender % [Freq]		**All Participants % [Freq]**
Would you ALWAYS use a lift during an evacuation?	**Males**	**Females**	
YES	8.8 [9]	4.0 [2]	7.2 [11]
NO	91.2 [93]	96.0 [48]	92.8 [141]

With regards to lift/stair choice during an evacuation, a large majority of both males (89.1% (82)) and females (83.0% (39)) stated that they would be influenced by what floor they were on in a building when deciding to use a lift during an evacuation (Yates'-χ^2=0.6, p>0.05) (see Table 85).

Table 85: Frequency/Proportion of males/females that would and wouldn't be influenced by the height of the floor they are on when deciding to use a lift during an evacuation

	Gender % [Freq]		**All Participants % [Freq]**
Would the height of the floor you were on influence your decision?	**Males**	**Females**	
YES	89.1 [82]	83.0 [39]	87.1 [121]
NO	10.9 [10]	17.0 [8]	12.9 [18]

The frequency/proportion of both males and females who specified the minimum and maximum number of floors they would consider travelling within a lift during an evacuation can be seen in Table 86. Of the males who specified a minimum number of floors they would consider travelling in a lift (N=82), 90.2% (74) specified that on average they would travel a minimum of 8.7 floors in a lift. Similarly, with female participants (N=39), 87.1% (34) specified that on average they would travel a minimum of 7.7 floors in a lift. Overall, there was no significant difference ($p>0.05$) between the minimum number of floors males and females would consider travelling in a lift during an evacuation.

Of the males who specified a maximum number of floors they would consider travelling in a lift (N=81), approximately a half (50.6% (41)) answered that there was no maximum number of floors. The remaining half approximately were evenly split between stating 100+ floors (25.9% (21)) or specifying on average they would travel a maximum of 20.3 floors (23.5% (19)). For female participants (N=39), a lower proportion (38.5% (15)) answered that there was no maximum number of floors, specified 100+ floors (15.4% (6)). Almost a half of females (46.2% (18)) specified on average they would travel a maximum of 23.7 floors in a lift. This represents a 16.7% (3.4 floors) increase compared to the males. However, of participants that specified a finite maximum number of floors, there was no overall significant difference between male and female participants ($p>0.05$).

Table 86: Frequency/Proportion of males/females lower and upper limits of how many floors they would consider travelling within a lift according to gender

	Lower Limit				Upper Limit			
Gender	**% No Minimum**	**% 100+**	**% Number**	**Avg. (floors)**	**% No Maximum**	**% 100+**	**% Number**	**Avg. (floors)**
Males	8.5 [7]	1.2 [1]	90.2 [74]	8.7	50.6 [41]	25.9 [21]	23.5 [19]	20.3
Females	12.8 [5]	0.0 [0]	87.1 [34]	7.7	38.5 [15]	15.4 [6]	46.2 [18]	23.7
All Participants	9.9 [12]	0.83 [1]	89.3 [108]	8.5	46.7 [56]	22.5 [27]	30.8[37]	22.0

Whilst a higher proportion of female (75.6% (34)) compared to male (60.4% (55)) participants would be influenced by the height of the building when considering to use a lift during an evacuation, this did not represent a significant difference (Yates'-χ^2=2.4, $p>0.05$) (see Table 87).

Table 87: Frequency/Proportion of males/females that would and wouldn't be influenced by the height of the building when deciding to use a lift during an evacuation

	Gender % [Freq]		All Participants % [Freq]
Would the height of the building influence your decision?	**Males**	**Females**	
YES	60.4 [55]	75.6 [34]	65.4 [89]
NO	39.6 [36]	24.4 [11]	34.6 [47]

A large proportion of both males (81.8% (45)) and females (77.4% (24)) who stated that the height of the building would influence their decision to use a lift also stated that the higher the building the more likely they would be to use a lift (Yates'-χ^2=0.04, p>0.05) (see Table 88).

Table 88: Frequency/Proportion of males/females that would and wouldn't be influenced by the height of the building when deciding to use a lift during an evacuation

	Gender % [Freq]		All Participants % [Freq]
The higher the building the...	**Males**	**Females**	
MORE likely to use a lift	81.8 [45]	77.4 [24]	80.2 [69]
LESS likely to use a lift	18.2 [10]	22.6 [7]	19.8 [17]

In Table 89 the frequency/proportion of males/females that would and wouldn't consider using a lift if they were familiar or unfamiliar with the building can be seen. A similar proportion of females (51.1% (93)) and males (48.6% (135)) stated that they would sometimes consider using a lift during an evacuation (Yates'-χ^2=0.2, p>0.05). Though a smaller proportion of males (15.4% (33)) would change their behaviour if unfamiliar with a building compared to females (28.0% (51)) though this did not represent a significant difference (Yates'-χ^2=0.2, p>0.05).

Table 89: Frequency/Proportion of males/females that would and wouldn't consider using a lift if they were familiar or unfamiliar with a building

			Would you consider using the lift/lift to evacuate? (if you were familiar) % [Freq]		Would sometimes consider using a lift to evacuate % [Freq]
			YES	**NO**	
Would you change your above answer(s) if you were <u>unfamiliar</u> with the building?	**Male**	**YES**	3.2 [9]	12.2 [34]	48.6 [135]
		NO	33.1 [92]	51.4 [143]	
	Female	**YES**	4.4 [8]	23.6 [43]	51.1 [93]
		NO	23.1 [42]	48.9 [89]	
	All Participants	**YES**	3.7 [17]	16.7 [77]	49.6 [228]
		NO	29.1 [134]	50.4 [232]	

Results - Age

Of all participants that answered whether they would consider using the lift during an evacuation and specified their age (N=444); 44.6% (198) were aged 18-30, 26.6% (118) were aged 31-40, 15.3% (68) were aged 41-50, and 13.5% (60) were over 50 years old.

The proportion of participants within each age group that would consider using the lift during an evacuation (see Table 90) does not differ very much between each age group (28.0%-41.2%) (χ^2=4.0, p>0.05). This suggests that people's age does not have a great influence upon their decision to consider using a lift during an evacuation.

Table 90: Frequency/Proportion of participants in each age group that would and wouldn't consider using a lift during an evacuation

	Age Range % [Freq]				All Participants % [Freq]
Would you consider using a lift during an evacuation?	**18-30**	**31-40**	**41-50**	**50+**	
YES	31.3 [62]	28.0 [33]	41.2 [28]	36.7 [22]	33.0 [154]
NO	68.7 [136]	72.0 [85]	58.8 [40]	63.3 [38]	67.0 [313]

A small proportion of participants (0.0%-13.1%) within each age group stated that they would always use the lift during an evacuation (see Table 91) (Yates'-χ^2=3.2, p>0.05).

Table 91: Frequency/Proportion of participants in each age group that would and wouldn't always use a lift during an evacuation

	Age Range % [Freq]				All Participants % [Freq]
Would you ALWAYS use a lift during an evacuation?	**18-30**	**31-40**	**41-50**	**50+**	
YES	13.1 [8]	3.0 [1]	7.1 [2]	0.0 [0]	7.2 [11]
NO	86.9 [53]	97.0 [32]	92.9 [26]	100.0 [21]	92.8 [141]

A large proportion of participants in all age groups (80.8%-94.2%) stated that the height of the floor they were on would influence their decision to use a lift (Yates'-χ^2=2.3, p>0.05).

Table 92: Frequency/Proportion of participants in each age group that would and wouldn't be influenced by the height of the floor they are on when deciding to use a lift during an evacuation

	Age Range % [Freq]				All Participants % [Freq]
Would the height of the floor you were on influence your decision?	**18-30**	**31-40**	**41-50**	**50+**	
YES	94.2 [49]	83.9 [26]	80.8 [21]	90.5 [19]	87.1 [121]
NO	5.8 [3]	16.1 [5]	19.2 [5]	9.5 [2]	12.9 [18]

In Table 93 the minimum and maximum number of floors participants would be prepared to travel in a lift during an evacuation can be seen according to participant age range. In all age groups a small proportion of participants specified that there would be no minimum distance (6.1%-11.5%) or 100+ floors (0.0%-2.0%). In all age groups the majority of participants (88.5%-91.8%) specified a finite minimum number of floors. Of these participants, those aged between 18-40 would on average consider travelling a minimum of approximately 9 floors in a lift. This represents approximately an 11.1% (1 floor) and 38.5% (2.5 floors) increase compared to the 41-50 and 50+ age groups respectively. However, overall there was no significant difference (p>0.05) between participants that stated they would travel a finite minimum number of floors in each age group.

With the exception of the 31-40 age group, the majority (approximately a half) of participants in each age group specified that there would be no maximum number of floors they would consider travelling within a lift (see Table 93). Indeed the majority of participants in all age groups (57.9%-71.4%) either specified no maximum or 100+ as the maximum number of floors they would consider travelling in a lift. Overall there was no significant difference (p>0.05) between participants that stated they would travel a finite maximum number of floors in each age group.

Table 93: Frequency/Proportion of participants lower and upper limits of how many floors they would consider travelling within a lift according to age range

	Lower Limit				Upper Limit			
Age	**% No Minimum**	**% 100+**	**% Number**	**Avg. (floors)**	**% No Maximum**	**% 100+**	**% Number**	**Avg. (floors)**
18-30	6.1 [3]	2.0 [1]	91.8 [45]	8.8	49.0 [24]	22.4 [11]	28.6 [14]	21.2
31-40	11.5 [3]	0.0 [0]	88.5 [23]	9.0	26.9 [7]	42.3 [11]	30.8 [8]	15.8
41-50	9.5 [2]	0.0 [0]	90.5 [19]	8.1	55.0 [11]	15.0 [3]	30.0 [6]	24.3
50+	10.5 [2]	0.0 [0]	89.5 [17]	6.5	52.6 [10]	5.3 [1]	42.1 [8]	27.0
All Participants	9.9 [12]	0.83 [1]	89.3 [108]	8.5	46.7 [56]	22.5 [27]	30.8 [37]	22.0

With the exception of the 41-50 age group, the majority of participants across all age groups (58.1%-81.0%) stated that the height of the building would influence their decision to use a lift during an evacuation (Yates'-χ^2=6.2, p>0.05).

Table 94: Frequency/Proportion of participants in each age group that would and wouldn't be influenced by the height of the building when deciding to use a lift during an evacuation

	Age Range % [Freq]				All Participants % [Freq]
Would the height of the building influence your decision?	**18-30**	**31-40**	**41-50**	**50+**	
YES	72.5 [37]	58.1 [18]	45.8 [11]	81.0 [17]	65.4 [89]
NO	27.5 [14]	41.9 [13]	54.2 [13]	19.0 [4]	34.6 [47]

A large majority of participants in each age group (77.8%-82.4%) stated that the higher the building the more likely they would be to use a lift (Yates'-χ^2=0.02, p>0.05).

Table 95: Frequency/Proportion of participants in each age group that would and wouldn't be influenced by the height of the building when deciding to use a lift during an evacuation

	Age Range % [Freq]				All Participants % [Freq]
The higher the building the...	**18-30**	**31-40**	**41-50**	**50+**	
MORE likely to use a lift	77.8 [28]	76.5 [13]	81.8 [9]	82.4 [14]	80.2 [69]
LESS likely to use a lift	22.2 [8]	23.5 [4]	18.2 [2]	17.6 [3]	19.8 [17]

In Table 96 the frequency/proportion of participants in each age group that would and wouldn't consider using a lift if they were familiar or unfamiliar with the building can be seen. The proportion of participants that would sometimes consider using the lift to evacuate ranged between 46.6%-55.1% in each age group; representing a small variation in behaviour between age ranges (χ^2=2.7, p>0.05).

Table 96: Frequency/Proportion of participants in each age group that would and wouldn't consider using a lift if they were familiar or unfamiliar with a building

			Would you consider using the lift/lift to evacuate? (if you were familiar) % [Freq]		Would sometimes consider using a lift to evacuate % [Freq]
			YES	NO	
Would you change your above answer(s) if you were <u>unfamiliar</u> with the building?	18-30	YES	2.3 [5]	26.6 [57]	55.1 [118]
		NO	26.2 [56]	44.9 [96]	
	31-40	YES	1.7 [2]	19.0 [22]	46.6 [54]
		NO	25.9 [30]	53.4 [62]	
	41-50	YES	8.8 [6]	10.3 [7]	51.5 [35]
		NO	32.4 [22]	48.5 [33]	
	50+	YES	3.4 [2]	11.9 [7]	47.5 [28]
		NO	32.2 [19]	52.5 [31]	
	All Participants	YES	3.7 [17]	16.7 [77]	49.6 [228]
		NO	29.1 [134]	50.4 [232]	

Results - Country

Participant responses were broken down according to which country each participant came from. The analysis focused on the top four countries which had the most participant responses: UK (144), China(121), US(60) and Germany(52). Each of these countries had more than 50 participants completing the survey.

The proportion of participants that would consider using a lift during an evacuation can be seen according to country in Table 97. Approximately 1 in 2 participants (52.5%) from the US and 1 in 3 participants (36.5%) from Germany would consider using a lift during an evacuation. These decrease for participants coming from both the UK (approx. 1 in 4 (26.4%)) and China (approx. 1 in 5 (21.5%)). Comparing all countries shows there to be a significant difference between the frequency of participants that would consider using a lift during an evacuation (χ^2=20.3, p<0.05). This significant difference is indeed caused by the higher number of participants that would consider using a lift coming from Germany and the US compared to participants coming from the UK and China.

Table 97: Frequency/Proportion of participants from each country that would and wouldn't consider using a lift during an evacuation

	Country % [Freq]				All Participants % [Freq]
Would you consider using a lift during an evacuation?	**UK**	**China**	**US**	**Germany**	
YES	26.4 [38]	21.5 [26]	52.5 [31]	36.5 [19]	33.0 [154]
NO	73.6 [106]	78.5 [95]	47.5 [28]	63.5 [33]	67.0 [313]

Of participants who specified their location country and whether they would always use a lift during an evacuation (N=112) see Table 98, the proportion of participants from each country that would always use the lift during an evacuation (see Table 98) was very small. Only a few participants from the UK and China stated that they would always use a lift (i.e. the two countries with the largest number of participants). Overall there was a significant difference between the frequency of participants that would always consider using a lift during an evacuation between countries (Yates'-χ^2=13.4, $p<0.05$), however, this was caused by the higher number of participants from China stating that they would always use a lift compared to the other countries.

Table 98: Frequency/Proportion of participants from each country that would and wouldn't always consider using a lift during an evacuation

	Country % [Freq]				All Participants % [Freq]
Would you ALWAYS use a lift during an evacuation?	**UK**	**China**	**US**	**Germany**	
YES	5.3 [2]	28.0 [7]	0.0 [0]	0.0 [0]	7.2 [11]
NO	94.7 [36]	72.0 [18]	100.0 [30]	100.0 [19]	92.8 [141]

Of participants who specified their location country and whether the height of the floor they were on would influence their decision to use a lift during an evacuation (N=101), a large proportion of participants from each country would be influenced by the height of the floor they were on during an evacuation (see Table 99). This ranged between 76.7%-100.0% and does not represents a significant difference between each country (Yates'-χ^2=6.9, p>0.05).

Table 99: Frequency/Proportion of participants from each country that would and wouldn't be influenced by the height of the floor they are on when deciding to use a lift during an evacuation

	Country % [Freq]				All Participants % [Freq]
Would the height of the floor you were on influence your decision?	**UK**	**China**	**US**	**Germany**	
YES	100.0 [36]	87.5 [14]	76.7 [23]	78.9 [15]	87.1 [121]
NO	0.0 [0]	12.5 [2]	23.3 [7]	21.1 [4]	12.9 [18]

In Table 100 the minimum and maximum number of floors participants would be prepared to travel in a lift during an evacuation can be seen according to participant country. A small proportion of participants in each country stated that there was no minimum number of floors they would consider travelling within a lift (6.7%-16.7%). A large majority of participants in all countries (83.3%-93.3%) would only consider using a lift to travel on average approximately 7 to 9 floors or more. Of participants that specified a finite minimum number of floors, there was no overall significant difference between each country (p>0.05).

The majority of participants (57.2-80.0%) across all countries specified they would either be prepared to travel 100+ floors or that there was no maximum number of floors they would consider travelling in a lift during an evacuation. The remaining participants specified a finite maximum number of floors they were prepared to travel within a lift, ranging between 15.1-49.0 floors. Those participants from Germany who stated a finite number of floors would consider travelling approximately at least double the number of floors in a lift compared to the respective participants from the other countries. However, it should be kept in mind that only three participants from Germany specified a finite maximum number of floors they would consider travelling within a lift. Of participants that specified a finite maximum number of floors, there was no overall significant difference between each country (p>0.05).

Table 100: Frequency/Proportion of participants lower and upper limits of how many floors they would consider travelling within a lift according to country

	Lower Limit				Upper Limit			
Country	**% No Minimum**	**% 100+**	**% Number**	**Avg. (floors)**	**% No Maximum**	**% 100+**	**% Number**	**Avg. (floors)**
UK	16.7 [6]	0.0 [0]	83.3 [30]	7.6	50.0 [18]	16.7 [6]	33.3 [12]	19.6
China	7.1 [1]	7.1 [1]	85.7 [12]	7.2	28.6 [4]	28.6 [4]	42.9 [6]	26.2
US	8.7 [2]	0.0 [0]	91.3 [21]	9.1	43.5 [10]	21.7 [5]	34.8 [8]	15.1
Germany	6.7 [1]	0.0 [0]	93.3 [14]	7.9	60.0 [9]	20.0 [3]	20.0 [3]	49.0
All Participants	9.9 [12]	0.83 [1]	89.3 [108]	8.5	46.7 [56]	22.5 [27]	30.8 [37]	22.0

Of all participants who specified their country and responded whether the height of the building would influence their decision to use a lift during an evacuation (N=98), the majority of participants across all countries stated that the height of the building would influence their decision to use a lift during an evacuation. Whilst it can be seen that less participants from the US and Germany would be influenced by the height of the building compared to both China and the UK, there was no overall significant difference between each country (χ^2=1.8, p>0.05).

Table 101: Frequency/Proportion of participants from each country that would and wouldn't be influenced by the height of the building when deciding to use a lift during an evacuation

	Country % [Freq]				All Participants % [Freq]
Would the height of the building influence your decision?	**UK**	**China**	**US**	**Germany**	
YES	71.4 [25]	80.0 [12]	63.3 [19]	61.1 [11]	65.4 [89]
NO	28.6 [10]	20.0 [3]	36.7 [11]	38.9 [7]	34.6 [47]

For all participants who specified the location country and specified if the height of the building would influence their decision to use a lift (N=64), the majority stated that the higher the building the more likely they would be to use a lift, ranging from 61.1%-100.0%. All participants in China stated that the higher the building the more likely they would be to use a lift whereas in the US, some 38.9% less participants stated they would be more likely to use a lift in a higher building. Despite this no significant difference between each country was recorded (Yates'-χ^2=4.5, p>0.05).

Table 102: Frequency/Proportion of participants from each country that would and wouldn't be influenced by the height of the building when deciding to use a lift during an evacuation

	Country % [Freq]				All Participants % [Freq]
The higher the building the...	**UK**	**China**	**US**	**Germany**	
MORE likely to use a lift	83.3 [20]	100.0 [11]	61.1 [11]	81.8 [9]	80.2 [69]
LESS likely to use a lift	16.7 [4]	0.0 [0]	38.9 [7]	18.2 [2]	19.8 [17]

In Table 103 the frequency/proportion of participant in each country that would and wouldn't consider using a lift if they were familiar or unfamiliar with a building can be seen. Participants from the UK were recorded as the least likely to sometimes consider using a lift to evacuate with some 35.7% (51) of all participants from the UK stating that they would sometimes use a lift to evacuate. In contrast, participants from Germany and the US were the most likely to sometimes consider using a lift to evacuate with some 61.5% (32) and 58.6% (34) of all participants from Germany and the US respectively stating that they would sometimes consider using a lift to evacuate. These represent a significant difference between the number of participants that would sometimes consider using a lift and never consider using a lift between each country (χ^2=15.1, $p<0.05$). This significant difference is due entirely to the low proportion of participants from the UK that would sometimes considering using a lift during an evacuation compared to the other countries (there was no significant difference between the remaining countries). This suggests that more people in the UK have reservations about sometimes using a lift during an evacuation compared to the other countries.

Table 103: Frequency/Proportion of participants from each country that would and wouldn't consider using a lift if they were familiar or unfamiliar with a building

			Would you consider using the lift/lift to evacuate? (if you were familiar) % [Freq]		Would sometimes consider using a lift to evacuate % [Freq]
			YES	NO	
Would you change your above answer(s) if you were <u>unfamiliar</u> with the building?	UK	YES	2.8 [4]	9.8 [14]	35.7 [51]
		NO	23.1 [33]	64.3 [92]	
	China	YES	3.4 [4]	27.6 [32]	49.1 [57]
		NO	18.1 [21]	50.9 [59]	
	US	YES	1.7 [1]	6.9 [4]	58.6 [34]
		NO	50.0 [29]	41.4 [24]	
	Germany	YES	7.7 [4]	25.0 [13]	61.5 [32]
		NO	28.8 [15]	38.5 [20]	
	All Participants	YES	3.7 [17]	16.7 [77]	49.6 [228]
		NO	29.1 [134]	50.4 [232]	

Results - BMI (Body Mass Index)

Of participants that provided height and weight information and answered whether they would consider using a lift during an evacuation (N=445) see Table 97, it can be seen that as participants BMI increases the proportion of them that would consider using the lift also increases with a 19.3% difference between the participants in the Underweight and the Obese group. This may be due to participants with higher BMIs having less physical ability/desire/speed to traverse the stairs during an evacuation. Despite this there was no significant difference between each BMI category (χ^2=4.9, p>0.05).

Table 104: Frequency/Proportion of participants according to BMI that would and wouldn't consider using a lift during an evacuation

	BMI % [Freq]				All Participants % [Freq]
Would you consider using a lift during an evacuation?	**Under weight**	**Normal weight**	**Over weight**	**Obese**	
YES	23.3 [7]	30.3 [76]	36.4 [40]	42.6 [23]	33.0 [154]
NO	76.7 [23]	69.7 [175]	63.6 [70]	57.4 [31]	67.0 [313]

Of participants that provided height and weight information and answered if they would always use a lift during an evacuation (N=144) see Table 105, the proportion that would always use a lift was very small. No underweight or obese participants responded that they would always use a lift. Whilst a slightly higher proportion of overweight participants responded that they would always use a lift (4.6%) compared to the normal weight participants, this was not significantly different between BMI groups (Yates'-χ^2=1.7, $p>0.05$).

Table 105: Frequency/Proportion of participants according to BMI that would and wouldn't always consider using a lift during an evacuation

	BMI % [Freq]				All Participants % [Freq]
Would you ALWAYS use a lift during an evacuation?	**Under weight**	**Normal weight**	**Over weight**	**Obese**	
YES	0.0 [0]	7.9 [6]	12.5 [5]	0.0 [0]	7.2 [11]
NO	100.0 [6]	92.1 [70]	87.5 [35]	100.0 [22]	92.8 [141]

Of participants that provided height and weight information and answered if their decision would be influenced by the height of the floor they were on (N=131) see Table 106, a large proportion of participants in each BMI group would be influenced by the height of the floor they were on during an evacuation. However, there appears to be no significant difference between each BMI (Yates'-χ^2=1.4, $p>0.05$).

Table 106: Frequency/Proportion of participants according to BMI that would and wouldn't be influenced by the height of the floor they are on when deciding to use a lift during an evacuation

	BMI % [Freq]				All Participants % [Freq]
Would the height of the floor you were on influence your decision?	**Under weight**	**Normal weight**	**Over weight**	**Obese**	
YES	83.3 [5]	89.7 [61]	88.6 [31]	77.3 [17]	87.1 [121]
NO	16.7 [1]	10.3 [7]	11.4 [4]	22.7 [5]	12.9 [18]

In Table 107 the minimum and maximum number of floors participants would be prepared to travel in a lift during an evacuation can be seen according to participant BMI. A small number of participants in each BMI group stated that there was no minimum number of floors they would consider travelling within a lift during an evacuation (1-12 participants). A large majority of participants in all BMI groups (60.0%-91.8%) would only consider using a lift to travel on average 6.3 to 8.6 floors; participants across all BMI groups would be prepared to walk a similar minimum number of floors. Of participants that specified a finite minimum number of floors, there was no overall significant difference between each BMI group (p>0.05).

With the exception of the underweight group, the majority of participants (64.7%-83.3%) across all BMI groups specified they would either be prepared to travel 100+ floors or that there was no maximum number of floors they would consider travelling in a lift during an evacuation. The remaining participants specified a finite maximum number of floors they were prepared to travel within a lift, ranging between an average of 18.2-44.4 floors. Of those participants in both the Underweight and Normal weight category specified an average maximum number of floors which was under half the maximum number of floors (18.2-20.0 floors) to those participants in the Overweight category (44.4 floors). However participants who specified a finite maximum number of floors in the Obese category specified considerably less floors (24.8 floors). Of participants that specified a finite maximum number of floors, there was no overall significant difference between each BMI group (p>0.05).

Table 107: Frequency/Proportion of participants lower and upper limits of how many floors they would consider travelling within a lift according to BMI

	Lower Limit				Upper Limit			
BMI	**% No Minimum**	**% 100+**	**% Number**	**Avg. (floors)**	**% No Maximum**	**% 100+**	**% Number**	**Avg. (floors)**
Under weight	20.0 [1]	20.0 [1]	60.0 [3]	6.3	20.0 [1]	20.0 [1]	60.0 [3]	20.0
Normal weight	8.2 [5]	0.0 [0]	91.8 [56]	8.6	45.9 [28]	21.3 [13]	32.8 [20]	18.2
Over weight	12.9 [4]	0.0 [0]	87.1 [27]	8.3	53.3 [16]	30.0 [9]	16.7 [5]	44.4
Obese	11.8 [2]	0.0 [0]	88.2 [15]	7.8	41.2 [7]	23.5 [4]	35.3 [6]	24.8
All Participants	9.9 [12]	0.83 [1]	89.3 [108]	8.5	46.7 [56]	22.5 [27]	30.8 [37]	22.0

Of participants that provided height and weight information and responded whether the height of the building would influence their decision to use a lift during an evacuation (N=84), as the BMI increases in each group the proportion of participants that responded that they would be influenced by the height of the building decreases. With the exception of the Obese group the majority of participants in each BMI group responded that they would be influenced by the height of the building.

Whilst there was no significant difference between the proportion of participants in each BMI group that would be influenced by the height of the building (Yates'-χ^2=4.6, p>0.05) this results perhaps suggest that participants with higher BMIs are less concerned about other occupants using a lift or delayed lift travel times during an evacuation in higher buildings.

Table 108: Frequency/Proportion of participants according to BMI that would and wouldn't be influenced by the height of the building when deciding to use a lift during an evacuation

	BMI % [Freq]				All Participants % [Freq]
Would the height of the building influence your decision?	**Under weight**	**Normal weight**	**Over weight**	**Obese**	
YES	100.0 [5]	68.7 [46]	67.6 [23]	45.5 [10]	65.4 [89]
NO	0.0 [0]	31.3 [21]	32.4 [11]	54.5 [12]	34.6 [47]

For all participants who specified their location country and specified that the height of the building would influence their decision to use a lift (N=64), the majority stated that the higher the building the more likely they would be to use a lift, ranging from 55.6%-100.0%. A smaller proportion of participants in the Obese group (55.6%) specified that the higher the building the more likely they would be to use a lift during an evacuation than the other BMI groups though overall there was no significant difference between BMI groups (Yates'-χ^2=2.4, p>0.05).

Table 109: Frequency/Proportion of participants according to BMI that would and wouldn't be influenced by the height of the building when deciding to use a lift during an evacuation

	BMI % [Freq]				All Participants % [Freq]
The higher the building the...	**Under weight**	**Normal weight**	**Over weight**	**Obese**	
MORE likely to use a lift	100.0 [5]	77.8 [35]	86.4 [19]	55.6 [5]	80.2 [69]
LESS likely to use a lift	0.0 [0]	22.2 [10]	13.6 [3]	44.4 [4]	19.8 [17]

In Table 110 the frequency/proportion of participant in each BMI group that would and wouldn't consider using a lift if they were familiar or unfamiliar with a building can be seen. Irrespective of BMI group, around half of all participants (44.0%-53.7%) in each BMI group would sometimes consider using a lift to evacuate with being no significant difference between each BMI group (χ^2=2.1, p>0.05).

Table 110: Frequency/Proportion of participants according to BMI that would and wouldn't consider using a lift if they were familiar or unfamiliar with a building

			Would you consider using the lift/lift to evacuate? (if you were familiar) % [Freq]		Would sometimes consider using a lift to evacuate % [Freq]
			YES	NO	
Would you change your above answer(s) if you were unfamiliar with the building?	Under Weight	YES	13.9 [4]	27.6 [8]	48.3 [14]
		NO	6.9 [2]	51.7 [15]	
	Normal Weight	YES	2.8 [7]	21.1 [52]	51.4 [127]
		NO	27.5 [68]	48.6 [120]	
	Over Weight	YES	3.7 [4]	8.3 [9]	44.0 [48]
		NO	32.1 [35]	56.0 [61]	
	Obese	YES	1.9 [1]	11.1 [6]	53.7 [29]
		NO	40.7 [22]	46.3 [25]	
	All Participants	YES	3.7 [17]	16.7 [77]	49.6 [228]
		NO	29.1 [134]	50.4 [232]	

A4.1 Lift Kinematic Derivation Formula

As mentioned in the main text, with regards to jerk, acceleration and maximum speed, there are three types of journey a lift can make: A) a lift reaches maximum speed, B) a lift reaches its maximum acceleration (but not maximum speed), C) a lift fails to reach its maximum acceleration (see Figure 72). In each journey type there are a series of key kinematic time points when a kinematic variable changes (e.g. t1, t2, t3, t4, etc) (see Figure 72, Table 111, Table 112, Table 113). These time points are used to determine which formula to use to calculate the time a lift arrives/passes a given floor.

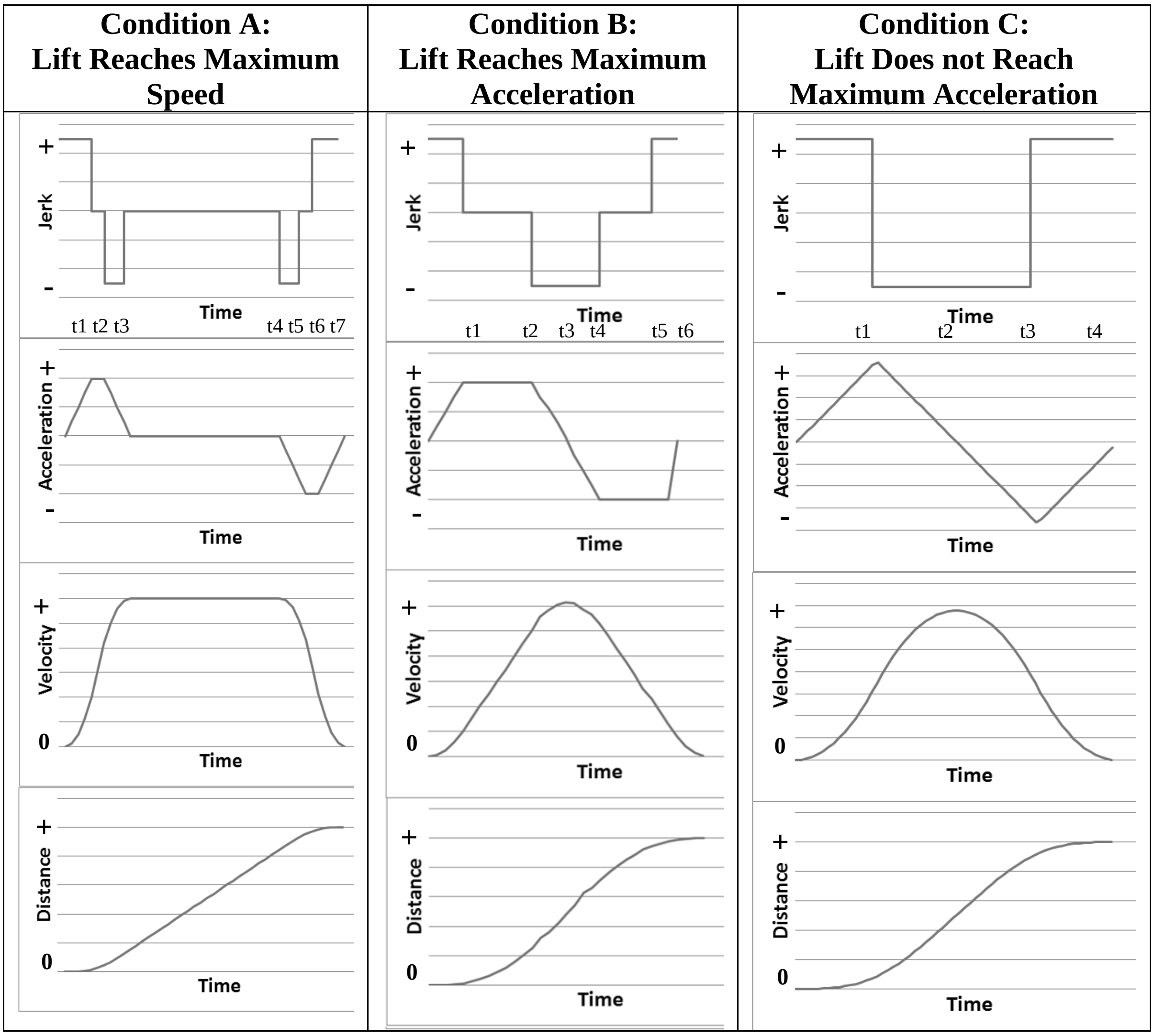


Figure 72: Three types of journey a lift can make with respect to jerk, acceleration and maximum speed [Peters, 1996]

Table 111: Key kinematic time points - Condition A: Lift Reaches Maximum Velocity

Condition A: Lift Reaches Maximum Velocity	
Time periods	**Description**
t1	Time to reach start of maximum positive acceleration
t2	Time to reach end of maximum positive acceleration
t3	Time to reach start maximum velocity
t4	Time to reach end of maximum velocity
t5	Time to reach start of maximum negative acceleration
t6	Time to reach end of maximum negative acceleration
t7	Time to reach end journey time

Table 112: Key kinematic time points - Condition B: Lift Reaches Maximum Acceleration

Condition B: Lift Reaches Maximum Acceleration	
Time periods	**Description**
t1	Time to reach start of maximum positive acceleration
t2	Time to reach end of maximum positive acceleration
t3	Time to reach maximum velocity (in this journey)
t4	Time to reach start of maximum negative acceleration
t5	Time to reach end of maximum negative acceleration
t6	Time to reach end journey time

Table 113: Key kinematic time points - Condition C: Lift Does not Reach Maximum Acceleration

Condition C: Lift Does not Reach Maximum Acceleration	
Time periods	**Description**
t1	Time to reach end of positive jerk / start of negative jerk / maximum positive acceleration (in this journey)
t2	Time to reach maximum velocity (in this journey)
t3	Time to reach end of negative jerk / start of positive jerk / maximum negative acceleration (in this journey)
t4	Time to reach end journey time

The lift motion formulae derived by Peters [Peters, 1996] specified the distance a lift would travel after a given length of time, treating distance on a continuous scale. However, the lift system within buildingEXODUS treats distance on discretized scale (i.e. the distance between each lift opening on each floor is fixed and is only implicitly represented within the animation). As such the formulae derived by Peter's were rearranged such that given the lift kinematic attributes and distance travelled would determine the time a lift would pass each floor between the start floor and the destination floor the specified location. This allows the animation of a lift moving vertically passing each floor to be represented.

The following formula describe the kinematic component of the lift model to represent the animation of a lift moving between floors on a given journey. The rearranged formula were derived by Peters[Peters, 1996]. Where rearranging the formula derived by Peters[Peters, 1996] was not possible (due to the high order), a binary search algorithm was used to iteratively search for the floor time stamp for a given distance using the respective transition time markers for that part of the journey as the initial boundaries for the search space (i.e. 0-t1, t1-t2, t2-t3, t3-t4, t4-t5, t5-t6, t6-t7) for each journey type. The following pseudo code describes how the time stamp for such a formula is searched for:

Formula Key:

d	Lifts overall journey distance	v	Maximum velocity	d(t)	Distance travelled at time ‘t’.
a	Maximum acceleration	j	Maximum Jerk		

searchTime = $ti + \frac{t_{i+1} - ti}{2}$

searchDistance = 0.0

toleranceLevel = 0.0001 {how accurate the iterative approximation needs to be}

upperBoundary = t_{i+1}

lowerBoundary = t_i

f(x) = {function used to determine the distance travelled at a given time}

```
while (d(t) -  searchDistance <  toleranceLevel)
{
        searchDistance = f(x)

        if ( searchDistance>d(t))
        {
            upperBoundary=searchTime
            searchTime=lowerBoundary + ((searchTime-lowerBoundary)/2);
        }else{
            lowerBoundary=searchTime
            searchTime=lowerBoundary + ((upperboundary -searchTime)/2);
        }

}
```

The following formulae, originally derived by Peters, specify the derived transition time markers (i.e. 0-t1, t1-t2, t2-t3, t3-t4, t4-t5, t5-t6, t6-t7) for each of the three types of lift journey along with methods for calculating the time stamp for a given distance used within the lift model in buildingEXODUS.

Condition A: Lift Reaches Maximum Velocity

1. ***Condition to check lift reaches maximum velocity***

$\frac{a^2.v+v^2.j}{j.a} \leq d$

2. ***Time Period Formula***

$$t1 = \frac{a}{j} \qquad t2 = \frac{v}{a} \qquad t3 = \frac{a}{j}+\frac{v}{a} \qquad t4 = \frac{d}{v}$$

$$t5 = \frac{d}{v}+\frac{a}{j} \qquad t6 = \frac{d}{v}+\frac{v}{a} \qquad t7 = \frac{d}{v}+\frac{a}{j}+\frac{v}{a}$$

3. ***Time Stamp Formula for floors between each time period***

The distance between the next lift floor and the initial start lift floor (d) is passed to the following rearranged equations which then provide the necessary distances travelled for each interval (i.e. using t1, t2, t3, etc determine d1, d2, d3, etc). Once these distances are calculated for each time interval it is then determined which interval the next floor is part of using the distance travelled (d). That intervals formula is then used to calculate the time at which the lift will arrive at the next floor. This time is then used to display the lift at the given time for the next floor in the simulation. This process is then repeated for the next floors in the sequence so providing the location and subsequent animation of the lift vertically moving through the geometry.

