Experimental Validation of the Taipei Underground Railway System under Emergency Operation Modes

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ABSTRACT

The Taipei Railway underground project consists of a tunnel with total length of 22.5 km, including five underground stations and three emergency stops. The emergency procedure design concept, in adapting the NFPA 130 as a design guide, is to provide a smoke-free escape route should a fire occurred in the tunnel or on the underground station platform.

A series of full-scale experiments have been conducted with t-squared fires, ranging from 5 to 20 MW, to validate the effectiveness of the emergency operation procedure. In order to revive the piston effect induced by train movement, a local train has been employed during the test with gasoline pans set on the rolling stock to simulate the 20 MW fire. The temperature and velocity of tunnel air movement has been recorded during the fire to analyze smoke movement and to identify whether a tenable condition

can be maintained. Test results indicated that the push-pull effect introduced by the tunnel ventilation system in this project can successfully maintain a favorable critical air velocity, normally more than 2.5 m/s, to prevent smoke from back-layering and is analyzed in this paper.

A 5 MW fire has been experimented on the platform of one of the underground stations. Following the performance-based design concept, the ceiling plenum has been adapted as smoke reservoirs to alleviate the smoke descending rate, and thus to facilitate more time for evacuation. A full-scale egress experiment, using 528 people, has been conducted on the platform and the concourse level. The crowd moving speed has been recorded and compared with the SFPE curve showing very good correlation. This experimental result also recommended that a stairwell pressurization system is needed in considering the handicapped citizens. On the other hand, when the TVF operated on an emergency mode, an upwind over 2.5 m/s has been introduced along the stairwell, so that the evacuees can run up stairs under tenable condition.

The full-scale tests conducted in this project validated the effectiveness of the emergency operation modes of the Taipei Railway Underground project in providing safe evacuation in case of fire and will be discussed in details in this paper.

INTRODUCTION

The Taipei Metropolitan area is expanding rapidly which necessitates the major railway penetrating the heart of the city to become underground. This project consists of a tunnel with total length of 22.5 km (73818.75 ft), including five underground stations and three emergency stops. Being lack of appropriate corresponding regulations in local fire code, a performance-based design was conducted to establish the emergency procedures in case of fire, and validated with a full-scale experiment afterwards, which is the main theme of this study.

The design concept is to provide a smoke-free escape route should a fire occur in the tunnel or on the underground station platform. The “smoke free” condition can be maintained by several design options. On the platform level, zoned smoke control can be exercised with the ceiling chamber acting as smoke storage shown in figure 1, to provide an effective method in keeping a favorable clear height and enabling a safe evacuation. Alternatively, the tunnel ventilation fan (TVF) can be operated in an exhaust mode so that air was “sucked-in” through the exits with a facing air velocity around 2.5 m/s to 3.0 m/s to prevent smoke from back-layering, as shown in figure 2.

On the other hand, in case of a fire occurred in tunnel section, the ventilation systems operate in a supply/exhaust mode so that an air velocity higher than the critical velocity can be created. This airflow velocity in the tunnel was designed at an air velocity exceeding the critical velocity and in opposing the egress direction to prevent smoke from back-layering (Kennedy, 1996). The critical velocity in the tunnel can be calculated as follows:

$$V_c = k_l k_g \left(\frac{gHQ_c}{\rho c_p A T_f} \right)^{1/3} \qquad (1)$$

$$T_f = \frac{Q_c}{\rho c_p A V_c} + T \qquad (2)$$

Where:

V_c = critical velocity, m/s (ft/s)

K_l = 0.61.

K_g = grade correction factor, $k_g = 1 + 0.0374(grade)^{0.8}$

A = net area perpendicular to the flow, m^2 (ft^2).

ρ = The density of air

C_p = the specific heat of air, kJ/kg-^oC (Btu/lb-^oF)

Q_c = The convective part of fire heat release rate, kW (Btu/s).

H = Characteristic length for the bouyant forces; height of the tunnel at the fire site, m (ft).

g = The gravity acceleration, m/s^2 (ft/s^2).

T = The temperaure of ambient air, ^oC (^oF).

T_f = The average temperature of the fire site gases, ^oC (^oF).

A solution of emergency operation procedure for tunnel ventilation system is attempted in this study using SES as a simulation tool. In this aspect, the NFPA 130 (2000) provides useful criteria either for design guide or acceptance test. The smoke management system was designed and would be tested for compliance so that it can:

1. provide a stream of non-contaminated air to passengers in a path of egress away from a train fire.
2. maintain the minimum air velocity in the evacuation path and not be less than the critical velocity in order to prevent back-layering of smoke in a path of egress away from a train fire.
3. limit the air temperature in a path of egress away from a train fire to 60 ^oC(140 ^oF).
4. provide emergency exit stairways throughout the tunnels, spaced so that the distance to an emergency exit shall not be greater than 381 m(1250 ft) unless otherwise approved by the authority having jurisdiction

In this study, analysis will be focused on the Wan-Hwa station and the tunnel section between mileage UK 30+450 and UK 37+795, with a tunnel length of 7.345 km (24097.7 ft) between the Wan-Hwa and Pan-chiao underground station. This is a single-bored double-track tunnel, with 6.6 m (21.65 ft) height, 10.725 m(35.2 ft) width and 70.8 m^2 (762.1 ft^2) cross-sectional area. The slope is +1.2% ~ -1.2%. There are totaled 9 vertical shafts and 17 emergency exits. The vertical shaft location and fan capacity are shown in table 1. Figure 3 shows the schematic diagram of fan TVF-P03 and P06.

EXPERIMENTAL SET-UP

In this full-scale experiments, the tunnel air temperature, velocity, and the smoke layer clear heights would be measured. K-type thermocouples measuring range at 0 ~ 1372 ^{o}C (2502 ^{o}F) with ± 0.75 % of reading value accuracy were used. A multi-channel Kanomax hot wire anemometer was installed to measure the velocity field, with measuring range at 0.05 ~ 50 m/s (0.16 ~ 164 ft/s) and ± 0.3 m/s (1.0 ft/s) accuracy. For spot air temperature and velocity measurement, a portable Testo probe was used with measuring range at 0.05~10 m/s (0.16 ~ 32.8 ft/s), and ±0.05 m/s (0.16 ft/s) and ± 0.5 ^{o}C(0.9 ^{o}F) accuracy.

