Performance-Based Approach for Fire Safety in Aboveground Mass Rapid Transit Stations

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Abstract

The majority of fire safety studies on train stations have been on underground stations, because underground developments are considered to have a higher level of risk from the effects of a fire within a confined space. As a result, fire safety requirements for underground stations are relatively more rigorous compared to aboveground stations, and this is consistent with general fire safety provisions required by fire codes for underground facilities. A literature review of both local and international fire safety provisions for stations has shown that fire safety provisions for aboveground stations are generally lacking. This chapter presents a three-stage performance-based approach to evaluate fire safety on aboveground stations utilizing Singapore's North-South and East-West lines as a case study. The assessment demonstrated that a significant portion of the platform of aboveground stations can continue to remain tenable from conditions resulting from a trainway fire, even with the consideration of wind in the adverse direction. The study also identified design consideration for fire safety provisions of aboveground stations that current local codes do not explicitly address.

Keywords

Trainway fire • Aboveground MRT stations • Performance-based

53.1 Introduction

The majority of fire safety studies on train stations have been on underground stations because underground developments are considered to have a higher level of risk from the effects of a fire within a confined space. A literature review of both local and international fire safety provisions for stations has shown that fire safety provisions for aboveground stations are generally lacking.

This chapter presents a performance-based approach to fire safety on aboveground stations utilizing Singapore's North-South and East-West lines as a case study. These existing stations were originally designed in accordance with NFPA 130 [1].

53.2 Assessment Procedure

The Singapore's North-South and East-West stations have a range of layouts, and the approach starts with grouping them into similar types and then identifying a number of representative stations that would then be the selected cases for further study within each group. Assessing the fire escape provisions for these selected cases would then be representative in capturing all the requirements on fire escape provisions for the other stations in the studied lines.

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The selection of the stations for the study includes the following:

1. Examination of station physical layouts in relationship to egress provisions to identify station groups and select the representative in each group.
2. Undertake preliminary analytical assessment to rank egress capability of stations to select the representative cases.
3. Undertake detailed analytical assessment on the selected worst cases to examine adequacy of fire escape provisions.

Following the selection of the representative cases, a performance-based fire safety approach is undertaken on each case to determine if the fire escape provisions are adequate for safe evacuation during a trainway[1] fire. The objective of the performance-based approach is to demonstrate that the root objective for the Station Means of Escape as stated in Clause R2.2.1 of the SFSRTS [2] is achieved:

> Occupants must be able to escape to a safe place, directly or through a protected exit, before untenable conditions are reached during a fire emergency.

53.2.1 Stage 1: Station Grouping

To systematically assess the range of designs, aboveground stations may be categorized into representative types based on their physical layout. Similar types are then placed into groups to determine representative station within each group for fire safety assessment purposes, as follows:

1. Types: the station type is determined on the basis of their physical layout and exit arrangements.
2. Groups: the station group is a collection of similar types such that the worst case within that group may be chosen as representative for case study purposes.

The station parameters to determine the types and group were based on the following criteria:

- Number of platforms
- Numbers of staircase and escalators between levels
- Roof profile

Considering the egress layout of the Singapore's North-South and East-West lines stations, eight groups of typical layouts were identified. Representative stations were then selected for stage 2 analysis. (Refer to Appendix A.)

[1] A trainway fire refers to a train carriage fire on the tracks adjacent to the station platform and is considered the largest fire source for the station.

53.2.2 Stage 2: Preliminary Analytical Assessment

In stage 2, the representative stations are then reassessed with simplified analytical procedures (ASET, RSET times, station occupancy) as a means of ranking the stations for further analysis. In the assessment of fire safety using a performance-based approach, the two most critical parameters are the ASET and RSET times, defined as follows:

ASET = available safe egress time. This represents the available time for the occupants to evacuate safely to a safe place, usually considered to be outside of the building (or in this case, station). In engineering applications, the ASET is determined to be the time when conditions become untenable because of effects of the fire such as smoke visibility and temperature. For aboveground stations, factors affecting ASET include the roof profile and the height of the roof edge above the platform.

RSET = required safe egress time. This represents the amount of time required by the occupants to evacuate safely to a point of safety, usually considered to be outside of the building (or in this case station). In engineering applications, the RSET is determined by calculation or simulating the amount of time for the occupants to move out of the building via the provided exit paths. Factors affecting RSET include queuing, travel distance, and the number and capacity of exits. These were assessed in accordance with Appendix B of SFSRTS [2].

