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Indoor and outdoor measurements of particle number concentration in near-highway homes

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Abstract

Exposure to high levels of traffic-generated particles may pose risks to human health; however, limited measurement has been conducted at homes near highways. The purpose of this study was to characterize differences between indoor and outdoor particle number concentration (PNC) in homes near to and distant from a highway and to identify factors that may affect infiltration. We monitored indoor and outdoor PNC (6–3000 nm) for 1–3 weeks at 18 homes located <1500 m from Interstate-93 (I-93) in Somerville, MA (USA). Median hourly indoor and outdoor PNC pooled over all homes were 5.2×10^3 and 5.9×10^3 particles/cm^3, respectively; the median ratio of indoor-to-outdoor PNC was 0.95 (5th/95th percentile: 0.42/1.75). Homes <100 m from I-93 ($n = 4$) had higher indoor and outdoor PNC compared with homes >1000 m away ($n = 3$). In regression models, a 10% increase in outdoor PNC was associated with an approximately equal (10.8%) increase in indoor PNC. Wind speed and direction, temperature, time of day and weekday were also associated with indoor PNC. Average mean indoor PNC was lower for homes with air

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CONFLICT OF INTEREST
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conditioners compared with homes without air conditioning. These results may have significance for estimating indoor, personal exposures to traffic-related air pollution.

Keywords

particles; near-highway; indoor; infiltration; residential; air conditioning

INTRODUCTION

Exposure to high levels of airborne particulate matter is associated with higher all-cause and cardio-pulmonary mortality, as well as incidence of lung cancer, asthma and a wide spectrum of cardiovascular diseases.[1–4] Although the association between exposure to fine particle mass concentration ($PM_{2.5}$; aerodynamic diameter <2.5 μm) and health effects is well established, fewer studies have focused on particle number concentration (PNC). Ultrafine particles (UFPs; aerodynamic diameter <0.1 μm) comprise over 80% (by number) of the particles in urban air, but are a negligible fraction of PM.[5] Past studies have shown associations between UFP and increased asthma symptoms, cardiovascular disease markers and decreased cognitive function.[6–10] UFP levels are elevated near highways and major roadways and may result in increased exposure for the estimated 30–45% of the urban US population that lives within 500 m of a major roadway.[11,12]

Most epidemiological studies of cardiovascular health effects of UFP do not account for infiltration of ambient UFP into residences when assessing exposure.[10,13–15] Because the US population spends most of its time indoors, use of ambient concentrations may lead to exposure misclassification and, hence, bias of the estimated impact of UFP.[16] For example, in the case of near-highway pollution, because indoor UFP levels may be lower than ambient measurements just outside the residence, use of ambient levels in exposure estimates may result in overestimation of exposure and a reduction in effect size. The majority of UFP infiltration research has involved unoccupied buildings or residents conducting scripted tasks.[17–20] Others have studied typical living conditions, but the homes studied were not near highways where outdoor UFP concentrations are typically elevated.[21–23] Overall, previous studies have shown that UFP can infiltrate homes, but questions concerning infiltration in homes near highways as well as the factors that modify infiltration remain unresolved.

The potential public health implications of near-highway UFP appear to be substantial; therefore, it is important to characterize infiltration under real-life conditions.[8] The purpose of this study was to (1) characterize differences between indoor and outdoor PNC (an approximate measure of UFP) in occupied homes near a highway; and (2) identify important environmental and behavioral factors that may affect infiltration.

METHODS

PNC Monitoring of Urban Residences

This project is part of the Community Assessment of Freeway Exposure and Health (CAFEH) study, a 5-year, cross-sectional, community-based participatory research study of near-highway air pollution and cardiovascular health in the Boston area. The central hypothesis of the study is that chronic exposure to UFP is associated with increases in blood markers of inflammation. The main highway of interest is Interstate-93 (I-93), an eight-lane highway with a traffic volume of approximately 1.5×10^5 vehicles per day. Traffic on I-93 is composed of >90% passenger vehicles, <7% light duty commercial vehicles and <3% heavy duty commercial vehicles.[24] Monitoring was conducted at homes in the eastern part of the city of Somerville, just north of Boston. Somerville covers 10.6 km^2 and has a population of 78,000, making it the most densely populated city in New England (7700 residents per km^2). The highway runs northwest to southeast and is elevated at several points along its approximately 4.4-km length through the city (Figure 1). Participants in the CAFEH study were selected from three recruitment areas based on distance from the highway: <100 m, 100–400 m and >1000 m. A subset of the participants ($n = 18$) was recruited for short-term (1–3 weeks) indoor/outdoor residential monitoring, including 4 homes located <100 m from the highway, 11 homes located 100–400 m from the highway and 3 homes located >1000 m of the highway (Figure 1).

