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Assessment of the Health Impacts and Economic Burden Arising from Proposed New Air Quality Objectives in a High Pollution Environment

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Abstract: We conducted a health impact assessment of the government's proposed new air quality objectives (AQO) in Hong Kong, a high pollution environment. We based this on the World Health Organization (WHO) 2005 Air Quality Guidelines (AQG) and used a lognormal probability density function to model possible changes in annual mean pollutant levels resulting from the new AQO. All of the proposed short-term AQO were based on WHO interim targets (IT) or AQG, but allowed additional exceedances of these single limit values. Compliance with these short-term AQO may reduce (18-30%) the current annual mean concentrations but the distribution proportions exceeding the annual or annualized AQG remain high (83-100%). For SO_2, the proposed 24-hr AQO of 125 µg m^{-3}, with 3 days exceedances, cannot ensure reduction of the current annual mean but may legally permit an increase of the pollutant concentration distribution. If the proposed legal limits of AQO are fully exploited by polluters, we estimated the annual number of avoidable deaths at 1860, and avoidable health care events at 5.2 million doctor visits and 92745 hospital bed-days with a total annual community cost of US$2.6 billion. The proposed AQO may only reduce the current air pollution health impacts by 17% but could achieve 41% reduction if additional exceedances were not permitted. An epidemiologic approach should be adopted to assess external costs arising from modifications of WHOAQG and support accountability in air quality management. This analysis of the WHOAQG in a high pollution setting demonstrates problems arising from the absence of annual limits for some pollutants and the discordance between the short-term and annual AQG, suggesting that revisions based on a lognormal probability model should be considered.

Keywords: Air pollution, decision analysis, air quality objectives, air quality guidelines, World Health Organization, sulfur dioxide, nitrogen dioxide, ozone, particulate, exceedance.

INTRODUCTION

WHO Air Quality Guidelines

The World Health Organization Air Quality Guidelines (WHOAQG) are based on a comprehensive review of the evidence on the relationships between air quality and adverse health effects and provide guidance to support actions to achieve clean air, which is a basic requirement of human health and well-being. Although adoption of the WHOAQG is not mandatory for all countries and jurisdictions, these guidelines indicate the minimum levels of air quality control needed for the protection of public health given the current state of our knowledge and epidemiologic evidence of air pollution effects [1].

After the introduction of the 1987 Hong Kong Air Quality Objectives (HKAQO), the government legislated in 1990 to restrict sulfur to 0.5% by weight in all land based fuels and a subsequently restricted road diesel sulfur to 0.005% in January 2005. As a result, SO_2 concentrations together with nickel and vanadium from high sulfur fuels declined from 1990 to 2003, resulting in health gains in terms of reduced morbidity and mortality [2-4].

However, the Hong Kong Special Administrative Region (HKSAR) government did not revise its 1987 HKAQO, despite updates of the World Health Organization Air Quality Guidelines (WHOAQG) in 2000 and 2005. For example the 24-hour AQG for SO_2 of 125 µg m^{-3} in the 1987 and 2000 WHOAQG [5,6] was revised to 20 µg m^{-3} in the 2005 WHOAQG [1], which is much lower than the current 24-hour HKAQO for SO_2 of 350 µg m^{-3}. The current levels of SO_2 have stabilized at around 20 µg m^{-3} in Hong Kong and are high when compared with other metropolitan cities, such as London where the annual mean SO_2 concentration declined from 15 µg m^{-3} in 2000 to 8 µg m^{-3} in 2004 and to 6 µg m^{-3} in 2007 (APPENDIX A). The levels of particulates and NO_2 in Hong Kong have remained more or less stable for many years (http://hedleyindex.sph.hku.hk) but much higher than in other comparably developed cities. Among 105 world cities with populations above one million [7], Hong Kong's air quality was ranked 74th in 2004 and 72nd in 2006 based on annual average PM_{10} concentrations. Following the online publication of the WHOAQG in 2006, the HKSAR government, under pressure from environmental concern groups and the public, commissioned an 18-month review of the 1987 HKAQO with a multinational consultant [8].

A comparison of the 1987 HKAQO with the current WHOAQG indicates how far adrift the present HKAQO and daily pollutant levels are from the WHO guidelines (Fig. **1**), in particular, a majority of the population are exposed to the high level recorded at roadside monitors. It is clear that average levels of pollution are much higher and exceedances frequent, particularly during the cool season due to air mass

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movements and other meteorological factors. The WHOAQG provide single limit values for ten-minute, hourly, 24-hourly and annual averaging times. While the annual mean levels provide a benchmark for long-term protection of population health, the limit values for shorter averaging times are potentially important drivers of controls on exposures because, if enforced, they can limit the number of very high short-term levels and reduction in their frequency would predictably reduce the annual mean. This concept is described in the WHOAQG Global Update 2005: "*For PM_{10}, the AQG for the 24-hour average is 50 µg m^{-3} and reflects the relationship between the distributions of 24-hour means (and its 99th percentile) and annual average concentrations*" [9]. The selection of the 99th percentile indicates that the 24-hour average level should not be exceeded on more than 1% of the days in a year. The WHO advisory does not make any provision for allowable exceedances of either the interim targets (IT) or guidelines for SO_2, NO_2 and O_3.

METHODS OF COUNTING EXCEEDANCES

In US, UK, Australia, and EU, attainment of air quality standards is assessed by predefined geographic areas within the country. Each monitor within a geographic area is assessed separately. If any monitor within an area has exceeded the allowable number of exceedances of a concentration limit, this whole area is regarded as an exceedance area where the air quality standard is violated. However, the total number of exceedance areas within a region is only a crude indicator of the extent of compliance with air quality standards because non-compliance might have occurred in the entire area or just in a single hotspot of a few square meters. In order to improve pollution control with better quantification of compliance over a geographic area, the exceedance time is counted. The exceedance time is an exceedance day or exceedance hour if the averaging time is 24-hr or 1-hr respectively.

The European Environment Agency uses an *average approach* to counting the exceedance time in a year for each of the zones and agglomerations in each member state. This approach is based on the average exceedance time among all monitors in urban and suburban areas [10].

The HKSAR Government has adopted a *maximum approach*, which is based on the maximum levels observed at all monitors. If any one monitor or multiple monitors exceed the concentration limit of an averaging time, one exceedance time period is counted. The government counts exceedances selectively based on 11 general monitors (Fig. **2**) without taking into account the exceedances at roadside monitors where the pollution levels significantly affect the average population exposures.

Exceedance counting using either the maximum or average approaches outlined in Table **1** shows that the number of exceedances is three when based on the maximum approach and two when based on the average approach. The number of exceedances is usually larger in the maximum approach than in the average approach (Table **1**), regulation is therefore more stringent when the monitoring is based on the maximum approach. In addition, compliance based on the maximum approach will ensure that the highest monitored level is at or below the limit, while compliance based on the average approach can be a combination of very high non-compliant levels at one monitor averaged with very low levels at another monitor. However, the chance of observing an exceedance increases with the number of monitors in the maximum approach (APPENDIX B) but not in the average approach, so exceedance counts based on the maximum approach are not comparable between cities when the numbers of monitors are different.

Comparison of Proposed HKAQO, 2005 WHOAQG and WHOIT

WHO has suggested a series of IT as incremental steps for highly polluted regions to reduce pollutant concentrations to WHOAQG levels [1]. The new HKAQO [11] were proposed with reference to the 2005 WHO guidelines but use a combination of the WHOIT level-1 (IT-1) and level-2 (IT-2) for PM, SO_2, and O_3 and only the WHOAQG for annual NO_2 limit in the absence of any other interim level. Since WHO did not explicitly provide annual AQG for SO_2 and O_3, the proposed HKAQO do not include annual limits for these two pollutants. All short-term WHOAQG and WHOIT were modified in the proposed HKAQO by introducing exceedances for NO_2, SO_2, and O_3 and extending

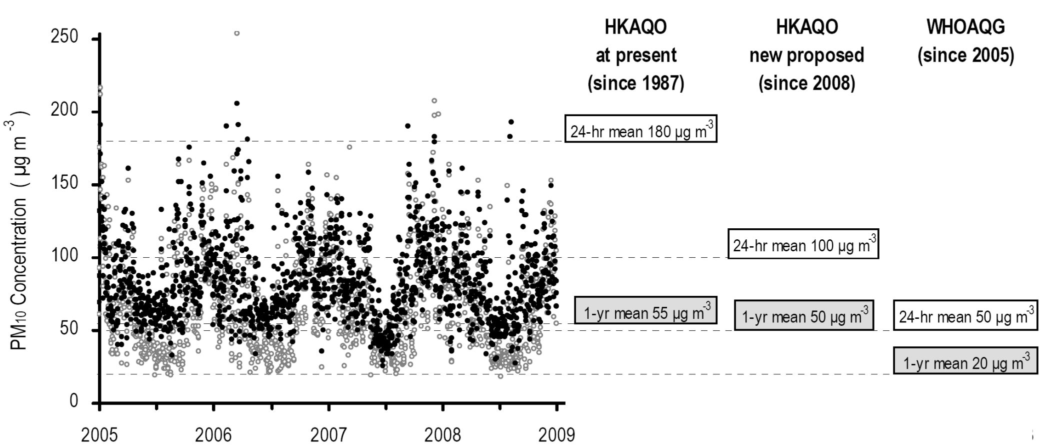

Fig. (1). Time-series plot of daily average PM_{10} concentrations showing the maximum at all general monitors (grey circles) and at all roadside monitors (black dots) in Hong Kong from year 2005 to 2009 compared with the 1987 HKAQO, 2005 WHOAQG and the proposed HKAQO.