Time Period	***Time Stamp Formula/Method***
$0 \leq t \leq t1$	$d(t) = \frac{j.t^3}{6}$ Rearranged to: $t = \sqrt[3]{\frac{6.d(t)}{j}}$
$t1 \leq t \leq t2$	$d(t) = \frac{a^3}{6.j^2} - \frac{a^2.t}{2.j} + \frac{a.t^2}{2}$ Was solved using $\frac{-b\pm\sqrt{b^2-4ac}}{2a}$ to give: $t = \frac{-(-\frac{a^2}{2.j}) \pm \sqrt{(-\frac{a^2}{2.j})^2 - 4.\frac{a}{2}.(\frac{a^3}{6.j^2} - d(t))}}{2\frac{a}{2}}$
$t2 \leq t \leq t3$	{iteratively search for solution} searchTime = t searchDistance = $\frac{a^3}{6.j^2} - \frac{t.a^2}{2.j} - \frac{j.t^3}{6} + \frac{a.t^2}{2} + \frac{j.v.t^2}{2.a} - \frac{j.v^2.t}{2.a^2} + \frac{v^3.j}{6.a^3}$

$t3 \le t \le t4$	$\mathrm{d(t)} = \frac{-a.v}{2.j} - \frac{v^2}{2.a} + v.t$ Rearranged to: $t = \frac{d(t) - \frac{a.v}{2.j} + \frac{v^2}{2.a}}{v}$
$t4 \le t \le t5$	{iteratively search for solution} $\mathrm{searchTime} = \mathrm{t}$ $\mathrm{searchDistance} = \frac{-a.v}{2.j} - \frac{v^2}{2.a} + v.t + \frac{t^2.j.d}{2.v} - \frac{t.j.d^2}{v^2.2} - \frac{t^3.j}{6} + \frac{d^3.j}{v^2.6}$
$t5 \le t \le t6$	{iteratively search for solution} $\mathrm{searchTime} = \mathrm{t}$ $\mathrm{searchDistance} = \frac{-a.v}{2.j} - \frac{v^2}{2.a} - \frac{d^2.a}{v^2.2} - \frac{d.a^2}{2.j.v} - \frac{a^3}{j^2.6} + v.t + \frac{a.d.t}{v} + \frac{t.a^2}{2.j} - \frac{t^2.a}{2}$
$t6 \le t \le t7$	{iteratively search for solution} $\mathrm{searchTime} = \mathrm{t}$ $\mathrm{searchDistance} = \frac{-v^2}{2.a} + v.t - \frac{j.d.v}{2.a^2} - \frac{d^2.j}{2.v.a} + \frac{t^3.j}{6} - \frac{a.v}{2.j} - \frac{d^3.j}{v^3.6} - \frac{t^2.j.d}{2.v} + \frac{j.d^2.t}{2.v^2} + \frac{a.t.d}{v} + \frac{t.a^2}{2.j} - \frac{t^2.a}{2} - \frac{a^3}{j^2.6} - \frac{d^2.a}{v^2.2} - \frac{d.a^2}{2.j.v} + \frac{t.d.j}{a} + \frac{t.v^2.j}{2.a^2} - \frac{t^2.v.j}{2.a} - \frac{j.v^3}{a^3.6}$ $v.t - \frac{j.d.v}{2.a^2} - \frac{d^2.j}{2.v.a} + \frac{t^3.j}{6} - \frac{a.v}{2.j} - \frac{d^3.j}{v^3.6} - \frac{t^2.j.d}{2.v} + \frac{j.d^2.t}{2.v^2} + \frac{a.t.d}{v} + \ldots \frac{t.a^2}{2.j} - \frac{t^2.a}{2} - \frac{a^3}{j^2.6} - \frac{d^2.a}{v^2.2} - \frac{d.a^2}{2.j.v} + \frac{t.d.j}{a} + \frac{t.v^2.j}{2.a^2} -$ $\frac{t^2.v.j}{2.a} - \frac{j.v^3}{a^3.6}$

Condition B: Lift Reaches Maximum Acceleration (but not Maximum Velocity)

1. ***Condition to check Lift Reaches Maximum Acceleration (but not maximum velocity)***

$$2.\frac{a^3}{j^2} \le d < \frac{a^2.v + v^2.j}{j.a}$$

2. ***Time Period Formula***

$$t1 = \frac{a}{j} \qquad t2 = \frac{-a}{2.j} + \frac{\sqrt{a^3 + 4.d.j^2}}{2.j.\sqrt{a}} \qquad t3 = \frac{a}{2.j} + \frac{\sqrt{a^3 + 4.d.j^2}}{2.j.\sqrt{a}}$$

$$t4 = \frac{3.a}{2.j} + \frac{\sqrt{a^3 + 4.d.j^2}}{2.j.\sqrt{a}} \qquad t5 = \frac{\sqrt{a^3 + 4.d.j^2}}{\sqrt{a}.j} \qquad t6 = \frac{a}{j} + \frac{\sqrt{a^3 + 4.d.j^2}}{\sqrt{a}.j}$$

3. *Time Stamp Formula for floors between each period*

Time Period	***Time Stamp Formula/Method***
$0 \leq t \leq t1$	$d(t) = \frac{j.t^3}{6}$ Rearranged to: $t = \sqrt[3]{\frac{6.d(t)}{j}}$
$t1 \leq t \leq t2$	$d(t) = \frac{a^3}{6.j^2} - \frac{a^2.t}{2.j} + \frac{a.t^2}{2}$ Was solved using $\frac{-b \pm \sqrt{b^2-4ac}}{2a}$ to give: $t = \frac{-(-\frac{a^2}{2.j}) \pm \sqrt{(-\frac{a^2}{2.j})^2 - 4.\frac{a}{2}.(\frac{a^3}{6.j^2} - d(t))}}{a}$
$t2 \leq t \leq t3$	{iteratively search for solution} $\text{searchTime} = \text{t}$ $\text{searchDistance} = \frac{a^3}{12.j^2} + \frac{a^{\frac{3}{2}}.\sqrt{a^3.4.d.j^2}}{12.j^2} - \frac{d}{4} - \frac{3.t.a^2}{4.j} + \frac{t^2.a}{4} + \frac{1}{4}.\frac{t^2.\sqrt{a^3.4.d.j^2}}{\sqrt{a}} + \frac{\sqrt{a^3.4.d.j^2}.\sqrt{a}.t}{4.j} - \frac{t^3 j}{6} - \frac{t.j.d}{a.2} + \frac{d.\sqrt{a^3.4.d.j^2}}{12.a^{\frac{3}{2}}}$
$t3 \leq t \leq t4$	{iteratively search for solution} $\text{searchTime} = \text{t}$ $\text{searchDistance} = \frac{-d}{4} + \frac{a.t^2}{4} - \frac{a^2.3.t}{4.j} + \frac{\sqrt{a^3.4.d.j^2}.t.\sqrt{a}}{4.j} - \frac{j.t.d}{2.a} + \frac{t^2.\sqrt{a^3.4.d.j^2}}{4.\sqrt{a}} - \frac{j.t^3}{6} + \frac{a^3}{j^2.12} + \frac{\sqrt{a^3.4.d.j^2}.a^{\frac{3}{2}}}{j^2.12} + \frac{d.\sqrt{a^3.4.d.j^2}}{12.a^{\frac{3}{2}}}$
$t4 \leq t \leq t5$	$d(t) = -d - \frac{a.t^2}{2} + \frac{\sqrt{a^3.4.d.j^2}.t.\sqrt{a}}{j} + \frac{a^2.t}{2.j} - \frac{a^{\frac{3}{2}}}{2}.\frac{\sqrt{a^3.4.d.j^2}}{j^2} - \frac{2.a^3}{3.j^2}$ Was solved using $\frac{-b \pm \sqrt{b^2-4ac}}{2a}$ to give: $\text{t} = \frac{-(\frac{\sqrt{a^3.4.d.j^2}.\sqrt{a}}{j} + \frac{a^2}{2.j}) \pm \sqrt{(\frac{\sqrt{a^3.4.d.j^2}.\sqrt{a}}{j} + \frac{a^2}{2.j})^2 - 4.\frac{-a}{2}.(-d - \frac{a^{\frac{3}{2}}}{2}.\frac{\sqrt{a^3.4.d.j^2}}{j^2} - \frac{2.a^3}{3.j^2} - d(t))}}{2.\frac{-a}{2}}$
$t5 \leq t \leq t6$	{iteratively search for solution} $\text{searchTime} = \text{t}$ $\text{searchDistance} = -d - \frac{2.a^3}{3.j^2} + \frac{a^2.t}{j} - \frac{a.t^2}{2} + \frac{j.t^3}{6} + \frac{\sqrt{a^3.4.d.j^2}.\sqrt{a}.t}{j} + \frac{2.d.t.j}{a} + \frac{(a^3.4.d.j^2)^{\frac{3}{2}}}{j^2.(3.a^{\frac{3}{2}})} - \frac{t^2.\sqrt{a^3.4.d.j^2}}{\sqrt{a}.2} - \frac{\sqrt{a^3.4.d.j^2}.a^{\frac{3}{2}}}{j^2} - \frac{2.\sqrt{a^3.4.d.j^2}.d}{a^{\frac{3}{2}}}$

Condition C: Lift Does not Reach Maximum Acceleration

1. ***Condition to check Lift Reaches Maximum Acceleration (but not maximum velocity)***

   $d < 2.\frac{a^3}{j^2} \leq$

2. ***Time Period Formula***

$$t1 = (\frac{1}{2}.\frac{d}{j})^{\frac{1}{3}} \quad t2 = (4.\frac{d}{j})^{\frac{1}{3}} \quad t3 = (\frac{27}{2}.\frac{d}{j})^{\frac{1}{3}} \quad t4 = (32.\frac{d}{j})^{\frac{1}{3}}$$

3. ***Time Stamp Formula for floors between each period***

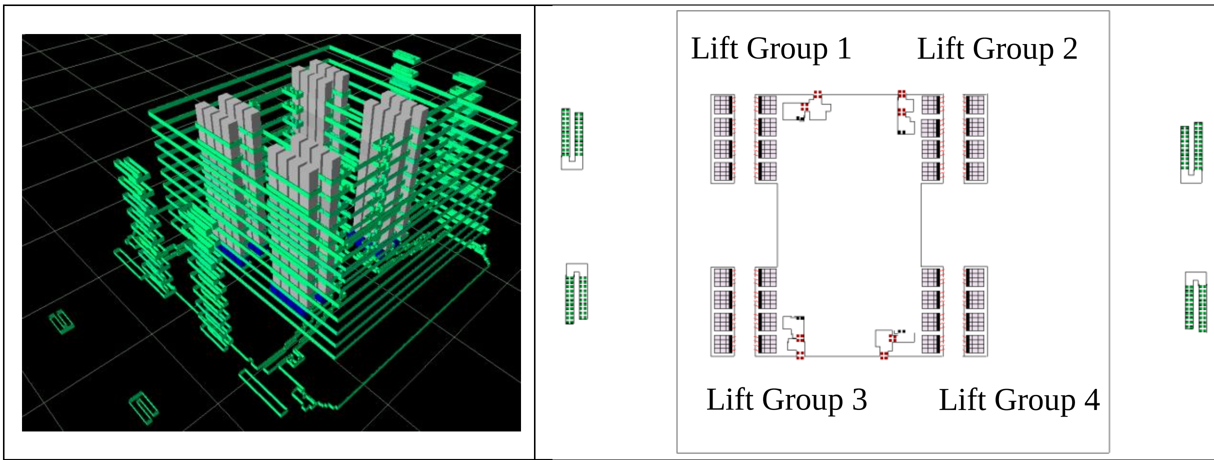
Time Period	***Time Stamp Formula/Method***
$0 \leq t \leq t1$	$d(t) = \frac{j.t^3}{6}$ Rearranged to: $t = \sqrt[3]{\frac{6.d(t)}{j}}$
$t1 \leq t \leq t2$	{iteratively search for solution} $\text{searchTime} = \text{t}$ searchDistance = $\frac{d}{6} + \frac{1}{2}.j^{\frac{2}{3}}.2^{\frac{2}{3}}.d^{\frac{1}{3}}.t^2 - \frac{1}{2}.j^{\frac{1}{3}}.2^{\frac{1}{3}}.d^{\frac{2}{3}}.t - \frac{j.t^3}{6}$
$t2 \leq t \leq t3$	{iteratively search for solution} $\text{searchTime} = \text{t}$ searchDistance = $\frac{d}{6} - \frac{1}{2}.j^{\frac{1}{3}}.t.2^{\frac{1}{3}}.d^{\frac{2}{3}} + \frac{t^2}{2}.j^{\frac{2}{3}}.2^{\frac{2}{3}}.d^{\frac{1}{3}} - \frac{j.t^3}{6}$
$t3 \leq t \leq t4$	{iteratively search for solution} $\text{searchTime} = \text{t}$ searchDistance = $\frac{-13.d}{3} - j^{\frac{2}{3}}.t^2.2^{\frac{2}{3}}.d^{\frac{1}{3}} + 4.j^{\frac{1}{3}}.t.2^{\frac{1}{3}}.d^{\frac{2}{3}} + \frac{j.t^3}{6}$

A5.1 Verification Test Results– Lift and Agent Lift Model

For each component of the developed lift and agent lift model a series of verification tests have been performed and results presented. This is intended to demonstrate that each component behaves as expected and produce appropriate results based on input parameters and simulated conditions. The geometry and population used in each test have been described in the following sections with results and a description of each test presented accordingly for each component of the lift and agent lift model in the respective sections of the chapter.

A5.1.1 Verification geometry

The verification test geometry has 10 floors with a floor to floor height of 3m (the total height of the building was 30m in height), with four stairwell cores, each stair being 1m wide, and four lift banks each containing eight lifts (see Figure 73) (not all lifts and stairs are used for all verification tests). With the exception of the ground floor all levels in the building have the same layout and configuration. Each stair allowed two agents to stand abreast side-by-side with occupants preferring to stagger their locations (i.e. prefer not to stand side-by-side) and maintain at least one tread spacing between themselves and the agent in front. Each stair is doglegged design where an intermittent landing (1m x 3.2m) connects the two legs; each leg being 1.5m in width and 4.6m in horizontal length allowing a maximum of 16 agents to simultaneously occupy each leg of the stairs at a time. Within the building all of the lifts have the capacity to service all floors. Due to the hypothetical nature of the building, aside from the external walls and the stair/lift cores, no furniture or internal obstructions were represented within the building geometry. A graphical view of the geometry can be seen in Figure 73 below. At the beginning of each simulation the lift doors are closed and immediately start moving at the start of a simulation.



3D Geometry View	2D Geometry View

Figure 73: Lift verification test geometry

A5.1.2 Verification population

For the lift verification tests no agents were required to be represented. However, buildingEXODUS requires at least a single agent in order to run a simulation. As such whilst a single agent has been used in the lift verification tests the agent behaviour will not influence the lift verification tests. The population used in all of the agent lift verification tests were generated from the standard buildingEXODUS population. The frequency of agents used in each test was different and has been specified in the respective sections within the chapter.

A5.1.3 Verification lift attributes

The delay times associated with a lift journey have been set to the following times, as defined by CBISE Guide D:

- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s

In buildingEXODUS each delay time is combined with the lift kinematics time calculations (determining the movement of the lift) to determine the time at which a lift passes given floors on its journey. As such these have been combined within the lift verification tests. The kinematic attributes of the lifts used have been stated within each the respective section.

A5.1.4 Verification test – Lift kinematics

A series of 14 lift movement/delay time verification tests were conducted to demonstrate the kinematics of the lift model behaves as expected given a series of input parameters. All tests involved a single journey of a single lift travelling from floor 0 to floor 9 (27 meters) each using different kinematic parameters (maximum speed, acceleration and jerk) (see Figure 73) of a lift and recorded the movement/event times within the model. Each test was intended to demonstrate the lift model representing each of the three types of lift journey (see Figure 33), with tests 1-4 only altering the maximum speed, tests 5-8 only altering the acceleration, and tests 9-14 only altering the jerk. These movement/event times were then input into the equations derived by Peters [Peters, 1996] (which the lift model rearranged equations were based on) to demonstrate the times calculated in the equations correlate with the distance travelled and the expected event times in the model. Each test was involved one simulation as no random seed variables are used in the lift mode (i.e. no variation would be produced from multiple simulations).

Table 114: Lift verification tests - altered kinematic parameters

Test	Journey Type	Max Speed (m/s)	Acceleration (m/s^2)	Jerk (m/s^3)
1	A	4	1.2	1.8
2	A	5.3	1.2	1.8
3	B	5.31	1.2	1.8
4	B	6	1.2	1.8
5	B	7	1.2	1.8
6	B	7	3.52	1.8
7	C	7	3.53	1.8
8	C	7	4	1.8
9	A	7	3	2
10	A	7	3	1.97
11	B	7	3	1.96
12	B	7	3	1.42
13	C	7	3	1.41
14	C	7	3	1.3

In Table 115 the calculated and the modelled time the lift passes each floor in the model (which includes the motor delay at the beginning of each journey), the time the lift door opens and the time the lift door closes (after the given dwell delay and door closing time) for a single journey can be seen. Events in buildingEXODUS are governed by the simulation clock which increments every 0.17 sec (0.166666· sec) for the lift model. This introduces a small margin of error when setting lift event times as events can only occur at times which are multiples of 0.17 sec (the maximum margin of error is 0.17sec between the lift calculated and modelled lift event time). This margin of error is only introduced for each individual event time (i.e. the margin of error is not aggregated for each event time). This margin of error can be reduced by decreasing the buildingEXODUS time step to below 0.17s however, considering the magnitude of this time compared to agent movement times the influence of this is expected to be very small upon a simulation.

Table 115: Calculated/simulated time lift passes each floor, door opening/closing times, in the model

Test	Calculated/ modelled/ Difference	Time lift passes each floor (sec)										Door Open Time	Door Close Time
		0	1	2	3	4	5	6	7	8	9		
1	Calculated	0.00	3.06	3.99	4.75	5.50	6.25	7.00	7.76	8.69	11.23	12.13	18.17
	Modelled	0.00	3.17	4.00	4.83	5.50	6.33	7.00	7.83	8.83	11.33	12.17	18.17
	Difference	0.00	0.11	0.01	0.08	0.00	0.08	0.00	0.07	0.14	0.10	0.03	0.00
2	Calculated	0.00	3.06	3.99	4.70	5.30	5.87	6.48	7.19	8.12	10.66	11.47	17.50
	Modelled	0.00	3.17	4.00	4.83	5.33	6.00	6.50	7.33	8.17	10.67	11.50	17.50
	Difference	0.00	0.11	0.01	0.13	0.03	0.13	0.02	0.15	0.05	0.01	0.03	0.00
3	Calculated	0.00	3.06	3.99	4.70	5.30	5.87	6.48	7.19	8.12	10.64	11.47	17.50
	Modelled	0.00	3.17	4.00	4.83	5.33	6.00	6.50	7.33	8.17	10.67	11.50	17.50
	Difference	0.00	0.11	0.01	0.13	0.03	0.13	0.02	0.15	0.05	0.03	0.03	0.00
4	Calculated	0.00	3.06	3.99	4.70	5.30	5.87	6.48	7.19	8.12	10.64	11.47	17.50
	Modelled	0.00	3.17	4.00	4.83	5.33	6.00	6.50	7.33	8.17	10.67	11.50	17.50
	Difference	0.00	0.11	0.01	0.13	0.03	0.13	0.02	0.15	0.05	0.03	0.03	0.00
5	Calculated	0.00	3.06	3.99	4.70	5.30	5.87	6.48	7.19	8.12	10.64	11.47	17.50
	Modelled	0.00	3.17	4.00	4.83	5.33	6.00	6.50	7.33	8.17	10.67	11.50	17.50
	Difference	0.00	0.11	0.01	0.13	0.03	0.13	0.02	0.15	0.05	0.03	0.03	0.00
6	Calculated	0.00	2.66	3.26	3.75	4.20	4.63	5.08	5.57	6.17	8.30	9.13	15.17
	Modelled	0.00	2.67	3.33	3.83	4.33	4.67	5.17	5.67	6.33	8.33	9.17	15.17
	Difference	0.00	0.01	0.07	0.08	0.14	0.03	0.09	0.10	0.16	0.03	0.03	0.00
7	Calculated	0.00	2.66	3.26	3.75	4.20	4.63	5.08	5.57	6.17	8.30	9.13	15.17
	Modelled	0.00	2.67	3.33	3.83	4.33	4.67	5.17	5.67	6.33	8.33	9.17	15.17
	Difference	0.00	0.01	0.07	0.08	0.14	0.03	0.09	0.10	0.16	0.03	0.03	0.00
8	Calculated	0.00	2.66	3.26	3.75	4.20	4.63	5.08	5.57	6.17	8.30	9.13	15.17
	Modelled	0.00	2.67	3.33	3.83	4.33	4.67	5.17	5.67	6.33	8.33	9.17	15.17
	Difference	0.00	0.01	0.07	0.08	0.14	0.03	0.09	0.10	0.16	0.03	0.03	0.00
9	Calculated	0.00	2.60	3.21	3.69	4.13	4.56	5.00	5.49	6.09	8.17	9.13	15.17
	Modelled	0.00	2.67	3.33	3.83	4.17	4.67	5.17	5.50	6.17	8.33	9.17	15.17
	Difference	0.00	0.07	0.13	0.14	0.04	0.11	0.17	0.01	0.07	0.17	0.03	0.00
10	Calculated	0.00	2.61	3.22	3.70	4.14	4.57	5.01	5.50	6.11	8.19	9.13	15.17
	Modelled	0.00	2.67	3.33	3.83	4.17	4.67	5.17	5.50	6.17	8.33	9.17	15.17
	Difference	0.00	0.06	0.12	0.13	0.02	0.10	0.15	0.00	0.06	0.14	0.03	0.00

11	Calculated	0.00	2.61	3.22	3.70	4.15	4.58	5.02	5.50	6.11	8.20	9.13	15.17
	Modelled	0.00	2.67	3.33	3.83	4.17	4.67	5.17	5.67	6.17	8.33	9.17	15.17
	Difference	0.00	0.06	0.11	0.13	0.02	0.09	0.15	0.16	0.05	0.13	0.03	0.00
12	Calculated	0.00	2.83	3.49	4.02	4.50	4.97	5.46	5.99	6.64	8.94	9.80	15.83
	Modelled	0.00	2.83	3.50	4.17	4.67	5.00	5.50	6.00	6.67	9.00	9.83	15.83
	Difference	0.00	0.00	0.01	0.15	0.17	0.03	0.04	0.01	0.03	0.06	0.03	0.00
13	Calculated	0.00	2.84	3.49	4.03	4.51	4.98	5.47	6.00	6.66	8.89	9.80	15.83
	Modelled	0.00	3.00	3.50	4.17	4.67	5.00	5.50	6.00	6.67	9.00	9.83	15.83
	Difference	0.00	0.16	0.01	0.14	0.16	0.02	0.03	0.00	0.01	0.11	0.03	0.00
14	Calculated	0.00	2.90	3.58	4.12	4.62	5.11	5.60	6.15	6.82	9.12	9.97	16.00
	Modelled	0.00	3.00	3.67	4.17	4.67	5.17	5.67	6.17	6.83	9.17	10.00	16.00
	Difference	0.00	0.10	0.09	0.04	0.05	0.06	0.06	0.02	0.01	0.04	0.03	0.00

To verify that the above lift event times are as expected for each floor, the motor delay time (0.5 sec)was subtracted from each of the above calculated/modelled floor times then used to calculate the travel distance a lift would have travelled using the formulae derived by Peters [Peters, 1996] (see previous section) (see Table 116). As can be seen in Table 116, using the calculated travel times the exact distance travelled by the lift for each floor on the lift journey is produced for each test with a slight difference (0.0m-1.07m) in the modelled distance due to the time discretisation within buildingEXODUS.

Table 116: Calculated lift travel distances from floor times

Test	**Calculated/ modelled/ Difference**	**Calculated lift travel distance using above travel times and Richards formula (m)**									
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.29	6.04	9.33	12.00	15.33	18.00	21.27	24.37	27.00
	Difference	0.00	0.29	0.04	0.33	0.00	0.33	0.00	0.27	0.37	0.00
2	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.29	6.04	9.62	12.15	15.66	18.11	21.54	24.13	27.00
	Difference	0.00	0.29	0.04	0.62	0.15	0.66	0.11	0.54	0.13	0.00
3	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.29	6.04	9.62	12.15	15.66	18.11	21.54	24.13	27.00
	Difference	0.00	0.29	0.04	0.62	0.15	0.66	0.11	0.54	0.13	0.00
4	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.29	6.04	9.62	12.15	15.66	18.11	21.54	24.13	27.00
	Difference	0.00	0.29	0.04	0.62	0.15	0.66	0.11	0.54	0.13	0.00
5	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.29	6.04	9.62	12.15	15.66	18.11	21.54	24.13	27.00
	Difference	0.00	0.29	0.04	0.62	0.15	0.66	0.11	0.54	0.13	0.00
6	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00

	Modelled	0.00	3.05	6.42	9.55	12.94	15.23	18.56	21.54	24.61	27.00
	Difference	0.00	0.04	0.42	0.55	0.94	0.23	0.56	0.54	0.61	0.00
7	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.05	6.42	9.55	12.94	15.23	18.56	21.54	24.61	27.00
	Difference	0.00	0.05	0.42	0.55	0.94	0.23	0.56	0.54	0.61	0.00
8	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.05	6.42	9.55	12.94	15.23	18.56	21.54	24.61	27.00
	Difference	0.00	0.05	0.42	0.55	0.94	0.23	0.56	0.54	0.61	0.00
9	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.29	6.75	9.96	12.25	15.74	19.07	21.09	24.28	27.00
	Difference	0.00	0.29	0.75	0.96	0.25	0.74	1.07	0.09	0.28	0.00
10	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.25	6.69	9.88	12.17	15.66	19.00	21.01	24.23	27.00
	Difference	0.00	0.25	0.69	0.88	0.17	0.66	1.00	0.01	0.23	0.00
11	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.24	6.67	9.86	12.14	15.63	18.96	21.90	24.21	27.00
	Difference	0.00	0.24	0.67	0.86	0.14	0.63	0.96	0.90	0.21	0.00
12	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.00	6.07	9.91	13.05	15.17	18.26	21.07	24.10	27.00
	Difference	0.00	0.00	0.07	0.91	1.05	0.17	0.26	0.07	0.10	0.00
13	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.65	6.03	9.86	12.99	15.11	18.19	21.00	24.04	27.00
	Difference	0.00	0.65	0.03	0.86	0.99	0.11	0.19	0.00	0.04	0.00
14	Calculated	0.00	3.00	6.00	9.00	12.00	15.00	18.00	21.00	24.00	27.00
	Modelled	0.00	3.37	6.47	9.26	12.28	15.37	18.36	21.08	24.03	27.00
	Difference	0.00	0.37	0.47	0.26	0.28	0.37	0.36	0.08	0.03	0.00

In addition to the floor travel times, the lift door opening/closing and dwell times within each test were recorded to verify attributes were being correctly modelled. In each test the lift door opening times were set to 0.8 sec. As can be seen in Table 115 the difference between the modelled lift arrival time for floor 9 (the time the door opening time is calculated from) and the calculated door opening time in each test is exactly 0.8 sec. The difference between the modelled floor 9 arrival time and modelled door opening time was 0.83 sec for each test with the difference of 0.03 sec due to the buildingEXODUS time step discretisation. Once the lift door is opened in each test it will stay open for the dwell time plus the door closing time before the animation of the door actually closes in the modelled. The dwell time (3.0 sec) and closing door time (3.0 sec) combined sum to 6.0 sec. As can be seen in Table 115 the difference between the all the modelled door opening and the modelled door closing times in each test is 6.0 sec exactly. Due to the combined time being a multiple of 0.17sec (0.166666· sec) meant that the difference time is represented exactly.

Results from the lift movement/delay times verification tests have shown the developed lift model to behaves as intended given the input parameters used and the time step used within buildingEXODUS.

A5.1.5 Verification test – Lift motion control verification

As previously mentioned the lift motion control floor sequence system within buildingEXODUS is used to control the floors a lift will service during a simulation. The two methods for a user to specify the lift floor sequence within the model are the floor sequence system and the shuttle floor sequence system. A series of 8 verification tests have been performed to demonstrate the model behaves as expected given a series of input parameters.

With exception of tests 7 and 8, all tests involved 26 agents (twice the capacity of a lift) located next to lift bank 1 on floors 7, 8, 9. A single lift (Lift 1) within lift group 1 was used for all tests. All agents were assigned to use the lift if the lift serviced their starting floor with agents assigned to use the stairs if they do not use the lift. Of the agents they were assigned to use a lift, their individual attributes were set such that no agent would redirect from the lift.

The lift attributes were set as follows:

- Max Speed = 4 m/s
- Acceleration 1.2 m/s^2
- Jerk = 1.8 m/s^3
- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s

Results from the lift motion control verification tests are presented in Table 117. The first three tests (Test 1-3) show the floor sequence control system to serve different floors. Tests 4-6 show the shuttle floor sequence control system to serve the same floor sequence as Tests 1-3 with the floor sequence control sequence. Tests 7 used the floor sequence control system and is identical to Test 3 however, 20 agents were present on each floor instead of 26. Due to the floor sequence control system being used in this test meant that the lift explicitly followed the stated floor sequence specified irrespective of the lift being full to capacity on the upper floors. As such the last journey for each floors agents involved the lift moving to the ground floor and was not full to capacity. Test 8 used the shuttle floor sequence control system and is identical to Test 6 however, 20 agents were present on each floor instead of 26. Due to the shuttle floor sequence control system being used in this test meant that the lift shuttle between floor pairs in the sequence. If a lift is not filled to capacity and no other agents are waiting in the lift catchment area for the current floor, the lift will move directly to the next floor pair in the sequence (i.e. not having to travel to the ground floor being partially full to empty). This difference in the modelled floor sequence compared to Test 7 can be seen in the fourth lift journey where the lift moves directly from floor 9 to floor 8 without moving to the ground floor. The results from the lift motion control verification tests have shown the model to behave as intended given a series of input parameters.

Table 117: Lift verification motion control verification tests and test results

Test	**System**	**Stated Floor Sequence**	**Modelled Floor Sequence in buildingEXODUS**
1	Floor sequence	9,0,9,0	9,0,9,0
2	Floor sequence	9,0,9,0,8,0,8,0	9,0,9,0,8,0,8,0
3	Floor sequence	9,0,9,0,8,0,8,0,7,0,7,0	9,0,9,0,8,0,8,0,7,0,7,0
4	Shuttle floor	9,0	9,0,9,0
5	Shuttle floor	9,0,8,0	9,0,9,0,8,0,8,0
6	Shuttle floor	9,0,8,0,7,0	9,0,9,0,8,0,8,0,7,0,7,0
7	Floor sequence (20 agents per floor)	9,0,9,0,8,0,8,0,7,0,7,0	9,0,9,0,8,0,8,0,7,0,7,0
8	Shuttle floor (20 agents per floor)	9,0,8,0,7,0	9,0,9,8,0,8,0,8,7,0,7,0

A5.1.6 Verification test – Agent lift/stair choice

A series of 5 verification tests were conducted to demonstrate the agent lift assignment model behaves as expected given a series of user-specified proportions for each floor (see Table 118).

Table 118: Lift/Stair choice verification test – overall proportion of lift users per floor

Test	**Floor**									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
2	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%
3	0%	50%	50%	50%	50%	50%	50%	50%	50%	50%
4	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
5	0%	0%	0%	0%	0%	20%	40%	60%	80%	90%

All tests involved all 4 lift banks (32 lifts) servicing all floors evacuating the building in a top-down evacuation strategy. All lifts had the following attributes assigned:

- Shuttle floor sequence: 9,0,8,0,7,0,6,0,5,0,4,0,3,0,2,0,1,0
- Max Speed = 4 m/s
- Acceleration 1.2 m/s^2
- Jerk = 1.8 m/s^3
- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s

Note that the kinematic attributes of the lifts are no consequence to the verification results however, the shuttle floor sequence is required to service all floors in order to give all agents the option to use either the stairs or the lift during each verification test. With the exception of the ground floor there were 100 agents distributed on each floor (900 agents in total). Each verification test involved assigning a different probability of a agents using a lift based on the floor they were initially located on. In addition to the overall proportion of lift users on each floor, agents should approximately evenly distribute between each lift bank on the respective floors. The difference between the stated and modelled proportion of lift users was calculated according to each floor and for each lift bank on each floor. For each test, the average proportion of lift users per floor and per lift bank over a series of 5 simulations was taken due to a random seed variable being used in the lift/stair choice algorithm. The results are presented in Table 119.

The range of differences between the stated and modelled proportion of lift users for a given floor for each verification test ranged between 0.0%-3.2% for the overall proportions and 0.0%-3.7% for each given lift group. These differences between the stated and the modelled proportion of lift users overall and per lift group represent an acceptable level of variation. The results from the lift choice verification tests have shown the model to behave as intended given a series of input parameters.

Table 119: Lift/stair choice verification test results - Stated/modelled (over five simulations) average proportion of lift users per lift group and per floor

Test	Floor	1				Overall	2				Overall	3				Overall
	Lift Group	**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**	
1	**Stated**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Modelled	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	**Stated**	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0
	Modelled	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0
	Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	**Stated**	12.5	12.5	12.5	12.5	50.0	12.5	12.5	12.5	12.5	50	12.5	12.5	12.5	12.5	50.0
	Modelled	10.2	13	12	12.6	47.8	8.8	13	12.2	13	47.0	9.2	12.6	12.2	13	47.0
	Difference	2.3	0.5	0.5	0.1	2.2	3.7	0.5	0.3	0.5	3.0	3.3	0.1	0.3	0.5	3.0
4	**Stated**	2.5	2.5	2.5	2.5	10.0	5.0	5.0	5.0	5.0	20.0	7.5	7.5	7.5	7.5	30.0
	Modelled	2.8	2.8	3.0	3.2	11.8	4.4	5.0	4.2	5.0	18.6	6.6	8.0	8.0	8.0	30.6
	Difference	0.3	0.3	0.5	0.7	1.8	0.6	0.0	0.8	0.0	1.4	0.9	0.5	0.5	0.5	0.6
5	**Stated**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Modelled	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Test	Floor	4				Overall	5				Overall	6				Overall
	Lift Group	**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**	
1	**Stated**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Modelled	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	**Stated**	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0
	Modelled	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0
	Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	**Stated**	12.5	12.5	12.5	12.5	50.0	12.5	12.5	12.5	12.5	50.0	12.5	12.5	12.5	12.5	50.0
	Modelled	11.2	13	10.4	13	47.6	11.6	13	13	13	50.6	12.4	13	13	13	51.4
	Difference	1.3	0.5	2.1	0.5	2.4	0.9	0.5	0.5	0.5	0.6	0.1	0.5	0.5	0.5	1.4
4	**Stated**	10.0	10.0	10.0	10.0	40.0	12.5	12.5	12.5	12.5	50.0	15.0	15.0	15.0	15.0	60.0
	Modelled	9.0	9.8	10.0	10.0	38.8	12.4	13.0	12.6	13.0	51.0	13.6	16.0	14.8	16.0	60.4
	Difference	1.0	0.2	0.0	0.0	1.2	0.1	0.5	0.1	0.5	1.0	1.4	1.0	0.2	1.0	0.4
5	**Stated**	0.0	0.0	0.0	0.0	0.0	5.0	5.0	5.0	5.0	20.0	10.0	10.0	10.0	10.0	40.0
	Modelled	0.0	0.0	0.0	0.0	0.0	4.8	5.0	4.8	5.0	19.6	8.4	10.0	9.2	10.0	37.6
	Difference	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.2	0.0	0.4	1.6	0.0	0.8	0.0	2.4

Test	Floor	7				Overall	8				Overall	9				Overall
	Lift Group	**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**	
1	**Stated**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Modelled	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	**Stated**	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0
	Modelled	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0	25.0	25.0	25.0	25.0	100.0
	Difference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	**Stated**	12.5	12.5	12.5	12.5	50.0	12.5	12.5	12.5	12.5	50.0	12.5	12.5	12.5	12.5	50.0
	Modelled	10.4	12	12.4	12	46.8	12.2	13	11.8	12.8	49.8	13	13	13	13	52.0
	Difference	2.1	0.5	0.1	0.5	3.2	0.3	0.5	0.7	0.3	0.2	0.5	0.5	0.5	0.5	2.0
4	**Stated**	17.5	17.5	17.5	17.5	70.0	20.0	20.0	20.0	20.0	80.0	22.5	22.5	22.5	22.5	90.0
	Modelled	17.2	18.0	18.0	18.0	71.2	19.6	20.0	19.8	20.0	79.4	22.0	23.0	22.8	23.0	90.8
	Difference	0.3	0.5	0.5	0.5	1.2	0.4	0.0	0.2	0.0	0.6	0.5	0.5	0.3	0.5	0.8
5	**Stated**	15.0	15.0	15.0	15.0	60.0	20.0	20.0	20.0	20.0	80.0	25.0	25.0	25.0	25.0	100.0
	Modelled	15.0	14.6	16.0	16.0	61.6	19.6	20.0	19.8	20.0	79.4	25.0	25.0	25.0	25.0	100.0
	Difference	0.0	0.4	1.0	1.0	1.6	0.4	0.0	0.2	0.0	0.6	0.0	0.0	0.0	0.0	0.0

A5.1.7 Verification test – Lift wait area congestion redirection

A series of 11 verification tests were conducted to demonstrate the agent lift wait area congestion redirection model behaves as expected given a variety of different congestion thresholds assigned to a single agent and a variety of different levels of congestion (number of agents) in a lift waiting area.

All tests involved a single bank of lifts (Lift group 1) only servicing the top floor (9) evacuating the building in a top-down evacuation strategy. All lifts had the following attributes assigned:

- Shuttle floor sequence: 9,0
- Max Speed = 4 m/s
- Acceleration 1.2 m/s^2
- Jerk = 1.8 m/s^3
- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s
- Start delay time = 120.0s

Note that the kinematic attributes of the lifts are no consequence to the verification results however, the shuttle floor sequence is required to service the upper floor in order to give all agents the option to use the lifts in lift group 1 during each verification test. In addition all lift group 1 lifts were assigned a start delay of 120 s in order to ensure that each verification test could be completed prior to the lifts servicing the upper floor. In all tests agents were only located on floor 9 in the lift group 1 catchment area, and a single agent was located outside of the catchment area (see Figure 74 as an example). The lift group 1 catchment area was set to 3m for each lift which formed the lift waiting area of 185 nodes (92.5 m^2 area).

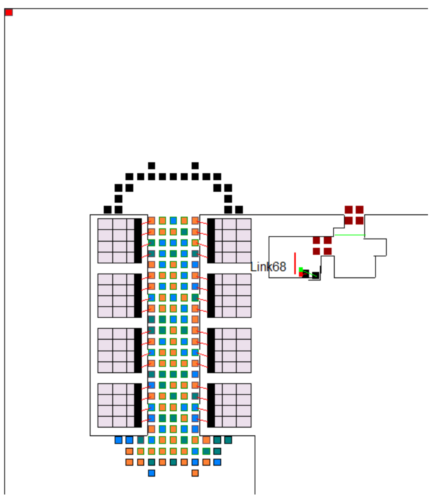


Figure 74: Starting location of single agent and lift catchment area agents (Test 4)

All agents in each test were assigned a lift wait time set to 9999 (i.e. they would not redirect due to wait time expiration) and a congestion threshold of 5.0 ped/m (i.e. they would not redirect due congestion). For each test the single agent initially outside the lift catchment area was assigned a different congestion threshold value with each test involving a different number of agents initially in the lift catchment area representing different levels of congestion (see Table 120). The number of agents in the lift waiting area in each test was set based on the boundaries of the single agent's congestion threshold to demonstrate the single agent correctly decided to redirect or maintain waiting for the lifts according to the congestion threshold assigned. Since no other agent entered into the lift catchment area after the single agent the congestion redirection probability was always set to 1 if the agents congestion threshold was reached or exceeded in each test (i.e. the single agent would always redirect if the congestion threshold was reached or exceeded).