The tenability parameters and limiting criteria [1] used in performance assessment are taken from SFSRTS [2]:

1. Smoke temperature (at $<$2.5 m, $<$60 °C; at $>$2.5 m, $<$200 °C[2])
2. Smoke visibility (at $<$2.5 m, $>$10 m for doors/walls, $>$30 m for illuminated sign)
3. Radiation ($<$2.5 kW/m^2)
4. CO toxicity (800 ppm for 15 min; 1500 ppm for 6 min)

For the assessment of stations, the largest fire hazard is the trainway fire itself. Hence, the selection of stations with critical egress provisions will need to consider how the station layout affects the tenability parameters.

The tenability parameters and limiting criteria are generally in direct relationship to the smoke level dropping below the height of 2.5 m. Hence, the longer it takes for the smoke to descend, the higher the inherent safety of the station

[2] The radiation from the smoke layer is limited by the temperature of 200 °C. The radiation from the fire plume of the burning train carriage is usually less critical, but needs to be considered where the accessible platform width is too narrow so that access to egress exits may be impeded.

design. Station design should therefore incorporate design features that provide a high ASET value: these include high roof profiles and high opening heights defined by the roof edge.

The types of roof profile for aboveground stations are as shown in Fig. 53.1.

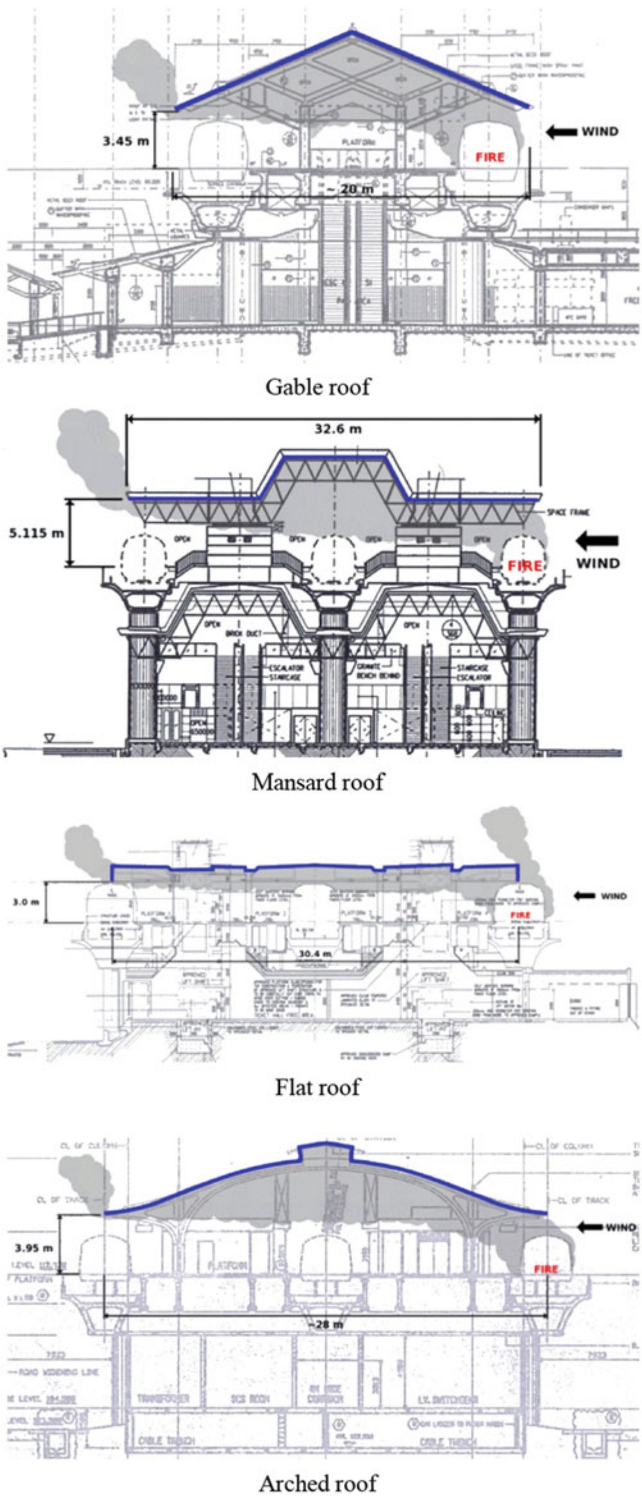

Fig. 53.1 Range of station roof profiles

The reservoir within the roof profile provides a buffer for smoke filling before it begins to spill out to the open sides and descends to the platform level. The time for which the volume provides this buffer may be estimated by a simple smoke-filling equation based on Zukoski et al. [3] as follows:

$$m_e = kQ_c{}^{1/3} z^{5/3}$$

where

m_e = rate of air entrainment (i.e., smoke production), kg/s
$k = 0.076$
Q_c = convective heat release rate (~0.7 Q, kW)
Z = height where entrainment is determined (m)