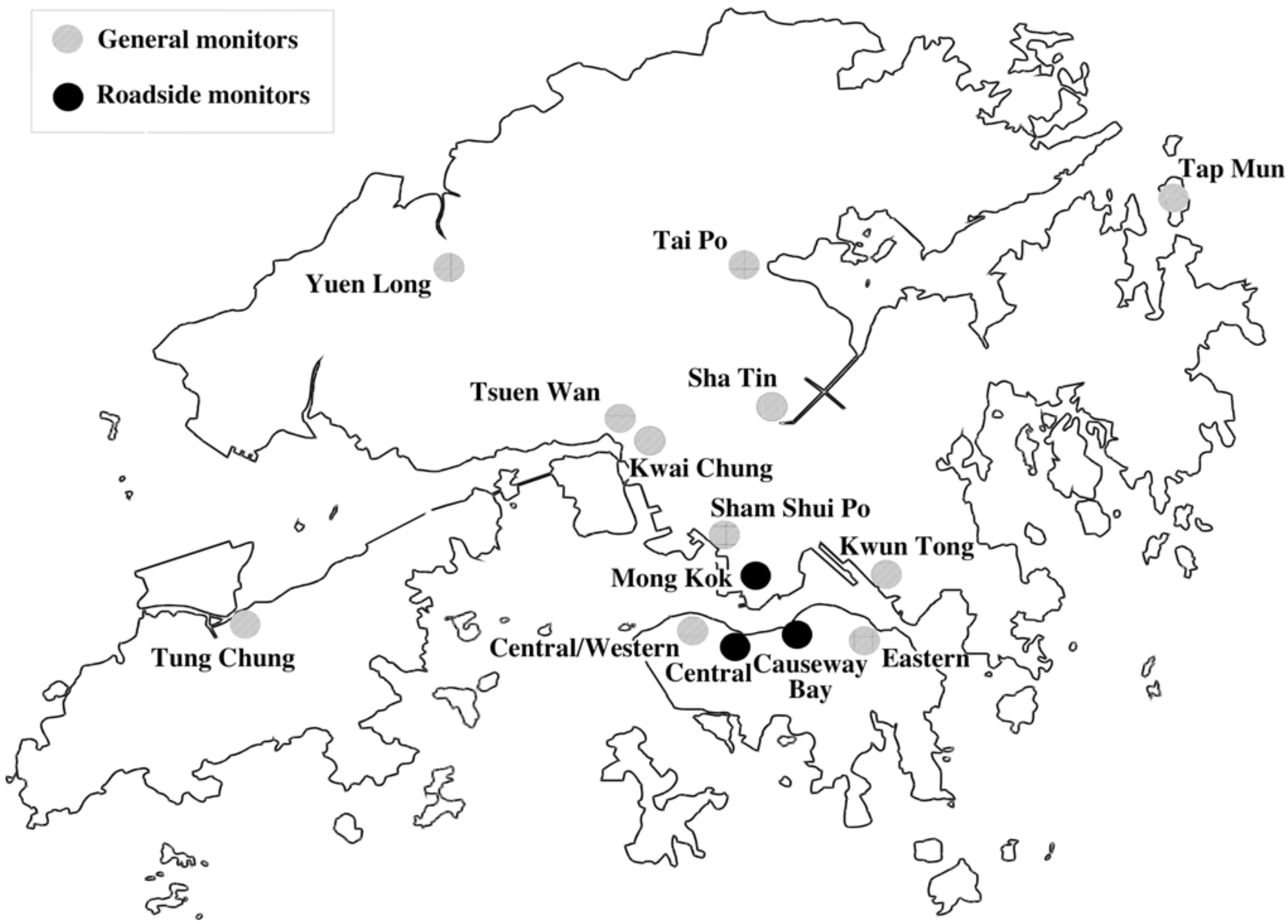

Fig. (2). Map of air quality monitors in Hong Kong. Location of 11 general monitors measuring PM_{10}, NO_2, SO_2 & O_3; $PM_{2.5}$ is available in Central, Tap Mun, Tsuen Wan, Tung Chung & Yuen Long in 2008; O_3 is not available in roadside monitors. Tap Mun is regarded as a background monitor in rural area with low population density.

exceedances for PM_{10} and $PM_{2.5}$ from 3 days up to 9 days (Table **2**).

The numbers of allowable exceedances in EU Directive 2008/50/EC [12] have been adopted in the proposed HKAQO for NO_2 and SO_2, and also referenced as a basis for justifying the additional exceedances in the proposed HKAQO for PM_{10}, $PM_{2.5}$ and O_3 [11]. However the 11 monitors in Hong Kong are between 4 to 25 fewer in number than those operating in EU cities, such as London, Paris, Berlin, and Madrid, which have comparable population sizes of 3-10 millions and land areas of 600-2700 km^2 [13]. This indicates that the numbers of exceedances in the proposed HKAQO are not correctly benchmarked to those in EU Directive [12] because of the lower number of monitors in Hong Kong (APPENDIX B).

Rationale and Aim of this Study

Air quality management policies should result in a shift in the distribution of pollutant concentrations to lower levels so that both the occurrence of high short-term levels and annual means can be reduced.

Our aim is to apply an epidemiologic approach to decision analysis to assess the annualized health impacts, which may result from the government's proposed new short-term AQO for PM_{10} and $PM_{2.5}$, NO_2, SO_2 and O_3, and to assess the level of population health protection in terms of the predicted annual pollutant levels arising from these AQO.

Table 1. Maximum Approach Versus Average Approach for Counting Exceedances (Ex.)

	Monitor 1 Level (μg m^{-3})	Monitor 2 Level (μg m^{-3})	Maximum Level at Monitor 1 and 2 (μg m^{-3})
day 1	**100**	40	**100**
day 2	40	10	40
day 3	**90**	40	**90**
day 4	**120**	**60**	**120**
	Average approach		Maximum approach
No. of Ex. of 50 μg m^{-3}	2 (=4/2)		3
4-day Mean	62.5 μg m^{-3} (n=8)		87.5 μg m^{-3} (n=4)

Levels exceeded 50 μg m^{-3} were highlighted in bold.

METHODS

Since the HKSAR government has adopted the maximum approach for counting exceedances to quantify compliance

Table 2. WHOAQG and WHOIT and the Proposed HKAQO (Shaded Area) Modified with More Exceedances

Pollutants	Averaging Time	IT-1		IT-2		IT-3		AQG	
		μg m^{-3}	Ex	μg m^{-3}	Ex	μg m^{-3}	Ex	μg m^{-3}	Ex
PM_{10}	24-hour	150	3	100	3→**9**	75	3	50	3
	1-year	70	0	50	0	30	0	20	0
$PM_{2.5}$	24-hour	75	3→**9**	50	3	37.5	3	25	3
	1-year	35	0	25	0	15	0	10	0
NO_2	1-hour							200	0→**18**
	1-year							40	0
SO_2	10-min							500	0→**3**
	24-hour	125	0→**3**	50	0			20	0
O_3	8-hour	160	0→**9**					100	0

"Ex" represents the number of exceedances in WHOAQG and IT; → precedes the proposed number of exceedances in HKAQO.

status over the whole city, the methods for predicting the annual mean from a short-term limit (Section A) were based on aggregation, into a single distribution, of the maximum pollutant concentrations at all general monitors for each averaging period in a year. Prediction of the annual mean is based on the maximum levels and so we used the term *annual mean maximum* to distinguish it from the *annual mean* in arithmetic. The methods for health impact assessment (Section B) were based on the annual mean pollutant levels, and the estimated change in annual mean is based on the percentage change of the predicted annual mean maximum. All of these methods are also applicable to calculate an annual mean by using the average approach in aggregating concentration distributions from multiple monitors [10].

Prediction of the Annual Mean with Short Term AQO Compliance

Understanding the relationship between the annual mean, short-term AQO and the number of exceedances based on a lognormal probability distribution (Fig. **3**), which is the normative pattern of air pollutant data in a defined region, is the key to conducting a quantitative health impact assessment of the effectiveness of air quality regulations and for assessing the relationship between the short-term and annual AQO. This is particularly useful when an annual AQO is not specified, as is currently the case for SO_2 and O_3.

When the highest allowable short-term level or exceedance limit is set at a certain *percentile*, a value below which a specified proportion of the pollutant concentrations can be identified, it is necessary to be able to estimate how this limit relates to the annual mean. We based our models on a lognormal probability density function [14] to estimate the annual mean from a given percentile in a lognormal distribution as follows:

Step 1. **Define the reference distribution of pollutant concentrations:** We selected the published air pollutant data of 2008 as our reference year. We established distributions of daily averages (calculated from hourly data starting 0:00 hr) for PM_{10} and SO_2, daily maximum of 8-hour moving averages (starting 0:00-8:00 hr) for O_3, and hourly averages for NO_2. To avoid the influence of extreme values, we excluded average values that were 3 (for daily data) or 4 (for hourly data) times the geometric standard deviation above the geometric mean. Then we computed the arithmetic mean (x), geometric mean (μ), geometric standard deviation (σ), and the maximum (max) of the reference distribution for each pollutant.

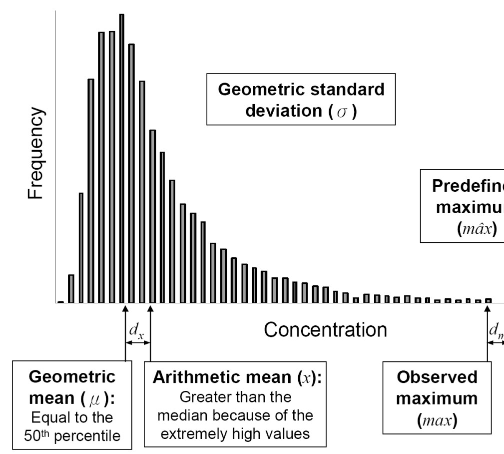

Fig. (3). Air pollutant concentration represented as a lognormal probability distribution.