As can be seen from the verification test results in Table 120, the correct device selection was made by the single agent according to the levels of congestion and the assigned congestion threshold for the single agent as made. The results have shown the model to behave as intended given a series of input parameters and simulated conditions.

Table 120: Lift wait area congestion redirection verification test results

Test	Number of people in lift catchment area	Level of congestion in lift catchment are (ped/m^2)	Single agent congestion threshold assigned (ped/m^2)	Device Selection
1	170	3.842	4	Lift
2	154	3.480	3.5	Lift
3	155	3.503	3.5	Stair
4	132	2.983	3	Lift
5	133	3.006	3	Stair
6	88	1.989	2	Lift
7	89	2.011	2	Stair
8	44	0.994	1	Lift
9	45	1.017	1	Stair
10	0	0.000	0	Stair

A5.1.8 Verification test – Missed lift redirection

A series of 6 verification tests were conducted to demonstrate the missed lift redirection model behaves as expected given a variety of different lift catchment area arrival times. All tests involved a single lift (within Lift group 1) only servicing floor 9 evacuating the building in a top-down evacuation strategy. The lift had the following attributes assigned:

- Shuttle floor sequence: 9,0
- Max Speed = 4 m/s
- Acceleration 1.2 m/s^2
- Jerk = 1.8 m/s^3
- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s

All tests involved a single agent initially located on floor 9 immediately outside Lift Group 1 catchment area. The agent was assigned to use the only available lift with a lift wait time set to 9999 (i.e. they would not redirect due to wait time expiration) and a congestion threshold of 5.0 ped/m (i.e. they would not redirect due congestion). For each test the agent was assigned different response times so that they arrived in the lift catchment area at different times. The kinematics/delay times of the lift determine the arrival/leave time on floor 9. Combined with the agent response/travel time determine if the agent will arrive in the lift catchment area before, during or after the lift services the agent's floor. This in turn determines if an agent will redirect from the lift to the stairs due to arriving in the lift catchment area too late.

As can be seen from the verification test results in Table 121, the agent correctly chose to maintain targeting the lift when they arrived in the lift catchment area before or whilst the lift was servicing their floor. The agent correctly chose to redirect to the stairs during tests when they arrived in the lift catchment area after the lift had closed the doors (i.e. already serviced the floor). The results have shown the model to behave as intended given a series of input parameters and simulated conditions.

Table 121: Missed lift redirection verification test results

Test	Lift Door Open Time (s)	Door Close Time (s)	Agent Response Time (s)	Agent Lift Area Arrival Time (s)	Agent arrival time compared to lift servicing period	Missed Lift Redirect	Device Selection
1	12.13	15.17	0.00	0.17	Before	FALSE	Lift
2	12.13	15.17	10.00	10.33	Before	FALSE	Lift
3	12.13	15.17	12.00	12.33	During	FALSE	Lift
4	12.13	15.17	13.00	13.33	During	FALSE	Lift
5	12.13	15.17	15.00	15.33	After	TRUE	Stair
6	12.13	15.17	16.00	16.33	After	TRUE	Stair

A5.1.9 Verification test – Lift wait location selection

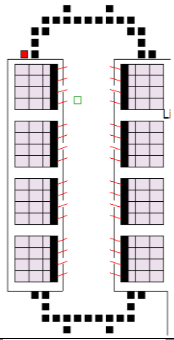
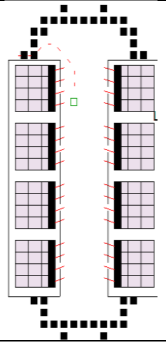
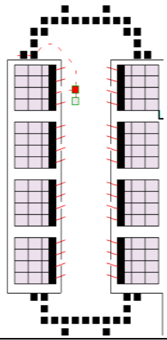
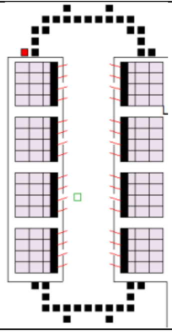
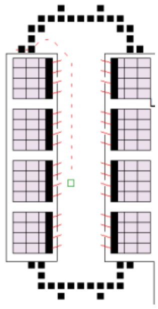
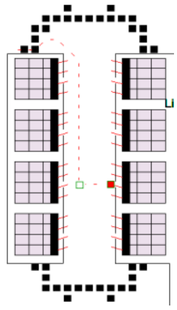
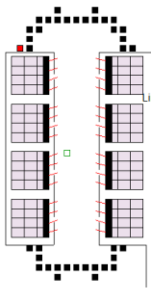
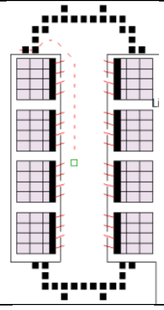
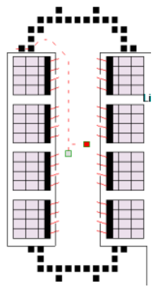
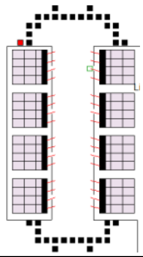
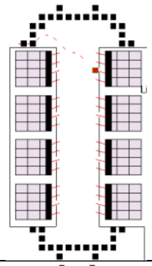
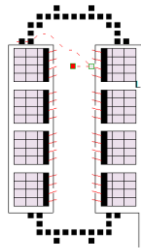
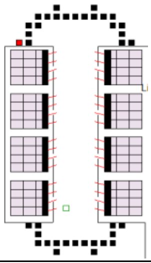
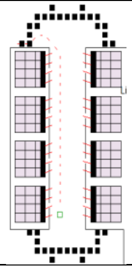
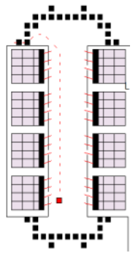
A series of 5 verification tests were conducted to demonstrate the lift wait location selection model behaves as expected. All tests involved a single lift (within Lift group 1) only servicing floor 9 evacuating the building in a top-down evacuation strategy. The lift had the following attributes assigned:

- Shuttle floor sequence: 9,0
- Max Speed = 4 m/s
- Acceleration 1.2 m/s^2
- Jerk = 1.8 m/s^3
- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s
- Start delay= 120.0s

Note that the kinematic attributes of the lift are of no consequence to the verification results however, the shuttle floor sequence is required to service the upper floor in order to give all agents the option to use the lifts in lift group 1 during each verification test. In addition the lift was assigned a start delay of 120 s in order to ensure that each verification test could be completed prior to the lifts servicing the upper floor. The lift group catchment area was set to 3m for each lift which formed the lift waiting area of 185 nodes (92.5 m^2 area). All tests involved a single agent initially located on floor 9 immediately outside Lift Group 1 catchment area. The agent was assigned to use the only available lift with a lift wait time set to 9999 (i.e. they would not redirect due to wait time expiration) and a congestion threshold of 5.0 ped/m^2 (i.e. they would not redirect due congestion). For each test the agent entered into the lift catchment area and randomly selected a location to wait in the catchment area for the lift. Due to a random seed variable being used to determine the wait location in the catchment area 5 verification tests were run in order to demonstrate a range of wait locations being selected.

The verification test results in Table 122 show the agent in each test to choose a different wait location in the lift waiting area when they entered the lift catchment area, move to the chosen wait location, then mill around the wait location once reached. The results have shown the model to behave as intended given the simulated conditions.

Table 122: Lift wait location selection verification test results

Test	Agent Enters Catchment Area (choose wait location)	Agent arrives at wait location	Agent location after 30 seconds (after milling)
1			
2			
3			
4			
5			

A5.1.10 Verification test – Lift wait time redirection

A series of 10 verification tests were conducted to demonstrate the lift wait time redirection model behaves as expected. The tests were segregated in to two parts to tests the standard wait time redirection component and test the adjusted wait time redirection component due to a lift opening. All tests involved a single lift (within Lift group 1) only servicing floor 9 evacuating the building in a top-down evacuation strategy. The lift had the following attributes assigned:

- Shuttle floor sequence: 9,0
- Max Speed = 4 m/s
- Acceleration 1.2 m/s^2
- Jerk = 1.8 m/s^3
- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s
- Capacity=1

For the standard wait time expiration tests a lift start delay of 120s was also included to ensure that the lift did not service any floor prior to agent's lift wait time expiring. For the adjusted wait time expiration tests there was no start delay as the test required the lift to service the upper floor at least once prior to agents redirecting due to wait time expiration. For both sets of tests the shuttle floor sequence is required to service the upper floor in order to give all agents the option to use the lifts in lift group 1 during each verification test. The lift group catchment area was set to 3m for each lift which formed the lift waiting area of 185 nodes (92.5 m^2 area).

The standard lift wait time expiration verification tests involved a single agent initially located on floor 9 immediately outside Lift Group 1 catchment area. The agent was assigned to use the only available lift with a congestion threshold of 5.0 ped/m^2 meaning they would not redirect due congestion. For each test the agent was assigned a different lift wait times upon entering the lift catchment area, the agent would wait for the assigned length of time in the lift catchment area before redirecting to the stairs. The adjusted lift wait time expiration verification tests were similar however, involved two agents immediately outside the lift catchment area. Since the lift used in each test can only hold one agent, the lift would service floor 9 where a single agent would board the lift, the remaining agent would then increment their lift wait time by 50%. The agent lift wait times were defined such that the waiting agent would always redirect prior to the lift servicing floor 9 in each test. These tests are intended to demonstrate that of agents waiting for a lift that experience a lift opening but unable to board the lift, would increase their lift wait time by 50%.

The verification test results in Table 123 for the standard lift wait time expiration model show the agent in each test to redirect to the stairs after waiting for the assigned lift wait time after entering into the lift catchment area. The verification test results in Table 124 for the adjusted lift wait time model show the waiting agent in each test to redirect to the stairs after waiting for the assigned lift wait time plus 50% of that time after entering into the lift catchment area.

The results have shown the model to behave as intended given the simulated conditions.

Table 123: Lift wait time redirection verification test results – standard lift wait time expiration

Test	Wait Time Assigned	Enter Lift Catchment Area	Redirection Time
1	20	0.17	20.17
2	15	0.17	15.17
3	10	0.17	10.17
4	5	0.17	5.17
5	0	0.17	0.33

Table 124: Lift wait time redirection verification test results – adjusted lift wait time expiration due to lift opening

Test	Wait Time Assigned	Enter Lift Catchment Area	Lift Open Door Time	Redirection Time
1	14	0.17	12.13	21.17
2	16	0.17	12.13	24.17
3	18	0.17	12.13	27.17
4	20	0.17	12.13	30.17
5	22	0.17	12.13	33.17

A5.1.11 Verification test – Open lift selection

A series of 7 verification tests were conducted to demonstrate the open lift selection model behaves as expected. The tests involved a different number of lifts (within Lift group 1) only servicing floor 9 evacuating the building in a top-down evacuation strategy. All lifts had the following attributes assigned:

- Shuttle floor sequence: 9,0
- Max Speed = 4 m/s
- Acceleration 1.2 m/s^2
- Jerk = 1.8 m/s^3
- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s

The frequency and capacity of lifts available varied for each test (see Table 125). For each test the shuttle floor sequence was required to service the upper floor in order to give all agents the option to use the available lifts in lift group 1 during each verification test. Where multiple lifts were used in a test, all lifts arrive at floor 9 at the same time. The lift group catchment area was set to 3m for each lift which formed the lift waiting area of 185 nodes (92.5 m^2 area).

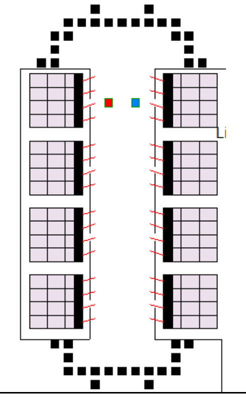
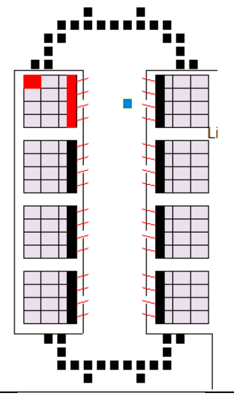
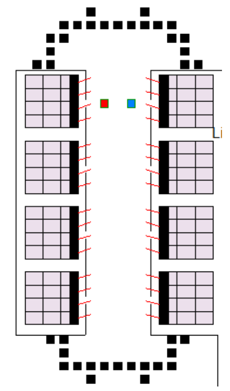
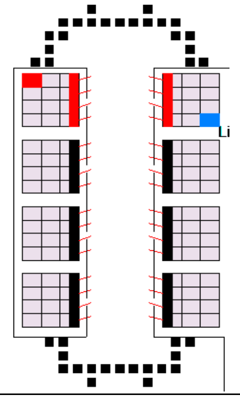
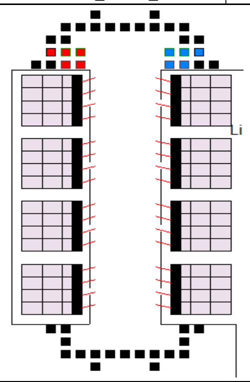
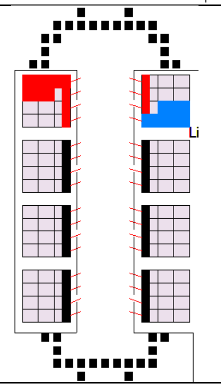
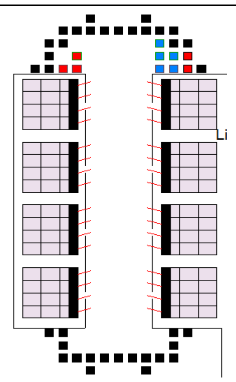
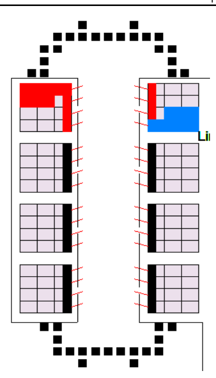
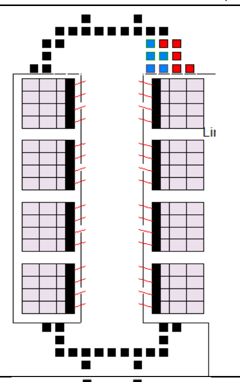
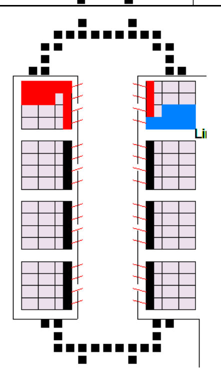
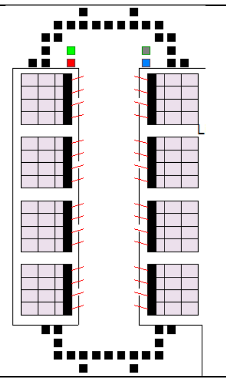
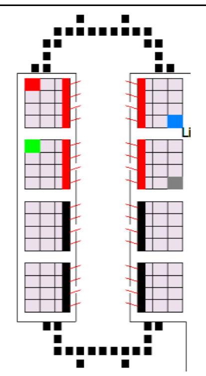
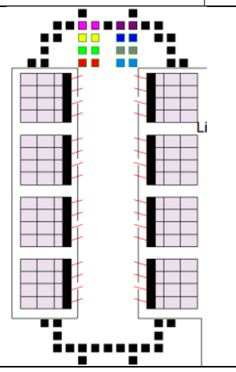
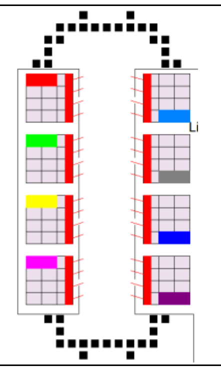
Table 125: Open lift selection verification tests - number of lifts available and lift capacities for each test

Test	Lifts available	Capacity of each lift (persons)
1	1	1
2	2	1
3	2	5
4	2	5
5	2	5
6	4	1
7	8	2

The open lift selection verification tests involved a different number of agents initially located inside the Lift Group 1 catchment area. All agents in each test were assigned a lift wait time set to 9999 (i.e. they would not redirect due to wait time expiration) and a congestion threshold of 5.0 ped/m (i.e. they would not redirect due congestion). The lift wait location was manually set for all agents to their initially starting location within the lift catchment area and milling was disabled (i.e. agents would wait in their start location instead of mill about a chosen location). This was done to maintain a fixed distance from the functioning lifts in each test. Each agent was assigned a given colour according to which lift they should use during each test in order to more clearly demonstrate which agent's should use which lift bank according to their initial starting location. The tests are intended to demonstrate that agents initially closer to an open lift will have priority in selecting to use it over those further away, with agents only electing to use a lift that they know they can board (i.e. has not been elected to be used by more agents than can fit inside the lift).

The verification test results in Table 126 shows the initial starting location of each agent and the lift used by each agent (the agents colour allows their initial location and lift selected to be identified). Each test demonstrates each agent to elect to use their closest available lift which they know they can board. The results have shown the model to behave as intended given the simulated conditions.

Table 126: Open lift selection verification tests results

Test	Initial agent lift wait locations	Lift used by agent(s)	Test	Initial agent lift wait locations	Lift used by agent(s)
1			2		
3			4		
5			6		
7					

A5.1.12 Verification test – Lift redirection to stairs

A series of 13 verification tests were conducted to demonstrate the lift redirection to stairs model behaves as expected. A different number of lift banks were used in each test and all lifts had the following attributes assigned:

- Shuttle floor sequence: 9,0
- Max Speed = 4 m/s
- Acceleration 1.2 m/s^2
- Jerk = 1.8 m/s^3
- Motor delay = 0.5s
- Dwell delay = 3.0s
- Door opening time=0.8s
- Door closing time= 3.0s
- Start delay = 120s

Note that the kinematic attributes of the lift are of no consequence to the verification results however, the shuttle floor sequence is required to service the upper floor in order to give all agents the option to use the lifts in lift group 1 during each verification test. In addition the lift was assigned a start delay of 120 s in order to ensure that lifts did not service any floor prior to agent's redirecting or passing through to the stairs from each of the available lift banks. Each lift group catchment area was set to 3m for each lift which formed the lift waiting area of 185 nodes (92.5 m^2 area) for each lift group. All tests involved 100 agents initially located on floor 9 with 25 agents immediately outside each of the 4 lift group's catchment area. Each agent was assigned to use their closest available lift group and was manually assigned a congestion threshold of -1.0f which ensured that all agents would redirect to the stairs from each lift catchment area due to congestion (i.e. even if no other agents were inside each lift catchment area agents would still redirect).

Each test that involved multiple stairs was run twice; once using the even redirect stair model (i.e. where agents are randomly assigned to evenly redirect to each of the available stairs) and once using the potential map to direct agents to their nearest stair. This was to demonstrate the difference between stair usage for each method of redirection. In the first seven tests (tests 1-7) agents were initially assigned to evenly use 4 lift banks and a different number of stairs were made available for them to redirect to. In the final six tests (tests 8-13) a different number of lift banks were made available and agents approximately evenly distributed between each lift bank before redirecting to the stairs.

Due to a random seed variable being used to determine which stair agent's redirected to when using the even redirect stair model 5 verification tests were run for each test in order to represent the average spread of agents that used each available stair.

The verification test results in Table 127 demonstrate that when agents redirect to the stairs using only the potential map, agents use their closest stair to redirect to which can cause uneven usage of the stairs (tests 4,7,9,13). The test also demonstrates that when the agents redirect to the stairs using the even redirect stair model, irrespective of the number stairs available or the initial distribution of agents assigned to each lift bank, approximately an even number of agents will redirect to each stair. The results have shown the model to behave as intended given the simulated conditions.

Table 127: Lift redirection to stairs verification test results

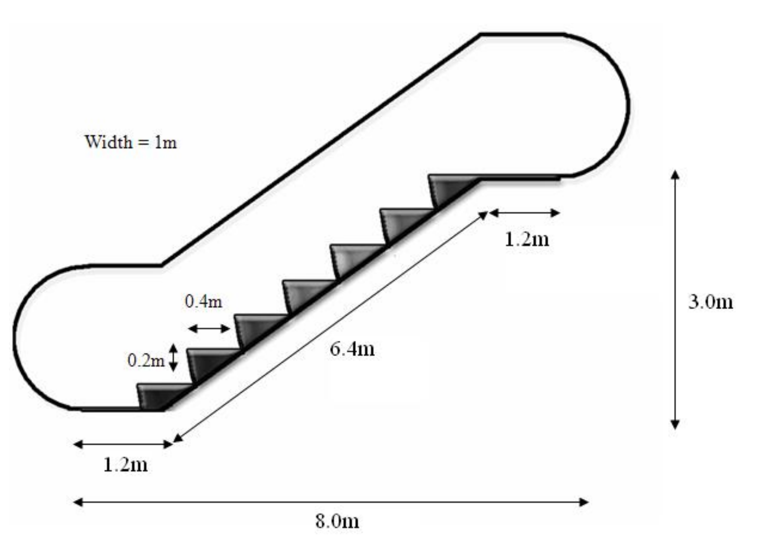
Test	Number of lifts	Number of Stairs Available	Average number/proportion of agents using each stair				Even usage on
			Stair 1	Stair 2	Stair 3	Stair 4	
1	4	4	24.2	24.8	25.8	25.2	On
2	4	4	25.0	25.0	25.0	25.0	Off
3	4	3	-	34.2	34.2	31.6	On
4	4	3	-	50.0	25.0	25.0	Off
5	4	2	-	-	47.0	53.0	On
6	4	2	-	-	50.0	50.0	Off
7	4	1	-	-	100.0	0.0	Off
8	1	4	23.2	30.0	24.0	22.8	On
9	1	4	100.0	0.0	0.0	0.0	Off
10	2	4	25.8	21.6	26.2	26.4	On
11	2	4	50.0	50.0	0.0	0.0	Off
12	3	4	22.8	24.0	26.2	27.0	On
13	3	4	32.0	34.0	34.0	0.0	Off

A6.1 Verification Test Results– Agent Escalator Model

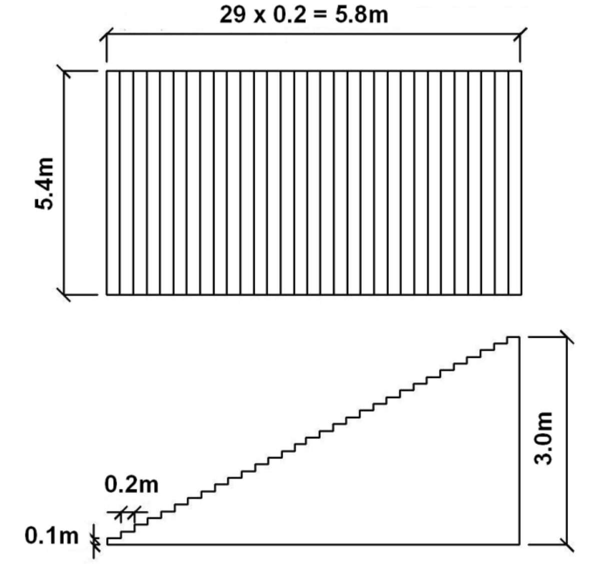
A series of component verification tests have been performed and results presented for the escalator agent model to demonstrate that each component behaves as expected and produce appropriate results based on input parameters. The geometry and population used in each test have been described in the following sections with results and a description of each test presented accordingly for each component of the escalator agent model.

A6.1.1 Verification geometry

The geometry used in each verification test consisted of a two level structure connected via an escalator and stair (Figure 75 and Figure 76).



A: Escalator dimensions



B: Stairway dimensions

Figure 75: Verification test geometry - escalator and stair dimensions

The escalator and stair transit node within buildingEXODUS were added to a transit node group with a combined catchment area of 135 nodes/33.75 m^2 at the base of the escalator/stair on the lower level.

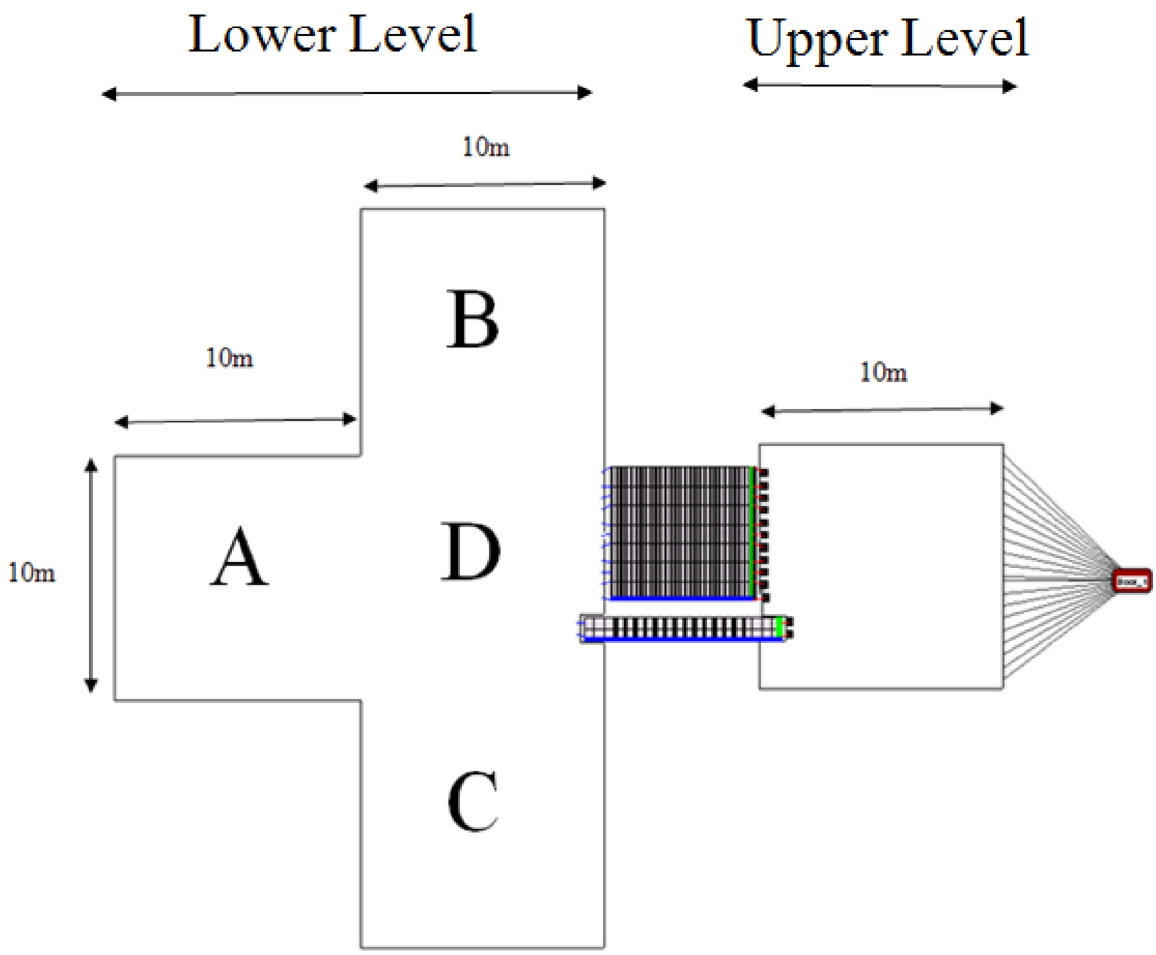


Figure 76: Escalator verification test geometry

For the verification tests agents were initially located on the lower level and were required to travel to the upper level via either the escalator or stairs. the lower level was split into four zones; A,B,C, D, each being 10m x 10m where agents will have different start locations in certain tests.

A6.1.2 Verification population

The population used in all the verification tests were generated from the standard buildingEXODUS population with walker speed, escalator up speeds and up walker speed values set to 1 m/s in order to more easily determine expected behaviour that uses such agent characteristics (though for the walker speed verification tests the walker speeds have been altered accordingly). The frequency of agents used in each test was different in each test and has been specified in the respective sections.

A6.1.3 Verification test – device choice

A6.1.3. 1Verification test – device choice – proportional system

The transit node proportional system which allows a users to state the probability that an agent will use each device within a transit node group. This device selection system has been verified by prescribing a given proportion of device users for the escalator/stair and measuring the difference between these values and the average recorded proportion of agents that used each device over a series of 5 simulations (see Table 128). An average of multiple simulations was used due to the proportional device selection system using incorporating randomly generated values to determine which device to use. The results demonstrates that the proportional system behaves as intended with between a 0.0%-3.2% difference between prescribed and observed values. This difference is caused by the random uniform distribution spread and is considered acceptable.

Table 128: Device Selection - Proportional system verification tests results

Test Number	Values Set Frequency / Proportion		Average Values Recorded Frequency / Proportion		Difference between values	
	Escalator	Stairs	Escalator	Stairs	Escalator	Stairs
1	0.0%	100.0%	0.0%	100.0%	0.0%	0.0%
2	25.0%	75.0%	26.0%	74.0%	1.0%	1.0%
3	50.0%	50.0%	47.4%	52.6%	2.6%	2.6%
4	75.0%	25.0%	78.2%	21.8%	3.2%	3.2%
5	100.0%	100.0%	100.0%	0.0%	0.0%	0.0%

A6.1.3. 2 Verification test – device choice – shortest travel time

The shortest travel time device selection system contains a two subcomponents which are used by agents to select a device within a transit node group: the travel time calculation (where agents calculate the expected movement time to traverse to and on each device) and the wait time calculation(where agents consider how long they are expected to wait for each given device based on the wait time of other agents targeting each device). Verification tests for both of these components have been carried out.

Travel Time Verification

The travel time verification tests involved a single agent initially placed at various location (within region 'D') each being different distances from the escalator/stair within the transit node catchment area. The agent was assigned a walker speed of 1m/s, a horizontal escalator walker speed of 1m/s and a stair walker speed of 1m/s.

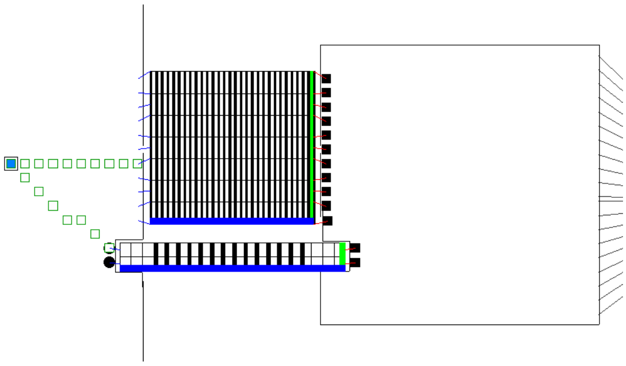


Figure 77: Travel time verification - example of initial agent start location and calculated route to each device

The travel time to and on each device was calculated manually and compared with the expected travel time within the model based the initial starting location of the agent. Results from the verification tests in Table 129 show correct calculated travel times along with the correct respective device selection within the model using the shortest time system.

Table 129: Travel time verification results

Test	Calculated: Travel distance (m) to...		EXODUS: Total Travel time (s) to…		EXODUS: Total Travel time (s) on…		EXODUS: TOTAL Travel time (s)		Calculated: TOTAL Travel time (s)		Device Selected
	Stair	Esc	Stair	Esc	Stair	Esc	Stair	Esc	Stair	Esc	
1	4.47	10.08	4.47	10.08	6.53	5.33	11.00	15.41	11.00	15.41	Stair
2	4.29	6.61	4.29	6.61	6.53	5.33	10.82	11.94	10.82	11.94	Stair
3	4.30	4.62	4.30	4.62	6.53	5.33	10.83	9.95	10.83	9.95	Escalator
4	5.59	4.00	5.59	4.00	6.53	5.33	12.12	9.33	12.12	9.33	Escalator
5	6.76	4.58	6.76	4.58	6.53	5.33	13.29	9.91	13.29	9.91	Escalator

Wait Time Verification

The wait time verification tests involved 3 agents initially located in region 'D' all initially within the transit node catchment area. A single agent was initially located a given distance from the escalator/stair (4.79m from escalator and 6.38m from the stair); it is this agent who's expected travel wait time was being recorded and used for the verification tests. The remaining two agents stood directly in front of the escalator (blocking it) targeting the escalator with their wait counter artificially set to different times for each test and a response time of 5 seconds (this is slightly over the time it takes the single agent to travel to the escalator). The two agents in front of the escalator were intended to represent the influence of a queue. This meant that the wait time calculation of the single agent should include the wait time of one of the agents directly in front of the escalator when determining which device to select.

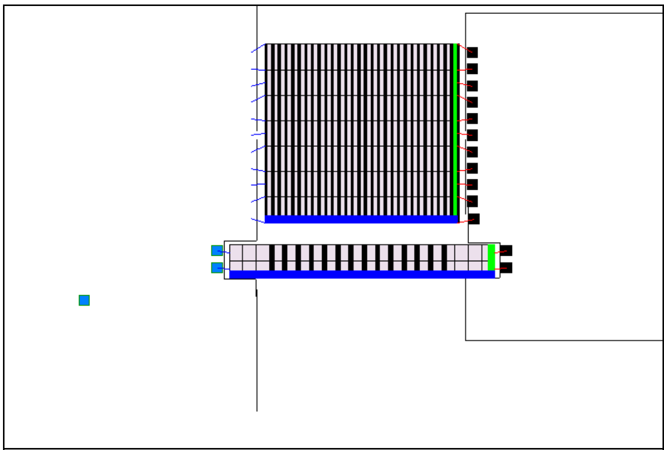
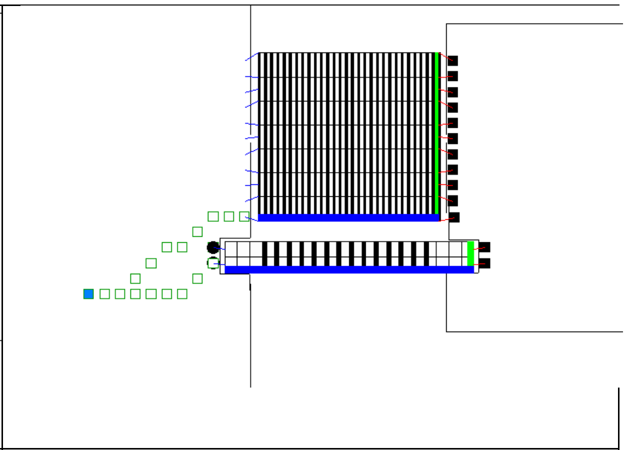
	
Initial start locations of agent and blocking agents	**Path calculation (with nodes of the expected route highlighted)**

Table 130: Wait time verification - initial agent start locations and single agent path calculation

For each verification test the wait time of the blocking agents in front of the escalator was gradually incremented so increasing the expected wait time to use the escalator. The results presented in Table 131 show that as the expected wait time increases for the escalator the total travel time to use the escalator also increases. When the expected total travel time for the escalator exceeds the expected total travel time for the stairs the single agent elects to use the stairs. The results show the model to calculate the correct total travel time using the adjusted wait time considering the two agents in front of the escalator.

Table 131: Wait time verification results

Test	EXODUS: Total Travel time (s) to…		EXODUS: Total Travel time (s) on…		Wait Time of agents in front (s)…		Calculated: TOTAL Travel time (s)		Device Selected
	Stair	Esc	Stair	Esc	Stair	Esc	Stair	Esc	
1	6.38	4.79	6.53	5.33	0.00	0.00	12.91	10.12	Escalator
2	6.38	4.79	6.53	5.33	0.00	1.00	12.91	11.12	Escalator
3	6.38	4.79	6.53	5.33	0.00	2.00	12.91	12.12	Escalator
4	6.38	4.79	6.53	5.33	0.00	3.00	12.91	13.12	Stair
5	6.38	4.79	6.53	5.33	0.00	4.00	12.91	14.12	Stair

A6.1.3. 3 Verification test – device choice – congestion threshold

The device selection congestion threshold verification tests involved a group of 35 agents waiting in the transit node catchment area (in section 'D') and a single agent initially located in section 'B' outside the catchment area (see Figure 78). The group of agents in the catchment area had responses times of 30 seconds and were manually assigned to use the stairs (giving the single agent enough time to traverse to and on the stairs/escalator before the group responded). Those agents were positioned in the catchment area such that they did not block the path of the single agent, however, are intended to represent the crowd of people attempting to use either the escalator or stair (filling approximately 25.9%/1.0 ped/m^2 of the transit node catchment area) The single agent initially in section 'B' had an instant response time and started moving at the start of the simulation. Upon entry to the catchment area by an agent the device selection method is defined by the congestion threshold value; with the proportional system being adopted prior to the congestion threshold being reached, and the shortest time system used when the congestion threshold is reached or exceeded.

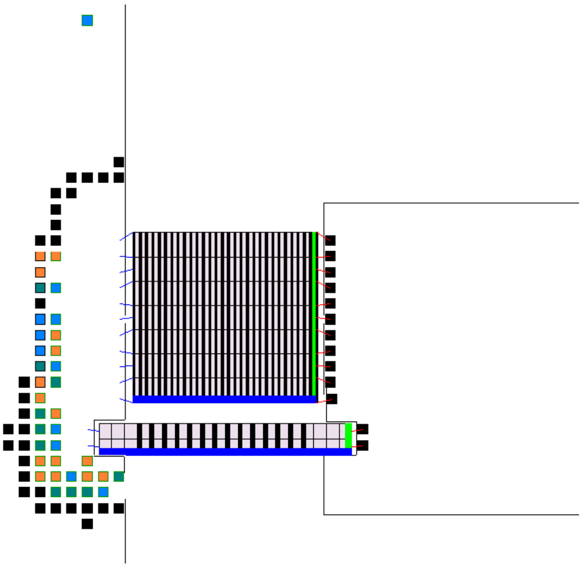


Figure 78: Device selection congestion threshold verification - initial starting location of agents

The transit node group catchment area contained 135 nodes (33.75 m^2) at the base on the escalator/stair. The proportion of users assigned to use the escalator prior to the congestion threshold being met was 100% (i.e. prior to the congestion threshold being met all agents should elect to use the escalator). Each of the verification tests involved a different congestion threshold to test if the single agent used the correct device selection method and the correct device was selected.

The test results shown in Table 132 show that prior to the congestion threshold being met the proportional system was used by the single agent reflected by the use of the escalator. When the congestion threshold is reached or exceeded the shortest time selection system is used reflected by the use of the stairs, being the nearest device to the single agent.

Table 132: Device selection congestion threshold verification results

Test	Congestion Threshold (% nodes)	# People in Catchment Area to reach Threshold	Threshold Density (ped/m^2)	Expected Device Selection	EXODUS Device Selection	Device Selection Method Used
1	50.0	67.5	2.0	Escalator	Escalator	Proportional
2	40.0	54	1.6	Escalator	Escalator	Proportional
3	30.0	40.5	1.2	Escalator	Escalator	Proportional
4	27.0	36.5	1.1	Escalator	Escalator	Proportional
5	25.9	35.0	1.0	Stair	Stair	Shortest Time
6	20.0	27	0.8	Stair	Stair	Shortest Time
7	10.0	13.5	0.4	Stair	Stair	Shortest Time
8	0.0	0.0	0.0	Stair	Stair	Shortest Time

A6.1.3. 4 Verification test – device choice – hybrid

Component testing of the transit node device selection system have been performed in the previous sections. In this section all of the components of the device selection system have been verified to demonstrate the system behaves as intended based on given input parameters. In the test 100 agents were initially located in section 'A' external to the transit node catchment area having a response times uniformly assigned between 0-20 seconds. The range of responses times was intended to allow the levels of congestion in the catchment area to gradually build up in order to allow for a greater variety of device selection methods to be used by agents. For each test the congestion threshold value for the transit node group was progressively decreased allowing agents to select a device based on the shortest time system more early in the simulation. Each verification test was simulated 5 times with the average results presented.

