Criteria for air quality in enclosed car parks

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This paper addresses concerns about the environment found within enclosed car parks in Hong Kong. These concerns have been expressed in terms of the levels of carbon monoxide found in car parks following a survey. The outcome has been the development of a code of practice for car park ventilation system design and performance. It is recognized, however, that too stringent criteria may lead to over-design of ventilation systems and unwarranted use of energy. The criteria need to take into account the levels of exposure likely to be experienced by two separate groups – car park users and car park employees or maintenance contractors. In public car parks the former group embraces the entire population as drivers or passengers, whilst the latter group can be expected to include only working adults. The criteria for exposure for each group are considered with respect to various health and occupational guidelines used in developed countries. In addition, the potential for impairment of driving performance is considered. Criteria for safe exposure levels in car parks are recommended.

Introduction

In a built-up metropolis such as Hong Kong there is great demand for but short supply of land and building space. This is manifest in very high prices and rents for commercial, industrial and residential property. Commercial and industrial buildings are almost invariably high-rise and densely populated. The trappings of an affluent and industrious society includes a relatively large vehicle population for the usable land area. The 270 000 or so private cars comprise 59% of all registered vehicles. There is a big demand for off-street parking. Large multistorey underground car parks are common solutions for both the government and developers (Fig. 1). Increased affluence and wider education are also making the people of Hong Kong more aware of environmental issues, not least air quality. Enactment of new legislation governing air quality[1] and vehicle emissions,[2] and strengthened environmental policies[3] have required responses from commerce and industry.

2. A report by the Consumer Council[4] highlighted the perceived poor quality of the environment within public car parks and stated that many did not meet World Health Organization (WHO) ‘standards’ for carbon monoxide (CO) concentrations in the air. This conclusion was based on CO measurements in 37 car parks undertaken by the Environmental Protection Department (EPD) during the summer of 1992. The report concluded that more than half of the car parks surveyed had unacceptable air quality in terms of CO level: that is, above 100 p.p.m. (115 mg/m^3) for 5 min. The results are summarized in Table 1. The report mentioned that legislative control of the air quality in car parks was under consideration by the government.

3. Subsequently the EPD issued a consultative document[5] in which the prescribed maximum level for CO is an average of 100 p.p.m. over 5 min. This compares with air quality design criteria for car parks used hitherto, such as those of the American Society of Heating, Ventilation and Air-conditioning Engineers (ASHRAE)[6] (maintained level of 50 p.p.m., peak not to exceed 125 p.p.m.) and the Institution of Structural Engineers[7] (50 p.p.m. normal, 100 p.p.m. peak, 250 p.p.m. at entrance and exit tunnels). Hong Kong’s EPD’s consultative document was recently published as a ‘practice note’.

4. Existing car parks may fall within the proposed legislative controls. They may have been designed using air change rate criteria, either on the basis of air changes per hour,[6,8] air flow per unit area,[6, 9, 10] air flow per parking space,[11] or air flow per operating engine.[10, 11] Given the local preference for ASHRAE’s guidelines, a target ventilation rate of six air changes per hour is likely to be the most common approach. With car park floor heights normally less than 3 m, the alternative recommended[9] ventilation rate of 7·5 l/s/m^2 would provide more than six air changes per hour. Whilst these design approaches have been found to be effective in maintaining air quality in car parks elsewhere,[12, 13] apparently they may not suffice for heavily used car parks in Hong Kong, even if the system is properly

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designed, commissioned and maintained. Alternative design approaches use either a simple dilution equation based on average vehicle emission data and assuming perfect mixing,[7, 11] or a dilution model that includes vehicle operation and emission data.[10] This latter approach is adopted in the EPD's practice notes.[5]

Assessment of exposure risk

5. The passage of laws to protect public health and the environment has brought into focus the need to assess both the risk and the economic impact. Risk assessment is complicated because individuals and organizations perceive risk differently, depending on who is perceived to be 'responsible' and who pays for any 'clean-up'. For car parks used by the general public, benefits and responsibilities arguably accrue to both patrons and owners. Risk assessments associated with air quality will take account of dose and consequent health effects. Exposure assessment is the determination or estimation of the magnitude, frequency, duration and route of exposure. Health effects may be characterized by individual lifetime risk, relative risk between exposed and unexposed persons, and temporary debilitating effects. Some of the key points that need to be considered in risk assessment are[14]

(*a*) the uncertainties in estimating the extent of health effects
(*b*) the most appropriate dose-response and exposure assessments
(*c*) which population groups should be the primary target for protection.