Step 2. **Define the percentile of the maximum value:** We used μ and σ in a lognormal probability density function (F) to compute the value at the 99.999999th percentile. This 99.999999th percentile value was used as a predefined maximum ($\hat{max}$) in the reference distribution. We then computed the difference in percentile (d_m) between max and $\hat{max}$ so that the value at the (99.999999 + d_m)th percentile of F is equal to max. The value for d_m is negative when the percentile of max is smaller than the percentile of $\hat{max}$.

Step 3. **Predict the geometric mean from a pollutant concentration limit:** When predicting the geometric mean for a limit with n allowable exceedances, i.e. a value limit close to the maximum, the percentile for the limit, on a daily basis, was defined as the $([1 - n/365] + d_m)^{th}$ and on an hourly basis was defined as the $([1 - n/8760] + d_m)^{th}$ percentile. The addition of d_m ensures that the highest percentile (when n=0) is less than 100% and thus valid in F. We can show empirically that d_m and σ are stable over several years. Assuming these two parameters to be constant in the near future, by using σ and the limit value at the defined percentile in F, we can compute the predicted geometric mean ($\hat{\mu}$).

Step 4. **Define the percentile of the arithmetic mean:** Since μ is the 50^{th} percentile in F, we computed the difference in percentile (d_x) between μ and x so that when using μ and σ in F, the value at the $(50 + d_x)^{th}$ percentile is approximately equal to x.

Step 5. **Predict the arithmetic mean from a maximum:** Based on the result in Step 3, we can assume value of σ and $\hat{\mu}$ in F to compute the predicted arithmetic mean at the $(50 + d_x)^{th}$ percentile.

Using data obtained from our model, we compared the predicted and the observed annual pollutant means of recent years, 2005 to 2007, by applying the μ and σ of these years. The differences for PM_{10}, NO_2 and SO_2 were small overall with a range of 0.0% to 1.0%, but for O_3 were greater and more variable with a range of 0.9% to 2.5% (Table **3**). Our model prediction of the annual means for PM_{10} (21.5 μg m^{-3}) and $PM_{2.5}$ (10.3 μg m^{-3}), based on WHO short term limit values for PM_{10} (50 μg m^{-3}) and $PM_{2.5}$ (25 μg m^{-3}), each with 3 allowable exceedances, were close to the annual WHOAQG for PM_{10} (20 μg m^{-3}) and $PM_{2.5}$ (10 μg m^{-3}). These results support the validity and reliability of the method for the prediction of the annual mean and concordance between short-term and annual WHOAQG.

Since the number of exceedances permitted in all of the proposed short-term HKAQO were higher than those stipulated by WHO (Table **2**), we applied our model to assess their impact on annual mean pollutant levels. Discordance between the short-term and annual AQO was also assessed. The distribution proportion of pollutant concentrations exceeding the annual WHOAQG or the predicted annual AQG based on the short-term AQG was computed by $1 - CP$, where CP is the cumulative probability in F using the annual (or predicted annual) AQG value, σ and $\hat{\mu}$.

Estimation of Population Health Impacts and External Costs

Observable Health Impacts when WHOAQG are Exceeded

We assume the ambient concentration is a reliable indicator of exposure prevalence and approximates to 100%. To account for the continuous nature of both the long- and short-term health impacts of air pollution [15], when the ambient concentration moving averages for the past 1 year for all pollutants, 24 hour for PM_{10}, $PM_{2.5}$ and SO_2, 1 hour for NO_2, and maximum 8 hr moving average over 24 hour for O_3 has exceeded the WHOAQG levels, we assume health impacts due to air pollution are measurable either clinically or by use of biomarkers. Similarly, although there are no identified thresholds for pollutant health effects, we conservatively exclude estimates for health impacts below the WHOAQG. There are no formally stated annual guideline values for SO_2 and O_3 [1] but health effects due to long-term exposures to relatively low levels of these two air pollutants have been demonstrated [16-19] and we would expect that compliance with short-term objectives will result in a much lower annual mean level. We derived these annualized values from the short-term guideline values using lognormal distribution models. Since all WHOIT values are higher than the WHOAQG values, the difference is regarded as an exceedance of the AQG for estimating excess health burdens attributable to any adopted regulatory level.

Excess Risks for Specific Health Outcomes

In studies of mortality, hospital admissions and primary care doctor visits, Poisson regression adjusted for autocorrelation and overdispersion was used to estimate the change in excess risks attributable to the daily variation per 10 μg m^{-3} of a single pollutant in a linear concentration-response relationship, taking into account season, temperature, humidity, holidays, and influenza periods (Table **4**).

In the absence of local cohort studies for long-term effects, we used short-term excess risks for the estimation of health effects due to exceedances of the annual WHOAQG. These excess risks for adverse health outcomes were applied to population mortality and health care utilization data to obtain the annual number of premature deaths (due to non-accidental causes), hospital utilization (due to cardiovascular and respiratory diseases) and physician consultations in primary care due to respiratory complaints. The total number of health events was based on daily primary care (private and public) doctor visits for respiratory complaints in 2004 [22,23], the daily numbers of hospital admissions with mean length of stay, and the daily registered deaths in 2000 to 2004 [24,25].

Table 3. Validation of the 2008 Lognormal Distribution Model for Years 2005-2007

Year of Data	2005				2006				2007			
Pollutant	PM_{10}	NO_2	SO_2	O_3	PM_{10}	NO_2	SO_2	O_3	PM_{10}	NO_2	SO_2	O_3
Observed annual mean maximum	69.2	78.8	40.8	66.3	68.5	79.1	41.5	70.9	70.1	79.4	38.8	71.2
Predicted annual mean maximum	68.7	78.6	40.5	67.9	68.5	78.9	41.4	72.2	70.1	79.4	39.2	71.8
Absolute difference (%)	0.7	0.2	0.6	2.5	0.1	0.3	0.2	1.8	0.1	0.0	1.0	0.9

Table 4. Excess Risks (%) (95% Confidence Intervals) for Mortality, Hospital Admissions, and Primary Care Doctor Visits Per 10 μg m^{-3} Change in Pollutant

	PM_{10}	NO_2	SO_2	O_3	References
Mortality					
All natural causes	0.24 (0.01, 0.46)	0.64 (0.36, 0.91)	1.36 (0.93, 1.78)	-0.11(-0.37,0.16)	[20]
Hospital Admissions					
Cardiovascular diseases	0.37 (0.18, 0.57)	0.73 (0.48, 0.98)	1.08 (0.72, 1.44)	0.24 (0.01, 0.47)	[20]
Respiratory diseases	0.50 (0.28, 0.71)	0.54 (0.27, 0.80)	0.76 (0.34, 1.18)	0.55 (0.31, 0.79)	[20]
Primary Care Doctor Visits					
Respiratory diseases	3.28 (2.52, 4.05)	3.42 (-0.62, 7.63)	0.68 (-3.03, 4.54)	1.50 (-1.18, 4.26)	[21]

Excess Number of Health Outcomes

For each pollutant (P), the annualized impact (I_p) in terms of number of health outcomes resulting from changes in air quality, was estimated as:

$$I_p = \sum_{h=1}^{k} (N_I \times ER_p \times L_{ph})$$

where h is the index of an hour in one year; k is the last hour in a year; N_I is the annual number of a health outcome I in the population equally divided into every hour; ER_p is the excess risk per 10 μg m^{-3} of pollutant P and was assumed as zero for negative excess risk [26]; L_p is the hourly exceedance (in 10 μg m^{-3} units) of the WHOAQG limit value (G) in annual or short-term averaging period for pollutant P by the hourly moving average (M) of all hourly concentrations over the annual or short-term averaging period respectively (for M>G only).

To combine the impacts due to different pollutants P, correlations (r) and partial correlations ($\check{r}$) between pollutants at the monitors were calculated on the basis of a previously published rule-of-thumb approach [26]. We assume that the contributions of PM_{10} and O_3 to the health impacts are independent of the other pollutants, the contribution by NO_2 was dependent on PM_{10}, and that by SO_2 was dependent on PM_{10} and NO_2 after accounting for each but not for both together. We estimate the proportional variation of NO_2 not explained by PM_{10} as 0.41 (i.e. $1 - r^2_{PM_{10} \cdot NO_2}$) and the proportional variation of SO_2 not explained by PM_{10} and NO_2 as 0.84 (i.e. $1 - \check{r}^2_{NO_2 \cdot SO_2 | PM_{10}} - \check{r}^2_{PM_{10} \cdot SO_2 | NO_2}$)*. The combined pollutant impact (C) associated with the different criteria pollutants was:

$$C = I_{PM_{10}} + 0.41(I_{NO_2}) + 0.84(I_{SO_2}) + I_{O_3}$$

The combined pollutant impact based on moving annual averages (C_Y) and moving short-term averages (C_H) were added to represent the total impact of air pollution (C_T) in terms of number of health outcomes in one year. For estimation of the change in C_T arising from the predicted change in annual mean attributable to the proposed HKAQO (see **METHODS** under **Section A**), C_Y was calculated assuming all L_p based on moving annual averages in a year are constantly equal to the difference between the predicted annual mean and the annual WHOAQG value. C_H was calculated by $C_Y \cdot C_{H_0} / C_{Y_0}$, where C_{H_0} and C_{Y_0} are the two types of combined impacts in the reference year 2008.