The results presented in Table 133 show that as the congestion threshold decreases more agents elect to use a device based on the shortest travel time algorithm so the total evacuation time approximately decreases as agents exhibit more optimal device selection behaviour.

Table 133: Device selection hybrid verification results

Test	Congestion Threshold (% nodes)	# People in Catchment Area to reach Threshold	Threshold Density (ped/m^2)	AVG. Stair Users (#/%)	AVG. Escalator Users (#/%)	TET (s)
1	50.0	67.5	2.0	3.6	96.4	109.8
2	40.0	54.0	1.6	26.2	73.8	93.0
3	30.0	40.5	1.2	44.8	55.2	80.0
4	20.0	27.0	0.8	53.8	46.2	73.8
5	10.0	13.5	0.4	60.4	39.6	67.6
6	0.0	0.0	0.0	64.8	35.2	66.0

A6.1.4 Verification test – walker/rider choice

The walker/rider choice verification tests involved a group of 100 agents from the standard EXODUS population with instant response times initially located in section 'A' of the geometry. The proportional device selection system was used for the transit node group to assign 100% of agents to use the escalator during the simulations (i.e. all agents would use the escalator). Each test progressively increased the proportion of agent's that should walk on the escalator and subsequently decrease the proportion of agents that should ride on the escalator. Each test was run 5 times in order to produce an average of the multiple simulations due to the walker/rider selection system incorporating random values to determine which device to use. Results presented in Table 134 show the difference between the defined and recorded proportion of agents that walked and rode in each test within EXODUS, ranging between 0-3.0%. These differences represent an acceptable degree of variation considering the implementation method incorporating a random uniform distribution element.

Table 134: Walker/Rider proportion verification test

Test	Defined		EXODUS		Difference	
	% Walkers	%Riders	% Walkers	%Riders	% Walkers	%Riders
1	0.0	100.0	0.0	100.0	0.0	0.0
2	20.0	80.0	18.0	81.0	2.0	1.0
3	40.0	60.0	42.6	57.0	2.6	3.0
4	60.0	40.0	62.0	38.0	2.0	2.0
5	80.0	20.0	80.6	19.4	0.6	0.6
6	100.0	0.0	100.0	0.0	0.0	0.0

A6.1.5 Verification test – side preference

The side preference verification tests involved a group of 100 agents from the standard EXODUS population with instant response times initially located in section 'A' of the geometry. The proportional device selection system was used for the transit node group to assign 100% of agents to use the escalator with 100% of agents assigned to ride on the escalator during the simulations (i.e. all agents would use the escalator and be influenced by the side proportions). Each test progressively increased the proportion of agent's that should use the left side of the escalator and subsequently decrease the proportion of agents that should walk on the escalator. Each test was run 5 times in order to produce an average of the multiple simulations due to the side preference system incorporating random values to determine which side the agent would use. Results presented in Table 135 show the difference between the defined and recorded proportion of agents that used each side of the escalator in each test within EXODUS, ranging between 0-3.6%. These differences represent an acceptable degree of variation considering the implementation method incorporating a random uniform distribution element.

Table 135: Side preference verification test

Test	Defined		EXODUS		Difference	
	% Left	%Right	% Left	%Right	% Left	%Right
1	0.0	100.0	0.0	100.0	0.0	0.0
2	20.0	80.0	21.8	78.2	1.8	1.8
3	40.0	60.0	36.4	63.6	3.6	3.6
4	60.0	40.0	60.2	39.8	0.2	0.2
5	80.0	20.0	79.4	20.6	0.6	0.6
6	100.0	0.0	100.0	0.0	0.0	0.0

A6.1.6 Verification test – side preference

The walker speed verification tests involved a single agent with an instant response time initially located in section ‘A’ of the geometry. The proportional device selection system was used for the transit node group to assign 100% of agents to use the escalator with 100% of agents assigned to walk on the escalator during the simulations. Each verification test progressively increased the escalator up walker speed of the agent with the escalator boarding and alighting being recorded in each test to demonstrate that the agent movement speed was being correctly represented. Results presented in Table 136 show the difference between the calculated and recorded escalator travel time in each test within EXODUS, with there being a 0.0% difference between the EOXDUS travel time and the calculated travel time in all tests.

Table 136: Walker speed verification test

Test	Defined Walker Speed (m/s)	Escalator Speed (m/s)	Hoz Dist (m)	Board Time (s)	Alight Time (s)	Recorded Speed (m/s)	EXODUS Time (s)	Calculated Time (s)	% Time Difference
1	0	0.50	8.00	12.25	28.25	0.00	16.00	16.00	0.0
2	0.2	0.50	8.00	12.25	23.68	0.20	11.43	11.43	0.0
3	0.4	0.50	8.00	12.25	21.14	0.40	8.89	8.89	0.0
4	0.6	0.50	8.00	12.25	19.52	0.60	7.27	7.27	0.0
5	0.8	0.50	8.00	12.25	18.4	0.80	6.15	6.15	0.0
6	1	0.50	8.00	12.25	17.58	1.00	5.33	5.33	0.0
7	1.2	0.50	8.00	12.25	16.96	1.20	4.71	4.71	0.0
8	1.4	0.50	8.00	12.25	16.46	1.40	4.21	4.21	0.0
9	1.6	0.50	8.00	12.25	16.06	1.60	3.81	3.81	0.0

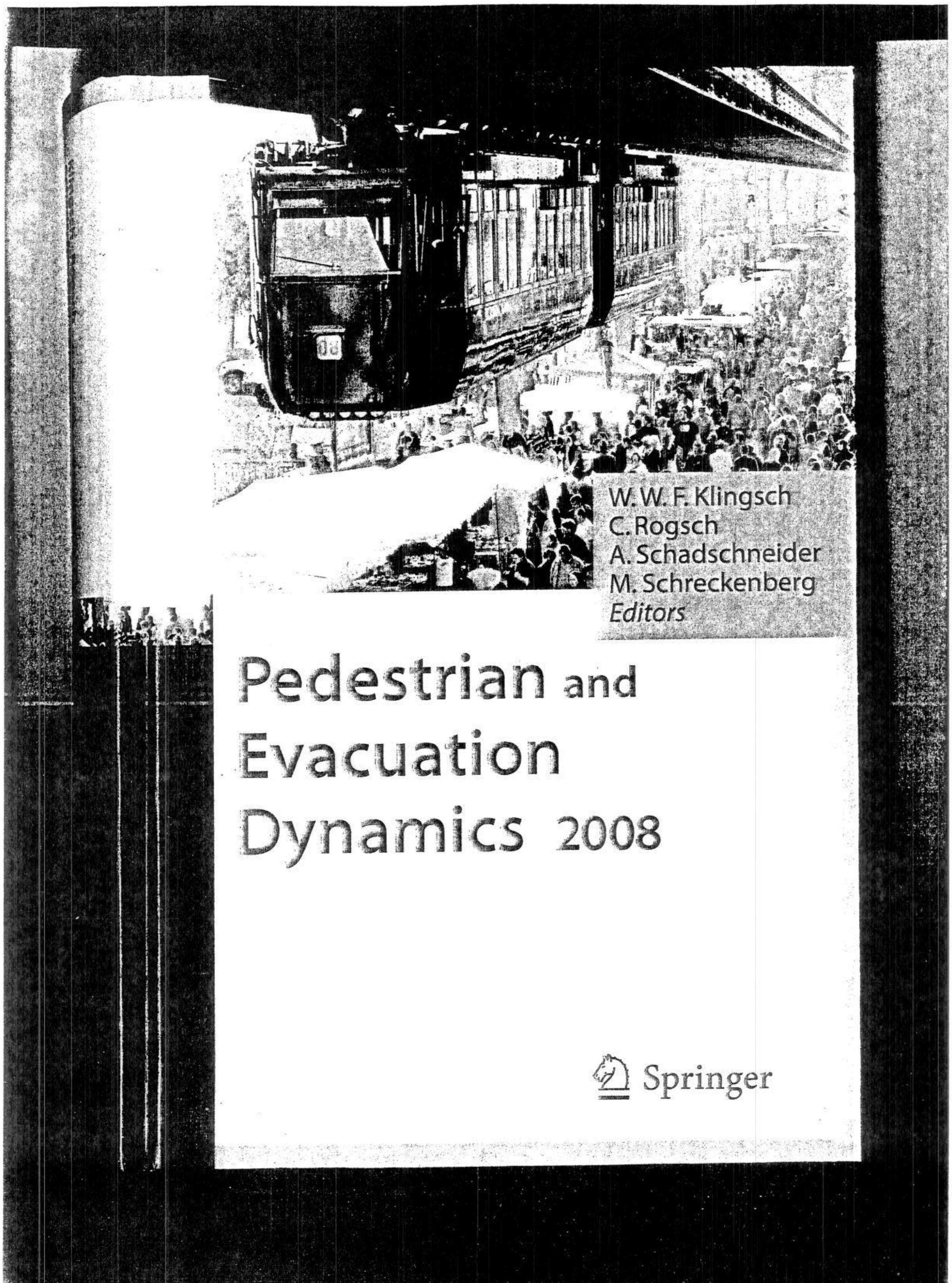
A6.1.7 Verification test – flow-rate

The flow-rate verification tests involved a group of 100 agents from the standard EXODUS population with instant response times initially located in section 'A' of the geometry. The proportional device selection system was used for the transit node group to assign 100% of agents to use the escalator. The escalator transit node was set to represent agent behaviour using the flow-rate model with each verification test having progressively higher capping flow-rates set. The horizontal escalator agent walker speeds were defined in the flow-rate model as all being 0.5m/s which meant that all agents effectively rode on the escalator. This was intended to ensure that agents did not traverse the escalator before the next agent boarded. Results presented in Table 137 show the difference between the defined and recorded proportion of agents that used each side of the escalator in each test within EXODUS, ranging between 0-0.8% for flow-rates 6.0-90.0 ped/min. For tests 6 and 7 involving 2.0 and 2.5 ped/min the main inhibiting factor of occupant flow onto the escalator was occupant walker speeds on the ground and escalator resulting in a larger variation between the prescribed and recorded flow-rate in EXODUS. To highlight this these tests were run again (tests 8 and 9) with agents assigned fast walk speeds of 4m/s and horizontal escalator walker speeds of 2m/s (for demonstration purposes). Including tests 8 and 9 the difference between the prescribed and simulated average flow-rates vary between 0.0-2.6%. These differences represent an acceptable degree of variation considering the flow-rate model is based on a restriction principle and is largely dependent on the agent behaviour at the entrance to the escalator.

Table 137: Flow-rate verification test

Test	Defined Flow-rate		Min Delay Time Between occ (s)	EXODUS Flow-rate	% Difference
	ped/sec	ped/min		Average Flow-rate (ped/min)	
1	0.1	6.0	10.0	6.1	1.6%
2	0.5	30.0	2.0	30.3	1.0%
3	0.7	40.0	1.5	40.4	1.0%
4	1.0	60.0	1.0	60.6	1.0%
5	1.5	90.0	0.7	89.3	0.8%
6	2.0	120.0	0.5	100.8	16.0%
7	2.5	150.0	0.4	105.0	30.0%
8	2.0	120.0	0.5	121.2	1.0%
9	2.5	150.0	0.4	154.0	2.6%

A7.1 Published papers from thesis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ISBN 978-3-642-04503-5 e-ISBN 978-3-642-04504-2
DOI 10.1007/978-3-642-04504-2
Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2009941802

Mathematics Subject Classification (2000): 49-XX, 4906, 65-XX, 65C05, 65C20, 68-XX, 68Q80, 68U05, 68U07, 68U10, 68U20, 68U35, 82-XX, 82C21, 90-XX, 90BXX, 91-XX, 91CXX, 93-XX, 93E25

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Modelling Pedestrian Escalator Behaviour

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Summary. This paper presents an escalator model for use in circulation and evacuation analysis. As part of the model development, human factors data was collected from a Spanish underground station. The collected data relates to: escalator/stair choice, rider/walker preference, rider side preference, walker travel speeds and escalator flow rates. The dataset provides insight into pedestrian behaviour in utilising escalators and is a useful resource for both circulation and evacuation models. Based on insight derived from the dataset a detailed microscopic escalator model which incorporates person-person interactions has been developed. A range of demonstration evacuation scenarios are presented using the newly developed microscopic escalator model.

1 Introduction

Escalators provide a means for pedestrians to traverse a small number of vertical levels (typically 1–5 floors) in a relatively short period of time, providing greater comfort and requiring less physical exertion compared with equivalent stairways. Consequently it is common to find escalators as the primary form of vertical transport in underground/subway stations. They provide a more attractive and efficient alternative to long stairs in both circulatory and evacuation situations. However, in the event of an emergency evacuation, escalators are typically turned off, in some cases they may be closed, preventing occupants from even using them as a stair and in other cases escalators may be used only if staff are present to supervise [1].

There are many reasons for the restricted use of escalators in emergency situations, most notably the possibility that the moving escalator may be carrying people to, rather than away from danger. Regardless of these concerns, escalators have been used both in the "off" and "on" condition to good effect in some evacuation situations. In the 9/11 World Trade Center evacuation escalators were used as a means of evacuation in both the North and South towers to move people from the Mezzanine to the lobby [2]. In both towers escalators were used as stationary stairs [2] while in the South Tower survivors

W.W.F. Klingsch et al. (eds.), *Pedestrian and Evacuation Dynamics 2008*,
DOI 10.1007/978-3-642-04504-2_66, © Springer-Verlag Berlin Heidelberg 2010

reported using moving escalators during the "unofficial" evacuation prior to the South Tower being hit [2]. It is clear that escalators are used for evacuation purposes and so there is a need to represent escalators within both evacuation and pedestrian dynamics circulation models. As a result there is a need to understand and quantify pedestrian behaviour associated with the use of escalators. Despite this, at present, there is little data pertaining to micro-level pedestrian dynamics on and around escalators and a subsequent lack of understanding.

2 Data Collection

As part of the EU FP6 project AVATARS, human factors data associated with escalator usage in underground stations was collected. The data was collected within the Provença station, Barcelona Spain using CCTV (Closed Circuit Television) video footage. Data was collected in both rush-hour and non rush-hour conditions. Two escalators were studied, an escalator moving in an upwards direction and an escalator moving in a downwards direction. Analysis of the video footage allowed the formation of a human factors dataset containing information pertaining to: escalator/stair choice, boarding/alighting behaviour, escalator side preference, proportion of walkers to riders, walker speeds and entry/boarding and exit/alighting flow-rates. In total some 7,206 data points were collected from the video footage relating to 1,283 people. The rush-hour data was collected from 895 people while the non rush-hour data was collected from 388 people.

3 Escalator Model

The core software used in this paper is the buildingEXODUS V4.0 evacuation model [3]. The basis of the model has frequently been described in other publications and so will not be described here. Here we describe the extension of the model to include escalators for both evacuation and circulation. The microscopic escalator model requires the identification and quantification of appropriate agent behaviour associated with the use of escalators and the development of appropriate behaviour rules to represent the behaviour.

3.1 Microscopic Escalator Model

The behaviour rules incorporated in the prototype microscopic escalator model are based on the study of the AVATARS data and include: escalator/stair choice model, proportion of riders/walkers, side preference for riders and walker speeds. In addition to the behaviours identified from the data analysis, additional behaviours associated with the existing stair model, such as inter-person spacing (staggering/packing behaviour [3]) are also included

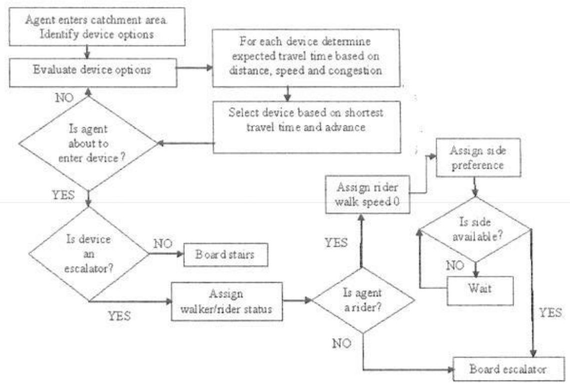

Fig. 1. Microscopic escalator model logic.

within the escalator model. The logic of the microscopic escalator model is summarised in Fig. 1.

When an escalator and stair or indeed any type of vertical transfer device is closely co-located, pedestrians approaching the device are required make a point-of-choice decision as to which device they will adopt. There are a number of factors which influence the selection decision including; personal preference, levels of energy expenditure required, level of urgency felt. In circulation situations all of these factors may exert an influence on the decision making process while in evacuation situations the desire to minimise ones egress time may become the overriding factor. This later factor is incorporated into the current device selection model.

4 Escalator Model Evacuation Demonstration

A simple demonstration case was developed to demonstrate the application of the microscopic escalator model in an evacuation scenario. The geometry consisted of two levels connected via two stairs and an escalator. The vertical drop was 6 m and the width of the stairs and escalator was 1.2 m. The horizontal speed of the escalator was 0.5 m/s with a horizontal length of 10 m. A total of 400 people are used in the simulation. A total of eight different scenarios were examined. Each case was run five times and all the results presented below represent the average for five simulations.

4.1 Evacuation Results

The results for the various scenarios are summarised in Table 1, it should be noted that in these scenarios, stair 2 is immediately adjacent to the escalator. Very early in the evacuation crowds develop at the head of the stairs/escalator and persist until near the end of the evacuation. In all scenarios the shortest travel time device selection algorithm ensures that "reasonable" use is made of the devices throughout the simulation. Without the device selection algorithm, agents would either use their nearest or their assigned device rather than use an alternative nearby device irrespective of local conditions such as queue length/congestion levels, possibly resulting in unrealistic longer than required evacuation times. In all other cases where the escalator is operating, the escalator takes the greater number of users due to the expected greater speed of transit afforded by the escalator.

Table 1. Summary results for escalator evacuation demonstration scenarios.

Scenario	Av. TET (s)	Av. CWT (s)	Av. max density (p/m^2)	Escalator usage	Stair 2 usage	Stair 1 usage
Scenario 1: Two stairs	302	61.0	4.0	0	203	197
Scenario 2: Two stairs + stopped esc	229	27.0	3.9	127	137	136
Scenario 3: Two stairs + escalator 0% riders	196	16.5	2.6	193	115	92
Scenario 4: Two stairs + esc 100% riders, 50% left, 50% right	210	16.9	3.1	198	101	101
Scenario 5: Two stairs + esc 100% riders, 100% right	221	20.7	3.6	169	117	114
Scenario 6: Two stairs + esc 50% riders, 100% right	210	18.0	3.1	197	101	102
Scenario 7: Two stairs + esc 50% riders, 50% left, 50% right	212	19.7	3.1	197	103	101
Scenario 8: Two stairs + esc 76% riders, 28% left, 72% right	211	18.5	3.1	193	104	103

With just two stairs in operation the average Total Evacuation Time (TET) is 302 s (see Scenario 1), when the stopped escalator is made available the average TET reduces to 229 s (see Scenario 2), a reduction of some 26%. Clearly, even a stopped escalator can provide considerable advantage however, it should be noted that these simulations do not attempt to represent the likelihood of trips or falls on the escalator (or stairs). When the escalator is functioning (Scenario 3) and we assume that 100% of the population will walk down the escalator the average TET reduces to 196 s, some 35% better than having two stairs only and 14% better than the case with the stopped escalator available. We also note that in Scenario 3 almost 50% of the population utilise the escalator and that the average maximum density at the entrance to the stairs/escalator and the average CWT attain their minimum values for this scenario. The evacuation time achieved in this scenario is the quickest of all the scenarios and indicates the advantage a moving escalator can have during an evacuation. Also, by reducing the average density at the entrance to the stair/escalator, the use of the escalator can be argued to reduce the possibility of adverse crowd related incidents occurring.

If we now assume that 100% of the escalator users will ride the escalator and they will equally utilise the left and right location on the escalator tread (Scenario 4) we find that the TET has increased slightly to 210 s. At first glance, this modest 7% increase in evacuation time compared to Scenario 3 does not appear to be logical however, when it is recalled that escalator walkers attempt to keep two treads between them and the person ahead the difference becomes more understandable. When full of walkers, the escalator has a reduced capacity compared with the situation in which it is full of riders. Thus in Scenario 4 the increased apparent capacity of the escalator partially compensates for the reduced travel speed produced by the stationary riders. Thus from a global perspective, in evacuations in which there is expected to be heavy use of escalator/stair combinations, there is little to be gained by having the escalator users walk down the moving escalator. Indeed, there may be advantages in reducing the chances of injury resulting from trips or miss steps by preventing the escalator users from walking. However this conclusion is derived from taking a global perspective, from an individual person's perspective, their personal evacuation time will be reduced by walking down the escalator and so this type of behaviour may be difficult to enforce.

If we consider the extreme of inefficient escalator usage and assume that 100% of the people will ride the escalator and 100% will utilise the right side (Scenario 5)—effectively halving the capacity of the escalator we note that the evacuation time increases to 221 s, a 5% increase over Scenario 4 and a 13% increase over Scenario 3. At first sight this modest increase in the total evacuation time is surprising however, it should be noted that the number of escalator users has decreased by some 15%. Thus the device algorithm has allowed the agents to make use of under utilised capacity on the neighbouring stairs. Had the escalator been the only device linking the two levels, we would have expected to incur a significantly greater increase in evacuation time.

With 50% the escalator users walking down the escalator and all the riders utilising the right side of the escalator (Scenario 6) the average total evacuation time is 210 s, which is 7% slower than the case with 100% walkers (Scenario 3) and equal to the case with 100% riders with an equal usage of both sides of the escalator tread (Scenario 4). This is a complex case with competing trends resulting from increased capacity and decreased speed due to the riders (all to one side) and decreased capacity and increased speed due to the walkers. These effects almost cancel each other however, we also note that the average Cummulative Wait Time (CWT) for Scenario 6 is larger than that for Scenario 3 in which there are 100% walkers. This increase in CWT is consistent with only a single lane being available for the walkers, thus if a walker is caught behind a slower walker, there is no chance for them to overtake and hence they will be forced to travel at the slower speed, hence increasing their personal CWT. We note that for Scenario 7, in which 50% of the escalator users are walkers—as in Scenario 6—but in which the riders occupy both the left and right lanes, the total evacuation time has increased slightly to 212 s, with a further increase in the average CWT. This is due to the walkers now being impeded in both lanes by riders, making it more difficult for them to pass without increasing their personal CWT.

The final scenario consists of the same distribution of riders with the same distribution of left/right usage as found in the AVATARS data (Scenario 8) i.e. 76% riders with 28% of riders occupying the left lane. Thus the break down of walkers to riders and left/right usage is the same as may be expected in a non-emergency circulation example. Here we find the total evacuation time is 211 s and is consistent with other cases involving 100% riders (Scenario 4) producing a total evacuation time of 210 s and 50% riders (Scenarios 6 and 7) producing evacuation times of 210 s and 212 s. This suggests that virtually any situation with more than 50% riders will produce similar total evacuation times.

5 Concluding Comments

This paper has presented a summarised analysis of human factors data relating to pedestrian escalator behaviour within a Spanish underground station. The dataset provides insight into pedestrian behaviour in utilising escalators and is a useful resource for both evacuation and circulation model developers.

A range of demonstration evacuation scenarios were performed using the newly developed model. The results suggest that under evacuation conditions, in which the simulated agents are assumed to select the device which is expected to produce the minimum total transit time, the best evacuation times can be obtained if all the escalator users walk down the escalator. However, if we assume that all the escalator users ride down the escalator, and that they display an equal preference for the left and right lanes on the escalator there is only a marginal increase in the total evacuation times. These results

suggest that from a global perspective, there is little to be gained by walking down the escalator, indeed, under crowded emergency conditions suggesting that escalator users ride the escalator may be a better strategy as it reduces the risk of injuries arising from miss steps. However this conclusion is derived from taking a global perspective, from an individual person's perspective, their personal evacuation time will be reduced by walking down the escalator and so this type of behaviour may be difficult to enforce. In addition, it must also be considered that this analysis is based on a single escalator/stairway group, and any difference between scenarios is expected to be magnified with the addition of other escalators/stairways groups in the geometry.

Acknowledgements

The authors are indebted to the EU Framework 6 programme for funding a portion of this work through project AVATARS (TST4-CT-2005.012462), their AVATARS partners (BMT, FGC, ATM, University of Salford and Buro Happold) for their co-operation and to the UK EPSRC for funding a portion of this work through project HEED (GR/S74201/01 and EP/D507790).

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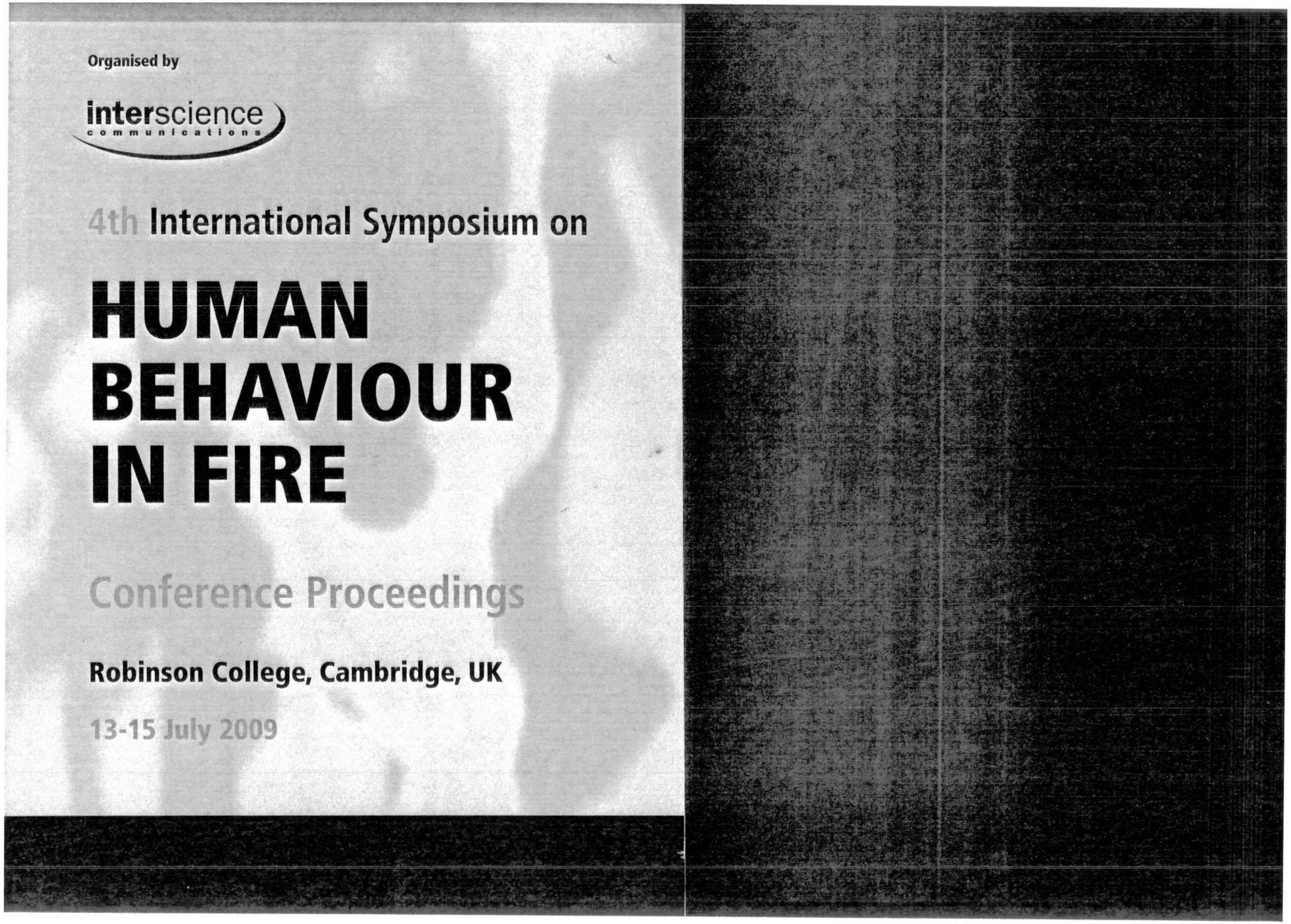

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Interscience Communications Ltd
West Yard House, Guildford Grove,
LONDON SE10 8JT, England

Human Behaviour in Fire 2009

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ISBN 978-0-9556548-3-1

p680, 134 tables and 276 illustrations

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INVESTIGATING THE USE OF ELEVATORS FOR HIGH-RISE BUILDING EVACUATION THROUGH COMPUTER SIMULATION

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ABSTRACT

This paper presents a description of a new agent based elevator sub-model developed as part of the buildingEXODUS software intended for both evacuation and circulation applications. A description of each component of the newly developed model is presented, including the elevator kinematics and associated pedestrian behaviour. The elevator model is then used to investigate a series of full building evacuation scenarios based on a hypothetical 50 floor building with four staircases and a population of 7,840 agents. The analysis explores the relative merits of using up to 32 elevators (arranged in four banks) and various egress strategies to evacuate the entire building population. Findings from the investigation suggest that the most efficient evacuation strategy utilises a combination of elevators and stairs to empty the building and clear the upper half of the building in minimum time. Combined stair elevator evacuation times have been shown to be as much as 50% faster than stair only evacuation times.

INTRODUCTION

Since the wide scale adoption of sprinkler systems in high-rise buildings, there has been an expectation that there would rarely, if ever, be a need to undertake full building evacuations. As a result there has been little appetite to seriously explore the use of elevator systems for evacuation. However, since the September 11th World Trade Centre attack, there has been a renewed interest in the possible use of elevators for evacuation of high-rise buildings[1,2]. Such events have also highlighted the need for high-rise buildings to be able to accommodate full scale evacuations and not simply cater for a defend in place strategy whereby only select floors/areas are evacuated. Furthermore, recent computer simulations of high rise building evacuation suggest that there is a critical floor population density for a given staircase capacity which effectively limits the height of high rise buildings that can be practically evacuated by stairs alone[3]. As a result, it is necessary to explore alternate means of evacuation, such as the use of elevators for high towers catering for large building populations.

Whilst fire protected elevators are considered a viable means for fire fighting services to fight fire and also assist in the evacuation of disabled occupants, most standards have yet to accept fire protected elevators as a viable means for the general population to evacuate during a fire. An exception is the current NFPA 101 Life Safety Code 2009 which stipulates in Annex B that elevators that meet a prescribed level of fire safety can be used to evacuate occupants prior to emergency Phase 1 recall (i.e. before smoke is detected in an elevator lobby, elevator machine room or shaft)[4]. Considering the added egress capacity elevator banks could provide a building population during an evacuation compared to using only stairs it is somewhat surprising that elevators have been ignored for so long. However, the key factor with most building codes for not allowing the use of elevators during an evacuation is the potential lack of safety and reliability afforded by such devices during a fire. The NFPA 101 Code for Safety to Life from Fire in Buildings and Structures in 1976[5] identified a number of concerns such as, possible malfunction of elevators during a fire related evacuation, exposure of a waiting population to fire hazards and jamming of elevator doors due to the pressure of large waiting crowds. Further to this, a number of authors[6,7,8] have stated potential technical problems with regards to using elevators during an evacuation which include power failure, overheating/short-circuiting of electrical equipment with serious consequences such as entrapment, smoke inhalation, doors opening on fire floors etc.

Despite there being a number of incidents in the last 40 years in which people have either died[9,10] or were trapped [9,11] inside elevators during fire situations, a number of technological solutions to address these issues have been suggested thereby making elevator systems more resilient[10,12]. Indeed there have been incidents in the last 40 years in which elevators have successfully been used to evacuate large populations of people in high-rise buildings. Such incidents include the Joelma building fire in Brazil of 1974 where some 300 of the 422 survivors evacuated using elevators[10], the Hiroshima Motomachi fire in Japan of 1996 where in excess of 50% of the building occupants safely used elevators either in part or for the entire vertical evacuation[10,13], and the Forest Laneway Fire in Canada of 1995 where some 162 (74%) survivors surveyed used the elevator to evacuate[14]. In addition, there are a number of high-rise buildings throughout the world which currently allow elevators to be used during non-fire evacuations for the general population e.g. Petronas Towers (Malaysia), Tapei 101 (China), Stratosphere tower (US), Barclays tower (UK) etc. Further to this, elevators are the most common used form of ingress in most high-rise buildings and as such are far more familiar to building occupants than egress stairs which typically do not form part of normal circulation roots. Using familiar ingress roots during an evacuation has the potential to reduce confusion and is further supporting evidence to use elevators within high-rise evacuations[13].

The renewed interest in using elevators for building evacuation is now beginning to focus beyond the strictly mechanical aspects of elevator capabilities in emergency conditions to operational issues and human factors issues. The operational questions concern strategies to optimise full building evacuation. For example, should elevator usage be restricted to use by the disabled, if used by the full building population should normal downward peak dispatching algorithms be used or should some kind of shuttling procedure be developed? Should part of the building be expected to use stairs while other parts use elevators? The human factors issues concern how individuals/groups of people would behave on and around elevators during an evacuation. Would for example people be prepared to wait for elevators during a full building evacuation? How many people would consider taking the stairs, how does this depend on factors such as; crowd densities in the elevator waiting area, location of waiting floor, position relative to the incident, etc and how would this impact the building evacuation? The human factors issues can be explored through studying past incidents where elevators were used, e.g. the WTC, through experimentation (evacuation trials) and through survey/questionnaire techniques. The operational questions may be addressed using computer evacuation simulation. Clearly the two are linked as the human factors issues will influence the efficiency of operational strategies however, it is useful to understand the impact of proposed operational strategies in an environment where building occupants are expected to behave in an "ideal" way.

In this paper we present a detailed elevator model implemented within the buildingEXODUS evacuation software. The elevator model includes a detailed representation of elevator kinematics include the representation of jerk, acceleration, and maximum speed. In addition, the non-kinematic elevator parameters include door opening/closing times, motor delay and "typical" operational parameters.

ELEVATOR MODEL

The core software used in this work is the buildingEXODUS V4.06 evacuation model. The basis of the model has frequently been described in other publications[3,15,16] and so will not be described again here. Suffice it to say that buildingEXODUS is an agent based model used for the simulation of both evacuation and circulation. The newly developed elevator model is implemented within the buildingEXODUS software (see Figure 1). The key components of the elevator sub-model described here include:

- Agent behaviour
- Elevator Representation and Attributes
- Elevator Motion Control
- Elevator Kinematics

AGENT BEHAVIOUR

Within buildingEXODUS the concept of assignment and navigation to location targets for individual agents already exists. Agents can be assigned a target destination i.e. a place to travel to in the geometry, and be assigned a task to perform at the target destination e.g. wait etc. Using this existing capability, three aspects of the agent elevator selection process needed to be developed, namely: elevator bank selection, elevator lobby wait location selection, open elevator car selection (see Figure 1). Due to the lack of available data pertaining to how pedestrians actually perform such selection tasks, the current model is based on a number of simplifying assumptions. The model is sufficiently flexible to allow for future changes as and when data is available.

Elevator Bank Selection

Currently there are two possible approaches the agents can adopt in selecting which elevator bank they will adopt. These are:

- Closest serviced elevator bank assignment (agents select their closest elevator bank).
- Closest serviced elevator bank assignment with even elevator bank usage (agents select their closest elevator bank on a given floor which has not already been adopted by a number of other agents, so ensuring that each elevator bank on a given floor is adopted by approximately the same number of agents).

Once a simulation has started agents do not change their elevator bank selection or redirect to another elevator bank after the initial choice is made. Once the agent's response time has expired they move towards the chosen elevator bank.

Elevator Lobby Wait location Selection

When an agent enters an elevator bank waiting area, if the agent's target is the current elevator bank, they randomly select a location in the elevator bank waiting area to wait. The agent then moves to the chosen location where they will wait for an elevator to arrive.

Open Elevator Car Selection

When an elevator door opens in a given elevator bank, the nearest agents who are waiting in the elevator waiting area move to use the elevator. Only the number of agents which can fit inside the elevator (derived from the elevators maximum capacity and the proportion of this reached) attempt to board the elevator. As a result there is no competition for elevator boarding and the boarding process is orderly. If multiple elevator cars open their doors simultaneously at a given floor, the agents select the nearest un-oversubscribed opened elevator car. This ensures that the nearest agents to an opened elevator car will board the car. While this may appear to be an over optimistic representation of passenger boarding in emergency situations, until data is available describing these situations, these assumptions appear reasonable.

ELEVATOR REPRESENTATION AND ATTRIBUTES

Within buildingEXODUS an elevator shaft is defined as a series of transit nodes which span each of the floors within the geometry (see Figure 1). The dimensions of the shaft in addition to the size of the door on each respective floor can be defined within the model by altering the attributes of each transit node. Once the shaft is defined, then an elevator can be associated with the shaft. There are a number of attributes which are used to define an elevator within buildingEXODUS, these are listed in the table below:

Table 1: Defining Elevator attributes

Attribute	Description
Maximum Speed	Defines the maximum rated speed of the elevator car (m/s).
Acceleration	Defines the constant rate of acceleration of the elevator car (m/s^2).
Jerk	Defines the rate of change in acceleration before and after constantly accelerating/decelerating (m/s^3).
Start floor	Defines the floor the car will start at the beginning of a simulation.
Door opening time	Defines the time it takes an elevator door to open.
Door closing time	Defines the time it takes an elevator door to close.
Dwell time	Defines the duration the car doors will stay open after the car doors have fully opened to service a given floor (providing no one enters the elevator).
Sensor break adjusted dwell-delay	Defines the adjusted dwell time after the first occupant enters an elevator car.
Motor delay	Defines the time, after an elevator's doors have closed, before the car starts to move i.e. the time it takes the motor to start.
Capacity	Defines maximum physical number of agents that can enter a car.
Max capacity	Defines the percentage of the 'Capacity' which the car actually reaches.
Serve Floor Sequence	Defines a sequence of numbers which represent the series of floors the car will serve.
Shuttle Floor Sequence	Defines a sequence of paired numbers which represent a series of 'pick up' and 'drop off' floors the car will shuttle between.
Exit Floors	Defines a list of floor numbers which form the drop off floors for both Shuttle floor and Serve floor sequence. For both sequences, if an elevator arrives on an exit floor, everyone currently in the car will exit at the indicated floor.

ELEVATOR MOTION CONTROL

The current elevator model provides two methods for controlling elevators i.e. the floor selection. The first system, currently under development, allows users to provide a proprietary floor dispatching algorithm in a C++ library and connect via a standard interface. This allows users to test out different floor dispatching algorithms. This is particularly useful when the software is used to simulate normal circulatory flows within a building. As such the system can be reactive according to different landing requests in the simulation. The second system allows users to manually define the floors an elevator/group of elevators will service from within a script file. Unlike the first system, this does not allow the floor sequence to change or be reactive to different scenarios during the simulation.

