Monitoring Personal Exposure to $PM_{2.5}$ in Hong Kong with Next Generation Sensors

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Civic Exchange is an independent, non-partisan public policy think-tank established in Hong Kong in 2000. With a vision to shape a liveable and sustainable Hong Kong, Civic Exchange's mission is to engage society and influence public policy through research, dialogue and the development of practical solutions. Civic Exchange undertakes research in three major areas: air quality, nature conservation and the urban environment, with an overarching framework of promoting wellbeing.
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When it was founded in 2009 at the City University of Hong Kong, the School of Energy and Environment became the only educational institution of its type in the region specialising in tackling sustainability and energy issues.
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Acknowledgements

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Executive Summary

Air pollution is a long-standing problem in Hong Kong. The fine particles called $PM_{2.5}$, produced largely by vehicles in urban areas, contribute to poor roadside air quality in this dense and compact city. In particular, these particles can cause cardiovascular and pulmonary health problems.

To measure and assess Hong Kong's air quality, the Environmental Protection Department uses an Air Quality Monitoring System (AQMS) network that, to date, consists of 16 fixed stations – 13 general stations and three roadside stations – spread around the city. While this network is important in broadly monitoring air pollutant concentrations across the territory, it is not set up to measure individual exposure to air pollution.

In order to better understand the state of air quality in Hong Kong through a personal exposure perspective, Civic Exchange has worked on this Study since mid-2015, in collaboration with the City University of Hong Kong. This Study measured individuals' exposure to $PM_{2.5}$ with small sensors: 73 volunteers were outfitted with personal exposure kits (PEK) the size of a lunch box, and their exposure levels to $PM_{2.5}$ concentrations were monitored over a four-day period, including the weekend. Daily activities such as commuting, working and resting were also logged. This is the first study of its kind and scale in Hong Kong.

This study used volunteers from a shared office environment, which was shown to be relatively clean. Still, exposure profiles varied greatly between individuals due to different home locations, commuting patterns, and personal lifestyles, including weekend behaviours. It is clear that home environments make a particularly large contribution to Personal Integrated Exposure (PIE), given the amount of time spent there: over half the volunteers' time was spent in their homes. Our results show that $PM_{2.5}$ concentrations in homes – as in other indoor (non-office) venues – varied significantly between individuals. This could be due to cooking, smoking, high level of localized air pollution entering through open windows, or other unknown sources. Since people spent such a significant amount of time at home (including up to 81% of their weekends), Indoor Air Quality (IAQ) should become a focal point for future research and policy development. Measurement, standardization and institutionalization are several possible measures that the government could start with to improve people's awareness towards IAQ.

More worryingly, $PM_{2.5}$ measurements collected by the volunteers were generally much higher than those taken at the nearest official air quality monitoring station, with readings showing both a much higher 24-hour mean concentration and a wider range of exposure. This indicates that people may commonly be exposed to $PM_{2.5}$ concentrations in their daily environments that are higher than suggested by the monitoring stations – the main point of reference for residents and health authorities alike. If this is true of the wider population, we may be significantly underestimating the true exposure risk to the local population.

While the volunteers spent relatively little time commuting, their exposure to high levels of $PM_{2.5}$ during that time is still a major concern. Our findings show that average $PM_{2.5}$ concentrations while commuting were always over 40 $\mu g/m^3$, which – although within Hong Kong's own Air Quality Objectives – is well above the healthy limits set by the World Health Organization of 25 $\mu g/m^3$. Pedestrians in particular were consistently exposed to almost double this limit (49.7 $\mu g/m^3$), which was higher than users of other modes of transport.

There is a clear need for data customized to the need of individuals (such as time and location specific information), particularly if the government is determined to promote walking as a short-distance means of transportation in Hong Kong. Stakeholders currently use air quality data from a monitoring station located in the same or a neighbouring district as a reference point for general exposure, yet the network is evidently not able to assess this with any degree of accuracy. The only way to provide such information at a reasonable price and with acceptable quality assurance would be to further explore the use of small sensors to complement the government's AQMS data. Tracking a representative sample of people's exposure and daily activity profiles would improve overall understanding of residents' changing exposure risk and its connection with location-specific factors, which will in turn help identify more targeted mitigation measures to reduce exposure risks and protect public health.

1 Introduction

1.1. Background

Hong Kong is a densely populated city, characterized by compact urban development with mixed land use and tall buildings. One advantage of a compact city is the high level of efficiency and mobility near transport nodes, such as railway stations, which are planned for high densities of people and activities. However, compactness also has trade-offs, like poor roadside air quality and traffic noise. In particular, roadside air quality is a long-standing issue and is widely considered as one of the key environmental problems in Hong Kong. In densely populated districts, hundreds of thousands of pedestrians are regularly exposed to toxic air pollutants in high concentrations that are undermining people's health and well-being on a daily basis.

