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Design Guidelines for Ventilation System for Pollution Control in Large, Semi-enclosed Bus Terminus

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SYNOPSIS

In response to complaints about poor air quality in bus termini, the Hong Kong Government is considering imposing legislative control over ventilation system design and operation of bus termini in Hong Kong. However, there are, as yet, no relevant air quality criteria and ventilation system design guidelines for Hong Kong. In this paper, measured air quality data for 5 semi-enclosed bus termini are reviewed. This provides a picture of the prevalent air quality in bus termini. To establish a design guide for ventilation systems for Hong Kong, a number of overseas design guides are examined and a ventilation system design method is proposed. The significance of design parameters, such as bus engine emission rates, utilization of the terminus, ventilation effectiveness, etc., are discussed.

1 Introduction

In Hong Kong, many bus termini are located on the ground floor or basement of large building complexes, adjacent to or below stations of mass-transit systems. The daily bus movements at such a transport interchange may exceed 2,500 (up to 160 during the peak hour), and the total number of commuters may reach 130,000 on a typical weekday. Often, passengers have to queue by the side of bus lanes and are exposed to bus engine exhaust. Notwithstanding that mechanical ventilation is provided for pollution control in semi-enclosed bus termini, there have been complaints about the poor air quality inside some bus termini. Although there is concurrently no statutory control over the air quality inside enclosed or semi-enclosed bus termini in Hong Kong, the Government has taken the initiative [1] to develop design guidelines and practice notes for the design and operation of ventilation systems for vehicular tunnels, car parks and transport interchanges.

Buses with diesel engines are the dominant source of pollutants in a bus terminus. Amongst various constituents of diesel bus exhaust [2-4], oxides of nitrogen, collectively quantified by NO_x (NO & NO_2), or NO_2 in particular, is the most critical pollutant in respect of the adverse impact on health of passengers, and on the visibility inside a bus terminus. Thus, the concentration of NO_x or NO_2 has been adopted as the air quality criteria in some ventilation system design guides in such applications [3,5-8].

2 Measured air quality data for five bus termini in Hong Kong

To ascertain the causes and seriousness of the air pollution problem in bus termini, the Environmental Protection Department (EPD) of the Hong Kong Government conducted air quality measurement in the summer of 1993 in 5 semi-enclosed bus termini (denoted as Sites A to E). This provides a picture of the prevalent concentration levels of pollutants in bus termini. EPD's measurement covered concentrations of SO_2, NO_x, NO, NO_2, CO and CO_2. The equipment used (Table 1) were installed within a mobile laboratory. During the measurements, air samples were drawn-in continuously from a representative sampling points at 2.5 m above ground level, with measurements recorded as 5 minutes time weighted averages (TWAs). The total duration of measurement was about one month per bus terminus. The measured maximum concentrations of the gaseous pollutants in the 5 bus termini are summarized in Table 2. As air samples were not taken within the breathing zone level (i.e. at about 1.5 m), deviations are expected between the measured air quality and that to which passengers were exposed.

Table 1 Equipment in EPD's Mobile Air Quality Monitoring Laboratory

Pollutant	Method of measurement	Manufacturer and model	Frequency of measurement	Detection limits
Sulphur dioxide	Pulsed fluorescence	Thermo Electron Model 43A (0-1 ppm)	Continuous	0.6 ppb
Oxides of Nitrogen	Chemiluminescence	Thermo Electron Model 42 (0-2 ppm)	Continuous	0.5 ppb
Carbon monoxide	Non-dispersive infrared absorption with gas filter correlation	Thermo Electron Model 48 (0-50 ppm)	Continuous	0.1 ppm
Carbon dioxide	Non-dispersive infrared absorption	Milton Roy Model 3300 (0-5000 ppm)	Continuous	400 ppm

Table 2 Five Minute & Hourly Maximum Concentrations of Gaseous Contaminants in five Bus Termini (shaded if exceeding HKAQO limits)

