# INCIDENTS ON FIRE AND VENTILATION PROVISION IN SUBWAY SYSTEMS IN HONG KONG

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*(Received 12 October 2011; Accepted 22 November 2011)*

## ABSTRACT

The railway system including underground subway in Hong Kong has been operating for many years. There were numerous incidents on fire and poor ventilation provision experienced under crowd conditions, particularly in train compartments, when the service was suspended due to numerous reasons such as electrical signal fault. A brief summary of these two key incidents on fire and inadequate ventilation in train compartments under crowd conditions occurred in the past 30 years will be reported in this paper. The objective is to raise public concern on the consequences of having fire and poor ventilation provision as millions of passengers travel through the railway system every year.

## 1. INTRODUCTION

Hong Kong's rail network is wholly comprised of public transport trains operated by a company with great shares held by the government. This includes the metro network and the commuter rail network that connects the northeastern and northwestern New Territories to the rest of Hong Kong. This rail system has been in service along the northern coast of Hong Kong to Canton since 1904. In 1910, the British Section of railway was opened. The rapid transit system came into operation in 1979. In 1982, the British Section began its transition towards electrification, with new electric multiple units providing rapid transit-like service. The light rail system began its operation in 1988. There were two railway companies originally but merged on 2 December 2007 to form a single rapid transit network [1].

Vast numbers of passengers pass through this large system every day [2]. The safety of such systems in urban cities is a great public concern. The subway system in Hong Kong has its own specific architectural and building features. The general characteristics summarized are [3]: located in town centres or other regional focal points; with different transport modes; being confined or semi-confined; and many egresses along a long travel distance.

Both the fire safety system and the environmental control system of the underground railway system are complicated. Tunnel ventilation system, smoke exhaust system, and air-conditioning system of stations are integrated. Although various steps have been taken to help ensure that the railway system is a relatively safe system to travel on, over the years, many incidents have occurred. Reassuringly, no big catastrophe has happened in decades. Perhaps, it is a matter of 'good luck'. There were even no big fires triggered as in the South Korean metro arson fire [5,6] with a bigger starting fire in 2004 [4]. However, potential hazards of those frequently occurring minor incidents should be avoided. Note that disorders due to suspended normal operation and large crowds strained up in the stations have been frequent.

By reviewing the incidents in the past 32 years, the causes of incidents on fire safety and inadequate ventilation provision due to system faults and others such as power fault, electrical signal fault and platform screen door temporary malfunctions are summarized and reported in the following. This will bring up that safety should be treated as the first objective to be achieved by the railway system operation in the future.

There are two serious safety concerns on the railway systems. The first concern is on fire hazards which occurred quite a number of times, having affected over 70,000 passengers since 1979. The second one is on inadequate ventilation provision, particularly in train compartments when the system suspended due to any reason including electrical signal fault. Therefore, the following two areas should be highlighted:

- High loading rate of occupants

The vast numbers of people moving through these concourses, platforms, underground enclosures and elevated structures causes the danger to life safety to compound. Passengers flow is very high during peak hours as shown in Fig. 1. At the morning peak hours, 8-car trains with a capacity of 2,500 passengers will run at 2.1 minute intervals. The loading reaches as high as 70,000 passengers per hour for a single direction, as observed in a survey conducted in one of the metro lines [1]. The high population density per load undoubtedly adds more pressure to the transport system and simultaneously increases the risk of fire hazards.

- Long evacuation time

Evacuation is the most important aspect of fire safety in any subway system. The large floor area, high headroom, long underground travel distance and limited egress as typical characteristics of a metropolis subway system would inevitably prolong the total evacuation time [7,8]. The problem is especially aggravated during rush hours for very deep platforms underground.

## 2. VENTILATION PROVISION IN A TRAIN COMPARTMENT

Air flow inside a train compartment is mainly induced by the mechanical, ventilation and air-conditioning system. There will be fluctuations in the regulation of air; train movements; air infiltration through the gaps between doors and cabins as a result of train movements; and air infiltration due to loading and unloading through carriage doors opening and closing at the stations for the boarding or exit of passengers.