Epidemiological studies around the world have demonstrated the association between exposure to air pollution and increased mortality. Airborne particulate matter (PM) is a key driver of health outcomes with fine particles ($PM_{2.5}$) especially relevant to cardiovascular effects. These particles, which are 2.5 microns or less in width, can be inhaled deeply into the respiratory tract, reaching the lungs. Air pollutants generated by traffic are greatly increased in urban areas with dense road networks, high traffic volume and high-rise buildings trapping pollutants inside street canyons. The complexity of air pollutants and the heterogeneity of its distribution make it difficult to fully characterize and track population exposure in urban areas. While the current air quality monitoring system (AQMS) managed by the Hong Kong Environmental Protection Department (HKEPD) is useful and important in regularly collecting air quality data at selected locations, there are far too few stations in the network and they spread out thinly in Hong Kong's urban terrain. Members of the general public may take the air quality data collected at a monitoring station located in the same district or a neighbouring station as a reference point. However, the network is not designed to inform individuals about their personal exposure to air pollution at specific locations.

In this respect, new monitoring techniques using small sensors have shown great promise in playing a complementary role to the fixed, large-scale monitoring network, and working in dense and complex urban environments with both temporal and spatial coverage at high resolution. They can be operated at a fraction of the cost of the conventional devices and can easily record the locations where people live, work or simply enjoy their time outdoors. The data obtained from new monitoring techniques can be combined with conventional monitoring data to provide the information needed for improving our knowledge about urban dwellers' exposure to air pollution.

1.2. Objectives of the study

In Hong Kong, residents are typically exposed to air pollution in five different micro-environments everyday: (a) indoor environment at home; (b) indoor environment in transportation mode(s); (c) indoor environment in the work place; (d) other indoor environments, and (e) outdoor environment on the streets. However, the exposure profile of one person will be quite different from another due to their different home and workplace locations, commuting patterns, and personal lifestyle. Tracking different people's exposure and daily activity profiles will improve the overall understanding of people's changing exposure risk and its connection with location-specific factors, which will in turn help identify targeted mitigation measures to reduce personal exposure risk and to protect public health.

To this end, this pilot Study aims to measure and analyze people's exposure to $PM_{2.5}$ in Hong Kong, with the following objectives:

(a) With the help of volunteer staff, to collect daily exposure data of individuals to $PM_{2.5}$ concentrations with the use of next generation sensors;
(b) To collect volunteers' daily activity data; and
(c) To analyze and characterize exposure profile of the volunteers, with the help of exposure data and time-activity information.

1.3. Report structure and companion readings

This final report is structured into four chapters. After this introductory Chapter 1, Chapter 2 will describe the study design and methodology, as well as the small sensors. Key findings of the Study will be explained and discussed in Chapter 3. Finally in Chapter 4, policy recommendations will be provided.

For readers who are interested in additional information related to this Study, please refer to the two companion readings below:

Technical report prepared by the City University of Hong Kong (CityU):

Personal Exposure Assessment in Urban Living: A Study of Hong Kong Air Pollution

Policy brief prepared by Civic Exchange:

What's in the Air We Breathe Everyday? Assessing Personal Exposure to $PM_{2.5}$ in Urban Living – A Case Study on Morgan Stanley Volunteers

2 Study Design

2.1. Methodology

Eight sets of high-precision $PM_{2.5}$ sensors were installed inside wearable, personal exposure kits (PEK) designed and assembled by the CityU team. Volunteers from Morgan Stanley, a global investment banking institution with its Asia-Pacific headquarters in Hong Kong, were recruited and trained to operate the PEK and to collect real time air quality exposure data. Each volunteer carried the PEK around the clock for four days. Measurements were stored in the PEK and were simultaneously transmitted to a server at CityU. At the end of each data collection cycle, the PEKs were returned to the CityU team for maintenance and calibration, and were then passed onto the next group of volunteers for the next cycle.

During each data collection cycle, volunteers also submitted time, locational and activities data, via a web-based platform or activity log sheets. This time-activity information was used to supplement air quality information for data analyses.

2.2. Personal Exposure Kit (PEK) Specifications

$PM_{2.5}$ concentrations were measured by the PEK, which is a mini Pelican box housing an OPC-N2 air sensor, a data collection system, and batteries (Figure 1). In addition, a compact temperature and relative humidity sensor was installed in the PEK, together with a light sensor, sound sensor and motion sensor. A Sim900a GPRS module connected to an antenna was included for real time wireless data transmission to the cloud server, at a time resolution of 10 seconds. A micro-SD card was also installed for data storage as a backup in case of telemetry failure. A QR code label was attached on the front cover, which was used for time activity data recording. The size of the PEK, weighing about 1.5 kg, is comparable to that of a typical lunch box. The PEK was designed for 8-hour operation on internal battery power, and can be operated / re-charged with an external charger.