Monetization of Health Outcomes

Assessment of the tangible loss due to the health outcomes attributable to air pollution included the direct health care costs for public and private hospital admissions, average costs of a bed day, public out-patient consultations (general, specialist, accident and emergency) for cardiovascular and respiratory diseases, primary care doctor visits, travel costs (excluding accident and emergency) and lost productivity [22]. All costs were based on the available health and economic data for year 2000 to 2004. The productivity loss for working ages (15 to 64 years) includes the person-years of life lost, time lost from work due to hospital admissions and primary care doctor visits. All losses were adjusted for by size of the labour force, employment rates, and sex-specific median daily salaries [27] for year 2004. The intangible loss was based on the average valuation of willingness-to-pay of US$1.28 million to avoid the loss of one statistical life in Hong Kong [28]. This is a conservative estimate comparable to the range US$0.4 to 9.7 million reported from Europe, Australia, New Zealand, US and Canada [29].

Estimates of Population Exposures to Roadside and Ambient Monitor Levels

Since high-rise buildings and narrow roads can substantially amplify the pollutant concentrations particularly at lower levels [30], health impact assessment based on the Hong Kong general monitors that were located 20m above ground could underestimate the ground level air pollution by up to 100% due to the street canyon effect [30]. This would lead to underestimated health impacts if a large proportion of population activities occur on or near to the ground level. To compensate for this we have taken into account the roadside pollutant concentrations and the average population time-activity to estimate population exposure levels [31]. Details are shown in APPENDIX C.

RESULTS

Prediction of the Annual Mean with Short Term AQO Compliance

Respirable Suspended Particulates (PM_{10})

In 2008, 366 24-hr averages of maximum values at 11 general monitors were obtained, with GM 58.1 μg m^{-3} (GSD

* " . " represents "between"; " | " represents "adjusted by"

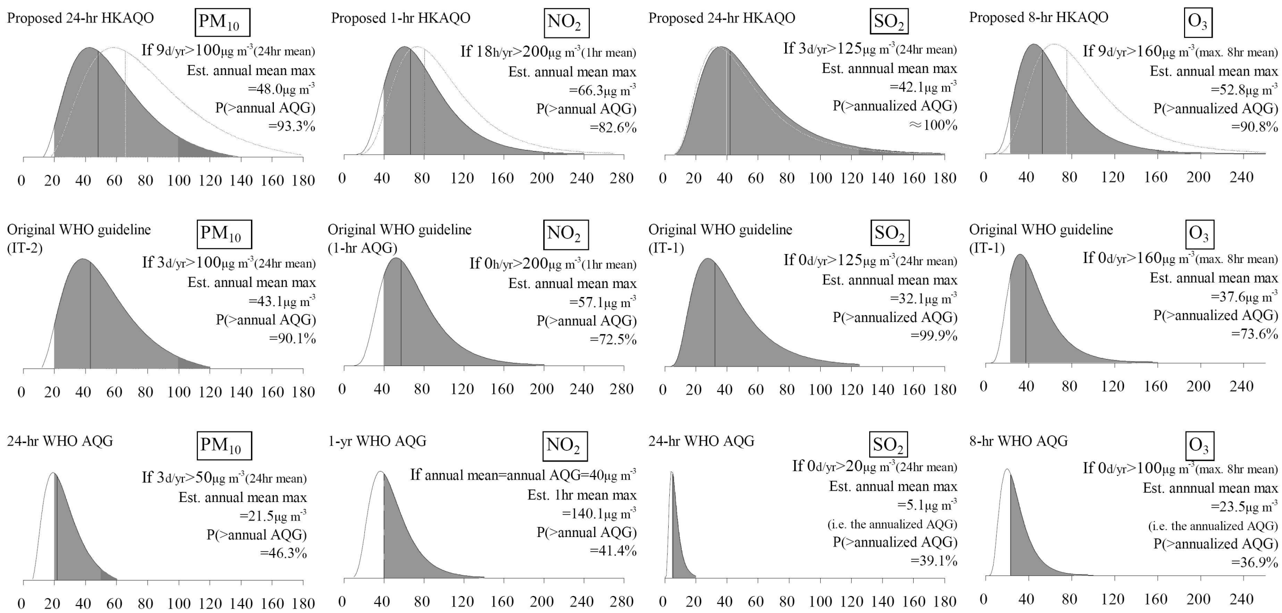

Fig. (4). Predicted distribution, annual mean maximum, and proportion of distribution (P) exceeding the annual AQG (shaded area) under different regulatory options..

1.65). The annual mean maximum PM_{10} was 65.5 μg m^{-3}. The three regulatory options considered were (i) the proposed HKAQO 24-hr PM_{10} of 100 μg m^{-3} with 9 days of exceedances, (ii) the original 24-hr WHOIT-2 of 100 μg m^{-3} with 3 days of exceedances and (iii) the 24-hr WHOAQG of 50 μg m^{-3} with 3 days of exceedances (Fig. **4**).

The annual mean maximum is predicted to be 48.0 μg m^{-3}, 43.1 μg m^{-3} and 21.5 μg m^{-3} respectively under options (i), (ii) and (iii). The proposed 24-hr and the annual AQO appear to be concordant with a lognormal distribution but adoption of the 24-hr HKAQO predicts an annual mean maximum which is 140% above the annual WHOAQG of 20 μg m^{-3}. The predicted distribution proportions with 24-hr averages exceeding the annual WHOAQG are 93.3%, 90.1% and 46.3% respectively for options (i), (ii) and (iii) and 40.5% for compliance with the annual WHOAQG.

The predicted percentage change in the 2008 annual mean maximum is -26.7%, -34.2% and -67.2% for adoption of options (i), (ii) and (iii) and -69.5% for compliance with the annual WHOAQG of 20 μg m^{-3}. As the 2008 annual mean for PM_{10} based on 10 urban general monitors was 51.4 μg m^{-3}, so adoption of short-term options (i), (ii) and (iii) corresponds to a predicted PM_{10} annual mean of 37.7 μg m^{-3}, 33.8 μg m^{-3} and 16.9 μg m^{-3} respectively, and compliance with the annual mean maximum consistent with the WHOAQG of 20 μg m^{-3} corresponds to an annual mean of 15.7 μg m^{-3}.

Fine Suspended Particulates ($PM_{2.5}$)

In 2008, 366 24-hr averages of maximum values at 4 general monitors were obtained, with GM 37.5 μg m^{-3} (GSD 1.73). The annual mean maximum $PM_{2.5}$ was 43.3 μg m^{-3}. The three regulatory options were (i) the proposed HKAQO 24-hr $PM_{2.5}$ of 75 μg m^{-3} with 9 days of exceedances, (ii) original 24-hr WHOIT-1 of 75 μg m^{-3} with 3 days of exceedances and (iii) the 24-hr WHOAQG of 25 μg m^{-3} with 3 days of exceedances (figure not shown).

The annual mean maximum is predicted to be 34.6 μg m^{-3}, 31.0 μg m^{-3} and 10.3 μg m^{-3} respectively under options (i), (ii) and (iii). The proposed 24-hr and the annual AQO appear to be concordant with a lognormal distribution. The adoption of the proposed 24-hr HKAQO predicts an annual mean maximum which is 246% above the annual AQG of 10 μg m^{-3}. The distribution proportions with 24-hr averages exceeding the annual WHOAQG are 97.7%, 96.4% and 42.0%, and 39.7% respectively for options (i), (ii) and (iii) and 39.7% for compliance with the annual WHOAQG.

The predicted percentage change in the 2008 annual mean maximum is -20.1%, -28.4% and -76.2% for options (i), (ii) and (iii) and -76.9% for compliance with the annual WHOAQG of 10 μg m^{-3}. As the annual mean for $PM_{2.5}$ in 2008 based on 3 urban general monitors was 38.2 μg m^{-3}, so for options (i), (ii) and (iii) the predicted $PM_{2.5}$ annual mean are 30.5 μg m^{-3}, 27.4 μg m^{-3} and 9.1 μg m^{-3} respectively, and compliance with the annual AQG of 10 μg m^{-3} corresponds to an annual mean of 8.8 μg m^{-3}.

Nitrogen Dioxide

In 2008, 8784 1-hr averages of maximum values at 11 general monitors were obtained, with GM of 3.2 μg m^{-3} (GSD 1.55). The annual mean maximum NO_2 was 80.5 μg m^{-3}. The two regulatory options considered were (i) the proposed HKAQO 1-hr NO_2 of 200 with 18 hours of exceedances and (ii) the original 1-hr WHOAQG of 200 μg m^{-3} with no exceedances (Fig. **4**).

The annual mean maximum is predicted to be 66.3 μg m^{-3} and 57.1 μg m^{-3} respectively under options (i) and (ii). The proposed 1-hr and the annual AQO of 40 μg m^{-3} are apparently discordant with a lognormal distribution. The adoption of the 1-hr HKAQO predicts an annual mean maximum which is 66% above the annual WHOAQG of 40 μg m^{-3} and we estimate that the 1-hr NO_2 should be set at 140 μg m^{-3} without exceedances for compliance with the annual WHOAQG of 40 μg m^{-3}. The distribution proportions with

1-hr averages exceeding the annual WHOAQG are 82.6% and 72.5% respectively for options (i) and (ii) and 41.4% for compliance with the annual WHOAQG.

The predicted percentage change in the 2008 annual mean maximum is -17.6% and -29.1% for adoption of options (i) and (ii) and -50.3% for compliance with the annual WHOAQG of 40 μg m^{-3}. As the 2008 annual mean for NO_2 based on 10 urban general monitors was 56.8 μg m^{-3}, so for options (i) and (ii) the predicted NO_2 annual means are 46.8 μg m^{-3} and 40.3 μg m^{-3} respectively, and compliance with the annual WHOAQG of 40 μg m^{-3} corresponds to an annual mean of 28.2 μg m^{-3}.

