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Mapping the Vertical Distribution of Population and Particulate Air Pollution in a Near-Highway Urban Neighborhood: Implications for Exposure Assessment

Chih-Da Wu^{1,*}, Piers MacNaughton¹, Steve Melly¹, Kevin Lane², Gary Adamkiewicz¹, John L. Durant³, Doug Brugge⁴, and John D. Spengler¹

¹Exposure, Epidemiology & Risk Program, Department of Environmental Health, Harvard School of Public Health, Boston, MA, USA

²Department of Environmental Health, Boston University School of Public Health, Boston, MA, USA

³Department of Civil and Environmental Engineering, School of Engineering, Tufts University, Medford, MA, USA

⁴Department of Public Health and Community Medicine, School of Medicine, Tufts University, Boston, MA, USA

Abstract

Due to data collection challenges, the vertical variation in population in cities and particulate air pollution are typically not accounted for in exposure assessments, which may lead to misclassification of exposures based on elevation of residency. To better assess this misclassification, the vertical distribution of the potentially highly exposed population (PHEP), defined as all residents within the 100-m buffer zone of above-ground highways or the 200-m buffer zone of a highway-tunnel exit, was estimated for four floor categories in Boston's Chinatown (MA, USA) using the three-dimensional digital geography (3DIG) methodology. Vertical profiles of particle number concentration (7–1000 nm; PNC) and PM_{2.5} mass concentration were measured by hoisting instruments up the vertical face of an 11-story (35-m) building near the study area throughout the day on multiple days. The concentrations from all the profiles (n=23) were averaged together for each floor category. As measurement elevation increased from 0 to 35 m PNC decreased by 7.7%, compared to 3.6% for PM_{2.5}. PHEP was multiplied by the average PNC for each floor category to assess exposures for near-highway populations. The results show that adding temporally-averaged vertical air pollution data had a small effect on residential ambient exposures for our study population; however, greater effects were observed when individual days were considered (e.g., winds were off the highways).

*Correspondence to: Chih-Da Wu, Landmark 406 West, 401 Park Drive, Boston, MA 02215, Tel: 617-384-8816. Fax: 617-384-8819. wu@hsph.harvard.edu.

Conflict of interest

The authors declare no conflict of interest.

Keywords

exposure assessment; near-highway pollution; 3-D digital geography (3DIG); three-dimensional population estimation; particulate matter (PM)

Introduction

Epidemiological studies have linked airborne particulate matter (PM) exposure to adverse health effects (Dockery, 1993; Dockery, 2007; Laden, 2006). Recently, studies have begun to show that populations living near busy roadways may be at greater risk due to higher exposures, especially to ultrafine particles (UFP; $<100\text{ }\mu\text{m}$ in aerodynamic diameter) (Brugge et al., 2007; Hoffmann et al., 2007). Previous investigations have measured pollutant distance-decay gradients along both horizontal and vertical transects perpendicular to major roadways (Karner et al., 2010; Keogh and Sonntag, 2011; Zhu et al., 2004). Keogh and Sonntag (2011) found that the number concentrations of UFP generated by motor vehicle traffic are highest within 100 m of the emission source, and Karner et al. (2010) reported that, based on review of 37 studies, UFP levels generally decreased to urban background within 100 to 200 m of highways.

The distance-decay behavior of UFP is a function of transformation processes and mixing in both the vertical and horizontal directions. In comparison to $\text{PM}_{2.5}$, UFP have a much shorter residence time in the atmosphere. UFP tend to grow into larger particles through a combination of coagulation, which is when solid or liquid particles adhere to one another, and condensation, which is when gases condense onto preexisting solid particles (Kumar et al., 2010). These processes tend to reduce the PN concentrations but will increase the $\text{PM}_{2.5}$ concentration as condensing gases add to the mass of particles. Also, UFP and $\text{PM}_{2.5}$ are subject to different loss mechanisms. Dry deposition is important for UFP because Brownian diffusion is the primary transport mechanism for particles $<300\text{ nm}$. $\text{PM}_{2.5}$ particles are transported primarily by advection but also are still too small to settle rapidly. Therefore, their residence time is longer, on the scale of days to weeks. Wet deposition by rain or snow is an efficient removal mechanism for these particles (Kumar et al., 2011).