2.3. Time-activity Reporting

All time-activity information reported by the participants were categorized into five main microenvironments, including office, home, commuting, indoor activities (other than home and office), and outdoor activities. For commuting, participants were asked to report transport mode(s) they used from seven predefined categories, which include railway, bus, minibus, ferry, taxi, walking and others. Indoor activities were classified into eating, entertainment, exercising, shopping, cinema/theatre, and others. Outdoor activities consisted of eating, entertainment, exercising, shopping, enjoying public space (such as parks), and others. The start and end times of all activities were recorded with a 10-minute resolution. The motion, sound and light sensors provide supplementary information to determine and improve the accuracy of time-activity reporting.

Figure 1. An anatomy of the personal exposure kit

1. Sim900a GPRS module
2. Antenna
3. Temperature & relative humidity sensor
4. $PM_{2.5}$ sensor
5. Light sensor
6. QR code

2.4. Data Collection Cycles

Data collection was carried out from 12 December 2015 to 3 May 2016. A total of 73 volunteers were involved over a 12-week period. For each cycle, the PEKs were delivered to individual volunteers on Thursday at noon, and were collected at noon on the following Monday, both in their workplaces.

Each volunteer carried the PEK with him/her during the entire four-day data collection period. The PEK was re-charged during sedentary periods at home or in the office. Each volunteer was also required to track his/her daily activities by entering a new record when their microenvironment or activity changed.

Real-time data was transmitted to the cloud server throughout the sampling period, and the data was inspected and validated every day by the CityU team. Volunteers would receive a reminder when their data transmission paused for 30 minutes or more. At the end of each data collection cycle, a questionnaire was given to each volunteer to survey their living environment, household ventilation condition, smoking habits within the household, and a brief description of their daily routine. After the 12-week period, there were a total of 61 successful data sets with complete and valid air pollutant concentrations and time-activity information. Other samples were unsuccessful mainly due to malfunctioning of the PEK, and/or incomplete collection of pollutant data or entry of time-activity information.

2.5. Calibration and Correction

Time synchronization and calibration were performed on each PEK prior to delivery to the volunteers. A side-by-side comparison test between each $PM_{2.5}$ sensor and a factory calibrated $PM_{2.5}$ monitor was performed before and after each sampling cycle, in order to provide an accurate measurement of the $PM_{2.5}$ mass concentration.

In order to minimize the effect of relative humidity on the light scattering PM sensor, a correction factor was applied to all the raw data collected (Ning, et al, 2017).

3 Key Findings

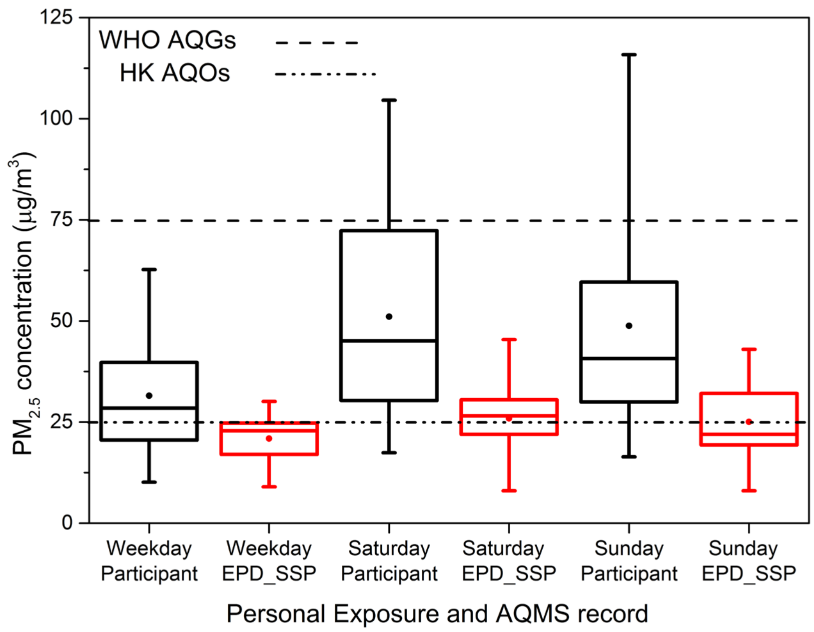
3.1. Personal exposure to $PM_{2.5}$ exceeded WHO guidelines

The majority of participants in the study were exposed to 24-hour mean $PM_{2.5}$ concentrations that met Hong Kong Air Quality Objectives (HKAQO) during weekdays, with less than 1% exceeding the AQO upper bound of 75 μg/m3. By contrast, at weekends this proportion rose to 10%.

Hong Kong's AQO targets are, however, three times higher than those set by the World Health Organization's Air Quality Guidelines (WHO AQG). Only about 40% of participants' readings were within this guideline, meaning that 60% of volunteers experienced daily integrated concentrations above the WHO's recommended limit of 25 μg/m3. At weekends this rose to over 80% of volunteers exceeding the WHO guideline limits. (Only 19% and 16% remained within the AQG on Saturdays and Sundays respectively).