Contaminant		Site A	Site B	Site C	Site D	Site E	HKAQO[1]
SO_2(µg/m³)	5 min	2623	1117	1912	1362	1395	-
	hourly	1025	910	968	299	762	800
NO_x (µg/m³)	5 min	7891	6015	5767	4024	3752	-
	hourly	6566	4390	2805	2655	985	-
NO (µg/m³)	5 min	4882	3898	3878	2643	2455	-
	hourly	4012	2862	1754	1632	1000	-
NO_2(µg/m³)	5 min	876	798	588	1775	1233	-
	hourly	433	300	199	436	287	300
CO (mg/m³)	5 min	32.5	11.9	8.23	24.4	21.15	-
	hourly	24.3	11.1	5.2	6	4.4	30
CO_2(mg/m³)	5 min	2137	1364	2612	9260	6040	-
	hourly	1786	1314	1714	850	963	-

Comparison of the maximum pollutant concentrations (Table 2) with various industrial work place air quality standards (Table 3) shows that none of the measured maximum concentration levels exceed the recommended upper concentration limits for used in occupational health. The figures are also within the air quality limits for underground carparks recently proposed by EPD [8] (Table 3). Concentration figures (hourly maximums) that exceed the respective limits set by the Hong Kong air quality objectives (HKAQO) [1] are shaded in Table 2.

3 Observed causes of poor air quality in bus termini

The dimensions, percentage of confinement (percentage of the perimeter of a bus terminus that is blocked), existing ventilation systems and utilization of the 5 bus termini studied are summaried in Table 4. Amongst them, Sites A and B had the poorest air quality (Table 2). This may be ascribed to the fact that these two sites have the highest percentage of confinement (~ 90%, Table 4) which made natural cross ventilation almost impossible. Thus, pollutant removal and dilution relied almost solely on the effectiveness of the mechanical ventilation systems.

Table 3 Comparison on various Industrial Work Place Standards

Contaminant	EPD[8] Proposed Guideline for Carpark	Industrial Workplace Standards OSHA[2] US	ACGIH[3] US	HSE[4] UK	OEL[5]HK
SO_2 (μg/m^3)	- -	13000 STEL 5000 TWA	13000 STEL 5200 TWA	13000 STEL* 5000 TWA	13000STEL 5200TWA
NO (μg/m^3)	- -	- 30000 TWA	Subject to BEI 31000 TWA	45000 STEL 30000 TWA	- 31000STEL
NO_2 (μg/m^3)	1800STEL 5mins.	1800 STEL -	9400 STEL 5600 TWA	9000 STEL 5000 TWA	9400STEL 5600TWA
CO (mg/m^3)	115STEL 5 mins.	229 Ceiling 40TWA	Subject to BEI 29 TWA	330 STEL 55 TWA	330STEL 55TWA
CO_2 (mg/m^3)	- -	54000 STEL 18000 TWA	54000 STEL 9000 TWA	27000 STEL 9000 TWA	54000STEL 9000TWA

1 Hong Kong Air Quality Objectives: Hourly maximum limits
2 Occupational Safety & Health Adminsitration, Department of Labor. "Code of Federal Regulations 29 Part 1910, Revised as July 1, 1992". Final rule limits.
3 American Conference of Government Industrial Hygienists. "Threshold Limit Values 1992-1993".
4 Health & Safety Executive. "Occupational Exposure Limits 1993".
5 A Reference Note on Occupational Exposure Limits for Chemical Substances in the Work Environment, Labour Department, Hong Kong, 1992.

STEL 15-minute TWA Short Term Exposure limit.
TWA 8-hour time weighted average.
* 10-minute TWA Short Term Exposure Limit.

Table 4 Summary of Dimension and Design Ventilation Rates of the 5 Bus Termini (Figures in brackets are measured values)

Bus Terminus	Appr. area m^2	Appr. Ht. m	Confinement %	Ventilation system	Total air flow m^3/s	ACH[1]	l/s per m^2	Bus no. at peak hour	Daily bus no.	Remarks
Site A	109 x 82	5.3	90	Exhaust only at H/L	120 (48.93)	9.12 (3.7)	13.43 (5.47)	36	484	cross vent minimal
Site B	203 x 73	11/9/7.4	89	Supply at H & exhaust at H/L	150 (162.4) supply*	3.36 (3.6)*	10.12 (10.96) *	110	1404	cross vent minimal
Site C	109.7 x 42.2	6.59	46	Exhaust only at H/L	104.92	12.38	22.66	95	1350	good cross vent
Site D	132 x 57.5	7.79	46.2	Supply only at H	142.38	8.67	18.76	167	2505	good cross vent
Site E	138.5 x 90.5	6.2	77	Exhaust only H/L	376.78	17.45	30.06	67	858	cross vent possible

H High level H/L High and low levels * only 50% of the flow rate operated over 80% of the time in a day.