The air flow across train compartments is observed to reduce when the train is not in motion [9,10]. This may be the technical reason for carriage doors to be kept open on the platform side while the train awaits signals to proceed at each station. Signaling failure, the category that has the highest out-break rate among all statistically recorded local subway system incidents, has the consequence of halting the movement of the train and thereby affecting the air flow rate inside the cabins. Due to the plunging effect of the train, at each start-up of the vehicle, air flow inside the tunnel is also reduced. As a result of this combination of factors, when all trains within the tunnel are stationary, the air infiltration rate through the emergency vents on the sides of the cabins is very limited.

If there is power failure in the system, ventilation provision from the air-conditioning system would fail to operate. All air flow would be solely dependent on infiltration through the emergency vents on the sides of the train compartment. Air movement driven by forces from natural ventilation would be weak in a stationary train. Trapped passengers would therefore experience air stiffness, as previous incidents proved, and as the leading author of this paper pointed out years ago. Additional large vents should be provided to ensure sufficient ventilation. Windows such as those used in the older type of trains manufactured in 1970s would be extremely useful.

According to the requirements laid down by the Environmental Protection Department, $CO_2$ concentration in local railway system should be no more than a maximum of 2500 ppm to maintain good air quality. A concentration above 3500 ppm would pose health concerns [11]. In compliance with current legislative requirement, the minimum ventilation rate (Q) for each carriage in stationary state can be estimated by the equation previously developed [9,10] as shown below:

$$Q = \frac{S}{C_s - C_o} \qquad (1)$$

where S is the $CO_2$ generation rate of each person, $C_s$ is the acceptable concentration of $CO_2$ inside the cabin and $C_o$ is the concentration of $CO_2$ of fresh air.

Assuming the $CO_2$ generation rate and outdoor $CO_2$ concentration would be standard at 0.238 l/min and 0.04% [12], the required ventilation rate is calculated to be 113.3 l/min/person and 76.77 l/min/person for $CO_2$ concentration at 2500 ppm and 3500 ppm respectively, which are similar to previous experimental results [9,10]. According to ASHRAE Handbook 2007 [13], for a ride of less than 2 minutes in duration, the ventilation rate inside a cabin for mass transit system should be 2.5 l/s/passenger – which is an even higher standard than the local benchmark of what is considered as good air quality in a railway system. However, the practice minimum travelling time between stations is 3 minutes [14] which is greater than the value for short trips used by ASHRAE.

A larger ventilation rate of 4.25 l/s/person is specified in ASHRAE Handbook 2007 [13] and the concentration of $CO_2$ inside the cabin calculated by equation (1) is approximately 1333 ppm. The ventilation rate for a cabin with 400 people should therefore be 1.7 $m^3/s$ and assuming the net compartment volume to be 50 $m^3$ there would be a net air volume change of about 29.4 $m^3$ air change per hour [9,10].

As previously stated in the news [15], the ventilation rate is about 800 l/s in each vehicle. Based on this datum, the number of people inside the train is estimated to be a maximum of 188 persons, which is much lower than 400. To comply with ASHRAE requirement, the ventilation rate should be enhanced to 1700 l/s to cope with the congested mass transit system in Hong Kong. The total air flow rate for a train with 8 cabins is 13.6 $m^3/s$.

However, referring to Figure 1, an even higher occupant load is expected during rush hours and the ventilation rate would become much larger than the calculated value. The ventilation should therefore have sufficient capacity to cater for the situation as such. It is advisable to construct a backup ventilation system inside the tunnel to provide sufficient pressure and air flow to generate an equivalent ventilation rate across the train compartment by infiltration through the manual operated emergency vents when the trains are not in motion. As observed, the dimensions of the type of emergency vent commonly seen locally are roughly 1.2 m (w) x 0.3 m (h) with an opening angle of only 30°. Cabins have 5 to 10 emergency vents, the number of which may vary for different manufacturers, but the maximum effective venting area in each compartment is still very limited for emergencies.