6. There is a great deal of data available on the effects of exposure to CO, including physical impairment and health risks due to short-term and long-term exposures, but it has not resulted in uniform agreement on exposure criteria amongst various agencies worldwide (Table 1).

7. The prescribed criteria for air quality, based on CO concentration, will be critical in the design and operation of car park and their ventilation systems and will impact on energy consumption. It is important that the criteria take into account a reasonable level of risk to both patrons and car-park employees. Endeavours to achieve unnecessarily low CO concentrations may cause undue capital investment and unwarranted use of electrical energy.

The environment within enclosed car parks

8. Concern about the environment within enclosed car parks embraces fire safety, thermal comfort and air quality. Employees and subcontractors providing security, maintenance and other services may regularly work in a car park for periods of up to 12 h. They may work in one location or move around a large area. For them the health risk is generally from long-term exposure to pollutants, and occupational health criteria would be applicable. Car park patrons, including regular daily users and irregular visitors, tend to occupy a

Fig. 1. Interior of a public car park

Table 1. EPD results and air quality guidelines and standards for CO

EPD results[4]	CO concentration for various time intervals: p.p.m. (mg/m³)					Notes
	Ceiling	5 min	15 min	1 h	8 h	
Maximum		330 (380)		230 (264)	161 (186)	Excludes one car park where the ventilation system was not running
Average		115 (133)		71 (82)	50 (57)	As above
Minimum		34 (39)		8 (9)	3 (4)	As above
HKAQO[1]				27 (30)	9 (10)	Protection of all members of society
WHO[18]			87 (100)	25 (29)	10 (11·5)	To prevent COHb levels exceeding 2·5–3% in non-smoking populations based on Coburn formulae
WHO[22]			100 (115)	25 (29)	10 (11·5)	
ACIGH[26]			#		25 (29)	TLV-TWA. #Previous STEL replaced by BEI of 8% CAHb
NIOSH[27]	200 (229)				35 (40)	Health effects: cardiovascular effects. For documents containing NIOSH recommendations for safety and health of carbon monoxide, see references 4 and 7
OSHA[28]				125 (144)	50 (55)	This is a standard for industrial workplaces[16]
HSE[24]			300 (330)		50 (55)	

car park for no more than 10 min, usually much less. For them it is discomfort and short-term effects from exposure that are of concern. For all drivers it is necessary to consider the impact of exposure on driving performance, lest this be a factor determining the safe levels of pollution.

9. The feeling of wellbeing or otherwise for people in car parks depends on a number of factors. With inside temperatures 1–8°C higher than those outside,[4] the summer temperatures of 30°C or more coupled with high humidity means the thermal comfort within enclosed car parks in Hong Kong can be most unsatisfactory. This discomfort can contribute to negative reactions to pollutants and odours. In extremes of thermal discomfort and high levels of pollution, sensitive people may find the conditions overwhelming.

10. The pollutants found in enclosed car parks are mainly due to vehicle emissions. There is a distinct difference between petrol- and diesel-engined vehicles, and the amount of pollutants discharged depends very much on the particular vehicle and the mode of operation. Williams[15] has summarized the contribution of motor vehicles to air pollution, distinguishing between primary pollutants which may affect people in the form in which they are emitted, and secondary pollutants which undergo or are formed by reactions in the atmosphere.