The Kanomax velocity probes were installed on one instrumentation tree consisting of 10 velocity measuring points along the tunnel height. The other four instrumentation trees were installed with ten temperature probes each, located at different distance from the fire source, which totaled 40 temperature measurement points.

The Testo probe was used at the egress passage near the fire location to measure the temperature when evacuees are passing through the fire point to reach the exit. The whole instrumentation set-up is shown in Figure 4.

To measure smoke layer clear height, twenty measuring posts with reflectors are located on either side of the fire, with 5 meters spacing each. The reflectors are marked every meter above the ground, to indicate the visibility during evacuation. Three video cameras were installed to record the whole fire and smoke plume developing process. One is located at the fire site to record the horizontal movement of smoke above the fire plume, and the other two were installed on either side of the fire to record the smoke migration and descending rate.

Kerosene was selected as the fuel for this experiment. The idealized heat release rate is estimated 2.72 MW/m^2 (239.5 Btu/s-ft^2) (Barnnet, 1994). With twenty-four Kerosene pans and size of 0.5 m (1.6 ft) × 0.5m (1.6 ft) each, this will add up to 16 MW (15200 Btu/s) fire load in total. During the experiment, the kerosene pans were installed along two tracks for a rectangle sized 1.5 m (4.9 ft) × 4 m (13 ft). To visualize the smoke development process more easily, smoke bombs of different colors were ignited at the same time when a fire was set. Instead of setting the whole carriage on fire, another 1m × 1m gasoline pan was set up on the luggage carriage. The experimental procedure is shown in Table 2.

In order to analyze the fire size quantitatively, four pre-tests using 1 m (3.28 ft) × 1m (3.28 ft) Kerosene pan were conducted with 4.65 kg (10.25 lb), 7.29 kg (16.07lb), 4.58 kg (10.1 lb) and 5.15 kg (11.35 lb) Kerosene respectively.

The fuel mass loss rate of the pre-tests were measured indicating that the average fuel mass loss rate is 0.0522 kg/s (0.115 lb/s), which led to a corresponding idealized heat release rate of 2.26 MW/m^2 (199 Btu/s-ft^2) and is close to the result by Barnnet (1994). To add up the 6 m^2 Kerosene pans, the total idealized heat release rate is 20 MW (19000 Btu/s) in this experiment。

DESIGN FIRE SCENARIO & EXPERIMENTAL RESULTS

The fire scenarios were classified into two categories, depending on whether a fire occurring at the station or inside the tunnel.

Test 1: Fire at the station, ventilation on Exhaust Mode

When a fire occurred at the platform, or a train caught fire and entering the station, a large crowd of evacuee will be expected to move from the platform through the stairs to reach the concourse level. The P6, P10 and the VS1, P3 fans were put on an exhaust mode to create a favorable downward air flow, such as shown in Figure 5(a), and validated further by figure 5(b) that an over 2.5 m/s air speed can be maintained successfully. This result also correlated very well with the SES simulation result as shown in figure 5(c).

Test 2: Fire at the Station, Ventilation on an Unbalanced Hybrid Mode

An innovative emergency operation mode has been developed to further improve the ventilation system performances. The design concept is to operate the system on an “Exhaust Only” mode for the first 6 minutes to comply with the NFPA 130, for a safe evacuation of the passengers as shown in figure 6(a). Then followed by an unbalanced push-pull mode to provide a smoke-free entry point for the firefighters through stairs A and C as shown in figure 6(b).

The experimental result, as shown in figure 6(c), validated this scenario successfully that during the passenger egress period, sensational air speed of 3.0 m/s can be maintained for more than 6 minutes. While the following 10 minutes or more, a 2.0 m/s clean air stream has been provided at the stairs A and C to facilitate firefighters to move in.

Test 3: A train caught fire in the tunnel, natural fire plume development observation

When a train caught fire at the front, a “supply-exhaust” ventilation mode to move the air further downstream is a straight-forward solution, as shown in Figure 7. On the contrary, the tail fire needs a ventilation mode to move the smoke in opposing the piston effect which is also simple and feasible. A dilemma exists when a fire started in the middle of the train, where smoke should not be blown to either side instantaneously since both sides are crowded with evacuees. If the train is still mobile, to decouple the fired section (or the unaffected sections) presents a feasible solution for the first step, followed by the “supply-exhaust” ventilation mode to the train-moving direction. On the other hand, the train might be decoupled and transporting passengers on unaffected sections to the nearest stations or emergency stops, leaving the coach on fire at site, while passengers are evacuated to the emergency exits in opposite directions to the air flow.

Based on the emergency procedure adapted in Taiwan, the train that caught fire will continue to travel into the nearest station if the train is still in mobile condition, so that the passengers can evacuate through the platform. However, in this experiment, it has been intentionally arranged to probe the feasibility of decoupling the train into two sections, and develop a new scheme for evacuation and firefighting. This is mainly due to the consideration that some of the trains are still using diesel locomotives, which can still be mobile even in electric power failure and thus allows more flexible to develop a new emergency operation mode.

The worst case scenario is when the train caught fire in the middle, while the train totally lost its power and evacuees need to run on the track to the emergency exits. If ventilation remains off-online and fire plume develops, will the smoke allow enough time for either side of people to reach exits? If this is the case, then air could be blown afterwards to one side where evacuation is completed. On the other hand, if people penetrate aside the fire point, would the radiation temperature impose any harm to the people exposed? All these questions have been answered through the following free plume test result.

