EVACUATION SIMULATION MODELING FOR A DEEP UNDERGROUND SUBWAY STATION

Bryan Chin Kok Siong, Benjamin Chan Jia Jun, Ko Sing Yen

AECOM Singapore Pte Ltd
300 Beach Road #23-00 The Concourse
Singapore 199555
e-mail: Bryan.chin@aecom.com, Benjamnjj.chan@aecom.com, Singyen.ko@aecom.com

ABSTRACT

Pathfinder, amongst other agent-based evacuation modelling software, contains an underlying approach that all agents are fully aware of their location with respect to all available exits in the evacuation model. This may or may not be true in real life. Building occupants may not be fully aware of all available exits in a building, particularly when exits are placed within less frequented areas (e.g. back-of-house facilities in a hotel or shopping mall). There is also an inherent tendency for building occupants to evacuate a building via routes/exits that they are familiar with. Agent-based evacuation simulation models have proved to be both useful and representative of occupant evacuation for typical multi-storey high-rise buildings. NFPA 130 requires that all occupants evacuate from the station platform within 4 minutes, with an underlying assumption that all exits will be utilized equally. In our case, evacuation modelling for a deep underground subway station showed mixed results. User judgment is then critical in assessing the sensibility of the evacuation simulation results and various amendments to the inputs would be required to arrive at a more logical result. This paper examines an evacuation simulation study carried out for a deep underground subway station, comparing differences in various user input parameters (e.g. various cost factors for occupant profiles, locations of final exits etc.) across the same simulation model, finally arriving at what we judged as being sensible. The key challenge faced was modelling the locations of the various final exits, simply modelling the actual layout of the station with the actual locations of the final exits gave somewhat skewed results. Judgment in making sensible changes to the model is required to ensure results obtained made adequate sense.

INTRODUCTION

The world is increasingly an urban environment. Its population is expected to increase significantly in the next four decades with majority of the increase occurring in urban areas. By 2050, 70% of all people will live in cities and the world urban population will have more than doubled compared to the turn of the century (UN, 2007, UN, 2013). Majority of this urbanization is expected to occur in ASEAN and the rapidly expanding cities will need to meet the increased demands for infrastructure adding to the existing problem of congestion. Investing in urban rail infrastructure is proven to be one of the most efficient solution for reducing traffic congestion, aiding population and economic growth whilst reducing emissions-related pollution. This is evident from the rapid investment and development of urban underground subway projects in the region in cities such as Jakarta, Kuala Lumpur, Singapore, Manila and Ho Chi Minh etc.

The design of underground subway stations poses many challenges, one of which is the fire safety of the passengers during a fire emergency. Several Codes and Design Guidelines are available and stipulate the fire and life safety requirements for underground subway stations though the National Fire Protection Association (NFPA) standard 130 on 'Fixed Guideway and Passenger Rail Systems' has become the de-facto guideline for many projects especially for the countries that have yet to develop their own fire safety code such as Singapore and Japan.

Modern subway stations typically comprise of a single volume space formed by the passenger platform with inter-connecting level(s) and continuous connection to the street level; with extensive use of staircases, escalators and lifts for efficient passenger movement. The basis of station platform design in the NFPA 130 is to evacuate all the passengers from the platform in four minutes (4min) and to reach of Point-of-Safety (POS) within six minutes (6min) via these vertical egress elements. In many jurisdictions, it is acceptable to carry out the station exit analysis based on the prescribed procedures in NFPA 130. The egress calculation procedure is a simple hydraulic model. For stations with multiple passenger platforms, platforms on multiple levels, or converging egress routes, the use of a more robust model is often necessary to analyze variations that influence the required safe egress time.

Studies were carried out comparing the platform evacuation time for NFPA 130, the SFPE Handbook of Fire Protection Engineering and Pathfinder. The comparison of evacuation times (4.94 minutes NFPA 130, 5.76 minutes SFPE, and 6.24 minutes Pathfinder) is consistent with expectations. The SFPE egress component flow rates are slower than NFPA 130, so the SFPE evacuation is longer. The main cause of the difference between Pathfinder and NFPA 130 and SFPE is that they assume full capacity and even use of all exits (Swenson, Thunderhead Engineering).

The use of dynamic evacuation model is expected to yield different results during a fire evacuation as not all the exits will be used to their full capacity during the evacuation. Passengers are expected to use familiar routes i.e. the front-of-house public staircases and escalators instead of the dedicated fire escape staircases that may only be accessible via the back-of-house/ platform buffer areas and this will further challenge the assumption of even use of all exits during evacuation.

OBJECTIVE

The objective of this paper is to examine the various user input parameters e.g. cost factors for occupant profiles, locations of final exits etc. and their impacts on the choice of exit routes and evacuation time by occupants during evacuation, using a deep underground subway station as a case study.

CASE STUDIES

The study involves the dynamic evacuation modelling of an underground station. The trial station is a 5-level underground train station that comprises the lower platform level at basement 5 (B5), upper platform level at basement 4 (B4), plant room level at basement 3 (B3), lower concourse level at basement 2 (B2) and upper concourse level at basement 1 (B1). The lower and upper platform levels are basically open central areas to facilitate passenger's waiting and boarding/alighting onto/from trains. The upper concourse level is designed as a ticketing hall where ticket machines, automatic fare gates, station control room are located. The platform and concourse levels are linked by open staircases and escalators at the public areas. Protected staircases are also provided at both ends of the trial station.

Egress provisions for the trial station will be in accordance with NFPA 130, such that passengers can clear both platforms within 4 minutes and reach a point of safety (concourse) within 6 minutes:

- Evacuation provisions (stairs, escalators) to be designed and provided at the platform level in the event a train on fire at platform trackway based on specific occupant load scenario;

- There will be a minimum of 2 no. escape / evacuation route typically at end of platform and concourse public area, with direct and protected access/egress route to point of safety and to outside;
- Unenclosed (open) escalators and stairs will be used as a means of egress;
- Enclosed (protected) escape staircases will be accessible from all occupied levels; these stairs will lead directly the ground level or will transfer via fire separated corridors to another stair that discharges at ground level.

For the purposes of the study, an evacuation scenario is considered where both lower and upper platforms will be evacuated simultaneously based on worst case passenger load. Six case studies were carried out for the dynamic evacuation modeling of the trial station.

Case Study 1

This case study (base model) models the final exits of the station's escape routes (i.e. protected staircases and station entrances) discharging at ground level. This shows how each of the exits is being utilized whilst passengers are evacuating the platforms.

Case Study 2

This case study looks at changing the current room queue time cost factor to 3 and its impact to the utilization of exits.

Case Study 3

This case study looks at changing the current room queue time cost factor to 5 and its impact to the utilization of exits.

Case Study 4

This case study looks at changing the location of the final exits in the model (case study 1) to the upper concourse level after the fare gates, with current room queue time cost factor set as 1, and its impact to the utilization of exits.

Case Study 5

This case study looks at changing the location of final exits in the model (case study 1) to the upper concourse fare gates, with current room queue time cost factor set as 1, and its impact to the utilization of exits.

Case Study 6

This case study looks at changing the location of final exits in the model (case study 1) to the top of escalators/open staircases at upper concourse, with current room queue time cost factor set as 1, and its impact to the utilization of exits.

MODEL SETTINGS

The trial station has a split platform configuration. Both the lower and upper platforms first connect to the lower concourse, then the lower concourse connects to the upper concourse. The upper concourse is further connected to an exit/entrance at grade. As the plantroom room level at B3 is a bypass level not accessible by public, this level was not be included in the model. The floor to floor heights of the various levels are indicated in the following Table 1 and Figure 1.

