Evacuation of Tall Construction Sites

A Collaborative Study between FSEG & Multiplex

Funded by IOSH

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Acknowledgements

- The presenter would like to thank the following without whose help this project would not have been possible:
  - My fellow key investigators (Dr Steve Deere, Dr Xie Hue, Dr Lynn Hulse and Mr David Cooney) and FSEG staff who assisted with the evacuation trials and walking experiments,
  - Multiplex for their help, assistance and infinite patience during this project, with particular gratitude to Mr Jim Senior, H&S Director for Multiplex Europe and the 100 and 22 BG H&S site managers,
  - The 1078 construction site workers who generously gave their time during the four evacuation trials and five walking speed experiments,
  - The Institution of Occupational Safety and Health (IOSH) for their financial support for this project.

Acknowledgements

- The full report will be freely available on the IOSH website some time in July 2019
  - Link will be publicised on FSEG website and FACEBOOK pages.
- The report is currently undergoing peer review.
- Until the report is officially released, all results presented here are considered provisional and subject to change.
- All the opinions expressed in this presentation are solely those of the author.

Construction Site Evacuation

- Construction is one of the most dangerous industries in the world.
- 2017-2018, 38 fatalities in accidents on UK construction sites
  - 4th highest rate of fatal injuries (per 100,000) in the work place
- HSE statistics: there are thousands of construction site fires annually.
- Fatal fires are rare however, there have been major fires in construction

Basingstoke, UK
Sept 2010

Shanghai
Nov 2010

Oakland USA
July 2017

Circular Quay Sydney
Feb 2018

- Catastrophic events, such as fire, severe weather, partial building collapse and unexpected events will require the full evacuation of the site.
- How do we plan for and manage construction site evacuation?

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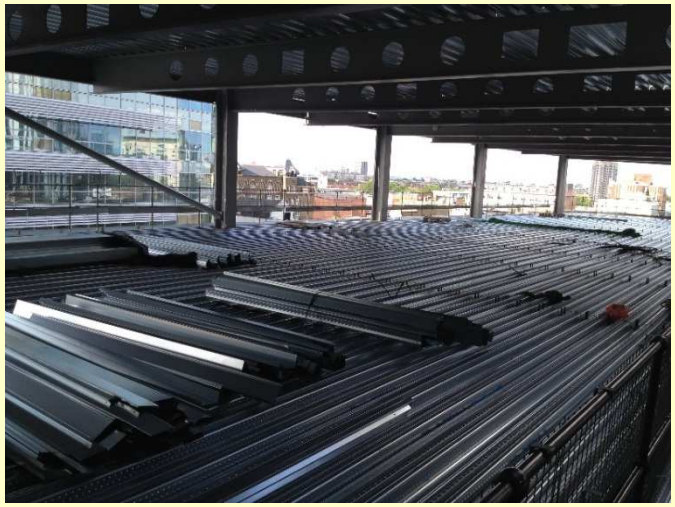
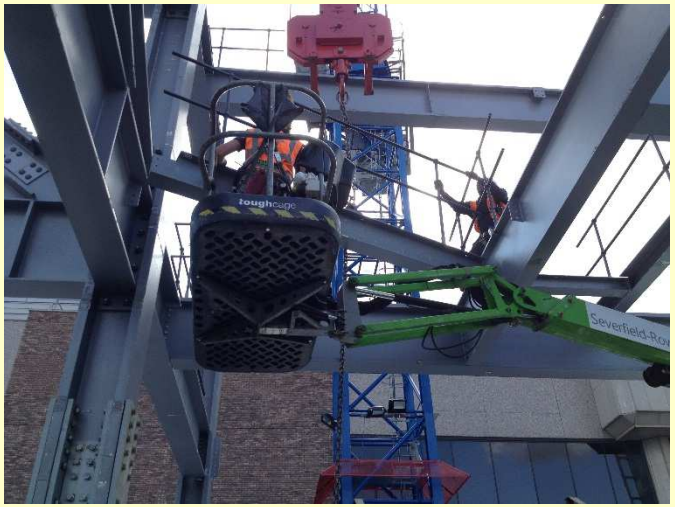
Examples of Health and Safety Guidance

- **HSE, The Regulatory Reform (Fire Safety) Order 2005 (FSO)**
  - **Regulation 15**. Procedures for serious and imminent danger and for danger areas (Page 12)
    – "…the procedures … must enable the persons concerned …… ***in the absence of guidance or instruction*** **……** to ***stop work and immediately proceed*** to a place of safety in the event of their being exposed to ….unavoidable danger."
- **HSE, The Construction (Design and Management) Regulations 2015 (CDM 2015)**
  - **Regulation 31**. Emergency routes and exits (Page 16)
    – "… a ***sufficient number*** of suitable emergency routes and exits must be provided to enable any person to reach a place of safety ***quickly*** in the event of danger."
- **HSE**, Fire safety in construction work HSG168 HSE Books 1997 ISBN 0 7176 1332 1
  - **Travel distance:** 190 – 196 (Page 35, 36)
    – "…It is important not to over-estimate how far people can travel before they are adversely affected by fire. ***Appropriate distances and the time taken to reach safety will depend on various factors*** …"

Construction Site Evacuation - Issues

- Does not have fire engineered evacuation solution
- Not governed by evacuation regulations.
- Physical layout constantly changing making wayfinding difficult and requiring evacuation rotes to be constantly updated
- Floor surfaces can be physically challenging hindering rapid movement.
- Some activities must be made safe prior to evacuation.
- Working at height.





FSEG Construction Site Evacuation Trails

- FSEG conducted 4 full-scale evacuation trials and 5 walking speed experiments using Multiplex sites.
- These 9 trials involving 1072 participants, generating around 2200 data points generating a unique evacuation evidence base consisting of:
  - The evacuation of 920 participants,
  - The measurement of 920 exit times,
  - The measurement of 275 response times,
  - Walking experiments involving 152 participants,
  - The measurement of 545 walking speeds over four different surfaces
  - The measurement of 126 stair ascent/descent speeds on two different types of temporary stairs,
  - The measurement of 59 ascent/descent speeds for ladders,
  - The measurement of 203 interpersonal distances on temporary stairs.

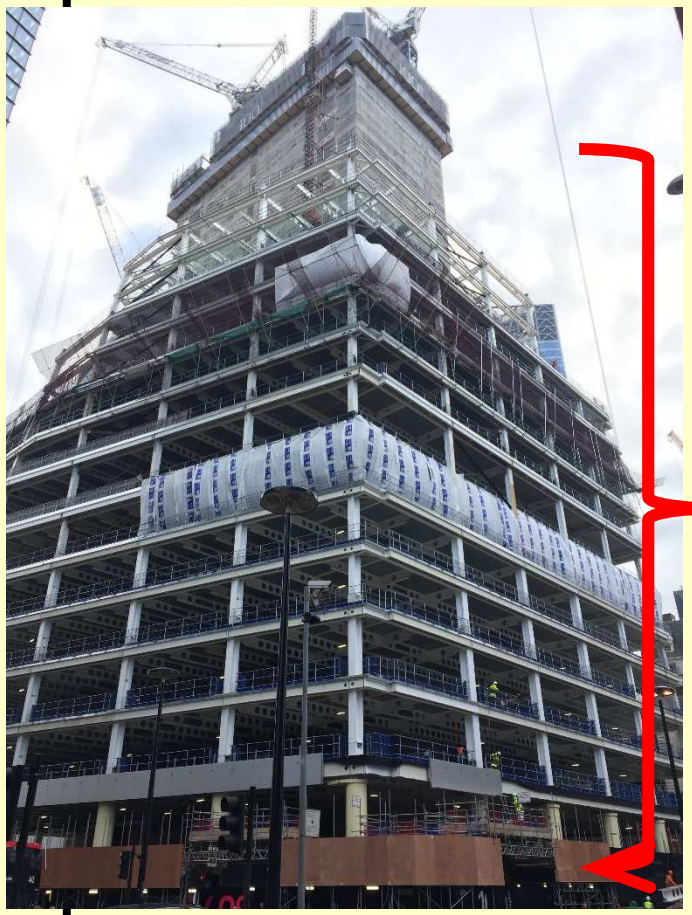
Three Areas of Construction

Jump/Slip Form

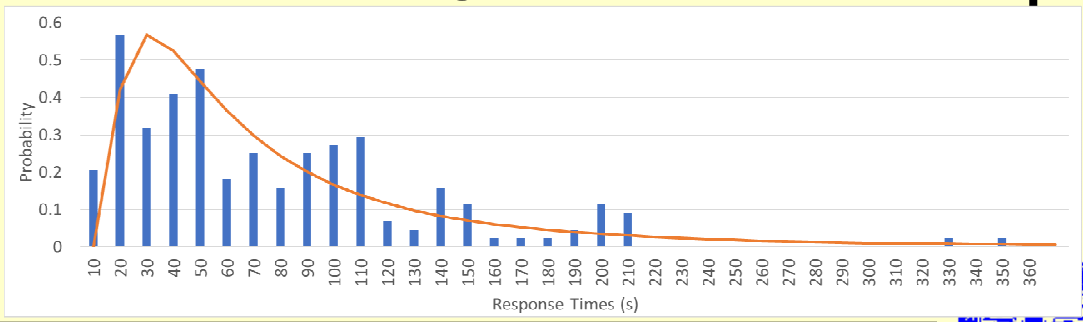
Core

Partially completed floors

Response Time Analysis – Main Building



- Based on data from three trials in two buildings involving 157 data points.
- Analysis suggests data from three trials are from the same distribution
- Represents workers involved in a variety of activities such as fitting rebar, glazing, MEP, etc., and includes those working at height and isolated workers
- Valid for heights of construction up to 39 levels.
- Excludes workers involved in concrete pour and workers in high tower cranes.

