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Occupational exposure to roadway emissions and inside informal settlements in sub-Saharan Africa: A pilot study in Nairobi, Kenya

Nicole S. Ngo^a, Michael Gatari^b, Beizhan Yan^c, Steven N. Chillrud^c, Kheira Bouhamam^d, and Patrick L. Kinney^e

^aDept. of Planning, Public Policy, and Management, 1209 University of Oregon, Eugene, OR 97403-1209, USA, nngo@uoregon.edu

^bInstitute of Nuclear Science and Technology, College of Architecture and Engineering, University of Nairobi, P.O. Box 30197, G.P.O., Nairobi, Kenya, mjgatari@yahoo.com

^cLamont-Doherty Earth Observatory, Columbia University, 61 Rt 9W, Palisades, NY 10964, USA, chilli@ldeo.columbia.edu (Chillrud) and yanbz@ldeo.columbia.edu (Yan)

^dEcole Nationale Supérieure d'Electricité et de Mécanique, kheira.bouhamam@ensem.inplnancy.fr

^eDepartment of Environmental Health Sciences, Mailman School of Public Health, Columbia University, 722 West 168th St., New York, NY 10032, USA, plk3@columbia.edu (Kinney)

Abstract

Few studies examine urban air pollution in sub-Saharan Africa (SSA), yet urbanization rates there are among the highest in the world. In this study, we measured 8-hr average occupational exposure levels of fine particulate matter (PM_{2.5}), black carbon (BC), ultra violet active-particulate matter (UV-PM), and trace elements for individuals who worked along roadways in Nairobi, specifically bus drivers, garage workers, street vendors, and women who worked inside informal settlements. We found BC and re-suspended dust were important contributors to PM_{2.5} levels for all study populations, particularly among bus drivers, while PM_{2.5} exposure levels for garage workers, street vendors, and informal settlement residents were not statistically different from each other. We also found a strong signal for biomass emissions and trash burning, which is common in Nairobi's low-income areas and open-air garages. These results suggest that the large portion of urban residents in SSA who walk along roadways would benefit from air quality regulations targeting roadway emissions from diesel vehicles, dust, and trash burning. This is the first study to measure occupational exposure to urban air pollution in SSA and results imply that roadway emissions are a serious public health concern.

Keywords

Air pollution; sub-Saharan Africa; black carbon; urbanization; vehicle emissions; PM_{2.5}

1.Introduction

Urbanization rates in Africa are among the highest in the world, where more than half the population is expected to reside in urban areas by 2035 (United Nations (UN) 2010). Recently, studies have addressed the public health issues associated with this rapid urban growth, including poor sanitation and an under-provision of medical goods or services. However, an understudied topic in this field is urban air pollution. The UN estimates roadways are responsible for up to 90% of urban air pollution in developing countries (UN Environment Programme (UNEP) 2011). Reasons for this include the importation of older vehicles, poor maintenance of vehicles, use of dirtier fuels, poor enforcement of air quality regulations (if any are in place), and neglected infrastructure unable to support the rapid increase in the vehicle fleet. Roadway emissions may adversely affect the health of residents in sub-Saharan Africa (SSA) who walk along the roadside, use public transportation, or drive a vehicle, and the small literature that exists suggests it is an urgent, growing issue (Gaita et al. 2014, Jonsson et al. 2004; Boman et al. 2009; Eliasson et al. 2009; Gatari et al. 2008; Gatari and Boman 2003; Van Vliet and Kinney 2007; Kinney et al. 2011; Odhiambo 2010; Jackson 2005; Dionisio et al. 2010).

Of particular concern are individuals who spend their workdays outside by the roadway since previous work has found these populations to be more susceptible to respiratory disease or lung cancer (Lewne et al. 2007). Air pollution in informal settlements in SSA is also a major concern, where acute respiratory tract infections and bronchitis are among the most frequent diagnoses (Gulis et al. 2004). Given the lack of data on this topic, in this pilot study, we measured occupational exposure levels for individuals who work by roadways in Nairobi, the capital and most populated city in Kenya, with a population of 3.1 million people and growing at annual rate of 4% (Kenya National Bureau of Statistics (KNBS) 2008). Currently, no air quality regulations are implemented in Kenya, nor is any long-term air quality monitoring occurring, making it difficult to ascertain how serious a problem urban air pollution is.