Figure 2 plots the volunteers' 24-hour mean $PM_{2.5}$ concentration exposure on weekdays and weekends with the corresponding HKAQO and the WHO AQG. The box defines the 25^{th}, 50^{th}, and 75^{th} percentiles, with the whiskers defining the extent of the 5^{th} to the 95^{th} percentiles, whereas the mean for each data set is plotted as a dot.

Figure 2. Boxplot of 24-hour $PM_{2.5}$ concentration on weekdays and weekends, relative to HKAQO and WHO AQG.

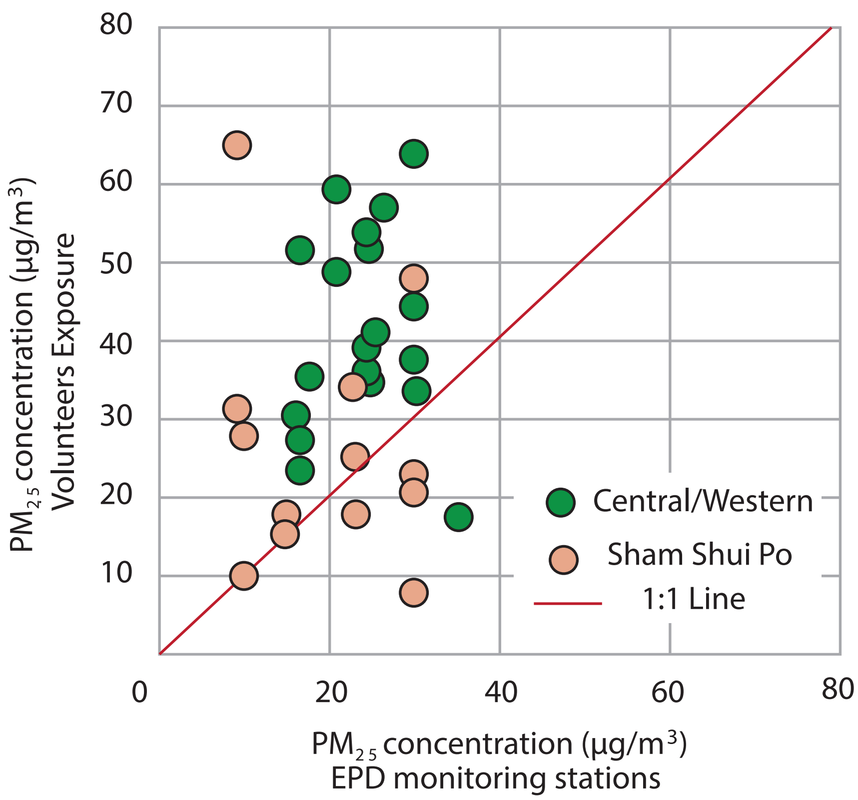


3.2. Actual personal exposure is generally higher than what official monitors show

Figure 2 also demonstrates that the $PM_{2.5}$ measurements recorded by the volunteers were in general much higher than those recorded by the nearest air quality monitoring station ("EPD_SSP", being the Sham Shui Po station closest to the volunteers' office in Yau Tsim Mong) over the same periods. $PM_{2.5}$ concentrations measured at the monitoring station are plotted in red as a reference, with the volunteer readings showing both a much higher 24-hour mean concentration and a wider range, especially towards the upper end. This indicates that people were actually exposed to very different $PM_{2.5}$ concentrations in their day-to-day urban environments than those suggested by the most common nearest monitoring station.

To verify this discrepancy, further analysis was performed for volunteers who also live in the Central/Western District, which has another district-level measuring station. Figure 3 plots the correlation between the volunteers' exposure data for each location and the air quality monitoring stations' data for the same time periods. The plot shows no statistically significant correlation between the PEK data collected by the volunteers and the concentrations recorded by the Hong Kong Environmental Protection Department's AQMS for the same area.

Figure 3. A correlation plot of volunteer exposure to $PM_{2.5}$ against measurements from air quality monitoring stations.



Put simply, one cannot reliably use AQMS data as a surrogate for personal exposure. This may seem self-evident due to the positioning and distribution of the monitoring network. However, since this is the only regularly tracked data source for such information it indicates a serious gap in our ability to assess residents' true exposure and a risk that we may be materially underestimating the extent of our exposure given current methodologies.

3.3. Time spent indoors vs. outdoors may significantly alter exposure and reduce the relevance of current monitoring

Given the variety of microenvironments which individuals regularly visit, inputs towards their Personal Integrated Exposure (PIE) can be assessed by factoring in pollutant concentration and the amount of time spent in different microenvironments.

During this study, the office worker volunteers spent more than 85% of their time indoors, including in offices, homes, and public venues. The largest proportion of this time was spent at home, accounting for 42% of their time during weekdays and 81% during weekends (Figures 4 and 5). Commuting and time outdoors, while representing the only area in which exposure is currently tracked by AQMS, formed only 15% of the volunteers' weekday time and even less (10%) at weekends. As a result, even improvements in the accuracy and localisation of AQMS data will not truly reflect the major microenvironmental factors influencing an individual's exposure and risk.