Our sample of homes was selected to include variation in characteristics such as home type and air-conditioning use. We attempted to exclude homes with indoor smoking by recruiting non-smoking participants or participants that reported that they did not smoke at home. Monitoring was conducted from 26 April 2010 through 15 October 2010, during the spring, summer and fall seasons. The majority of homes studied were multi-family (of 2–3 apartments) units built between 1900 and 1949. A separate PNC monitor was deployed at each of two homes simultaneously, when possible. Monitors were placed at the level on which the participant lived, which could be either the first ($N = 10$), second ($N = 7$) or third ($N = 1$) floor of the building. The placement of the monitor within the home was limited by practical considerations—such as proximity to a window or access for maintenance—and varied between homes. All participants provided signed informed consent; the study was approved by the Institutional Review Board at the Tufts University School of Medicine.

Pollutant Measurement

Water-based condensation particle counters (WCPCs) (Model 3781; TSI, Shoreview, MN, USA) were used to measure PNC of particles in the 6–3000-nm size range. The WCPCs collected 1-min averaged PNC. Each WCPC was housed in a box that contained indoor and outdoor sampling lines of similar length (~ 2 m) made of stainless steel and flexible conductive Tygon tubing (<di>-inch diameter). In addition, a QTRAK (Model 1851; TSI) or a HOBO (Onset Computer Corporation, Pocasset, MA, USA) recorded temperature and humidity. The indoor line was located on the top of the box, and the outdoor line ran through a specially designed window guard that extended ~0.5 m from the side of the house. A solenoid valve switched the flow of air between the two lines at approximately 15-min intervals. The monitoring equipment was placed in the living room ($N = 15$) or bedroom ($N = 3$); monitoring was not done in the kitchen in an attempt to avoid particles generated by cooking. The flow rate was held constant at 0.12 l/min, and sampling instruments were checked for adequate flows and functioning at least twice for each home (at the start of monitoring and at each download). Hourly geometric means are reported based on ~30 min of data from indoor and outdoor sampling, respectively.

Meteorology

Ambient meteorology was recorded continuously throughout the 6-month study at a stationary site established on the roof of the Mystic Activity Center (MAC), a local community center in the Mystic View Housing Development (Figure 1).[25] The MAC was approximately 43m west of I-93, 18m west of Route-38 (Mystic Avenue) and 9m high. Meteorological measurements, including wind speed, wind direction, temperature and relative humidity, were recorded at 5-min intervals using a Vantage Pro2 weather station (Davis Instrument Corporation, Hayward, CA, USA). Wind direction data were collected according to the 16 cardinal wind directions (N, NNE, NE, etc.). Because the highway is oriented northwest to southeast, we created four categories encompassing winds from the west and east, and from the northwest and southeast parallel to the highway. We examined the effect of wind direction using these categories. All meteorological variables were averaged over each hour with the exception of wind direction, for which the hourly mode was used.

Home and Participant Information

Participants completed a questionnaire covering demographics, smoking, time-activity, air-conditioning type, number of windows, heating type and home age. In addition, each reported his/her typical use of air conditioning, seasonal frequency of window opening and how much the windows were opened. Data were also collected about residential characteristics, such as architectural style and age, the floor on which the monitoring took place, and room and orientation of the monitor to the highway and street. We did not collect time-resolved information on indoor activities such as cooking, cleaning or movement of people within the home. Homes were geocoded to parcel centroids and corrected visually using Orthophotos to assign the location to the center of the living space. Distance from I-93 was defined as the distance from the Orthophoto-corrected location to the edge of the nearest lane of travel of the highway, excluding ramps. Selected characteristics of the 18 residences are presented in Table 1, and their locations are shown in Figure 1. The median monitoring time was 14 days (range: 7–21 days), yielding a total of 4686 h of data, of which 4655 h had both indoor and outdoor measurements and were included in analyses. For the sampled residences, distance from I-93 ranged from 33 m to 1483 m (median: 152 m). Fourteen of the residences were multi-family homes, three were single-family homes and one was located in a low-rise apartment building. Fourteen of the residences were equipped with air conditioning: six with central air-conditioning and eight with window-mounted units. We did not collect systematic information on real-time use of air conditioning.