We measured occupational exposure levels to particulate matter with an aerodynamic diameter $< 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$), black carbon (BC), ultra violet active-particulate matter (UV-PM), and trace elements in Nairobi for individuals who worked by roadways or inside informal settlements. UV-PM is component of $\text{PM}_{2.5}$ that captures yellow-brown colored components of PM sources such as biomass emissions or second-hand smoke (SHS) (Andreae and Gelencser 2006, Yan et al. 2011). Additionally, few studies have examined air pollution in informal settlements, where 1/3 of residents in Nairobi live and work, yet residents in these areas experience high exposure levels from the open burning of waste, traffic, cook stoves, and dust (Gulis et al. 2004, Dionisio et al. 2010, Arku et al. 2008, Salon and Gulyani 2010, Muindi et al. 2014). While measuring occupational exposure is not unusual, to the authors' knowledge, this is the first study to measure occupational exposure levels in SSA.

1.1. Background

Respiratory disease, an illness associated with poor air quality, is the second leading cause of morbidity in Kenya and though issues of indoor air pollution in rural areas of SSA have been explored, there is less work examining the effects of urban air pollution on the burden of disease (World Health Organization (WHO) 2009; Dherani et al. 2008). Kenya provides an interesting setting for this study because it is a country experiencing rapid urban growth. In 2009, 8.9 million or 20% of Kenya's population resided in urban areas (KNBS 2009) and by 2020 it is estimated that 50% of the population will live in urban areas (KNBS 2008). This rapid growth is being met with increased demand for vehicles. Between 1992 and 2001, the number of vehicles in Kenya increased by 46%, wherein 2004 about 18% of vehicles used diesel fuel, and it is expected 30,000 vehicles will be added each year (UN 2006).

Currently, Kenya has draft air quality regulations that were last updated in 2008, but it is unclear when these regulations will be implemented. Although, in the past couple decades, the Kenyan government has made some progress in placing more restrictions on fuel emission standards. For example, in 2006, Kenya started to phase out the use of leaded gasoline, and in 2010, required that imports and exports of diesel fuel be low sulfur diesel (National Environmental Management Authority (NEMA) and Motor Vehicle Inspection Unit (MVIU) 2009). However, many challenges remain. Currently, the inspection of vehicles for safety and performance is conducted through the Motor Vehicle Inspection Unit (MVIU) and the Ministry of Transport (NEMA 2011). But there are only 17 MVIU centers, making it impossible to inspect exhaust emissions for the 1.4 million vehicles in Kenya. Consequently, understanding the potential health impacts of roadway emissions is critical to informing future urban and transportation policies and air quality regulations.

2. Materials and Methods

2.1. Research location and participants

Despite Nairobi's proximity to the equator (1.32° S and 36.9° E), it experiences mild seasonal variation due to its high altitude (approximately 1.6 km) (Gatari and Boman 2003). Nairobi has two rainy seasons from March to May and October to December, so to avoid the rainy season, this pilot study took place for 3 weeks between August 2 and 18, 2011. We obtained ethical approval to conduct this study through Columbia University's Institutional Review Board and approval of research from Kenya's Ministry of Education, Science, and Technology.

To observe variation in exposure levels of PM_{2.5} across and within occupations, we recruited 3 individuals from 4 occupations (i.e., 12 participants). These occupational groups were street vendors, bus drivers, mechanics, and women who lived and worked in or near Mathare, one of the oldest informal settlements in Nairobi. Each participant carried the pump for 3 days throughout the week for 8 hours each day (N=12 participants*3 days=36), and each week, another set of participants from each study population would carry the pump. Four of the participants were women and the rest were male. In week 1, participants carried pumps from 8:30am to 5:30pm, then in weeks 2 and 3 between 7:30am and 4:30pm on Tuesday, Wednesday, and Thursday. The reason for moving the sampling an hour

earlier during weeks 2 and 3 was due to heavy traffic, making it difficult to access some of the participants after 8:00 am. The morning rush hour starts at 6:30am and ends at 9:30am, and evening rush hour is from 4pm to 6pm. We recruited individuals who worked in the eastern (week 1), southern (week 2), and western (week 3) parts of Nairobi (Figure S1). The western part of Nairobi is characterized as suburban and affluent, while the eastern part of Nairobi is characterized as working class and is where most of the informal settlements are located, so pollution emissions may differ by site (Odhubo 1997). We did not take measurements in the Central Business District (CBD), except for bus drivers who started their route there, due to heavy construction in the area.