Figure 4. Time allocation and contribution to personal integrated exposure (PIE) of $PM_{2.5}$ on weekdays

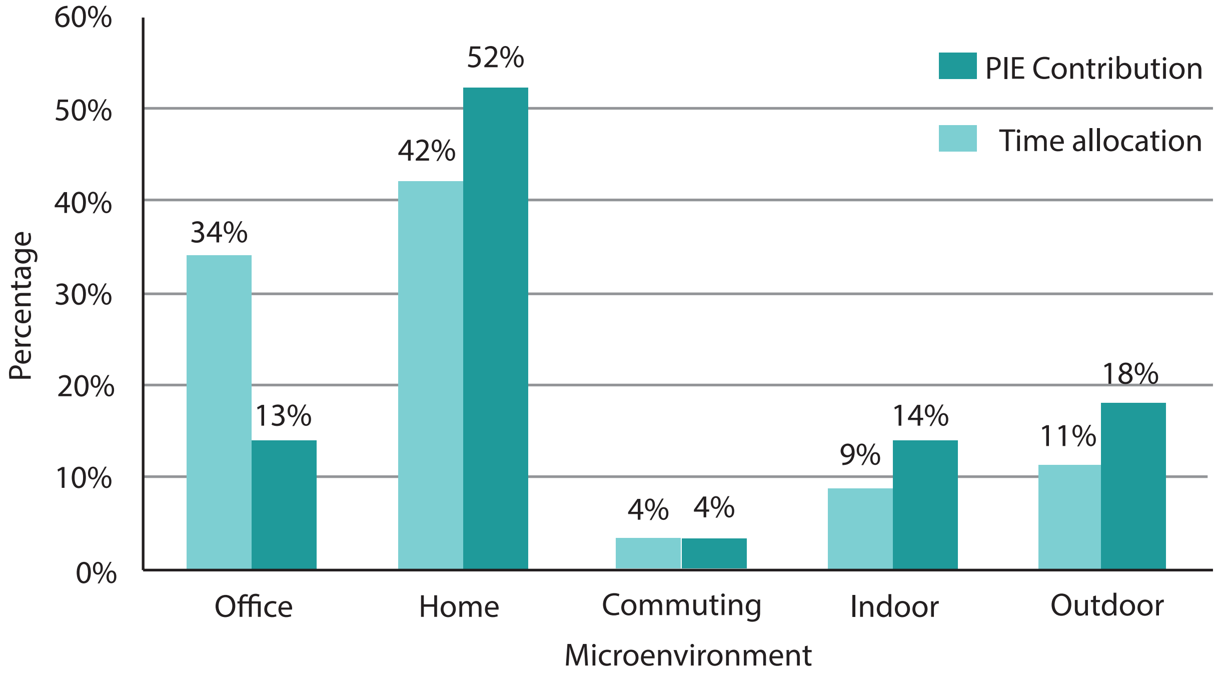
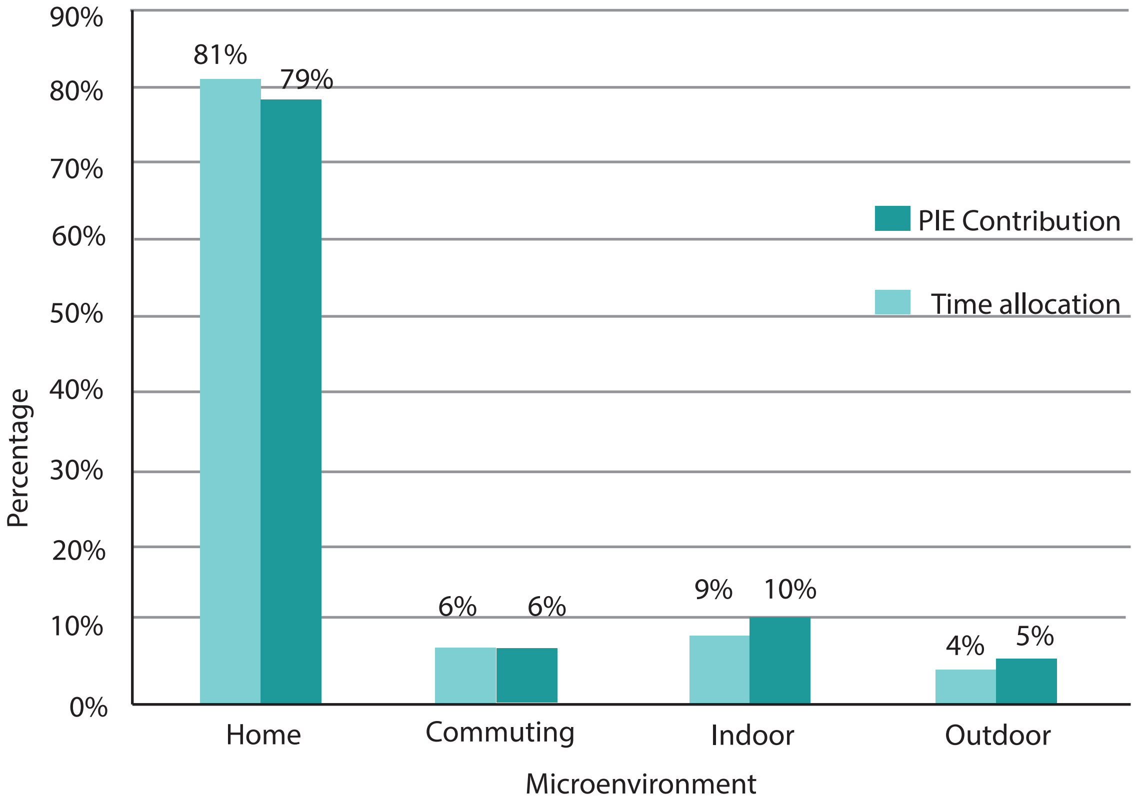