Without mechanical ventilation, the fire plume is dominated by buoyancy and natural wind. Figure 7 shows the temperature distribution of such a case. The smoke layer thickness is around 2.5 m (8.2 ft) or a clear height of 4 m (13.1 ft), which correlates well with the simulation result. The minor differences among the instrumentation trees are due to their locations to the fire and natural wind directions. This result is very important, indicating that when undisturbed, the fire plume could maintain at over 4 m (13.1 ft) clear height for more than 10 minutes in this case. This result contributes directly to emergency cases when a train caught fire in the middle where smoke cannot be blown to either side instantaneously, and will be discussed later

Test 4: A train caught fire at the front, loosing mobility, two supply-two exhaust ventilation mode

In this experiment when the train suddenly stops, the piston effect introduced a surge of air speed around 5 m/s (16.4 ft/s) as indicated in Figure 9. After the ventilation system started, the air speed is kept nicely at around 2.25 m/s (7.38 ft/s) as shown. The temperature measurements shown in Figure 10 indicated that the smoke thickness downwind is around 2.6 m (8.5 ft), and 1.6 m (5.2 ft) upwind. After 5 minutes, the temperature distribution showed that the fire and smoke plume had been cooled down by the entrained air as shown in figure 10 to nearly 40 ^{o}C (104 ^{o}F). The upwind direction still successfully maintains a smoke-free condition when the whole evacuation process had been completed as experimented. The velocity and temperature measurement were taken near the fire location indicating the actual impact of the fire plume, without considering any other effects such as when smoke pass by the diesel-electric locomotive.

On the other hand, in downwind direction the plume was totally disturbed by the airflow and the whole tunnel is filled with dense smoke with essentially no visibility. This phenomenon also validated the correct evacuation route proposed in this study.

Test 5: The Worst Case Scenario – Fire in the middle of train, Loosing Mobility, Modified two-supply-two-exhaust Ventilation Mode

When a fire occurred in the middle of the train, instantaneous start of the supply-exhaust ventilation mode could be disastrous since passengers located on the downwind side essentially has no chance to survive. In test 1, an important finding is that when undisturbed, the smoke plume could maintain a clear height of 4 m for more than 300 seconds. In this case, the conductor played a key role in guiding passengers to evacuate on either one side within this time period. When cleared, ventilation was started immediately to blow the smoke to this direction, and keeping the air speed at 2.5 m/s (8.2 ft/s) to prevent smoke from back-layering. Passengers on the other side can then be evacuated to the upwind easily as indicated before.

This worst-case scenario was demonstrated successfully in our experiment. Some passengers, instead of waiting for the ventilation system to take effect, choose to pass through the fire point and join the evacuation instead of waiting for instructions. This is considered a common reaction when people are in panic, and should be considered. The temperature at this passing point was measured 45 ^{o}C (113 ^{o}F), lower than the 60 ^{o}C (140 ^{o}F) indicated in the NFPA 130 code and is considered safe. A handicapped passenger joined this experimental process and demonstrated this point successfully. The whole process takes less than 6 minutes to complete.

FULL-SCALE EGRESS EXPERIMENT

Conventionally, the evacuation process is considered similar to a hydraulic flow, while the total egress time needed is the larger of the walking time needed from the farthest exit or the time needed to pass through exits. However, this over-simplified model has some discrepancy in predicting a massive crowd during egress where bottleneck and pushing and taking over are likely to occur. In this study, a full-scale egress experiment has been completed with 528 attendants. The number of evacuees was picked exactly the same as design conditions following the NFPA 130, while observers were distributed evenly in the crowd to record the time elapsed in each escape route.

A fire was set at the platform level, with light cut down to 25 % of the original, simulating the emergency lighting condition. A handicapped citizen was mixed in the crowd to reflect its impact on slowing down the crowd moving speed. The crowd density D and the flowing velocity V were then measures from the head counts which simulated the real fire scenario pretty well.

The experimental result was correlated using regression method and plotted in figure 11, indicating a very good accuracy in compared with the SFPE handbook.

The traveling distance from the most remote point in Wan-Hwa station is 75m. For the island type platform, 105 seconds would be needed to complete the evacuation process with 528 people. While for the side-type platform, 142 seconds is needed due to a larger crowd density. In addition, the smoke diction, humane confirmation and announcement of the fire, each step takes time to complete, which adds up with around 4 minutes for all passengers to leave the platform, and 6 minutes to reach points of safety, and compiling with the NFPA 130 criteria.

CONCLUSIONS

Should a fire occur, whether in an underground station or in the tunnel, a smoke-free escape route should be maintained by effective smoke management system. A performance-based design, following the NFPA 130 as the design guide, could come up with an effective design system in achieving this goal. The full-scale experiments conducted in this study validated this point successfully and the TRUPO project has been in commercial operation since 1999 with a satisfactory safety record ever since. The emergency standard operation procedure (S.O.P.) developed in this study has also become the model for other future underground railway projects in Taiwan.

ACKNOWLEDGEMENT

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NOMENCLATURE

CFAST Program: CFAST is the Consolidated Model of Fire Growth and Smoke Transport. It is the kernel of the zone fire models which are supported by BFRL, NIST.

Critical Velocity: The minimum air velocity past a fire to prevent back-layering.

NFPA 130: Standard for Fixed Guideway Transit Systems. This standard shall cover fire protection requirements for underground, surface, and elevated fixed guideway transit systems including trainways, vehicles, transit stations, and vehicle maintenance and storage areas; and for life safety from fire in transit stations, trainways, vehicles, and outdoor vehicle maintenance and storage areas.

SES Program: The Subway Environment Simulation (SES) computer program is a designer-oriented tool which estimates of the airflows, temperature, and humidity characteristics, as well as the air conditioning requirements for both operating and proposed multiple-track subway systems of any given design and operating characteristics.

t^2-fire: A t^2-fire is one where the burning rate varies proportionally to the square of time. The t^2-fire general equation is $Q = \alpha t^2$, where Q is heat

release rate (normally in kw or Btu/sec), t is time (normally in seconds), α is fire growth coefficient (normally in kw/sec^2 or Btu/sec^3).