Site investigations were undertaken in the 5 bus termini and ventilation rate measurements were conducted in Sites A and B to identify the cause of poor indoor air quality in these bus termini. The observed causes, which are believed to be rather typical for similar bus termini in Hong Kong, include:

- Utilization was underestimated or has grown beyond the expected limit.
- Fresh air intake and exhaust locations were inappropriate.
- Insufficient space for installation which led to duct size reductions, and thus reduction in air flow rate, and equipment inaccessible for maintenance.

- The ventilation system not properly balanced and/or the flowrate being maintained not verified since the system was installed, or after subsequent modifications.
- Ventilation systems are manually operated or timer controlled, without regard to the actual pollutant concentrations inside the bus termini.
- Vehicle engines, particularly those of air-conditioned buses (and taxies), remain running when queuing up inside a bus terminus.
- Inadequate maintenance (e.g. in some termini, low level exhaust grilles were damaged by vehicle, and intake grilles and filters were clogged-up by accumulated dust).

4 Ventilation system design for bus terminus

To maintain acceptable environmental conditions inside a semi-enclosed bus terminus requires a properly designed ventilation system. For this, a design guide needs to be established which includes the threshold pollutant concentration and the method to determine the required ventilation rate. In the absence of such a guideline for Hong Kong, several relevant design guides, standards or design examples available from the literature [3, 6-8 & 12] were studied. These methods were applied to Site B to give a comparison on the ventilation system that will result by using each of these methods to design the mechanical ventilation system. The respective design criteria and the ventilation rate calculated are summaried in Table 5. The results of applying the guidelines for all the 5 termini are summaried in Table 6.

For the CIBSE Guide [5] and the design example of Cockram and Bearman [7], the pollutant concentration limit was set at 5 ppm of NO_x and the ventilation requirement was 80 times the exhaust volume. The pollutant concentration criterion adopted in the ASHRAE Handbook [3] and in Brociner's example [6] was NO_2 concentration of 5 ppm and ventilation requirement was 75 times the exhaust volume. There are no exact ventilation requirement specified for bus terminus in the Australian Standard [11]. Criteria for enclosed drive-in-facilities were selected but, the routing and frequency of use of a driveway in a bus terminus may be very different. Considerable deviations amongst the required ventilation rates determined from these design guides exist (Table 5). Also, the design (or measured) ventilation rates for these termini were greater than or close to the ventilation rates determined using these guides (Table 6) but the air quality was still found unacceptable.

The intake air were assumed to be free of any pollutants in all the above guides and design examples. However, in many cases (e.g. Site A, C and E), the roadside air, which is drawn-in via openings or driveways for ventilating a bus terminus, is already contaminated by the heavy traffic (e.g. the roadside NO_x concentration in Kwun Tong was 0.132 ppm [13]). Therefore, the quality of the intake air should be included in the method for determining the required ventilation rate.

Instead of the abovementioned guides, equation (1), derived from first principles on the basis of a simplified perfectly mixed condition [12], is recommended for use in determining the required ventilation rate for a semi-enclosed bus terminus :

$$V = \frac{N(E_1t_1 + E_2t_2 + E_3t_3 + E_4t_4)(t_1 + t_2 + t_3 + t_4)}{3600(C_m - C_o)\eta_{vent}} \quad (1)$$

where:

V = ventilation rate (m^3/s)
N = max. total no. of buses entering the terminus during the peak hour (no. of buses/hour)
E_1 = emission rate of a bus during deceleration mode (mg/s)
t_1 = total duration of a bus under deceleration mode (s)
E_2 = emission rate of a bus during idling mode (mg/s)
t_2 = total duration of a bus under idling mode (s)
E_3 = emission of a bus during acceleration mode (mg/s)
t_3 = total duration of a bus under accerleration (s)
E_4 = emission of a bus during cruising mode (mg/s)
t_4 = total duration of a bus under cruising mode (s)
C_m = allowable maximum concentration (mg/m^3)
C_o = concentration in ambient air (mg/m^3)
η_{vent} = ventilation effectiveness factor

Results of applying this method to all the five sites are included in Table 6.