Sulfur Dioxide

In 2008, 366 24-hr averages of maximum values at 11 general monitors were obtained, with GM 33.8 μg m^{-3} (GSD 1.73). One extreme value $>\mu+3\sigma$ was observed and excluded, leaving 365 maximum values with GM 33.7 μg m^{-3} (GSD 1.71). The annual mean maximum SO_2 was 39.5 μg m^{-3}. The three regulatory options considered were (i) the proposed HKAQO 24-hr SO_2 of 125 μg m^{-3} with 3 days of exceedances, (ii) the original 24-hr WHOIT-1 of 125 μg m^{-3} with no exceedances and (iii) the 24-hr WHOAQG of 20 μg m^{-3} with no exceedances (Fig. **4**).

The annual mean maximum is predicted to be 42.1 μg m^{-3}, 32.1 μg m^{-3} and 5.1 μg m^{-3} respectively under options (i), (ii) and (iii). The annualized AQG is estimated as 5.1 μg m^{-3} based on the 24-hr WHOAQG of 20 μg m^{-3}. The adoption of the proposed 24-hr HKAQO predicts an annual mean maximum which is 725% above the annualized AQG of 5.1 μg m^{-3}. The distribution proportions with 24-hr averages exceeding the annualized AQG of 5.1 μg m^{-3} are ~100%, 99.9%, and 39.1% respectively for options (i), (ii) and (iii).

The predicted percentage change in the 2008 annual mean maximum is +6.6%, -18.7%, and -87.1% for options (i), (ii) and (iii) respectively. As the 2008 annual mean for SO_2 based on 10 urban general monitors was 20.8 μg m^{-3}, so for options (i), (ii) and (iii) the predicted SO_2 annual means are 22.2 μg m^{-3}, 16.9 μg m^{-3} and 2.7 μg m^{-3} respectively.

Ozone

In 2008, 8784 1-hr averages of maximum values at 11 general monitors were obtained, with GM 63.9 μg m^{-3} (GSD 1.80), for calculations of 366 maximum values of daily 8-hr averages, with GM 91.1 μg m^{-3} (GSD 1.63). The annual mean maximum O_3 was 75.3 μg m^{-3}. The three regulatory options considered were (i) the proposed daily maximum 8-hr HKAQO of 160 μg m^{-3} with 9 days of exceedances, (ii) the original daily maximum 8-hr WHOIT-1 of 160 μg m^{-3} with no exceedances and (iii) the daily maximum 8-hr WHOAQG of 100 μg m^{-3} with no exceedances (Fig. **4**).

The annual mean maximum is predicted to be 52.8 μg m^{-3}, 37.6 μg m^{-3} and 23.5 μg m^{-3} respectively under options (i), (ii) and (iii). 23.5 μg m^{-3} is considered as the annualized AQG and is concordant with the daily maximum 8-hr WHOAQG. The adoption of the 8-hr HKAQO predicts an annual mean maximum which is 125% above the annualized AQG of 23.5 μg m^{-3}. The distribution proportions with daily maximum 8-hr averages exceeding the annualized AQG of 23.5 μg m^{-3} are 90.8%, 73.6% and 36.9% respectively for options (i), (ii) and (iii).

The predicted percentage change in the 2008 annual mean maximum is -29.9%, -50.1% and -68.8% for options (i), (ii) and (iii) respectively. As the 2008 annual mean for O_3 based on 10 urban general monitors was 36.1 μg m^{-3}, so for options (i), (ii) and (iii) the predicted O_3 annual means are 25.3 μg m^{-3}, 18.0 μg m^{-3}, and 11.3 μg m^{-3} respectively.

Estimation of Population Health Impacts and External Costs

Population Exposure Estimates Including Roadside Pollution Levels

The 2008 annual mean roadside levels for PM_{10} (68 μg m^{-3}), NO_2 (98 μg m^{-3}), and SO_2 (23 μg m^{-3}) were 10-72% higher than the values reported at general monitors (Table **5**) (data not available for O_3). Applying the proportion of total population time spent near to the ground level (APPENDIX C), we estimated the notional exposure level to be approximated by taking 61.2% roadside and 38.8% general monitor levels. We estimated that the 2008 annual mean exposure levels for PM_{10}, NO_2, SO_2 and O_3 as 61.6 μg m^{-3}, 82.0 μg m^{-3}, 22.1 μg m^{-3} and 31.9 μg m^{-3} respectively (Table **5**).

Estimation of Health Impacts and External Costs

For our 2008 air pollutant levels, we estimated that the annual health outcomes attributable to air pollution exceeding the WHOAQG included 2,174 deaths, 129,525 hospital bed-days, 8.6 million doctor visits, and the total annual community cost at US$3.10 billions (Table **5**). For air pollutant levels that would be compliant with the proposed short-term HKAQO, the annual numbers reduce to 1,860 deaths, 92,745 hospital bed-days, and 5.2 million doctor visits, with a total annual community cost of US$2.58 billions (Table **5**). This indicates a 17% reduction when compared with the total annual loss attributable to 2008 air pollutant levels. This reduction would be increased to 41% (Table **5**), if the WHO interim targets, on which the proposed short-term HKAQO are based, were not modified by a large number of legally permitted exceedances (Table **2**).

Sensitivity analyses of the annual community cost attributable to 2008 pollutant levels (Table **6**) showed a 5% reduction when we assume 50% exposure to roadside levels and 50% to general monitor levels; a 26% reduction when only the general monitor levels were used; a 39% reduction if short-term WHOAQG were used as the annual AQG for SO_2 and O_3; a 3% reduction if only statistically significant excess risks (Table **4**) were used; and a 26% increase if intangible costs due to suffering and pain for morbidity were included. A 33% reduction is estimated if only exceedances of annual AQG are taken into account compared with 67% if only exceedances of the short-term AQG are considered.

Table 5. Estimated Costs and Numbers of Health Events Attributable to Predicted Annual Levels of Air Pollution Exceeding the Annual and Short-Term WHOAQG

	Annual Mean (μg m^{-3})				Number of Health Events Attributable to Air Pollution			Cost Attributable to Air Pollution (US$ in Billion)		
	PM_{10}	NO_2	SO_2	O_3	Deaths	Hospital Bed-Days	Doctor Visits	Tangible Loss (*A*)	Intangible Loss (*B*)	Total (*A+B*)
Annual WHOAQG	20	40	#5.1	#23.5	0	0	0	0.00	0.00	0.00
General monitor levels in 2008	51	57	21	36						
Roadside monitor levels in 2008	68	98	23	n.p.						
*2008 air pollutant levels	62	82	22	†32	2,174	129,525	8,579,338	0.41	2.69	3.10
					{1,071-3,309}	{71,084-187,747}	{4,130,658-15,793,133}	{0.20-0.68}	{1.33-4.10}	{1.53-4.78}
**2008 air pollutant levels that approach the proposed short-term HKAQO	45	68	24	22	1,860	92,745	5,187,243	0.28	2.30	2.58
					{1,018-2,675}	{52,347-132,997}	{2,488,953-10,219,906}	{0.15-0.47}	{1.26-3.31}	{1.41-3.78}
**2008 air pollutant levels that approach the original short-term WHOAQG and IT behind the proposed HKAQO	41	58	18	16	1,323	67,694	3,953,330	0.21	1.64	1.84
					{704-1,921}	{38,050-97,245}	{2,038,698-7,485,557}	{0.11-0.35}	{0.87-2.38}	{0.98-2.72}

*Assumed 61.2% exposure to roadside levels and 38.8% to ambient levels (APPENDIX C); **Based on the predicted percentage changes; #annualized AQG; "n.p." data not provided by the government; †assumed roadside O_3 level was 81% of the ambient O_3 level based on a Korean city [32] where ambient O_3 level (37.1 μg m^{-3}), roadside NO_2 level (94.3 μg m^{-3}) and ambient NO_2 level (42.0 μg m^{-3}) were similar to the 2008 levels in Hong Kong; { } range based on the lower and upper 95% confidence intervals of excess risks (Table **4**).

DISCUSSION

Health Impacts of Air Pollution

The progressive decline in air quality in Asia, signaled by continuing reduction in daily visibility is one of the most pressing public health priorities in the region. The WHOAQG provide a sound basis for immediate effective action to control pollutant exposures and protect population health. Obstacles to implementing effective action on the mitigation of pollution include skepticism [33] about the evidence for a causal relationship between the environment and disease and the perceived costs of pollution abatement to vested interests and the wider community. While causality is not disputed when Koch's postulates can be satisfied for an infectious disease, the silent inflammatory injury caused by air pollutants does not carry an International Classification of Disease rubric and there is no adequate public health legislation to address this problem. The massive external costs of pollution remain largely unaccounted for in many jurisdictions.

The evidence for causality on population health effects of air quality will always be based, for obvious practical reasons, on observational studies rather than true experiments such as randomized controlled trials. However natural experiments also provide a possible approach for drawing inferences based on the principle of "post hoc ergo propter hoc" and the application of Occam's Razor. These include the closure of the Utah Steel Mill [34], traffic reduction during the Atlanta Olympics [35]; migration to cleaner air during the California Children's Health Study [36], the Hong Kong fuel sulfur restriction [4] and the Dublin coal sales ban [37] which all led to demonstrable health gains. In the US, reduction of pollution over longer timescales led to measureable health benefits, as indicated by the extended Harvard Six Cities study cohort [38]. No studies have demonstrated strong evidence of a threshold for any of the four criteria pollutants considered here and as emphasized by Williams and Chiotti [39] the adoption of the single limit values in the WHOAQG do not necessarily provide a basis for a pollution abatement strategy.