Hence, for a fire size of 15.2 MW, the entrainment rate at $z = 3$ m is determined as

$$m_e = 0.076 \times (0.7 \times 15{,}200)^{1/3} \times 3^{5/3} = 10.43 \text{ kg/s}$$

Assuming an average smoke temperature of 200 °C, the smoke density is 0.744 kg/m^3. Hence, the volume of smoke production rate is estimated to be 10.43/0.744 = 14.0 m^3/s. For a prismatic or gable-shaped roof of 20 × 150 m at 6 m high, and with edge opening of 3 m high, the smoke will fill out the roof at (20 × 150 × 3)/2/14.0 = 321 s or 5.3 min. The actual time will take much longer as the growth phase of the fire to reach the peak fire size has been ignored.

Based on the foregoing, the smoke filling time is directly related to the volume under the roof. However, when the smoke layer reaches below the lower edge of the roof, it will begin to spill out from under the roof to the external environment. The rate at which this spill rate occurs can be estimated as shown in Fig. 53.2 [4].

The smoke spill depth represents the clear height below the roof edge. Hence, the greater the height of the opening below the roof edge, the greater the rate at which smoke can spill out from below the roof.

The other factor that influences the containment of smoke below the roof is the roof width. A CFD (Computational Fluid Dynamics) study based on a simplified model of the station determined that with wider roof widths, the extent of the smoke layer ‘thickening’ is more extensive, but does not appear to be as significant (Fig. 53.3). Nonetheless, it is assumed to be the limiting height if the height of the smoke layer is close to 2.5 m from the platform level.

The RSET is determined by calculation or simulating the amount of time for the occupants to move out of the platform via the provided exit paths. Factors affecting RSET include queuing, travel distance, and the number and capacity of exits. In stage 1 the grouping of the station into eight typical groups takes into account the egress location and layout, and

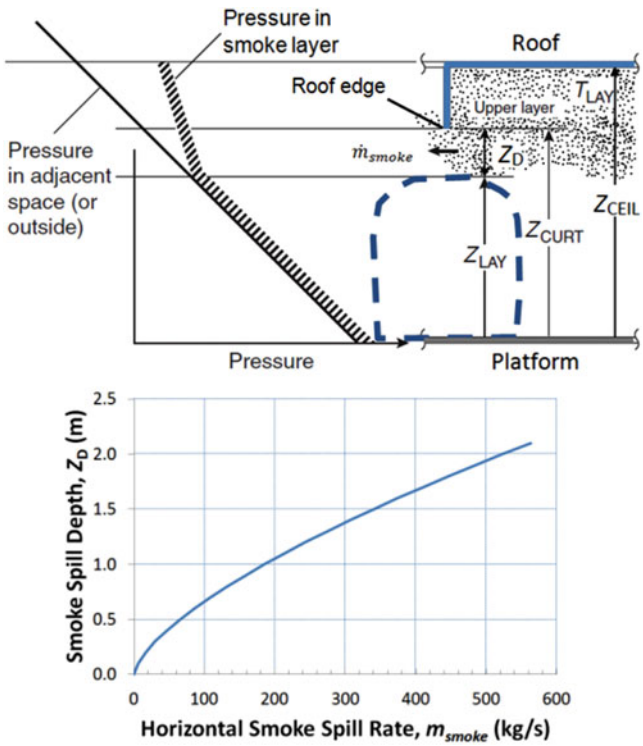

Fig. 53.2 Rate of horizontal smoke spill from below roof edge

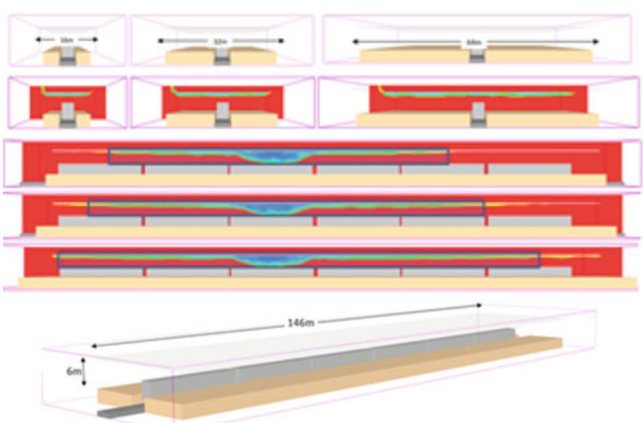

Fig. 53.3 CFD study of roof width using simplified model of station

a station with the lowest exit capacity will require the highest evacuation time.