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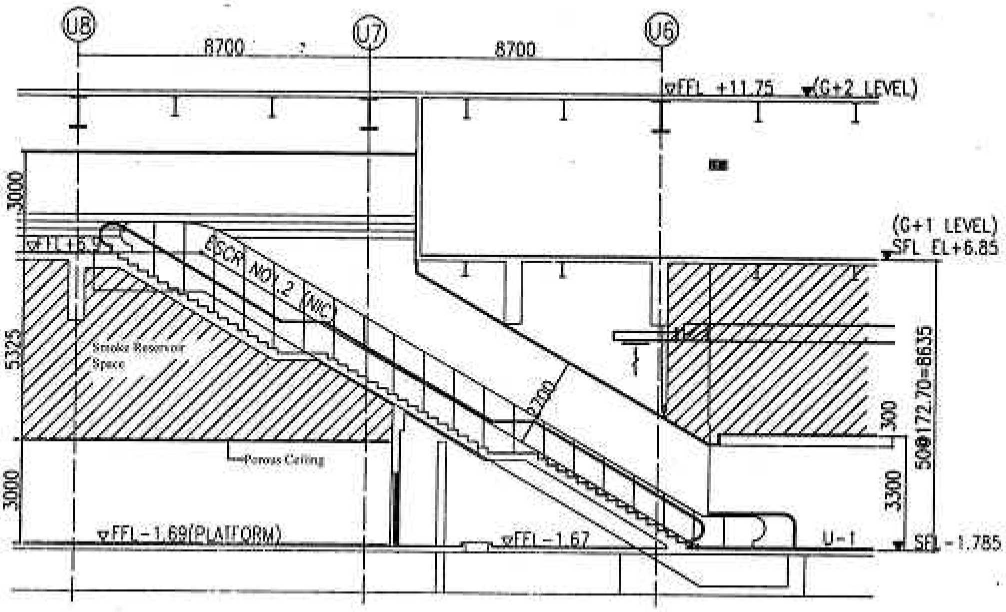

Figure 1 A Cross-sectional view of the Wan-hwa underground station

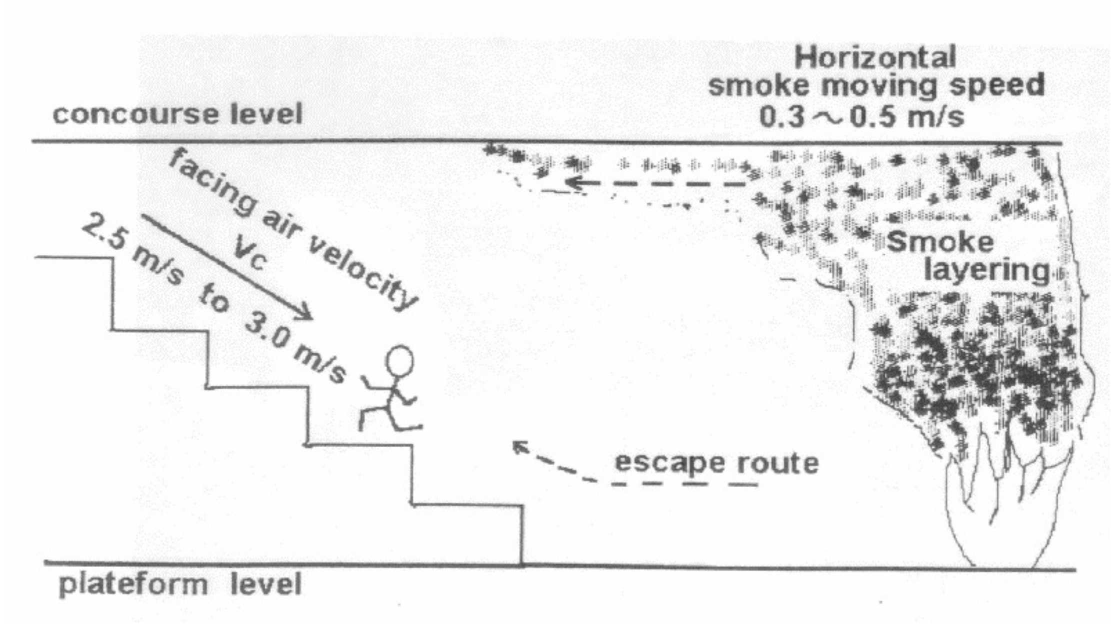

Figure 2 Using ventilation exhaust mode to provide an opposing air velocity at the stairs during egress and to prevent smoke from back-layering

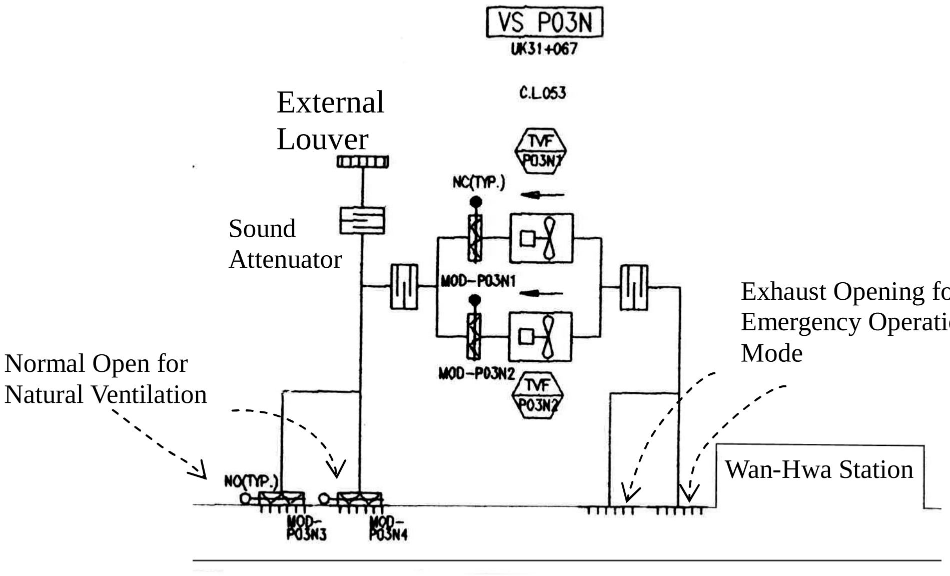

Figure 3 Tunnel ventilation air flow schematic diagram (TVF P03)