In the past we have shown that large scale health impacts and community costs occur at current levels of pollution in

Table 6. Sensitivity Analysis of the Estimated Costs and Numbers of Health Events Attributable to Predicted Annual Levels of Air Pollution and Population Exposures to PM_{10}, NO_2, SO_2 and O_3

Annual Community Cost Attributable to 2008 Exposure Level if:	US$ in Billion
(a) calculated as in Table **5**	3.10
(b) ratio of roadside to general monitor levels is 1:1	2.95
(c) only general monitor levels are used	2.28
(d) only statistically significant excess risks are used	3.01
(e) intangible costs due to suffering and pain for morbidity are included	3.91
(f) only exceedances of annual AQG are counted	2.08
(g) only exceedances of short-term AQG are counted	1.02

Hong Kong and most of the harm has been measured at concentrations below the current 1987 HKAQO. However these estimates are conservative because the risks estimated from a majority of studies, mostly time series, are underestimated compared with cohort studies [40] or evidence from interventions [4,37]. Identification of sources of pollutants with important and reliably measured impacts provides a basis for calculation of health benefits and reduction of community costs from pollutant abatement [26,41].

Lognormal Distribution Model

In an environment with a known high level pollutant distribution pattern, we have described and tested a statistical method to demonstrate the relationship between the regulatory short-term limit and the resulting arithmetic annual mean to support health impact assessment and policy decisions. In this report, we have shown how these two important limits can be mutually predicted by applying a lognormal probability density function. We found that Larsen (1971) [42] in US had also applied the lognormal distribution model, as an application of Gumbel's [43] extreme value theory [44], to develop general equations to estimate averaging time of air pollutant concentrations and their distribution properties including geometric mean, arithmetic mean, maximum and percentile concentration. However, these general equations which were established based on seven years of US data in the 1960s [42] and were identified as having limitations in taking account of non-stationary sequences (such as seasonality) [45] may not be suitable today for other countries with different environmental characteristics. For example, Larsen's equations were based on an assumption that the annual arithmetic mean for 1-hr averages is the 70^{th} percentile of the distribution, but the annual arithmetic means for the Hong Kong 1-hr NO_2 distribution from 2005 to 2008 were all distributed around the 59^{th} percentile and equations developed in other jurisdictions may erroneously estimate the annual arithmetic mean concentrations. Our modelling method on the other hand does not require a pre-determined percentile or constant in the calculations of any summary statistics so that it can be applicable in other countries.

We have developed methods to establish models for health impact assessments and air quality policy appraisal using the most recently available year of data as the reference. Each model is specific for each air pollutant. We validated our model using historical data over several years for both the maximum and average approaches to the aggregation of air pollutant levels. The relationship between the annual mean and a high percentile is robust for both approaches. We have also demonstrated that our model is a good predictor of the short-term and annual limits of both PM_{10} and $PM_{2.5}$ in WHOAQG. These estimates were not influenced by using larger (11 stations) or smaller (5 stations) dataset, indicating that our modeling method is unlikely to be affected by different numbers of monitoring stations.

The value of the application of the lognormal distribution model can be demonstrated for the estimation of the effects of different numbers of exceedances on the annual mean; determining concordance in a set of short and longer term single limit values; identification of valid short term limits and averaging times based on an annual limit; and decision analysis support in prediction of an annualized limit whenever an evidence-based short-term limit is selected.

Assessing Regulatory Limits Based on WHOAQG

Our approach to an analysis of the possible or likely impacts of the proposed revisions to the HKAQO has demonstrated key problems relevant to health protection. For example, we have applied the model to demonstrate that increases in the number of allowable exceedances increases the annual mean and negates the health protection value of the stated WHO targets and guidelines. At present, there are no formal advisories with respect to the determination of the number of allowable exceedances in setting air quality standards. The WHOAQG allows 3 exceedances per year for 24-hr PM_{10} of 50 μg m^{-3} resulting, with compliance, in an annual WHOAQG of 20 μg m^{-3}, but EU and UK allow up to thirty-five exceedances of 50 μg m^{-3} per year without explicitly justifying the reasons. Our model indicates that a 24-hr limit of 50 μg m^{-3} with thirty-five exceedances will result in an annual mean of 29 μg m^{-3}, which is 45% above the annual WHOAQG. The current EU annual limit for PM_{10}, set at 40 μg m^{-3}, is far more permissive than the estimated mean 29 μg m^{-3} based on the 24-hr EU limit. This is reflected in the reported data among 288 stations which failed compliance with the EU Directive [12] for PM_{10} in 2008, where 67% violated the 24-hr limit, 0% violated the annual limit, and the remaining proportion violated both limits [46]. These findings indicate that the annual limit becomes redundant when it is far more permissive than the short-term limit. Our lognormal distribution model can be applied to ensure concordance of single limit values for the shorter- and longer-term limits and provides assistance to setting standards which, if enforced, will reliably ensure that both types of exposure reduction targets are met in a rational way for health protection.

Our model was also applied to deduce an 1-hr limit (140 μg m^{-3}) concordant with the annual AQG of 40 μg m^{-3} for NO_2 since we found a marked divergence between the WHO 1 hour limit of 200 μg m^{-3} and the annual AQG. This could be a significant problem for air quality management in a high pollution environment. Our model predicts that even if the 1-hr AQG of 200 μg m^{-3} is applied without the eighteen hours exceedances added by the Hong Kong government, the annual mean will still be 43% higher than the annual AQG of 40 μg m^{-3}, indicating that the AQG is inappropriately high and discordant with the recommended annual WHOAQG. In Hong Kong where the 2008 annual mean roadside NO_2 level was 98 μg m^{-3} and the 90^{th} percentile in a distribution of maximum 1-hr levels was 180 μg m^{-3}, setting a short-term limit as high as 200 μg m^{-3} with 18 exceedances obviously will not sufficiently influence emission control policies to achieve exposure reduction to the annual AQG level. A further evidence of the effect of discordance is found in the EU Directive [12] for NO_2 annual limits of 40 μg m^{-3} and 1-hr average of 200 μg m^{-3} with 18 exceedances. In 2008 among 186 monitoring stations that violated the EU Directive [12] for NO_2, 90% only violated the annual limit, 1% only violated the 1-hr limit and the remaining proportion violated both limits [46]. These data indicate that the short-term limit becomes redundant when it is far more permissive than the annual limit, as predicted in our model. We conclude from both Hong Kong and EU experience that a tighter limit for 1-hr NO_2, not above

140 μg m^{-3} without allowable exceedances, is necessary and should be considered in future revisions of WHOAQG.

Our model, given the Hong Kong standard deviation, reliably predicts the annual WHOAQG for PM_{10} (20 μg m^{-3} - predicted as 21.5 μg m^{-3}) and $PM_{2.5}$ (10 μg m^{-3} - predicted as 10.3 μg m^{-3}) from the 99^{th} percentiles, and provides provisional annual limits for SO_2 (5.1 μg m^{-3}) and O_3 (23.5 μg m^{-3}) in the absence of recommended annual values in the WHOAQG. We find that our estimated annualized AQG are also supported by epidemiologic evidence. The daily mortality attributable to SO_2 in Canada and Finland with annual average concentration of 14 μg m^{-3} [18] and 7 μg m^{-3} [17] respectively, and the reduced fetal growth attributable to SO_2 in Australia with annual average concentration of 3 μg m^{-3} [19] support the argument that the annualized AQG for SO_2 should be at least as low as 5 μg m^{-3} and that the current 24-hr AQG of 20 μg m^{-3} is valid. The demonstration of asthma hospital admissions attributable to O_3 in Finland with annual average concentration of 22 μg m^{-3} [16] indicates that the annualized AQG for O_3 should be at least as low as 23.5 μg m^{-3} and supports the short-term AQG of 100 μg m^{-3}. Annualized limits are important to risk assessment, air quality management and any process of accountability.

Sulfur emissions had been substantially reduced in Hong Kong after the 1990 sulfur restriction regulation, since when there have been no decreasing trends in concentrations at both roadside and general monitors. Modelling of possible outcomes of the proposed HKAQO for SO_2 indicates that the selection of an interim target as high as 125 μg m^{-3} may lead to upward trends in ambient concentrations. The political perspective of setting limit values which will not lead to a high prevalence of violations conflicts with the need to achieve sustained reductions in the highest levels observed in order to achieve annual targets which are known to be health protective. The lack of an explicit annual guideline for SO_2 in the WHOAQG is a problem if the short term value is treated as a proxy for an annual guideline because the predicted annual mean resulting from full compliance with the current short term AQG is as low as 2.7 μg m^{-3} (5.1 μg m^{-3} for annual mean maximum). If the short-term objectives alone are adopted as a proxy for an annual guideline then the maximum percentile may be several times higher than the short-term objective with corresponding detriment to health. Our model predicts that if the annual mean SO_2 is 20 μg m^{-3}, the maximum percentile for 24-hr SO_2 will be 78 μg m^{-3}, nearly four times as high as the short-term AQG. Estimation of and compliance with the two annualized AQG values for SO_2 and O_3 is necessary for assessment of the annualized health impacts arising from these pollutants.