Data Processing and Analysis

WCPCs were cleaned in the laboratory at the Harvard School of Public Health approximately every 3 weeks according to manufacturer's recommendations. TSI Aerosol Instrument Manager software was used to download data from the CPC, TSI TrakPro software for the QTRAK and Boxcar/HOBOWARE for the HOBO. Approximately 8 min of data per hour (~10% of all measurements), representing the mixed-air transition from indoor-to-outdoor and outdoor-to-indoor cycles, were excluded from the data set.

Summary statistics and Spearman's correlations were calculated to compare indoor and outdoor PNC for each home. We evaluated the significance of potential predictors of indoor PNC by fitting a mixed-effect linear regression model. The model included indoor hourly PNC at homes as the dependent variable and a random intercept for home. Because of the skewed distribution of PNC, values were log-transformed for modeling. Adjustment for autocorrelation in hourly averages was made using an AR(1) correlation structure in which the error at time *t* was dependent upon the error at time *t* minus 1 h, similar to previous studies of particulate matter and other traffic-related air pollutants.[26,27] We considered time-dependent variables of wind speed, wind direction, traffic volume, traffic speed, temperature and hourly precipitation for inclusion in the model. Also evaluated for model inclusion were time-invariant variables of distance from highway (<100 m, 100–400 m and >1000 m), side of highway, distance from other roadways, total road length within buffers of 50 m, 100 m, 150 m and 200 m, average daily traffic within buffers of 50 m, 100 m, 150 m and 200 m, which were calculated with ArcGIS using state roadway network layers and other variables including obstruction between the home and the highway, floor of the house on which monitoring was performed, air-conditioning type, stove vented to the outdoors, vented bathroom, years at the residence, home age, participant smoking, participant work status and participant education that were obtained through participant questionnaires and field logs. Potential predictors of PNC were first evaluated individually, and the predictors with *P*-values <0.15 were included in the initial multivariate model. The multivariate model was then reduced to only those predictors with $P<0.10$. The goodness-of-fit of the model was evaluated using Akaike's Information Criterion. The form of the model is given below:

$$\log\left(\mathrm{PNCin}_{ij}\right) = b_i + \beta_0 + \beta_1 \log\left(\mathrm{PNCout}_{ij}\right) + \beta_2 \mathbf{X}_j + \beta_3 \mathbf{Z}_i + \beta_4 \sin\_day + \beta_5 \cos\_\mathrm{day} + \epsilon_{ij}$$

Where $\log(\mathrm{PNCin}_{ij})$ is the log of indoor PNC at home *i* and hour *j*, b_i is the random effect for home *i*, β_0 is the overall intercept, $\log(\mathrm{PNCout}_{ij})$ is the log of outdoor PNC at home *i* at hour *j*, $\mathbf{X}_j$ is a matrix of time-dependent covariates and $\mathbf{Z}_i$ is a matrix of time-invariant covariates. Sine and cosine terms for day of year were used as harmonic regression coefficients to account for seasonal variation and ε_{ij} is the error term.

RESULTS

Descriptive Statistics of Indoor, Outdoor and Ratios for PNC

Ambient hourly temperatures during the monitoring period (April—October 2009) ranged 2–38 °C, with an average temperature of 22±6 °C. Average hourly relative humidity was 65±20% and average hourly wind speed was 2.2±1.3 m/s. The highest percentage of wind was from the west direction (36%), followed by northwest (30%), east (21%) and southeast (13%). There were 34 days (20% of the monitoring period) with more than 3 mm of rain.

Homes were evaluated individually as well as grouped into clusters based on residential characteristics. As expected, the PNC data obtained at each home had many short-term peaks of high concentrations: the highest indoor 1-min peak was 3.2×10^5 and the highest outdoor peak was 2.7×10^5. The high peaks resulted in a skewed distribution. Figure 2 shows boxplots of 1-h averaged indoor and outdoor PNC for all monitored homes arranged by distance from highway. The median PNC was higher outdoors than indoors for 12 homes, and the opposite was true for six homes, although there was substantial overlap in the range of indoor and outdoor concentrations.

We analyzed data for hours with both indoor and outdoor measurements ($N = 4655$). When hourly data from all homes were pooled, the median indoor PNC was 5.2×10^3 particles/cm^3 (5th/95th percentile: 1.4×10^3/25.5×10^3), and the median outdoor PNC was 5.9×10^3 particles/cm^3 (5th/95th percentile: 2.0×10^3/22.4×10^3). The Spearman's correlation between indoor and outdoor PNC was 0.86. The median ratio of indoor-to-outdoor PNC (I/O ratio) for all hours of data was 0.95 (5th/95th percentile: 0.42/1.75).