This sequence can be defined in two different ways: floor-sequence or shuttle-floor-sequence, along with an exit floor list. Using a floor-sequence, a user specifies the sequence of floors an elevator will service during the simulation. The assigned elevator(s) will serve each of the floors specified in the sequence once. Using a shuttle-floor-sequence, a user specifies a paired-sequence of pick-up/drop-off floors where the elevator could pick people up from and shuttle them to. This shuttle process would repeat until their where no more people in the pick-up floor catchment area or floor (depending on the settings). The process is then repeated for the next pick-up/drop-off floor in the sequence. For both systems, the exit floor list defines which floor(s) the agents in the car will exit the elevator.

For the shuttle-floor sequence system, using a top-down strategy, if an elevator does not fill to it's maximum capacity at a pick-up floor, an optional feature is to then move the elevator to the next pick-up floor to fill up the remaining spaces in the elevator car. This reduces the amount of redundant shuttle trips an elevator makes when it is not full and so would increase the efficiency of the overall evacuation. This assumes that the number of passengers which enter each elevator is detected either via automated means e.g. weight sensors, or manually via an operator within the car.

ELEVATOR KINEMATICS

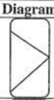
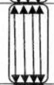
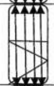
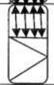
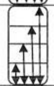
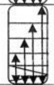
The kinematics or motion of an elevator car is defined by it's jerk, acceleration and maximum speed. There also are a number of other factors which influence an actual elevators journey such as friction, ware and tare of machine parts etc, however these are not considered within the current model. As such the kinematics of the elevator model should be considered "ideal". Specifying the cars jerk, acceleration and maximum speed is sufficient to determine the location of the car at any point in time. The time at which the elevator passes each respective floor between it's original location and it's destination is determined using a series of formula based on the work of Motz[17] and Peters[18].

SIMULATIONS

A series of 11 full building evacuation scenarios have been performed using the new elevator model using a hypothetical building (see Figure 1). The building consisted of 7,840 agents distributed over 50 floors with four stairwell cores and four elevator banks each containing eight elevators. In most of the scenarios all the elevators can service all floors. The purpose of allowing all elevators and stairs to service all floors was to allow for flexibility in exploring a variety of different evacuation procedures without being inhibited by physical vertical partitioning/zoning of the elevator shafts. For each simulation, different combinations of elevators and stairs were used to evacuate the entire population. In each case, the priority of the elevators was to service the upper floors first, sequentially working down to the lower floors. Several scenarios examined the use of shuttle elevators and sky lobby arrangements. The full list of scenarios is summarised in Table 2.

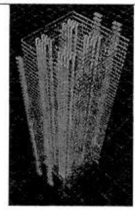
The different frequency of elevators used in certain scenario is intended to explore the impact of elevator number in evacuation efficiency and to explore the affects of elevator banks being rendered inoperable during an evacuation (e.g. due to fire, technical fault etc). For each scenario all elevators initially started on the ground floor. Due to the hypothetical nature of the building, aside from the external walls and the stair/elevator cores, no furniture or internal obstructions were represented within the simulation. With the exception of the ground floor, there were 160 agents located on each floor (7,840 occupants in total). Agents were modelled as non-connected individuals and were not constrained by groups. The population used the default population attributes within buildingEXODUS[15] and consisted of people with different movement capabilities reflecting the variety of the different ages, genders and abilities. All agents were assumed to react instantly at the beginning of each scenario so response time is not considered a parameter within this analysis.

Table 2: Overview of evacuation scenarios

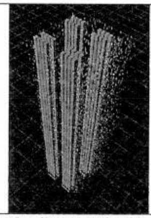
Scenario	Diagram	Description
1		Stairs only
2		8 elevators (1 elevator bank)
3		16 elevators (2 elevator banks)
4		24 elevators (3 elevator banks)
5		32 elevators (4 elevator banks)
6		32 elevators, with the lower half of the building (floors 0-24) population using the stairs and the upper half (25-49) using the elevators to shuttle to the ground floor.
7		32 elevators, with the lower-half of the building (floors 0-24) population using the stairs and the upper half (25-49) using the elevators to shuttle to the middle floor (floor 25) from the occupants floor of origin, then continue their evacuation via the stairs.
8		32 elevators, with the lower-half of the building (floors 0-24) population using the stairs and the upper half (25-49) initially using the stairs to walk to a sky lobby on floor 25 where occupants would be shuttled via elevators to the ground floor.
9		32 elevators, 4 shuttle zones - each elevator bank servicing a series of 12 floors of occupants, with each zone being evacuated from the top-down of the zone to the ground floor.
10		32 elevators, 4 shuttle zones + 1 Stair zone - each elevator bank servicing a series of 10 floors of occupants, with each zone being evacuated from the top-down of the zone to the ground floor. Occupants below floor 10 only use the stairs to evacuate.
11		32 elevators, 4 Sky lobbies – there is a sky lobby every 10 floors in the building (4 sky lobbies in total) with each elevator bank servicing one of the sky lobbies. Occupants travel down the stairs to the next sky lobby below where the lifts shuttle them to the ground floor. Occupants below floor 10 only use the stairs to evacuate.

During the elevator simulations, agents using the elevators were assigned to use their nearest lift bank which was not already over subscribed by agents i.e. an equal number of agents used each elevator bank on each floor. Likewise during simulations in which the stairs were used, an equal number of agents were assigned to use each stair on each floor. This concept of equal core load balancing was considered appropriate as unequal use of an elevator bank or stairwell has the potential to significantly increase total evacuation time and levels of congestion. While this may in fact occur in real situations, it was not considered appropriate to consider these issues in the current analysis as the primary concern here is to investigate optimal performance.

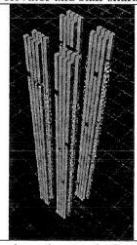
The defining attributes for the elevator kinematics and physical characteristics were based on the Chartered Institution for Building Service Engineers (CIBSE) Guide D: Transportation Systems in buildings[19]. Each elevator had a maximum capacity of 13 occupants, a maximum speed of 6 m/s, acceleration rate of 1.2m/s² and a jerk rate of 1.8 m/s³. In addition each elevator had a door opening time of 0.8s, door closing time of 3.0 seconds, a dwell delay of 3.0 seconds and a motor delay time of 0.5 seconds. Using these parameters approximately 28.4s are required for a car to travel from the ground floor to the top floor and fully open its doors. At the beginning of each simulation each elevator started at the ground floor. For each elevator simulation not involving stairs, where elevators serviced multiple floors (i.e. non-sky lobby scenarios), a top-down-shuttle evacuation strategy was employed by each of the elevators whereby all the elevators evacuate the occupants on the top floor first and shuttle them to the ground floor. This process is repeated until all people evacuated that floor. The elevators then proceed to the floor below this and the process is repeated until all of the floors in the sequence have taken all occupants on those floors to the exit floor.



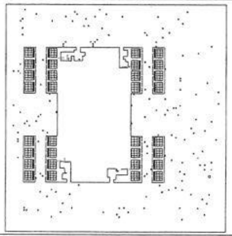
(a) Multi-floor view showing building core, elevator and stair shafts



(b) Floors and walls removed, start of scenario 5 with elevators near ground level



(c) Part way through scenario 5, with elevators at different levels, occupants gather in elevator lobbies.



(d) Two-dimensional view of a single floor, near start of scenario 5, showing distribution of agents around core, stairs and four elevator banks.

Figure 1: Sequence of views from buildingEXODUS of high-rise building elevator evacuation, (a), (b) and (c) depicting 3D virtual reality view and (c) depicting two dimensional view

RESULTS AND DISCUSSION

Still sequences from the simulation of scenario 5 are depicted in Figure 1. As part of the development of the elevator sub-model, a three-dimensional virtual reality visualisation capability has been developed which is integral to the buildingEXODUS user interface. The new interface is capable of displaying virtual reality three-dimensional graphics (see Figure 1a, b, c) as well as the usual two-dimensional visualisation (see Figure 1d). The three-dimensional representation shows the progress of the elevator cars during the simulation. The results for the various simulations are presented in Table 3 with the egress curves for the various scenarios presented in Figure 2.

Table 3: Summary of evacuation statistics for the various scenarios

Scenario	Number of elevators	Total Evacuation Time (TET)	Time to clear upper half of building	Average PET	% Time saved (compared to stairs only)	Evacuation time of last stair user	Evacuation time of last elevator user
1	0	36.1 min	20.9 min	17.6 min	-	36.1 min	-
2	8	81.0 min	48.1 min	46.1 min	-125%	-	81.0 min
3	16	43.1 min	24.8 min	24.4 min	-19.5%	-	43.1 min
4	24	34.2 min	19.5 min	19.2 min	5.1%	-	34.2 min
5	32	26.3 min	14.8 min	15.0 min	27.1%	-	26.3 min
6	32 + half stairs top down	18.1 min	14.9 min	9.1 min	49.9%	18.1 min	16.2 min
7	32 + half stairs top middle	35.2 min	12.2 min	17.6 min	0.32%	35.2 min	35.2 min
8	32 + half stairs, 1 x Sky Lobby	19.6 min	18.3 min	9.6 min	45.7%	18.7 min	19.6 min
9	32 + 4 Shuttle Zones	23.9 min	22.5 min	10.2 min	33.8%	-	23.9 min
10	32 + 4 Shuttle Zones + 10 Stairs	20.3 min	19.1 min	8.5 min	43.8%	13.0 min	20.3 min
11	32 + 4 x Sky Lobbies	18.2 min	17.0 min	7.4 min	49.6%	13.0 min	18.2 min

The base line comparison for all the cases is the stair only evacuation (scenario 1). This produced a Total Evacuation Time (TET) of 36.1 min with 20.9 min required to clear the top half of the building. The Average Personal Evacuation Time (PET) for the simulation was 17.6 min. This indicates that on average, a person required 17.6 min to exit the building. The TET for scenarios 2 (8 cars) and 3 (16 cars) are 48.1 min and 24.8 min respectively, both being considerably longer than the stair only case. From Figure 2 we also note that for these cases the evacuation rate increases towards the later stages of the evacuation unlike in the stair only case which tends to decrease towards the later stages of the evacuation. The increase in evacuation rate is due to the elevator cars having to travel a much shorter distance towards the end of the evacuation as the remaining agents are located on the lower floors. It is not until 24 cars are used in the evacuation (scenario 4) that the TET is marginally better than the

stair only case, being 34.2 min or 5.1% faster. However, even with 24 cars the average PET (19.2 min) is still greater than the stair only case. From Figure 2 we note that the stair only curve out performs the 24 car case right up to nearly the end of the evacuation (88.7% of the stair only case or 93.4% of the 24 car case). However, from Table 3 we note that the 24 car case (scenario 4) does clear the upper half of the building marginally faster than the stair only case (scenario 1), clearing the upper part of the building in 19.5 min compared to 20.9 min.

It is not until 32 cars are used (scenario 5) that we see a substantial improvement over the stair only performance. In this case the TET is 26.3 min, some 27.1% faster than the stair only case and the average PET is 15.0 min compared with 17.6 min for the stair only case. The upper half of the building is also cleared substantially faster than the stair only case, requiring only 14.8 min compared with 20.9 min. Comparing the 8 elevator scenario with the other elevator only scenarios, we can see there was a 2, 2.4 and 3 times speed-up in total evacuation time respectively for the 16, 24 and 32 elevator scenarios. This suggests that for a given population distribution and number of floors, the speed up in evacuation performance does not necessarily increase linearly with the number of cars used.

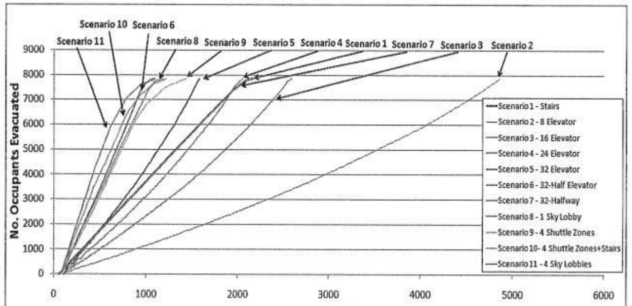


Figure 2: Number of agents evacuated as a function of time for the various scenarios

In scenario 6 we explore an evacuation strategy in which the bottom half of the building use the stairs to evacuate while the top half use 32 elevators to evacuate the occupants direct to the ground. This strategy produces the best overall evacuation time of 18.1 min; almost 50% faster than the stair only case. As is to be expected, the time to clear the top half of the building is similar to that of scenario 5 at 14.9 min but the average PET is greatly decreased to 9.1 min. In this scenario, the last agents out of the building are the stair users resulting in the decrease in the evacuation rate towards the very end of the evacuation as seen in Figure 2. Scenario 7 introduces a variation on scenario 6 in which the elevators take the upper occupants not to the ground but to the central floor. From here the occupants make their way down the stairs. We find that the TET for this scenario increases to 35.2 min, only marginally faster than the stair only case and the average PET, at 17.6 min is identical to that of the stair only case. However, we note that the time to clear the upper half of the building is the quickest of all the scenarios, requiring only 12.2 min. While the time to evacuate the entire building is equivalent to the stairs only case, using this strategy does provide the quickest way to clear the upper half of the building. For emergency situations where it is essential to evacuate the upper part of the building as quickly as possible this is clearly the best strategy. In scenario 8 we introduce a sky lobby.

Here the agents in the upper part of the building are required to descend to the central floor, by stairs, from where they can take an elevator to descend all the way to the ground. The agents below the central floor all must use the stairs to evacuate to the ground. In this case the TET is 19.6 min, some 46% faster than the stair only case. However, it requires some 18.3 min to clear the top half of the building. As a result, scenario 8 is not as efficient as scenario 6. Furthermore, it is noted that the last person to evacuate from the building made use of the elevators. Thus the elevator evacuation took longer than the stair evacuation. This is a result of the stairs providing a staggered arrival rate of agents to the elevators. As a result, on occasion, the elevator car is not filled to capacity or is forced to wait for agents. If local elevators could be used to shuttle agents to the sky lobby rather than requiring the agents to use the stairs, this may improve the performance of this scenario.

In scenario 9 four shuttle zones are introduced with each group of eight elevators servicing the 12 floors within their allocated zone (the bottom zone has 13 floors). In each zone the elevators service the floors from the top down. In this case the TET has increased to 23.9 min which is some 34% faster than the stair only case, but considerably slower than scenario 6. Using this approach also requires some 22.5 min to clear the upper half of the building, some 1.6 min slower than the stair only case. Clearly this is a very inefficient strategy for emptying the building and clearing the upper half of the building. In scenario 10 we extend this concept by making all the building occupants below the 10^{th} floor use the stairs rather than the elevators. In this case we have four shuttle zones with each group of eight elevators servicing 10 floors. While this case represents an improvement over scenario 9, with a TET of 20.3 min which is 44% quicker than the stair only case, the time required to clear the upper half of the building is 19.1 min, only 1.8 min faster than the stair only case.

In scenario 11 we introduce four sky lobbies, one on every 10^{th} floor with each sky lobby being serviced by eight elevators (a single elevator bank). Within each zone, agents must descend, using stairs, to the sky lobby where they can board an elevator which takes them directly to the ground. Below the 10^{th} floor, all agents use the stairs to evacuate. This case produces a TET of 18.2 min which is some 50% faster than the stair only case and the upper half of the building is cleared in 17 min. This scenario produces comparable times to scenario 6 in terms of the overall evacuation time but a slightly longer time to clear the upper half of the building. However, we note that the average PET is only 7.4 min, considerably lower than any other scenario. Indeed, from Figure 2 we note that this scenario produces the best evacuation rate of all the scenarios for most of the evacuation duration. Over the first 17 min (93.3%) of scenario 11, more agents are evacuated using this strategy than in any other case. This means that the introduction of multiple sky lobbies makes it possible to evacuate a greater number of people in the same amount of time for the majority of the evacuation than in any other strategy examined. The performance of this scenario could potentially be further improved through the introduction of local elevator cars that ferry the occupants to the sky lobby rather than use the stairs. We further note from Figure 2 that scenarios involving zoning/multiple sky lobbies (scenarios 9,10,11) produce increasingly inefficient evacuation performance towards the end of the evacuation sequence. This is because the elevators servicing the zones/sky lobbies on the lower levels are left idle whilst the elevators servicing the upper levels are still in operation.

CONCLUSION

This paper has presented a description of the newly developed elevator sub-model within buildingEXODUS intended for both evacuation and circulation applications. A range of demonstration full building evacuation simulations were performed using the newly developed model exploring different evacuation strategies. The demonstrations apply to a hypothetical 50 floor building with four staircases and a population of 7,840 agents in which the agents behave in an "ideal" manner. The results suggest that for this type of building:

- For a given building population and number of floors, the speed up in evacuation performance achieved using an elevator only strategy - in which each elevator visits each floor – is sub linear with increasing number of elevator cars.
- Using an elevator only strategy in which each elevator visits each floor, the total evacuation time can be reduced by 27% and the time to clear the top half of the building reduced by 29% using 32 elevator cars compared to a stair only strategy.
- A more efficient evacuation strategy involves using elevators in conjunction with stairs. If 32 elevators are used to clear the top half of the building while the occupants in the lower half of the building utilise the stairs, the building can be emptied 50% faster compared with the stair only strategy. The time to empty the top half of the building is reduced by 29% compared to the stair only case.
- The most efficient overall strategy involved using 32 elevators arranged into four sky lobbies where the occupants on the first 10 floors used the stairs and within each sky lobby zone the occupants used the stairs to descend to the sky lobby. In this case the building could be evacuated 50% faster than the stair only case and the upper half of the building could be emptied 19% faster than the stair only case. While the upper half took 14% longer to empty than in the case where the elevators were used to evacuate only the top half of the building, this case produced the highest overall egress rate for more than 90% of required evacuation time.
- It is suggested that the performance of the sky lobby cases could be improved if local elevators were used to shuttle occupants from local floors to the sky lobbies.

The next phase in the development of the buildingEXODUS elevator modelling capability is to address some of the key human factors issues associated with occupant behaviour in selecting to use elevators or stairs. To date only a few studies have focused on these human factors issues. The EXODUS development team are attempting to address these issues through an international survey aimed at understanding and quantifying some of the factors associated with occupant device selection in both circulation and evacuation situations. The survey can be found on the FSEG web pages at: http://fseg.gre.ac.uk/elevator/. Thus far some 425 people from 23 countries have completed the survey. Interested readers are urged to complete the survey and to pass on the web address to as many people as possible, preferably from outside the fire engineering community.

With the increasing number of high-rise and super high-rise structures being planned and built around the world, the viability of using stairs only for full building evacuations is coming more and more into question. As a result, building engineers around the world are increasingly turning to elevators as a means to safely address full building evacuation scenarios. However, whilst there has been considerable progress in solving the mechanical issues associated with using elevators for evacuation, considerably more effort is required to fully address the operational and human factors issues associated with elevator usage in emergency situations.

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Robinson College, Cambridge, UK

13-15 July 2009

Proceedings of the 4th International Symposium on Human Behaviour in Fire 2009
held at the Robinson College, Cambridge, UK
13-15 July 2009

A conference organised by:
Interscience Communications Ltd
West Yard House, Guildford Grove,
LONDON SE10 8JT, England

Human Behaviour in Fire 2009

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ISBN 978-0-9556548-3-1

p680, 134 tables and 276 illustrations

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EXTENDED MODEL OF PEDESTRIAN ESCALATOR BEHAVIOUR BASED ON DATA COLLECTED WITHIN A CHINESE UNDERGROUND STATION

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ABSTRACT

This paper presents data relating to pedestrian escalator behaviour collected in an underground station in Shanghai, China. While data was not collected under emergency or simulated emergency conditions, it is argued that the data collected under rush-hour conditions - where commuters are under time pressures to get to work on time - may be used to approximate emergency evacuation conditions – where commuters are also under time pressures to exit the building as quickly as possible. Data pertaining to escalator/stair choice, proportion of walkers to riders, walker speeds and side usage are presented. The collected data is used to refine the buildingEXODUS escalator model allowing the agents to select whether to use an escalator or neighbouring parallel stair based on congestion conditions at the base of the stair/escalator and expected travel times. The new model, together with the collected data, is used to simulate a series of hypothetical evacuation scenarios to demonstrate the impact of escalators on evacuation performance.

INTRODUCTION

In certain situations such as in deep underground/subway stations, which are well catered for by escalators for normal pedestrian flows, escalators can provide an attractive and efficient alternative to long stairs in evacuation situations. In emergency situations, escalators also offer a larger throughput capacity than a typical single lift/elevator car for the same number of floors as there is no service wait time for occupants. However, in the event of an emergency evacuation, escalators are typically turned off, in some cases they may even be closed, preventing occupants from using them as a stair and in some cases escalators may be used only if staff are present to supervise[1].

There are many reasons for the restricted use of escalators in emergency situations including; the possibility of an unexpected shut down during operation possibly causing some riders to fall, the possibility that pedestrians may be trapped in a location because they can not traverse in the opposite direction to which the escalator is moving, and the possibility that the moving escalator may be carrying people to, rather than away from danger. In situations where the escalator has stopped, the high riser height makes it difficult for some people to utilise the escalator as a stair and the uneven riser height for some of the treads increases the probability of a miss step resulting in a fall.

Regardless of these concerns, escalators have been used both in the "off" and "on" condition in some evacuation situations. In the 9/11 World Trade Center evacuation escalators were used as a means of evacuation in both the North and South towers to move people from the Mezzanine to the lobby[2]. In both towers escalators were used as stationary stairs while in the South Tower survivors reported using moving escalators during the "unofficial" evacuation prior to the South Tower being hit[2]. As a result there is a need to understand and quantify pedestrian behaviour associated with the use of escalators.

Despite this, at present, there is little data pertaining to micro-level pedestrian dynamics on and around escalators (see[3] for example) and a subsequent lack of understanding. Consequently evacuation and circulation models that attempt to represent escalators typically do so at a macro-level, simply specifying escalator flow rates. However, flow rates are usually derived from manufacturer specifications which are based on ideal assumptions of usage, seldom achieved in practice.

A micro-level escalator model was developed for the buildingEXODUS software based on data collected within a Spanish underground/subway station[4] to represent more accurate pedestrian behaviour during circulation/evacuation scenarios. Here we present additional data collected from a Chinese underground/subway station, where higher densities of people were involved at the base of the stair/escalator making the decision to use the stair/escalator more complex. In this paper we present the newly collected Chinese escalator data along with modifications to the escalator model that take into consideration crowd density in the decision to board the escalator or stair.

DATA COLLECTION

The data was collected in the Peoples Square underground/subway station, Shanghai, China. The station itself is located in the very centre of the city and as such is located near a number of large office buildings, shopping centres and tourist attractions. Consequently it is used by a large number of people everyday, especially during the peak rush-hour periods where platform crowd densities often exceed 2 people/m². Within this study, two identical escalators were videoed at different times, both moving in an upwards direction linking the platform level to the above lobby level identified as Escalators A and D. Each escalator has a horizontal speed of approx 0.5 m/s, a vertical drop of 4.2 m with a total length of 12.49 m (length of horizontal parts and length of incline). Stairways run parallel with both escalators and so provide an alternate means to traverse the area. The effective width of the stair is 3.6 m while the effective width of the escalator is 1.1 m. The platform is double sided, which means that trains arrive on both sides of the platform (going in opposite directions). Subsequently pedestrians on the platform level can approach the escalator/stairway from either the stairway or escalator side. Escalator A was videoed during the rush-hour and Escalator D was videoed during non-rush hour. For each escalator, two digital video cameras were used to record the footage. Both the escalator entrance (on the platform level) and the exit (on the lobby level) were videoed. Each camera recorded footage for 1 hour (the total amount of footage collected was 4x1hrs = 4 hours). Analysis of the video footage allowed the formation of a human factors dataset contained information pertaining to: escalator/stair choice, escalator side preference, proportion of walkers to riders, walker speeds and entry/boarding and exit/alighting flow-rates.

ESCALATOR USAGE OBSERVATIONS

In total around 4,787 people were recorded using each escalator; 2,752 during the rush hour (Escalator A) and 2,035 during the non-rush hour (Escalator D). In addition, some 2,451 stair users adjacent to Escalator A during the rush-hour period were also recorded.

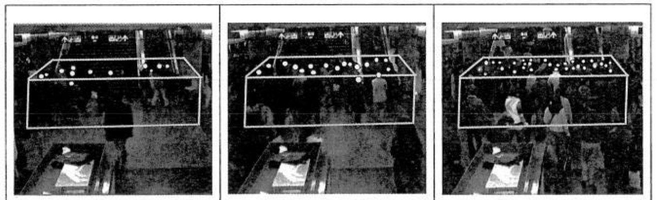
Escalator/Stair choice

When pedestrians approached each of the escalators, they were presented with a choice to use either the escalator or the adjacent stair. The frequency of pedestrians that used Escalator A (i.e. rush-hour) and the adjacent stairway was recorded. The camera view used for Escalator D (i.e. non-rush hour) did

not provide a full-length view of the stairway and subsequently the frequency of stair users was not recorded.

People arrived at the stairs in batches corresponding to the arrival of trains. The congestion at the base of the stair/escalator varied with each batch and during the time that the batch passed through the stair/escalator. The frequency of stair and escalator users appeared to vary with the density at the base of the stair/escalator. To facilitate a consistent method of measuring the crowd density at the base of the stair/escalator, a region measuring approximately 3m x 6m in front of the staircase and escalator (including the escalator flat section) was defined (see Figure 1). The number of people within this region was counted every few video frames to determine the number of people within the region and hence the crowd density within the region. Presented in Figure 1 are three views of the region showing three different crowd densities.

To highlight each person within the catchment area a white circle has been placed on each occupant's head. This region was then considered "congested" when the number of people in the area, who intended travelling up the stair/escalator, equalled or exceeded 18. This represented an average of 1+ people/m² and approximately corresponds to Fruins' level of service D and above (i.e. 0.72-1.1 people/m²)[3] . Level of service D was selected as the critical crowd density as it represents the situation in which normal walking speeds are reduced for the majority of occupants due to difficulty in bypassing slower occupants. The critical level of congestion (i.e. 18 people in the 3m x 6m catchment area) is presented in Figure 1b. This density is intended to represent the lowest accepted level of congestion during the congested periods. A significant difference in the level of congestion is evident by comparing the heavily congested period shown in Figure 1c with the low congestion period shown in Figure 1a. For any one batch, a start up period of time was required before the density at the base of the stair/escalator reached the critical density. Having reached the critical density, it would normally remain at or above the critical density until just before the end of the batch. Thus for any one batch, it could be possible to measure people using the stair/escalator during congested and non-congested periods.



(a): Approximately 12 people (0.67 p/m² average)	(b): Approximately 18 people (1 p/m² average)	(c): Approximately 31 people (1.7 p/m² average)

Figure 1: Different levels of congestion at the base of the stair/escalator

In total 4,531 pedestrians were recorded ascending to the upper level using the escalator or the adjacent stair; 1,182 during non-congested periods (20 train arrivals) and 3,349 during congested periods (8 train arrivals) (see Table 1). During the non-congested periods 907 escalator users were recorded and 275 stair users were recorded. During the non-congested period, regardless of arrival side, the escalator was the most preferred device. Approximately 76% of the pedestrians that arrived on the escalator side preferred to use the escalator and 75% of the pedestrians that arrived on the stair side preferred to use the escalator. This suggests that the side of approach to the device does not exert an influence on the choice to use a particular device. Furthermore, if the stair and escalator were equally attractive we would expect that 50% of the pedestrians would make use of each device however; we find that the escalator attracts almost 77% of the pedestrians which suggests that there is a strong bias to use the escalator. It should be noted that these results only apply for vertical drops equivalent to that in the trial and only in non-congested conditions.

Table 1: Non-congested escalator/stair users

Train Arrival Side	Arrival Frequency	Escalator User Frequency	Stair Users Frequency	% Escalator Users
Escalator	7	532	172	75.6%
Stair	9	184	63	74.5%
Both	4	191	40	82.7%
Overall	20	907	275	76.7%

In the congested periods over twice as many pedestrians were observed compared to the non-congested periods in under half as many train arrivals. Also, during the congested periods, none of the trains arrived only on the escalator side. Approximately the same proportion of pedestrians were observed to use the escalator when trains arrived from either the stair or both sides simultaneously. This suggests that during congested periods the side of approach has little influence upon stair/escalator usage. However, significantly more pedestrians utilise the stair compared to the escalator. During congested periods, crowds form around, the entrance of the escalators, the base of the stair and along the platform. In these circumstances some pedestrians will be forced into using a device simply based on proximity to the device.

Table 2: Congested escalator/stair users

Train Arrival Side	Arrival Frequency	Escalator User Frequency	Stair Users Frequency	% Escalator Users
Stair	3	250	463	35.1%
Both	5	923	1713	35.0%
Overall	8	1173	2176	35.0%

In these circumstances, the relative width of the escalator and stair is expected to have a significant influence on the proportion using either device. Given that the stair is some 3.3 times wider than the escalator, if there were an equal preference to use the stair and the escalator based on width alone then we would expect the stair to attract some 330% more users. However, we find that the stair attracts some 190% more users. Thus, while the relative widths of the devices are exerting an influence on whether or not pedestrians use a particular device, pedestrians are also exercising some discretion concerning device usage. Thus, during non-congested periods, pedestrians can exercise a clear choice as to which device they use. However, during congested periods, while some pedestrians are forced into using a device simply based on proximity to the device other pedestrians exercise some choice in device usage.

Proportion of Walkers and Riders

When boarding an escalator, pedestrians can either ride or walk along the escalator. Walking along the escalator decreases the transit time relative to simply riding the escalator. Whether pedestrians

elected to walk or ride the escalator was recorded during both the rush-hour and non-rush hour period. It was observed in most train arrivals within the data that riders who typically were among the first to board the escalator from an arriving train blocked pedestrians behind them from having a choice to walk up the escalator. This meant the proportion of walkers in the data was often not a reflection of pedestrian choice but a by-product of decisions made by other pedestrians to ride. Almost all walkers were among those pedestrians who boarded the escalator first. The frequencies of walkers and riders during the rush-hour and non-rush hour period can be seen in table 3. While there are slightly more walkers in the rush-hour period, the overall number of walkers is only 2.4%.

Table 3: Walker/Rider frequencies during rush-hour and non-rush hour periods

	Train Arrival Frequency	Walker Frequency	Rider Frequency	% Walkers
Rush-hour	28	92	2,660	3.3%
Non-rush hour	25	27	2,008	1.3%
Overall	53	119	4,668	2.4%

Side Preference Behaviour

When pedestrians board an escalator, they occupy a particular location on the escalator tread, either left or right. The side can be dictated by national custom though can be violated by foreign visitors or the careless. The side occupied by the escalator user can impact the efficiency of the escalator since if a large number of riders do not adopt a common side preference, they can inhibit other pedestrians from walking up the escalator. The side which all escalator users occupied was recorded during the non-rush hour period. The breakdown of side preference of walkers and riders is summarised in Table 4. It can be seen that overall almost all occupants adopted either the left or ride side to traverse the escalator. Approximately equal numbers of walkers used the left and right side and approximately equal numbers of riders elected to use either the right or left side of the escalator. The left and right users do not add up to the total as some pedestrians used the centre or changed location during their travel and these are not included.

The data shows that there appears to be no common side preference whereby walkers and riders elect to use opposite sides of the escalator as found in other countries[4]. As a result higher crowd densities were observed on the escalator compared to those escalators where there is a walker and rider lane (i.e. walkers require at least tread spacing in order to walk whereas riders can occupy each tread).

Table 4: Side preference for escalator users during the non-rush hour period

		Left	Right	Total
Non-rush-hour	**All**	964	993	2,035
		47.37%	48.80%	
	Walkers	9	8	27
		33.33%	29.93%	
	Riders	984	956	2,008
		49.00%	47.61%	

Walker Speeds

Due to obstructed views it was not possible to measure the walking speeds of all the escalator walkers. However, the average speed of 79 walkers traversing each escalator was determined. Due to the blocking behaviour of riders, the walker speeds were typically of those who were among the first occupants to board the escalator. In total 57 walkers were recorded in the rush-hour with an average horizontal speed of 0.9 m/s. During the non-rush hour period, 22 walkers were recorded with an average horizontal walking speed of 0.67 m/s.

ESCALATOR MODEL

The core software used in this paper is buildingEXODUS V4.1 beta[5]. The software can be used to simulate both evacuation and circulation scenarios. The existing escalator model within the software has the capacity to represent escalator/stair choice, proportion of riders/walkers, side preference for riders and walker speeds[4]. Using the data collected above, the escalator model was further refined to include a device selection algorithm based on levels of congestion at the base of the stair/escalator. Three approaches to represent agent device selection are incorporated within the modified escalator model. The first approach simply requires the engineer to prescribe a fixed proportion of device users, which may be based on observed data for up/down direction of travel and time of day. This approach is most appropriate for circulation scenarios and relies on data which is representative of the type of scenarios being considered. Using this approach, when an agent enters the catchment area they are assigned a device to use based on the assigned probabilities.

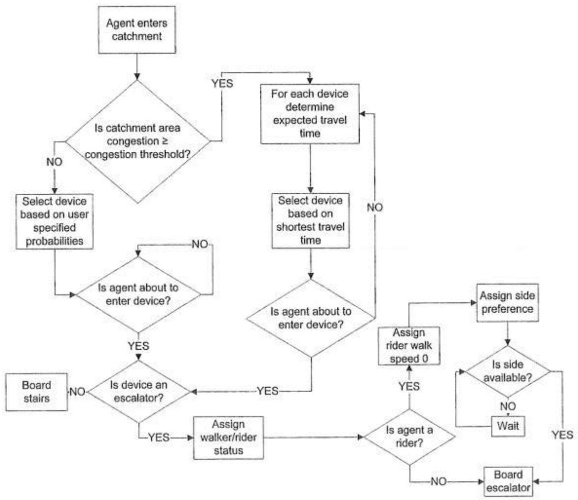


Figure 2: Microscopic escalator model logic

The second approach relies on the agent making a decision as to which device to use. The decision is based on the assumption that the main motivation of the agent is to reduce their overall travel time. This approach is most appropriate for scenarios involving highly motivated pedestrians such as those involved in an evacuation. The shortest perceived travel time selection system is a theoretical

framework which ensures that agents select the device which they expect to get them to their desired vertical level in the shortest period of time. This is determined by the agent initially estimating the time it would take to travel to the device based on the distance from their current position and their speed, taking the number of people along the straight-line path to the device into account. In addition, the expected travel time incurred on the device is also estimated. This calculation is based on the distance to be travelled on the device and the agents' device travel speed, taking into account travel direction and any additional speed afforded by the device e.g. moving escalator. The agent selects the device within the device group which provides the shortest expected travel time and moves towards the selected device. While in the catchment area and prior to boarding the desired device, the agent occasionally reassesses their personal situation and may select a more favourable route and device. In this way the agent adapts their path in response to the changing numbers of people within the catchment area ahead of their current location.

The third approach, which is the new methodology based on the data presented in this paper, incorporates the influence of congestion into the device selection process. This approach combines the fixed proportion model with the shortest travel time model influenced by local congestion levels. Below a specified threshold crowd density, the agents select the device to use based on specified probabilities. These probabilities are based on the observed pedestrian preferences under non-congested conditions. Above the threshold crowd density, pedestrians select which device to use based on the shortest travel time algorithm. The logical functionality describing the third approach is presented in Figure 2. As this approach is adaptive, it is suggested that this methodology can be used for both circulation and evacuation applications. The method requires several parameters to be specified by the user. These are the congestion threshold density (CT), which in this work is taken as 1 people/m^2 and the device preference probabilities under non-congested conditions, which from the data presented here is 77% bias towards the escalator for upward movement. These parameters are expected to be dependent on direction of travel and size of vertical drop. In addition, it is suggested that for circulation applications, these values may also be dependent on culture.

ESCALATOR MODEL EVACUATION DEMONSTRATION

A simple case was developed to demonstrate the extended the microscopic escalator model in an evacuation scenario involving 400 agents. The geometry consisted of two levels connected via two stairs and a dual lane escalator (see Figure 3). The vertical drop was 4.2 m and the width of the each stair and the escalator was 1.1 m. The horizontal speed of the escalator was 0.5 m/s with a horizontal length of 11.5 m. The catchment area at the entrance to the group of stairs/escalator measures 8.5 x 3.5m. A total of seven scenarios are examined, requiring the agents to travel from the lower to the upper level. These consisted of various combinations of stair/escalator users and escalator model parameter configuration. The escalator walk speed distribution used in these simulations was selected from the maximal values in the dataset presented in this paper.

The results for the various scenarios are summarised in Table 5, it should be noted that in these scenarios, stair2 is immediately adjacent to the escalator. Very early in the evacuation crowds develop at the foot of the stairs/escalator and persist until near the end of the evacuation. The extent of this congestion in each scenario is dependent on how well balanced the device usage was, which is in turn dependent on the throughput of each device and the device selection method employed. We also note that in the case where the escalator is static (scenario 2), there is almost equal usage of the devices effectively treating the static escalator as a third staircase. Whilst in reality a static escalator may prove more physically taxing to traverse than a stair due to the increased tread height on the escalator, no data was collected regarding escalator/stair choice using a static escalator, nor pedestrian performance on a static escalator.

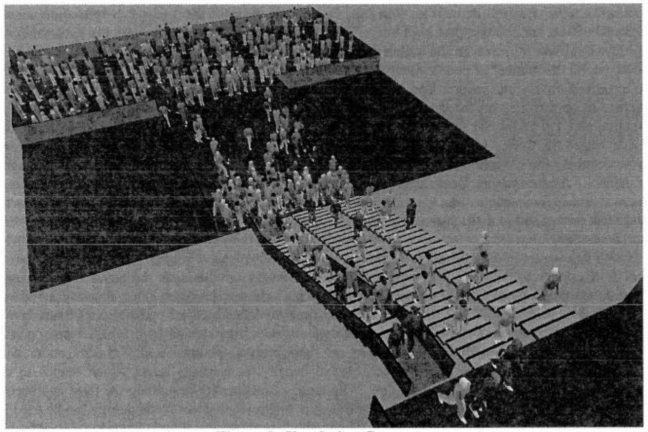


Figure 3: Simulation Geometry

Scenario 1 represents a situation akin to common practices in an actual evacuation whereby the escalator is turned off and cordoned off whilst pedestrians are required to use only the stairs. Out of all scenarios run this produced the longest Total Evacuation Time (TET) of 383s. Another common practice during an evacuation is to turn the escalator off but allow pedestrian to walk up the device. If we assume that pedestrians are evenly assigned to use each device, regardless of the number of people in front of them or device queue length (scenario 2), the TET reduces to 282s, a decrease of 26.2% compared with scenario 1, along with reductions in average Cumulative Wait Time (time lost to congestion – CWT). When the escalator is turned on, using the perceived shortest time selection method with all escalator users riding (scenario 3), the TET reduces to 257s, a 9.0% (25s) decrease compared to when the escalator is off and used as a stair (scenario 2). If we now assume that all escalator users walk on the moving device (scenario 4), the TET reduces to 231s, a decrease of 18.3% compared to scenario 2. During this scenario on average 84% of the population used the escalator, highlighting the influence of higher effective travel speeds on the escalator compared to the adjacent stairs. This scenario produces the minimum evacuation time and is perhaps somewhat unrealistic as not all pedestrians would be able to walk up the escalator e.g. elderly, obese, disabled.