Table 1: Floor to floor height of each level

Level	Floor to floor height (m)
Lower Platform (B5)	10.0
Upper Platform (B4)	6.6
Plantroom (B3)	6.1
Lower Concourse (B2)	6.6
Upper Concourse (B1)	4.95 m (to station entrance at grade)

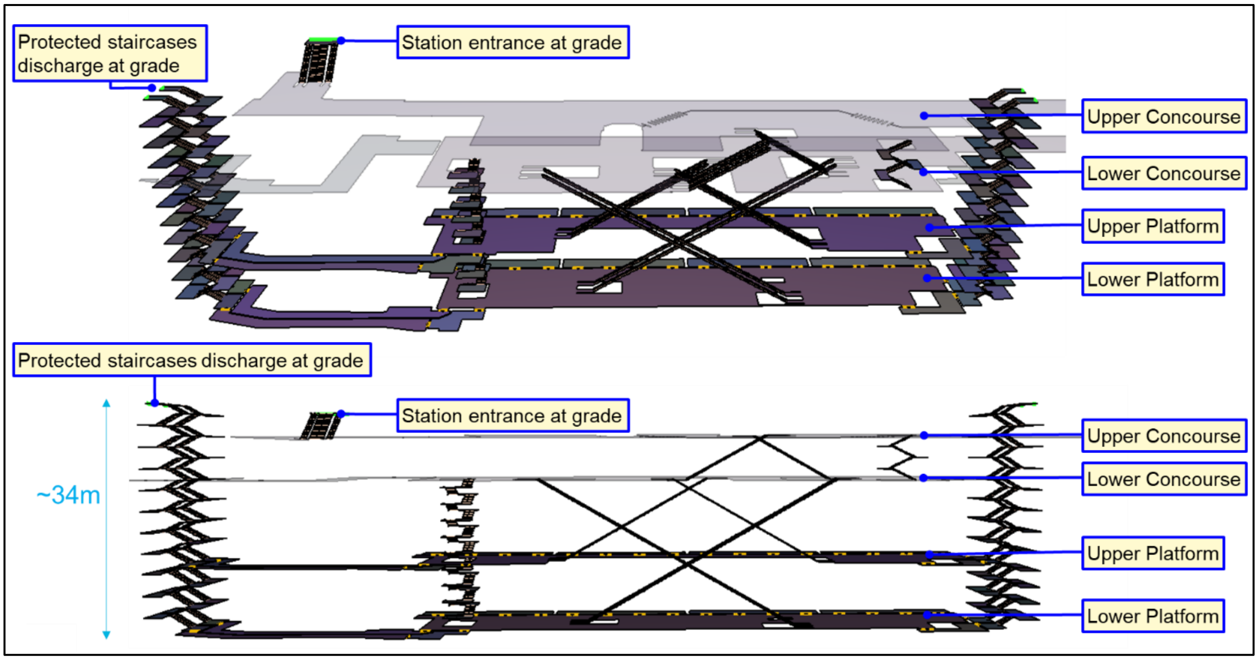

Figure 1: Evacuation model – station elevation

The model includes the key egress provisions such as protected corridors leading to the enclosed fire stairs at both ends of the platform, escalators and open stairs.

General assumptions and model inputs are as follows:

- One egress simulation has been conducted for the platform.
- Worst case passenger loads calculated using NFPA130 principles, i.e. 2639 persons
- Assumed maximum unimpeded walking speed:
  a) Flat surface = 1.19m/s
  b) Stairs / Escalator (stationary) = 0.92 m/s
- Assumed escalator speed moving in direction of egress is 0.75 m/s. One escalator moving in the direction of egress will be discounted from the model.
- People are assumed to continue walking on the moving escalator during emergency evacuation.
- A stationary escalator shall be treated as a 1200mm wide fixed stair in emergency evacuation

The egress components provided at each level are tabulated in the tables and figures below.

Table 2: Egress capacity for lower platform

Component	Quantity	Width
Protected staircase	4	ES01 – 2.2 m ES02 – 2.2 m ES03 – 2.2 m FS01 – 2.2 m
Escalator (from lower platform to lower concourse)	4	1.2 m each ESC02: 1 no. in operation in direction of egress, 0.75 m/s ESC01/03: 2 nos. stopped during emergency ESC04: 1 no. discounted
Open Stair (lower platform to upper platform)	1	ST01 – 1.5m

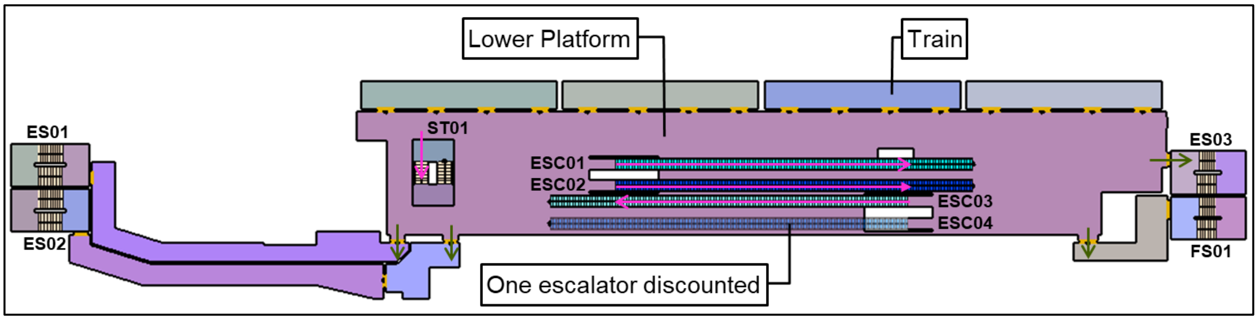

Figure 2: Egress components for lower platform

Table 3: Egress capacity for upper platform

Component	Quantity	Width
Protected staircase	4	ES01 – 2.2 m ES02 – 2.2 m ES03 – 2.2 m FS01 – 2.2 m
Escalator (from upper platform to lower concourse)	4	1.2 m each ESC06: 1 no. in operation in direction of egress, 0.75 m/s ESC05/07: 2 nos. stopped during emergency ESC08: 1 no. discounted
Open Stair (upper platform to lower concourse)	1	ST01 – 1.5m

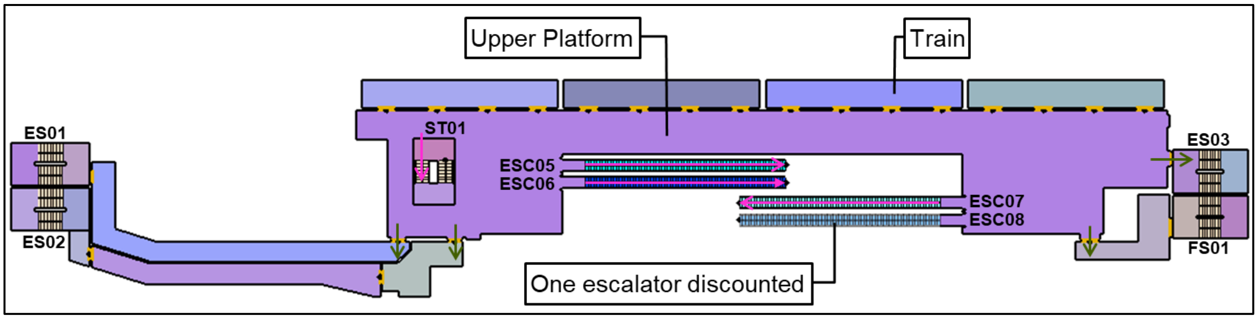

Figure 3: Egress components for upper platform

Table 4: Egress capacity for lower concourse

Component	Quantity	Width
Escalator (from lower concourse to upper concourse)	5	1.2 m each ESC09: 1 no. in operation in direction of egress, 0.75 m/s ESC11/12/13: 3 nos. stopped during emergency ESC10: 1 no. discounted
Open Stair (from lower concourse to upper concourse)	1	ST02 – 1.5m

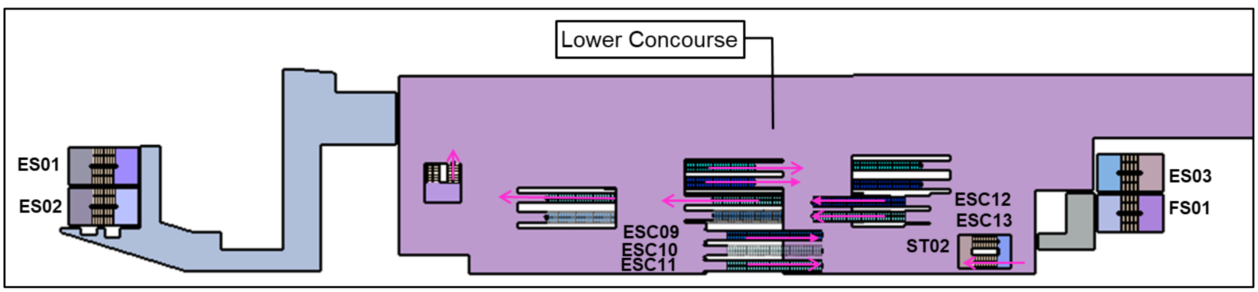

Figure 4: Egress components for lower concourse

Table 5: Egress capacity for upper concourse

Component	Quantity	Width
Escalator (from lower concourse to upper concourse)	2	1.0 m each ESC14: 1 no. in operation in direction of egress, 0.75 m/s ESC15: 1 no. stopped during emergency
Open Stair (from lower concourse to upper concourse)	1	ST03 – 2.5m

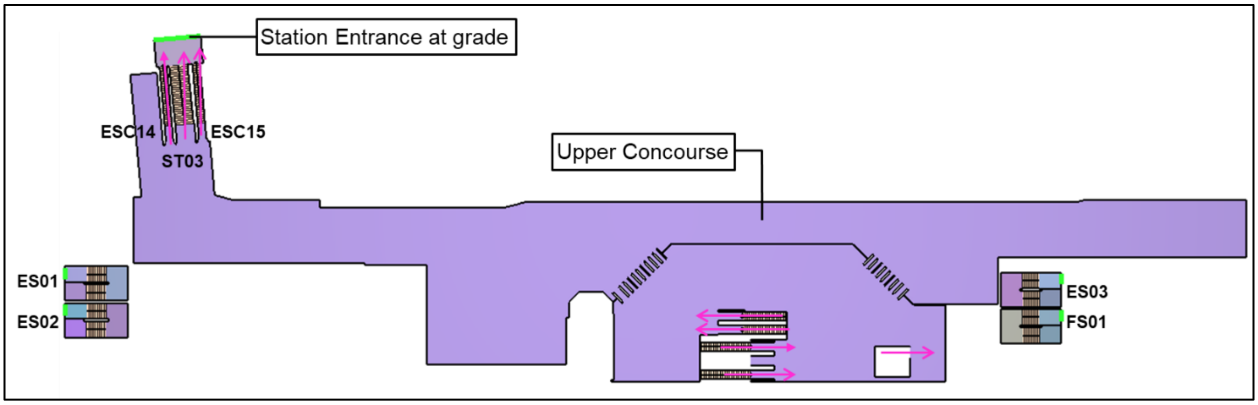

Figure 5: Egress components for upper concourse

The following Table 6 summarizes the case studies and associated variables.