A more specialized design for the air supply system should be imposed inside the tunnel, with the aim not to force air to flow through the tunnel but to flow across compartments instead. The construction concept may be summarized as an independent ventilation system operated by separated power sources, with the air supply pumped in the tunnel from the vent tower and exhausted at the other vent towers in a simple method. Air ducts with a monitoring system to control dampers at all supply points should be incorporated to direct the air to the inlets vents of the trains in-need of ventilation, and to force out the exhaust air through the outlets. Such a design would not only enhance the ventilation inside the carriages but also reduce the energy wasted, since air would be blown across the whole tunnel area to achieve the requirement ventilation rate in each cabin. Failsafe vents may be fitted into this system according to the needs of the train manufacturer.

Automatic vent points in addition to manual emergency vents should be installed in every carriage in a complete adoption. Those air supply points modifications can be applied to the existing air-conditioning system of each cabin and air may be exhausted through additional grill under the chairs. Such vertical air flow can drive $CO_2$ away from the cabin with greater efficiency and effectiveness.

(a) Station A

(b) Station B

(c) Station C

(d) Station D

**Fig. 1: Crowded conditions in some local stations**

## 3. FIRE INCIDENTS

Life safety in underground subway system in urban cities is always a priority concern. Heat and smoke emitted from fires in stations or tunnels would be the most serious concern among life-threatening emergencies. Compared to other cities in China, the subway system in Beijing has constructed relatively reliable prescriptive codes for the stations [16]. Performance-based design is also adapted as an approach for upgrading the old systems and designing the new lines or systems [17]. In Taipei, the fire safety code for subway stations and railway tunnels was implemented by the Highway and Traffic Department. Generally speaking, smoke control in all subway systems should follow NFPA 130 [18] and Computational Fluid Dynamics (CFD) [19] should be employed when necessary. In Hong Kong, the overseas standards for constructions of special usage might be applied to public transport interchanges and special premises other than those with typical building geometry and common usage such as offices and shops. However, it is not clear whether such guidance for subway fire safety is appropriate for the design of prescriptive codes. It has been proposed that the railway transit systems in Hong Kong should adopt a 'total fire safety concept' [20] with the application of software fire safety management to monitor hardware fire safety provisions, both passive and active.

Fire in subway systems may be caused by many reasons. The fire-related incidents on record that occurred in the past 30 years have been summarized as shown in Table 1. Total number of passengers affected by fire incidents was over 70,000. There have been no casualties or serious fire disasters up to a scale similar to that of the Daegu subway train fire [5] that occurred on 18 February 2003. Even the arson fire with a bigger ignition source [4,6] than the South Korean one [5] did not lead to disaster. Most of the fire incidents were small fires or smoke caused by power fault or human operation mistake or negligence. However, certain fire safety problems occurred in the retail shop areas at stations and other fire sources. The fire load density at the circulation space may be so low and insignificant, but the fire load of retail shops and combustible luggage should at all events be surveyed and studied. For retail shops, which exist in almost every transport station in Hong Kong, the fire load density in their vicinities would be very high; therefore, they need to be grouped together in areas and protected separately from the other parts. As for luggage, the fire load density is not expected to be high since the hand luggage of the passengers would usually have very low fire load density, but during special periods such as holidays, with the increasing amount and variety of luggage pieces, there will be a rise in the risk of fire and attention should be paid to such scenario. Another possible fire source would be transport vehicles such as buses, cars or train compartments due to the presence of combustibles in their components.