Based on the foregoing preliminary assessment, the stations selected for a detailed performance-based assessment are as follows:

1. For representative station with worst case ASET: station with low, wide, and flat roof.
2. For representative station with worst case RSET: station with the lowest exit capacity

53.3 Stage 3: Detailed Assessment: Performance-Based Approach

In undertaking a detailed assessment using a performance-based (PB) approach, the data and analytical process are much more detailed and elaborate.

The local fire authorities require the performance-based (PB) process to include the development of a Fire Engineering Design Brief (FEDB) to document the assumptions and methodology to be undertaken, and upon approval of the FEDB, to prepare the full analytical work in the Fire Engineering Report (FER), which is to be peer reviewed by a qualified person.

The FEDB is required to include details of the following:

1. Project scope
2. Relevant performance-based issues to be addressed
3. Building characteristics
4. Occupant characteristics
5. Fire hazards/Fire scenarios
6. Trial designs
7. Method of evaluation
8. Design parameters
9. Notes of discussion/consultations
10. References
11. Credentials and endorsement of fire safety engineer (FSE)

Of the foregoing, the more critical details are item 5, fire hazards/fire scenarios, and item 8, design parameters.

The fire hazards scenario is considered the most important design parameter, as the design outcome is dependent upon how best to provide for the relevant fire safety systems to mitigate its effects and therefore provide a safe design. With the availability of advanced fire simulation models, such as FDS [5], the effects of fire are simulated by representing it as a rate of heat release.

For stations, the greatest fire hazard is the train car itself, as most of the contents at a station platform are noncombustible. The fire is simulated at the undercarriage and the fire perimeter is taken as the dimensions of a single carriage (approximately 23 × 3 m). For the older train cars used in the North-South Line and East-West Line, a train car fire size of 15.2 MW is proposed. The fire size is conservatively large in comparison to modern carriages which have less combustible material and are of the order of about 6–7 MW [6].

The train fire is assumed to develop at a fast growth rate until it reaches its peak fire size of 15.2 MW. It is then conservatively[3] assumed to sustain the heat release rate at the peak value for the duration of the simulation, taken as 20 min.

[3] Conservative because fire loads will eventually be consumed and the fire size will reduce accordingly.