There is limited data on the vertical profiles of pollutants near roadways, particularly in urban settings. Zhu and Hinds (2004) measured vertical profiles of particle number concentration (PNC) and size distribution near Interstate 405 in Los Angeles and found that the highest total PNC occurred 3–7 m above the ground and decreased by 50% at the highest elevations monitored (17.7 m). In Taipei, Wu et al. (2002) also showed that the mass concentrations of PM_{10} , $\text{PM}_{2.5}$ and PM_1 (particulate matter ≤ 10 , 2.5 and $1\text{ }\mu\text{m}$ in aerodynamic diameter, respectively) decreased to about 60%, 62% and 80% at 79 m compared to the maximum at 2 m above the ground. These studies of vertical gradients focused solely on the pollutant, not on the exposed population.

In contrast, studies focusing on vertical distribution of population often do not include pollutant data. For example, in classifying the population in Tsukuba City, Japan, by the vertical distribution of residences, Lwin and Murayama (2009) used detailed governmental databases including the number of floors, height of buildings, and area of buildings. Wu and

Lung (2012) focused on the 3-D spatial distributions of potentially highly exposed populations under traffic impacts in Taipei. They developed a GIS-based methodology, called three-Dimensional Digital Geography (3DIG), to estimate the number of floors in each building and thereby better assess the population distribution horizontally and vertically. However, in these two studies no vertical air pollution data was collected. Thus, if there were substantial variation in the vertical distribution of traffic-related pollutants in cities with high-rise apartments, the assumption that concentration profiles do not decay with elevation would result in exposure misclassification and limit the ability to predict health outcomes. Such assumptions are standard in highway and roadway proximity studies.

In this study we applied 3DIG to determine the 3-D distributions of a population in close proximity to two interstate highways in the Chinatown neighborhood of Boston (MA, USA). In addition, we measured the vertical distribution of particle number concentration (PNC; 7–1000 nm) and mass concentration of PM_{2.5} with a fine spatial resolution (<1 m) and over a wide range of meteorological conditions. The objective of this work was to assess the vertical distribution of exposed populations and their relative potential exposures to air pollutants.

Materials and Methods

Study area

Chinatown is bordered by Interstate 93 (I-93) to the east and by residential and commercial areas in the north and west; it is divided north from south by Interstate 90 (I-90) (Figure 1) (Brugge and Leong, 2003). The area covers 0.49 km² and has a population density of ~13,000 persons/km², which is 2.7-times higher than the citywide average (U.S. Census Bureau, 2010). Housing in Chinatown includes numerous high-rise (15 floors) buildings; thus, many people in this area live or work many floors above ground level (Kim and Perkins, 2003).

I-93 runs underneath Boston in the Central Artery Tunnel and carries ~170,000 vehicles per day in three southbound and four northbound lanes. Southbound traffic emerges from the tunnel on the eastern edge of Chinatown (Perkins et al., 2013). The tunnel is vented passively through the tunnel exits; thus, high levels of traffic exhaust are released next to the Chinatown area. I-90 (~130,000 vehicles per day) is depressed 6 m below grade where it passes through Chinatown. Diesel trains, which move in and out of South Station on rail lines that parallel I-93 and I-90 (Figure 1), are another potential source of air pollution for Chinatown.

GIS Database

All spatial data layers and image files – including roads, highways, and census data – were obtained from MassGIS (<http://www.mass.gov/mgis>). The population of Chinatown was estimated using data from the 2010 census, and census blocks were used since they have the finest spatial resolution. There are 32 census blocks in Chinatown. USGS color ortho images (2008/2009) were obtained to represent land-use patterns in the study area. The 2011 Boston property parcel database (Assessing Department, City of Boston) was used to identify

residential areas and provide building type, number of floors and floor height. ArcGIS 9.3 and SAS 9.3 were used to analyze the data.