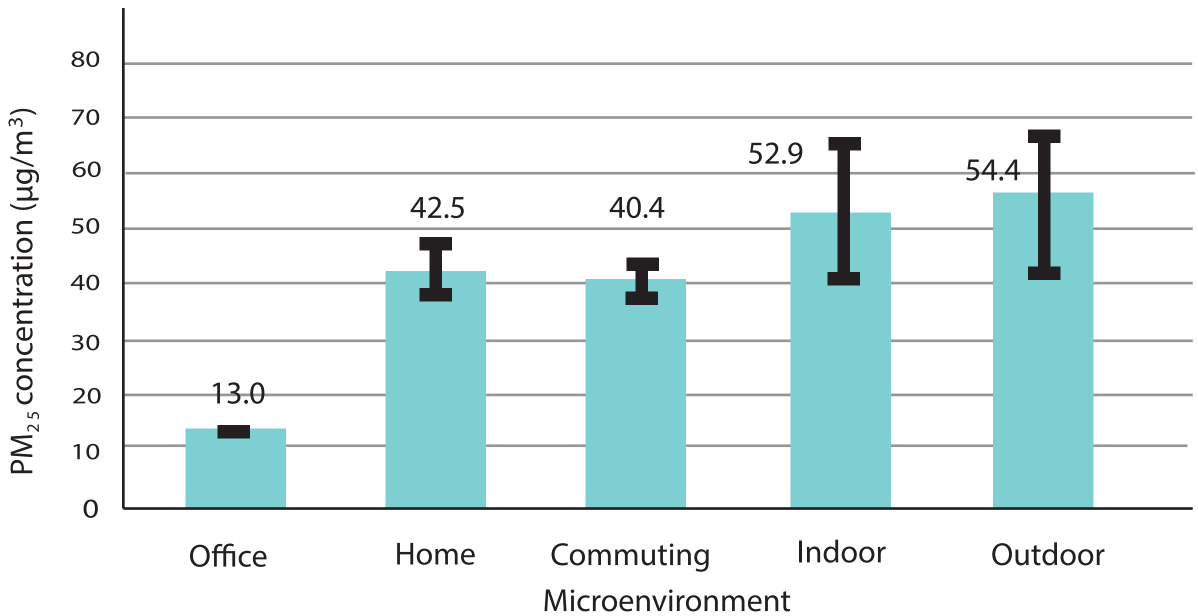
Figure 5. Time allocation and contribution to personal integrated exposure (PIE) of $PM_{2.5}$ on weekends



3.4. Personal exposure to $PM_{2.5}$: Differences in exposure by microenvironment from a major contributing factor to individual exposure

Weekday measurements indicated that the home environment contributed 52% of volunteers' PIE even though only 42% of time was spent there, showing a disproportionately large contribution. By contrast, 34% of weekday time was spent in the office environment, but its contribution to PIE was only 13%.