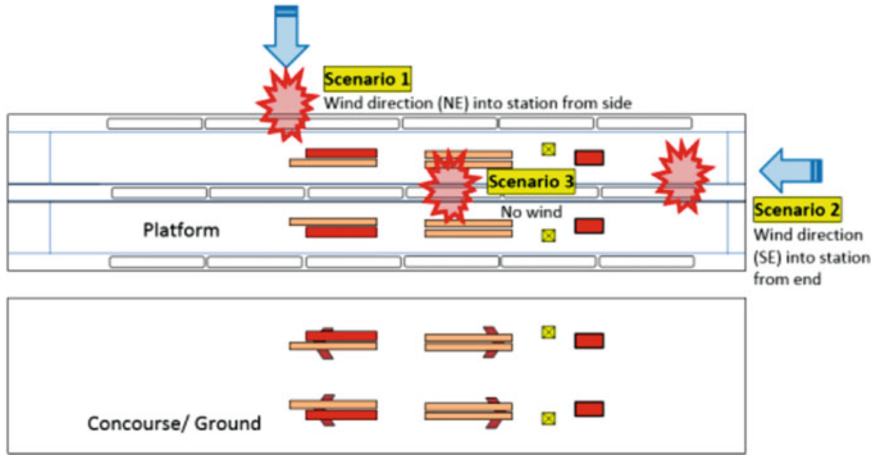

Fig. 53.4 Fire scenarios for trainway fire

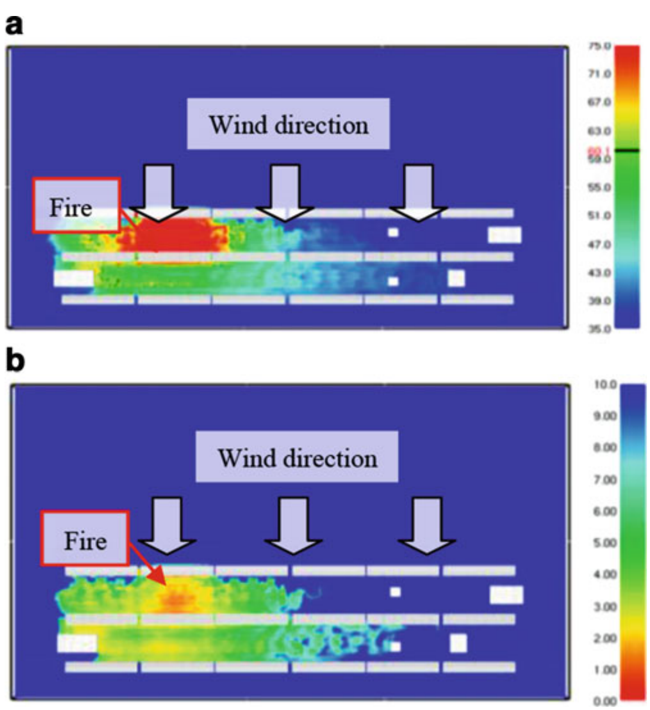

Fig. 53.5 Scenario 1 results (wind from side). (**a**) Temperature, (**b**) Visibility

The corresponding soot yield adopted is 0.035 kg/kg fuel, based on polyurethane as plastic fuel. A CO yield of 0.030 kg/kg fuel is adopted as the fire would be adequately ventilated in an open-sided aboveground station environment, and CO production would be minimal.

It is determined that the worst location for the fire is in the middle of the platform (for three-track platforms) where smoke is most contained in the middle before it reaches and spills out the open sides. An important factor affecting the behavior of the fire and therefore potentially affecting the ability of occupants to safely evacuate is the wind speed and direction. The worst case wind directions are blowing onto the platform side, potentially blocking movement of passengers on the platform, and blowing from one of the station ends, filling the platform with smoke. Taking into consideration the two critical parameters identified in stage 2 (opening height at roof edge and roof width), three fire scenarios are proposed for further study on such a station (Fig. 53.4).

- Scenario 1: Wind direction into station along the length of the station
- Scenario 2: Wind direction from the end of the station
- Scenario 3: No wind

The Singapore's North-South East-West lines are served by six-car trains. For the purpose of this study, the occupant load is based on the conservative assumption that the trains and platform are loaded with passengers.

With the station loaded with passengers on the platform, any signs of fire will be readily noticed. A pre-movement time of 30 s would not be unreasonable for those that are in direct sight of the fire and 60 s for other passengers. However, in a high occupant density situation, most of the time taken to evacuate would be taken up by queuing time.

53.4 Fire Engineering Analysis

The CFD analysis adopted for the fire simulations is utilizing the Fire Dynamics Simulator (FDS), developed by the National Institute of Standards & Technology (NIST). FDS has been accepted by many regulatory bodies, including the local fire authority.

The egress simulations were undertaken using FDS-EVAC v2.2.1 [7]. This simulation software is developed at VTT Technical Research Centre of Finland and is fully embedded in the Fire Dynamics Simulator (FDS) model.

The simulation results for the two-key tenability criteria of visibility and temperature showed that a station with a low and wide flat roof would be the most critical (Figs. 53.5, 53.6, and 53.7). For the results shown here, the color range of yellow to red for both visibility and temperature indicates that the tenability criteria limits have been exceeded. The

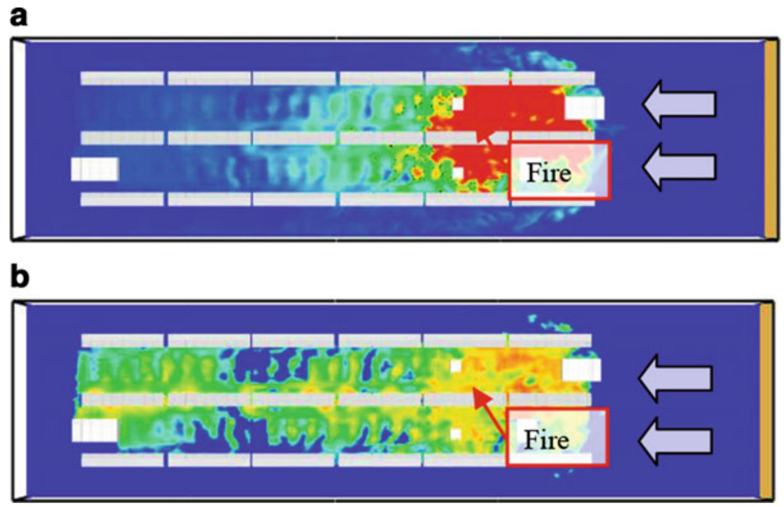

Fig. 53.6 Scenario 2 results (wind from end). (**a**) Temperature, (**b**) Visibility