Indoor and Outdoor PNC by Distance from Highway

Table 2 provides median values for indoor, outdoor and I/O ratios of PNC with homes from both sides grouped together and categorized by distance from highway. For presentation, homes were arranged in four distance groups: <100 m, 100–250 m, 250–400 m and >1000 m from highway. There was a statistically significant difference in medians of outdoor PNC between each distance category. The highest median outdoor PNC (7.3×10^3 particles/cm^3) was observed for homes within 100m of the highway, and the lowest median outdoor PNC (4.0×10^3 particles/ cm^3) was observed for homes in the urban background. Near-highway homes also had higher indoor PNC overall, whereas homes in the urban background had substantially lower PNC, by approximately half. The median I/O ratios for homes in the near highway (<100 m), 100–250 m, 250–400m and urban background (>1000 m) groups were 1.03, 0.87, 0.95 and 0.97, respectively, with no clear trend.

Exceptions to this general trend were seen. For example, home H14 had a lower median outdoor PNC than surrounding homes, possibly due to precipitation or wind direction towards the highway. H1 was a home located in the urban background area 1483 m from the highway and had I/O ratios consistently >1.0. This suggests that an indoor source (e.g., a gas stove or other appliance), which coupled with possible low ambient concentrations, may have contributed to I/O ratios consistently >1.0.

Impact of Air Conditioning on Indoor PNCs and Ratios

The relationships between indoor and outdoor PNC appeared to be influenced by air-conditioning use. The median I/O ratio for homes without air conditioning was 1.01, for homes with window units was 0.96 and for homes with central air was 0.93. However, these ratios do not take into consideration whether air conditioning was or was not in use, because we did not have a direct measure of use. Instead, we evaluated PNC under the assumption that air conditioners were used on days when cooling degree days (CDDs) exceeded zero. CDDs were calculated by subtracting 18.3 °C from the average daily temperature. For sampling days with CDD>0, we found that homes with window units had a 16% lower (95%CI: −42%, 23%) mean indoor PNC concentration compared with homes with no air conditioning, and homes with central air conditioning had a mean PNC that was 19% lower (95%CI: −46%, 23%). For days with CDD>10, we found that mean PNC were 25% lower (95%CI: −54%, 23%) for homes with window-mounted units and 28% lower (95%CI:

−57%, 21%) for homes with central air conditioning compared with homes without air conditioning. However, these reductions were not statistically significant.

The effect of air-conditioning use on indoor PNC is illustrated in two homes, H13 and H8 (Figure 3). The data is for 14 June 2010, a weekday when the ambient temperature reached ~28 °C. It is evident that the outdoor concentrations for each home had the same diurnal pattern: outdoor PNC were lowest between midnight and 0600 hours, and large peaks were seen around 1200 and 1500 hours after which concentrations slowly declined. Windows at H13 were left open all day, and the plot shows that indoor concentrations followed the same pattern as outdoor concentrations, with brief excursions presumably due to indoor particle generation. H8 used central air conditioning during the monitoring day and had a markedly lower diurnal pattern for indoor concentrations. The median I/O ratio for hourly PNC on 14 June was 1.21 for H13 and 0.49 for H8.

PNC by Time of Day

Further examination was made of PNC and I/O ratios according to four time categories: morning (0600–1159 hours), afternoon (1200–1759 hours), evening (1800–2359 hours) and night (0000–0559 hours) (Table 3). Overall median indoor and outdoor PNC were similar with nighttime having the lowest concentrations. Median I/O ratios were similar for each time of day category. The ratios were essentially unchanged when two homes with the highest indoor PNC (H1 and H16) were excluded from the data set. The interquartile range was also similar across time periods, but a bit smaller during the night.

Predictors of Indoor PNC

Two regression models of hourly indoor PNC concentration are presented in Table 4. The first model includes only statistically significant predictors: outdoor PNC, wind speed, wind direction, ambient temperature >18.3°C, weekday and time of day. We used interaction terms in both models to evaluate whether wind direction affected PNC differently on the east and west sides of I-93. There was no significant interaction effect, suggesting similar effects of wind direction for both east and west side homes.

Air conditioning was a strong, but not statistically significant, predictor of indoor PNC in univariate models and is included in a second model along with significant predictors. Homes with window-mounted units showed lower indoor PNC and central air conditioning, even lower indoor PNC, compared with no air conditioning. However, these decreases were not statistically significant in the model. We attempted to account for air-conditioner use by evaluating the difference between outdoor and indoor air temperature (delta T) as a predictor. An increase in delta T indicates that indoor air is cooling, suggesting air-conditioner use. An increase in delta T was associated with a small but significant decrease in indoor PNC in our data set (data not shown). The decrease of indoor PNC was the largest for homes with central air conditioning during nighttime hours in the absence of indoor sources.