Next, we briefly describe the study populations. Mechanics in Nairobi mostly work in garages near roadways, but it is not unusual for mechanics to be called to the street to fix vehicles. During week 3, the mechanic was on strike at his shop the first day, so he worked on the street for that day only. Street vendors sell goods while walking along the roads or between street lanes in different areas of Nairobi, typically by busy roadways or roundabouts. Bus drivers operate two types of diesel vehicles in Nairobi, 40-passenger buses or 14-passenger minibuses, and both are inexpensive forms of public transportation relative to taxis or motorbikes. Private bus companies own and operate the larger buses, while individuals own the 14-passenger vehicles. We measured exposure levels for 40-passenger bus drivers only since they were more consistent in routes and hours. We also recruited three women from Kosovo, a village in Mathare, who worked in or near Mathare.

2.2. Sample Collection

Fine particle concentrations were collected on pre-weighed Teflon filters using portable Model 400 BGI air samplers carried in backpacks. Each participant was trained by staff at the Institute of Nuclear Science and Technology (INST) on how to use and carry the pump with tubing extending to have the inlet nozzle of the cyclone placed on the shoulder strap near the breathing zone. The sampler inlet tube was positioned to draw air at 4 L/min (LPM) through an anodized aluminum cyclone (BGI Inc., Waltham, MA). This flow rate was able to draw particles of aerodynamic diameter less or equal to 2.5 μm into the sampler and depositing them onto a Teflon filter fitted into a plastic cassette downstream of the cyclone. The vacuum pump of the BGI personal sampler is powered by a rechargeable battery-pack with a capacity of >8-hr operation. Flow rates were measured and recorded before and after each sampling event by trained staff from Columbia University (CU) and INST using rotameters (SKC) that were pre-calibrated by a mass flow meter (TSI Model 4199). The times of the sampling period were recorded using a digital minute timer on the pump. After sampling, filter cassettes were separated from the tubing and pumps, then capped and placed in airtight plastic bags.

The Teflon (PTFE) filters were originally pre-weighed at Columbia University following the standard protocols described below. The filters were then loaded inside of a HEPA filtered laminar flow hood into the sampling cassettes that had been previously acid cleaned, then identified with a barcode ID and finally double ziplock bagged in preparation for transport to Nairobi. The sampling cassettes could then be quickly attached to the cleaned KTL sampling cyclones in the field greatly reducing chance for contamination during set up and

similarly during breakdown. All participants were asked to perform their typical routine throughout the day, opening windows and taking breaks as usual. All participants were compensated for the inconvenience of carrying the pump during their work hours. A research assistant also randomly checked on participants twice a day every day to ensure participants carried the pumps properly and to address any problems. We did not take any field blanks and instead used lab blanks as a proxy for field blanks.

Originally, 36 filters were analyzed, but two were dropped due to low final flow rates (i.e., flow rates more than 10% different from the target flow rate of 4 LPM were dropped). Additionally, six filters had visual evidence of non-homogenous distribution of particles on the filter. T-tests for PM_{2.5} were conducted without the filters with a non-homogenous distribution and results were similar. The filters with non-homogenous loading could not be used for XRF or optical measurements (BC or UV-PM). Also, on three occasions the pump stopped working momentarily due to a loose battery connection, but field technicians addressed the problem and lost time was properly compensated for via the built in counter.

2.3 Gravimetric analysis

All filters were pre- and post- weighed at CU after equilibration for at least 24 hrs in controlled temperature and humidity conditions in a HEPA-filtered weighing chamber that contained a UM2X microbalance after using polonium sources for discharging static electricity. A minor buoyancy correction was made to all filters to correct for any differences in atmospheric pressure pre and post weighing.

2.4. Black carbon and UV-PM analysis

The optical device used for measuring BC and UV-PM levels consists of a balanced deuterium tungsten halogen light source (DH-2000-BAL), an integrating sphere (ISP-50-8-R), a lab-made filter holder, and an Ocean Optics USB4000-VIS-NIR miniature fiber-optic spectrometer (Yan et al. 2011). Teflon filters from different manufacturer's lots (Pall Corporation) may have slight difference in background and absorbance tendency; for minimizing this effect, lab blanks from the same manufacturer's lot number were used as white reference.