Table 5 Relevant Standards and Guidelines on Ventilation Design for Bus Terminus and Their Application to Site B Bus Terminus

Standard/ Guide	Particular Area	Criteria	Ventilation Requirement	Ventilation Requirement for Site B				
				For Site B	Supply Rate m^3/s	Exhaust Rate m^3/s	Total Vent Rate m^3/s	Tot.Vent Rate *l/s per m^2
ASHRAE [3]	drive-way	to maintain visibility and control odor, limit NO_2 to 5ppm	75 times vehicle exhaust	75 x 109 l/s per bus x 10.39 buses		84.94		
	partially enclosed platform	pressurization of the platform	85 l/s per m^2 of platform area		34		118.94	11.47
New York example [6]		limit NO_2 to 5ppm		75 x 109 l/s x 10.39		84.94		
	totally enclosed platform	pressurization of the platform	10 l/s per m^2 of platform area		4		88.94	8.57
CIBSE [5]	general	below 5ppm NO_x	80 times vehicle exhaust	80 x 73.32 l/s x 10.39 buses		60.94	60.94	5.88
London example [7]	enclosed parking space	below 5ppm NO_x	4.9m^3/s per engine running	4.9x110/4		134.75	134.75	13
Australian Standard 1668.2 [11]**	enclosed driveways associated with bldgs	-	200 l/s per metre length of each lane	200 x 54 x 8		86.4	86.4	8.33
Equation (1)		limit to 1ppm NO_2					370	25

* Based on an area of 10,373 m^2 which excluded the area for the taxi and mini-bus lanes. This area is about 70% of the total area of Site B

** There are no exact ventilation requirement guidelines for bus terminus in this Standard. Criteria for enclosed drive-in-facilities were selected for comparision.

Table 6 Application of design guideline to all five bus termini

	Site A	Site B	Site C	Site D	Site E
Approximate area m^2 Max. bus no. in peak hour Minmium flow rate	8938 36	10373 110	4629 95	7590 167	12534 67
Original design value supply/exhaust m^3/s total m^3/s l/s per m^2	 0/120(49) 120 13.43	 140(162)/60 140# 13.50	 0/104.92 104.92 22.66	 142.38/0 142.38 18.76	 0/376.78 376.78 30.06
ASHARE [3] supply/exhaust m^3/s total m^3/s l/s per m^2	 46.33 /27.8 74.13 8.29	 34 /84.9 118.94 11.47	 34.94 /73.33 108.27 23.39	 56.1 /129.92 186.02 24.51	 47.1 /51.75 98.85 7.89
New York [6] supply/exhaust m^3/s total m^3/s l/s per m^2	 5.45/27.8 33.25 3.7	 4/84.94 8.94 8.57	 4.11/73.33 77.44 16.73	 6.6/129.92 136.52 17.99	 5.54/51.75 57.29 4.57
CIBSE [5] supply or exhaust m^3/s total m^3/s l/s per m^2	 19.67 19.67 2.2	 60.77 60.77 5.86	 51.90 51.90 11.5	 91.24 91.24 12.02	 36.62 36.62 2.92
London [7] supply or exhaust m^3/s total m^3/s l/s per m^2	 44.1 44.1 4.93	 134.75 134.75 13	 116.38 116.38 25.14	 204.58 204.58 26.95	 82.08 82.08 6.55
AS1668 [11] length of driveway m supply or exhaust m^3/s total m^3/s l/s per m^2	 432 109 109 12.20	 545 86.4 86.4 8.33	 411 82.2 82.2 17.76	 660 132 132 17.4	 554 110.8 110.8 8.84
Equation (1)* required flowrate m^3/s	 121	 370	 320	 561	 225

* C_m (NO_2)= 1.8 mg/m^3, C_o(NO_2)= 0.0752 mg/m^3, η_{vent} assumed to be 0.5
Figure in ( ) indicate flowrate measured on site in m^3/s
50% part load operating most of the time during normal week day.