Sensitivity analyses were conducted by excluding two homes (H1 and H16) that had unusually high indoor PNC. We suspect that the high levels in H16 may have been because of indoor cigarette smoking, despite our exclusion criteria. The high levels in H1 may have been because of an indoor source that we were unable to identify. In the first model, exclusion of these homes resulted in a negligible change to the effect estimates. However, in the second model, the variable for central air conditioning became statistically significant ($P = 0.07$). Sensitivity analyses were also conducted for homes that reported a smoker in the household and no substantial differences were seen, perhaps because smoking was restricted in the home, as indicated in the survey data. We also built models of hourly I/O ratios; however, there was no difference in the significant predictors in these models (Supplementary Table 1). Thus, we have decided to present the indoor PNC model only.

DISCUSSION

We monitored indoor and outdoor PNC at 18 homes in an urban community with a major interstate highway (~1.5×10^5 vehicles per day) and identified an overall median I/O ratio of approximately 1.0. Both indoor and outdoor PNC were generally highest among homes located <100m from the highway and lowest in homes located >1000m from the highway. Homes with air conditioning showed lower indoor PNC compared with homes without air conditioning and showed a decreasing trend with warmer weather. In our sample of homes, outdoor PNC was the most important predictor of indoor PNC: a 10.0% increase in outdoor PNC corresponded to an approximately equal (10.8%) increase in indoor PNC. Other significant predictors of indoor PNC included temperature, weekday, time of day, wind speed and wind direction.

We sampled for approximately 14 consecutive days at each home, which was a longer time period than most other studies. Our results show a higher combined I/O ratio than two studies conducted near major traffic sources. Zhu *et al.*[18] measured PNC in unoccupied bedrooms of four apartments near Interstate 405 in California. The apartments were located ≤60m from the highway and I/O concentration ratios were between 0.5 and 0.67.[18] McAuley *et al.*[17] reported I/O ratios of 0.1–0.5 for a sample of homes near a major border crossing. Both the Zhu *et al.* and McAuley *et al.* studies were conducted in the absence of indoor sources and with either mechanical ventilation (Zhu *et al.*) or closed windows and no mechanical ventilation (McAuley *et al.*). These conditions may be responsible for the lower ratios reported in these two studies.

Other infiltration studies in homes have been conducted away from major traffic sources including northern California,[22] the Boston area[19,23] and Ontario.[28] Some studies reported average or median I/O ratios of <1.0 during warm months and during periods of low ventilation rates and minimal indoor sources.[22,28] In contrast, other studies reported I/O ratios >1.0, the highest being 33 when homes were occupied.[19,23] Past studies have identified outdoor PNC and ventilation conditions as predictors of daily indoor PNC.[20,29] We identified wind speed as a significant predictor in our study, which was also documented in a previous study.[30] The housing stock within our study area may be older and not as well sealed as that of other studies, which would increase the possibility of infiltration. Although we did not specifically monitor air exchange rates, supporting information showed that our study participants reported opening windows frequently throughout the monitoring period. When this information is applied in the near-highway context, it is possible that at homes closer to the highway infiltration of highly polluted air may increase indoor PNC, whereas in the background area, cleaner ambient air would dilute indoor concentrations.

Air-conditioned buildings have been shown to have lower PNC and other ambient pollutants than outdoor air.[31–33] This may be due to increased filtration by air-conditioning units or that air conditioners recirculate air. Our data indicate that there was a reduction in indoor PNC in air-conditioned homes compared with homes without air conditioning, but this reduction was not statistically significant, perhaps because of small sample size and inability to identify specific times of use.

A limitation of our study is that we did not monitor during cooler months when we would expect less infiltration from reduced window opening to preserve heat. However, we were able to capture a broad range of ventilation conditions from window opening and air conditioning during warmer months. We would suggest additional monitoring of homes during the winter when homes are more tightly closed. Another limitation is that we were unable to determine the composition or size distribution of the PNC measured. We acknowledge that there are differences in composition of PM generated indoors compared with outdoors and possible differences in associations with cardiovascular health effects.[34] Outdoor-generated PM generally contains more nitrates, metals, sulfates and acids than indoor-generated PM, which contains more dust, endotoxins, mold spores and fresh combustion products.[35] Past research has shown shifts in infiltration according to size fraction due to changes in ventilation and time of day.[18,19,32] Understanding the size distribution would help us to better explain our findings. In addition, we did not record real-time indoor activities, which would have assisted in determining the sources of particles measured indoors. Potential sources such as cooking could not be thoroughly evaluated because of the lack of real-time data. The number of homes studied provides us with data to identify a general range of exposure based on the characteristics identified, but may not represent the general housing stock of Somerville or other near-highway communities. Larger buildings with HVAC systems would be expected to have lower I/O ratios than the homes in our study.[32] Our study instruments were sensitive to particles >6 nm, and therefore, we may have underestimated total particle number; however, our methods compare well with previous studies. We did not have data on air-conditioning use and instead used proxy measures. Future studies would benefit from real-time data on air-conditioning use, in order to fully evaluate its impact on indoor particle concentrations.