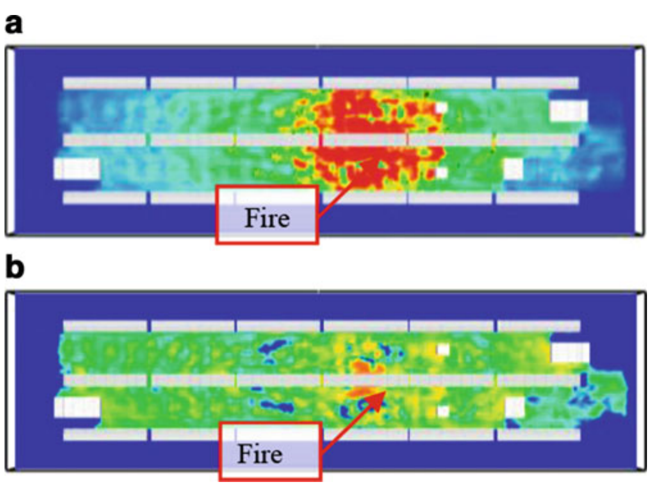

Fig. 53.7 Scenario 3 results (fire in middle—no wind). (**a**) Temperature, (**b**) Visibility

results are shown at the end of the simulation taken at 20 min, when the smoke conditions have stabilized, that is, reached steady state.

53.5 Discussion

At steady-state conditions, the visibility for the station in group D (Fig. 53.8), with low, wide, and flat roof, is low in the vicinity of the burning car, with an average visibility of more than 5 m at 2.5 m above platform level. The tenability limit for temperature is exceeded for about a half car length on either side of the burning car, beyond which conditions remain tenable. Based on the foregoing results, this type of stations may be considered to be the most affected by the effects of fire for safe egress.

For station with a low roof profile, if deep waffle beams and ceiling panels are also present, this would further constrain the flow of smoke to the external environment. The smoke layer would descend below 2.5 m from the platform

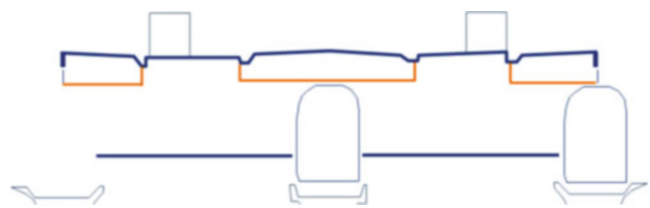

Fig. 53.8 Sectional view of station D

level before reaching a steady state at the vicinity of the fire source.

Although achieving tenability at steady-state conditions is desirable, performance-based design is also acceptable when an adequate margin of safety for egress can be demonstrated. This margin is usually represented by the ASET/RSET ratio, and the norm for acceptance is achieving an ASET/RSET ratio of at least 2; that is, occupants must be able to have at least twice the time available for escape before untenable conditions are reached. To better assess if occupants are able to escape and are not be incapacitated by untenable conditions, a transient analysis of the environmental conditions and egress movements over time is undertaken.

53.5.1 Transient Tenability Analysis

In a transient tenability analysis (TTA), conditions of the paths to exits are assessed for tenability over time to determine if occupants are prevented from safely evacuating to a safe place. This analysis is applied to Scenario 3, which appears to provide the worse results of the three.

The results from the radiation and CO contour (Fig. 53.9) indicate that only areas very close to the plume exceeded the tenability limits. Hence, it may be considered that the egress movement of occupants is not impacted by either radiation or CO levels at the platform.