In respect of the design criteria in air quality (C_m), the Hong Kong air quality objectives (HKAQO) [1] is by far the only established air quality standard in Hong Kong. However, the HKAQO figures (close to those for outdoor in ASHRAE Standard 62-89 [9]) are meant to be a primary air quality guideline and is not applicable to bus termini.

Industrial workplace air quality standards (e.g. NO_2 concentration of 5 ppm as STEL,Table 3) appear to be a more relevant reference and are the basis of the design guides reviewed above. However, industrial workplace standards are, in general, applicable to healthy adults only but users of bus termini include children, the elderly and people of varied health conditions. EPD has proposed to use 1 ppm NO_2 (1.8 mg/m^3, 5 minutes STEL) as the criteria for enclosed carparks with diesel vehicles [8]. Although commuters will stay inside a bus terminus for a longer time than they would in carparks, the same is recommended for bus termini.

The ventilation rate required to dilute the pollutants, and hence to maintain an acceptable air quality, is directly proportional to the rates that pollutants are produced in a given space. Therefore, the likely peak rate of pollutant emission needs to be determined. However, diesel bus engine exhaust data from different sources vary largely. The following are a few examples:

a) The following bus exhaust rates were given in ASHRAE 1991 [3] (engine size is not specified):

Mode of operation	idling	accelerating	cruising	decelerating
Exhaust volume flow rate l/s	55	225	163	143

The average durations of bus movements observed in Site B were 120s, 20s, 120s and 20s for the idling, accelerating, cruising and decelerating modes respectively. This set of operating time is adopted in calculating ventilation rate using equation (1) (results shown in Table 5 and 6). The average exhaust, according to the figures above is 109 l/s. This value, however, is much greater than that estimated from the following 2 sets of data from UK [6,7].

b) Homles (1988) [10] gives the following bus exhaust rates:

Engine size/ mode of operation	idling 320 rpm	full load 800 rpm
6 litres	16 l/s	40 l/s
8 litres	21.33 l/s	53.33 l/s
10 litres	26.66 l/s	66.66 l/s

Assuming that the time for idling and full load is at the ratio of 3:1, the average exhaust will be 36.66 l/s for a 10 litres engine. When the exhaust rate under the acceleration mode is accounted for by doubling the give exhaust rate, the total exhaust rate becomes 73.32 l/s (adopted as the emission data for the calculations by CIBSE, see Table 5 and 6).

c) According to Cockram 1982 [7], the mean exhaust volume flow rate over 15 minutes was estimated to be 61 l/s (adopted as emission data for London example in Table 5 and 6) for a 12 litres engine that runs at 396 rpm for 13 minutes and at 1998 rpm for 2 minutes [7].

As a much lower NO_2 concentration limit (1 ppm c.f. 5 ppm) was adopted, and outdoor air concentration was accounted for, in using equation (1) to determine the required ventilation rates for the 5 bus termini in Hong Kong, the ventilation rates are much higher than those determined from the other guidelines (Tables 5 & 6).

Equation (1) was derived on the basis of a well mixed, single zone model and its use requires detailed information on bus service frequency, bus emission rates and ambient air pollution concentrations. Accurate data however are, as yet, unavailable. Thus, further work is required to :

- obtain a set of update data on bus emission for various engine size and age under different modes of operation;
- ascertain bus termini utilisation (usage factor) and the idling, acceleration, cruising and deceleration time for bus termini of different layout designs;

- establish a database on concentration of pollutants in the ambient air at various locations in Hong Kong;
- experimentally obtain data on ventilation effectiveness for different air distribution layouts or system layouts.

5 Conclusion

There is a need to develop a practical design guideline for ventilation system in semi-enclosed bus termini in Hong Kong. A design method and an air quality criteria have been proposed in this paper. Besides a proper ventilation rate, the system layout, proper installation, testing and commissioning, operation and maintenance are important factors to maintaining acceptable air quality in bus termini.

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