**Table 1: Reported fire incidents of Hong Kong subway since 1979**

| Report date | Incident date | Time of incident | Time incurred | Cause | Number of passengers incurred |
|---|---|---|---|---|---|
| 10 July 1980 | 10 July 1980 | 20:54 | 2 hours | 12 workers was blocked by the fire in MTR tunnel, five injured | 12 |
| 7 August 1997 | 6 August 1997 | 17:00 | -- | Power failure with smoke spilled into carriage | -- |
| 7 February 1998 | 6 February 1998 | 07:27 | 50 min | High-tension cable short circuit caused smoke and sparks | 20,000 |
| 19 May 1998 | 18 May 1998 | 14:03 | Insignificant | Smoke found in train | > 200 |
| 14 June 1998 | 13 June1998 | 07:30 | 1.5 hour | Power cable fire | 40,000 |
| 8 January 2000 | 7 January 2000 | 20:42 | 118 min | Fire at tunnel | 1,000 |
| 11 October 2001 | 10 October 2001 | Afternoon | -- | Electrical fire of a transformer at North Point station | -- |
| 6 January 2004 | 5 January 2004 | 09:12 | 28 min | Arson fire on train toward Admiralty | 12000 |
| 4 June 2004 | 3 June 2004 | 17:25 | 5 min | Sparks and smoke found on train at Mong Kok station | -- |
| 7 October 2004 | 18 September 2004 | 09:00 | 10 min | Train emitting smoke near Siu Ho Wan | 600 |
| | | -- | -- | Signaling failure at Tung Chung station | -- |
| | 6 October 2004 | -- | 4 min | Smoke detected at Nam Cheong station due to mechanical failure of brake | 1000 |

Total number of passengers affected in fire : Over 70,000

There is very limited guidance or reference to relevant overseas standards for fire safety that could apply to the subway system in Hong Kong. Fire Engineering Approach (FEA) is considered a viable means to achieve fire safety.

Assessment of fire load density and heat release rate is of high importance in the evaluation of fire risk in any area. Fire load density may be regarded as the amount of combustibles stored in a given area, which is expressed as heat potential per unit floor area in $kJm^{-2}$. Heat release rate (HRR) is the essential parameter used in quantitative description of fire size. Its significance is that it has been described as the single most important variable in evaluation of fire hazard. Apart from this, 'design fire scenario' is one of the primary uncertainties to be determined in fire safety engineering research studies. The analysis would entail the consideration for a wide range of possible fire scenarios, with a selected group of scenarios serving as the design fire scenarios. The possible fire source in a PTI would be a retail shop fire, a vehicle fire or a luggage fire during holidays. The fire load density of different areas should be calculated separately due to the fact that in some areas the fire load density may be significantly higher than that in other areas, for example the retail shop area. To measure the HRR of combustibles, bench-scale tests have been carried out for numerous times. The fire behavior and HRR of materials and subassembly used in transportation vehicles, retail shops and so on can be tested by the cone calorimeter developed at the National Institute of Standards and Technology (NIST) by Babrauskas [26]. These instruments are available at commercial and research laboratories worldwide. Since the size of the design fire used has been a matter of much argument and conflict, full-scale tests also need to be included. Bigger fires as raised by the leading author [6,22,23] should be watched through proper research [24].

The performance qualities of smoke extraction systems and fire suppression systems are also very important for fire safety in subway system. An effective ventilation system is needed in order to provide acceptable indoor air quality and extract smoke when the fire occurs. In smooth operation it should prevent the conflagration of fire and smoke spreading to adjoining buildings and maintain a tenable condition for enough time to ensure evacuation. Many sprinkler systems have been installed in retail shops in Hong Kong subway stations; they are also needed to ensure efficient suppression in case of fire and prevent fire from spreading to other areas. Since performance-based codes are not yet formulated, the validity of using prescriptive criteria as the acceptance criteria of a fire engineering approach solution would need to be justified on a case-by-case basis.

Peak hour evacuation may be considered the most important implementation of fire safety measures. Evacuation design in subway systems is not only necessary for fire safety concern alone, but also for other emergencies which will be discussed in the following sections.

## 4. PLATFORM SCREEN DOORS

Safety concerns in platform screen door system operation:

In 2000, the first platform screen door (PSD) systems were installed in Hong Kong subway stations. The whole installation scheme was completed in October 2005. PSD systems can be categorized into two types: full-height PSDs with total door height measuring from the station floor to the ceiling; and half-height PSDs which are chest-height sliding doors at the edge of the platform.