In simulations using the more advanced device selection algorithm we note that results are strongly dependent on the value of the CT (see scenarios 5 and 6). With the CT set to 4p/m² and an even distribution between the devices in non-congested situations (scenario 5), the TET becomes 280s which is comparable with the case with the stopped escalator (scenario 2). This poor performance is due to the level of congestion in the decision area never exceeding the CT and as a result, the pedestrians were not free to select which device to use.

Furthermore, the last pedestrian to utilise the escalator did so some 51.9s before the last stair user alighted the stairs. Thus the stairs are seen as the bottleneck in this scenario and hence the results for scenario 5 are similar to those for scenario 2. In scenario 6 the CT is set to 1 p/m² while all other parameters are identical to scenario 5. Here we find that the TET is 250s, a decrease of 10.7% compared to scenario 5. The improvement in TET is due to the agents being able to exercise a choice

(based on minimising perceived travel times) in which device to use and as a result, more agents selecting the escalator. The better throughput provided by the escalator also reduces the average density at the foot of the stair/escalator compared with scenario 5.

Table 5: Summary results for escalator evacuation demonstration scenarios

Scenario	Av. TET (s)	Av. CWT (s)	Av. Max Density (p/m²)	Av Escalator usage	Av. Stair2 usage	Av. Stair1 usage
1: 2 stairs (50% on each)	383	73.4	3.9	0.0	197.6	202.4
2: 2 stairs + stopped Escalator (33.3% on each device)	282	23.2	2.6	140.3	123.8	136.0
3: 2 stairs + Escalator (shortest time, 100% Ride)	257	15.2	2.1	238.0	81.8	80.3
4: 2 stairs + Escalator (shortest time, 100% Walkers)	231	7.5	1.4	334.3	52.8	13.0
5: 2 stairs + Escalator (CT = 4 p/m², 33.3% on each device, 100% Walkers)	280	17.6	2.2	143.6	134.6	127.8
6: 2 stairs + Escalator (CT = 1 p/m², 33.3% on each device, 100% Walkers)	250	8.6	1.2	185.8	106.8	107.4
7: 2 stairs + Escalator (CT = 1 p/m²; 11.65% Stair1, 11.65% Stair2, 76.7% Escalator; 97.6% riders, 50% left + right)	254	11.8	1.9	190.8	104.0	105.3

The final scenario is configured based on the data collected from the Shanghai underground station with the CT= 1p/m². In this case the TET is 254s and is; 9.9% faster than the case when the escalator is stopped and used as a stair (scenario 2), 33.7% faster than the case where the escalator is closed (scenario 1) and about the same time as when everyone walks up the working escalator with an even split between devices in the non-congested periods (scenario 6). Of all the scenarios, we suggest that scenario 6 is the most realistic evacuation scenario (at least for a Shanghai based evacuation) as it uses relevant human factors data.

CONCLUDING COMMENTS

This paper has presented an analysis of human factors data relating to pedestrian escalator behaviour within a Chinese underground station. The presented data relates to: escalator/stair choice, rider/walker preference, rider side preference and walker travel speeds. Key findings from this analysis include; below a critical threshold crowd density, 77% of pedestrians prefer to use the escalator to travel up (non-congested conditions) and above the critical threshold density (congested conditions) this decreased to 35% of pedestrians, thus in congested periods, while more pedestrians elected to use the escalator than would be expected based on relative widths, the ability to choose a device was severely limited; pedestrians did not exhibit a side preference when using the escalator; 97% of the pedestrians rode the escalator up; walker speeds in the up direction were faster during the rush-hour compared to non rush-hour periods. These observations are expected to be dependent on direction of travel and size of vertical drop. In addition, it is suggested that for circulation applications, these observations may also be dependent on culture.

The dataset provides insight into pedestrian behaviour in utilising escalators and is a useful resource for both evacuation and circulation model developers. The existing escalator model within EXODUS has been extended using the newly collected data. The current escalator model has the capacity to represent three different device selection methods: assigned probabilities, shortest perceived travel time and congestion influenced device selection. The model was used to examine a hypothetical evacuation in which the pedestrians had to travel up a single level with an escalator and two stairs located side by side linking the two levels. The results suggest that under evacuation conditions, allowing the escalator to function as normal can provide significant benefit to pedestrians by reducing overall evacuation times. Significant benefit could be derived from the escalator even in situations where all the pedestrians rode up the escalator.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Han Xin and Dr Jun Chi Ma of the Shanghai Institute of Disaster Prevention and Relief (SIDPR) of Tong Ji University, Shanghai, China for their assistance in collecting the human behaviour data.

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Stairs or Lifts? - A Study of Human Factors associated with Lift/Elevator usage during Evacuations using an online Survey

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Abstract This paper presents an overview of human factors data collected via an online survey related to the use of lifts (elevators) and stairs during both circulation and evacuation scenarios. Survey participants were presented with a series of hypothetical situations and asked how they would behave. The survey was split into two broad sections, the first dealing with normal circulation usage of lifts/stairs and the second dealing with evacuation usage of lifts/stairs. Detailed demographic information about each participant was also collected. In total some 468 people from 23 countries completed the survey. An overview of the survey and initial results are presented in this paper.

Introduction

How will people behave when given the option to use lifts during emergency evacuation situations within high-rise buildings? In countries such as the UK, Australia, Malaysia, China and USA, lifts are either being used or being considered for use as part of building evacuation systems. In past ad-hoc egress situations lifts have been used to good effect to assist in the rapid evacuation of high-rise buildings [1]. In such cases lifts were not intended to form part of the evacuation system but were used by residents for rapid egress. Computer modelling also suggests that if used correctly, the combined use of lifts and stairs can speed up full building evacuation process by as much as 50% compared to the use of stairs alone [2]. However, in these modelling examples, due to lack of human factors data, ideal "compliant" occupant behaviour was assumed. This meant that all the agents that were designated to use the lifts waited to use the lifts for as long as required. However, how many people would actually consider using a lift rather than the stairs? How long would people wait for a lift? Some evidence suggests that when faced with large queues occupants will not be prepared to wait for lifts [3]. Under what conditions will people wait for the lift? Would people in different countries behave differently? Answers to these questions are essential if engineers are to realistically model building evacuation using lifts and design reliable evacuation systems in which both stairs and lifts are used.

While several studies have postulated human response to the use of lifts during evacuations [4, 5], certain studies have interviewed survivors who used lifts during real evacuations/drill [1, 3, 6] and some studies have conducted surveys [6], there is still a lack of understanding regarding the key factors which influence human behaviour relating to lift/stair selection during evacuations. Indeed whilst past studies have provided insight into such behaviour, most have been narrow in their focus resulting in questionable general applicability, for example, focusing on narrow population age groups (e.g. students, elderly); involving populations with little or no experience of high-rise buildings; drawn from potentially biased populations (e.g. businesses involved in fire engineering), or from a very narrow cultural diversity. Further to this, very little publically accessible data pertaining to human factors associated with normal lift usage is available. Use of lifts for evacuations may be related to experiences and expectations drawn from normal lift usage and so an understanding of human factors associated with normal lift usage is considered important. To address the above issues and attempt to gain a better understanding of human factors associated with lift/stair use during circulation and evacuation scenarios, an online survey (http://fseg.gre.ac.uk/elevator) was developed, asking participants how they would behave with regards to lift/stair usage within a series of hypothetical situations. The use of a publically accessible online survey was intended to reach as wide an international audience as possible coming from a broad variety of different cultural backgrounds.

Survey Description

The survey was made available in two languages English and Chinese. The later was selected as it enabled a specific cultural group, other than English only speakers, to respond to the survey. In addition, in 2009 China possessed six of the world's ten tallest completed buildings and cities such as Shanghai and Beijing have a large number of high-rise residential and office buildings. The survey is split into three parts, the first addresses circulation issues, the second evacuation issues while the third part concerns requests participant demographic information. The survey requires approximately 20 minutes to complete. The first part of the survey explores the influence of travel distance, queues and groups on exit/stair choice. Here participants are requested to state the maximum number of floors they would consider walking on the stairs in a variety of situations. Each situation explored the influence of direction (travelling up/down), familiarity (being familiar/unfamiliar), trip purpose (being in a leisure/business activity) and time pressure (having/not having time pressure). The second part of the survey focused specifically on evacuation usage and informed participants that it was safe to use a lift during the hypothetical evacuation. Participants were then asked a series of questions related to whether they would consider using a lift and, if so, a variety of questions as to some of the influences effecting this selection and the amount of time they would wait for a lift.

Participant Characteristics and Demographics

In total 468 participants either fully or partially completed the survey, of which 424 provided complete main demographic information. Of all participants 60.6% (269) were male and 39.4% (175) were female. Of all participants who provided age data (N=444), the average age was 35.0 years: 44.6% between 18-30 years, 26.6% between 31-40 years, 15.3% between 41-50 years, 9.7% between 51-60 years and 3.8% were over 60 years. Considering participants who provided their occupation (N=449): 18.9% were students, 7.6% were from the fire safety/protection profession and 1.6% came from the lift industry. The remaining 71.9% of participant occupations were either classified as coming from other professions or non-specific (e.g. office worker, staff, assistant etc). Of all the participants, 63.5% confirmed that their place of work/study possessed lifts with these buildings varying from 2 to 78 floors with an average of 10.1 floors, with over half (54.9%) of those buildings being over 5 floors in height. Approximately 15.6% of all participants had at least one lift in their place of residence, varying from 3 to 35 floors with an average of 10.8 floors in height, with approximately three quarters (75.3%) of those buildings being greater than 5 floors in height. Whilst overall participants came from some 23 different countries, six countries made up approximately 88.9% of all participants: UK (30.8%), China (25.9%), US (12.8%), Germany (11.1%), Japan (5.6%), Australia (2.8%). Using the WHO (World Health Organisation) classification of body mass indexing (BMI), of the participants who provided plausible height/weight information (N=445), 6.7% were classed as underweight, 56.4% were normal weight, 24.7% were overweight, 11.0% were obese and just 1.1% were classed as being morbidly obese.

Results - Circulation and Evacuation Usage

Each section within the survey is based around a hypothetical scenario. The core part of the scenario description, unless stated otherwise, is identical for each question and consists of the following information:

- You are familiar with the layout of the building.
- The lifts/stairs are located in the same area.
- You are not carrying or wearing anything to restrict your movement.

- A lift is not currently on your floor and you do not know how long you will have to wait for a lift to return.

Circulation Usage

The first part of the survey, addressing circulation behaviour, explored issues to do with vertical travel distance, queue length in the lift waiting area and group behaviour. Three specific variations of the core scenario were presented to the participants. Additional situational information relating to the nature of these various scenarios is presented in Table 1. Given these specific situations, participants were asked what is the maximum number of floors they would consider travelling on the stairs before electing to use a lift. Participant responses either stated that they always consider using the stairs, never consider using the stairs (always use the lift), or sometimes consider using the stairs (specifying a finite number of floors they would walk on the stairs). Answers to the various questions were further categorised according to: building familiarity, whether or not travel was time critical and whether or not the travel was for leisure or business. While these factors have varying influences upon the responses, due to space limitations these various categories have been collapsed into direction of travel and trip purpose with the average results presented in Table 2.

Table 1. Additional situation information provided for each section.

Base Case	Queues	Groups
You are alone in a lift waiting area on your floor.	There are a number of people in the lift waiting area on your floor.	You are travelling with a group of 2-4 people. The people in the group are all of similar physical ability and fitness to yourself. The lift waiting area on your floor is empty.

In the base case, 87.8% of the participants would always or sometimes consider using the stairs to travel down and 84.2% to travel up. This is rather a high percentage of people who would consider using the stairs, with slightly more participants prepared to travel down the stairs compared to up. On average participants were prepared to walk 2.0 floors further down than up, 6.7 floors down and 4.7 floors up.

When faced with a queue in the lift waiting area, slightly more participants would always or sometimes consider using the stairs compared to the base case, with 89.4% of participants always or sometimes consider using the stairs to travel down (compared with 87.8%) and 87.3% to travel up (compared with 84.2%). This highlights a slight decrease in attractiveness of the lift due to congestion in the waiting area. When faced with a queue, participants were prepared to walk slightly further up/down (mean 5.0/7.0 floors) compared to the base case (mean 4.7/6.7 floors).

When travelling in a small group, slightly fewer participants would consider using the stairs compared to the base case, with 81.0% of participants always or sometimes considering using the stairs to travel down (compared with 87.8%) and 76.4% to travel up (compared with 84.2%). This highlights a decrease in attractiveness of the stair when travelling in groups compared to the queue scenario where an increase was observed. On average participants were prepared to walk 5.3 floors down (median 4.0) and 4.2 floors up (median 3.0). This represents a 20.9% (1.4) and 10.6% (0.5) decrease in the number of floors participants would consider walking on the stairs in the down and up direction respectively compared to the base case. When travelling in groups there is a considerable reduction in the distance people are prepared to travel on stairs.

Table 2. Overall Combined Average Results Irrespective of Time Pressure or Familiarity for the Base, Queue and Groups cases.

		Base Case	Queues	Groups
Up	**Always use lift**	15.8% [592]	12.7% [474]	23.5% [875]
	Always consider using Stairs	3.7% [138]	4.5% [169]	4.3% [161]
	Sometimes consider using Stairs	80.5% [3008]	82.8% [3091]	72.1% [2682]
	Median Stair Travel (floors)	3.8	4.0	3.0
	Mean Stair Travel (floors)	4.7	5.0	4.2
	Total Frequency	3738	3734	3718
Down	**Always use lift**	12.2% [450]	10.6% [392]	19.0% [701]
	Always consider using Stairs	5.6% [208]	7.6% [281]	5.0% [184]
	Sometimes consider using Stairs	82.2% [3036]	81.8% [3027]	76.0% [2799]
	Median Stair Travel (floors)	5.1	5.3	4.0
	Mean Stair Travel (floors)	6.7	7.0	5.3
	Total Frequency	3694	3700	3684

Evacuation Usage

The evacuation section of the survey was intended to investigate whether participants would consider using a lift to evacuate if they were informed that it was acceptable to do so during an emergency, and if so, identify and quantify influencing factors that would cause them to redirect to use the stairs. For the evacuation base scenario the following additional information was provided to the participants:

- You are travelling alone.

- You have been instructed that it is acceptable to use either a lift or stairs to evacuate from your building in emergency situations. During an evacuation you are free to choose to use a lift or stairs.

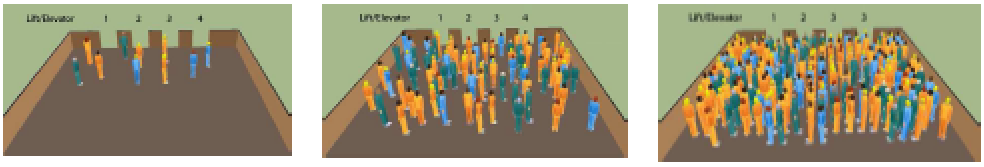
Of the participants who answered whether they would consider using a lift to evacuate (N=467), approximately a third (33.0% (154))) said that they would consider using a lift. Thus, two thirds of the participants would not consider using a lift to evacuate, even though they knew it was acceptable to do so.

Of the participants who would consider using a lift and answered whether or not they would always use a lift (152), a small proportion (7.2% (11)) said that they would always use a lift. Of the 154 participants who would consider using a lift, 78.6% (121) replied that the height of the floor they were on would influence their decision. These participants were then asked to specify a maximum/minimum number of floors above/below which they would not consider using the lift. Of the participants who specified a maximum number of floors they would be prepared to travel by lift (120), 46.7% (56) answered that there was no maximum number of floors, 22.5% (27) answered 100+ floors, and the remaining 30.8% (37) specified a varying number of floors with an average maximum of 21.9 floors. Of the participants who specified a minimum number of floors they would be prepared to travel by lift (121), 9.9% (12) answered that there was no minimum number of floors, 0.83% (1) answered 100+, and the remaining 89.3% (108) specified a varying number of floors with an average minimum of 8.4 floors. When asked if the height of the building would influence their decision to use a lift (N=136), almost two thirds (65.4% (89)) said that the height of the building would influence their decision. Of this group (N=86), 80.2% (69) said that the higher the building the more likely they would be to use a lift.

For the remaining evacuation related questions, the following additional scenario information was provided:

- You are instructed to evacuate from a multi-storey building.
- It is not a drill but you are not in immediate danger.
- You have a choice to use one of the 4 lifts servicing your floor or the stairs.
- Each lift has a capacity of 10 people.
- The lift waiting area on your floor is crowded with people.

Participants were then asked, given that they were located on progressively higher floor ranges in the building, would they consider using a lift to evacuate and if so, after arriving in the lift waiting area, what level of crowd size/density already waiting for the lift would cause them to redirect to use the stairs. To quantify the crowd density, six different crowd densities (ranging from A to F) were presented to the participants based on graphics generated by the vrEXODUS software, three of which are presented in Fig. 1. Participants where then asked for each floor range to specify the crowd density that would deter them from waiting for a lift and to estimate, providing the crowd density was below that stated level, how long they would be prepared to wait in the crowd for a lift before they decided to use the stairs.



A: 10 people, 0.13p/m^2 C: 80 people, 1.0p/m^2 F: 200 people, 2.5p/m^2

Fig. 1. Three of the six Crowd Levels in the lift waiting area.

As with the circulation based questions, answers to the various questions were further categorised according to building familiarity. While there were some differences due to building familiarity, due to space limitations the responses have been collapsed into a single category and the average results are presented here (see Fig. 2 and Table 3).

Table 3. Frequency of participant responses that would consider using a lift as a function of crowd density (familiar and unfamiliar combined).

Floor Range Location	Proportion of participants that would consider waiting to use lift on a given floor range		Of participants that would initially choose to use a lift, the crowd density in the lift waiting area that would cause a proportion of those participants to redirect to use the stairs.								
	Yes	No	#	Doesn't Matter	A 0.13 p/m^2	B 0.5 p/m^2	C 1.0 p/m^2	D 1.5 p/m^2	E 2.0 p/m^2	F 2.5 p/m^2	F+ 2.5 p/m^2+
2-10	11.3% [39]	88.7% [306]	38	15.8% [6]	18.4% [7]	44.7% [17]	73.7% [28]	78.9% [30]	78.9% [30]	84.2% [32]	84.2% [32]
11-20	33.3% [114]	66.7% [228]	114	10.5% [12]	14.0% [16]	31.6% [36]	60.5% [69]	84.2% [96]	86.8% [99]	89.5% [102]	89.5% [102]
21-30	63.5% [216]	36.5% [124]	214	7.0% [15]	5.6% [12]	25.7% [55]	61.7% [132]	82.2% [176]	89.7% [192]	93.0% [199]	93.0% [199]
31-40	77.8% [256]	22.2% [73]	252	9.9% [25]	2.8% [7]	19.0% [48]	49.2% [124]	77.8% [196]	86.9% [219]	90.1% [227]	90.1% [227]
41-50	79.0% [260]	21.0% [69]	254	9.1% [23]	2.8% [7]	14.6% [37]	39.0% [99]	64.2% [163]	83.5% [212]	90.6% [230]	90.9% [231]
51-60	80.5% [265]	19.5% [64]	257	10.5% [27]	3.1% [8]	13.2% [34]	33.5% [86]	56.4% [145]	72.8% [187]	84.8% [218]	89.5% [230]

Presented in Table 3 is the overall proportion of participants that would consider using a lift/stair for each floor range. As the floor height increases the proportion of participants that would consider using the lift also increases. We note that approximately 10% of the population would use a lift even if located on the lowest floors i.e. 2-10. The proportion of the population that would use the lift increases to approximately 80% at floor range 31-40 and remains at this level for the higher floor ranges. This suggests that when located on or above floors 21-30, the majority of people on each floor would elect to use the lift compared to the stairs. Above floor 30, approximately 20% of the population are not prepared to use the lifts to evacuate irrespective of floor height.

In addition, presented within Table 3 is the cumulative proportion of those participants that would choose to redirect to use the stairs based on crowd density within the lift waiting area. We note that of those prepared to wait to use the lift given a crowd in the lift waiting area, an average 10.5% of the population would be prepared to wait for the lift, regardless of floor height or crowd density. Furthermore, the average crowd density that participants would be prepared to tolerate before redirecting to the stairs increases as the floor height increases. For a floor height of 2-10, 70% of the population waiting for the lift would redirect to the stairs when the average congestion levels are between B and C (0.5 p/m^2 and 1.0 p/m^2), while for a floor height of 21-30, this increases to between C and D (1.0 p/m^2 and 1.5 p/m^2) and for a floor height of 51-60, this increases to between D and E (1.5 p/m^2 and 2.0 p/m^2). Participants who would consider using a lift for a given floor range were asked, providing the crowd level did not reach or exceed the density which would cause them to redirect, what was the maximum time they would be prepared to wait to use a lift. For each floor range a small number of participants (0%-7%) stated that they would wait for a lift for "as long as it takes" with an average proportion of 5.8% for all floor ranges. In addition, a small number of participants (6.1% (14)) said that they would not be prepared to wait for a lift, regardless of floor height.

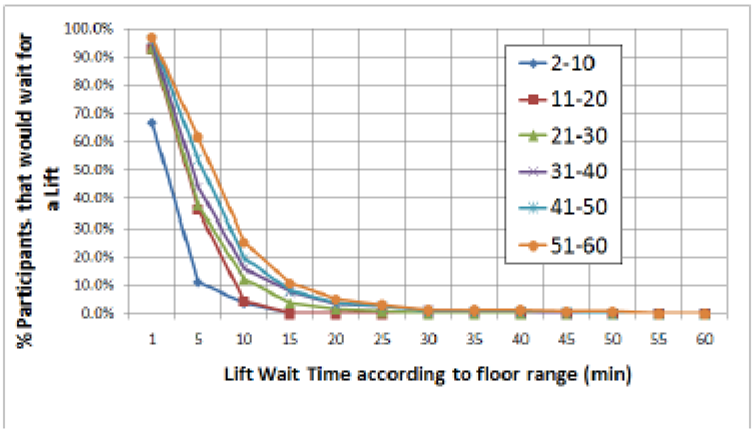


Fig. 2. Cumulative proportion of participants that would wait for a lift (grouped into 5 min intervals) for each floor range.

In Fig. 2 the normalised cumulative frequency distribution of the remaining participants who specified the maximum time they would be prepared to wait for a lift on each floor range can be seen. As the floor height increases the proportion of participants that would wait a longer amount of time in the lift waiting area also approximately increases. This reflects participants increased tolerance to waiting a longer amount of time for a lift on progressively higher floors in light of the added travel time and energy expenditure they would need to expend travelling on the stairs. Fig. 2 also suggests that the majority of participants who initially chose to use a lift in floor range 2-40 would only be prepared to wait between 1-5 minutes for a lift before redirecting to the stairs. For the floor range 40-60 the majority of participants would be prepared to wait between 5-10 minutes. For all floor ranges, approximately less than 10% of participants would be prepared to wait more than 15 minutes for a lift before redirecting to the stairs; highlighting participants intolerance to wait long periods of time for a lift during an evacuation.

Conclusion

This paper has presented an analysis of data collected from participant responses to an online survey in order to gain an understanding of human factors associated with lift/stair selection in both circulation and evacuation scenarios. In normal circulation conditions, between 90%-85% of the survey population would be prepared to use the stairs to travel down/up. On average participants were prepared to walk 6.7/4.2 floors in the down/up direction respectively. Results suggest that a queue in the lift waiting area does not influence these numbers greatly however, travelling in groups does. When travelling is a small group (up to four people), the percentage of the survey population prepared to use the stairs to travel down/up decreases to 80%/76% and the distance they are prepared to walk down/up decreases to 4.8/3.2 floors.

In evacuation conditions, despite being informed that the lifts were a safe and acceptable option, two thirds of the sample (308) said they would not consider using a lift to evacuate. This suggests that if buildings are being designed on the assumption that occupants will utilise lifts for evacuation, an extensive training campaign will be essential. This poses difficulties for buildings that are largely frequented by casual visitors. Of the participants whom would consider using a lift (152), less than 10% said that they would always use a lift, while over 75% (121) said that the height of the floor they were on would influence their decision to use a lift. The height of the building was also a significant factor in determining whether or not they would use the lift. Of the participants who specified a maximum number of floors they would be prepared to travel by lift (120), almost 70% (83) effectively indicated that there was no maximum number of floors while of those specifying a minimum number of floors, almost 90% (108) specified a varying minimum number of floors with an average minimum of 8.4 floors. As the floor height increases the proportion of participants that would consider using the lift increases. Approximately 10% of the population would use a lift even if located below the 10th floor. The proportion of the population that would use the lift increases to approximately 80% up to floor 40 and remains at this level even for higher floors. This suggests that approximately 20% of the population will not use a lift to evacuate irrespective of floor height. A very small proportion of participants stated that they would wait in a lift waiting area regardless of crowd density and/or would wait for "as long as it takes" for a lift to service their floor. However, the majority of participants indicated there was a critical level of crowd density in the lift waiting area which, if reached or exceeded, they would redirect to the stairs. Furthermore, this critical density appears to increase as the floor height increases; reflecting the decreased attractiveness of using the stairs on progressively higher floors. The majority of participants also specified a finite time they would be prepared to wait for a lift; while this was dependent on floor height (the higher the floor, the longer the acceptable wait time), less than 10% of participants were prepared to wait more than 15 minutes regardless of floor height.

These results clearly show that in evacuation situations, building occupants are prepared to utilise lifts for evacuation but that this is strongly dependent on floor height, crowd density and expected lift wait time. Participants in the study clearly exhibit anticipatory behaviour and would expect a given level of service from an lift system during an evacuation. Further analysis of the survey data is currently underway examining the impact of pedestrian characteristics such as age, gender, country, building familiarity etc on both circulation and evacuation behaviours. The data is being used to enhance the agent based model associated with lift usage within the evacuation modelling software buildingEXODUS.

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Fire Technology
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DOI: 10.1007/s10694-010-0176-7

Human Factors Associated with the Selection of Lifts/Elevators or Stairs in Emergency and Normal Usage Conditions

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Received: 6 April 2010/**Accepted:** 7 August 2010

Abstract. This paper presents an overview of human factors data collected via an online survey related to the use of lifts (elevators) and stairs during both circulation and evacuation scenarios. Survey participants were presented with a series of hypothetical situations and asked how they would behave. The survey was split into two broad sections, the first dealing with normal circulation usage of lifts/stairs and the second dealing with evacuation usage of lifts/stairs. Detailed demographic information about each participant was also collected. In total some 468 people from 23 countries completed the survey. An overview of the survey and initial results are presented in this paper.

Keywords: Highrise building evacuation, Human behaviour, Human factors, Evacuation modelling, Survey, Lifts, Elevators

Nomenclature

N	Number of participants that gave a response to a specific question(s) or provided demographic information
y	Proportion people that would consider using a lift
x	Floor number that the people are located on above ground level
p	Probability (that the observed values are different from the expected due to chance)
χ^2	Chi-square value

1. Introduction

In countries such as the UK, Australia, Malaysia, China and USA, lifts are either being used or being considered for use as part of building evacuation systems. In past ad hoc egress situations lifts have been used to good effect to assist in the rapid evacuation of high-rise buildings [1, 2]. In such cases lifts were not intended to form part of the evacuation system but were used by occupants for rapid egress. Computer modelling also suggests that if used correctly, the combined use of lifts and stairs can speed up full building evacuation process by as much as

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Published online: 31 August 2010

50% compared to the use of stairs alone [3]. However, in these modelling examples, due to lack of human factors data, ideal "compliant" occupant behaviour was assumed. This meant that all the agents that were designated to use the lifts waited to use the lifts for as long as required without consideration to the local time evolving conditions. However, how many people would actually consider using a lift rather than the stairs in an emergency? How long would people wait for a lift? How would people react to local conditions? Some evidence suggests that when faced with large queues occupants will not be prepared to wait for lifts, for example, a survivor from the 77th floor of North Tower of the World Trade Center who evacuated on 9/11 said [4]:

> Let me add too that, at the 44th floor there was what they call an inter-zone elevator bank, we were led off the stairwell at the 44th floor and shown to that elevator where there are hundreds of people milling and I looked at that and I turned around to my team and I said 'no, I am not waiting for an elevator in a building on fire. Let's go' and I walked back to the stairwell and they did too and then we proceeded down (WTC1/077/0001 P2, line 22–27)

Under what conditions will people wait for the lift? Would people in different countries behave differently? Answers to these questions are essential if engineers are to understand how lifts are likely to be used in an emergency situation, develop realistic computer models that predict building evacuation using lifts and design reliable evacuation systems in which both stairs and lifts are used.

While several studies have postulated human response to the use of lifts during evacuations [5, 6], certain studies have interviewed survivors who used lifts during real evacuations/drill [1, 4, 7] and some studies have conducted surveys [7], there is still a lack of understanding regarding the key factors which influence human behaviour relating to lift/stair selection during evacuations. Indeed whilst past studies have provided insight into such behaviour, most have been narrow in their focus resulting in questionable general applicability, for example, focusing on narrow population age groups (e.g. students, elderly); involving populations with little or no experience of high-rise buildings; drawn from potentially biased populations (e.g. businesses involved in fire engineering etc), or from a very narrow cultural diversity. Further to this, very little publically accessible data pertaining to human factors associated with normal circulation lift usage is available.

Use of lifts for evacuations may be related to experiences and expectations drawn from normal lift usage and so an understanding of human factors associated with normal lift usage is considered important. To address the above issues and attempt to gain a better understanding of human factors associated with lift/stair use during circulation and evacuation scenarios, an online survey (http://fseg.gre.ac.uk/elevator) was developed (see Appendix A1), asking participants how they would behave with regards to lift/stair usage within a series of hypothetical situations. The use of a publically accessible online survey was intended to reach as wide an international audience as possible coming from a broad variety of different cultural backgrounds.

The call for participation to complete the online survey was undertaken via several different media e.g. website link, leaflet distribution, online forums, email mailing lists, friends/family/colleagues, snow balling, etc. Whilst the survey is currently on line at the time of writing this paper, the results presented represent data collected from approximately July 2008 to July 2009 over a period of one year. Due to the nature of being a publically accessible online survey, the survey was prone to participants perusing through the survey without completing any questions. This occurred approximately 10 times and the respective records were removed from the database. Indeed the potential for abuse in the survey (e.g. people completing the survey with malicious intent) existed. To minimise the potential of this influencing the final analysis, each participant's computer IP address and time stamp were recorded. If an IP addresses occurred multiple times, response were analysed to ascertain whether or not the answers provided appeared malicious. Despite this no records were identified as being malicious. In addition, as the participants completed the survey unsupervised, there was potential for erroneous or incomplete data entry. As a result, not all the frequencies of the replies equals the number of participants and so frequencies of participants who completed each question have been stated.

2. Survey Description

The survey was made available in two languages, English and Chinese (simplified Chinese). The latter was selected as it enabled a specific cultural group, other than English only speakers, to respond to the survey. In addition, in 2009 China possessed six of the worlds ten tallest buildings [8]. Furthermore, cities such as Shanghai and Beijing have a large number of high-rise residential and office buildings. The survey consisted of four sections and required approximately 20 min to complete. The first three sections addressed the influence of travel distance, queues and groups within a circulation setting. Each situation explored the influence of direction (travelling up/down), familiarity (being familiar/unfamiliar), trip purpose (being in a leisure/business activity) and time pressure (having/not having time pressure). In each question participants were requested to state the maximum number of floors they would consider walking on the stairs before redirecting to use the lift. Participants could respond that they would either always use the lift; always consider using the stairs; or state the maximum number of floors that they would consider walking on the stairs before choosing to use a lift.

The fourth section of the survey focused specifically on evacuation usage and informed participants that it was acceptable to use a lift during an evacuation. Participants were then asked a series of questions related to whether they would consider using a lift during an evacuation. If participants were prepared to consider using a lift during an evacuation, initial questions in the section explored the potential effects of a variety of influences upon this selection. The final questions in the section posed a hypothetical evacuation scenario and asked participants whether they would be prepared to wait for a lift on progressively higher floors. Of the participants that would be prepared to wait for a lift for each floor range, they were asked whether the crowd density and wait time in the lift waiting area would cause them to redirect to use the stairs.

3. Participant Characteristics and Demographics

In total 468 participants either fully or partially completed the survey, of which 424 provided complete main demographic information (e.g. gender, age, height and weight). Of all participants 60.6% (269) were male and 39.4% (175) were female. Of all participants who provided age data (N = 444), the average age was 35.0 years: 44.6% between 18 years and 30 years, 26.6% between 31 years and 40 years, 15.3% between 41 years and 50 years, 9.7% between 51 years and 60 years and 3.8% were over 60 years. Considering participants who provided their occupation (N = 449): 18.9% were students, 7.6% were from the fire safety/protection profession and 1.6% came from the lift industry. The remaining 71.9% of participant occupations were either classified as coming from other professions or non-specific (e.g. office worker, staff, assistant etc). Of all the participants, 63.5% confirmed that their place of work/study possessed lifts with these buildings varying from 2 to 78 floors with an average of 10.1 floors, with over half (54.9%) of those buildings being over 5 floors in height. Approximately 15.6% of all participants had at least one lift in their place of residence, varying from 3 to 35 floors with an average of 10.8 floors in height, with approximately three quarters (75.3%) of those buildings being greater than 5 floors in height. Whilst overall participants came from some 23 different countries, six countries made up approximately 88.9% of all participants: UK (30.8%), China (25.9%), US (12.8%), Germany (11.1%), Japan (5.6%), Australia (2.8%). Using the WHO (World Health Organisation) classification of body mass indexing (BMI), of the participants who provided plausible height/weight information (N = 445), 6.7% were classed as underweight, 56.4% were normal weight, 24.7% were overweight, 11.0% were obese and just 1.1% were classed as being morbidly obese.

The data collected represents participants from a wide variety of different age ranges, physical levels of fitness, countries, occupation types and levels of lift usage familiarity. With such a diverse sample of participants it is hoped the general applicability of the results is increased.

4. Results—Circulation and Evacuation Usage

Each section within the survey is based around a hypothetical scenario. The core part of the scenario description, unless otherwise stated, is identical for each question and consists of the following information:

- You are familiar with the layout of the building.
- The lifts/stairs are located in the same area.
- You are not carrying or wearing anything to restrict your movement.
- A lift is not currently on your floor and you do not know how long you will have to wait for a lift to return.

4.1. Circulation Usage

The first part of the survey, addressing circulation behaviour, explored issues to do with vertical travel distance, queue length in the lift waiting area and group behaviour. Three specific variations of the core scenario were presented to the participants. Additional situational information relating to the nature of these various scenarios is presented in Table 1. Given these specific situations, participants were asked what is the maximum number of floors they would consider travelling on the stairs before electing to use a lift. Participant responses either stated that they always consider using the stairs, never consider using the stairs (always use the lift), or sometimes consider using the stairs (specifying a finite number of floors they would walk on the stairs). Answers to the various questions were further categorised according to: building familiarity, whether or not travel was time critical and whether or not the travel was for leisure or business. While these factors have varying influences upon the responses, due to space limitations the response frequencies and average number of floors for the familiarity and trip purpose categories have been combined (and hence the number of replies is greater than the sample size of 468). These overall frequencies and average number of floors according to the direction of travel and scenario categories are presented in Table 2.

For all data collected regarding the number of floors participants that were prepared to walk on the stairs for each circulation situation, from both a visual analysis and from using a Kolmogorov–Sminov test, none of the participant frequency distributions for each situation fitted a normal curve (even when using a log transformation). Almost all of the frequency distributions followed a skewed distribution to the left with a number of outliers typically around multiples of five (participants typically tended towards these round numbers when specifying higher numbers of floors).

It has been stated in a number of psychological studies that "people's ability to discriminate change in a physical stimulus diminishes as the magnitude of the stimulus increases" [9]. Applying this to the survey question as to the maximum number of floors a person would consider walking on the stairs, it is postulated that those participants who stated that they would consider walking a maximum of more than 50 floors would be inaccurate due to participants inability to conceptualise such a large number of floors. As such those responses have been removed from the results. Due to the low number of participant responses

Table 1
Additional Situation Information Provided for Each Section

Base case	Queues	Groups
You are alone in a lift waiting area on your floor	There are a number of people in the lift waiting area on your floor	You are travelling with a group of 2 to 4 people. The people in the group are all of similar physical ability and fitness to yourself. The lift waiting area on your floor is empty

Table 2
Overall Combined Average Results Irrespective of Time Pressure or Familiarity for the Base, Queue and Groups Cases

	Base case	Queues	Groups
Up			
Always use lift	15.8% [592]	12.7% [474]	23.5% [875]
Always consider using stairs	3.7% [138]	4.5% [169]	4.3% [161]
Sometimes consider using stairs	80.5% [3008]	82.8% [3091]	72.1% [2682]
Median stair travel (floors)	3.8	4.0	3.0
Mean stair travel (floors)	4.7	5.0	4.2
Total frequency	3738	3734	3718
Down			
Always use lift	12.2% [450]	10.6% [392]	19.0% [701]
Always consider using stairs	5.6% [208]	7.6% [281]	5.0% [184]
Sometimes consider using stairs	82.2% [3036]	81.8% [3027]	76.0% [2799]
Median stair travel (floors)	5.1	5.3	4.0
Mean stair travel (floors)	6.7	7.0	5.3
Total frequency	3694	3700	3684

specifying greater than 50 floors (ranging between 0 and 8 for each question) the influence upon the results is minimal. Due to each frequency distribution not fitting a normal curve, the non-parametric Wilcoxon signed-rank test has been used to compare participants paired answers (who would sometimes consider using the stairs) in each circulation situation using a 95% confidence interval.

4.1.1. Base Case. In the base case, 87.8% of the participants would always or sometimes consider using the stairs to travel down and 84.2% to travel up. Somewhat surprisingly, this is rather a high percentage of people who would consider using the stairs, with slightly more participants prepared to travel down the stairs compared to up. Of the participants that would sometimes consider walking on the stairs, on average these participants would walk 42.6% (2 floors) further in the down direction than in the up direction. Significantly more participant responses (67.4% (1928), $p < 0.05$) stated they would walk further on the stairs in the down direction compared to the up direction. It should also be kept in mind however, that 26.6% (761) of participant responses stated they would not change the number of floors they would consider walking on the stairs regardless of travelling in the up or down direction. In addition, 5.9% (170) of participant responses actually stated they would consider walking further on the stairs in the up direction compared to the down direction. This highlights that whilst a significant number of participants were recorded as being prepared to walk further in the down direction than in the up direction, this should not be assumed to apply to all participants with approximately 1 in 3 of participant responses stating alternate behaviour.