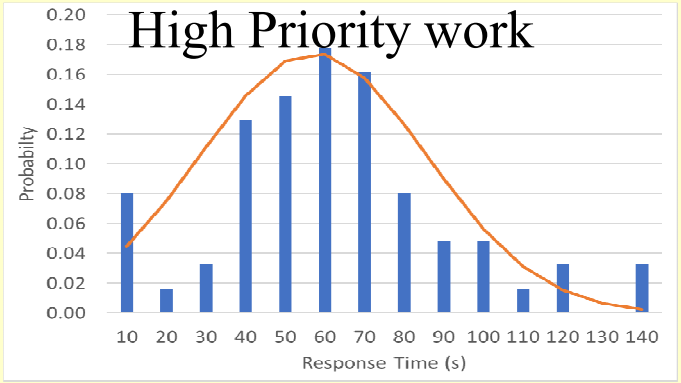


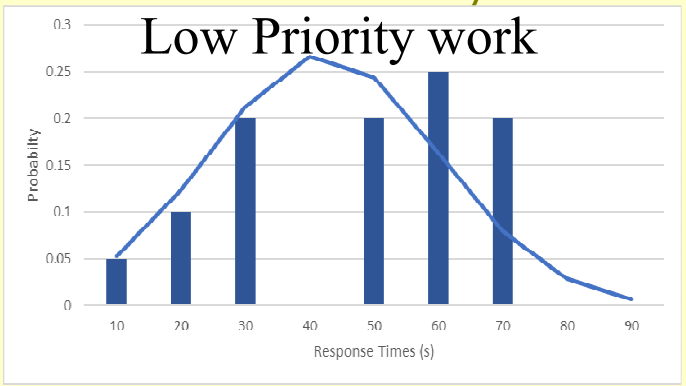
Exceptionally Long Response Times

- Glaziers cannot begin evacuation process until glazing made safe.

- Isolated workers prolong response unless staff intervention

Formworks Response Time Analysis





- RT distribution for workers in the FW is different to that in the MB
  - 88 response times from 3 trials collected
- Generally shorter than in MB
  - FW average across 3 trials 29 s – 58 s
  - MB average across 3 trials 62 s – 75 s
- FW RT is NORMAL rather than Log-normal
- FW RT distribution is dependent on phase of work:
  - HP (prior to concrete pour) generally longer with average of 58 s.
  - LP (after concrete pour) generally shorter with average of 29 s.

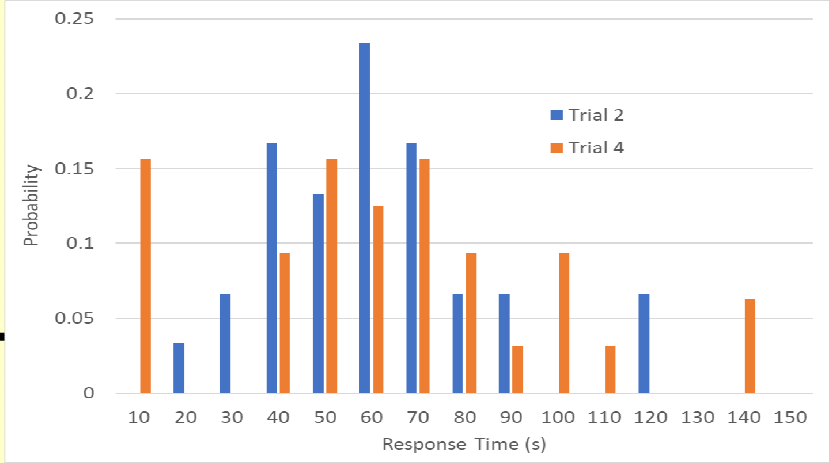
Is RT Dependent on Height of Construction?

RT Distribution for the MB

- Comparing the RT distributions for the three trials excluding FW:
  - Independent two Tail T Test, 99% confidence level
- Trial 1 and Trial 4 have similar worker distribution
  - Majority of workers located below Level 10, with remainder located below Level 19.
- Trial 3 significantly different worker distribution,
  - Majority of workers located above Level 22, with 42% located between Level 33 and Level 38.
- **Trial-1 Feb (100 BSG 15 floors)** vs **Trial-3 Oct (100 BSG 38 floors),**
  - T Test suggests distributions are identical (P = 0.64 at 99% confidence level).
- **Trial-3 Oct (100 BSG 38 floors)** vs **Trial-4 Nov (22 BSG 19 floors),**
  - T Test suggests distributions are identical (P = 0.3 at 99% confidence level).
- Results suggest:
  - Data from all three distributions are from similar distributions.
  - **Height does not appear to influence RT distribution within the MB for construction sites up to 39 Levels.**

RT Distribution for the FW

- Important that nature of work being undertaken in the FW is the same.
- Trials 2 and 4 involved similar phase of work – installing rebar prior to a concrete pour, hence High Priority.
  - Both involved 22 BG and both involved a jumpform
  - Trial 2 involves 28 workers while Trial 4 involves 32 workers
- Trial 2, FW at Level 13 while for Trial 4 FW at Level 33
- **Trial-2** vs **Trial-4**
  - T Test suggests distributions are identical (P = 0.705 at 99% confidence level).
- Results suggest:
  - Data from both distributions are from similar distributions.
  - **Height does not appear to influence RT distribution within the MB for construction sites up to 33 Levels.**



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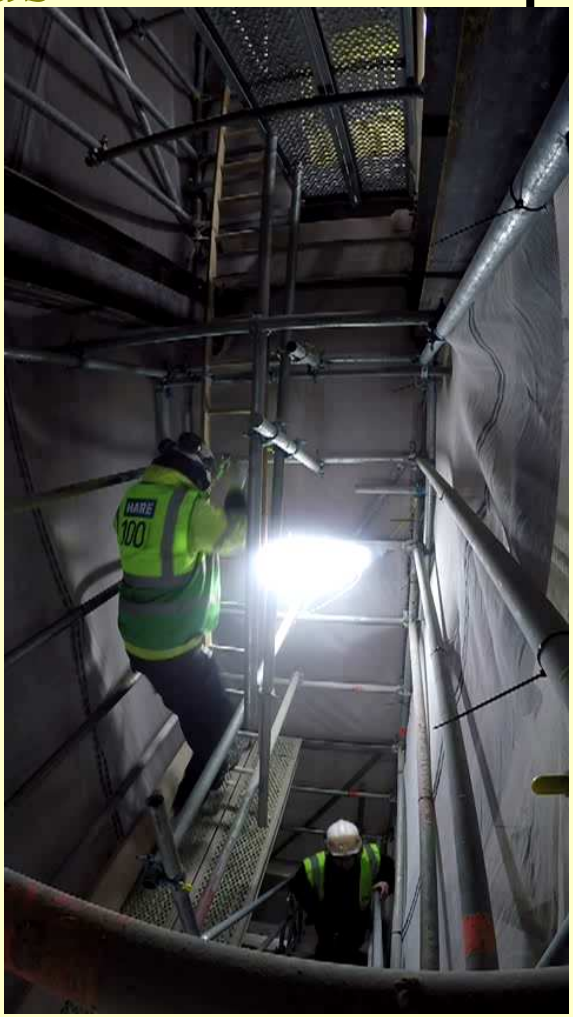
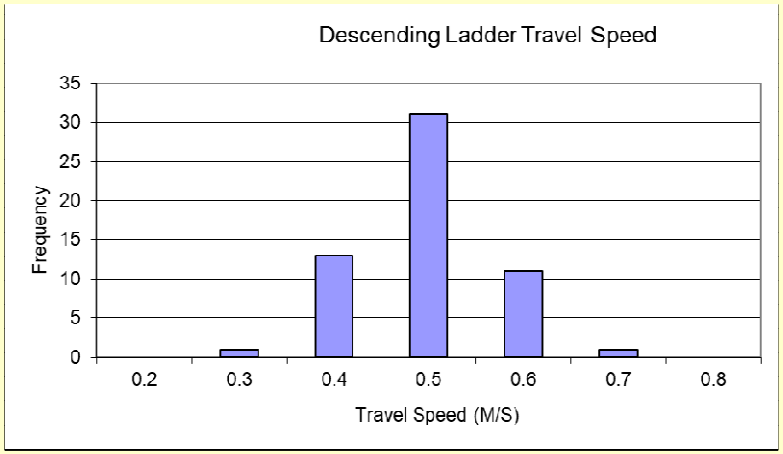
Vertical Speeds – Ladders and Scaffold Stairs

Ladder Travel Speeds

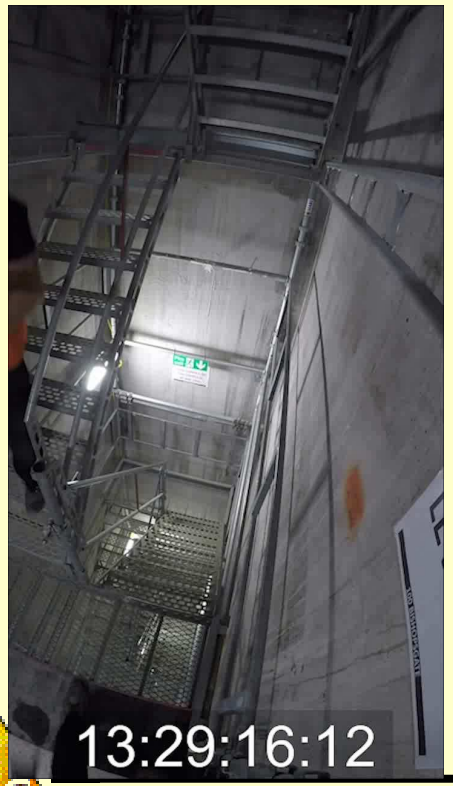
- Collected data for 59 workers using ladders.
  - Speed ascending ladder:
    - Average 0.42 m/s
    - Range: 0.39 – 0.44 m/s
  - Speed descending ladder:
    - Average: 0.45 m/s
    - Range: 0.29 – 0.61 m/s
  - **Descent ladder speed is 64% of stair speed.**
  - **Ascent ladder speed is 67% of stair speed.**





Scaffold Stairs

- Two types of scaffold stairs were used on the construction sites.
- Dogleg stairs: each flight is off-set by a landing
- Layered stairs: each flight is arranged on top of each other resulting in limited head clearance per flight – impacts travel speed.
- Results for Parallel stairs presented here.