11. Petrol and diesel produce oxides of carbon and hydrogen as a consequence of incomplete combustion. Of the most concern are the primary pollutants: CO, carbon dioxide (CO_2), nitrogen oxide (NO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), smoke and particulate material, lead and the range of organic compounds known generally as volatile organic compounds (VOCs). VOC emissions arise largely from evaporative and futile losses rather than from combustion. Of these pollutants, CO, NO_x(= NO + NO_2), SO_2 and lead compounds are toxic. NO_2 is the most toxic substance but typically accounts for around 5% of the total NO_x emitted.[16] Total hydrocarbons (THC) include polynuclear (or polycyclic) aromatic hydrocarbons (PAH), a group of several hundred organic compounds, the best known of which is benzo[a]pyrene (BAP), a suspected human carcinogen.

12. Although catalytic converters are used extensively, because of the low sulphur content of petrols supplied in Hong Kong, hydrogen sulphide (H_2S) emissions are not regarded as significant in the context of health impacts.

13. Petrol engine NO_x emissions are small at idle and low speeds, and increase roughly in proportion with speed. Similar patterns emerge for THC emissions. CO emissions are generally highest at idle and very low speeds (0–20 k.p.h.)[16] For petrol-engined vehicles at idle and low speeds, CO emissions are typically an order of magnitude greater than NO_x emissions, and given that permitted concentrations are of a similar magnitude, it is the CO level that dominates vehicle exhaust dilution requirements. Ball and Campbell[17] have illustrated that dilution rates required for petrol engines in various conditions were dominated by the need to dilute CO, whereas NO_x dominated for diesels, but at much lower rates. In Hong Kong, petrol-engined cars dominate, with diesels accounting for less than 1% of the total. If car park CO is within safe levels it is generally accepted that all other contaminants will also be within safe levels.

CO inhalation

14. CO is a colourless, odourless, tasteless and non-irritant gas, slightly lighter than air, which is mainly encountered as a product of incomplete combustion. CO's primary toxic action is the inhibition of cell oxidation following inhalation exposure, mainifest in increased carboxyhaemoglobin (COHb) levels in the blood. Hypoxia caused by CO leads to deficient function in sensitive organs and tissues of the heart and brain. At COHb levels below 10% it is mainly cardiovascular and neurobehavioural effects that are of concern. Cardiovascular effects may have health implications for the general population in terms of curtailment of certain physically demanding activities. High risk groups include the elderly, the very young, pregnant women and, in particular, chronic angina patients.[18] The absorption and elimination of CO is estimated using the widely accepted mathematical model of Coburn *et al.*[19] The most influential factors in determining COHb levels are CO concentration, duration of exposure and alveolar ventilation, which is dependent on work rate.

15. The risks associated with exposure to elevated levels of CO also need to take account of everyday exposures. The primary source of CO in the urban environment is motor vehicles. Ambient air concentrations in urban areas depend on the weather and traffic density and vary greatly according to time and distance from the source. Primary air standards are intended to protect the population at large and take into consideration daily exposure of the very young, the very old and the seriously ill. Hong Kong's Air Quality Objectives (HKAQO)[1] set targets for outside ambient air in Hong Kong that are similar to the primary air standards of the US.[20] The prescribed levels for CO (Table 1) are intended to protect against the occurrence of COHb levels above 2%.[21] These levels are rarely exceeded at street-side monitoring stations in Hong Kong. Readings are generally around a few parts per

million,[1] although peaks of the order of 20 p.p.m. are found on occasions.

16. CO is widely generated indoors due to inadequate ventilation of combustion appliances. Short-term concentrations of 10–30 p.p.m. have been measured in German kitchens, and values of 50 p.p.m. and higher were found in 17% of homes in Dutch cities. Entrainment from integral or attached garages into living and working spaces can cause excessive CO levels. Levels found in workplaces, such as in car repair shops, may exceed 500 p.p.m.[18] Tobacco smoking is also an important source of CO indoors, and this can be the largest constituent of CO intake in those who do not smoke. As a consequence, healthy persons have endogenous COHb levels of 0·5–1%. The average COHb level in the general population of non-smokers is 1·2–1·5%, in cigarette smokers around 3–4%, but for heavy smokers it can exceed 10%.[18]