Some Aspects of the WHOAQG

The 2005 WHOAQG provide the best available consensus statement on the relationships between four criteria air pollutants and health outcomes. It provides a strong basis for the establishment of effective regulatory strategies for pollution abatement. The interim targets are specifically provided for countries with the lowest levels of financial and technological resources as entry level positions to initiate air quality management. They are not intended as a default for advanced regions with high GDP per capita. Besides, the important property of the 24-hr limits as the 99^{th} percentile of the annual distribution clearly implies that, from a regulatory perspective, exceedances of this limit should not occur on more than three or four days in a year in order to maintain compliance with the annual target. However the importance of these principles appear to be widely unrecognised. The HKSAR government has adopted the lowest IT together with further permissive modifications based on increased exceedances of single limit values. This will inevitably limit the size of the benefit achievable in terms of future health gains. Our findings demonstrate the undesired effect of modifying the WHO single limit values and emphasize that the current WHOAQG may be misinterpreted and misapplied, particularly in persistently high pollution environments where the short-term single limit values are of doubtful utility unless being prescriptively used to drive pollution abatement with continuous evaluations. The addition of permitted exceedances of short-term regulatory limits may completely invalidate an air quality control strategy based on the selected annualized targets in the WHO report. A more explicit description of the important relationship between the short-term and annual limits is needed in the context of exposure reduction and air quality management strategies which will achieve the health protection afforded by the AQG.

The present version of WHOAQG [1] includes the diplomatic declaration "In formulating policy targets, governments should consider their own local circumstances carefully before using the guidelines directly as legal standards". But this accommodation should be considered together with the WHO recommendation "that countries with areas not meeting these guideline values undertake immediate action to achieve these levels in the shortest possible time" [1]. Lack of cohesion with the guidelines is also reflected in the government's own policy statement that it aims "to achieve progressively the long term target of achieving the ultimate AQG" [11] but only "as a long-term aspirational goal" [47]. These statements do not specify estimates of the contributions which may be made by up to nineteen suggested interventions nor the timescale on which they may be implemented. The WHO report lacks any discussion of timelines for progression from WHOIT to WHOAQG and the need to regard the AQG limit as an indicator of safer, rather than safe, air in which there is no threshold for pollutant effects. The absence of a threshold is now supported by many studies on PM excess risks for health outcomes [40,48-52] and NO_2 effects on childhood lung growth and function [53].

Experience with implementation of the guidelines and analysis of the relationship between resultant short and longer term pollutant concentrations would assist revision of the guidelines and their interpretation by regulatory authorities. While the WHOAQG remains the best available synthesis of worldwide evidence of air pollution effects, continuous improvements of the guideline may focus on the scientific evidence of health effects at low concentrations and provide detailed specifications to aid the selection of WHOIT or WHOAQG and to quantify the likely effects of modifying the number of allowable exceedances. Providing permissive options for interim targets but lacks standardization of the adoption strategies as well as methodology for assessing the impact of lax limits may fail to deliver protection to human health.

Limitations of the Present Study

Our lognormal distribution model is based on the 2008 air pollution data in Hong Kong. Generalizability may therefore be limited to the predictions for the changes in annual pollutant levels in the years around 2008. Previously established methods for this analysis [42] may be preferred, but our method is empirically tested and simple to use. However if other cities apply our methods, local data should be used to develop a model specific to their own environment to obtain valid results, since the GSD and the percentiles between parameters of the model could be different.

We have applied a rule-of-thumb approach in excluding extreme values which may be due to unusual natural events such as a sandstorm [54], and setting the 99.999999th percentile as a predefined maximum. Sensitivity analyses indicated that without exclusion of extreme values or using 99.9th percentile as the predefined maximum the predicted annual mean estimate could vary by approximately ±1%. As, our model was based on one year data, it lacks a prediction range for the annual mean. Such a range can be based on the lowest and highest GSD in historical data. Preliminary analysis indicated this range is within ±10% of the predicted mean. Nevertheless, we cannot necessarily assume that GSD in the future will be consistent with the dispersion of values in the past and a periodical update of the model with new pollutant data is necessary to maintain its reliability.

Although our health impact assessment is based on an approach to environmental accountability [26], there are still several potentially major limitations to be resolved. First, when exposure level is below the WHOAQG we assumed no observable health effects despite the fact that no thresholds for pollutant health effects have been identified. Second, we used short-term excess risks derived from time series studies to calculate the long-term health effects due to exceedance of the annual AQG. Since the long-term excess risks, such as those derived from cohort studies, are usually much larger than the short-term excess risks by an order of magnitude [15,40], the total health impacts estimated in this report could be underestimated to the same extent. Third, we directly combined the short- and long-term health impacts so that our total impact is approximately 40% more than the total based on effects of annual exceedance alone. The postulated overlapping between the short- and long-term effects [15] which raises the question of how best to avoid double counting is unresolved at present and we have not adjusted for possible overlapping effects in our calculations. If there are no long-term effects then our estimates may be inflated by about 20% to 40% but the cohort effect estimates indicate that this is very unlikely. Overall our health impact assessment method is conservative, with sources of underestimation tending to be very much larger than sources of overestimation.

CONCLUSION

The Hong Kong government has modified the WHO interim targets and guidelines by increasing the number of allowable exceedances, an approach which will invalidate the short-term limits as modifiers of annual pollutant levels. In particular, the proposed 24-hr AQO for SO_2 at 125 μg m^{-3} with 3 days of exceedance may allow increases in the current levels rather than ensure reduction of air pollution in Hong Kong. None of the other proposed new AQO will provide adequate protection to the public as the distribution proportions exceeding the annual AQG levels remain unacceptably high at 83% to 100% above the annual guidelines. Modifications of the health based guidelines should be carefully evaluated in terms of a health impact assessment.

The reductions in mass concentrations must not be considered in isolation but should be assessed in the context of health gains and avoidable community costs. The estimation of the health benefits and the value of pollution abatement should be based on the principal types and sources of exposure. Experience arising from the implementation of the WHO guidelines will allow the current recommendations to be evaluated and improved. Formalisms such as our approach based on the lognormal probability density function linked to a cost benefit analysis can provide support for accountability measures.

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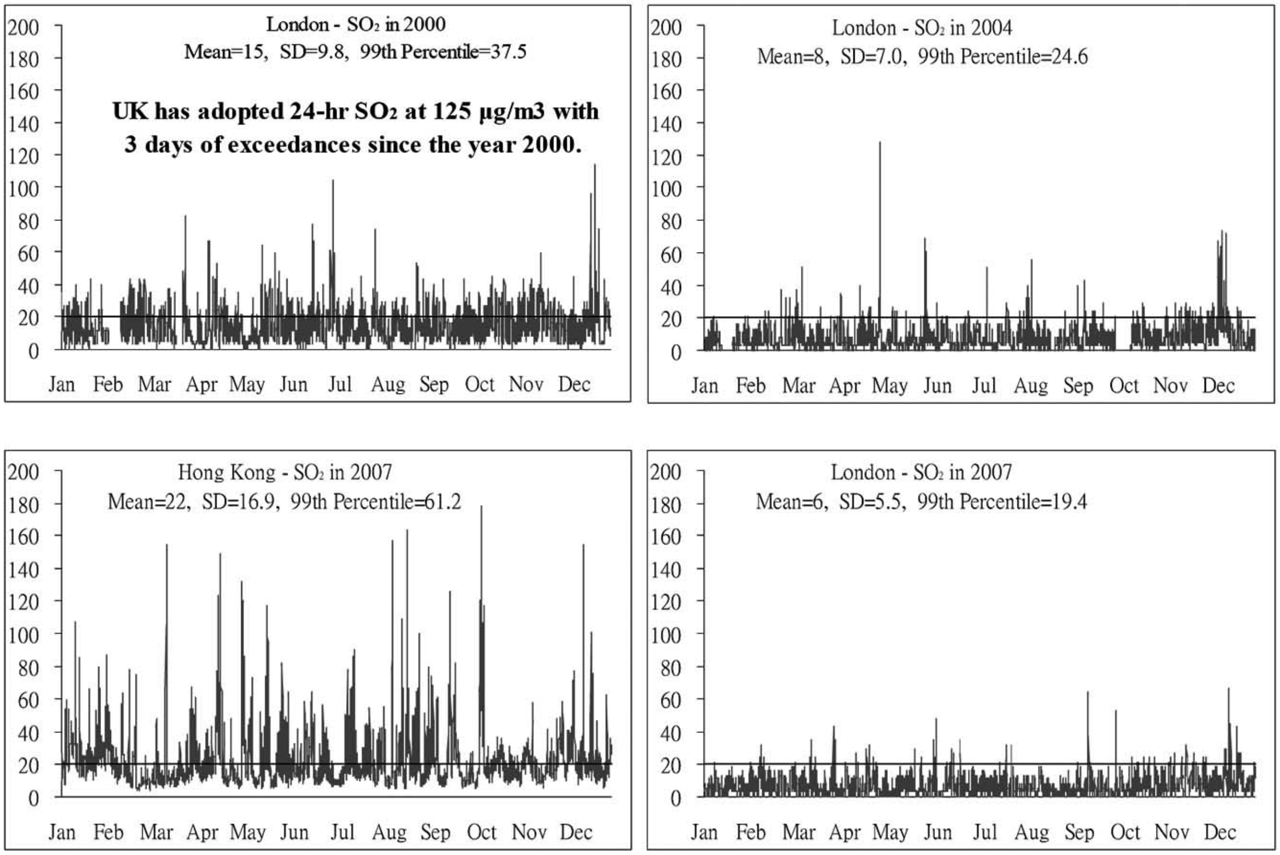
ABBREVIATIONS

AQG	=	Air Quality Guideline
AQO	=	Air Quality Objective
EEA	=	European Environment Agency
EPD	=	Environmental Protection Department
EU	=	European Union
GDP	=	Gross domestic product
GM	=	Geometric mean
GSD	=	Geometric standard deviation
HK	=	Hong Kong
HKSAR	=	Hong Kong Special Administrative Region
hr	=	Hour
IT	=	Interim targets
NO_2	=	Nitrogen dioxide
O_3	=	Ozone
PM_{10}	=	Particulate matter with aerodynamic diameter <10 μm
$PM_{2.5}$	=	Particulate matter with aerodynamic diameter <2.5 μm
SO_2	=	Sulfur dioxide
UK	=	United Kingdom
US	=	United States
WHO	=	World Health Organization
yr	=	Year

APPENDIX A

Comparison of Hourly SO_2 Concentration (y-Axis Unit: µg m^{-3}) in London 2000, 2004 and 2007, and Hong Kong 2007



Data of London Marylebone Road station, a roadside station located at the centre of London with the most number of air pollutants being simultaneously measured [55].