Dogleg stair down

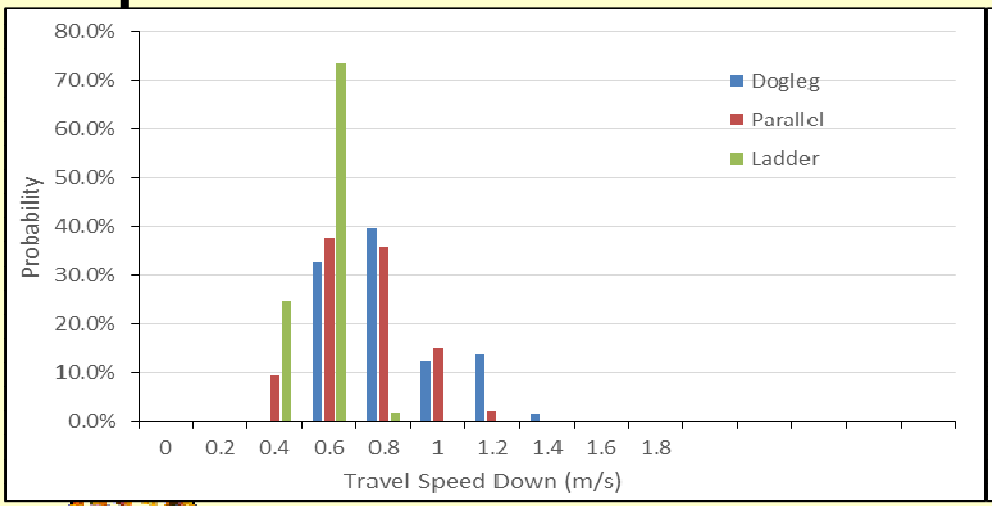
Parallel stair down

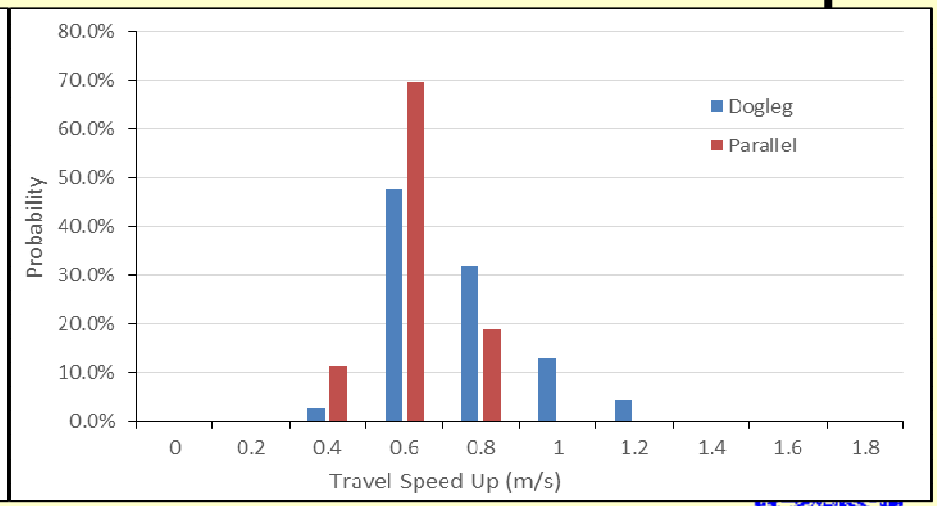
Ladders vs Scaffold Stairs vs Building Stairs

- Ladders are clearly a bottleneck in any evacuation route and their use should be limited

Descent	Dogleg stairs (m/s)	Parallel stairs (m/s)	Ladder (m/s)	Standard stairs average (Fruin) (m/s)
Min	0.42	0.36	0.29	(Male 51-80) 0.53
Average	0.72	0.64	0.45	(Male 30-50) 0.70
Max	1.21	1.15	0.61	(Male 17-29) 1.01

Ascent	Dogleg stairs (m/s)	Parallel stairs (m/s)	Ladder (m/s)	Standard stairs average (Fruin) (m/s)
Min	0.38	0.33	0.39	(Male 51-80) 0.51
Average	0.63	0.50	0.42	(Male 30-50) 0.63
Max	1.10	0.75	0.44	(Male 17-29) 0.67





Walking Speeds – The Impact of Floor Surface

Walking Speed Trials – Surfaces

Concrete surface

Metal deck with rebar

Along and across metal decking

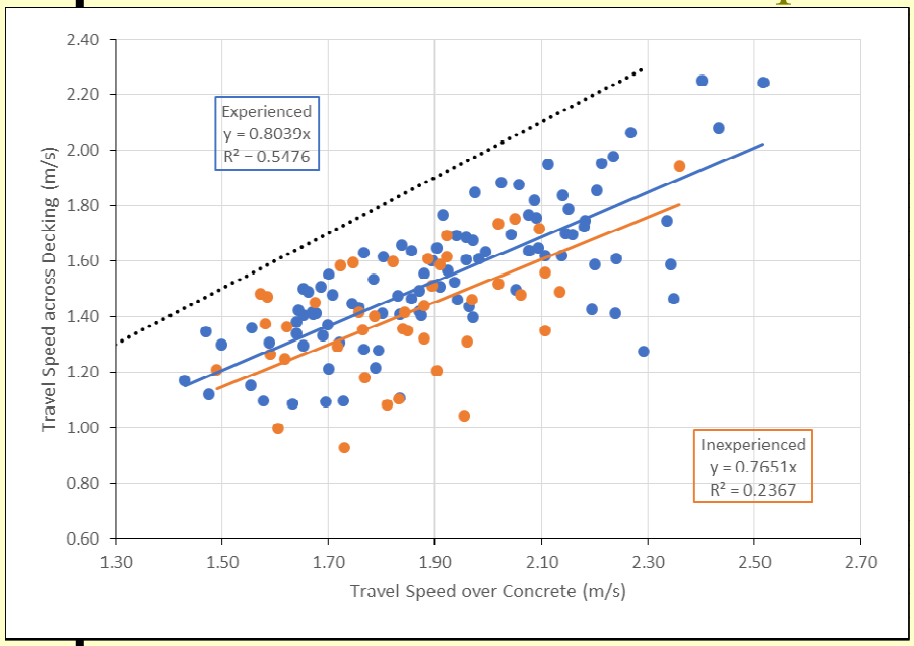
Walking Speed Trials – 144 data pts per category

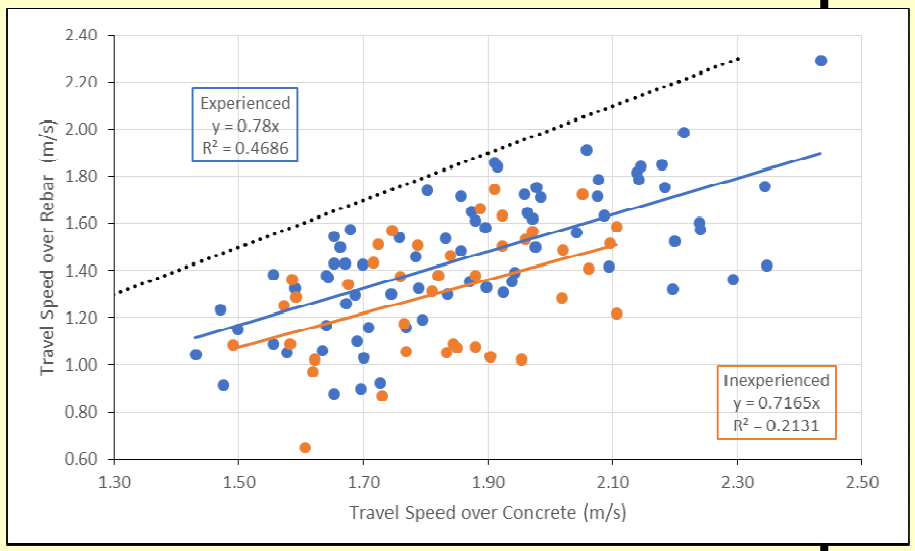
Person 1 walking in both directions across metal decking