Guidelines for occupational exposure

17. The aforementioned Consumer Council report[4] includes figures on ‘occupational exposure limits’ for non-smokers, which were abstracted from an early WHO publication[22] and are reproduced here in modified form as Table 2. These guidelines would prevent COHb levels exceeding 5% in non-smoking occupational groups. The given safety factors are obtained by dividing the concentrations in columns 5 and 6 by those in column 1. Unless otherwise indicated, the guidelines given in Table 2 ‘. . . should be considered as desirable rather than maximum acceptable limits’.[22]

18. The WHO guidelines on exposure that would prevent COHb levels exceeding 2·5–3% in general non-smoking populations are given in Table 1 using two different 15-min limits: 100 p.p.m.[22] and 100 mg/m^3 (87 p.p.m.).[18] Table 3 gives an estimate of COHb uptake under different types of work. Table 4 show approximate times, calculated from Coburn’s equation, at various exposures to reach a COHb level of 3·5% where there is no other exposure to CO during the day.[23] These exposures are somewhat longer than those of Table 2, even when the safety factors are taken into account. The data given in these tables show that there is a measure of inconsistency between CO dose and estimated COHb uptake.

Table 2. Guidelines for exposure conditions that would prevent COHb levels exceeding 5% in non-smoking populations (WHO[22])

CO concentration		Exposure time not to be exceeded		Concentration that would produce 5% COHb‡		Safety factor	
p.p.m.	mg/m^3	Light work*	Heavy work†	Light work	Heavy work	Light work	Heavy work
200§	230	15 min	—	298	—	1·5	—
100§	115	30 min	15 min	157	193	1·6	1·9
75	86	60 min	30 min	87	105	1·2	1·4
50	55	90 min	60 min	64	62	1·3	1·2
35	40	4 h	2 h	37	41	1·1	1·2
25	29	8 h	8 h	31	30	1·2	1·2

* Light work = 181 l/min[1]
† Heavy work = 30 l/min[1]
‡ Calculated using Coburn’s equation
§ Maximum permissible concentration

Table 3. Predicted COHb levels for subjects engaged in different types of work (WHO[22])

CO concentration: p.p.m.	Exposure time not	Predicted COHb level for those engaged in		
		Sedentary work	Light work	Heavy work
100	15 min	1·2	2·0	2·8
50	30 min	1·1	1·9	2·6
25	1 h	1·1	1·7	2·2
10	8 h	1·5	1·7	1·7

Table 4. CO exposure duration required to reach 3·5% COHb (ACGIH[23, 26])

CO concentration: p.p.m.	Time: min		
	Sedentary work	Light work	Heavy work
1000	18	10	8
500	24	13	11
300	34	18	15
200	46	24	21
150	58	31	27
100	86	46	39
75	117	62	53
50	191	102	87
Alveolar ventilation: l/min	6	15	20

19. The American Conference of Government Industrial Hygienists (ACGIH) has influenced occupational exposure standards worldwide, including those of the UK’s Health and Safety Executive (HSE)[24] and Hong Kong’s Labour Department.[25] ACGIH threshold limit values (TLVs) ‘. . . refer to airborne concentrations of subtances and represent conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect. Because of wide variation in individual susceptibility, however, a small percentage of workers may experience discomfort from some substances at concentrations at or below the threshold limit; a smaller percentage may be affected

more seriously by aggravation of a pre-existing condition or by development of an occupational illness'.

20. Two categories of TLVs are specified. The TLV-TWA is the time-weighted average concentration for a normal 8-h workday and a 40-h work week to which nearly all workers may be repeatedly exposed, day after day, without adverse effect (see appendix). For CO this was, up to 1992, 50 p.p.m., but has since been reduced to 25 p.p.m.[23] Until recently the short-term exposure limit (TLV-STEL) for CO was 400 p.p.m.,[23] this being '. . . the maximal concentration to which workers can be exposed for a period up to 15 minutes continuously without suffering from 1) irritation, 2) chronic or irreversible tissue change, or 3) narcosis of sufficient degree to increase accident proneness, impair self-rescue, or materially reduce work efficiency, provided that no more than four excursions per day are permitted, with at least 60 minutes between exposure periods, and provided that the daily TLV-TWA also is not exceeded'.[26] The TLV-STEL should be considered a maximal allowable concentration, or ceiling, not to be exceeded at any time during the 15-min excursion period. The TLV-STEL has since been replaced by a biological exposure index (BEI).