Table 6: Summary of variables for case studies

Case study	Cost factor (room queue time)	Location of evacuation model final exits
Case study 1 (Base case)	1	Final exits all located at grade
Case study 2	3	Final exits all located at grade
Case study 3	5	Final exits all located at grade
Case study 4	1	Final exits for protected staircases remain at grade; Exit point at station entrance relocated to upper concourse to shorten the distance.
Case study 5	1	Final exits for protected staircases remain at grade; Exit point at station entrance relocated to upper concourse fare gates A and B.
Case study 6	1	Final exits for protected staircases remain at grade; Exit point at station entrance relocated to top landing of escalators and open stairs at upper concourse.

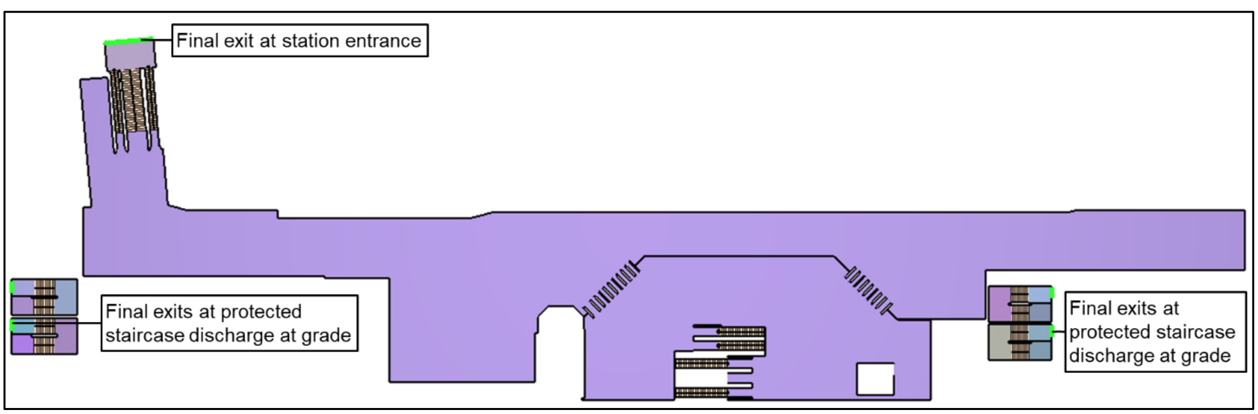

Figure 6: Final exit locations for case studies 1, 2 and 3

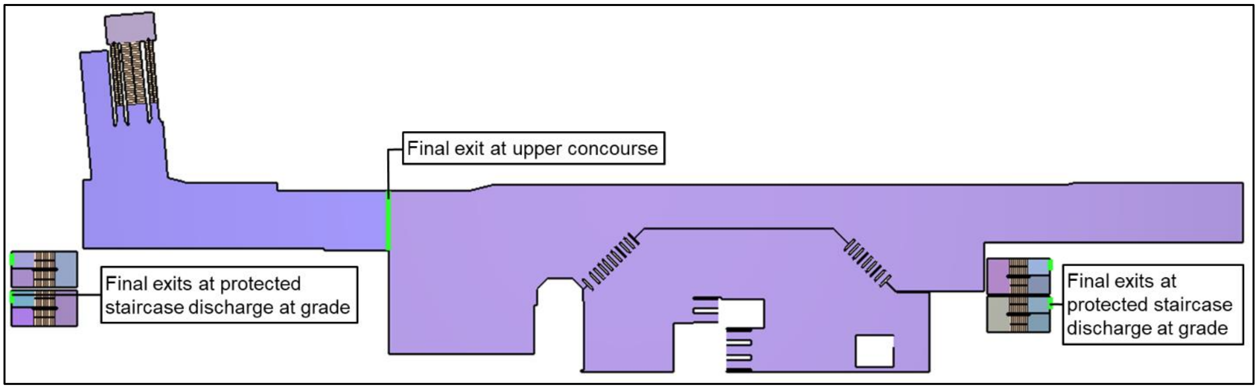

Figure 7: Final exit locations for case study 4

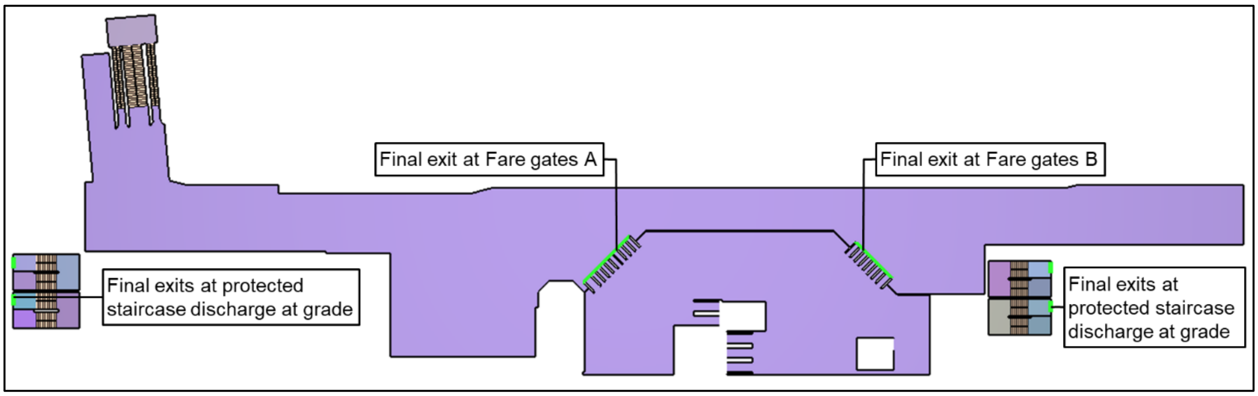

Figure 8: Final exit locations for case study 5

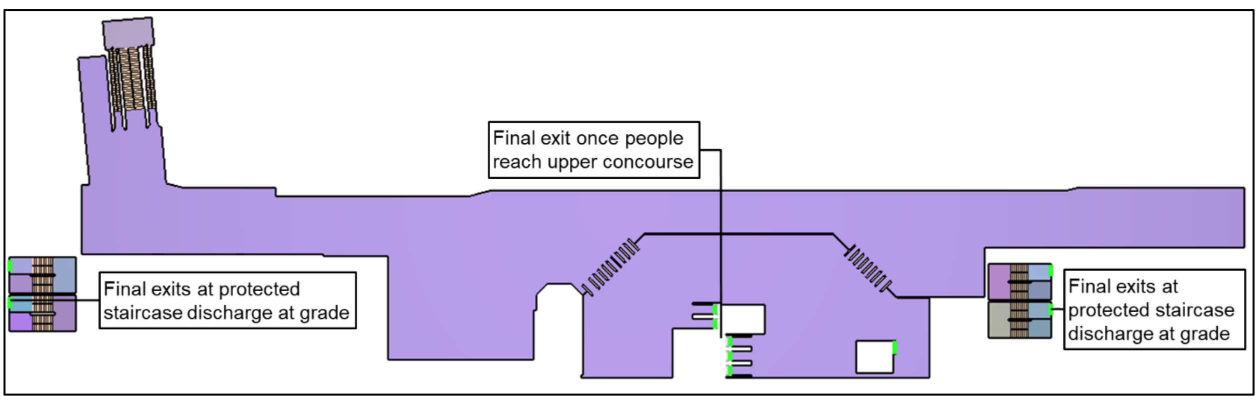

Figure 9: Final exit locations for case study 6

RESULTS/FINDINGS

Case study 1 – Final exits at ground level (base model)

The results of this pathfinder simulation run showed that 89.4% of the passengers exit the station via the 4 numbers of escape staircases, while 10.6% of the passengers exit the station via the main station entrance. Figure 10 below provides an indication on the usage pattern of the various exits. The distribution of the number of passengers who exit via the various escape staircases (ES-01/ES-02/ES-03/FS-01) and station entrance are as shown in Figure 11 below. The time taken for the last person to leave the lower platform was 192s (3min:12s), while the last person left the upper platform at 203s (3min:23s).