4.1.2. Queues. When faced with a queue in the lift waiting area, slightly more participants would always or sometimes consider using the stairs compared to the base case, with 89.4% of participants always or sometimes consider using the stairs to travel down (compared with 87.8%) and 87.3% to travel up (compared with 84.2%). This represents a slight decrease in attractiveness of the lift due to the queue in the lift waiting area. When faced with a queue, of the participants that would sometimes consider walking on the stairs, on average these participants were prepared to walk 6.4% (0.3 floors) and 4.5% (0.3 floors) further in the up and down direction respectively compared with the base case (i.e. no queue in the lift area). Thus, irrespective of direction of travel, a significant number of participant responses stated they would walk further on the stairs if a queue was present in the lift waiting area than if there was not (32.1% (1826)), $p < 0.05$). It should also be kept in mind however, almost a half (49.5% (2813)) of participant responses, which would sometimes consider using the stairs, stated that they would not change the number of floors they would consider walking on the stairs regardless of there being a queue in the lift waiting area. In addition, 18.4% (1044) of participant responses actually stated they would consider walking fewer floors if there was a queue in the lift waiting area.

4.1.3. Groups. When travelling in a small group, slightly fewer participants would consider using the stairs compared to the base case, with 81.0% of participants always or sometimes considering using the stairs to travel down (compared with 87.8%) and 76.4% to travel up (compared with 84.2%). This highlights a decrease in attractiveness of the stair when travelling in groups compared to the queue scenario where an increase was observed. On average participants were prepared to walk 5.3 floors down and 4.2 floors up. This represents a 20.9% (1.4 floors) and 10.6% (0.5 floors) decrease in the number of floors participants would consider walking on the stairs in the down and up direction respectively compared to the base case. Irrespective of direction of travel, a significant number of participant responses stated they would walk further on the stairs if travelling alone than when travelling in a small group (51.5% (2612), $p < 0.05$). It should also be kept in mind however, that 30.2% (1531) of participant responses stated they would not change the number of floors they would consider walking on the stairs regardless of being in a group. In addition, 18.4% (932) of participant responses actually stated they would consider walking more floors on the stairs if travelling within a small group.

As participants were requested to specify the maximum number of floors they would consider travelling on the stairs in each question, it is possible to determine the minimum proportion of expected lift users for a given travel distance (see Figure 1). It can be seen that irrespective of the direction of travel or scenario, the majority of participants would not be prepared to walk greater than 5 to 7 floors on the stairs. Whilst some differences can be seen between each scenario/direction, the curves begin to converge when the travel distance begins to exceed 10 floors and this reflects the small number of participants that are prepared to walk greater than this distance on the stairs. Indeed almost all participants that would sometimes consider using a lift/stairs would elect to use a lift if required to travel greater than 20 floors.

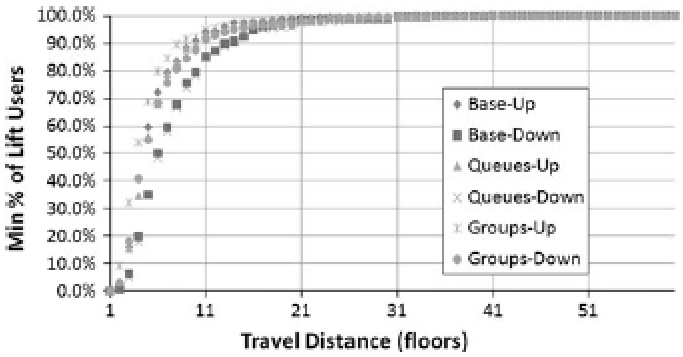

Figure 1. Minimum proportion of lift users for a given travel distance (number of floors) in the up and down direction for the three scenarios.

4.2. Evacuation Usage

The evacuation section of the survey was intended to investigate whether participants would consider using a lift to evacuate if they had been informed that the lifts were considered safe to use in the event of an emergency evacuation. Furthermore, of those who indicated that they would be prepared to use the lift to evacuate, the survey attempted to identify and quantify the influencing factors that would cause this group to redirect to use the stairs. For the evacuation base scenario the following additional information was provided to the participants:

- You are travelling alone.
- You have been instructed that it is acceptable to use either a lift or stairs to evacuate from your building in emergency situations. During an evacuation you are free to choose to use a lift or stairs.

Of the participants who answered whether they would consider using a lift to evacuate (N = 467), approximately a third (33.0% (154)) said that they would consider using a lift. Thus, two thirds of the participants would not consider using a lift to evacuate, even though they knew it was acceptable to do so. Thus a surprisingly large number of people would not consider using the lift in an emergency even if they were informed that it was safe to do so. This large number suggests that it may not be a simple matter to convince people to utilise lifts for emergency evacuations, even if the building design is reliant on this assumption. Responses to this question have been further broken down according to participant demographic sub-groups (see Figure 2) including Gender, Age, Country (top four countries according to frequency of participants) and Body Mass Index (BMI). With regards to gender, males participants were 8.4% more likely than females to consider using a lift during an evacuation, though this does not represent a significant difference (χ^2 = 3.6, $p > 0.05$). Participants aged over 40 years old were 18.6% more likely to consider using a lift than those aged 40 years old or below, again though this does not represent a significant difference (χ^2 = 3.4, $p > 0.05$).

Approximately 1 in 2 participants (52.5%) from the US and 1 in 3 participants (36.5%) from Germany would consider using a lift during an evacuation. These decrease for participants coming from both the UK (approx. 1 in 4 (26.4%)) and China (approx. 1 in 5 (21.5%)). Comparing all countries shows there to be a significant difference between the frequency of participants that would consider using a lift during an evacuation ($\chi^2 = 20.3$, $p < 0.05$).

As participants BMI increases, the proportion of participants from each BMI group that would consider using a lift to evacuate also increases. This suggests that a person's physical condition and fitness also have an influence on their decision to consider using a lift to evacuate, with those people who are overweight or obese having a higher chance of considering using lifts during an evacuation than those that are either under or normal in weight. Despite this, no significant difference between each BMI group and the proportion of participant that would consider using a lift was recorded ($\chi^2 = 4.93$, $p > 0.05$).

Of the participants who would consider using a lift and answered whether or not they would always use a lift (152), a small proportion (7.2% (11)) said that they would always use a lift. Of the 154 participants who would consider using a lift, 78.6% (121) replied that the height of the floor they were on would influence

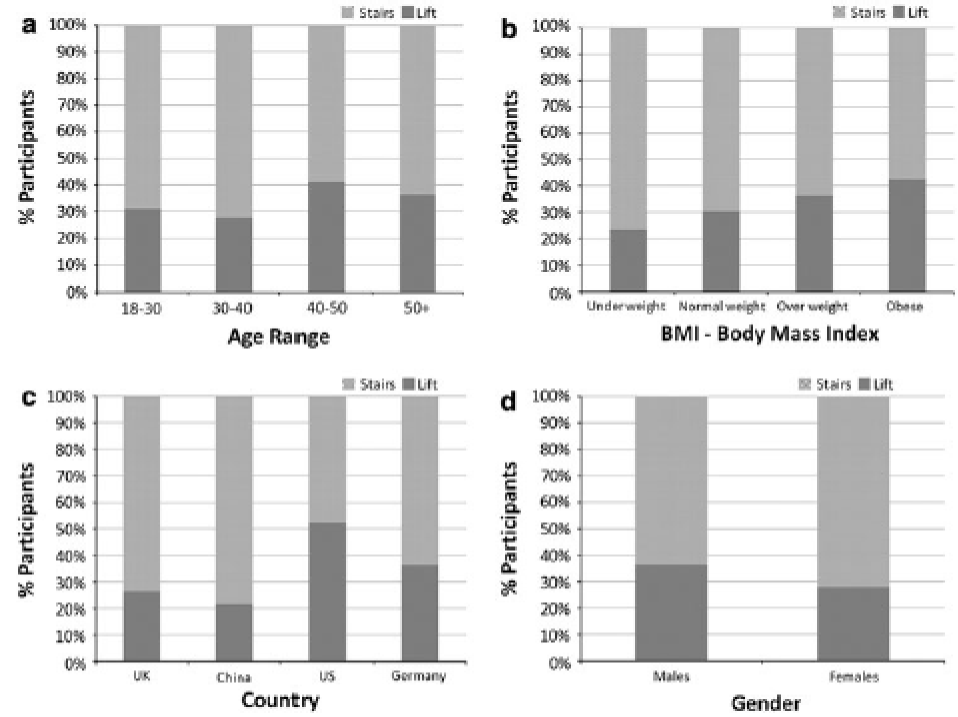

Figure 2. Proportion of lift/stairs users that provided respective demographic details and answered whether they would consider using the lift/stairs during an evacuation.

their decision. These participants were then asked to specify a maximum/minimum number of floors above/below which they would/would not consider using the lift. Of the participants who specified a maximum number of floors they would be prepared to travel by lift (120), 46.7% (56) answered that there was no maximum number of floors, 22.5% (27) answered 100+ floors, and the remaining 30.8% (37) specified a varying number of floors with an average maximum of 21.9 floors. This suggests that of participants which would consider using a lift during an evacuation, almost a third have reservations about travelling for long distances in a lift. This highlights that even people who would elect to use a lift during an evacuation may still have concerns with regards to lift usage.

Of the participants who specified a minimum number of floors they would be prepared to travel by lift (121), 9.9% (12) answered that there was no minimum number of floors, 0.83% (1) answered 100+, and the remaining 89.3% (108) specified a finite number of floors with an average minimum of 8.4 floors. These results suggest that of participants which would consider using a lift during an evacuation, a large majority would on average prefer to use the stairs to travel short distances (i.e. less than 8 floors) than use a lift.

When asked if the height of the building would influence their decision to use a lift (N = 136), almost two thirds (65.4% (89)) said that the height of the building would influence their decision. Of this group (N = 86), 80.2% (69) said that the higher the building the more likely they would be to use a lift. The most common reasons cited by these participants for their response was to save travel time (40.3%), reasons of safety (5.2%) or both (13.0%).

For the remaining evacuation related questions, the following additional scenario information was provided:

- You are instructed to evacuate from a multi-storey building.
- It is not a drill but you are not in immediate danger.
- You have a choice to use one of the 4 lifts servicing your floor or the stairs.
- Each lift has a capacity of 10 people.
- The lift waiting area on your floor is crowded with people.

Participants were then asked, given that they were located on progressively higher floor ranges in the building, would they consider waiting to use a lift to evacuate and if so, after arriving in the lift waiting area, what level of crowd size/density already waiting for the lift would cause them to redirect to use the stairs. To help quantify the crowd size/density, six different crowd sizes/densities (ranging from A to F) were presented to the participants based on graphics (see Figure 3) generated by the EXODUS evacuation simulation software [3, 10]. Participants where then asked for each floor range to specify the crowd size/density that would deter them from waiting for a lift. Participants could either answer that the crowd size/density would not matter or specify a crowd size/density based on the selected graphic. Providing the crowd in the lift waiting area did not reach or exceed the participants stated level, participants were required to estimate how long they would be prepared to wait in the crowd for a lift before they decided to use the stairs.

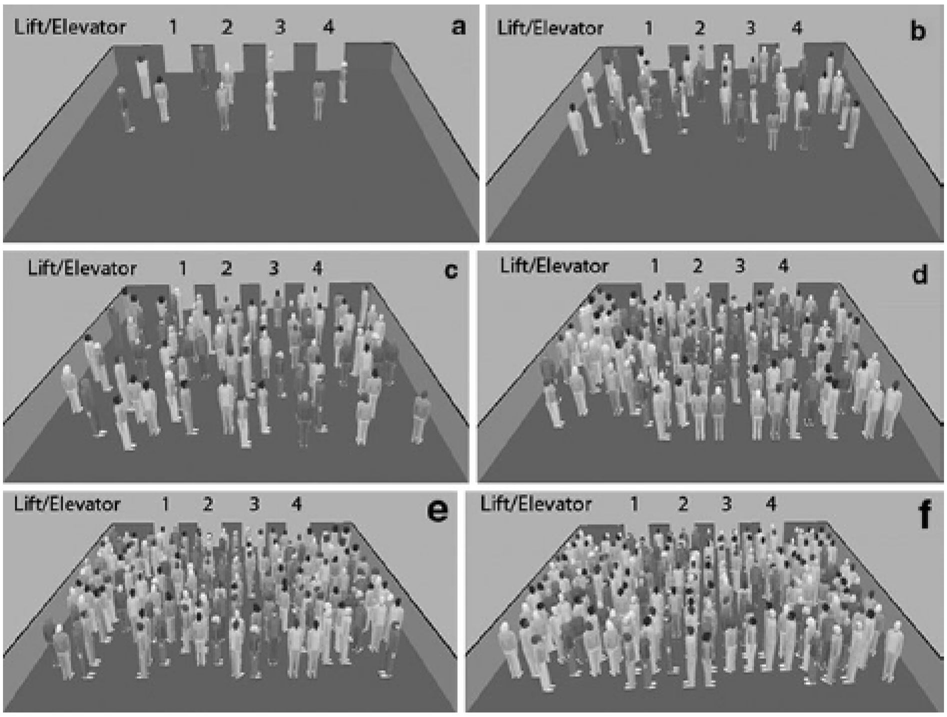

Figure 3. The six crowd levels in the lift waiting area.

Presented in Figure 4 is the overall proportion of participants that would consider using a lift/stair for each floor range. As the floor height increases the proportion of participants that would consider using the lift also increases. We note that approximately 10% of the population would use a lift even if located on the lowest floors i.e. 2 to 10. The proportion of the population that would use the lift increases to approximately 80% at floor range 31 to 40 and remains at this level for the higher floor ranges. In addition, the results suggests that when located on or above floors 21 to 30, the majority of people on each floor would elect to use the lift compared to the stairs. Above floor 30, approximately 20% of the population are not prepared to use the lifts to evacuate irrespective of floor height.

In Figure 5, the mid-points of each floor range (e.g. 5, 15, 25 etc.) with the respective proportion of participants that would consider using lifts during the evacuation has been plotted. Using regression analysis, the relationship between the floor number and percentage of participants shows the following formula to approximate the data:

$$y = 0.3207 \ln(x) - 0.4403 \quad \text{for} \quad 5 \leq x \leq 55$$

where 'y' equals the proportion people that would consider using a lift and 'x' represents the floor number that the people are initially located on above ground

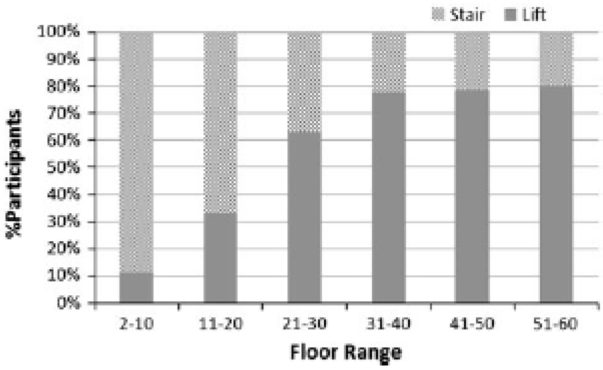

Figure 4. Proportion of participants that would consider using a lift/stair for each floor range.

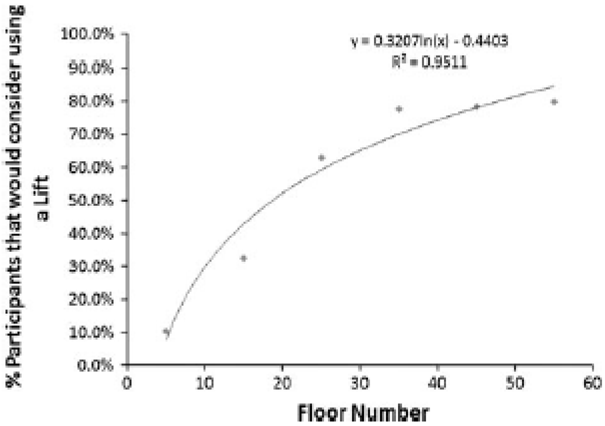

Figure 5. Proportion of participants that would consider using a lift according to floor number.

level. An R^2 goodness of fit value of 0.95 was obtained from this formula which suggests it to be a good predictor according to the data collected. It should be highlighted that this formula is only applicable between floor ranges 5 and 55 (the lower and upper mid points of the floor ranges).

Within Table 3 the proportion/frequency of participants that would consider using a lift to evacuate on each floor range along with the cumulative proportion/frequency of those participants that would consider using a lift who would choose to redirect to use the stairs if they encountered a crowd of a given level of congestion in a lift waiting area can be seen.

As the floor height increases, the proportion of participants that would wait within a crowd of a higher density also approximately increases with the majority of participants that would consider using a lift, irrespective of floor range, redirecting to the stairs after a congestion level of 1.5 p/m^2 being reached in the lift

Table 3
Frequency of Participant Responses that Would Consider Using a Lift as a Function of Crowd Density (Familiar and Unfamiliar Combined)

	Proportion of participants that would consider waiting to use lift on a given floor range		Of participants that would initially choose to use a lift, the crowd density in the lift waiting area that would cause a proportion of those participants to redirect to use the stairs								
Floor range location	Yes	No	#	Doesn't matter	A 0.13 p/m²	B 0.5 p/m²	C 1.0 p/m²	D 1.5 p/m²	E 2.0 p/m²	F 2.5 p/m²	F+ 2.5 p/m²+
2 to 10	11.3% [39]	88.7% [306]	38	15.8% [6]	18.4% [7]	44.7% [17]	73.7% [28]	78.9% [30]	78.9% [30]	84.2% [32]	84.2% [32]
11 to 20	33.3% [114]	66.7% [228]	114	10.5% [12]	14.0% [16]	31.6% [36]	60.5% [69]	84.2% [96]	86.8% [99]	89.5% [102]	89.5% [102]
21 to 30	63.5% [216]	36.5% [124]	214	7.0% [15]	5.6% [12]	25.7% [55]	61.7% [132]	82.2% [176]	89.7% [192]	93.0% [199]	93.0% [199]
31 to 40	77.8% [256]	22.2% [73]	252	9.9% [25]	2.8% [7]	19.0% [48]	49.2% [124]	77.8% [196]	86.9% [219]	90.1% [227]	90.1% [227]
41 to 50	79.0% [260]	21.0% [69]	254	9.1% [23]	2.8% [7]	14.6% [37]	39.0% [99]	64.2% [163]	83.5% [212]	90.6% [230]	90.9% [231]
51 to 60	80.5% [265]	19.5% [64]	257	10.5% [27]	3.1% [8]	13.2% [34]	33.5% [86]	56.4% [145]	72.8% [187]	84.8% [218]	89.5% [230]

waiting area. At congestion level E to F (2.0 p/m^2 to 2.5 p/m^2) the proportion of participants that would redirect to the stairs begins to plateau which is due to very few participants being prepared to wait in a crowd of such a high density. Little variation can be seen in the proportion of participants which would always wait for a lift for each given floor range regardless of the congestion level, ranging between 7.1% and 14.3%, representing a small proportion of all participants that would consider using a lift.

For floor range 2 to 10, 70% of the population waiting for the lift would redirect to the stairs when the average congestion levels are between B and C (0.5 p/m^2 and 1.0 p/m^2), while for a floor range of 21 to 30, this increases to between C and D (1.0 p/m^2 and 1.5 p/m^2) and for a floor range of 51 to 60, this increases to between D and E (1.5 p/m^2 and 2.0 p/m^2). Participants who would consider using a lift for a given floor range were asked, providing the crowd level did not reach or exceed the density which would cause them to redirect, what was the maximum time they would be prepared to wait to use a lift. For each floor range a small number of participants (0% to 7%) stated that they would wait for a lift for ''as long as it takes'' with an average proportion of 5.8% for all floor ranges. In addition, a small number of participants (6.1% (14)) said that they would not be prepared to wait for a lift, regardless of floor height.

In Figure 6 the normalised cumulative frequency distribution of the participants who specified the maximum time they would be prepared to wait for a lift on each floor range can be seen. As lift wait time increases the proportion of participants that would be prepared to wait for a lift decreases exponentially. However, as the floor height increases the proportion of participants that would wait a longer amount of time in the lift waiting area also generally increases (see Figure 6). This reflects participants increased tolerance to waiting a longer amount of time for a lift on progressively higher floors in light of the added travel time and energy expenditure they would need in travelling on the stairs. The majority of participants who initially chose to use a lift on floor range 2 to 40 would only be

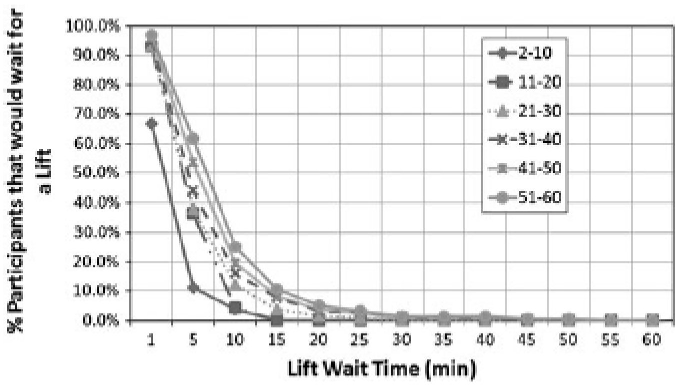

Figure 6. Cumulative proportion of participants that would wait for a lift as a function of wait time (grouped into 5 min intervals) for each floor range.

prepared to wait between 1 and 5 min for a lift before redirecting to the stairs. For floor range 40 to 60 the majority of participants would be prepared to wait between 5 and 10 min. For all floor ranges, less than approximately 10% of participants are prepared to wait more than 15 min for a lift before redirecting to the stairs; highlighting participants intolerance to waiting long periods of time for a lift during an evacuation.

5. Limitations of the Survey

There are number of inherent limitations with any online survey, in particular those posing hypothetical situations and asking participants to quantify their behaviour. Such issues include:

- *Anchoring* As previously mentioned, it has been stated in a number of psychological studies that "people's ability to discriminate change in a physical stimulus diminishes as the magnitude of the stimulus increases" [9]. Thus, in this survey, questions in which the participants may provide responses representing a large number of floors or a long period of time may be considered less reliable. Indeed this is reflected in the data where participants who said that they would consider walking further than 10 floors on the stairs tended to anchor towards multiples of 5 when answering such questions in the circulation section.
- *Conceptualisation* In the survey participants are required to predict their decision making process using hypothetical situations. This gives rise to the question as to whether their responses would reflect what they would do in the actual situation i.e. relying on participants ability to accurately predict their own behaviour, and accurately discriminate between different influences. The more complicated a given hypothetical scenario the higher the probability that participant responses will become inconsistent with what they would actually do due to their inability to accurately conceptualise the influencing factors. It may also be conjectured that people make such decisions posed in the survey subconsciously and that asking participants to consciously make such decisions could potentially influence their answers.
- *Unsupervised* Since participants performing the survey were not supervised, this gives rise to the potential for participants misreading, misunderstanding or erroneous answering questions.
- *Survey fatigue* Since participants were unsupervised and the survey could take up to 20 min to complete, some participants may become tired of doing the survey/questions part-way through and begin to give any answer in order to answer as few questions as possible and complete the survey as quickly as possible.
- *Other influencing factors* The hypothetical situations presented within the survey were intended to present each participant with as simple situation with as little information to process in order to more accurately record the potential influence of different factors. There may be a variety of other influencing factors and

varying degrees with which these influence each other which were not captured/tested within the study.

Such survey limitations should be considered when interpreting or applying the results in other contexts. Ideally, the questions posed in this study would be examined in unannounced egress trials. However, this would require that the trials were conducted in buildings in which a lift evacuation system was already in place. This however has the disadvantage of studying a problem which has already been cast in concrete and steel, potentially a difficult problem to correct.

6. Conclusion

This paper has presented an analysis of data collected from participant responses to an online survey in order to gain an understanding of human factors associated with lift/stair selection in both circulation and evacuation scenarios. In normal circulation conditions, between 90% and 85% of the survey population would be prepared to use the stairs to travel down/up. On average participants were prepared to walk 6.7/4.2 floors in the down/up direction, respectively. These results suggest that a surprisingly large number of people are prepared to use the stairs in normal circulation conditions for relatively short journeys, especially in the up direction. Results suggest that a queue in the lift waiting area does not influence these numbers greatly however, travelling in groups does. When travelling in a small group (up to four people), the percentage of the survey population prepared to use the stairs to travel down/up decreases to 80%/76% and the distance they are prepared to walk down/up decreases to 4.8/3.2 floors.

In evacuation conditions, despite being informed that the lifts were a safe and acceptable option, two thirds of the sample (308) said they would not consider using a lift to evacuate. This suggests that caution must be taken when designing evacuation systems for buildings that utilise lifts. It is all too easy to assume that everyone or even the majority of people will utilise the lifts for evacuation if offered the opportunity. It is suggested that simply providing signage that indicates it is safe to utilise the lift in an evacuation will not be sufficient to convince occupants to use the lifts for evacuation. At the very least, an extensive training campaign will be essential to convince occupants that it is safe to utilise the lifts. Even this approach poses difficulties for buildings that are largely frequented by casual visitors.

Segregating the responses according to demographic information showed there to be no statistically significant difference between the number of participants that would consider using a lift during an evacuation according to age, gender, and BMI demographic sub-groups. However, a significant difference was noted between the number of participants that would consider using a lift during an evacuation according to country; with almost twice the proportion of US participants (approx. 1 in 2 (52.5%)) considering using a lift during evacuation compared to the proportion of Chinese participants (approx. 1 in 5 (21.5%)). This suggests that there are potentially cultural differences with regards to the acceptance of using lifts during evacuations.

Of the participants whom would consider using a lift (152), less than 10% said that they would always use a lift, while over 75% (121) said that the height of the floor they were on would influence their decision to use a lift. The height of the building was also a significant factor in determining whether or not they would use the lift. Of the participants who specified a maximum number of floors they would be prepared to travel by lift (120), almost 70% (83) effectively indicated that there was no maximum number of floors while of those specifying a minimum number of floors, almost 90% (108) specified a varying minimum number of floors with an average minimum of 8.4 floors. As the floor height increases the proportion of participants that would consider using the lift increases. Approximately 10% of the population would use a lift even if located below the 10th floor. The proportion of the population that would use the lift increases to approximately 80% up to floor 40 and remains at this level even for higher floors. This suggests that approximately 20% of the population will not use a lift to evacuate irrespective of floor height. A very small proportion of participants stated that they would wait in a lift waiting area regardless of crowd density and/or would wait for "as long as it takes" for a lift to service their floor. However, the majority of participants indicated there was a critical level of crowd density in the lift waiting area which, if reached or exceeded, they would redirect to the stairs. Furthermore, this critical density appears to increase as the floor height increases; reflecting the decreased attractiveness of using the stairs on progressively higher floors. The majority of participants also specified a finite time they would be prepared to wait for a lift; while this was dependent on floor height (the higher the floor, the longer the acceptable wait time), less than 10% of participants were prepared to wait more than 15 minutes regardless of floor height.

These results clearly show that in evacuation situations, building occupants are prepared to utilise lifts for evacuation but that this is strongly dependent on floor height, crowd density and expected lift wait time. The results suggest that people adapt their behaviour according to changing local conditions. It is essential that such behaviour is represented within evacuation simulation models if representative and meaningful predictions of lift evacuation are to be achieved. The human behaviour data generated from this study is being used to enhance the agent lift/stair behaviour model implemented within the buildingEXODUS evacuation model. The software will then be used to re-examine the ideal lift evacuation strategies presented in an earlier paper [3].

Finally, participants in the study clearly exhibit anticipatory behaviour associated with waiting for lifts and would expect a given level of service from a lift system during an evacuation. Such expectations should be considered when attempting to develop efficient lift evacuation operational strategies. Further analysis of the survey data is currently underway examining the impact of pedestrian characteristics such as age, gender, country, BMI etc in evacuation behaviours.

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FIRE AND MATERIALS
Fire Mater. (2011)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/fam.1086

Investigating evacuation lift dispatch strategies using computer modelling

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SUMMARY

This paper presents a detailed description of an agent-based lift (elevator) model developed within buildingEXODUS software intended to represent evacuation scenarios. The main components of the lift model are described including the lift: kinematics, attributes and dispatch control. The agent–lift interaction model is also described, including the lift bank selection, the lift waiting area behaviour (wait location selection and wait duration) and the lift car selection and entry. The lift model is used to investigate a series of full building evacuation scenarios based on a hypothetical 50 floor building with four staircases and a population of 7840 agents. The analysis explores the relative merits of using up to 32 lifts (arranged in four banks) and various egress lift dispatch strategies to evacuate the entire building population. Findings from the investigation suggest that the most efficient evacuation strategy utilizes a combination of lifts and stairs to empty the building and clear the upper half of the building in minimum time. Combined stair lift evacuation times have been shown to be as much as 50% faster than stair only evacuation times. The introduction of the agent milling behaviour resulted in reductions in evacuation times compared with the same scenarios without milling behaviour. Copyright © 2011 John Wiley & Sons, Ltd.

Received 27 September 2010; Revised 19 January 2011; Accepted 25 January 2011

KEY WORDS: evacuation; simulation; lifts; elevators; high-rise building

1. INTRODUCTION

Since the wide-scale adoption of sprinkler systems in high-rise buildings, there has been an expectation that there would rarely, if ever, be a need to undertake full building evacuations. As a result, until the last decade, there has been little appetite to seriously explore the use of lift systems for evacuation. Since the September 11 World Trade Centre attack, there has been an increased interest in the possible use of lifts for evacuation of high-rise buildings [1, 2]. Such events have also highlighted the need for high-rise buildings to be able to accommodate full scale simultaneous evacuations and not simply cater for a defend in place strategy whereby only select floors/areas are evacuated or phased evacuations whereby floors are progressively evacuated in a given sequence. Furthermore, recent computer simulations of high-rise building evacuation suggest that there is a critical floor population density for a given staircase capacity, which effectively limits the height of high-rise buildings that can be practically evacuated by stairs alone [3]. As a result, it is necessary to explore alternate means of evacuation, such as the use of lifts for high towers catering for large building populations.

Whilst fire protected lifts are considered a viable means for fire fighting services to gain access to upper floors and also assist in the evacuation of disabled occupants in a number of national

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building codes/guidelines, most have yet to accept fire protected lifts as a viable means for the general population to evacuate during a fire. However, recently a number of guidance and regulatory bodies have begun to include the provision for the use of lifts during evacuation for the general population. This includes the 2009 International Building Code (IBC) and the NFPA 101 Life Safety Code 2009, which stipulate that lifts that meet a prescribed level of fire safety can be used to evacuate the general population prior to Phase 1 Emergency Recall (i.e. before smoke is detected in a lift lobby, lift machine room or shaft) [4, 5]. Considering the added egress capacity lift banks could provide a building population during an evacuation compared to using only stairs it is somewhat surprising that lifts have been ignored for so long. However, the key factor with most building codes for not allowing the use of lifts during an evacuation is the potential lack of safety and reliability afforded by such devices during a fire. The NFPA 101 Code for Safety to Life from Fire in Buildings and Structures in 1976 [6] identified a number of concerns, such as possible malfunction of lifts during a fire related evacuation, exposure of a waiting population to fire hazards and jamming of lift doors due to the pressure of large waiting crowds. Further to this, a number of authors [7–9] have stated potential technical problems with regard to using lifts during an evacuation, which include power failure, overheating/short-circuiting of electrical equipment with serious consequences, such as entrapment, smoke inhalation and doors opening on fire floors.

Despite there being a number of incidents in the last 40 years in which people have either died [10, 11] or were trapped [10, 12] inside lifts during hazardous situations, a number of technological solutions to address these issues have been suggested thereby making lift systems more resilient [11, 13]. Indeed there have been incidents in the last 40 years in which lifts have successfully been used to evacuate large populations of people in high-rise buildings. Such incidents include the Joelma building fire in Brazil of 1974 where some 300 of the 422 survivors evacuated using lifts [11], the Hiroshima Motomachi fire in Japan of 1996 where in excess of 50% of the building occupants safely used lifts either in part or for the entire vertical evacuation [11, 14], and the Forest Laneway Fire in Canada of 1995 where some 162 (74%) survivors surveyed used the lift to evacuate [15]. In addition, there are a number of high-rise buildings throughout the world, which currently allow lifts to be used during both fire/non-fire evacuations for the general population, e.g. Burj Khalifa (UAE), Shanghai World Financial Center (China), Petronas Towers (Malaysia), Tapei 101 (China), Stratosphere tower (US), Canary Wharf site (UK), Eureka Tower (Australia), etc. Further to this, lifts are the most common used form of ingress in most high-rise buildings and as such are far more familiar to building occupants than egress stairs, which typically do not form part of normal circulation routes. Using familiar ingress routes during an evacuation has the potential to reduce confusion and is further supporting evidence to use lifts within high-rise evacuations [14].

The renewed interest in using lifts for building evacuation is now beginning to focus beyond the strictly mechanical aspects of lift capabilities in emergency conditions to operational issues and human factor issues. The operational questions concern strategies to optimize full building evacuation. For example, should lift usage be restricted to use by the disabled, if used by the full building population should normal downward peak dispatching algorithms be used or should some kind of shuttling procedure be developed? Should part of the building be expected to use stairs while other parts use lifts? The human factors issues concern how individuals/groups of people would behave on and around lifts during an evacuation. Would for example people consider using lifts during a fire given that they have traditionally been taught to not use them? Would people be prepared to wait for lifts during a full building evacuation? How many people would consider taking the stairs, how does this depend on factors such as crowd densities in the lift waiting area, location of waiting floor and position relative to the incident, and how would this impact the building evacuation? The human factor issues can be explored through studying past incidents where lifts were used, e.g. the WTC, through experimentation (evacuation trials) and through surveys/questionnaires techniques [16, 17]. The operational questions may be addressed using computer evacuation simulation. Clearly, the two are linked as the human factors issues will influence the efficiency of operational strategies; however, it is useful to understand the impact of

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DOI: 10.1002/fam

the proposed operational strategies in an environment where building occupants are expected to behave in an 'ideal' way.

The first published accounts of simulating lifts for evacuation were in the 1970s when Bazjanac developed a computer simulation tool to conduct both partial and full building evacuation lift simulations [18]. Since then a variety of numerical- and simulation-based lift models have been developed, e.g. ELVAC [19], ELEVATE [20], BTS [21], etc., which can be used to simulate lift evacuations. The focus of such models is typically the control and vertical movement of lifts about a building and often simplify the movement of occupants outside lifts as a product of distance, occupant speed, flow rates, and arrival rates. The primary use of such models is by the lift industry to develop lift dispatch algorithms for use during normal circulation situations. In addition to these lift centric models, more recently a number of circulations/evacuation models have also developed the capacity to represent lifts, e.g. STEPS, EVACNET4, Legion, EvacSim [22]. Typically, the focus of such models is based on agent behaviour; the lift control along with associated lift attributes and performance metrics within such models is typically less developed compared to the lift centric models.

In this paper we present a lift model implemented within the buildingEXODUS evacuation software, which includes a sophisticated representation of lift kinematics and 'ideal' agent–lift interaction. In addition, the lift model, utilizing ideal agent behaviour, is used to explore the relative benefits of different lift evacuation strategies.

2. THE LIFT AND AGENT–LIFT INTERACTION MODELS

The core software used in this work is buildingEXODUS V4.06. The basis of the software has frequently been described in other publications [4, 23, 24] and so will not be described here. Suffice it to say that buildingEXODUS is an agent-based model used for the simulation of both evacuation and circulation. The newly developed lift model is implemented within the buildingEXODUS software. The key components of the lift sub-model described here are

- Agent–Lift interaction model
- Lift attributes
- Lift dispatch
- Lift kinematics.

2.1. Agent behaviour

The agent–lift interaction behaviour implemented within this version of buildingEXODUS is considered to represent ideal and orderly occupant behaviour. Thus at best, the implemented behaviour is expected to be a simplification of reality and at worst; it may be an idealized representation of reality. It was necessary to implement simplified ideal behaviours due to the lack of available human behaviour data describing how people would actually behave when attempting to use lifts in emergency evacuation situations. However, the model is sufficiently flexible to allow for future changes when human performance data becomes available. The implementation of these ideal agent behaviours allows a comparative study of different lift dispatch strategies under a set of common, albeit ideal, agent behaviours.

The underlying concept behind the agent–lift interaction model involves three core agent behaviours: lift bank selection; lift waiting area selection and wait duration; and lift car selection and entry (see Figure 1). These behaviours are implemented within buildingEXODUS using the software's existing Itinerary concept. Within buildingEXODUS, the Itinerary concept allows agents to be assigned a series of tasks, e.g. the wait task, to undertake at given target locations throughout the geometry prior to exiting. For example, an agent may be directed to move to a prescribed location in the geometry and wait at that location for a specified period of time before moving off to complete their next assigned task. Each of the three core agent–lift behaviours is briefly described.

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Fire Mater. (2011)
DOI: 10.1002/fam

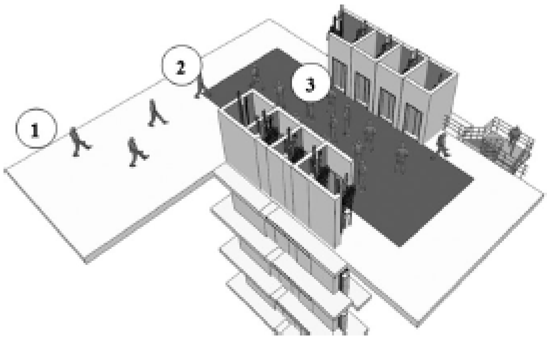

Figure 1. Agent–lift interaction model—Three key decision points: (1) lift bank selection; (2) lift waiting area behaviour and (3) open lift car selection.

2.1.1. Lift bank selection. Within the software there are three possible approaches, which can be used to specify the lift bank that agents will select to use during the evacuation simulation:

- Closest serviced lift bank assignment. In this case, when faced with a choice of several lift banks, agents simply select their closest lift bank on a given floor.
- Closest serviced lift bank assignment with even lift bank usage. In this case agents select their closest lift bank, on a given floor, which have the least number of agents waiting to use the lift bank. In this way each lift bank on a given floor is adopted by approximately an equal number of agents.
- Manually assign which lift bank an agent will use. Unlike the first two approaches which are automated means of assigning agents to lift banks, it is also possible to explicitly specify which lift bank each agent will use.

Once a simulation has started agents do not change their lift bank selection or redirect to another lift bank after the initial choice is made. When the agent's response time has expired the agent moves towards the selected or assigned lift bank.

2.1.2. Lift waiting area behaviour. When an agent enters a lift bank waiting area, if the agent's target is the current lift bank, they randomly select a location in the lift bank waiting area to wait. The agent then moves to the chosen location where they will wait for a lift to arrive. When agents arrive within a given range (with a default set to 1 m) of their wait location they exhibit milling behaviour whereby they will 'mill' about their chosen wait location. This involves agents randomly moving around the available nodes within a given radius of their chosen wait location providing they remain located within the lift waiting area. The milling behaviour reduces the potential of agents becoming blocked by other agents already waiting, which subsequently allows more agents to enter into the lift waiting area. In addition, this means that agents spread across the lift waiting area more evenly. This has an added benefit of decreasing the average time it takes agents to board lifts as more agents are typically waiting closer to the open lifts.

As soon as an agent enters the lift wait area they are assigned a parameter called the 'maximum lift wait time'. This is intended to represent the maximum time that the agent is prepared to wait for a lift. When the maximum lift wait time expires the agent will abandon their attempt to evacuate via the lift, move to their nearest staircase, and complete their evacuation using the stairs.