In the United Kingdom 2000, the AQO of '*24-hr average not exceeding 125 µg m^{-3} for 3 days was adopted and set to be achieved by the end of year 2004*'. This was the best available air quality guideline at that time. As a result of the implementation efforts made in air pollution mitigation (including the use of road charging system) and importantly the promise of achieving the target in time, UK successfully met the AQO by the end of year 2004 with reduction of annual mean concentration from 15 µg m^{-3} in year 2000 to 8 µg m^{-3}, and a further reduction to 6 µg m^{-3} by the end of 2007.

APPENDIX B

Relationship Between the Number of Air Pollution Monitoring Stations and the Number of Exceedances

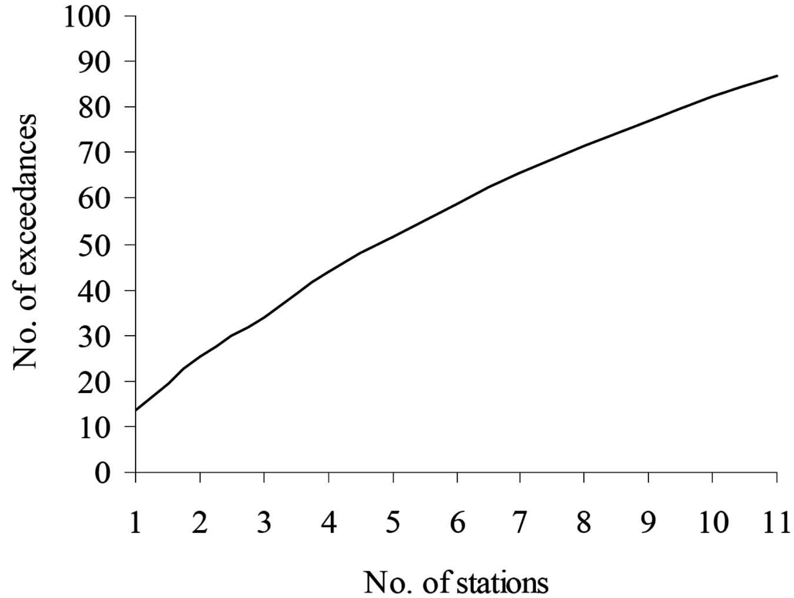
***Background*:** Efforts have been made in comparing the WHOAQG with the air quality objectives/targets/standards/strategy in different jurisdictions, such as US, EU, UK, Australia, New Zealand, Singapore, Japan [11]. The air quality limits and the number of allowable exceedances are often compared between jurisdictions without taking into account the number of monitoring stations. We hypothesize that when the effect due to variation in location is eliminated, the number of monitoring stations is related to the number of observable exceedances.

Method: We used NO_2 hourly average data from 11 general monitoring stations in 2008 and assessed the number of hourly exceedances above the WHOAQG for NO_2 of 200 µg m^{-3} based on the maximum level among these stations. When 11 stations were used, the number of exceedances based on 11 stations in one combination, i.e. ${}_{11}C_{11}$, was obtained. When 10 stations were used, the average of the number of exceedances based on maximum level among 10 stations in ${}_{11}C_{10}$ combinations was obtained. Similarly, the average numbers of exceedances for combinations using 9 stations to 1 station were also obtained. By taking the average number of exceedances of all possible combinations can therefore preserve the same geographical effect due to 11 different locations of the monitoring stations for 1 to 10 stations being taken into account.

Results: Increases in the number of monitoring stations within the same geographical area is associated with increases in the number of exceedances over a year. In 2008, if 1 station is in used, on average 14 hours exceeded the WHOAQG 1-hr NO_2 of 200 µg m^{-3}. The number of hourly exceedances increases to 25, 34, 44, 52, 59, 65, 71, 77, 82 and 87 for 2 to 11 stations in used.

(APPENDIX B) contd….

Figure showing the relationship between the number of general monitoring stations in used and the average number of exceedances of WHOAQG 1-hr NO2 of 200 µg m^{-3} in 2008.



APPENDIX C

Fraction of Population Exposure to Roadside Pollution Levels

Background: Population exposure represents the average level of exposure to a pollutant taking into consideration the average daily duration of work, travel and leisure activities among different age groups [56]. It is a practically valid measurement of average human exposure level in the population and can be different from the monitoring station measure of the average ambient levels over a territory. In places where population-based personal exposure data are absent, use of all available monitoring stations that represent different types of exposure may also help to modify population exposure estimates for health impact assessment. This is particularly important in modern urban environments where buildings are high-rise and roads are narrow resulting in canyon effects [30] that can substantially amplify the pollutants particularly at lower levels. In Hong Kong, the average distance from ground to the sampler inlet of 10 general monitoring stations was 20m [57]. This is 4-18m higher than that in US [58] and other jurisdictions in Asia [59-60]. The roadside station pollutant levels were therefore taken into account in our estimation of the average population exposure level.

Method: Numbers in the demographic subgroups were obtained from HKCSD [61]. The proportion of the population below the height of 20m (approximately equivalent to the height of six storeys assuming one storey is about 3.5m high) was derived from the database of the number of storeys of 40,747 private and public housing buildings in Hong Kong [62,63]. The time-microenvironment-activity pattern of different population subgroups was based on a local telephone survey on 396 people (aged 6 to 75+) [31]. We defined the fraction of population exposure to roadside pollution levels using the proportion of population time spent below the height of general stations:

$$\sum_{i=1}^{q}\sum_{j=1}^{r} n_i P_j t_{ij} \beta$$

where n_i is the number of the i^{th} population subgroup for i=1,…,q; P_j is the proportion of the population in the j^{th} microenvironment-activities below the height of the general monitoring stations for j=1,…,r; t_{ij} is the proportion of time spent by the i^{th} subgroup in the j^{th} microenvironment-activities in one day; β is the proportion of a population subgroup in the sub-categories of a microenvironment-activity.

Results: Among the 40,747 private and public housing buildings comprising all residential addresses with the total number of storeys 387,957, among which 175,098 were situated at six storeys or lower so that proportion of population homes at or below the average height of the general monitoring stations was approximately 45.1% (=175,098/387,957). Among the 39,353 private buildings comprising office addresses, the total number of storeys was 351,215, with 166,860 situated at six storeys or lower so the proportion of population situated in offices at or below the average height of the general monitoring stations was approximately 47.5%. In 2006 there were 6,864,346 person-days per day of exposure, of which 4,2000,124 (61.2%) were for those at or below six storeys, including population time at home (42.6%), work (13.4%), commuting (9.6%), school (8.6%), and other leisure activities out of home.

(APPENDIX C) contd….

Table Showing Population Time at or Below 20m (the Mean Height of 10 Urban and Suburb General Monitoring Stations)

Microenvironment-Activities	**Sub-Groups**	**1. Aged 0-2**	**2. Aged 3-5**	**3. Aged 6-17**	**4. Aged 18-60**	**5. Aged 60+**	**Person-Day Per Day at or Below 20m =*n·P·t·β***	**Proportion of Person-Day Per Day at or Below 20m =*n·P·t·β* / 6,864,346**
	n	**118,866**	**150,010**	**938,439**	**4,615,392**	**1,041,639**		
	P / ***h***							
1. At home	45.1	{23}	{19}	13.78	12.92	16.33	1,788,152	26.0%
2. At work (ground level)	100				{8} (β=0.128)		196,929	2.9%
3. At work (in office)	47.5			0.73	4.13 (β=0.872)	1.04	363,969	5.3%
4. In school	100		{4}	4.33	0.84	0.08	359,323	5.2%
5. In restaurant	100			0.8	0.86	0.58	221,839	3.2%
6. In shopping mall	100			1.38	0.94	1.92	318,061	4.6%
7. Commuting	100			1.14	1.62	1.06	402,121	5.9%
8. Outdoor activities	100	{1}	{1}	0.73	0.8	2.23	290,379	4.2%
9. Others	100			0.89	1.03	0.61	259,353	3.8%
						Total:	**4,200,124**	**61.2%**

n=number of population; ***P***=proportion of population at or below the height of general monitoring stations; ***h***=number of hours spent in one day based on average weekday pattern in the population [31]; ***t***=proportion of time spent in one day (i.e. *h*/24); ***β***= proportion of a population subgroup for sub-categories of a microenvironment-activity (β is 1 if not specified); { } are assumptions of the present study. "Commuting" included private car/taxi, bus, truck/van, train, MTR, and tram. "Outdoor activities" included mainly walking and other activities. "Others" included church, cinema/theater, night club/bar, indoor gym, parking/garage/gas station, and industrial buildings. Ground-level workers (aged 18-60) included transport and related workers, railway engine and motor vehicle drivers, transport labourers, salespersons, street vendors and related workers, messengers (e.g. postman), watchers and security workers [61].

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