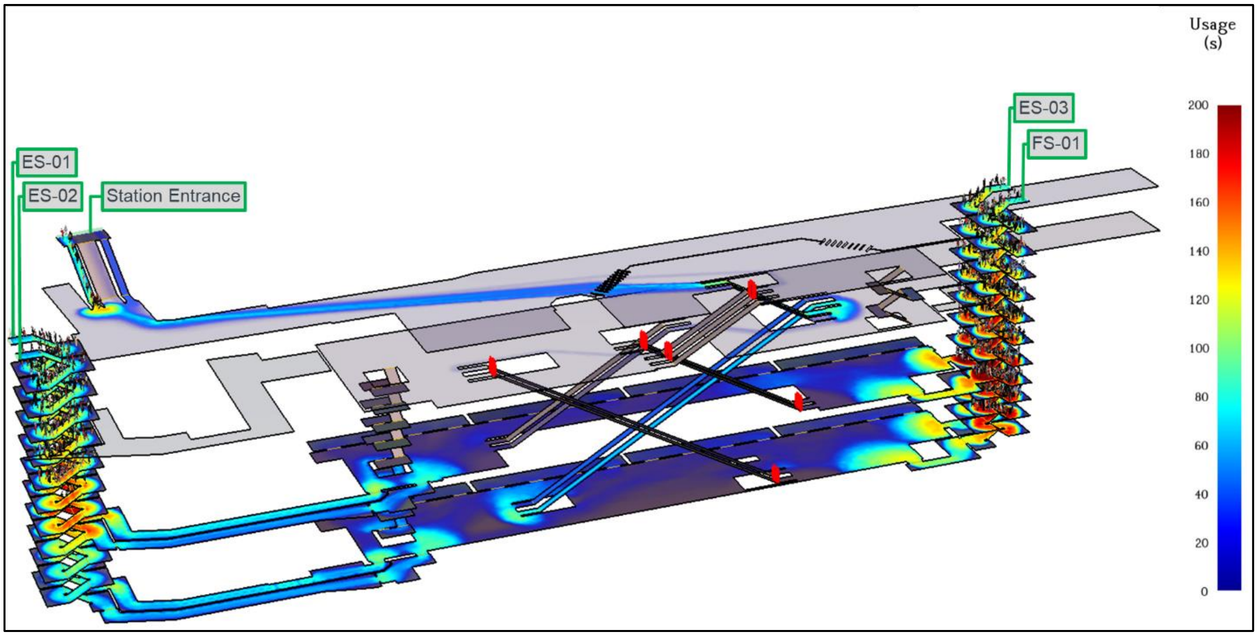

Figure 10: Cumulative usage of exits (case study 1)

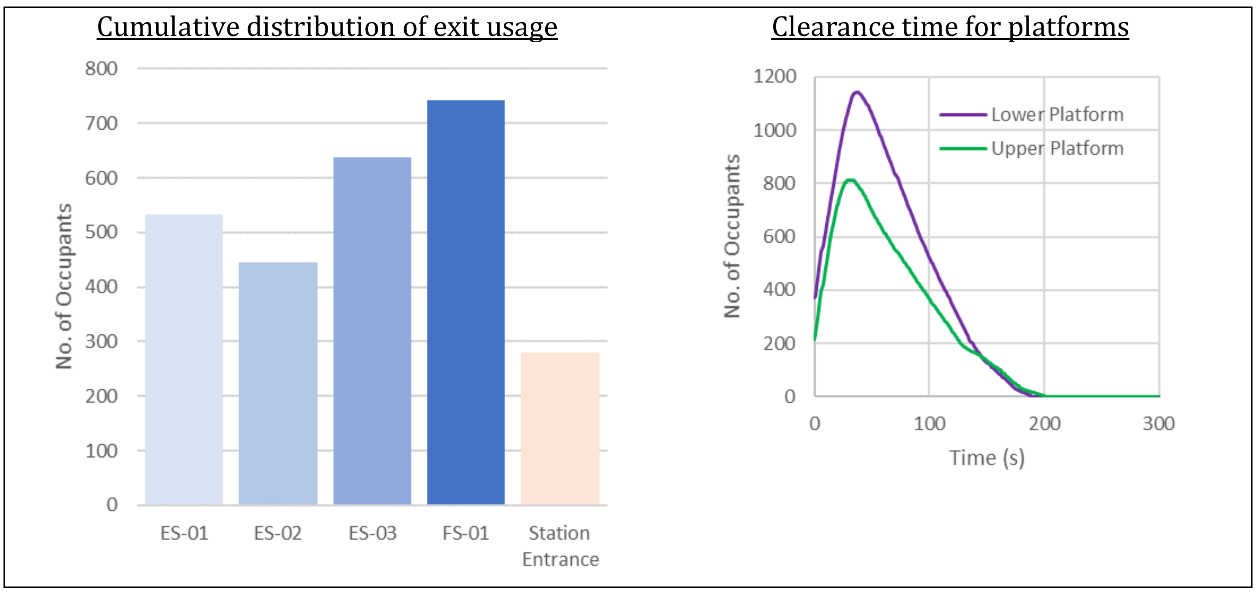

Figure 11: Cumulative distribution of exit usage / Platform clearance time (case study 1)

In the pathfinder model, the cost for passengers to travel to a final exit is proportional to the distance/travel time. The travel route from the platforms to the station entrance is longer than those routes to the final exits of the escape staircases.

While the results showed that the exit provisions for the station meet the requirements of NFPA130 for platform clearance time, it is observed that the distribution of exit usage by the passengers may not be reflective of reality. A large portion of passengers chose to use the unfamiliar escape staircases rather than the station entrance.

Case study 2 – Increasing the room queue time cost factor to 3

The results of this pathfinder simulation run showed that 77.3% of the passengers exit the station via the 4 numbers of escape staircases, while 22.7% of the passengers exit the station via the main station entrance. Figure 12 below provides an indication on the usage pattern of the various exits. The distribution of the number of passengers who exit via the various escape staircases (ES-01/ES-02/ES-03/FS-01) and station entrance are as shown in Figure 13 below. The time taken for the last person to leave the lower platform was 171s (2min:51s), while the last person left the upper platform at 207s (3min:27s).

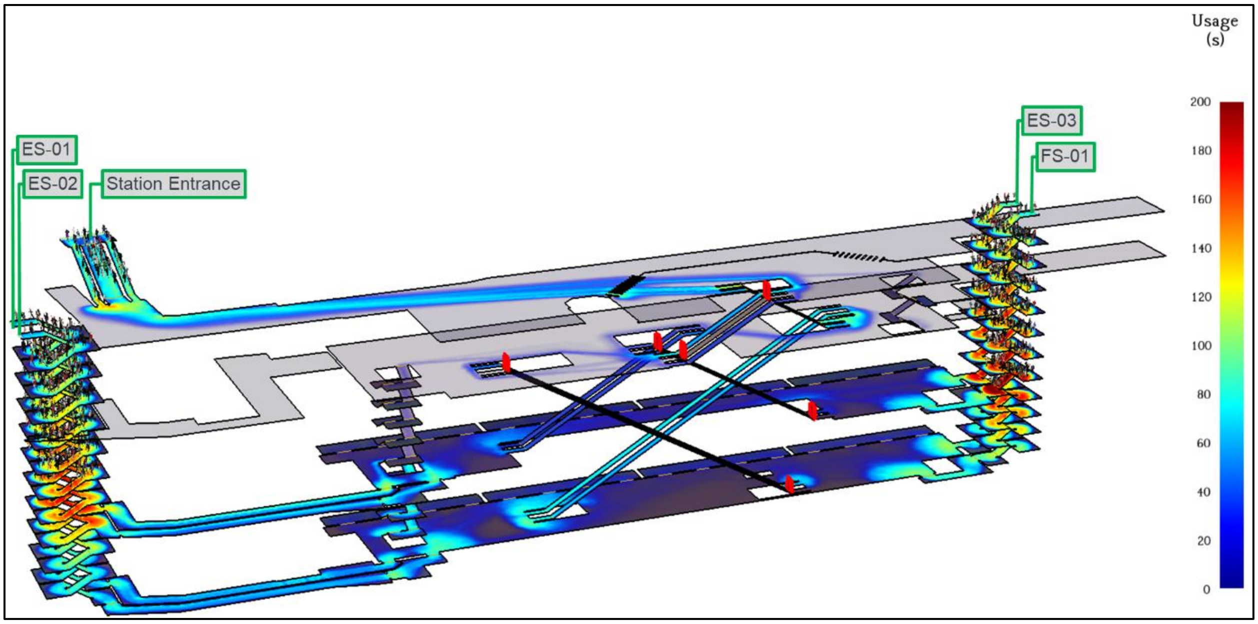

Figure 12: Cumulative usage of exits (case study 2)