PM Measurements

Vertical profiles of PM were measured at the Pine Street Inn (PSI), which is located on the southern edge of the study area 100 m west of I-93 and 400 m south of I-90 (Figure 1). PSI was selected as the monitoring site because of its proximity to both highways and because it has an 11-story tower (about 35 m) connected to the main building. I-93 is approximately 12 m above grade where it passes PSI. The height of buildings in the vicinity of PSI is six stories (20 m). The tower extends an additional 15 m above the surrounding buildings.

Vertical profiles were measured using PM monitors that were raised and lowered along the outside of the tower in a customized case. The case was hooked to a cable that was fed through a pulley at the top of the tower and back down to a battery-powered winch at ground level. The pulley was secured to the crenellations on the 11th floor, 35 m above ground level. The case was raised and lowered at a constant velocity of 10 cm/s. The height of each measurement above ground level was based on the data-recording interval of each instrument and the start and end time of the profile, which took ~5 min to complete. The spatial resolution was ~10 cm for temperature, relative humidity, and PNC and ~1 m for PM_{2.5}. The data for PNC, temperature, and relative humidity were averaged to the nearest meter. The data collected on the way up was averaged with the data collected on the way back down, resulting in a single 10-minute profile with a spatial resolution of 1 m.

Vertical profiles were measured in the morning (09:00 to 11:00), afternoon (12:00 to 15:00), and evening (16:00 to 18:00) on seven Fridays from November 2011 to March 2012. During each monitoring session, profiles were collected once per hour for three or four hours. In total, at least two profiles were collected for each hour from 09:00 to 18:00 over the course of the monitoring campaign.

The monitoring case contained a condensation particle counter, a PM_{2.5} monitor, and a monitor for temperature and relative humidity (Table 1). The particle instruments received air from outside the box via 8 cm of conductive tubing. The temperature and relative humidity probes were clipped to the outside of the box. A handheld digital anemometer and compass were used to make wind speed and direction measurements on the roof of PSI during each profile, except from 20 January 2012 to 15 March 2012 when a stationary meteorological station located on the roof of the PSI was used (Table 1).

Quality Assurance

Quality assurance was primarily implemented in the field. Before each monitoring session, all the instruments were synchronized to the same time. The SidePak had a zero calibration that was conducted with the zero filter. Flow rates in the range of 1400–1600 mL/min for the SidePak and 500–700 mL/min for the CPC-3781 were required to proceed with monitoring. During data processing, data flagged with errors by the instrument were discarded.

Quality control experiments were also conducted. The CPC-3781 was compared to a newer CPC (TSI model 3783) and agreement was within 29% in the field and 7% in the laboratory.

The R^2 between the two instruments, which is a measure of how correlated the variations in PNC are, was 0.82. The particle instruments were exposed to a spike of PM to determine the response times of the instruments. For both the CPC and the SidePak the response times were ~ 1 s; thus, lag-time corrections were not implemented in the data processing.

The SidePak overestimates the $PM_{2.5}$ concentration compared to Federal Reference Method (FRM) $PM_{2.5}$ samplers. A linear regression between the FRM and SidePak concentrations produced the following correlation (Yanosky, 2002):

$$C_{FRM} = 0.33C_{SidePak} + 2.25 \quad (1)$$

This correlation was used to adjust the measured $PM_{2.5}$ concentrations

Vertical population distribution

In the property parcel database, building types were classified into 18 subclasses. Of these, apartments, condominiums and “residential lands” were classified as residential areas, and “mixed-use lands” were classified as commercial-residential areas. The first (ground) floors in the commercial-residential buildings are generally used for commerce while the upper floors for residences. Building floors were divided into four categories: **I** for residential floors one and two, **II** for residential floors three and four, **III** for residential floors five and six, and **IV** for all residential floors 7 and higher. The population on each floor category in a census block was calculated using Equation (1):

$$PC_j = \sum_{k=1}^{32} \frac{FL_{jk}}{F_k} \times P_k \quad (2)$$

where PC_j is the total population of floor category j , FL_{jk} is the number of floors in floor category j of census block k , F_k is the total number of floors of census block k . The ratio of FL_{jk} to F_k represents the percentage of a specific floor category in a census block. P_k is the total population of census block k . The results were then compared with the typical areametric approach (Bielecka et al., 2005), which consisted of calculating a weighting factor based on the ratio of surface area of residential buildings of each buffer zone to the total study area.