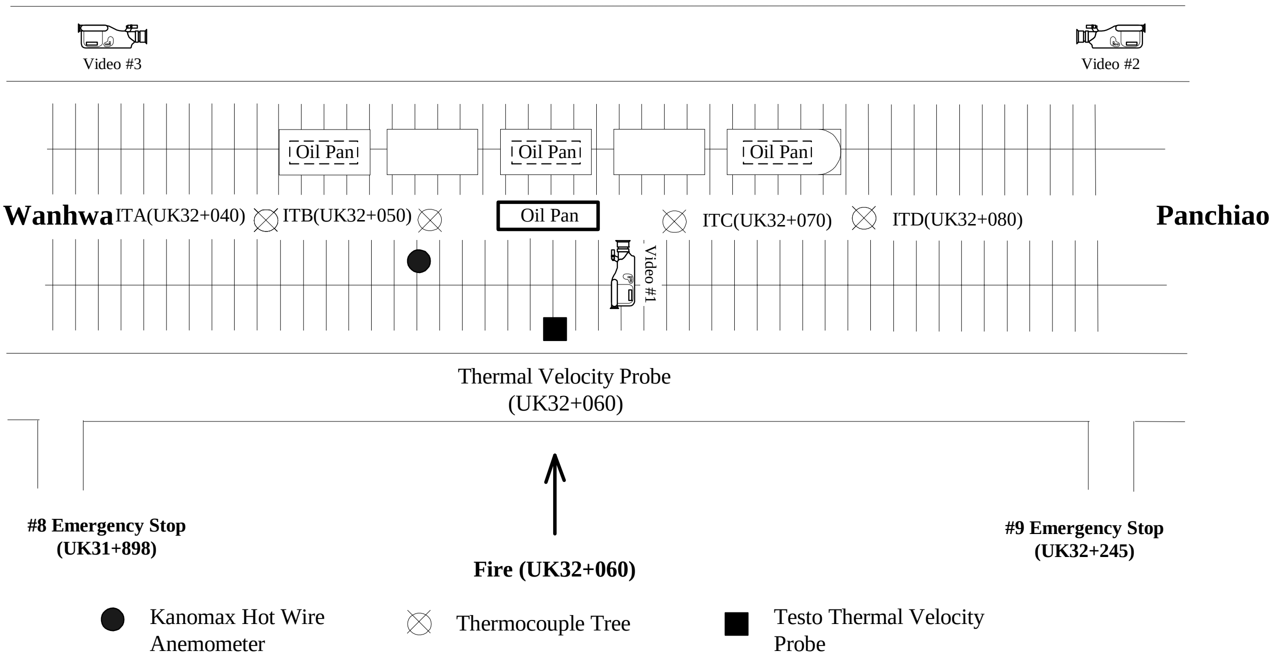

Figure 4 General instrumentation locations (Top View)

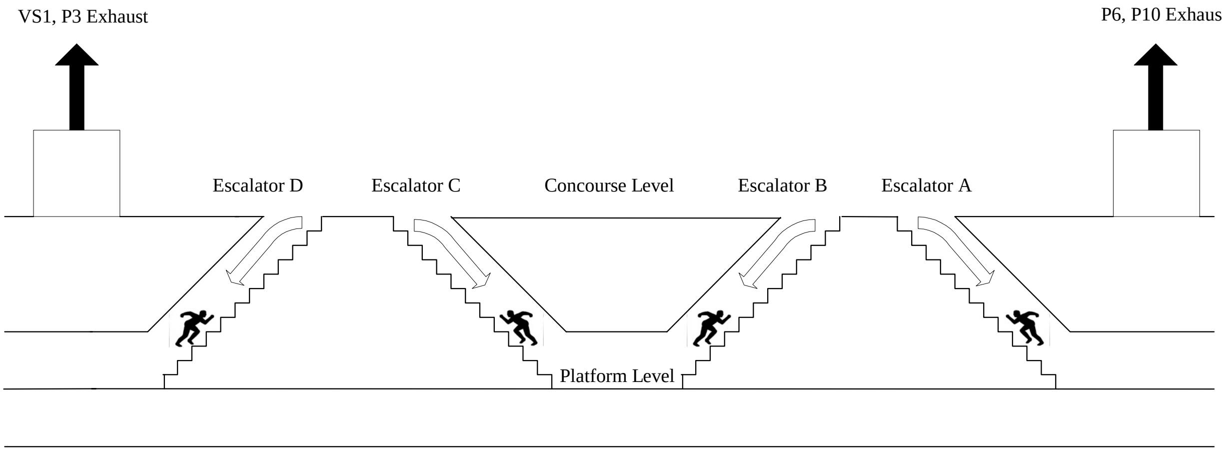

Fig 5(a) The air flow directions of test 1 during evacuation, lasting for 6 minutes