2.1.3. Open lift car selection. When a lift door opens in a given lift bank, the nearest agents who are waiting in the lift waiting area move to enter the lift. Only the number of agents, which can fit inside the lift (derived from the lifts maximum capacity and the proportion of this reached) attempt to board the lift. As a result there is no competition for lift boarding and the boarding process is orderly. If multiple lift cars open their doors simultaneously at a given floor, the agents select the

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Table I. Defining lift attributes.

Attribute	Description
Maximum speed	Defines the maximum rated speed of the lift car (m/s).
Acceleration	Defines the constant rate of acceleration of the lift car (m/s^2).
Jerk	Defines the rate of change in acceleration before and after constantly accelerating (m/s^3).
Start floor	Defines the floor the car will start at the beginning of a simulation.
Door opening time	Defines the time it takes a lift door to open.
Door closing time	Defines the time it takes a lift door to close.
Dwell time	Defines the duration the car doors will stay open after the car doors have fully opened to service a given floor (providing no one enters the lift).
Sensor break adjusted dwell-delay	Defines the adjusted dwell time after the first occupant enters a lift car.
Motor delay	Defines the time, after a lift's doors have closed, before the car starts to move i.e. the time it takes the motor to start.
Theoretical capacity	Defines maximum physical number of agents that can enter a car.
Max % of theoretical capacity	Defines the percentage of the 'Theoretical Capacity' which the car actually reaches.
Serve floor sequence	Defines a sequence of numbers which represent the series of floors the car will serve.
Shuttle floor sequence	Defines a sequence of paired numbers which represent a series of 'pick up' and 'drop off' floors the car will shuttle between.
Exit floors	Defines a list of floor numbers which form the drop off floors for both Shuttle floor and Serve floor sequences. For both sequences, if a lift arrives on an exit floor, everyone currently in the car will exit at the indicated floor.

nearest under-subscribed opened lift car. This ensures that the nearest agents to an opened lift car will board the car.

2.2. *Lift attributes*

Within the software a lift shaft is defined as a series of transit nodes, which span each of the floors within the geometry. The dimensions of the shaft in addition to the size of the door on each respective floor can be defined within the model by altering the attributes of each transit node. Once the shaft is defined, then a lift can be associated with the shaft. There are a number of attributes which are used to define a lift within the software, these are listed in Table I.

2.3. *Lift dispatch*

The current lift model provides two methods for controlling the lift dispatch. The first approach enables the interaction of buildingEXODUS with proprietary floor dispatching algorithms using *C++* libraries with connection via a standard interface. This approach is particularly useful when the software is used to simulate normal circulatory flows within a building in which the lifts are controlled by a specific lift company's dispatching algorithm. As such the system can be reactive according to different landing requests in the simulation.

The second system enables the manual specification of the floors a lift/group of lifts will service using a script file. Unlike the first approach, this does not allow the floor sequence to change or be reactive to dynamic lift calls that may occur during the simulation. The floor sequence can be specified in one of two ways: floor-sequence or shuttle-floor-sequence, along with an exit floor list. When using a floor-sequence, the sequence of floors a lift will service during the simulation is specified. The assigned lift(s) will serve each of the floors specified in the sequence once, and take the agents to the ground floor and then visit the next floor in the sequence. Using a shuttle-floor-sequence, a paired-sequence of pick-up/drop-off floors is specified where the lift will visit the pick-up floor, allowing agents to board and shuttle the agents to the drop-off floor. This shuttle process would repeat until there were no more people in the pick-up floor catchment area or floor

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(depending on the settings). The process is then repeated for the next pick-up/drop-off floor in the sequence. For both systems, the exit floor list defines which floor(s) the agents in the car will exit the lift.

For the shuttle-floor sequence system, using a top–down strategy, if a lift does not fill to its maximum capacity at a pick-up floor, an optional feature is to then move the lift to the next specified pick-up floor to fill up the remaining spaces in the lift car. This reduces the amount of redundant shuttle trips a lift makes when it is not full and so would increase the efficiency of the overall evacuation. In a real situation it is assumed that the number of passengers that enter each lift car is detected either via automated means, e.g. weight sensors, or manually via an operator within the car.

2.4. Lift kinematics

The kinematics or motion of a lift car is defined by its jerk (rate of change of acceleration), acceleration and maximum speed. There are also a number of other factors that influence an actual lift's journey, such as friction, wear and tear of machine parts, however, these are not considered within the current model. As such the kinematics of the lift model should be considered 'ideal'. Specifying the car's jerk, acceleration and maximum speed is sufficient to determine the location of the car at any point in time. The time at which the lift passes each respective floor between its original location and its destination is determined using a series of formulae.

The first significant work in deriving the formulae for the 'ideal lift kinematics' was by Motz [25] in 1986. In 1996 Peters [26] derived the necessary time–distance formulae; giving the necessary attributes of a lift, would produce the distance travelled at a given time in a lift's journey. These formulae have been implemented in varied forms within buildingEXODUS to provide the model with the time a lift passes/arrives at each floor in a lift journey, hence providing the animation of a lift car moving within the geometry.

With regard to jerk, acceleration and maximum speed, there are three types of journeys a lift can make: (i) a lift reaches maximum speed, (ii) a lift reaches its maximum acceleration (but not maximum speed) and (iii) a lift fails to reach its maximum acceleration [26]. Figure 2 presents each of the three types of journeys, which can be made by a lift in terms of the changing values of jerk, acceleration, velocity and distance travelled, over time.

3. THE SIMULATIONS

A series of 11 full building evacuation scenarios have been performed using the new lift model using a hypothetical building. The configuration of the software used for each scenario and the nature of each scenario is briefly described.

3.1. The building configuration

The building has 50 floors with a floor-to-floor height of 3 m (the total height of the building was 150 m in height), with four stairwell cores, and four lift banks each containing eight lifts (see Figure 3). With the exception of the ground floor all levels in the building have the same layout and configuration. In certain scenarios specific floors were designated as sky lobbies where agents from multiple floors move to the sky lobbies and wait to use the lifts during the evacuation. In such buildings, it is common to find that sky lobbies are intended to be refugee areas with sufficient occupant capacity and fire/smoke/water protective measures in place to protect the enclosed population. However, the influence of such configuration factors upon evacuation dynamics is considered beyond the scope of the study.

Each stair allowed two agents to stand abreast side-by-side with occupants preferring to stagger their locations (i.e. prefer not to stand side-by-side) and maintain at least one tread spacing between themselves and the agent in front. Each stair is doglegged design where an intermittent landing ($1\,m \times 3.2\,m$) connects the two legs; each leg being 1.5 m in width and 4.6 m in horizontal length allowing a maximum of 16 agents to simultaneously occupy each leg of the stairs at a time.

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DOI: 10.1002/fam

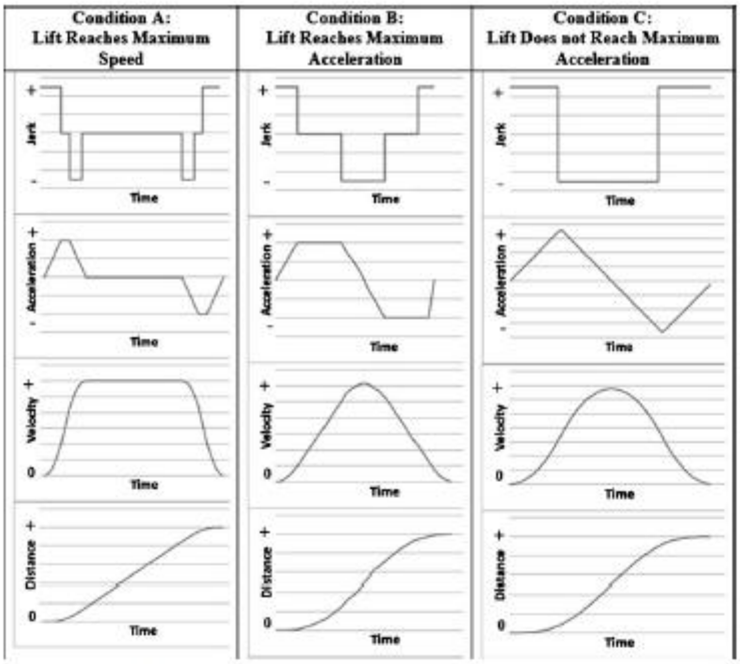
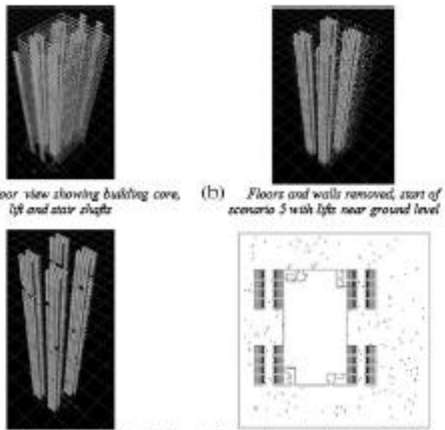


Figure 2. Three types of journeys a lift car can make with respect to jerk, acceleration and maximum speed [26].



(a) *Multi-floor view showing building core, lift and stair shafts*

(b) *Floors and walls removed, start of scenario 5 with lifts near ground level*

(c) *Part way through scenario 5, with lifts at different levels, occupants gather in lift lobbies.*

(d) *Two-dimensional view of a single floor, near start of scenario 5, showing distribution of agents around core, stairs and four lift banks.*

Figure 3. Sequence of views from buildingEXODUS of high-rise building lift evacuation, (a)–(c) depicting 3D virtual reality view and (c) depicting two-dimensional view.

Within the building all of the lifts have the capacity to service all floors. It is recognized that many high-rise buildings include vertical partitioning of lifts, where lifts are restricted to service a given range of floors. However, the purpose of allowing all lifts and stairs to service all floors was to allow for flexibility in exploring a variety of different evacuation procedures without being

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inhibited by physical vertical partitioning/zoning of the lift shafts, which is typically dictated by ingress performance requirements. Owing to the hypothetical nature of the building, apart from the external walls and the stair/lift cores, no furniture or internal obstructions were represented within the building geometry (see Figure 3).

Still sequences from an example simulation are depicted in Figure 3. As part of the development of the lift submodel, a three-dimensional virtual reality visualization capability has been developed, which is integrated into the buildingEXODUS user interface. The new interface is capable of displaying virtual reality three-dimensional graphics (see Figures 3(a)–(c)) as well as the usual two-dimensional visualization (see Figure 3(d)). The three-dimensional representation shows the progress of the lift cars during the simulation.

3.2. *Building population*

The building population comprised 7840 agents. With the exception of the ground floor, there were 160 agents located on each floor. Agents were modelled as non-connected individuals and were not constrained by groups. The population used the default population attributes within buildingEXODUS [23] and consisted of people with different movement capabilities reflecting the variety of the different ages, genders and abilities. All agents were assumed to react instantly at the beginning of each scenario hence response time is not considered a parameter within this analysis.

3.3. *Agent–lift interaction*

During the lift simulations, agents using the lifts were assigned to use their nearest lift bank, which was not already over subscribed by agents, i.e. an equal number of agents used each lift bank on each floor. Likewise during simulations in which the stairs were used, an equal number of agents were assigned to use each stair on each floor. This concept of equal core load balancing was considered appropriate as unequal use of a lift bank or stairwell has the potential to significantly increase the total evacuation time (TET) and levels of congestion. While this may in fact occur in real situations, it was not considered appropriate to consider these issues in the current analysis as the primary concern of this study is to investigate the comparative benefits of different operational strategies assuming 'ideal' human factors. In addition, agents who are assigned to use the lifts are given an infinite maximum lift wait time and thus will wait in the lift waiting area until they are serviced by a lift.

3.4. *Lift attributes*

The defining attributes for the lift kinematics and physical characteristics were based on the Chartered Institution for Building Service Engineers (CIBSE) Guide D: Transportation Systems in buildings [27]. Each lift had a maximum capacity of 13 occupants, a maximum speed of 6 m/s, acceleration rate of $1.2\,m/s^2$ and a jerk rate of $1.8\,m/s^3$. In addition each lift had a door opening time of 0.8 s, door closing time of 3.0 s, a dwell delay of 3.0 s and a motor delay time of 0.5 s. Using these parameters approximately 31.5 s are required for a car to travel from the ground floor to the top floor and fully open its doors. At the beginning of each simulation each lift started at the ground floor. For each lift simulation not involving stairs, where lifts serviced multiple floors (i.e. non-sky lobby scenarios), a top–down-shuttle evacuation strategy was employed by each of the lifts whereby all the lifts evacuate the occupants on the top floor first and shuttle them to the ground floor. This process is repeated until all people evacuated that floor. The lifts then proceed to the floor below this and the process is repeated until all of the floors in the sequence have taken all occupants on those floors to the exit floor.

3.5. *The scenarios*

In each of the 11 full building evacuation scenarios, different combinations of lifts and stairs were used. In each case, the priority for the lifts was to service the upper floors first, sequentially working down to the lower floors. Several scenarios examined the use of shuttle lifts and sky lobby arrangements. The full list of scenarios is summarized in Table II.

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Table II. Overview of evacuation scenarios.

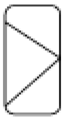
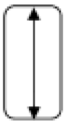
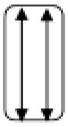
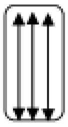
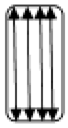
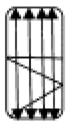
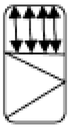
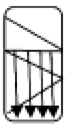
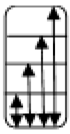
Scenario	Diagram	Description
1		Stairs only (4 stairs)
2		8 lifts (1 lift bank)
3		16 lifts (2 lift banks)
4		24 lifts (3 lift banks)
5		32 lifts (4 lift banks)
6		32 lifts, with the lower half of the building (floors 0–25) population using the stairs and the upper half (26–49) using the lifts to *shuttle to the ground floor*.
7		32 lifts, with the lower-half of the building (floors 0–25) population using the stairs and the upper half (26–49) using the lifts to *shuttle to the middle floor (floor 25)* from the occupants floor of origin, then continue their evacuation via the stairs.
8		32 lifts, with the lower half of the building (floors 0–25) population using the stairs and the upper half (26–49) *initially using the stairs to walk to a sky lobby on floor 26 where occupants would be shuttled via lifts to the ground floor.*
9		32 lifts, 4 shuttle zones—each lift bank servicing a series of 12 floors of occupants, with each zone being evacuated from the top–down of the zone to the ground floor.

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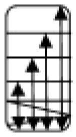
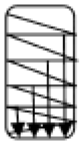
Table II. *Continued.*

10		32 lifts, 4 shuttle zones +1 Stair zone—each lift bank servicing a series of 10 floors of occupants, with each zone being evacuated from the top–down of the zone to the ground floor. Occupants below floor 10 only use the stairs to evacuate.
11		32 lifts, 4 Sky lobbies—there is a sky lobby every 10 floors in the building (4 sky lobbies in total) with each lift bank servicing one of the sky lobbies. Occupants travel down the stairs to the next sky lobby below where the lifts shuttle them to the ground floor. Occupants below floor 10 only use the stairs to evacuate.

The different frequency of lifts used in certain scenarios is intended to explore the impact of lift number in evacuation efficiency and to explore the effects of lift banks being rendered inoperable during an evacuation (e.g. due to fire, technical fault, etc). For each scenario all lifts initially started on the ground floor.

4. RESULTS AND DISCUSSION

The results for the various simulations are presented in Table III with the egress curves for the various scenarios presented in Figure 5. It is noted that the results presented in this paper are slightly different from those presented in a previous investigation [28]. This is because all the simulations were run again, including the stair only cases. Furthermore, in the work reported previously, the milling behaviour exhibited while agents' wait in the lift waiting area was not included. In the previous work, agents would simply stand still in the lift waiting area until it was their turn to board a lift. This has the potential to create obstacles in the lift waiting area which can block the movement of other agents, in particular when they attempt to reach their wait location in the lift waiting area. With the milling behaviour included, agents in the lift waiting area may move around and are spread more evenly throughout the lift waiting area, making blockages less likely and as a consequence typically allowing more agents to enter into the lift waiting area when large crowds occur.

The base line comparison for all the cases is the stair only evacuation (scenario 1) as this is akin to typical evacuation practice whereby the lifts are not used. This produced a TET of 35.9 min with 20.3 min required to clear the top half of the building. The Average Personal Evacuation Time (PET) for the simulation was 17.6 min. This indicates that on average, a person required 17.6 min to exit the building.

The TET for Scenario 2 (8 cars) and Scenario 3 (16 cars) were 71.1 and 39.1 min, respectively, both being longer than the stair only case. The Average Lift Wait Time (LWT) represents the overall average time agents spent waiting to be serviced by a lift. The LWT for the 8 car scenario (Scenario 2) was the longest of all cases being 36.1 min, which was some 46.0% longer than the 16 car scenario. The longest LWTs were achieved in Scenarios 2–5, where only lifts were used and agents on the lower floors waited the longest to be served by a lift due to the top–down lift dispatch strategy employed (see Figure 4).

From Figure 5 it is noted that for Scenarios 2–5 the evacuation rate increases towards the later stages of the evacuation unlike in the stair only case, which tends to decrease towards the later stages of the evacuation. The increase in evacuation rate is due to the lift cars having to travel a shorter distance towards the end of the evacuation as the remaining agents are located on the lower floors, again due to the top–down lift dispatch strategy.

It is not until 24 cars are used in the evacuation (Scenario 4) that the TET decreases compared to the stair only case, being 29.0 min or 19.2% faster. However, even with 24 cars the average PET

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Table III. Summary of numerical predictions for the 11 evacuation scenarios.

Scenario	Number of lifts	Evacuation time of last *lift* user (min)	Evacuation time of last *stair* user (min)	% Time saved (compared to stairs only)	Time to clear upper half of building (min)	Average PET (min)	Average LWT (min)	Time taken to evacuate proportion of the population (min)		
								25%	50%	75%
1	0	—	35.9	—	20.3	17.6	—	9.3	17.5	25.8
2	8	71.1	—	−100.0%	41.2	40.8	36.1	24.1	43.0	58.9
3	16	39.1	—	−8.9%	22.2	22.5	19.5	13.5	23.6	32.3
4	24	29.0	—	19.2%	16.2	16.6	15.1	10.0	17.3	23.7
5	32	23.2	—	35.4%	12.9	13.3	12.0	8.1	13.9	18.8
6	32 + half stairs top down	13.4	18.6	48.2%	12.3	8.6	6.2	5.0	8.5	11.9
7	32 + half stairs top middle	35.4	33.1	1.4%	12.3	17.6	5.9	9.3	17.6	25.8
8	32 + half stairs, 1 × sky Lobby	18.8	18.7	47.6%	17.7	9.6	0.0	5.5	9.7	13.8
9	32+4 shuttle zones	23.5	—	34.5%	22.4	10.2	10.2	5.7	9.9	13.9
10	32+4 shuttle zones + 10 stairs	20.0	7.3	44.3%	18.7	8.1	6.8	4.2	7.2	11.7
11	32 + 4 × sky lobbies	18.3	7.3	49.0%	17.1	7.2	0.8	3.8	6.4	9.9

(16.6 min) is still only marginally less than the stair only case. From Figure 5 we note that the stair only curve out performs the 24 car case for the first 16.3 min (45.4% of the stair evacuation and 56.2% of the 24 car case) where some 46.2% (3620) agents evacuated. However, from Table III we note that the 24 car case (scenario 4) does clear the upper half of the building 20.2% faster than the stair only case (Scenario 1), clearing the upper part of the building in 16.2 min compared to 20.3 min.

When 32 cars are used (scenario 5) there is a substantial improvement over the stair only case, with the TET being reduced by 35.4% and the overall average PET being reduced by 24.4% compared with the stair only case. Furthermore, the use of 32 lifts provided a substantial benefit to the agents initially located in the top half of the building with the upper half of the building being cleared substantially faster than the stair only case, requiring only 12.9 min compared with 20.3 min. Comparing the 8 lift scenario with the other lift only scenarios, there was a 1.8, 2.5 and 3.1 times speed-up in the TET, respectively, for the 16, 24 and 32 lift scenarios. This suggests that for a given population distribution and number of floors, the speed-up in evacuation performance does not necessarily scale directly as the increase in the number of cars used.

In scenario 6 an evacuation strategy in which the population located at the bottom half of the building use the stairs to evacuate while those on the top half use 32 lifts to evacuate directly to the ground is explored. This strategy produces the second shortest overall evacuation time of 18.6 min; almost 50% faster than the stair only case. For the first 9.3 min during the stair only scenario 25% of the population evacuated, however, during the same period of time in scenario 6, over twice as many agents evacuated.

Presented in Figure 6 is the floor clearance time for each floor and each scenario. Here the floor clearance time is interpreted as the time required for all agents to clear all floors on and

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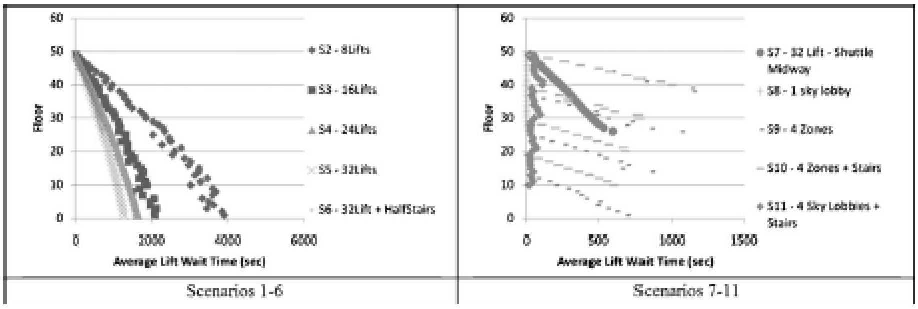

Figure 4. Average lift wait time (LWT) for agents.

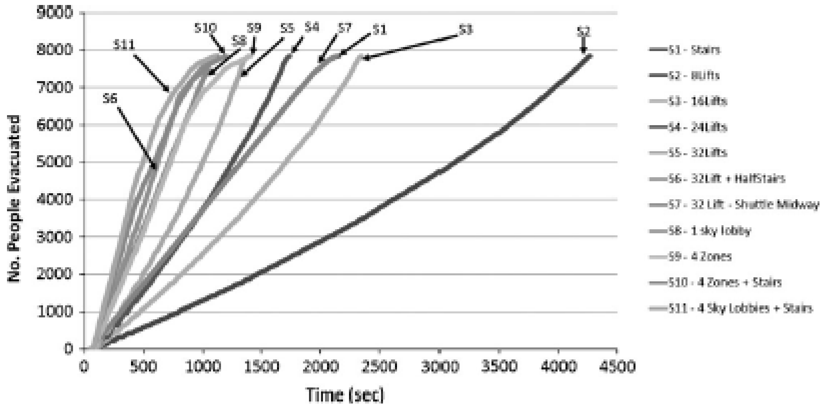

Figure 5. Number of people evacuated against time (s) for each scenario.

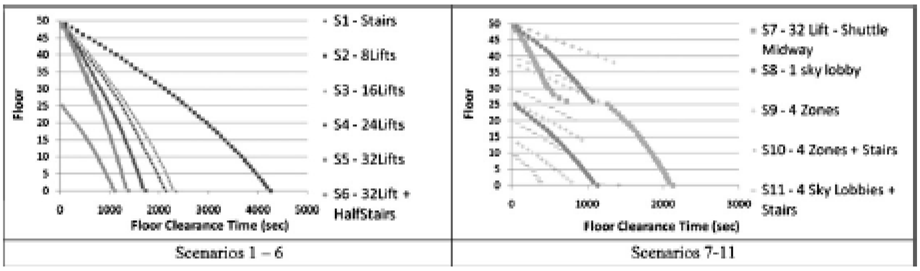

Figure 6. Floor clearance times for each scenario.

above a given floor, i.e. includes not only agents who were originally situated on a floor, but those agents located on higher floors who pass through the floor as they evacuate. As expected, the time required to clear each floor down to floor 25 in Scenario 6 is similar to that in Scenario 5 (see Figure 6). Indeed, the time to clear the top half of the building in Scenario 6 (12.3 min) is similar to that of scenario 5 (12.9 min) (see Table III). However, the average PET in Scenario 6 is 8.6 min which is significantly less than the average PET for Scenarios 5 and 1, which are 13.3 min and 17.6 min, respectively. The parallel usage of both the stairs and lifts allowed the

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DOI: 10.1002/fam

lower floors to be cleared in a shorter amount of time (see Figure 6) compared to Scenarios 1–5. In this scenario, the last agents out of the building were the stair users, resulting in a decrease in the evacuation rate towards the very end of the evacuation as seen in Figure 5. Owing to this scenario only containing half the number of lift users, all of which were located in the top half of the building, it is not surprising that the LWT decreased by almost 50% compared to Scenario 5 in which the same number of lifts were used to evacuate twice as many agents, i.e. the entire building.

Scenario 7 introduces a variation on Scenario 6 in which the lifts take the upper agents not to the ground but to the central floor, from where they continue their evacuation using the stairs. We find that the TET for this scenario increases to 35.4 min, only marginally faster than the stair only case and the average PET, at 17.6 min is identical to that of the stair only case. Furthermore, it required approximately the same amount of time to evacuate 25, 50, 75 and 100% of the building population as in the stair only case (Scenario 1) (see Table III). However, it is noted that the time to clear the upper half of the building is joint quickest (along with Scenario 6), requiring only 12.3 min. While the time to evacuate the entire building is equivalent to the stair only case, using this strategy does provide one of the quickest ways to clear the upper half of the building. Despite the lifts shuttling occupants a shorter distance to the middle floor instead of the ground floor (as in Scenario 6), only a marginal decrease (4.8% (0.3 min)) in LWT was recorded. The reason for this is to do with the congestion that developed on the 25th floor. The lifts discharged occupants onto the 25th floor faster than the stairs could accommodate agents moving away from the floor. This caused large crowds to form around the stair entrance and eventually began to spill over into the respective lift waiting areas where agents alighted the lifts. Towards the end of the upper half of the building's evacuation this caused some agents to be delayed from alighting the lift due to being blocked by agents queuing for the stairs (see slight tailing off of floor clearance times for floors 27 and 26 in Figure 6). This highlights the importance of the relative positioning and discharge capacities of stairways and lifts banks in building design when considering employing lift evacuation strategies.

In Scenario 8 the sky lobby concept is introduced. Here, the agents in the upper part of the building are required to descend to the central floor, by stairs, from where they can take a lift to descend all the way to the ground. The agents below the central floor must all use the stairs to evacuate to the ground. As in Scenario 6, the parallel usage of both the stairs and lifts more efficiently utilizes the full vertical throughput of both stairs and lifts over the entire duration of the evacuation. This creates a more even utilization of load carrying capacity reflected in the similarity of the floor clearance times for the upper and lower half of the building (see Figure 6). This is also reflected in the fact that the evacuation time of the last lift and stair user is approximately the same. In Scenario 8 the TET is 18.8 min, some 47.6% faster than the stair only case (Scenario 1). However, it requires approximately the same amount of time (17.7 min) to clear the top half of the building as it does to evacuate the entire building (18.8 min) as agents initially located in the top half of the building are required to walk down the stairs to the middle floor. The LWT for Scenario 8 was the shortest of all the scenarios with the majority of lift users (initially located above the 25th floor) able to board an open lift immediately after entering the lift waiting areas. One of the reasons why the LWT in Scenario 8 is so small is that within the model, cars will keep their doors open while they are not full to capacity and there are agents remaining in the lift waiting area targeting the lift bank. As a result, agents may end up waiting inside a partially full lift until there are no other agents in the lift waiting area targeting the lift bank. The staggered arrival of agents to the lift waiting area (having to initially travel on the stairs) increased the likelihood of this occurring and as a consequence, most of the agents arrived in the lift waiting areas found a car waiting for them. It can be argued that this behaviour is intended to model the situation that, either the lift operator or other lift passengers, will keep the lift door open if the lift is not filled to capacity and there are other occupants in the lift waiting area.

In Scenario 9 four shuttle zones are introduced with each group of eight lifts servicing the 12 floors within their allocated zone (the bottom zone has 13 floors). In each zone the lifts service the floors from the top down. In this scenario the TET has decreased to 23.5 min which is some 34.5%

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faster than the stair only case (Scenario 1), but considerably slower than Scenario 6. In Scenario 9, the last agents to evacuate are located in the top zone (see Figure 6) where the lift cars have a longer journey. Using this approach requires 22.4 min to clear the upper half of the building, some 2.1 min slower than the stair only case. Clearly this is a very inefficient strategy for emptying the building and clearing the upper half of the building. In Scenario 10 this concept is extended by making all the agents below the 10th floor use the stairs rather than the lifts. In this case we have four shuttle zones with each group of eight lifts servicing 10 floors. While this case represents an improvement over Scenario 9, with a TET of 20.0 min which is 44.3% quicker than the stair only case, the time required to clear the upper half of the building is 18.7 min, only 1.6 min faster than the stair only case (Scenario 1). The LWT for Scenario 10 is a third smaller than that in Scenario 9 due to the effects of having less lift users (the lower 10 floors use the stairs) and fewer floors in each shuttle zone allowing lifts to service each floor quicker.

In Scenario 11, four sky lobbies are introduced, one on every 10th floor with each sky lobby being serviced by eight lifts (a single lift bank). Within each zone serviced by a sky lobby, agents must descend, using stairs, to the sky lobby where they can board a lift which takes them directly to the ground. Below the 10th floor, all agents use the stairs to evacuate. Scenario 11 produces a TET of 18.3 min which is almost 50% faster than the stair only case (Scenario 1) while the upper half of the building is cleared in 17.1 min, 16% faster than the stair only case. This scenario produced the fastest TET, being 2% (0.3 min) faster than Scenario 6 but took 39% (4.8 min) longer to clear the upper half of the building with the upper most zone taking the longest to clear (see Figure 6). It is also noted that the average PET for Scenario 11 is only 7.2 min, 11% lower than the next lowest PET (for Scenario 10). Furthermore, from Figure 5 it is noted that this scenario produces the best evacuation rate of all the scenarios investigated. The first 75% of the building population evacuated some 2 min sooner than the next fastest scenario (Scenario 6). Indeed in the same time that it took 25% of occupants to evacuate in the stair only case, almost three times as many occupants (75%) had already evacuated in Scenario 11.

The LWT for Scenario 11, at 0.8 min was the second shortest of all the scenarios investigated and was only marginally greater than that of Scenario 8. Due to the sky lobbies in Scenario 11 servicing fewer floors than the sky lobby in Scenario 8, the agents in Scenario 11 travelled a shorter distance, on average, to a sky lobby than those in Scenario 8. Thus the agent arrival rate in Scenario 11 was less staggered than that in Scenario 8, resulting in the slightly higher LWT found in Scenario 11. It is also noted that lift users initially located on floors closer to the sky lobbies in Scenario 11 experienced longer LWTs than those further away (see Figure 4).

It is noted that of all the evacuation strategies examined, the introduction of multiple sky lobbies (Scenario 11), allows the greatest number of agents to be evacuated at any given time during the evacuation and produces the shortest overall TET. However, the multiple sky lobby scenario (Scenario 11) does not produce the shortest time to clear the upper half of the building. This was achieved in Scenarios 6 and 7, each of which were 28% faster than Scenario 11. Furthermore, Scenario 6 produced an overall evacuation time which was only 2% greater than that produced by Scenario 11.

The performance of the multiple sky lobby scenario could potentially be further improved through the introduction of local lift cars that ferry the agents to the sky lobby rather than use the stairs. Furthermore, a potential practical advantage of the multiple sky lobby approach is that it requires little or no input from an operator or automated means of person detection in the lift waiting areas (e.g. determining if any evacuees are still waiting in a lift lobby) as the lifts shuttle between the same floors for the entire duration of the evacuation. Consequently, there is little risk of a person being left behind and potentially waiting for a lift which may have already serviced their floor. It is also noted that scenarios involving zoning/multiple sky lobbies (Scenarios 9, 10, 11) produce increasingly inefficient evacuation performance towards the end of the evacuation sequence (see Figure 5). This is because towards the end of the evacuation, the lifts servicing the zones/sky lobbies on the lower levels finish sooner and are left idle whilst the lifts servicing the upper levels are still in operation. The performance of these scenarios could potentially be increased by using the idle lifts from the lower floors to assist in shuttling the remaining occupants on the upper floors/zones to the exit level.

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DOI: 10.1002/fam

Within the scenarios presented in this paper, the hazard e.g. fire has not been represented. As a result the impact that the developing hazardous environment may have on agent behaviour has not been represented. This is primarily due to the large number of possible hazard scenarios that could have been included and partly due to the desire to keep the analysis as general as possible. However, it is likely that in the event of a situation involving a fire, occupants on the fire floor would be discouraged from using the lifts due to uncertain lift wait times and the increased likelihood of exposure to the hazard. As such those occupants would likely either make use of the stairs or the lifts on adjacent floors/sky lobbies. The consideration of the influence that a developing hazardous environment may have on agent behaviour and any subsequent lift floor prioritization is left for further investigation.

The building configuration used in this analysis allowed all lifts to service all floors. This was done to allow greater flexibility in exploring a variety of evacuation lift floor dispatch strategies. It is, however, noted that it is common practice in tall buildings with multiple lift banks that each lift or lift bank may service a restricted range of floors. Clearly, such vertical partitioning of lift zones would restrict the possibility of using certain evacuation lift dispatch strategies.

Finally, it is worth noting several simplifications in the modelled agent behaviour. The agent–lift interaction model was considered to be ideal. This meant that agents optimally selected which lift bank to use so that there was an equal distribution of agents between lift banks. In a real emergency situation this is unlikely to be the case and one or more lift banks may become overloaded as people select their most familiar or usual lift bank or they simply select their nearest lift bank. In addition, the lift boarding behaviour adopted by the agents within the model was orderly. In a real emergency situation, there may be competition to board the lifts, especially if the population is forced to wait for extended periods of time and/or environmental conditions within the building/lift-waiting area worsen. To achieve near ideal lift boarding behaviour it may be necessary to assign fire wardens or uniformed emergency response personnel to the lift waiting areas to manage lift usage. Finally, in the current model, the agents waited patiently for the lift to arrive, regardless of the duration of the wait time. In one scenario, the average wait time was as much as 36 min (see Table III). In a real emergency situation it is questionable whether occupants would be prepared to wait this long for a lift, especially if environmental conditions within the building/lift-waiting area worsen or if there were large crowds in the lift waiting area. Under these conditions, waiting occupants may be prepared to wait for a certain period of time before deciding to use the stairs. Indeed recent survey studies suggest that irrespective of the floor, most individuals would not be prepared to wait longer than 10 min for a lift during an evacuation [16, 17]. Compared to the simulated scenarios, only Scenarios 6–9 and 11 had average LWTs lower than 10 min. The remaining LWTs for Scenarios 2–5 and 10 ranged from 10.2–36.1 min, potentially indicating unrealistic lift wait behaviour for these scenarios. These simplifications to the agent–lift interaction model contribute to the overall lift efficiencies presented in this work. In real emergency situations, human behaviour issues may result in lower efficiencies being achieved. To address these simplifications, the authors have surveyed 468 people in 23 countries to determine likely occupant-lift behaviours in emergency and circulation situations[16]. The information derived from the survey will be used to refine the agent–lift interaction submodel.

5. CONCLUSION

This paper presents a description of the newly developed lift and agent–lift interaction submodels within buildingEXODUS intended for both evacuation and circulation applications. Agent behaviour exhibited within the current model is considered 'optimal' in that: each lift bank was utilized by approximately an equal number of agents, once the agents selected a lift they made no attempt to redirect, and when the lift door was opened only the nearest agents that could be accommodated within the lift would elect to use the lift. With simplifications to reality, these ideal agent behaviours has allowed a comparative study of different lift dispatch strategies under a set of common, albeit ideal agent behaviours, to be conducted. Using this model, a series of 11 lift-stair

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Fire Mater. (2011)
DOI: 10.1002/fam

evacuation scenarios were investigated involving a hypothetical 50 floor building consisting of four staircases and up to four lift banks, each with eight lifts and a building population of 7840 agents. The results suggest that for this building:

- For a given building population and number of floors, the speed-up in evacuation performance achieved using a lift only strategy—in which each lift visits each floor—is sub-linear with increasing number of lift cars.
- Using a lift only strategy in which each lift visits each floor, the TET can be reduced by 35% and the time to clear the top half of the building reduced by 37% using 32 lift cars compared to a stair only strategy.
- A more efficient evacuation strategy involves using lifts in conjunction with stairs. If 32 lifts are used to clear the top half of the building while the occupants in the lower half of the building utilize the stairs, the building can be emptied 50% faster compared with the stair only strategy. The time to empty the top half of the building is reduced by 39% compared to the stair only case.
- The most efficient overall strategy involved using 32 lifts arranged into four sky lobbies where the occupants on the first 10 floors used the stairs and within each sky lobby zone the occupants used the stairs to descend to the sky lobby. In this case the building could be evacuated 50% faster than the stair only case and the upper half of the building could be emptied 16% faster than the stair only case. While the upper half took 39% longer to clear than in the case where the lifts were used to evacuate only the top half of the building, this case produced the highest overall egress rate.
- It is suggested that the performance of the sky lobby cases could be improved if local lifts were used to shuttle occupants from local floors to the sky lobbies.

While there are many possible lift evacuation strategies that may be implemented to assist in high-rise full building evacuation, as demonstrated in this paper, evacuation efficiency is dependent on the nature of the lift strategy employed. Selecting the correct lift evacuation strategy to employ in a particular building is dependent not only on the number and capabilities of the available lifts, but also on the nature of the particular emergency scenario being addressed and the life safety priorities associated with the scenario. The work presented here suggests that for the 50 floor building investigated:

- Minimizing the overall TET can be achieved by utilizing the 32 available lifts into a four sky lobby configuration (Scenario 11).
- Minimizing the overall time to clear the upper half of the building AND the time that occupants must wait for a lift can be achieved by using all 32 available lifts to shuttle the upper half of the building down to the 25th floor, from where the occupants use the stairs to evacuate. The occupants in the lower half of the building use the stairs to evacuate (Scenario 7).
- Minimizing the time to clear the upper half of the building AND the overall evacuation time can be achieved by using all 32 available lifts to shuttle the upper half of the building directly to the ground. The occupants in the lower half of the building use the stairs to evacuate (Scenario 6).

It should also be highlighted that there are expected to be a number of factors that influence the efficiency of lift evacuation in addition to the lift dispatch strategy including human factors and building height. The next phase in the development of the buildingEXODUS lift modelling capability is to address some of the key human factors issues associated with occupant behaviour in selecting to use lifts or stairs. To date only a few studies have focused on these human factors issues. The EXODUS development team is attempting to address these issues through an international survey aimed at understanding and quantifying some of the factors associated with occupant device selection in both circulation and evacuation situations.

With the increasing number of high-rise and super high-rise structures being planned and built around the world, the viability of using stairs only for full building evacuations is coming more and more into question. As a result, building engineers are increasingly turning to lifts as a

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DOI: 10.1002/fam

means to safely address full building evacuation scenarios. However, whilst solving the mechanical issues associated with using lifts for evacuations has made considerable progress in recent times, considerably more effort is required to fully address the operational and human factors issues associated with lift usage in emergency situations.

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DOI: 10.1002/fam