Parallel buffers of 50, 100, 150, 200 m were generated around the outside of interstate highway polygons for this study. The total number of floors and the population of each floor category within different buffer zones were calculated using zonal statistics in GIS. The northern part of I-93 in the study area is in a tunnel (Figure 1); however, most of the residential buildings in this area were located within 200 m of the tunnel exit. Previous studies (e.g., Frase et al., 2003) have demonstrated that tunnel exits are a significant source of PM. Therefore, we defined “Potentially Highly Exposed Population (PHEP)” as the number of residents living within either 100 m of a highway or 200 m of the tunnel exit or both. The PHEP of each floor category of each census block was then multiplied by the corresponding air pollutant concentration to assess exposures for near-highway populations.

Results

Vertical gradients of PM

Seven days of monitoring were performed yielding a total of 23 profiles for each pollutant: 1 day (3 profiles) in the early morning (06:30–08:00), 2 days (6 profiles) in the morning (09:00–11:00), 2 days (8 profiles) in the afternoon (12:00–15:00), and 2 days (6 profiles) in the evening (16:00–18:00). The profiles were averaged during each time period and plotted in Figure 2. The temperature profiles were generally close to neutral or slightly negative, the latter indicating weakly stable conditions. During these conditions, PNC decreased slightly with elevation.

The early morning profiles demonstrate the impact of atmospheric instability on PNC (Figure 2). The temperature profile indicates neutral conditions up to 20–25 m elevation giving way to unstable conditions higher up. PNC was well mixed below 20 m and then dropped off to 50% of the ground-level concentration at 35 m. In contrast, the PM_{2.5} concentration profiles showed very little vertical variation (Figure 2). On average, PM_{2.5} decreased by ~4% at 35 m compared to ground level while PNC decreased by ~8%. In addition, the slope of the PM_{2.5} variation with height was not statistically different from zero (P-value = 0.098), whereas the slope of PNC was significant (P-value < 0.0001).

Effect of Wind Direction on Particulate Matter

Wind direction strongly influenced both PNC and PM_{2.5} mass concentration at PSI (Figure 3). Winds were predominantly from the southwest to northwest with the exception of February 3, 2012, when they came from the north, and February 15, 2012, when they came from the east. The high concentrations in the evening profile (Figure 2) were largely driven by the February 15 measurements. PNC increased by a factor of two with north winds (possibly reflecting inputs from I-90 or the tunnel exit) and by a factor of four with east winds (possibly reflecting inputs from I-93) compared to days with west winds. PM_{2.5} increased four-fold with eastern winds but only showed a slight increase with northern winds. It should be noted that our results are likely biased due to the small number of monitoring days and total number of profiles. Other variables, such as atmospheric stability and pollutant source strength, which varied from hour to hour and day to day, may also have confounded the results. Despite the potential for biases and confounding, these data are useful for showing the viability of combining vertical monitoring with population distribution.

3-D distribution of potentially exposed population under highway impacts

The total area of residential buildings in Chinatown was 0.05 km², occupying 10% of the surface area. The population density in these residential areas was very high (~130,000 persons/km²) due to the large number of people living in high-rise apartments. The results indicate that 1,828 (28.9 %), 2,138 (33.7 %), 836 (13.2 %) and 1,535 (24.2 %) residents in Chinatown live in floor categories I, II, III, and IV, respectively. The vertical distribution of population in Chinatown is shown in Figure 4.

Populations within the specific buffer distances from highway traffic are shown in Table 2. The cumulative population estimates using 3DIG were 394 (6.2%), 1863 (29.4%), 2959 (46.7%), and 4099 (64.7%) for the 50-m, 100-m, 150-m, and 200-m highway buffer zones, respectively. The area-weighting approach, which considered only the footprint of residential areas, yielded consistently lower population estimates in all four buffer zones: 0.4% in the 50-m buffer, 2.7% in the 100-m buffer, 4.8% in the 150-m buffer, and 6.6% in the 200-m buffer. This method ignores the increased population density in areas such as buffer zones that contain high-rise residential buildings.