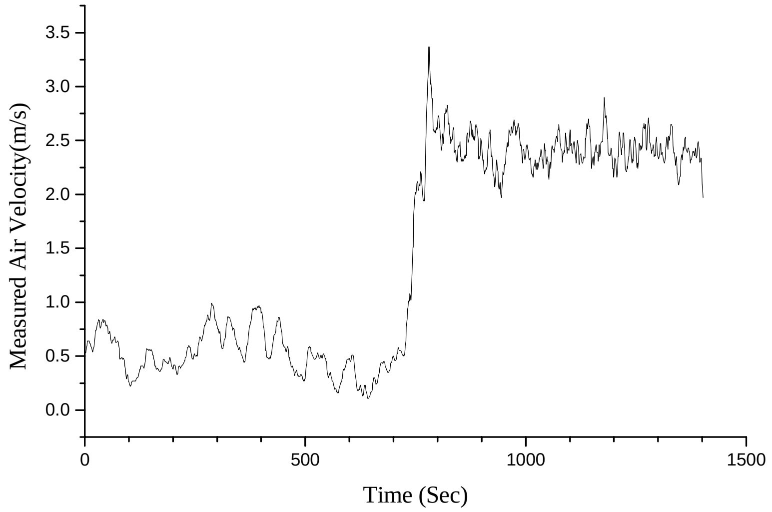

Fig 5(b) The measured air flow velocities at the stair B of test 1

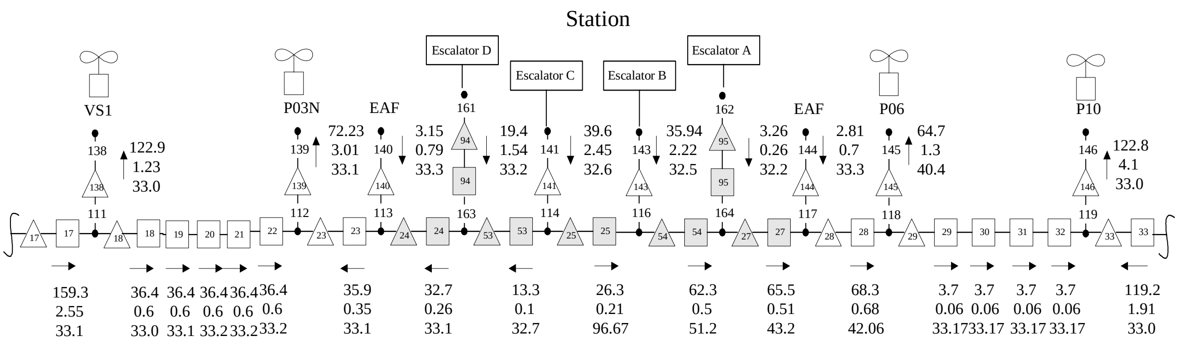

Fig 5(c) SES simulation result of test 1

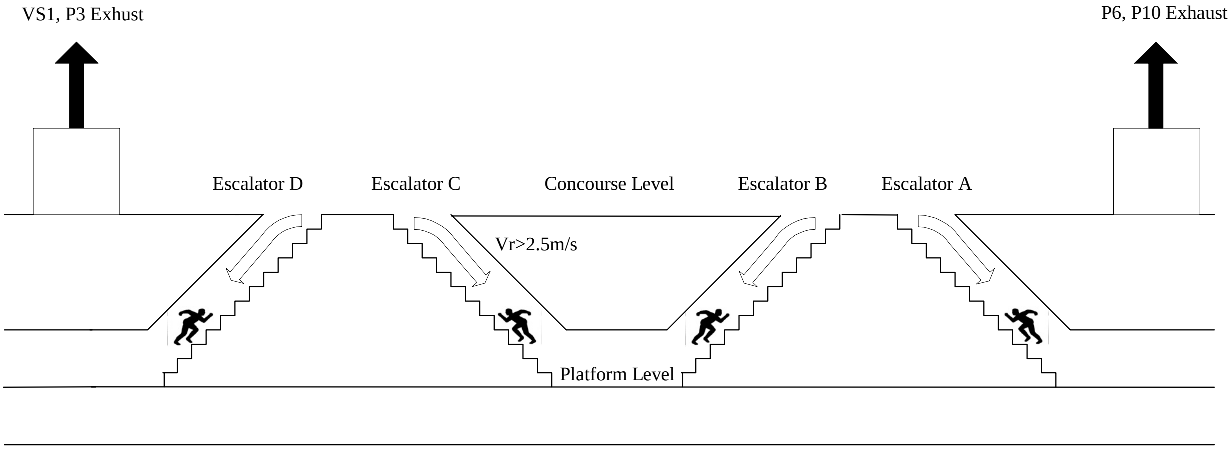

Fig 6(a) Emergency operation mode of test 4 for the first 6 minutes (For evacuation)

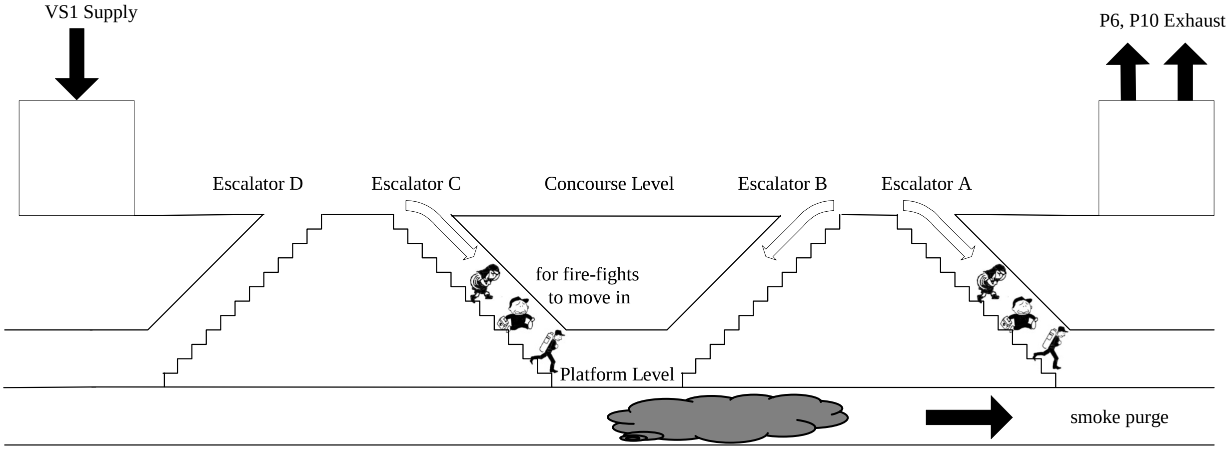

Fig 6(b) Emergency operation mode of test 4 after 6 minutes (For fire-fighting entry)