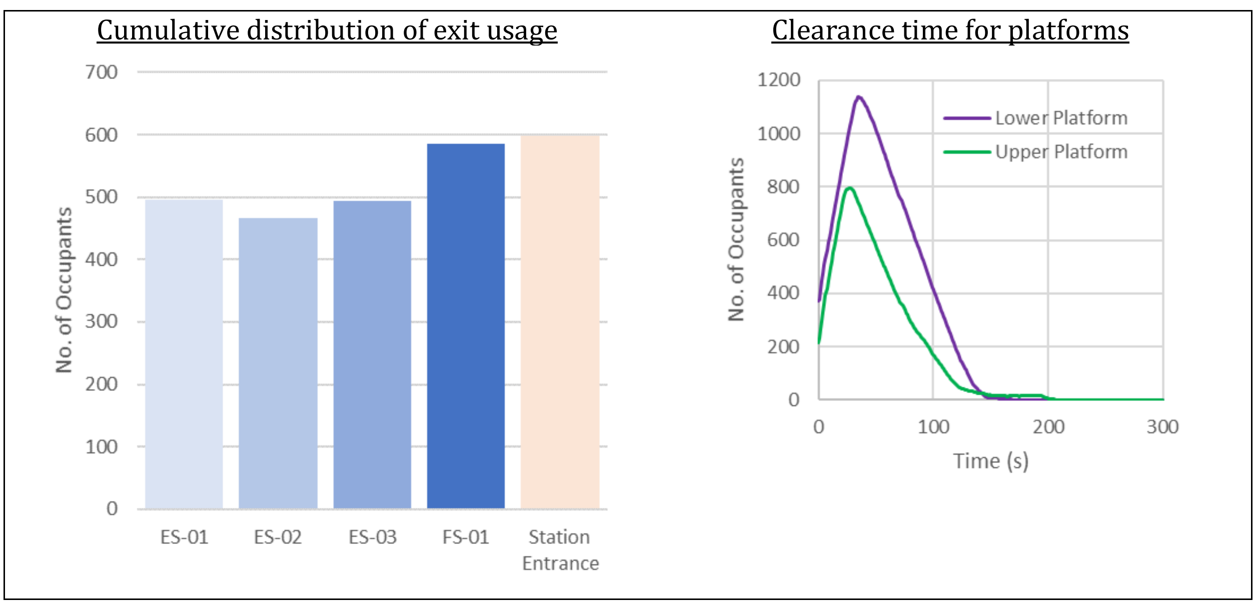

Figure 13: Cumulative distribution of exit usage / Platform clearance time (case study 2)

Compared with case study 1, the proportion of passengers using the unfamiliar escape staircases has decreased slightly. The increase in the room queue time cost factor led to a greater number of passengers choosing to exit via the longer travel route to the station entrance.

Case study 3 – Increasing the room queue time cost factor to 5

The results of this pathfinder simulation run showed that 74% of the passengers exit the station via the 4 numbers of escape staircases, while 26% of the passengers exit the station via the main station entrance. Figure 14 below provides an indication on the usage pattern of the various exits. The distribution of the number of passengers who exit via the various escape staircases (ES-01/ES-02/ES-03/FS-01) and station entrance are as shown in Figure 15 below. The time taken for the last person to leave the lower platform was 169s (2min:49s), while the last person left the upper platform at 215s (3min:35s).

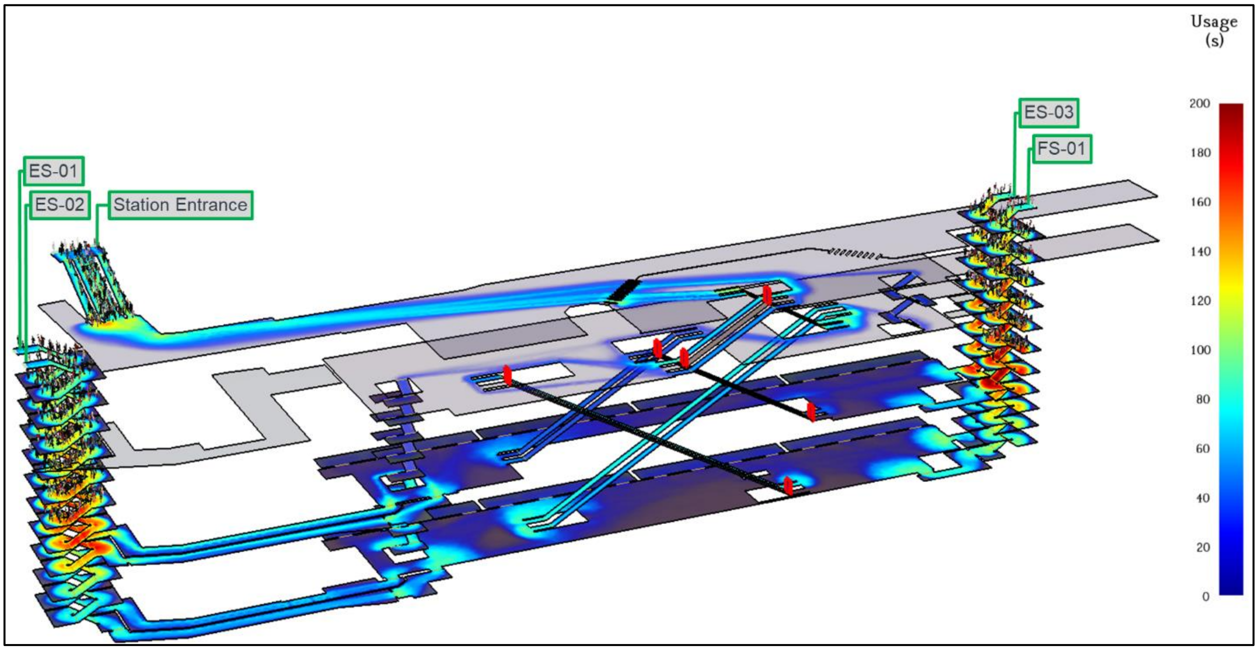

Figure 14: Cumulative usage of exits (case study 3)

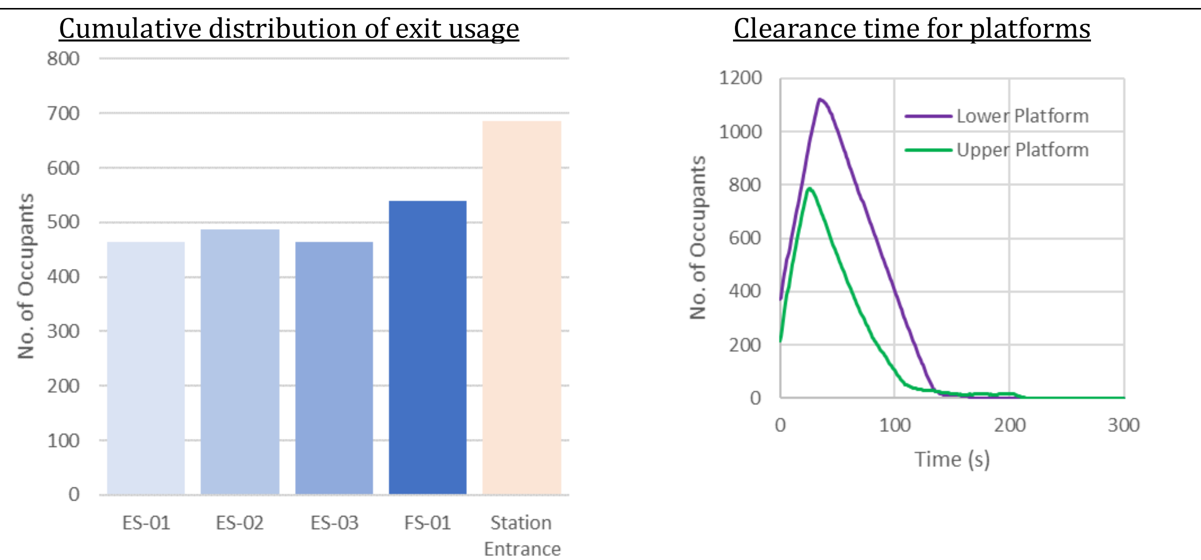

Figure 15: Cumulative distribution of exit usage / Platform clearance time (case study 3)

Compared to both case studies 1 and 2, the proportion of passengers who chose to use the unfamiliar escape staircases decreased slightly with the room queue time cost factor increased to 5. The result does not appear to be realistic, with approximately 75% of the passengers choosing the escape staircases over the station entrance.

Case study 4 – Exit (Station Entrance) relocated to upper concourse level

The results of this pathfinder simulation run showed that 67.6% of the passengers exit the station via the 4 numbers of escape staircases, while 32.4% of the passengers exit the station via the main station entrance. Figure 16 below provides an indication on the usage pattern of the various exits. The distribution of the number of passengers who exit via the various escape staircases (ES-01/ES-02/ES-03/FS-01) and station entrance are as shown in Figure 17 below. The time taken for the last person to leave the lower platform was 244s (4min:4s), while the last person left the upper platform at 172s (2min:52s).