Most PSDs are made of toughened glass and they are intended to be burning-resistant and sustainable even in fire for hours. However, there were reports of accidents in Hong Kong observing that the glass panes of those PSDs could break suddenly [25-28]. In view of human safety, the compatibility of the train and PSDs is a concern. All trains must stop at the exact positions where the train doors are parallel to and facing the PSDs. Otherwise, passengers would not be able to board and alight smoothly. Any unopened doors of the train or PSDs, or unmatched location of train doors and PSDs will lead to chaos in passenger evacuation. In both Hong Kong and Beijing, reports of inability of train to stop at the correct position matching with PSDs have been numerous. One of the most notable incidents is the 31 March 2010 incident [28] during which the train stopped at the station but the train doors and PSDs did not open, due to the fact that the two sets of doors were unable to match in position. On the safety of PSD system, there is a need for more in-depth studies [29] regarding the problems and emergency management.

## 5. TIMELINE ANALYSIS

Crowd movement is a concern in dealing with safety [30]. There have been many hazards in extremely crowded spaces, such as the Lan Kwai Fong tragedy in Hong Kong [31]. Those incidents were only in open areas without any hazards or terrorist attack. An accidental small fire in a crowded building could be very serious. Much greater damage would occur due to terrorists. Therefore, emergency evacuation in subway stations should be designed carefully, especially under heavy passenger loading.

The 'timeline analysis' or timeline approach [32,33] was commonly applied in performance-based design (PBD) of big railway stations. The Available Safe Egress Time (ASET) was simulated by fire models by referring only to reported data on tenability criteria on thermal exposure and smoke. The Required Safe Egress Time (RSET) was estimated with evacuation software. ASET and REST are then compared with the safety margin (ASET – RSET) evaluated.

However, there have been serious concerns [30] while implementing PBD in Hong Kong or Fire Engineering Approach (FEA) since 1998. Firstly, scenarios with small design fires were used to get long ASET even for many projects on crowded and big halls. Secondly, human behavior under local conditions was not investigated in depth. Thirdly, the occupant loading was low to give short RSET. Fourthly, the safety margin (ASET – RSET) is only taken as a percentage of RSET, not several times of RSET. ASET was commonly estimated by free fire models with reference to lower values on tenability limits recommended by different international design guides such as CIBSE Guide E [33]. Apart from carbon monoxide, smoke toxicity of other chemical species are not included. The estimated ASET is then very long. The increase in carbon monoxide upon discharge of water by sprinkler and water mist was seldom discussed. Only one or two small fire scenarios were used to estimate ASET. RSET was simulated by evacuation model without including human behavior of local citizens. Therefore, the estimated RSET is very short.

This approach leads to concern as several post-flashover big fires had occurred in Hong Kong and Mainland China. As reported before, the timelines of fire development and evacuation process with all those components reported in the literature should be briefly reviewed for suitability in Hong Kong. On the other hand, the new fire codes at New Zealand on performance-based design [34] would include smoke toxicity and much bigger design fires of 20 MW and 50 MW for non-storage and storage areas respectively.

## 6. CONCLUSION

Safety in stations, tunnels and train vehicles should be taken as the top priority of operating the railway system. Fire hazard and inadequate ventilation provision have been two key incidents frequently experienced in the local railway system since 1979. Performance-based design [e.g. 33] on providing fire safety for crowded subway stations should be watched. The local railway system is always crowded with passengers in the stations, public transport interchanges and train compartments. Particularly, the timeline analysis in designing evacuation should be applied with justification. Ventilation must be provided adequately in the train compartments under crowded conditions while the train stops. During Second World War, subway stations in London, UK were fully crowded with people while using as air raid shelters against bombing by the German. A question:

Can the local deep underground local subway stations carry out this function?

Projects with ASET very close to RSET [30] should be reviewed carefully. This is new and also under consideration in New Zealand [34]. The fire safety inspection scheme on checking assumptions made in performance-based design is a good starting point [35].

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