CONCLUSION

Our results suggest that under typical living conditions in housing in the CAFEH study area, PNC can readily enter the indoor environment in homes near a highway and in urban background neighborhoods during warm periods. Indoor PNC was associated with outdoor concentration, meteorology and time of day. Use of both central air-conditioning and window units appeared to affect indoor concentrations in our sample, but the effect did not reach statistical significance, perhaps because of too few days of air-conditioner use and the limited number of homes included in our evaluation. Our results show higher I/O ratios than most previous published articles, perhaps because of sampling under typical living conditions that include high ventilation rates and elevated outdoor concentrations. Our results imply that relatively high outdoor PNC near traffic sources may be good proxies for indoor exposure under typical, warm-weather conditions, particularly for non-air-conditioned residences. Measurement error in the CAFEH study of near-highway PNC, and perhaps other studies, may be small when using outdoor residential PNC as a measure of indoor exposure for participants living near highways.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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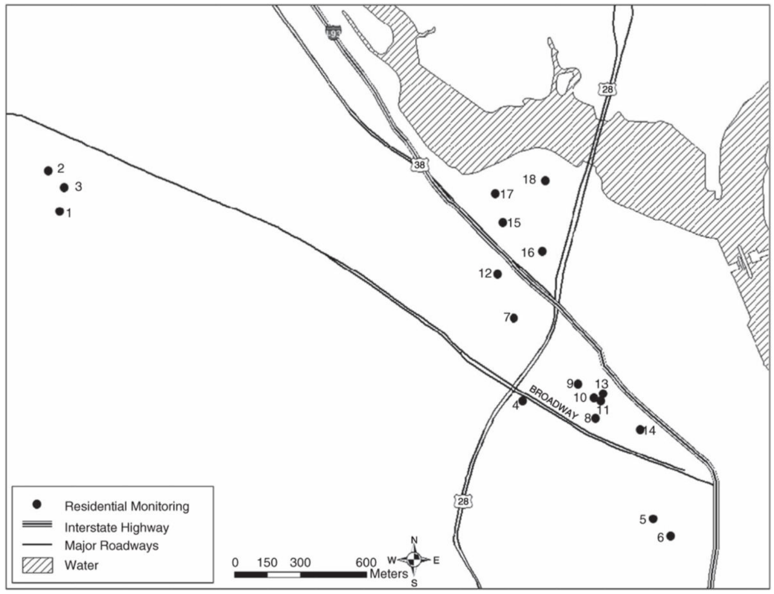

Figure 1.

Somerville study area showing near-highway and residential sites.

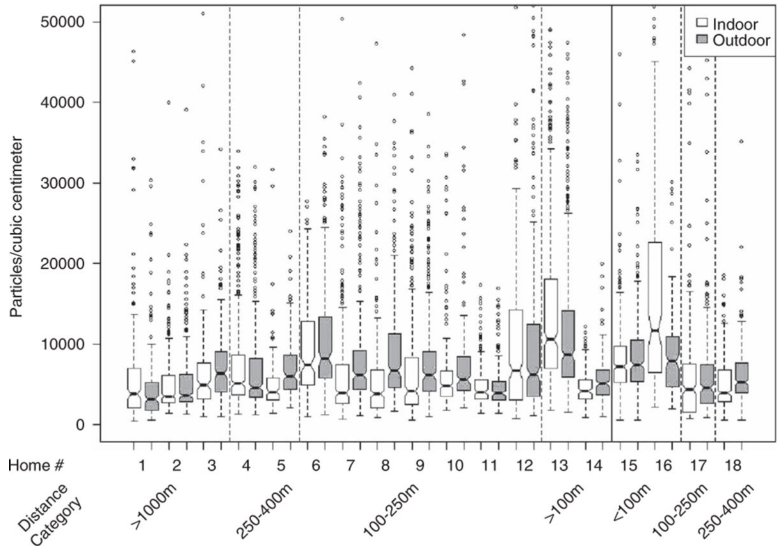

Figure 2.