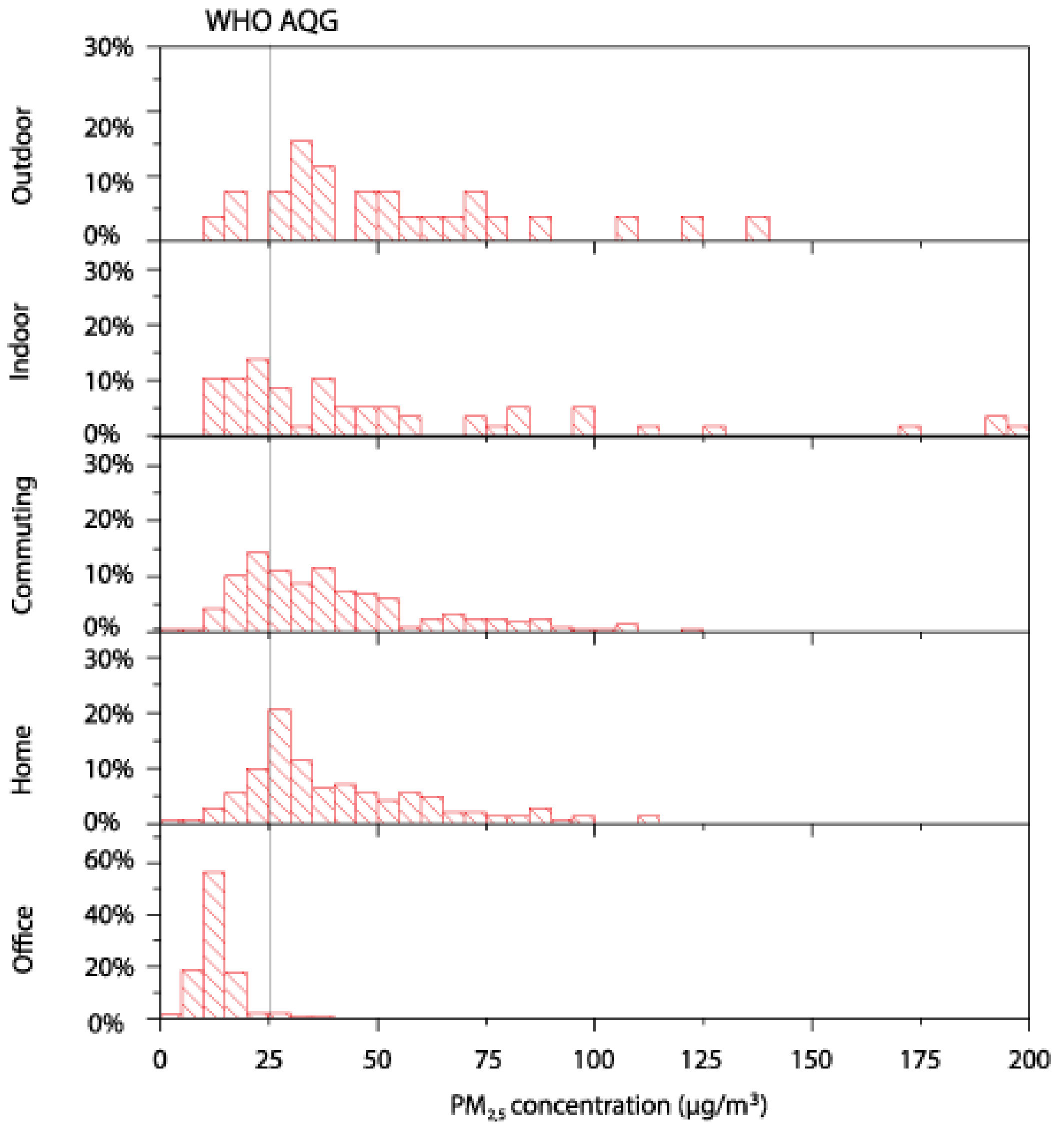
Figure 6. Mean $PM_{2.5}$ concentration by microenvironment on weekdays (the error bar defines the 95% confidence interval)



Mean $PM_{2.5}$ concentration in the office on weekdays was 13.0 μg/m^3, significantly lower than the other four microenvironments measured which ranged from 40.4 μg/m^3 for commuting to 54.4 μg/m^3 outdoors (Figure 6). Concentrations at home were on average three times higher than in the office, and in fact higher than while commuting.

The majority of office measurements fell below the 24-hour average concentration of 25 μg/m^3 suggested by the WHO AQG, likely as a result of an effective ventilation and air conditioning system in this particular workplace (since all participants shared the same employer). A large proportion of $PM_{2.5}$ measurements in other settings were higher than the WHO guideline (Figure 7). Some outdoor environment readings were as high as 140 μg/m^3 and in other indoor environments (excluding home and office) approached

Figure 7. $PM_{2.5}$ concentration distribution by microenvironments on weekdays



200 μg/m^3, significantly above both the WHO AQG and the Hong Kong AQO (75 μg/m^3). Individuals' time in these environments will therefore have a disproportionate contribution towards their PIE and exposure risk.

During weekends, the office became a largely irrelevant microenvironment (over the 12-week sample period, only one volunteer went back to the office during the weekend). Mean $PM_{2.5}$ concentrations were about 50 µg/m^3 and therefore similar to the weekday figure. Over 80 per cent of weekend $PM_{2.5}$ measurements exceeded the 25 µg/m^3 24-hour guideline. Given that over 80 per cent of weekend time was also spent at home, this reinforces the contribution of this particular microenvironment towards overall PIE.

3.5. Personal exposure to $PM_{2.5}$: impact of different transport modes

The main transport modes used by the volunteers during the sampling period were Mass Transit Railway (31%), walking (25%), bus (21%), taxi (12%), minibus (6%), and ferry (2%). According to Table 1, the highest mean $PM_{2.5}$ concentration was recorded on ferries (61.9 µg/m^3), followed by walking (49.7 µg/m^3) and minibus (46.8 µg/m^3).