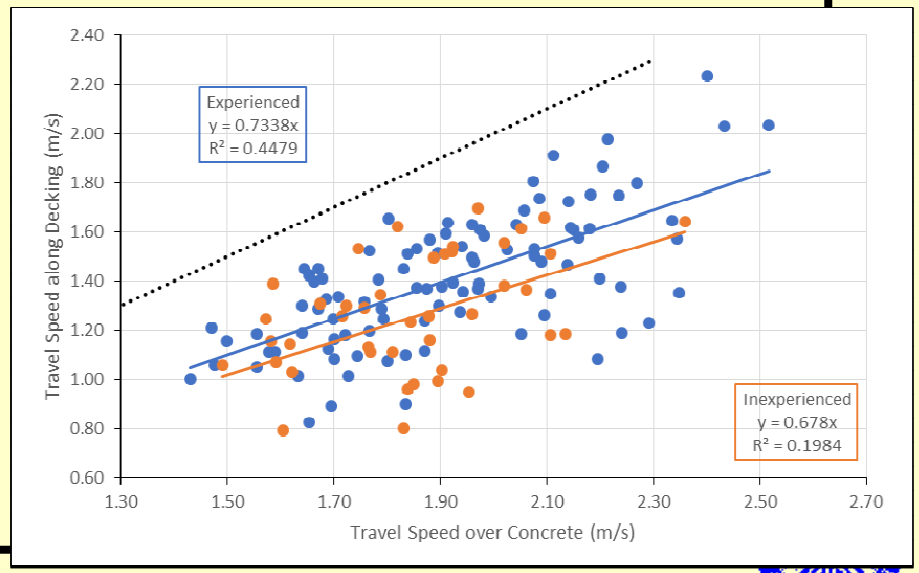
Person 1 walking across rebar

Person 20 walking across concrete

Travel Speed Trials Results

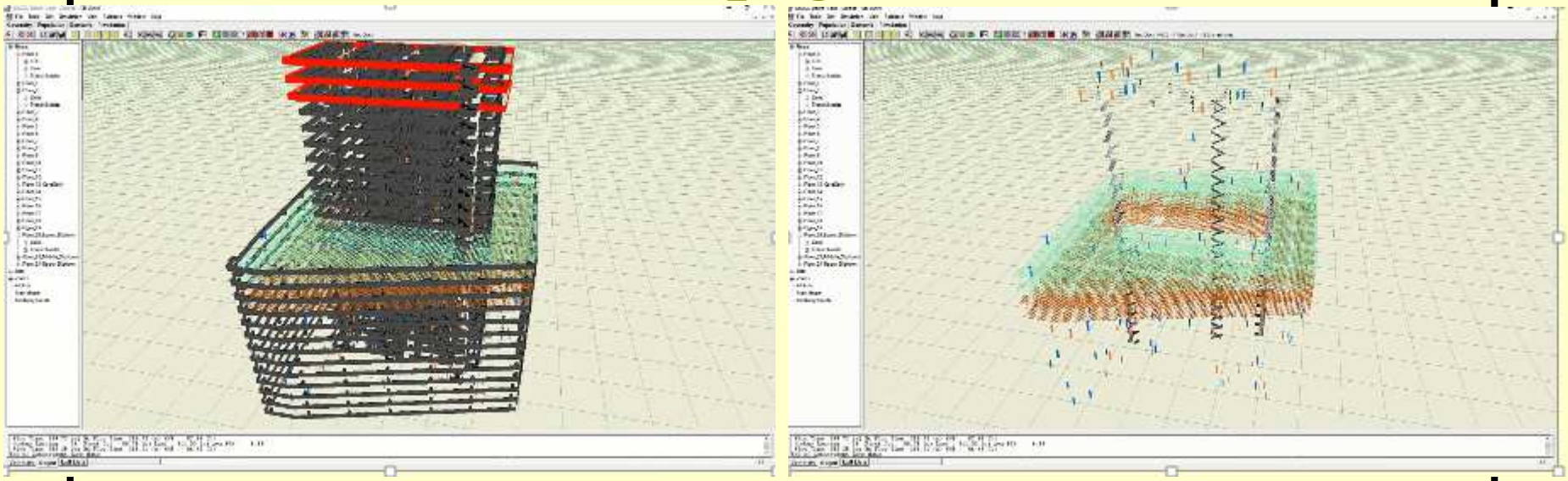






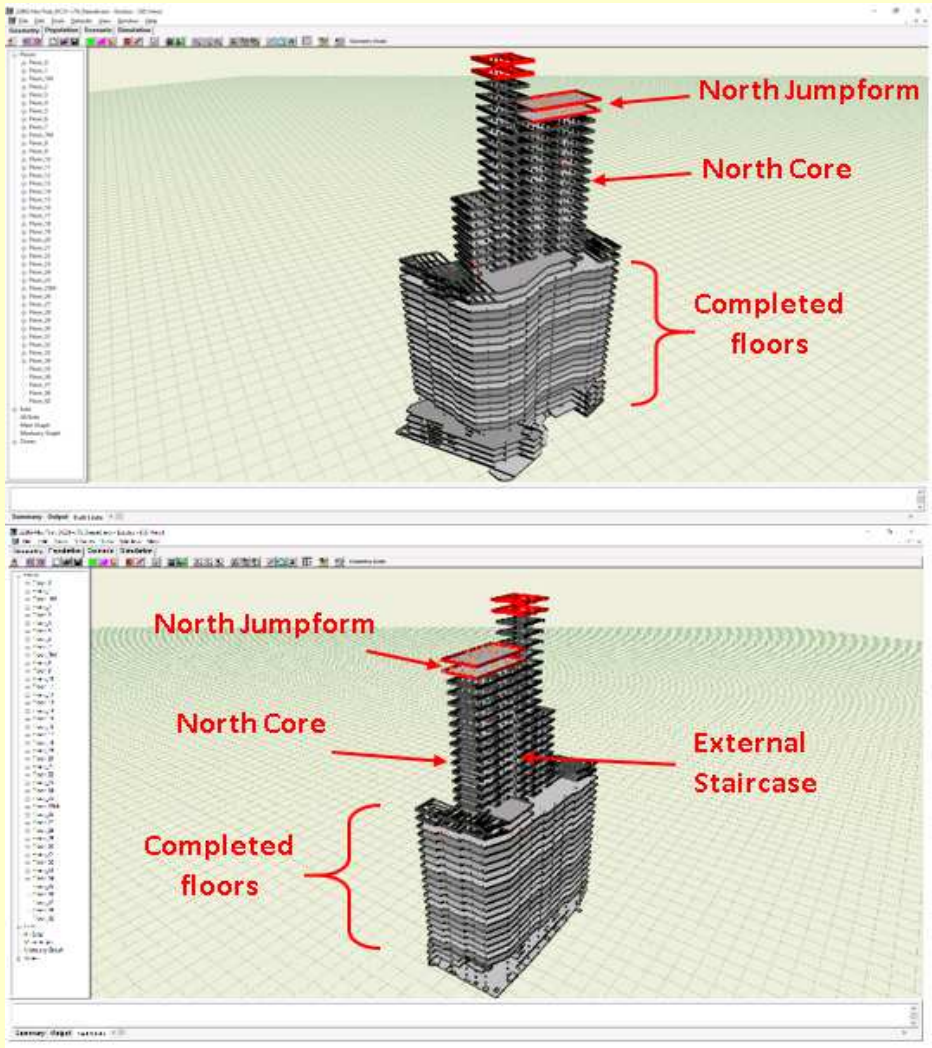
- Generally Speeds follow trend:
  - Concrete > Across Decking > Rebar > Along decking
  - But large variation.
- Speed reduction can be as much as 30%

100 Bishopsgate Demo

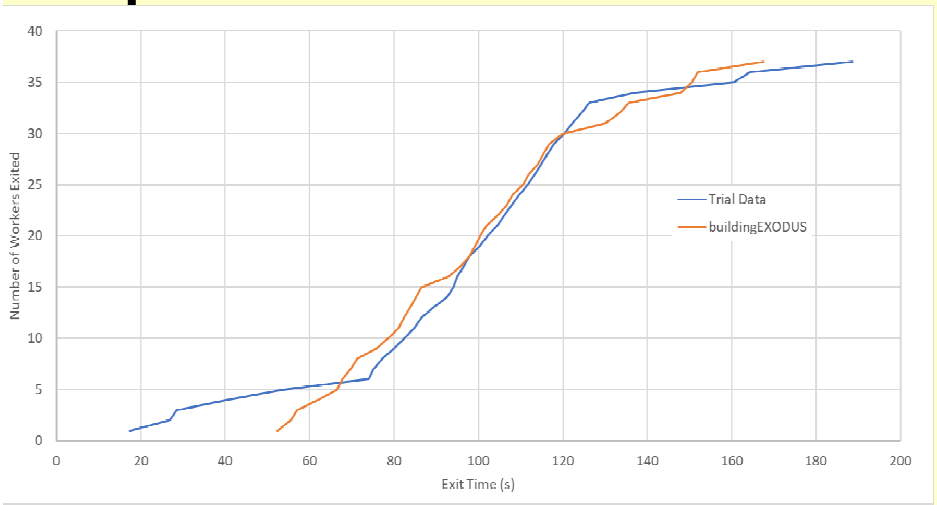


- Demonstration of high-rise construction site evacuation using the modified buildingEXODUS evacuation simulation software.
- 24 floors: 13 floors in construction, 8 core levels and 3 slip levels
- 184 agents: 20 in the slip, 164 elsewhere
  - Brown floor tiles represent Rebar flooring
  - Cyan floor tiles represent Metal Decked flooring
  - In the 2D window, direction of the metal decking is indicated by a line on each node

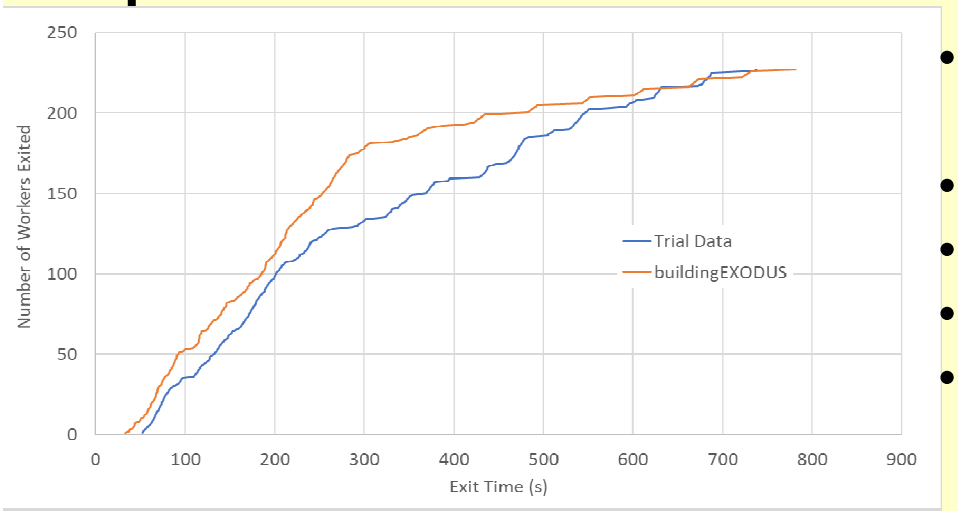
Validation Case – 22 BG evacuation



22 Bishopsgate Validation



- Exit from Jumpform
- Involves 37 workers
- HPFW RT distribution used
- 11% difference between predicted and measured evac time for the Jumpform.