Boxplots of indoor and outdoor particle number concentrations for monitored homes arranged by distance to highway. The solid line represents I-93. Homes to the left of this line are located west of the highway, and homes to the right of this line are located east of the highway. The dashed lines separate highway distance categories. The whiskers represent 1.5 IQR.

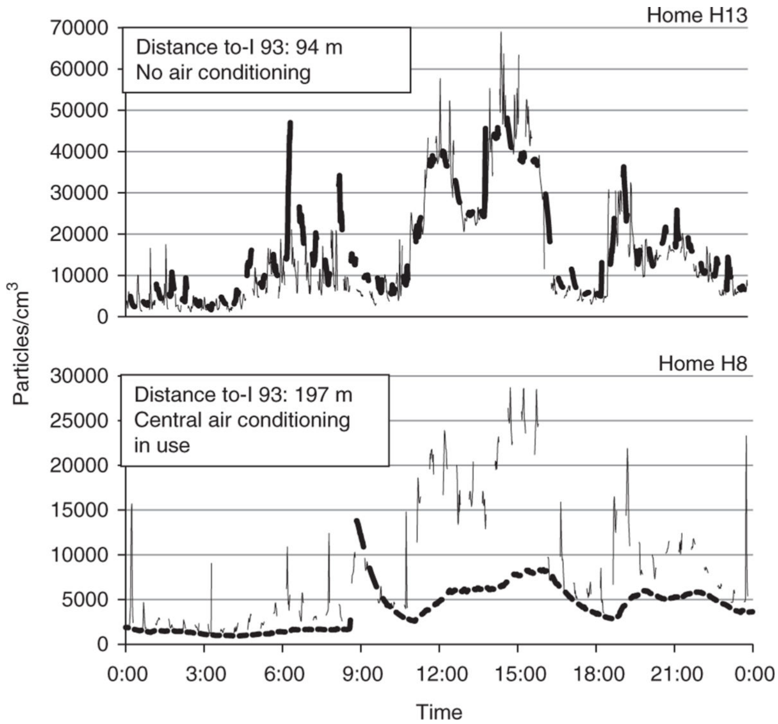

Figure 3.

Time-series data for two homes monitored simultaneously on 14 June 2010 for indoor (thick line) and outdoor (thin line) particle number concentration. Note the different scales of the y-axes.

Table 1.

Selected characteristics of 18 homes monitored.

Home	Start date	End date	Highway distance (m)	Type of home	AC type	Median indoor PNC (10^3/cm^3)	Median Outdoor PNC (10^3/cm^3)	Median I/O PNC ratio[a]
West of the highway								
1	9/28/10	10/5/10	1483	Single family	Central	3.8	3.2	1.25
2	4/26/10	5/8/10	1424	Multi-family	Central	3.5	3.6	0.96
3	10/8/10	10/15/10	1408	Multi-family	None	4.9	6.3	0.81
4	8/4/10	8/18/10	402	Apartment building	None	5.1	4.6	1.06
5	10/5/10	10/12/10	289	Multi-family	Central	4.1	6.0	0.69
6	8/17/10	8/24/10	221	Multi-family	Central	7.4	8.1	0.84
7	6/24/10	7/10/10	206	Single family	Window	3.9	6.1	0.63
8	6/11/10	6/26/10	197	Multi-family	Central	3.8	6.6	0.64
9	7/7/10	7/21/10	152	Multi-family	None	4.2	6.0	0.76
10	7/10/10	7/21/10	138	Multi-family	Window	4.8	5.5	0.81
11	5/11/10	5/22/10	123	Multi-family	Window	4.0	3.9	1.03
12	7/22/10	8/4/10	118	Multi-family	Window	6.6	6.2	1.00
13	5/28/10	6/16/10	94	Multi-family	Window	10.6	8.6	1.12
14	9/28/10	10/5/10	85	Multi-family	Window	4.1	5.1	0.85
East of the highway								
15	8/27/10	9/11/10	33	Multi-family	Window	7.2	7.4	0.97
16	7/22/10	8/4/10	68	Multi-family	None	11.7	7.8	1.55
17	6/24/10	7/7/10	101	Multi-family	Central	4.4	4.5	1.00
18	8/27/10	9/11/10	304	Single family	Window	3.9	5.3	0.84
All homes						5.2	5.9	0.95

Abbreviations: AC, air conditioning; I/O, indoor/outdoor; PNC, particle number concentration.

[a]Ratio of indoor-to-outdoor PNC.

Table 2.

Median PNC for monitored homes categorized by distance from highway.