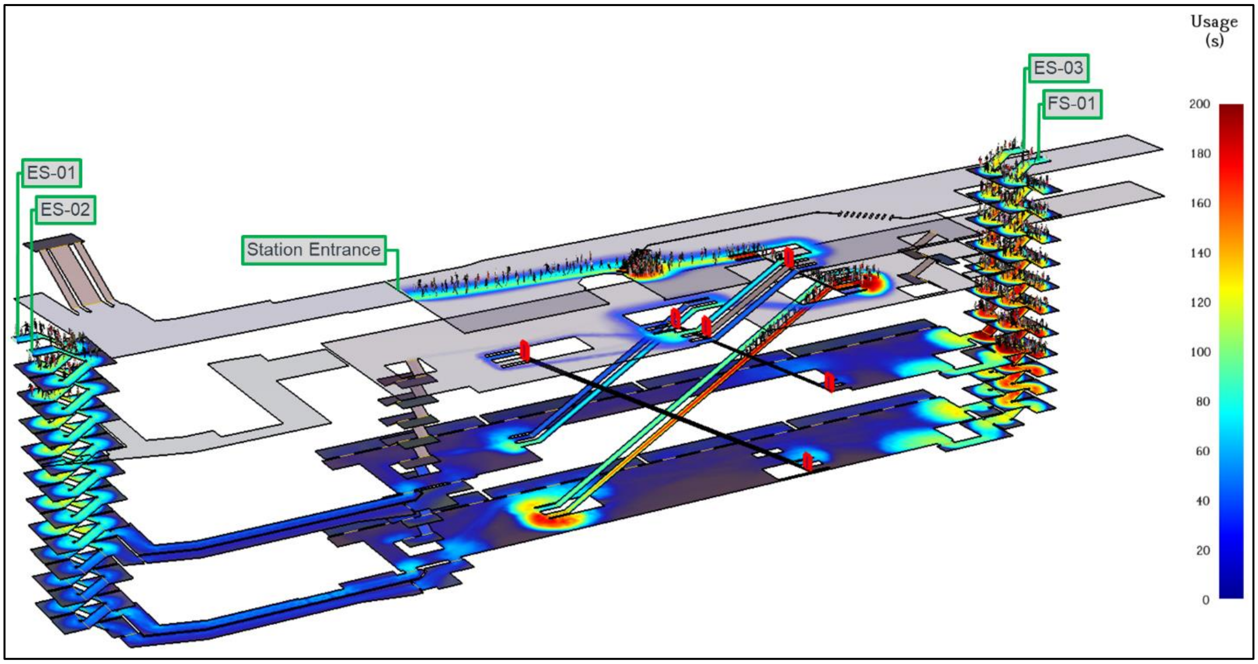

Figure 16: Cumulative usage of exits (case study 4)

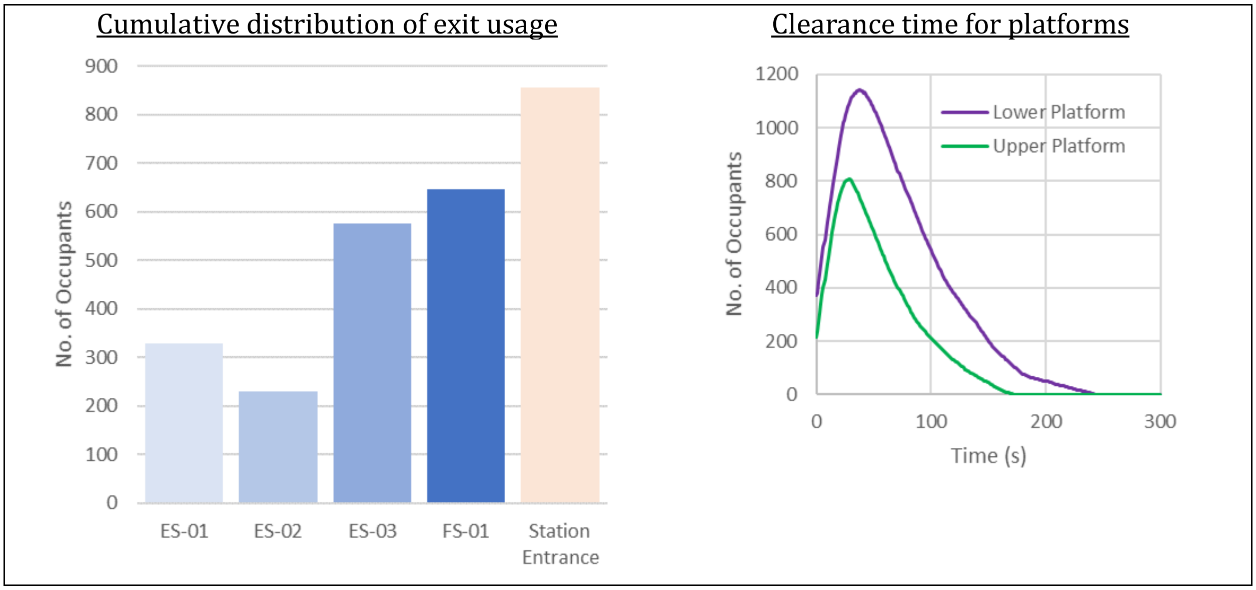

Figure 17: Cumulative distribution of exit usage / Platform clearance time (case study 4)

Compared with case study 1, the proportion of passengers who chose to use the unfamiliar escape staircases decreased. With the reduction of travel distance/time for passengers to exit via the station entrance decreased, a larger proportion of passengers (an increase from about 10% to 33% of the passengers) chose to exit via the station entrance.

Case study 5 – Exit (Station Entrance) relocated to fare gates

The results of this pathfinder simulation run showed that 53.3% of the passengers exit the station via the 4 numbers of escape staircases, while 46.7% of the passengers exit the station via the main station entrance (fare gates). Figure 18 below provides an indication on the usage pattern of the various exits. The distribution of the number of passengers who exit via the various escape staircases (ES-01/ES-02/ES-03/FS-01) and station entrance are as shown in Figure 19 below. The time taken for the last person to leave the lower platform was 259s (4min:19s), while the last person left the upper platform at 207s (3min:27s).

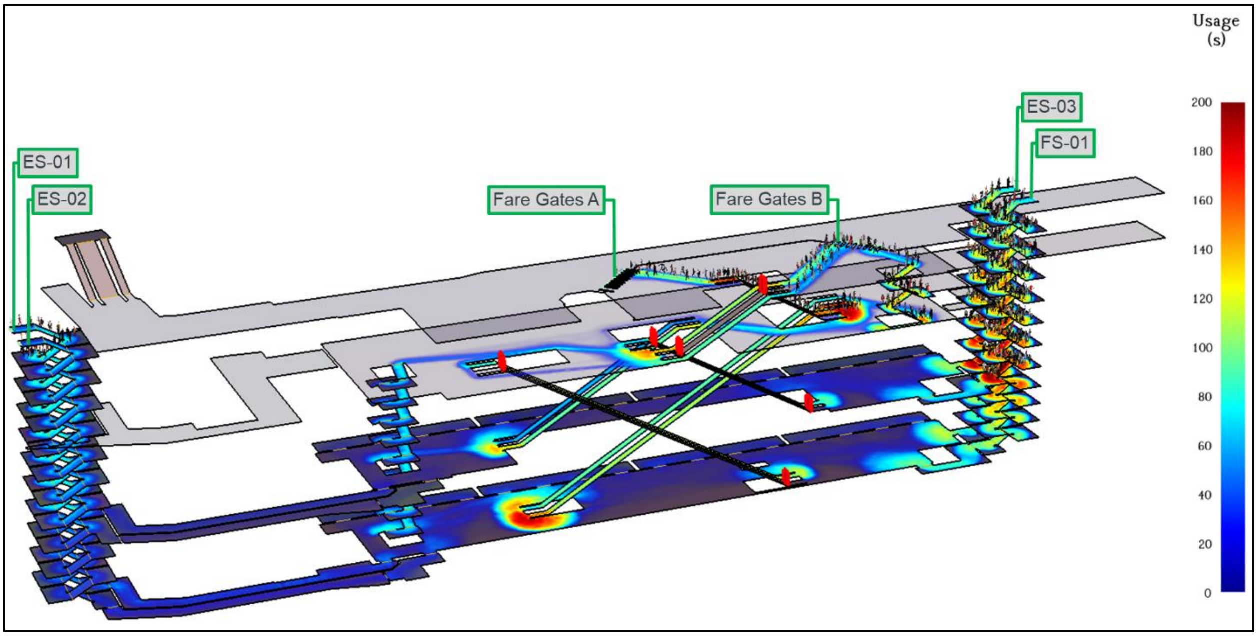

Figure 18: Cumulative usage of exits (case study 5)