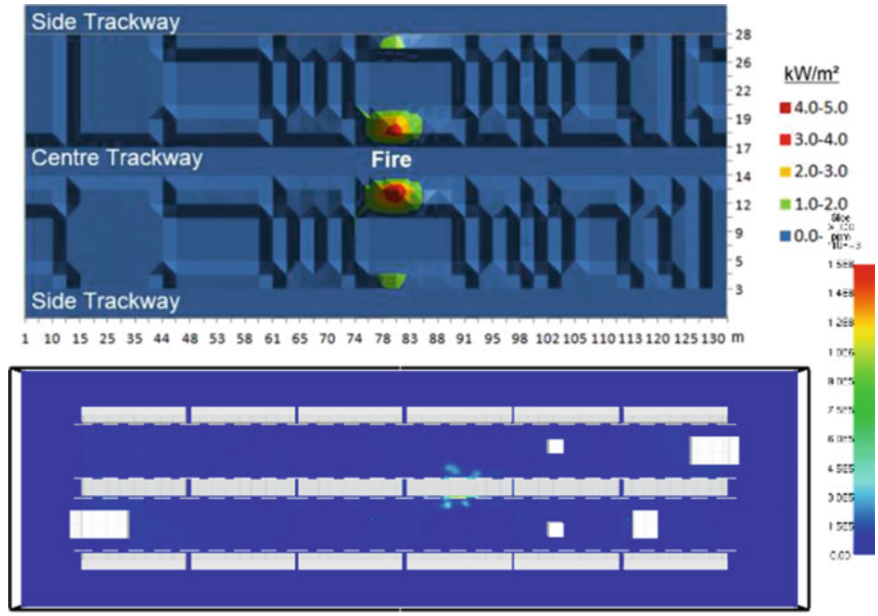

Fig. 53.9 Fire plume radiation and carbon monoxide emission contours

On the basis that the CO only exceeded the limits at areas close to the burning car, it would indicate that the smoke may be more limiting for visibility than toxicity. However, because the typical platform width is approximately 10 m and is bounded by platform screen doors (PSD) on both sides, occupants would be able to safely maneuver away from the fire towards the exit points, even at a reduced visibility of 5 m. The main tenability condition that would potentially impact passengers being exposed to it would therefore be temperature.

The transient assessment of occupant safety following the progression of the temperature limit state and the areas occupied by occupants during egress over time are discussed further by Poon [8]. The graphic progressions at various stages are shown in Fig. 53.10. The exits closest to the fire location have been considered to be blocked by their proximity to the fire location. The tenable extent of the temperature limit appears to have reached steady state at about 500 s.

More importantly, it can be seen that occupants were able to safely remain within the tenable areas of the platform and away from the growing limits of the temperature field. At no time were the paths of egress blocked off, nor did the areas occupied by occupants while queuing became untenable, even at steady state. Hence, it may be considered that tenable conditions for safe egress were achieved even at steady state, which therefore complies with the root objective of SFSRTS Clause R2.2.1 in providing safe access for occupants to escape.

53.6 Conclusion

A performance-based approach is presented as a case study to assess the escape provision for aboveground stations utilizing Singapore's North-South East-West line stations. The approach incorporates a selection process to identify the representative stations from the range of layout types of aboveground stations. Detailed analysis of the representative stations showed that stations with a high and deep roof profile could comfortably meet the safety criteria, even at steady state, and station with a low, wide, and flat roof had localized areas of untenable conditions near to the fire at steady state. However, a transient tenability analysis of egress and tenability conditions over time demonstrated that at no time were the required paths of egress blocked off, nor did the areas occupied by occupants while queuing became untenable, as the conditions approached steady state. It was therefore considered that tenable conditions for safe egress were achieved even at steady state. Stations with higher exit capacity and distributed exits such as group B would require the least egress time.

As actual station data were used with a conservative fire size, and the scenarios were considered to have captured the worst case fire and wind configurations, sensitivity analysis was only considered in terms of undertaking detailed analysis for the other stations identified in stage 3 (Detail Assessment: Performance-Based Approach). As they all produced highly favorable results, the extent of the study was considered sufficiently robust to not affect the final outcome.

53.7 Recommendations

It was found that the key design parameters for aboveground stations are the roof profile and distributed exits throughout the platform to meet the fire safety criteria. To minimize the risk of smoke affecting safe egress in aboveground stations, it is recommended that stations are designed with a high and deep roof to provide for tenable conditions and exits with high capacities and well distributed for a prompt egress.