- Exit from building of entire population
- Involves 227 workers
- MB RT distribution used
- Travel speeds based on collected data
- 6% difference between predicted and measured evac time for the building.

22 Bishopsgate Validation

- Uncertainty in validation data-set includes: starting floor for some workers, location on starting floor, presence of clutter, precise response time distribution.
- Objective measure of acceptable agreement between model prediction and experimental data has been specified using a performance metric defined using the ERD, EPC and SC.
- The level of acceptability is based on bEX which was subjectively acceptable.
- The performance measures are:

For the overall predicted exit curve:

(i) ERD ≤ 0.23

(ii) 0.8 ≤ EPC ≤ 1.2

(iii) SC ≥ 0.80 with s/n = 0.07

(iv) Difference between the predicted total evacuation time for the entire building and the measured value to be within 6%.

While for the predicted jumpform exit curve:

(i) ERD ≤ 0.11

(ii) 0.8 ≤ EPC ≤ 1.2

(iii) SC ≥ 0.75 with s/n = 0.05

(iv) Difference between the predicted total exiting time for the jumpform and the measured value to be within 11%.

Exploring Improvements in High-Rise Construction Site Evacuation using the buildingEXODUS evacuation software

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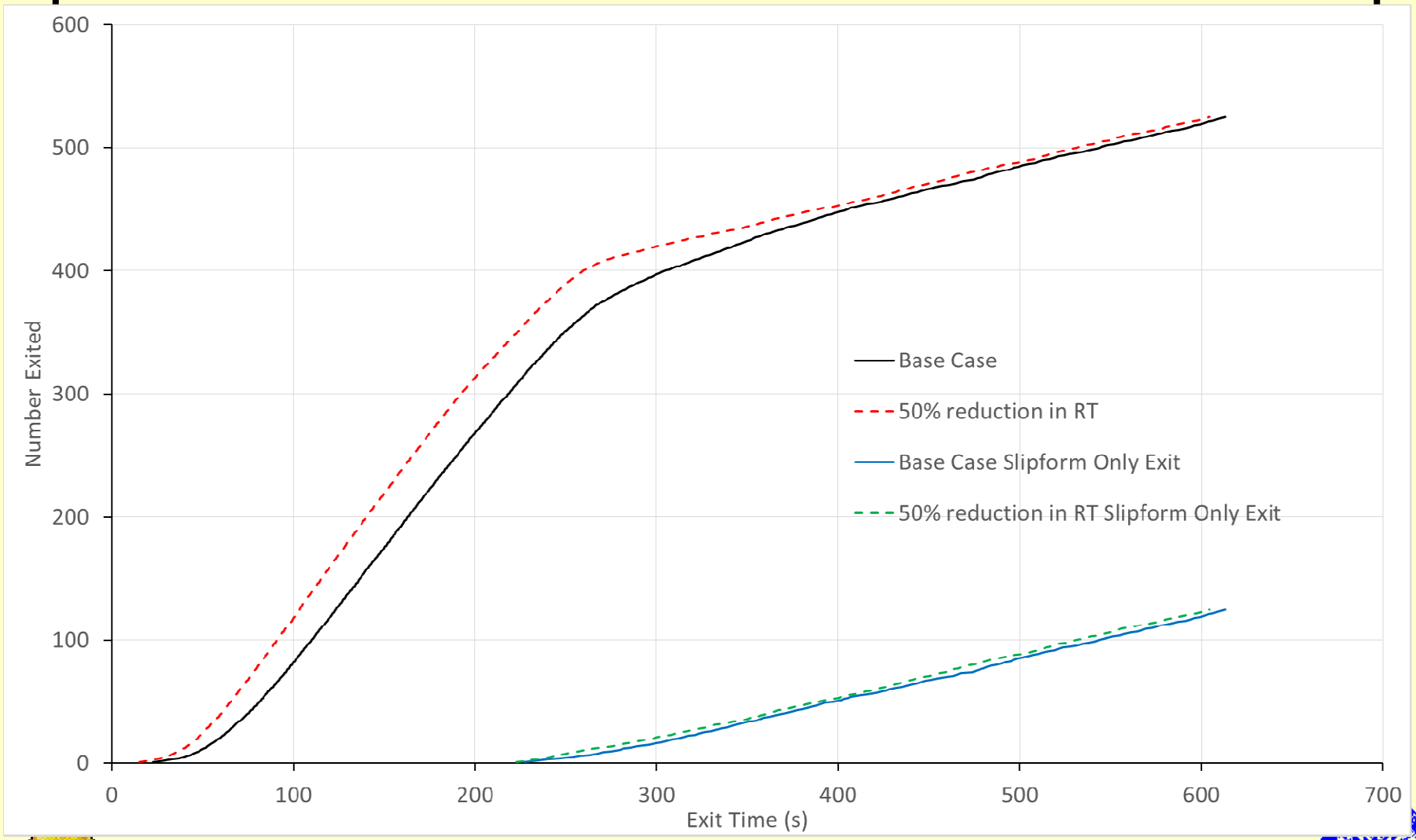
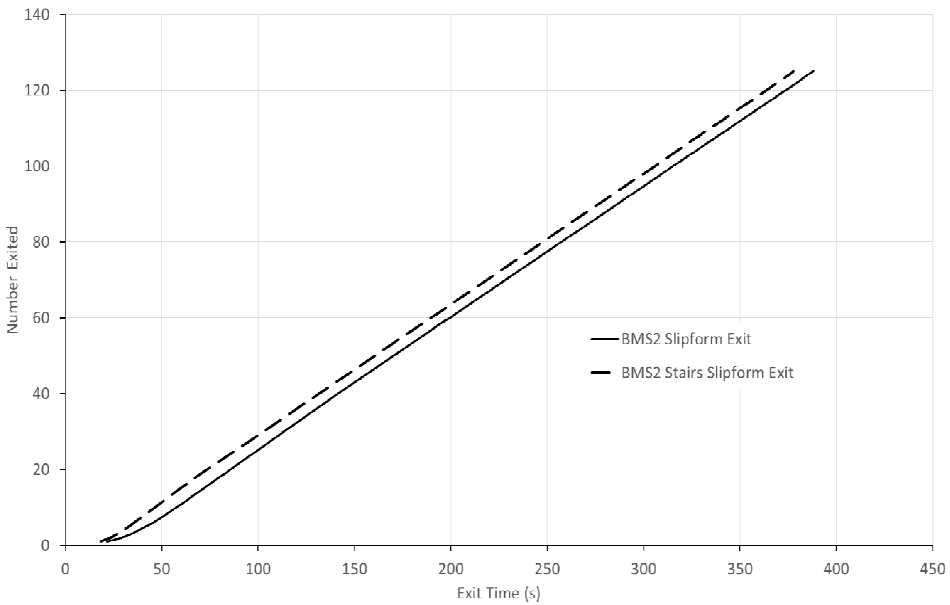
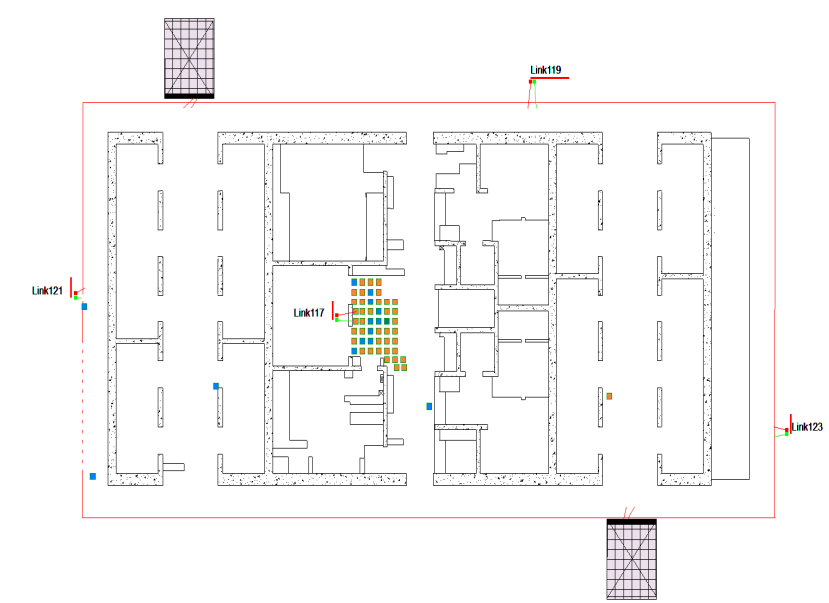
50% Reduction in Response Time



50% Reduction in Response Time – Congestion in Formworks





	Upper Deck				Middle Deck			
	Start Time (s)	Most severe (s)	End Time (s)	No. of agents	Start Time (s)	Most severe (s)	End Time (s)	No. of agents
Ladders	35	146	311	49	45	177	376	25