2.5. Trace elements analysis

The filter samples were analyzed for elemental constituents in particulate matter via polarized-energy dispersive x-ray fluorescence (ED-P-XRF, XEPOS manufactured by Spectro, Germany). The XEPOS is an energy dispersive, polarized excitation x-ray fluorescence spectrometer with a 50 W, 50 kV Pd tube as primary source, the radiation of which is modified by four secondary targets to optimize the excitation across the entire elemental range [43, 44]. The autosampler tray allows for 11 analyses at a time (a combination of 9 samples and/or field blanks, one lab blank, and one internal filter standard) facilitated through the use of custom designed filter-holders made from Teflon to ensure an accurate counting geometry and limit the chances for contamination of the instrument and filter during XRF analysis. Approximately 10% of the total samples were analyzed as replicates. The system has been calibrated for Teflon filters and concentrations reported in ng/cm² for a suite of major and trace elements, including Al, P, S, K, Ca, Ti, V, Mn, Fe, Co,

Ni, Cu, Zn, Se, and Pb. Concentrations for Si, Cl and Br are reported as nominal ng/cm² since these elements have not been calibrated against known concentrations but the relative changes in concentration between samples are valid. All concentrations are then multiplied by the active area of the filter and divided by the volume of air sampled to give concentrations (real or nominal for Si, Cl and Br) in ng/m³.

3. Results

3.1. PM_{2.5}

Figure 1 shows a box plot of the 8-hr average PM_{2.5} concentrations for each study population and column 3 in Table 1 shows summary statistics. We used t-tests to compare concentrations across groups. We found bus drivers had the greatest exposure to PM_{2.5} and were the only occupation that experienced statistically different exposure levels from the other three groups ($P < 0.05$), while exposure levels of PM_{2.5} for street vendors, mechanics and women in Mathare were not statistically different from each other. We also performed a two-way ANOVA to test the effect of occupation and week on exposure levels and found that occupation was a significant factor, but the timing of the sampling was not significant, except for street vendors. The difference in exposure levels among street vendors is likely due to the high exposure levels experienced by the street vendor during week two, who worked near a busy, congested roundabout.

3.2. BC and UV-PM

Columns 4–7 in Table 1 show 8-hr average BC and UV-PM levels and their contributions to PM_{2.5}. Across all groups, BC contributed at least one-third to PM_{2.5} levels, while exposure to UV-PM was low for all occupations except for women in Mathare. Bus drivers experienced the highest BC levels, where BC levels actually exceeded the difference in PM_{2.5} levels between bus drivers and other occupations (Figure 2). We then performed a simple linear regression of PM_{2.5} on BC by occupation and found that a 1 µg/m³ increase in BC corresponded to a 1.6, 1.7 and 1.1 µg/m³ increase in PM_{2.5} for bus drivers, women in Mathare, and street vendors (resp.) ($P < 0.01$). Figure 3 shows a scatter plot between BC and PM_{2.5} by occupation. We also observed a negative, but insignificant correlation between BC and UV-PM.

We then performed a two-way ANOVA and results showed that occupation was a significant factor for BC and UV-PM exposure ($P < 0.01$), and similar to results for PM_{2.5}, BC levels for bus drivers were statistically different from the other groups. We found variation across sites only mattered for street vendors.

3.3. Trace elements

Table S1 shows summary statistics for trace elements and their detection limits (DLs), which were calculated using the average of three lab blanks. For concentrations below the DL, half the DL was used instead. We used a two-way ANOVA and found occupation was a significant determinant ($P < 0.05$) of Br, Cu, Ni, and Co, but the week or site did not matter. Next, we observed correlations among trace elements across all study populations, then by occupation (Table S3–S7). We found positive, significant correlations ($P < 0.01$) among

crustal elements (Si, Al, Ca, Ti, Fe, Mn) and BC for bus drivers and women in Mathare. Among street vendors, we found evidence of dust, but weak correlations with BC. We also found high correlations between K and Cl for bus drivers and mechanics. For women in Mathare and street vendors, we observed positive, significant correlations between Pb and Zn. Finally, we used simple linear regressions and measured the slopes between trace elements for different occupations. We show significant slopes ($P < 0.01$) in Table S2, and results support the correlations we examined among trace elements.