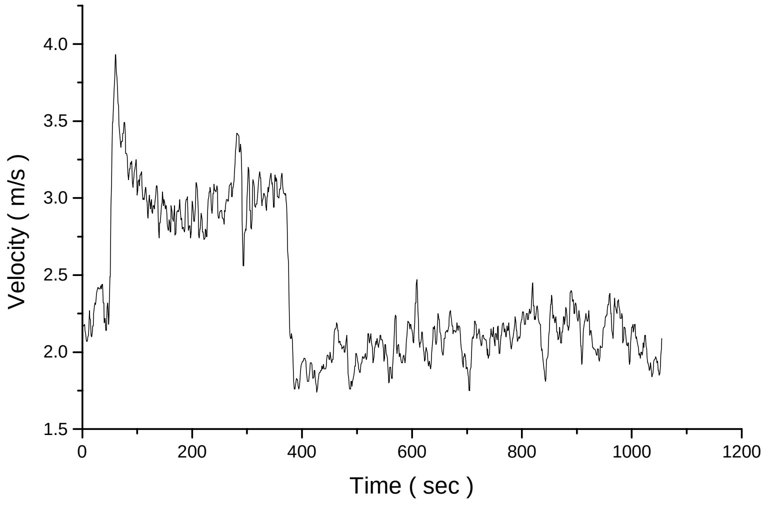

Figure 6(c) The measured air flow velocities at the stair B of test 4

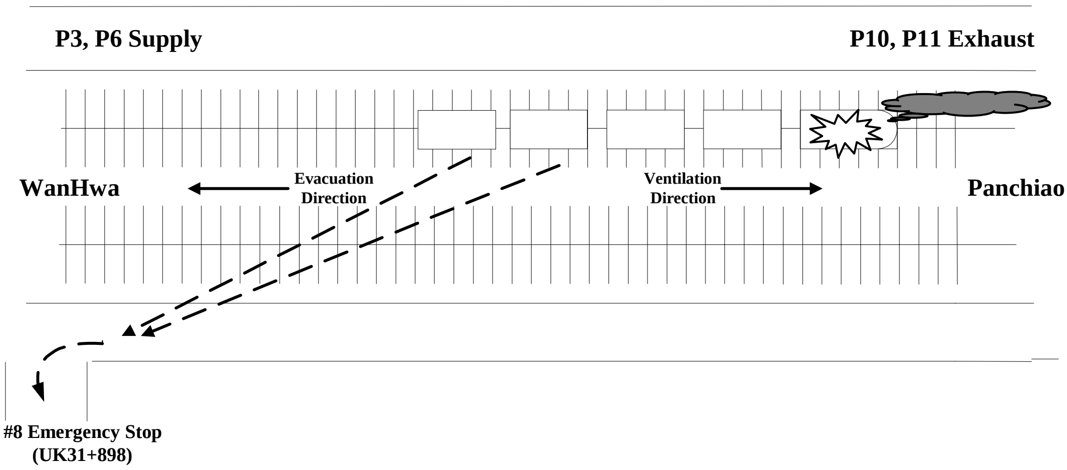

Figure 7 The ventilation mode when a train caught fire at the front

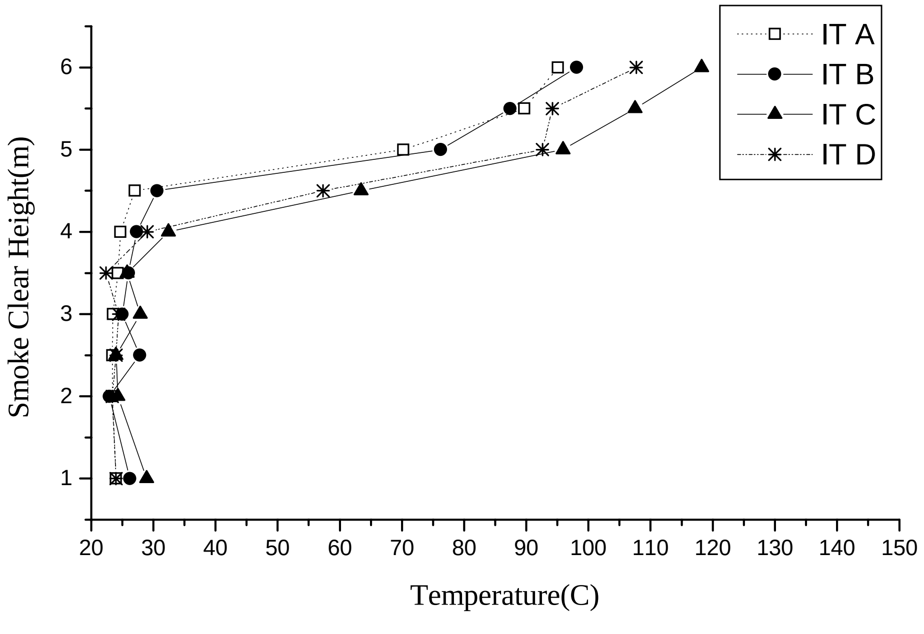

Figure 8 The temperature measurement of all instrument trees in test 3

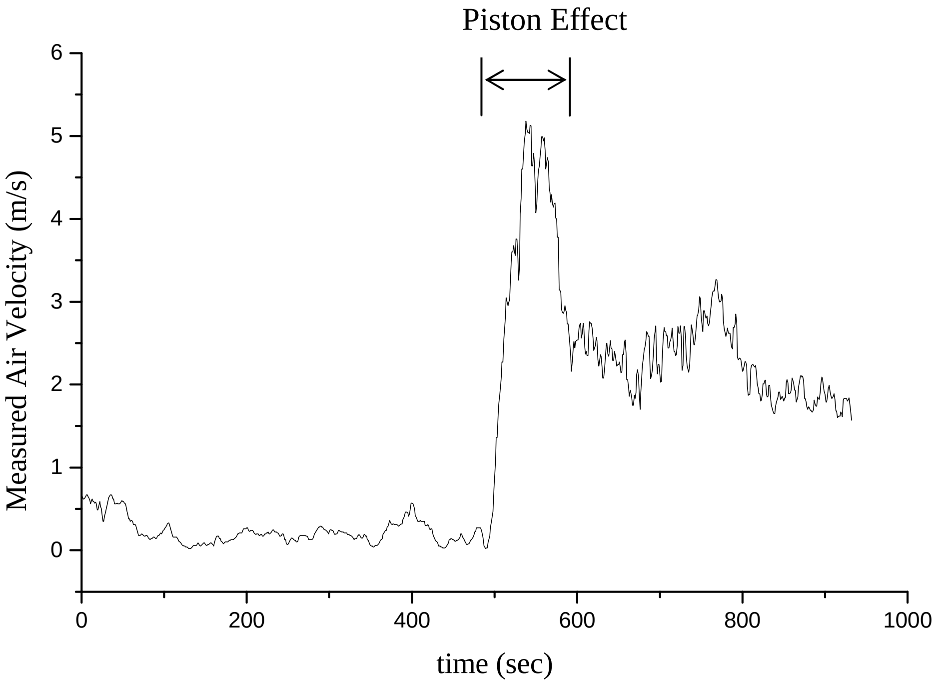

Figure 9 The measured air velocities of test 4

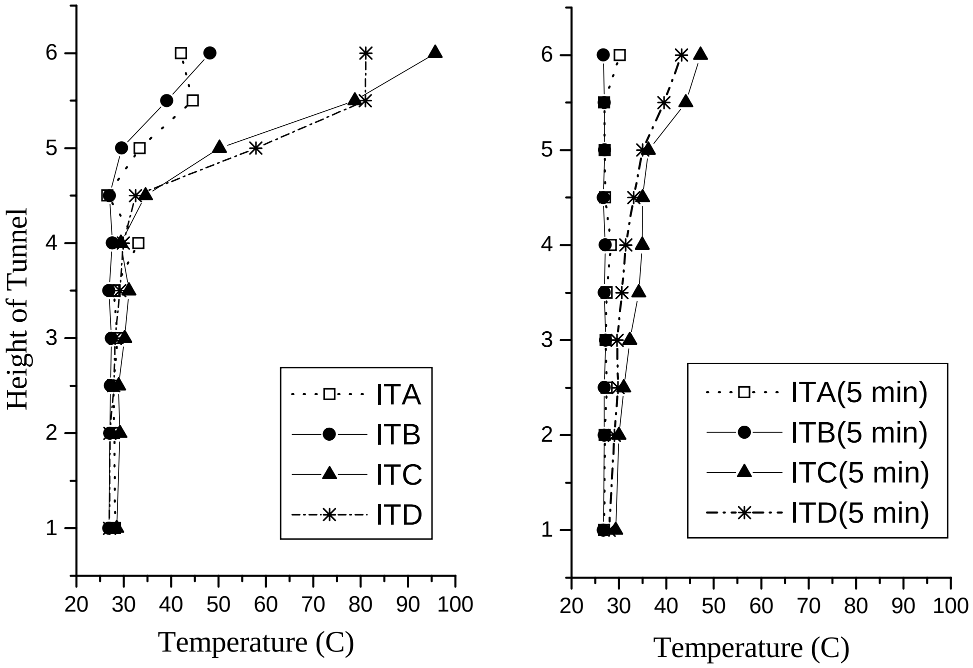

Figure 10 The measured temperature distribution along the tunnel height at fire occurrence and after 5 minutes of fire occurrence in test 4

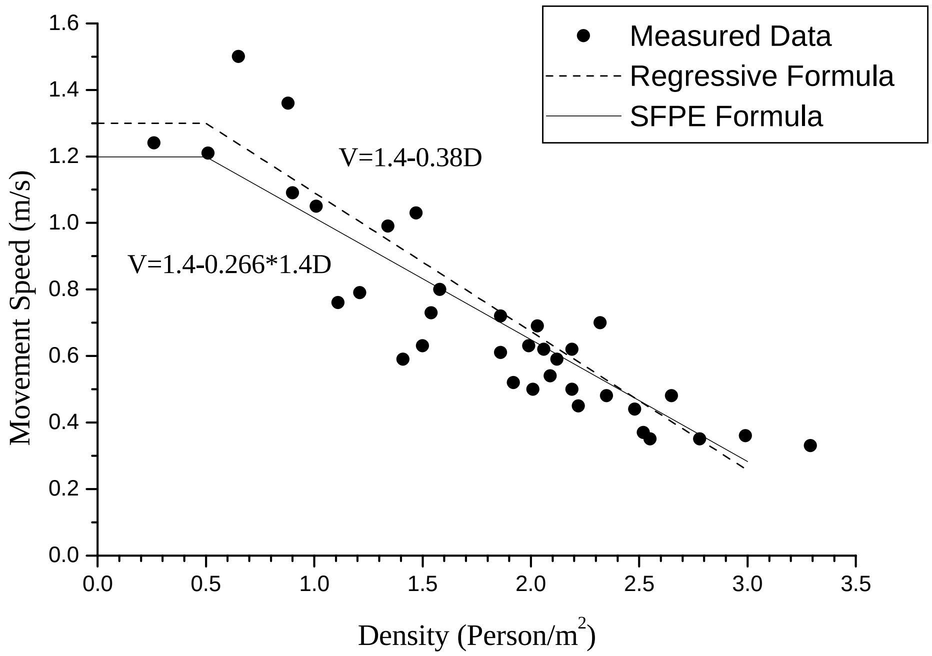

Figure 11 The comparative result of egress experiment with the SFPE Handbook

Table 1 List of vertical shaft location and fan capacity

Vertical Shaft Location	**Vent Shaft**	**Fan Capacity(m^3/sec)**
UK 30+450	#1	118 × 1
UK 31+067	P3N	100 × 1
UK 31+397	P6N	100 × 1
UK 32+567	P10N	120 × 1
UK 33+201	P11N	120 × 1
UK 34+495	P15N	120 × 1
UK 35+328	P17N	100 × 1
UK 35+923	P18N	100 × 1
UK 36+675	P20N	120 × 1

Table 2 Experimental procedure of the full-scale hot smoke test

	Experimental Procedure
Step 1	Data Acquisition System hook-up
Step 2	Train accelerates until reaching 60 km/hr speed
Step 3	Train stops
Step 4	Set fire
Step 5	Train decoupled (for test 2-2, 2-4 and 2-5)
Step 6	Ventilation started on emergency mode
Step 7	Put out fire
Step 8	The experiment completed and ready for next test