21. Biological monitoring consists of an assessment of overall exposure to pollutants through measurement of the appropriate determinant(s) in biological specimens collected from a worker at a specified time. BEIs represent the levels of determinants which are most likely to be observed in specimens collected from a healthy worker who has been exposed to a pollutant to the same extent as a worker with inhalation exposure to the TLV of that pollutant. BEIs do not indicate a sharp distinction between hazardous and non-hazardous exposures, and it is possible for an individual to exceed the BEI without incurring increased health risk. For CO the determinants are COHb in blood, for which the BEI is 'less than 8% haemoglobin', and CO in end-exhaled air, for which the BEI is 'less than 40 p.p.m.'. Samples are taken at the 'end of shift'. It is noted that some workers with increased susceptibility to the effect of CO are left unprotected by the recommended BEI.

Occupational safety standards

22. The US National Institute for Occupational Safety and Health (NIOSH) provides recommendations for safety and health standards in the workplace[27] which are transmitted to the Occupational Safety and Health Administration (OSHA) of the US Department of Labor for use in legal standards.[28] NIOSH recommended CO limits (Table 1) are based on cardiovascular and behavioural evidence:[29] '. . . The recommended TWA standard of 35 p.p.m. CO is based on a COHb level of 5 per cent, which is the amount of COHb that an employee engaged in sedentary activity would be expected to approach in eight hours during continuous exposure. The ceiling concentration of 200 p.p.m. is based upon the restriction of employee exposure to CO to transient excursions above 35 p.p.m. which would not expect to significantly alter his level of COHb.' The recommended standard does not take into consideration the smoking habits of the worker.

23. The HSE published limits[24] form part of the requirements of the Control of Substances Hazardous to Health (COSHH) Regulations. The HSE's occupational exposure standard (OES) is the concentration of an airborne substance, averaged over a reference period, at which, according to current knowledge, there is no evidence that it is likely to be injurious to employees if they are exposed by inhalation, day after day, to that concentration. The current OES for CO is 50 p.p.m. 8-h TWA, and 300 p.p.m. 15-min STEL.

24. It is apparent from this review that the primary health concern for workers is the COHb uptake which, in turn, determines limits of CO dosage (the integral of exposure over time). The long-standing 8-h TWA of 50 p.p.m. is based on an estimated 5% COHb uptake, although NIOSH argues that 8-h exposure to 35 p.p.m. achieves this level. The more recent ACGIH TLV of 25 p.p.m. is '. . . recommended to retain blood COHb levels below 3·5%, to prevent adverse neurobehavioural changes, and to maintain cardiovascular exercise capacity'.[20] The reason is the interpretation of data which 'indicate that COHb levels as high as 5% identified for OSHA permissible exposure limits (PELs) and NIOSH recommended limits (RLs) place workers with cardiovascular and respiratory disease, those who are pregnant, or those with the need to perform psychomotor tasks at higher risk of adverse effects'.[23]

25. Studies on the impact of CO exposure on driving performance have produced inconsistent results. Wright *et al.*[30] reported a significant deficit in 'careful driving' habit, but statistically insignificant facilitation of emergency type actions with a 3·4% increase of COHb level. On the other hand, McFarland[31] reported that 6% COHb had no effect on driving ability. City driving itself can lead to significant CO exposure. If 3·5% COHb uptake is taken as a limit, a STEL of 200 p.p.m. is suggested. The data given in Table 4 suggest that

Table 5. Summary of CO levels measured in various car parks in Hong Kong

Physical size	Total number	5-min TWA: p.p.m.		15-min TWA: p.p.m.		1-h TWA: p.p.m.	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Under 3000 m^3	12	13	156	8	92	6	61·4
3000–10 000 m^3	15	15·4	115	12	51·6	8·2	34·5
10 000–30 000 m^3	14	6·4	506·6	3	361·6	2	153·8
Over 30 000 m^3	11	5·5	256·8	5·3	177	5	129

this would leave ample allowance for CO exposure associated with city driving.