4. Discussion

4.1. Pollution sources

We show that BC is an important contributor to $PM_{2.5}$ for individuals who work by roadways and inside informal settlements. The near one-to-one correlation in regression results between BC and $PM_{2.5}$ suggests exposure to a source super enriched in BC, such as vehicle smoke due to poor engine maintenance which is a common feature on Nairobi roads, bus fleets and open air garages. Compared to other occupational groups in this study, bus drivers experienced the greatest levels of exposure to BC and $PM_{2.5}$, which is unsurprising since they drive along busy routes and in buses with poor ventilation. We also found high correlations between BC and crustal elements (Si, Al, Ca, Ti, Fe, Mn) for bus drivers, which characterizes traffic related re-suspended dust, likely from unpaved roads.

Another interesting result showed that exposure levels for women in Mathare were not statistically different from other at-risk groups, like mechanics or street vendors. Women who work inside informal settlements could be exposed to BC from diesel emissions since walking is the primary means of commuting in these areas, but also to BC from smoke from cook stoves, kerosene lamps or trash burning (Salon and Gulyani 2010, Antony Chen et al. 2006), which are common in these areas. Additionally, similar to bus drivers, in our analysis of trace elements for these women, we found high correlations between BC and crustal elements. Exposure to dust away from roadways is also common in informal settlements since many public spaces remain unpaved. This is further confirmed in a study by Ngo et al. (2015) which found Mathare residents spent at least 6 hours outside each day. We also found high levels of Cl and UV-PM for women in Mathare, which could reflect biomass emissions and the high utility of kerosene stoves. Further, we show a positive, significant correlation between Pb and Zn for women in Mathare, which are common metals used in many materials and likely a signal of garbage combustion and not gasoline since leaded gasoline was phased out in Kenya in 2005 (Chillrud et al. 1999).

We also found statistically significant differences among occupational groups in exposure to Br, Cu, Ni, and Co, which is typically found in the burning of unsorted waste that is common in Nairobi. For example, the foam in vehicle seats and a variety of plastics contain brominated flame retardants and the burning of old vehicle seats in areas like the “Jua Kali” sector, where many open air garages are located, is not unusual. Cu is also common in brake linings, but is normally correlated with other elements such as Ti or Al (Hjortenkrans et al. 2007). Results also show high correlations between K and Cl for bus drivers and mechanics, which suggest exposure to biomass emissions, but the difference in slopes between Cl and K in Table 3 suggest exposure to these trace elements was from different sources.

In summary, we found BC and re-suspended dust were important contributors to $PM_{2.5}$ levels, suggesting traffic emissions are an important pollution source for these occupational groups who work outside. We also show a strong signal for biomass emissions and trash burning, which is common in Nairobi's low-income areas and open-air garages.

4.2. Comparison to other studies

4.2.1. $PM_{2.5}$ —We then compared results from our study to other occupational or personal exposure studies of $PM_{2.5}$. A study in Nairobi by Kinney et al. (2011) observed 11-hr personal exposure levels of $PM_{2.5}$ along busy roadways and roundabouts and found average concentrations of $PM_{2.5}$ between $58 \mu g/m^3$ and $98 \mu g/m^3$, which are similar to our results. Another study by Gaita et al. (2014) in Nairobi also found traffic, mineral dust, industry and combustion were important pollution sources. Compared to other countries, we found bus drivers in Nairobi experienced more than five times higher concentrations of $PM_{2.5}$ than did bus drivers in Sweden (Lewne et al. 2007). Exposure levels for mechanics in Nairobi, however, were similar to those experienced by garage workers in the same study. Levels for bus drivers in Nairobi were two to three times those experienced by truck drivers in a study conducted in the U.S. (Davis et al. 2007). Participants in our study also experienced at least 1.5 times the levels found at high-traffic areas often used by diesel vehicles in New York City (Kinney et al. 2000).