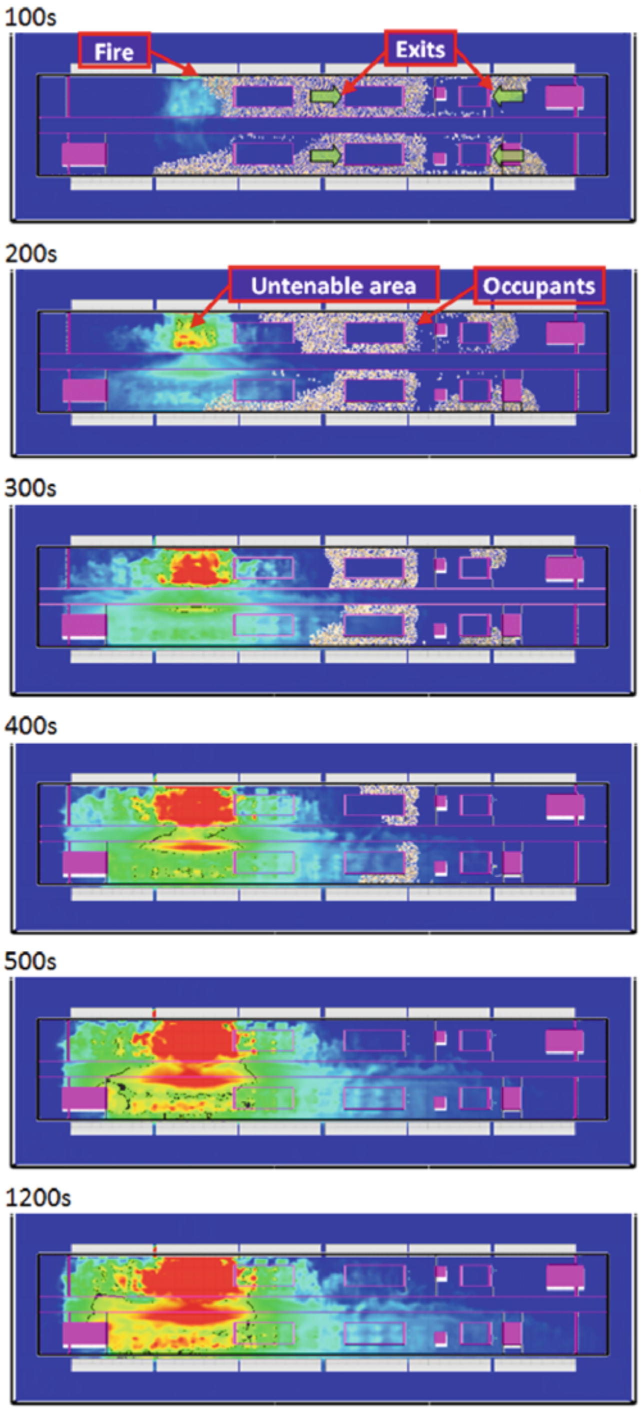

Fig. 53.10 Progression of temperature limit state and areas occupied by occupants during egress over various time steps

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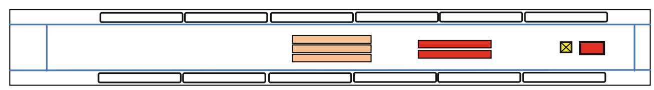
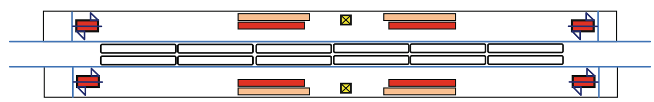
Leong Poon & Assoc.: Tan Beng Leong, Zhao Ya

Appendix A: Station Groups and Different Layout Types

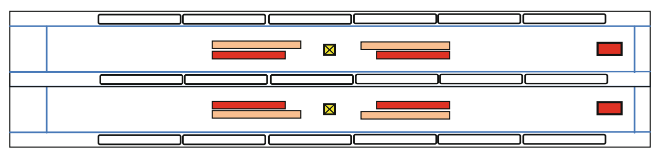
Group A:



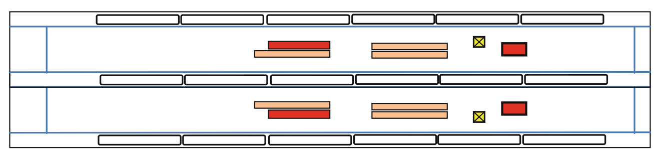
Group B:



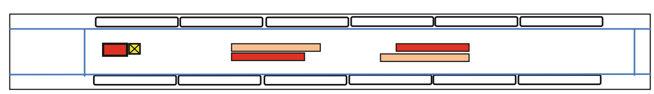
Group C:



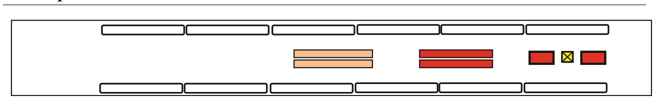
Group D:



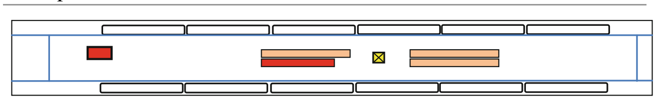
Group E:



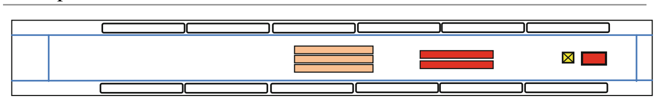
Group F:



Group G:



Group H:



Legends

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