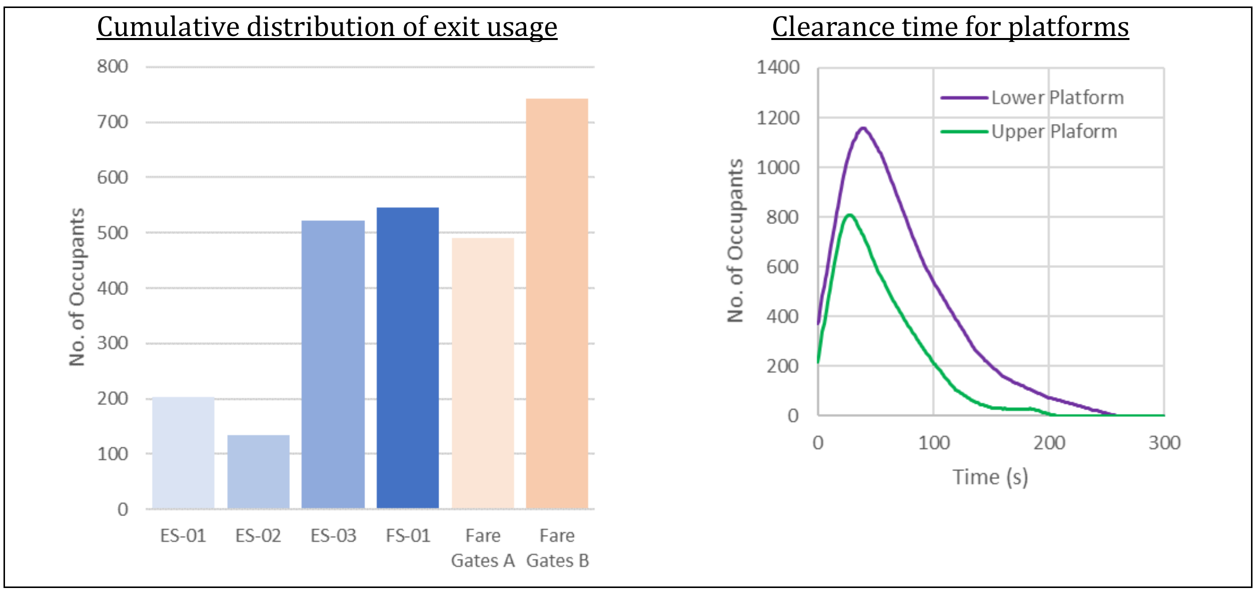

Figure 19: Cumulative distribution of exit usage / Platform clearance time (case study 5)

A common observation in all 4 case studies earlier was the uneven distribution of the passengers escaping through the fare gates. As one of the fare gates was en-route to the station entrance for passengers at the upper concourse, all passengers exited via 1 set of fare gates only. To overcome this, the final exits to represent the station entrance were shifted just after the fare gates.

With the final exits located just after the fare gates, the fare gates on both sides were utilized. Furthermore, the distribution of exit usage by the portion of passengers who chose to use the unfamiliar escape staircases and the station entrance (fare gates) was almost even.

Case study 6 – Exit (Station Entrance) relocated to upper concourse level at top of escalators/staircases

The results of this pathfinder simulation run showed that 44.3% of the passengers exit the station via the 4 numbers of escape staircases, while 55.7% of the passengers exit the station via the main station entrance (ESC 09/11/12/13, ST 02). Figure 20 below provides an indication on the usage pattern of the various exits. The distribution of the number of passengers who exit via the various escape staircases (ES-01/ES-02/ES-03/FS-01) and station entrance are as shown in Figure 21 below. The time taken for the last person to leave the lower platform was 284s (4min:44s), while the last person left the upper platform at 244s (4min:4s).

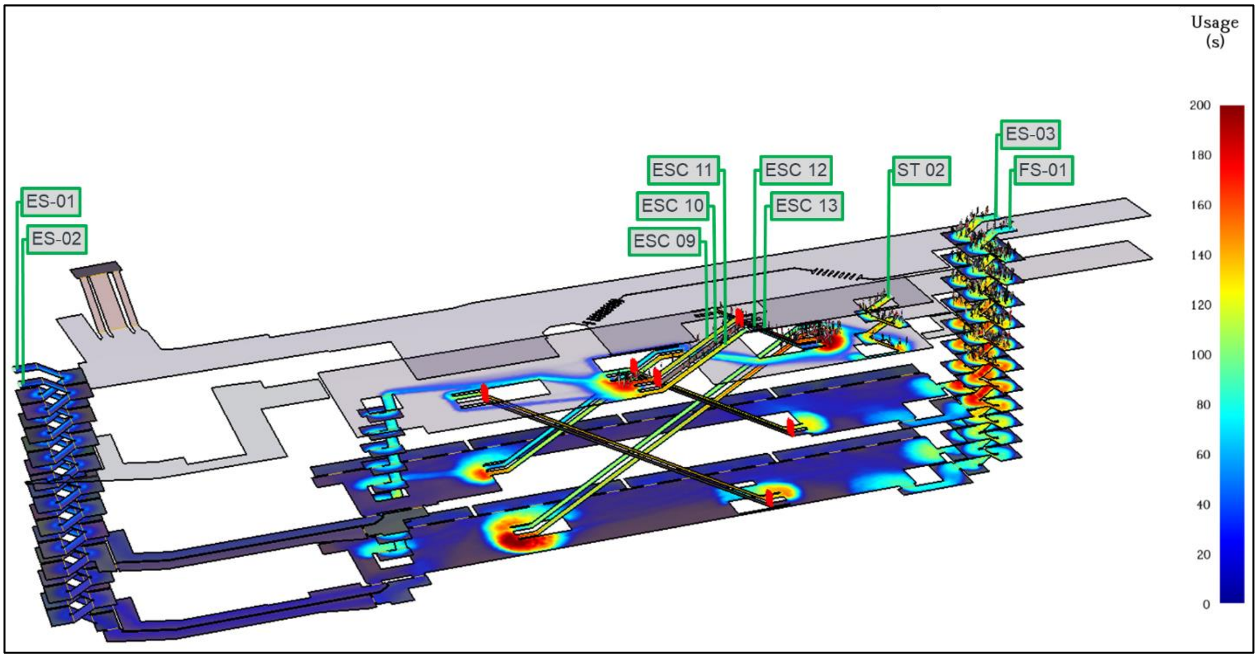

Figure 20: Cumulative usage of exits (case study 6)

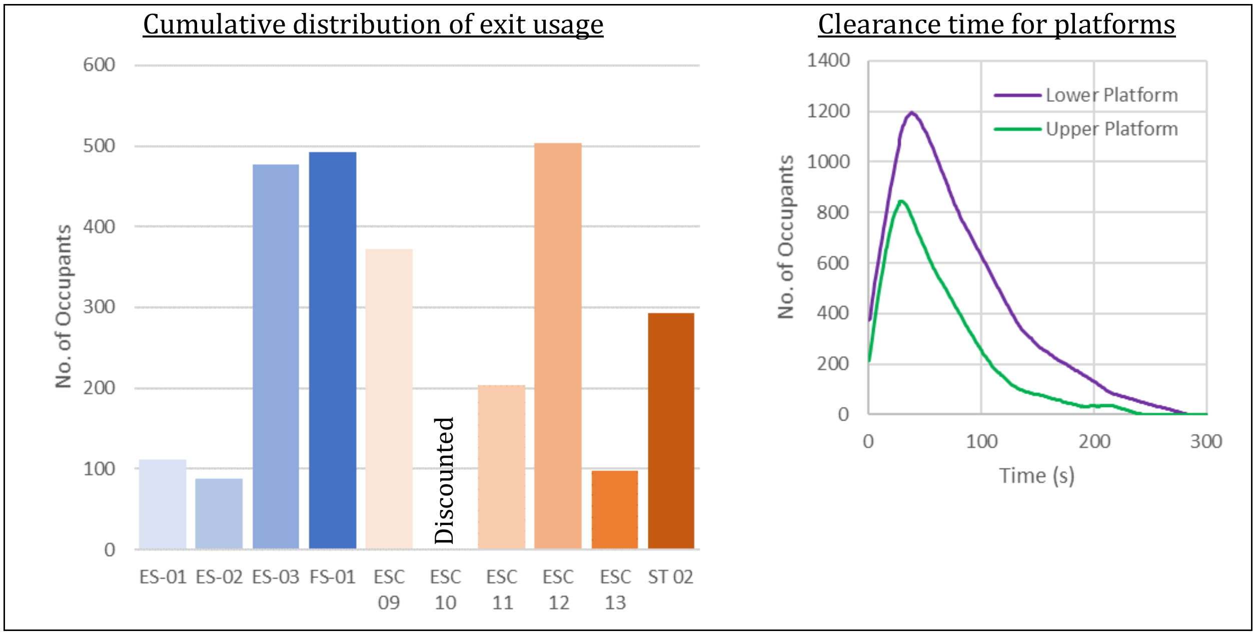

Figure 21: Cumulative distribution of exit usage / Platform clearance time (case study 6)

The proportion of passengers who chose to exit via the public escalators/staircases (station entrance) were slightly more than those who chose the escape staircases.