PNC measurement	Within 100 m	100–250m	250–400m	>1000 m	Total
Number of homes	4	8	3	3	18
Number of hourly measurements	1152	2025	857	621	4655
Indoor concentration (10^3 cm $^{-3}$)	8.0 (5.1–13.5)	4.6 (2.8–8.4)	4.4 (2.9–7.7)	3.9 (2.7–6.7)	5.2 (3.2–9.1)
Outdoor concentration (10^3cm $^{-3}$)	7.3 (5.0–11.0)	5.9 (3.9–9.5)	5.2 (3.8–8.9)	4.0 (2.7–7.0)	5.9 (3.8–9.3)
I/O ratio[a]	1.03 (0.91–1.20)	0.87 (0.64–1.03)	0.95 (0.70–1.06)	0.97 (0.91–1.19)	0.95 (0.76–1.09)

Abbreviations: I/O, indoor/outdoor; PNC, particle number concentration.

Interquartile ranges are shown parenthetically.

[a]Ratio of indoor-to-outdoor PNC.

Table 3.

Summary statistics of PNC given in thousands (PNC × $10^3/cm^3$) for 18 residences according to time of day.

PNC measurement	Minimum	5th percentile	25th percentile	Median	75th percentile	95th percentile	Maximum
All hours (N = 4655 hourly measurements)							
Indoor	0.5	1.4	3.2	5.2	9.1	25.5	129.3
Outdoor	0.5	2.0	3.8	5.9	9.3	22.4	87.7
I/O ratio[a]	0.06	0.42	0.76	0.95	1.09	1.75	9.90
Morning (N = 1157 hourly measurements)							
Indoor	0.6	1.9	3.6	5.8	9.8	27.5	118.2
Outdoor	0.5	2.4	4.3	6.4	9.5	21.5	54.5
I/O ratio[a]	0.06	0.47	0.77	0.96	1.13	2.10	9.90
Afternoon (N = 1178 hourly measurements)							
Indoor	0.7	1.8	3.6	6.2	12.0	30.8	129.3
Outdoor	0.6	2.3	4.0	6.3	11.4	29.4	83.5
I/O ratio[a]	0.12	0.44	0.81	0.99	1.15	1.99	9.32
Evening (N = 1163 hourly measurements)							
Indoor	0.7	1.7	3.6	6.2	10.9	27.1	111.0
Outdoor	1.0	2.5	4.7	7.2	10.9	23.7	87.7
I/O ratio[a]	0.13	0.36	0.73	0.95	1.09	1.77	6.18
Nighttime (N = 1157 hourly measurements)							
Indoor	0.5	1.0	2.3	3.5	5.3	9.6	42.8
Outdoor	0.5	1.5	2.9	4.2	6.0	10.1	22.3
I/O ratio[a]	0.11	0.41	0.72	0.92	1.04	1.25	5.28

Abbreviations: I/O, indoor/outdoor; PNC, particle number concentration.

[a]Ratio of indoor-to-outdoor PNC for hours when both measurements were made.

Table 4.

Regression model results of indoor PNC.

Covariate	Model not including air conditioning		Model including air conditioning	
	% Change in indoor PNC	95% CI	% Change in indoor PNC	95% CI
Outdoor PNC	10.8[a],*	10.6, 11.0	10.8[a],*	10.6, 11.0
Wind speed (m/s)	5.1*	3.9, 6.3	5.1*	3.9, 6.3
Wind direction				
Southeast (ref)	—			
West	6.1*	1.9, 10.5	6.1*	1.9, 10.6
Northwest	7.4*	2.8, 12.1	7.4*	2.9, 12.2
East	9.0*	4.3, 13.9	9.0*	4.4, 14.0
Hourly temperature >18.3 °C	−7.9*	−10.0, −4.7	−7.9*	−10.0, −4.7
Air conditioning				
None (ref)	—	—	—	—
Window units	—	—	−15.2	−39.8, 19.5
Central air	—	—	−25.0	−48.0, 8.2
Weekday	−3.5*	−6.4, −0.5	−3.4*	−6.3, −0.4
Hour category				
1800 hours–2309 (ref)	—	—	—	—
1200–1759 hours	3.2	−0.1, 6.6	3.2	−0.1, 6.6
0600 hours-1159	5.5*	2.4, 8.8	5.5*	2.4, 8.8
0000–0600 hours	−1.3	−4.7, 2.1	−1.3	−4.7, 2.1

Abbreviations: CI, confidence interval; PNC, particle number concentration.

*Statistically significant associations ($P<0.10$).

[a]Corresponds to a 10% increase in outdoor PNC.