To our knowledge, there is only one other occupational exposure study that measured $PM_{2.5}$ levels in a developing country, and it occurred in Peru and while exposure levels for bus drivers in Peru were greater, they were similar in magnitude to our results (Han et al. 2005). A related literature in developing countries measures personal exposure levels to $PM_{2.5}$ in buses during rush hour. One such study measured 3-hr personal exposure levels to $PM_{2.5}$ in buses in Mexico City, but they were lower than the levels we observed in our study (Gomez-Perales et al. 2004). However, exposure levels were similar to those found in buses traveling during rush hour in another study in Guangzhou, China (Chan et al. 2002).

4.2.2. Trace elements—Comparisons of trace element concentrations to other studies was challenging since the mass was not assessed against a reference material and most air quality studies report 24-hr concentrations. We compared our results to those from a study by Gatari et al. (2008), which measured 24-hr average background levels of trace elements at 25m above ground in an industrial area in Nairobi. Although their study values are 24-hr averages in ng/m^3 , while in this study we gather 8-hr averages in ng/m^3 , to the authors' knowledge, the study by Gatari et al. (2008) is only one of two studies to measure trace elements of $PM_{2.5}$ in Nairobi. On average, all the samples in our study were above DLs and were greater than measurements from Gatari et al. (2008), except for K and P, which is unsurprising given the difference in sampling hours, location, and height above ground. Another study by Gaita et al. (2014) also measured 24-hr background concentrations in an urban and suburban site and found BC, Fe, S, and Cl contributed to 80% of all detected elements, while in our study Fe, S, and K were the biggest contributors to $PM_{2.5}$, though the standard deviations for these elements were also large.

4.3. Limitations, future work, and policy implications

Since this was a pilot study, a major drawback is the small number of filters collected and, as a result, in Table S1, the standard deviations are high relative to the means. Additionally, we did not observe variation across different seasons due to logistic and temporal constraints, nor did we measure background pollution levels simultaneously, so we cannot compare results to a baseline. In a prior study, Kinney et al. (2011) measured average PM_{2.5} levels on a rooftop in Nairobi of about 35 ug/m³ in July 2009.

Future work should consider consistent, daily pollution monitoring of background pollution levels. Studies with a larger sample size would reduce standard errors and clarify possible sources. Other future work should include observing street-level pollution near roadways throughout the year to compare seasonal variation in occupational exposure levels. Also, measuring 24-hr exposure levels may be a better assessment of exposure in informal settlements or for individuals who work by roadways since these are low-income occupations, so they are likely exposed to other pollution sources throughout the day. Finally, to our knowledge, there has been no rigorous evaluation of health impacts from air pollution in SSA using micro-level data. Results from such studies would motivate air quality regulations in this region. With respect to policy implications, according to results in our study, regulating diesel emissions could reduce PM_{2.5} levels dramatically for these vulnerable populations, particularly bus drivers, and have important health benefits for the large portion of Nairobi residents who walk or work along roadsides or who live and work in low-income areas. Additionally, correlations among trace elements suggest roadside dust is another critical issue, so investments into road infrastructure or paved sidewalks could further reduce the burden of disease. The mixture of roadside dust, diesel exhaust, and garbage combustion found in this study reinforce the poor air quality conditions from roadways in Nairobi.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
A box plot of 8-hr occupational exposure levels for the 3-week study period. The line in the middle of the box represents the median.

Figure 2.
A graph of the composition of $PM_{2.5}$ broken down by BC, UV-PM, and other species.

Figure 3.
scatter plot of BC and PM2.5 by occupation.

Table 1

Summary statistics of 8-hr average PM_{2.5}, BC, and UV-PM concentrations (µg/m³)

Occupation	N	Mean PM _{2.5} ± SD	Mean BC ± SD	%BC of PM _{2.5}	Mean UV-PM ± SD	% UV-PM of PM _{2.5}
Bus drivers	7 ⁺	103.8±28.3	63.9±18.6	62	0.6±1.0	0.6
Mathare	9	62.7±20.5	19.6±10.0	34	16.1±9.6	28
Mechanic	9 ⁺	57.8±18.4	26.0±8.3	42	4.9±5.0	8
Street vendors	9 ⁺	69.7±21.6	30.0±12.7	43	6.1±5.5	9

Note:

⁺The sample size in these occupations for PM_{2.5} is different from the sample size for BC and UV-PM because some filters had a non-homogenous distribution (as discussed in the Methods section) and could not be analyzed for BC or UV-PM. For BC and UV-PM measurements, for bus drivers N=6, for mechanics N=7, and for street vendors N=6.