Vertical gradient at different floor categories

PNC and PM_{2.5} mass concentration for the four floor categories were estimated based on the vertical measurements at the PSI, which was within the 100-m buffer of I-93 (Table 3). For both PNC and PM_{2.5}, the pollution levels did not become statistically significantly different from the first floor category until the highest floor category. PM_{2.5} had a smaller standard deviation at the highest floor category, which resulted in a lower p-value despite a smaller relative decrease in concentration. Since PM_{2.5} varied little with height from 0–35 m, only the vertical distribution of PNC was considered for further analysis. Due to the lack of vertical measurements above the 11th floor, exposure estimates for residents on the 12th floor and higher (97 residents; 1.5% of total) were not calculated and were excluded from the PHEP. The first two floors appear to have the highest daytime exposure to PNC based on our vertical data.

A total of 2236 residents (about 35% of the population of Chinatown) were classified as PHEP and are potentially experiencing higher outdoor concentrations of PM, which may infiltrate indoors and increase human exposure. Their vertical distribution within the 100-m highway and 200-m tunnel exit buffer zones of was 794 (12.5%), 935 (14.7%), 283 (4.5%), and 224 (3.5%) residents for floors 1 and 2, floors 3 and 4, floors 5 and 6, and floors 7 to 11, respectively. The remainder of Chinatown residents (64.7%) lived in census blocks beyond the 100-m highway buffer and the 200-m tunnel exit buffer and were not included in the PHEP analysis.

Maps showing PHEP multiplied by PNC (residents $\times$ particles/cm³) in each of the four floor categories are presented in Figure 5. In the maps in the left column, the average of all vertical PNC profiles from Table 3 was used for the calculation. Maps in the right column show the results from only the NE wind profiles. The PNC for the NE wind profiles of the four floor categories is 57000/cm³ in floors 1 and 2, 55000/cm³ in floors 3 and 4, 55000/cm³ in floors 5 and 6, and 45000/cm³ in floors 7 to 11. Compared with the average profile maps (left side of Figure 5), some of the polygons in the maps generated from the NE wind profiles have undergone color change, suggesting that adding vertical air pollution data could help to better define exposures for near-highway populations during certain meteorological conditions.

Discussion

Our study developed a “Residents $\times$ Particles” methodology to account for the vertical distribution of exposed population and pollution for potential use in exposure assessment. In

areas where sharp decreases in PNC with elevation have been observed, assessing exposures based purely on the horizontal distance from a major roadway will result in misclassification: residents at higher elevations who are exposed to lower PNC levels will be classified in the same exposure category as residents below them. Compared to other studies looking at vertical profiles (e.g., Zhu and Hinds, 2005, Wu et al., 2002), which showed pronounced decrease in the PNC and $PM_{2.5}$ with elevation, our profiles were relatively uniform with elevation. Therefore, the 3DIG methodology suggests less misclassification in this study area than would be anticipated based on previous studies.

In general, buildings in cities lead to a more irregular flow field, resulting in greater mixing (Kumar et al., 2011). In addition, urban areas have increased mechanically-generated turbulence from vehicles, especially in close proximity to roadways. Therefore, more mixing and less pronounced concentration gradients will occur within the scale height of buildings in a city and greater dilution will occur aloft. Thus, ground-based measures of PNC may be reasonably accurate up to approximately six stories in Chinatown (Table 3). More research is needed using more monitoring periods throughout the year, multiple locations within the highway buffer and extending up to 20–30 stories to better assess the temporal and spatial variation of PM with elevation. In addition, increased monitoring will improve the statistical strength of pollution trends.