Exposure limits for car parks

26. It is evident from Table 5 that CO levels in underground car parks vary considerably. Not only is there considerable variation between car parks but also within a given car park. Measurements taken by the author show variation between 10 and 260 p.p.m. in one particular large car park, with the heaviest concentration adjacent to the ramps (Fig. 2), as is generally to be expected.

27. Notwithstanding that the ACGIH's guidelines are intended for use in the practice of industrial hygiene and should be interpreted and applied as such, they do offer an indication of risk from exposure to CO in car parks. However, it should also be remembered that all these occupational guidelines have been established for single chemicals and do not take into account the effects of exposure to mixtures.

28. Car park management can control workers' exposure by implementing working practices that maintain shift exposures within the 8-h TWA. Fee collectors and the like can be housed in pressurized rooms, and security staff trained to avoid long periods in areas where high concentrations are expected. If exposed workers are not drawn from vulnerable groups, then the 8-h TWA of 35 p.p.m. (OSHA) or 50 p.p.m. (HSE) would be appropriate. Imposing the lower limit would reduce the working time for exposures to elevated levels.

29. The 15-min STEL is relevant in that it gives an indication of the levels to which users may be exposed without serious harmful effects. According to ACGIH, exposure to 200 p.p.m. for 15 min for a smaller adult engaged in light work could produce a COHb level of 5%. According to WHO,[18] if the 1-h mean value of 25 p.p.m. is taken as a short-term guideline value, then very high CO levels in the air could occur for shorter exposure times; for example, a 5-min exposure could reach 300 p.p.m.

30. From Table 4 it can be concluded that car park users carrying objects to and from a vehicle (light work) and exposed to 100 p.p.m. for a duration of 15 min are subject to a very low health risk. This would allow exposure up to 200 p.p.m. for durations of around 5 min with little apparent effect. At these levels it is also unlikely that driving performance will be affected.

Fig. 2. Narrow ramps and sharp corners as found in many Hong Kong car parks

31. The actual CO dose will depend on CO levels in the breathing zone. This may be estimated from the routes followed by users in leaving and returning to their vehicles. Well-planned pedestrian routing coupled with good traffic management (control of vehicular flow, good directional signs, reduced queuing, etc.) can significantly impact on CO dose, which may be well below that estimated from the CO levels prevailing in the car park. That is to say, breathing zone exposures could be much less than design control limits.

Pollutant load

32. Many factors influence the CO level at a given location within a car park. To make a reasonable estimate of the pollutant load for use in the dilution-based design approach[5, 10] valid data on both vehicle emissions and traffic volume and flow patterns are required, otherwise ventilation rates may be impractically high.

33. CO emission from a particular vehicle will depend on engine size, condition (tuning)

and operation, that is on whether the vehicle is travelling at or near car park limit speed (typically 8 k.p.h.), idling or accelerating.[16] Cold emissions from a vehicle leaving the car park are generally greater than hot emissions whilst entering to park.[16] Comprehensive vehicle exhaust emission data are not readily available for vehicles used in Hong Kong. US Environmental Protection Agency (EPA) data are available,[32] but as a result of EPA controls there has been a significant reduction in CO discharged from vehicles in recent years, although test data on vehicles indicates that, generally, actual vehicle emissions exceed EPA standards.[33] The use of historic 'rule of thumb' data[17, 34] can lead to considerable overestimates.