Table 1. Mean $PM_{2.5}$ concentrations by mode of commuting

Commuting mode	Mean $PM_{2.5}$ concentrations (µg/m^3)
Ferry	61.9
Walking	49.7
Minibus	46.8
MTR	42.9
Taxi	41.6
Bus	40.9
Others	40.8

One reason for high $PM_{2.5}$ concentrations on ferries is that exhaust emitted from the diesel engines on board can easily enter the passenger cabins and form swirling eddies behind the vessels. Even though ferries in Hong Kong are burning marine light diesel with sulphur content not exceeding 0.05%, the sulphur content is still higher than the diesel used by motor vehicles, which is 0.001% or lower.

The high $PM_{2.5}$ concentrations pedestrians are exposed to are easy to understand, as people walking on the streets are directly exposed to air pollutants directly emitted from vehicle tailpipes. In locations where dispersion conditions are unfavourable due to tall buildings and the lack of wind corridors, air quality will be even worse and will remain so for a long period of time.

4 Recommendations

4.1. Complementing the existing AQMS with personal exposure measurements

People's exposure to air pollution arising from diverse activities and changing indoor and outdoor environments over the course of a day cannot be represented by the AQMS data gathered at stationary locations. To support the AQMS, it is recommended that HKEPD should collaborate with universities and other research institutions to deploy technologically-proven devices, such as next-generation sensor-based systems and portable measurement systems, to track pedestrian exposure to air pollution at various locations on a regular basis. With more data, the government will be able to identified "exposure hotspots" in the city, and then implement effective mitigation measures, such as ventilation modification and traffic management schemes, to reduce people's exposure and the associated health risks.

Personalized air quality information, especially in offices and homes, may provide information for individuals to understand their exposure to air pollution and the health implications. The government may assist interested parties in installing air quality monitoring devices in their offices and homes for the sake of education and awareness building. New monitoring techniques using small sensors – as applied in this study – have shown great promise in playing a complementary role to the fixed monitoring network, especially in dense and complex urban environments with both temporal and spatial coverage at high resolution. They can be operated at a fraction of the cost of the conventional devices and can easily record the locations where people live, work or simply enjoy their time outdoors. The data obtained from the new monitoring techniques can be combined with conventional monitoring data to provide the information needed for improving our knowledge about urban dwellers' exposure to air pollution.

This study, which represents a first attempt to characterize the air pollution exposure profiles for Hong Kong people, includes important observations and findings. However, it is still a pilot-scale investigation, so there is room for improvement. For example, the size and the weight of the PEK could be further reduced, making it more user friendly to the volunteers. The number of samples should also be scaled up for more representative results and for better understanding of the subject.

4.2. Bringing current HKAQO closer to WHO AQG standards

Hong Kong has not fully fulfilled the updated 2014 HKAQOs, even though it already uses a less stringent standard than the WHO. For example, concentrations of $PM_{2.5}$ recorded at the Causeway Bay roadside station exceeded both the 24-hour limit (75µg/m^3) and the annual limit (35µg/m^3) in 2015, imposing a potential health risks to residents and pedestrians.

If HKAQO are loose, it may create a misperception that compliance would mean clean and healthy air, even though the same air quality would be seen as having negative health consequences, when measured by the WHO AQG. The Hong Kong government should take a more proactive attitude during the current HKAQO review and further tighten AQOs for the sake of health protection.

4.3. Expanding air quality programmes to homes and other indoor environments

The government has put strong emphasis on offices and public places in terms of Indoor Air Quality (IAQ) management over the past decade. A voluntary IAQ Certification Scheme was launched in 2003, which aims to recognize good IAQ management practices, and to provide incentives for property owners and managers to pursue the best level of IAQ.

But there has been insufficient effort in promoting IAQ at home, where the contribution to Personal Integrated Exposure (PIE) is the highest according to this study. The government should, for the sake of protecting public health, inform and educate people about the importance of IAQ at home. Apart from implementing the voluntary IAQ Certification Scheme for Offices and Public Places, a comprehensive IAQ management programme should be developed exclusively for homes as well. A special task force should be formed by HKEPD to take up the responsibility of promoting household IAQ, through talks and roadshows to residents, owners' corporations and different communities.

In May 2017, the Environmental Protection Department launched a series of YouTube videos called “Clean Air and You” in Cantonese, Putonghua and English – some of which addressed indoor pollution. This should be seen as a good first step in larger engagement.

Using both mass media like TV and online social media, the government should launch a comprehensive campaign on IAQ. This would inform the general public on the sources and corresponding mitigation measures of household air pollutants emitted from cooking, smoking, cleaning agents, furniture, or even pets and plants. It is important to educate the public on their daily habits, which can help prevent household air pollution, such as regularly cleaning up the ventilation system and keeping the dwelling dry and clean. To further reduce household $PM_{2.5}$ concentrations as well as the overall PIE level, the public should know exactly where they can consult IAQ service providers for professional assessment and advice. All these require substantial efforts from the task force to spread the message to the public.

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