To help characterize the impact of using just one sampling location to determine the exposures across the whole buffer region, the PSI data were compared to PNC and $PM_{2.5}$ data collected at different locations in the Boston area (Figure 6). The data from Padró-Martínez et al. (2012), collected in neighborhoods west of I-93 in Somerville (4 km north of Chinatown) suggests that the concentrations are higher within 100 m of the highway. PSI is located 100 m from I-93 and therefore likely more similar to the 75–100-m buffers closer to the highway shown in Figure 6. PSI is more similar to the Harrison Avenue (25-025-0042) monitoring station in Roxbury, which is located 1,700 m west of I-93 and 2.5 km southwest of PSI. Although the Harrison Ave station is far from I-93, it is located next to a bus terminal, leading to higher concentrations and wide standard deviations in $PM_{2.5}$ (17.8 $\mu\text{g}/\text{m}^3$ compared to 5.01 $\mu\text{g}/\text{m}^3$ at PSI). These comparisons suggest that PSI data likely underestimate PNC and $PM_{2.5}$ mass concentration within the buffer region. In addition, the variation in PNC with distance from I-93 in Somerville shows that pollution within the buffer is not homogenous as assumed by this study.

Infiltration of ambient UFP is an important factor that affects the indoor exposure level. Fuller et al. (2013) characterized the differences between indoor and outdoor particle number concentration (PNC) in homes near to and far from I-93 in the same Somerville neighborhood studied by Padró-Martínez et al. (2012). Fuller et al. monitored indoor and outdoor PNC for 1–3 weeks at 18 homes located <1500 m from I-93. Their results suggest that PNC can readily enter the indoor environment in homes near a highway and in urban background neighborhoods. The median ratio of indoor to outdoor PNC was 0.95 (5th, 95th percentile: 0.42, 1.75). Use of air conditioning appeared to decrease indoor concentrations. Residential buildings in Chinatown tend to use central air conditioning more frequently than in Somerville, which may reduce the extent of infiltration compared to homes that do not use AC.

The results of this study were subject to several additional limitations in the data collection procedure. The 3-month sampling period during the winter that was used is not likely to be representative of annual conditions. The monitoring was conducted on Fridays, so the results cannot be generalized to other days of the week, particularly weekend days when traffic levels are lower. The daytime ambient concentration may be an inaccurate proxy of exposure since it does not reflect indoor pollution levels or the night-time exposure. For many residents the majority of time spent at home is at night.

Conclusion

This study developed a “Residents $\times$ Particles” method to improve exposure assessments by integrating the vertical distributions of population with vertical PM concentrations. The results showed that combining vertical air pollution data and population data by floor for near-highway populations may help to reduce exposure misclassification. More research along these lines is needed in additional locations and with more extensive air monitoring campaigns to determine the extent of misclassification due to neglecting the vertical distribution of population and pollution.

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Figure 1.

The location of the Chinatown study area (0.49 km², population density ~13,000 persons/km²) and the vertical air pollution monitoring site, Pine Street Inn (PSI). PSI was selected as the monitoring site because of its proximity to two highways and an 11-story high-rise building. Interstate 93 (I-93) borders the east side of Chinatown, and Interstate 90 (I-90) runs north-south through the study area. This area includes many high-rise (15 floors) buildings. The PM vertical profiles were collected at the PSI site, located 100m west of I-93 and 400m south of I-90.

Figure 2.

Daily variation in vertical profiles of PNC, $PM_{2.5}$ and temperature at PSI. The morning profiles are an average of 6 profiles collected hourly on 12/16/11 and 2/3/12 from 09:00 to 11:00; the afternoon profiles an average of 8 profiles collected on 12/9/11 and 1/20/12 from 12:00 to 15:00; and the evening profiles an average of 6 profiles collected on 11/18/11 and 2/15/12 from 16:00 to 18:00.

Figure 3.

Effect of wind direction on vertical profiles of PNC and PM_{2.5} at PSI. Profiles were collected weekly from November 2011 to March 2012 from 07:00 to 18:00 and averaged by wind direction. The legend shows what wind direction goes with each color. The numbers on the legend indicate the number of profiles collected during each wind condition.