34. In heavily used car parks with hourly parking, traffic volume can be relatively high, with strong CO 'line sources' generated when there is congestion and queues form. Users often tend to seek parking close to exits, which can increase cruising distance and idling times. Traffic management is another factor in determining CO load. Even with reliable data on vehicle type and turnover, given the variables in cruising and idling times, estimating the CO 'load' in a large car park is not an easy matter.

Car park ventilation systems

35. The dispersal of high concentrations by removal or dilution will be dependent on the effectiveness of the ventilation system. Mechanical ventilation systems for enclosed car parks can be classified as

(*a*) supply-only systems
(*b*) exhaust-only systems
(*c*) combined supply and exhaust systems.

36. Combined systems can provide control of both supply and exhaust functions. Such systems allow more control of the distribution of intake (outside) air and, by adjustment and balancing, can prevent uncontrolled migration of polluted air to other parts of the car park. Car park ventilation systems can also be classified according to air flow pattern as unidirectional (displacement) systems – in which the supply and exhaust locations are arranged to establish an overall flow through a significant volume of the car park, and multidirectional (mixing) systems – in which supply and exhaust points are arranged so that a number of relatively small flow fields are established over relatively short distances. Fig. 3 illustrates the two types of system.

37. Properly designed and maintained unidirectional systems can provide a sweeping action which moves pollutants quickly to the exhaust vents. A disadvantage of such systems, particularly in large area car parks, is

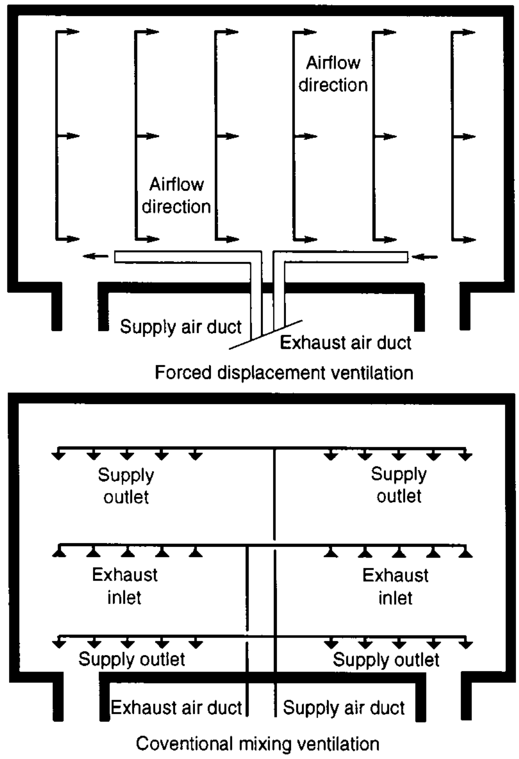

Fig. 3. Ventilation systems: (a) forced displacement; and (b) conventional mixing

that high pollutant gradients can be established, as the supply air is contaminated sequentially and cumulatively as it flows towards the exhaust side. This can result in high pollutant levels in areas near the exhaust vents. High total air flow and low infiltration from adjacent areas are required if effective ventilation is to be achieved.[34]

38. Multidirectional systems provide sources of outside air for the dilution of pollutants, and when properly designed and operated can provide for more 'localized' control of pollutants. However, such systems increase the likelihood of short circuits in the ventilation flow. For example, if supply and exhaust grills are too closely coupled, air can flow from the supply grill to the exhaust grill without adequate mixing with the pollutant-laden air in the region of the flow path. This can result in a significant volume of air being moved, but limited impact on overall pollutant loading. Short circuits may be exacerbated by obstruction and parked vehicles.[35] External short circuits can also occur when intake and exhaust ports on the exterior of the car park structure are too close, or are coupled by adverse environmental conditions, particularly wind.[36] Studies have suggested that displacement ventilation is superior to mixing ventilation as far as ventilation effectiveness is concerned.[35]

39. Short circuit ventilation can increase ventilation system efficiency if the resulting flow pattern is through the regions of highest pollutant source, as it removes the pollutants

before they have had time to mix throughout the volume of car park. However, too much reliance on 'localized ventilation' can lead to inefficient removal of pollutants once they are outside the ventilation zone of the localized ventilation system. Adequate flow must be maintained in all parts of the car park. In Hong Kong the combined supply and exhaust system is favoured, with the following considerations