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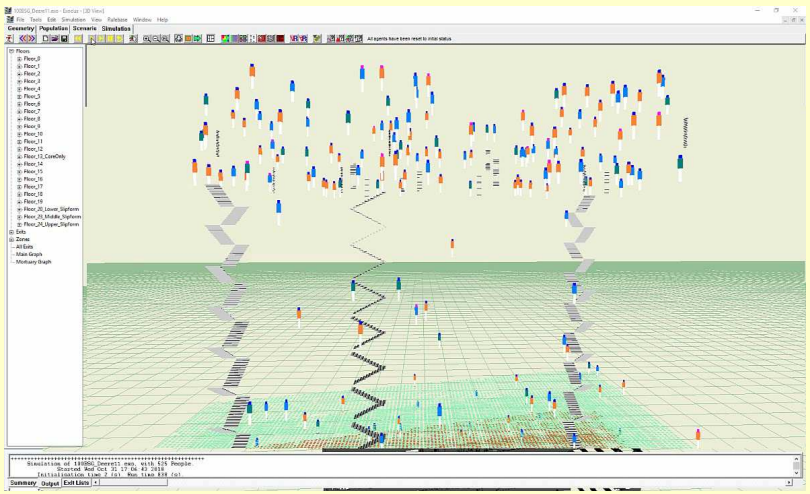
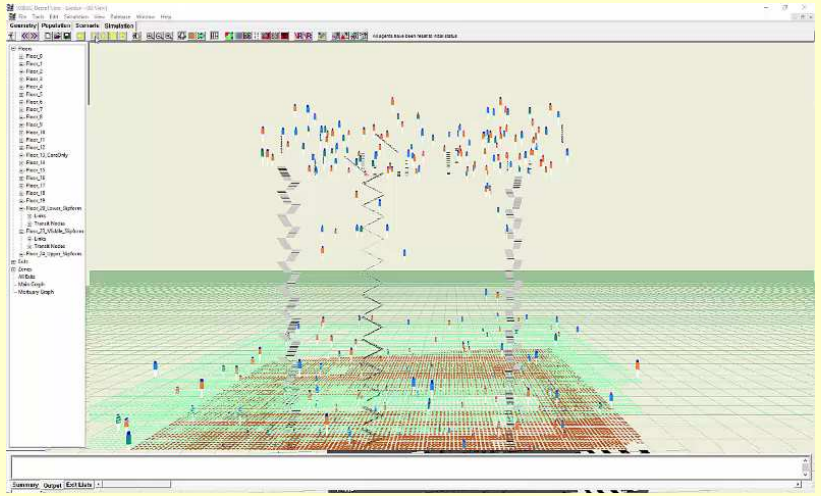
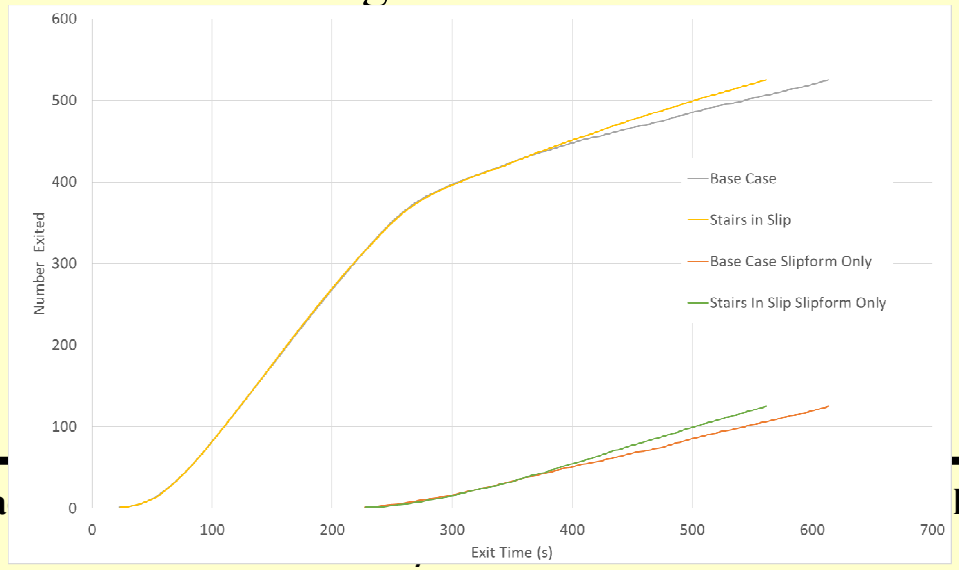
Potential issue with ladders in formworks



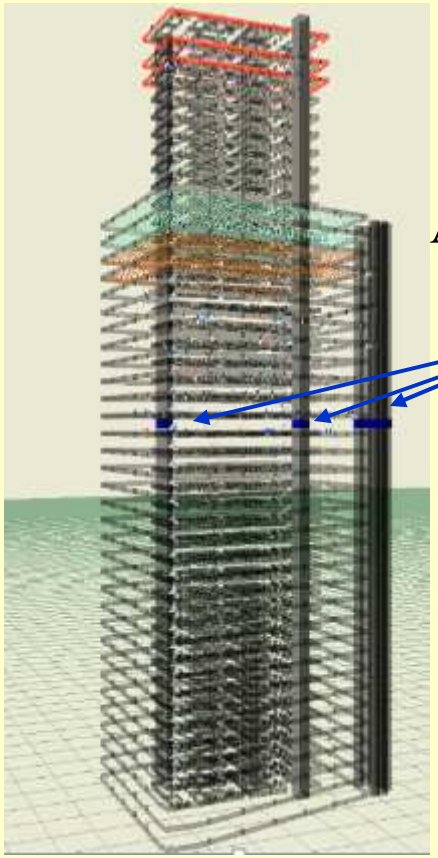
125 workers in slipform: 6 m 27 s
to clear slipform with ladders
10 m 13 s to evacuate building



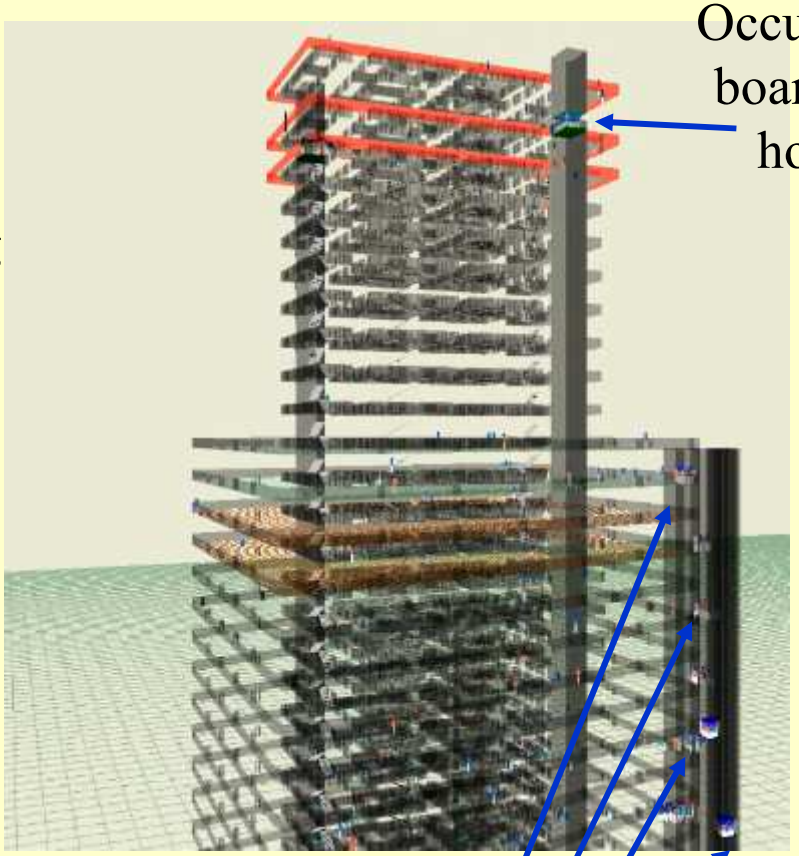
125 workers in slipform: 5 m 20 s
to clear slipform with layered stairs
9 m 21 s to evacuate building



Use of Hoists for Evacuation



Ascending hoists



Occupants boarding hoist

Occupied Descending hoists

https://www.facebook.com/FSEG.UK/videos/2273834856165399/

Use of Hoists for Evacuation

Fast Hoists with High Capacity			
Height of construction	Stairs Only	Hoist Only	50/50 Stairs/Hoist
23 Levels	615 s	25% (463 s)	23% (471 s)
43 Levels	852 s	30% (592 s)	19% (692 s)

Slow Hoists with High Capacity			
Height of construction	Stairs Only	Hoist Only	50/50 Stairs/Hoist
23 Levels	615 s	4% (589 s)	7% (570 s)
43 Levels	852 s	-26% (1078 s)	4% (821 s)

Slow Hoists with Low Capacity			
Height of construction	Stairs Only	Hoist Only	50/50 Stairs/Hoist
23 Levels	615 s	-37% (845 s)	8% (568 s)
43 Levels	852 s	-80% (1530 s)	-16% (991 s)

Concluding Comments

- A unique evidence base has been developed characterising, for the first time, the performance and behaviour of construction workers during evacuation, based on:
  - 4 full-scale unannounced evacuation trials conducted on 2 different high-rise sites at 2 different phases of construction involving a total of 932 construction workers.
  - 5 walking speed experiments involving 152 construction workers.
- The Evidence Base consists of:
  - response times for workers in the main building and the formworks,
  - worker walking speeds on different surfaces: concrete, decking and decking with rebar,
  - worker ascent/descent speeds on temporary dogleg/parallel scaffold stairs and ladders.
- The data has been incorporated in the building evacuation simulation tool buildingEXODUS, providing it with a unique capability to simulate evacuation from high-rise construction sites.
- The performance of the software has been validated using measured data collected from the trials.
- The validated software has been used to explore how evacuation procedures for high-rise construction sites can be improved, including:
  - the impact of reducing worker response times,
  - replacing ladders with temporary scaffold stairs within the formworks, and
  - using hoists to assist in evacuation

Additional Material
MIXED REALITY TRAINING ENVIRONMENT

While the system demonstrated in the next few slides has been developed by FSEG and partners as part of an EU Horizon2020 project (AUGGMED) for applications to security scenarios, the system could be applied to safety related applications such as:

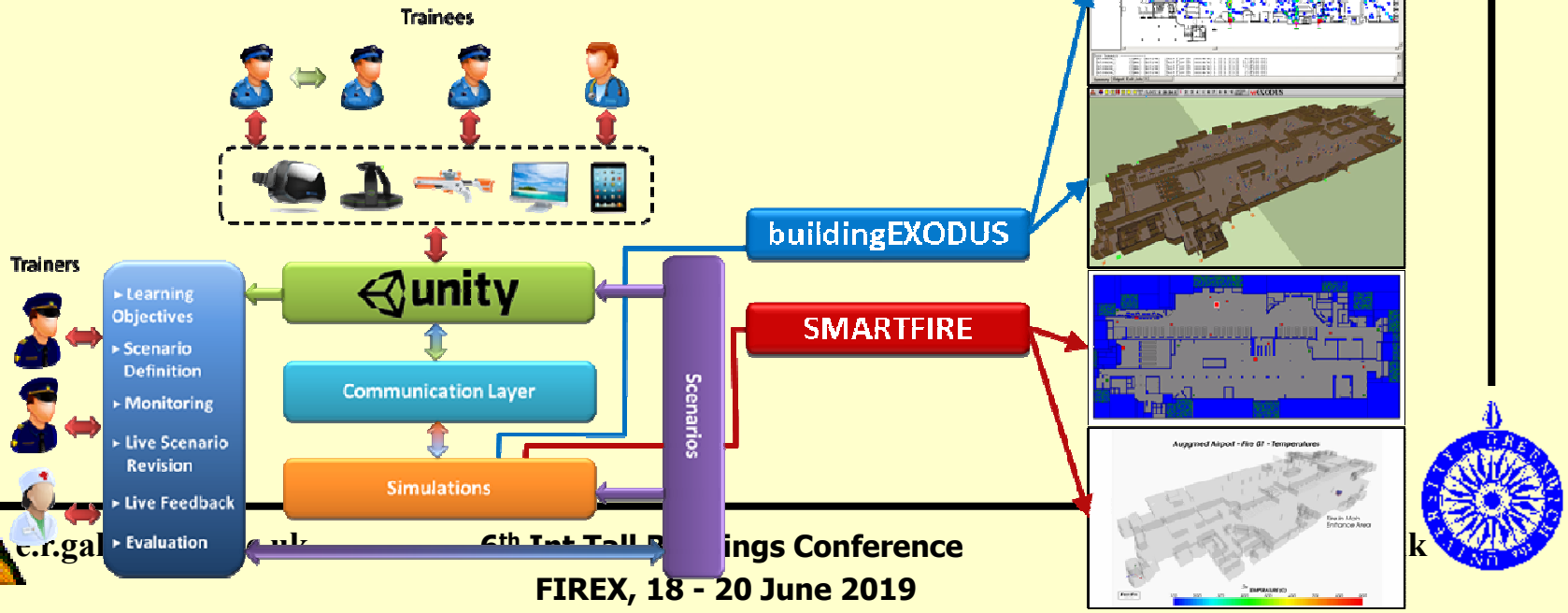
- training occupants of high-rise buildings in evacuation procedures and
- assisting in the development of evacuation procedures

For info concerning AUGGMED see FSEG website at https://fseg.gre.ac.uk/fire/auggmed.html

AUGGMED – Automated Serious Game Scenario Generator for Mixed Reality Training

- Aim was to develop a serious game platform to enable single and team-based training of security staff, police, counter-terrorism officers, etc responding to terrorist scenarios in crowded places
- AUGGMED platform will generate non-linear scenarios designed to improve skills such as: problem solving, analytical thinking, quick reactions,

▪Scenarios include advanced simulations of crowds (EXODUS) and hazardous environments including fire (SMARTFIRE) and explosions.

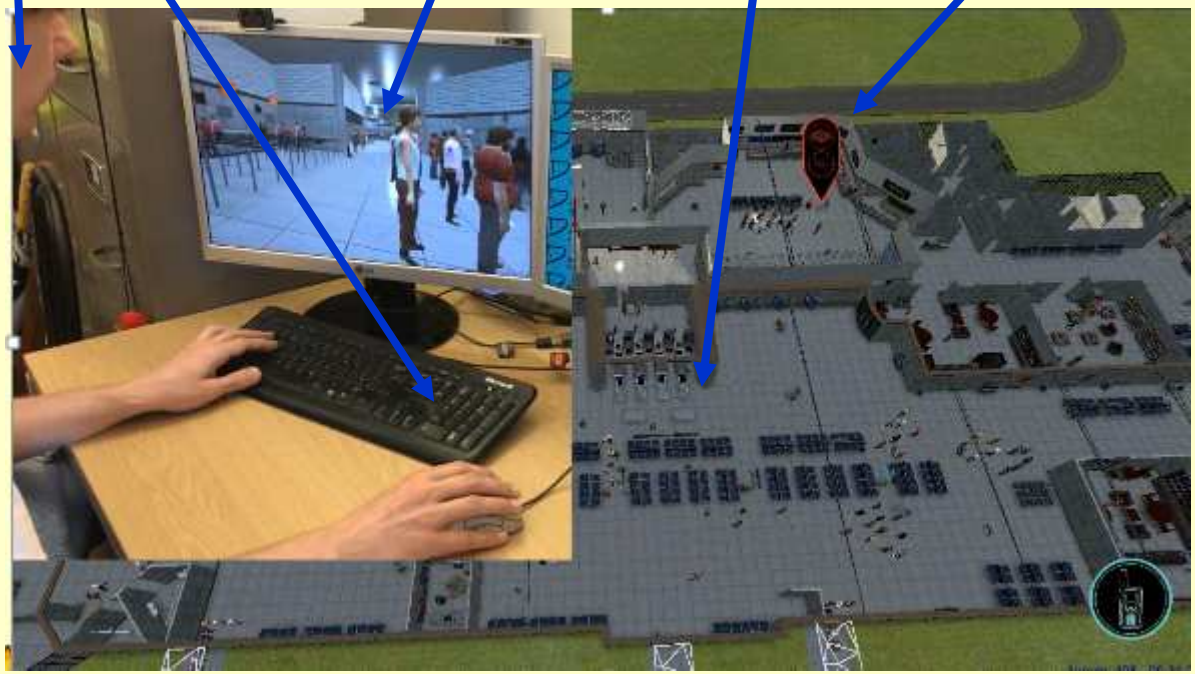


Capabilities

- As part of the AUGGMED training environment, three capability levels were developed:
  - **Level 1:** trainee uses mouse + keyboard, views game play on computer screen. No mobility, no tactile feedback. Trainees can join locally or remotely.
  - **Level 2:** trainee using immersed VR head mounted display and hand controllers. Limited mobility and tactile feedback. Trainees can join locally or remotely.
  - **Level 3:** AR environment, training on site, full mobility and advanced tactile feedback. Trainees can join locally or remotely.

Level 1 : External user control of EXODUS agent

- 'God's View' on main screen, used by 'trainer'
- External user's view (trainee) on insert, user is controlling the flagged agent
- Trainee experiences the crowded environment and can explore the environment using keyboard and mouse.



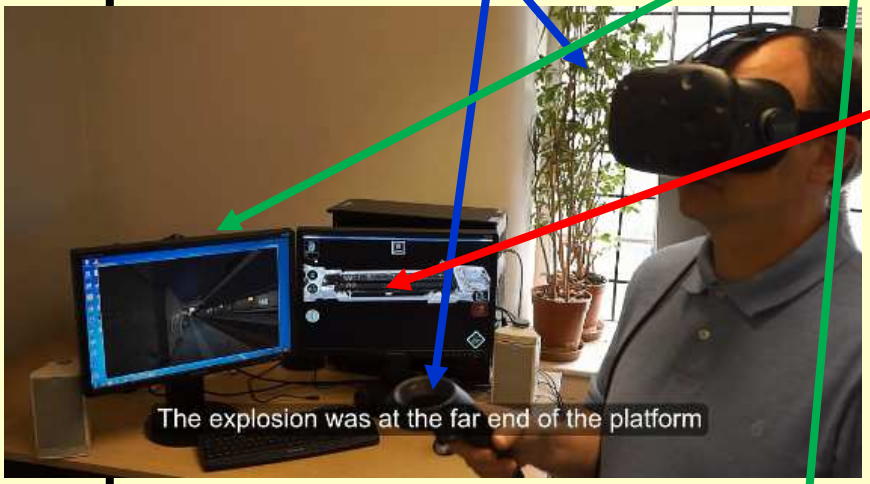
Level 2 : Immersive VR Environment – triage scenario

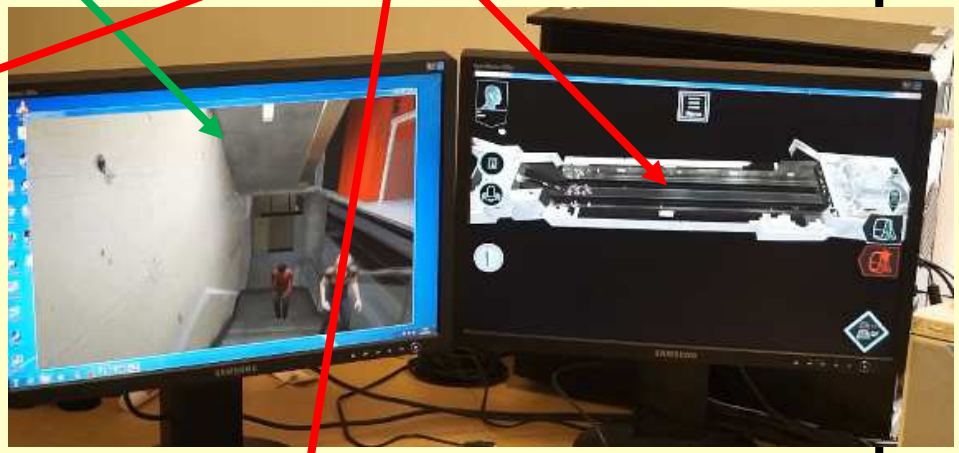
- Bomb blast in Muntaner Metro station with many casualties
- Trainee is meant to triage the seriously injured and ignore the walking wounded.