Figure 4. Vertical distribution of population in the study area using 3DIG. The bar charts of each census block indicate the percentage of population in each floor category relative to the total population of each census block.

Figure 5.

PHEP multiplied by PNC (residents $\times$ p/cm³) of the four floor categories. Maps in the left and right columns show the results from the average of PNC profiles of each floor category and the NE wind profiles, respectively. The average of PNC profiles of each floor category is 41000/cm³ in floors 1 and 2, 40000/cm³ in floors 3 and 4, 40000/cm³ in floors 5 and 6, and 37000/cm³ in floors 7 to 11. The PNC of the NE wind profiles of the four floor categories is 57000/cm³ in floors 1 and 2, 55000/cm³ in floors 3 and 4, 55000/cm³ in floors 5 and 6, and 45000/cm³ in floors 7 to 11. White represents land that is not zoned for residential use or blocks that are out of the 100 m buffer zone to highways and 200 m buffer zone to tunnel exit.

Figure 6.

Comparison of PSI data (this study) to daytime, weekday PNC and PM_{2.5} data collected from November to March at two sites near I-93: Harrison Avenue (in Roxbury) and Somerville. Somerville data was collected 3 m above ground-level from 2009 to 2010 as described in Padro-Martinez et al., 2012. Harrison Avenue data was collected 6 m above ground at MassDEP site 25-025-0042 in Dudley Square, Boston, from 2012 to 2013.

Table 1

Instruments used for data collection in this study.

Instrument	Model	Output	Data Recording Interval (s)
Pulley System			
Condensation Particle Counter	TSI 3781	7–1000 nm Particle Count ($\#/cm^3$, $\pm 10\%$)	1
SidePak Aerosol Monitor	TSI AM51	$<2.5 \mu m$ PM Concentration (mg/m^3)	10 (moving average)
HOBO Temperature and Relative Humidity Probe	HOBO U12-011	Temperature ($^{\circ}C$) and Relative Humidity (%)	1
Turbometer	271	Wind Speed and Direction	NA
Defender 500 Series	BIOS 510-H	Flow Rate (mL/min , $\pm 1\%$)	NA
Stationary Monitor			
Condensation Particle Counter	TSI 3783	7–3000 nm Particle Count ($\#/cm^3$, $\pm 10\%$)	60 (moving average)
Davis Instruments Vantage Vue Sensor	Davis 6357	Temperature, Wind Speed and Wind Direction	1800

Table 2

Vertical distribution of population in four floor categories within different highway buffer zones.

Buffer	Residential floor category					Sum
	I (1F and 2F)	II (3F and 4F)	III (5F and 6F)	VI (7F and up)		
50m	93(1.50%)	102(1.60%)	44(0.70%)	155(2.50%)		394(6.20%)
100m	640(10.10%)	679(10.70%)	224(3.50%)	321(5.10%)		1863(29.40%)
150m	1017(16.10%)	1120(17.70%)	387(6.10%)	434(6.80%)		2959(46.70%)
200m	1286(20.30%)	1445(22.80%)	556(8.80%)	812(12.80%)		4099(64.70%)

Number in the parentheses indicates the percentage of the total population in Chinatown.

Table 3

Descriptive statistics of PNC (#/cm³) and PM_{2.5} (µg/m³) for each of the four floor categories based on 23 vertical profiles measured on 7 days.

Floor Category	Elevation (m)	PNC			PM _{2.5}		
		PNC	St. Dev.	P-value ¹	PM _{2.5}	St. Dev.	P-value
1F and 2F	0–5.5	41000	4600	NA	7.9	0.66	NA
3F and 4F	6.5–11.5	40000	4300	0.35	7.8	0.70	0.50
5F and 6F	12.5–16.5	40000	4300	0.12	7.8	0.75	0.17
7F and up	17.5–34.5	37000	6800	0.0084	7.5	0.66	0.00036

¹ One tailed p-values were calculated testing the hypothesis that the pollution levels were not lower for the upper floor categories compared to the first floor category. The profiles were standardized to an average pollution day based on the monitoring data to account for diurnal and daily variability in the magnitude of the profiles over the study period.