(*a*) avoiding long flow fields that permit the contaminant levels to build up above an acceptable level at the end of the flow field
(*b*) providing short flow fields in areas of high pollutant emission
(*c*) providing an efficient, adequate flow throughout the volume of the parking structure
(*d*) avoiding stratification of engine exhaust gases
(*e*) the contaminant level of the outside air drawn in for ventilation (it is possible that the 'fresh air' intake into car parks will be polluted at or above the HKAQO[1] level)
(*f*) the thermal comfort of occupants.

40. It should be noted that the guidelines of 7·5 l/s may work only if a reasonable even mixing of the air flow and the contaminant source is achieved. Otherwise localized problems will exist, even if a higher ventilation rate is provided. From the standpoint of efficient extraction, exhaust points from both high and low levels are preferred, but this is seldom provided in Hong Kong installations.

Ventilation system control

41. The monitoring of CO concentrations in the environment of a car park is not a straightforward matter. There are several basic methods used in a variety of commercial equipment. Most of this equipment is not highly accurate. At levels in the 10–100 p.p.m. range, overall accuracy may be no better than ± 10 p.p.m., even when the equipment is properly zeroed, ranged and calibrated.[37]

42. Readings of CO concentration over time will depend on sensor response and logging frequency. Recording transient variations, occurring when cars pass by or engines start nearby, and obtaining TWA values will depend on the instrument used. It is conceivable that different instruments with different operators will measure different TWA values for the same location and time duration. Clearly, when setting strict air quality standards it is necessary to define the type of instrument to be used, the method to be used, the locations to be sampled and the sampling time as part of the standard.

43. In order to avoid unnecessary use of energy, ventilation fans should operate only when unacceptable CO levels arise. It will be prudent to install a control system activated either by sensors or by time-switching control, with settings based on operating experience. Energy savings can significantly affect the cost of the ventilation system. The choice and location of a CO sensor will be particularly critical. They are not necessarily expensive, but due consideration must be given to service life, reliability, operating checks, calibration, cleaning, etc. Accuracy at around 50 p.p.m. may be greater than ± 20%.

Conclusions

44. Given that higher level transient excursions are not necessarily very risky, it should be possible to allow levels up to around 200 p.p.m. for durations up to 15 min. This can be achieved with well-planned pedestrian routing, good traffic management, and possibly localized ventilation for areas with high pollution sources, such as exit ramps. It would not be prudent to allow high CO levels to persist on account of possible entrainment to other parts of the building.

45. It is also clear that present design methods for car parks need to be evaluated against actual installations. More data are required on pollutant sources and estimations of pollutant load. Consistent measurement of CO levels is not easy, neither is measurement of ventilation effectiveness in large volumes such as car parks. Further field studies are required.

46. The recommended CO level proposed by the EPD[5] is far too conservative as far as health risk to the general population is concerned. The car parks surveyed by the EPD are not so dangerous to health as implied in the Consumer Council report.[4]

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Appendix. Time-weighted average (TWA)

48. The term '8-h reference period' relates to the procedure whereby the occupational exposures in any 24-h period are treated as equivalent to a single uniform exposure for 8 h (the 8-h TWA exposure).[24] The 8-h TWA may be represented mathematically by

$$(C_1T_1 + C_2T_2 + \ldots\ldots + C_nT_n)/8$$

where C_1 is the occupational exposure and T_1 is the associated exposure time in hours in any 24-h period.

49. The short-term reference period adopted by ACGIH, OSHA, HSE, etc., is 15

min. Exposure should be recorded as the average over the specified short-term reference period and should normally be determined by sampling over that period. Where the exposure period is less than 15 min the sampling result should be averaged over 15 min. An example quoted by HSE[24] is a 5-min sample producing a level of 600 p.p.m. immediately followed by a period of zero exposure. The 15-min average exposure would then be 200 p.p.m.

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