Trainee controls movement of his avatar using hand controller and is immersed in scenario by headset

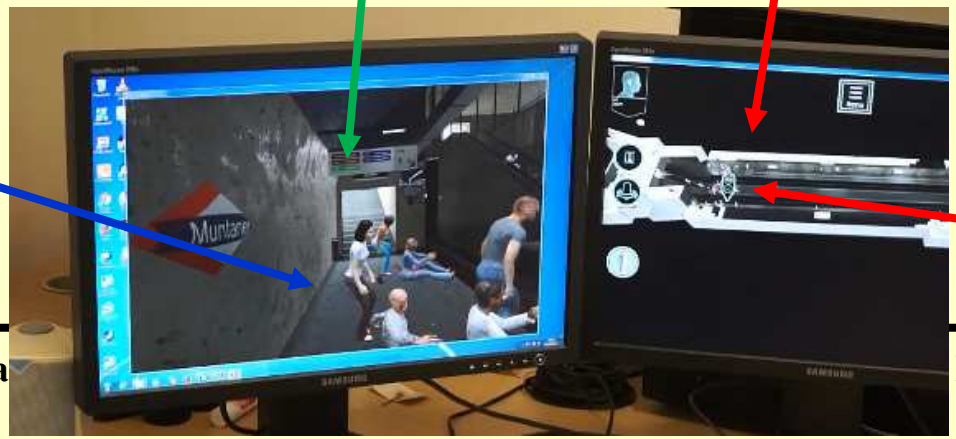
Trainee's view

Trainer's view





Trainee arrives at scene and begins triage process



Current location of trainee

FSEG

e.r.galea@gre.a

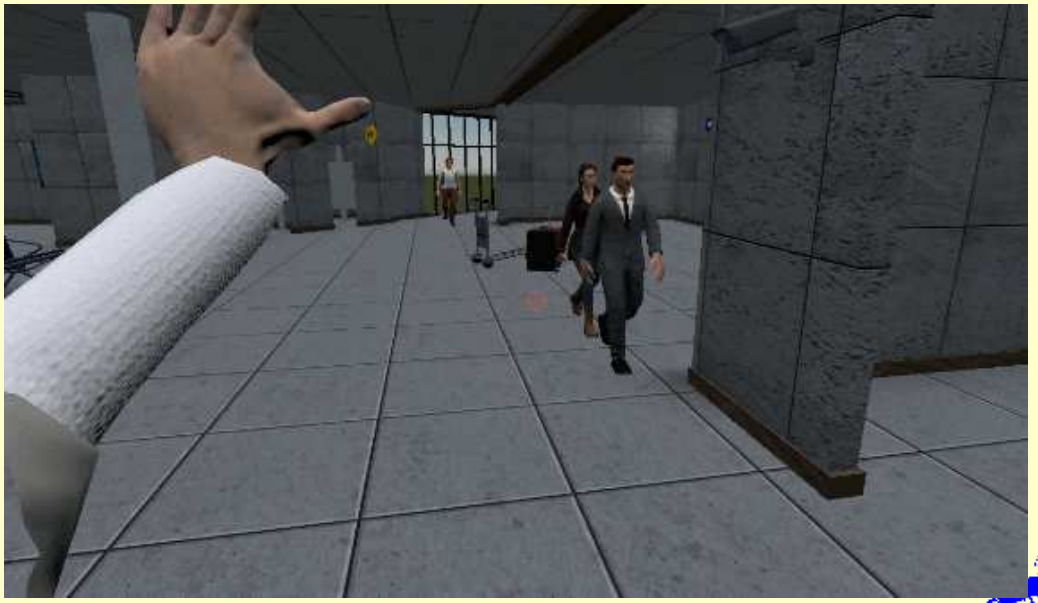
http://fseg.gre.ac.uk

Additional EXODUS Behaviours

- As part of the AUGGMED developments, EXODUS software enhanced allowing ‘Hand Gestures’ and ‘Voice Commands’ to be made by the ‘real person’ trainee and simulated avatars react to these commands.
- In this example, the real persons AVITAR is issuing the ‘stop’ voice and hand command. As in real life, some of the simulated agents react while others don’t, resulting in the in the real person having to issue a second ‘stop’ command.

- Simulation environment can support multiple players.
- Players do not have to be co-located. They can be located in:
  - different rooms
  - different cities or
  - different countries

  and simultaneously interact with each other.



Level 2 : Immersive VR Environment – terrorist scenario

- Marauding armed terrorist is active in a passenger terminal.
- Special forces trainee using Level 2 environment to practice tactics involved in locating and neutralising active shooter in crowded space

Headset provides immersive environment

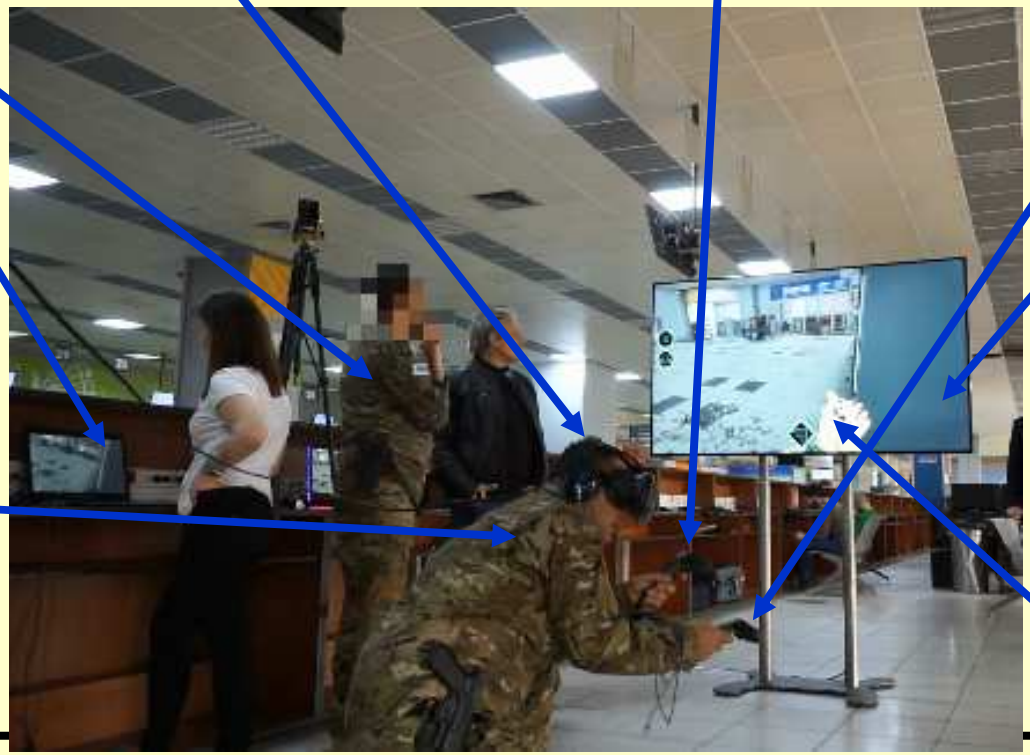
Hand controller allows trainee to move through environment

Hand controller simulating trainee weapon

Trainer1

Trainer2 with multiple views on screen

Trainee

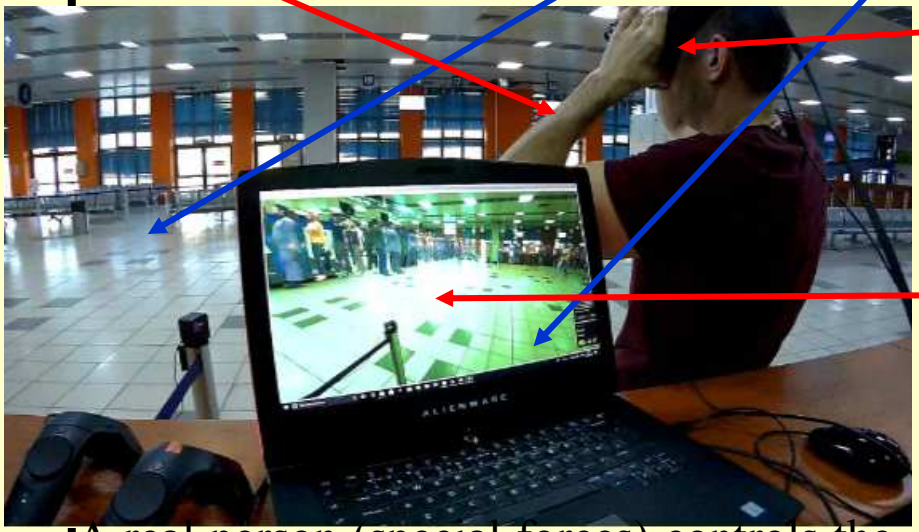


Trainee's view. Screen can show both Trainer and Trainee views.

It currently shows the trainee view, note gun held by trainee

Level 3 : Augmented Reality Environment

Trainee is in the real facility, view on screen is view seen by trainee through headset



Imposed on the trainee's view of the real facility is the simulated scenario. Hundreds of passengers are queuing up waiting to be processed or simply walking through the terminal.

A real person (special forces) controls the Avatar representing the terrorist and is also immersed in the environment, opens fire and kills a number of the simulated population who attempt to flee or take cover.

Hand of the real person (terrorist) seen in the real and simulated view with the weapon