CONCLUSION / FUTURE RESEARCH

Through the series of pathfinder simulation runs, it was found that the choice of exit routes by the passengers strongly depends on the cost of the travel route/time. passengers in the pathfinder models would opt to take the shorter exit routes. The underlying reason is that all passengers have full knowledge of all exit routes. This may not be true in actual situations. Escape staircases are often provided at the ends of station platforms and located at the back of house (BOH) areas. During day to day operations of subway stations, these BOH areas are accessible only by staff and majority of the passengers do not have access to these areas. Most passengers are unlikely to be aware of the existence of these escape staircases located at the BOH areas.

Increasing the room queue time cost factor does increase the usage of the station entrance by passengers for evacuation. However, the effect of this change does not seem significant beyond a value of 5. Varying the locations of exits/length of exit routes can be an option to “promote” passengers in the Pathfinder models to use routes that they are familiar with, i.e. station entrance(s) where they enter/exit the stations. However, there is no clear and definitive method/rule in this approach. User judgement is important and prudent. As the route to the final exit (station entrance) is shortened, more passengers would choose to evacuate via the station entrance. Refer to Figure 22 below.

Figure 23 summarizes the lower platform evacuation times across case studies 1 to 6. The results of the Pathfinder simulations show that the platform evacuation time increases as more passengers evacuate via the station entrance. In the trial station considered, the split in overall egress capacity between the station entrance and escape staircases is about 60% to 40%. Platform evacuation time did not decrease even though the exits were more evenly used. This suggests that other factors such as layout and queuing of passengers could influence the platform evacuation time. This also suggests that the simplifying assumption of even usage of exits in the NFPA130 calculations could undermine the actual platform evacuation time.

Based on the case studies conducted, either case study 5 or 6 could be a better representation of an actual evacuation scenario. This is with due consideration to the actual layout of the station (split platform configuration) and day-to-day circulation of passengers (majority of passengers unlikely to be aware of the existence of the escape staircases). Furthermore, for case study 6, the locations of the final exits cannot be further shortened.

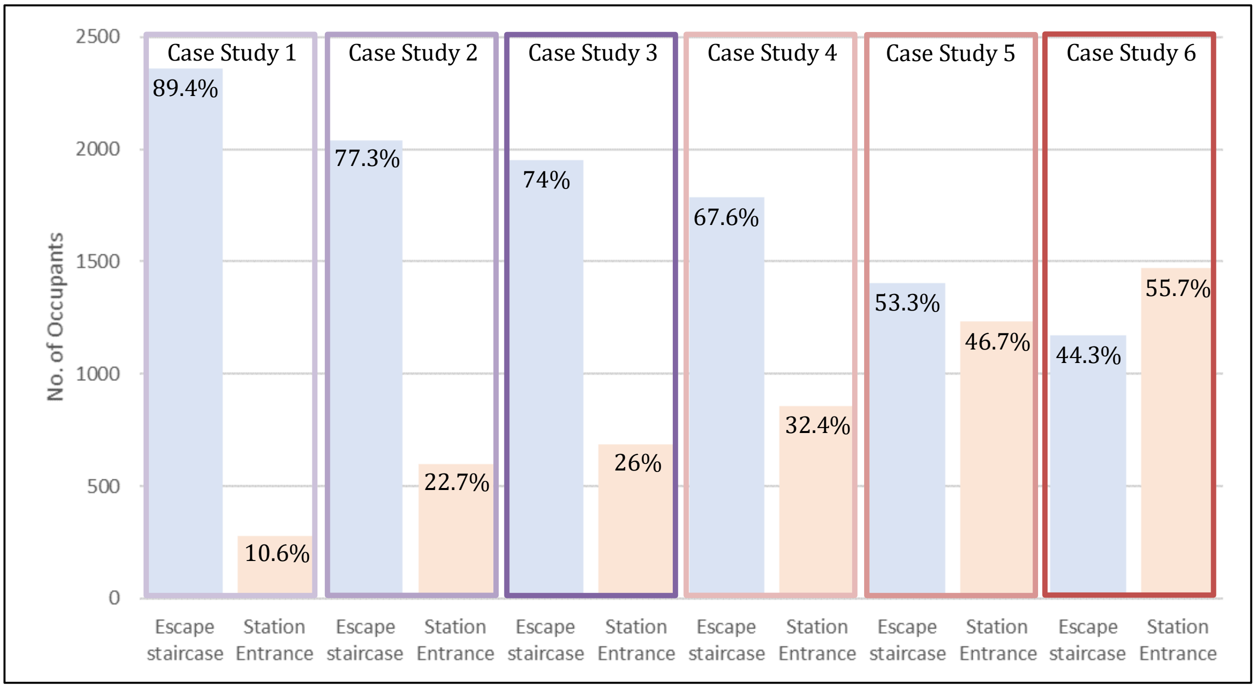

Figure 22: Cumulative distribution of exit usage (Summary)

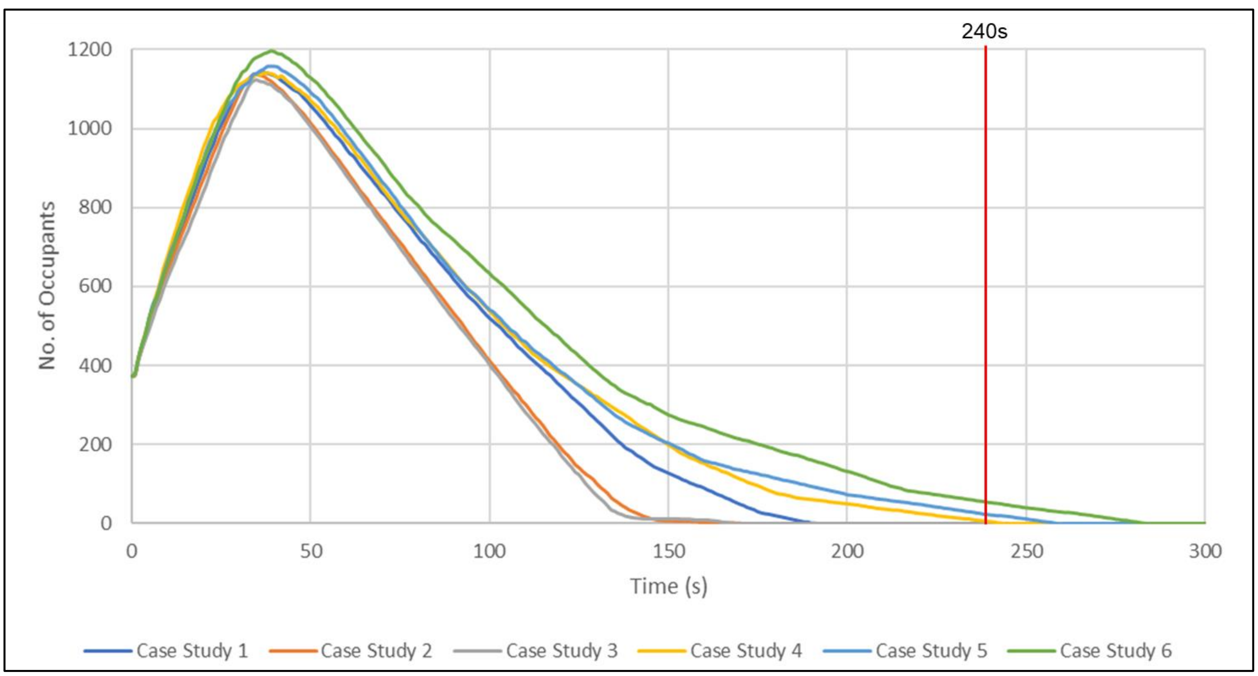

Figure 23: Lower platform clearance time (Summary)

Setting up the pathfinder egress simulation model is a fairly straightforward process and for the most part, the results of the pathfinder simulation can provide insights on the evacuation routes/exits available. Interpreting the results can sometimes be as much user judgement as it is guesswork. Varying the locations of final exits in the pathfinder model appears to be a viable option to "promote" passengers in the simulation runs to use certain exits.

More research could be conducted in the future to provide some numerical data regarding the use of unfamiliar and prominent exits by occupants. This would prove useful to give designers a better sense of the reality of egress simulation results.

REFERENCES

National Fire Protection Association, NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems, 2017.

Society of Fire Protection Engineers, The SFPE Handbook of Fire Protection Engineering, Third Edition, National Fire Protection Association, 2002.

UN, 2007. World Population Prospects: The 2007 Revision. Technical Report. United Nations, Department of Economic and Social Affairs, Population Division.

UN, 2013. World Population Prospects: The 2012 Revision. Technical Report ESA/P/WP.228. United Nations, Department of Economic and Social Affairs, Population Division.