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Exposure to carbon monoxide, fine particle mass, and ultrafine particle number in Jakarta, Indonesia: Effect of commute mode

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HIGHLIGHTS

- Traffic-related pollutant exposures of Jakartans are among the highest in the world.
- Causes include two-stroke engines, missing catalytic converters, and high sulfur fuel.
- Car owners averaged 22 ppm CO and 60% of total daily CO exposure during commutes.
- Inhaled dose during commuting varied significantly with commute mode and time.
- Portable, real-time instruments uncovered determinants of pollutant exposures.

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ABSTRACT

We measured real-time exposure to $PM_{2.5}$, ultrafine PM (particle number) and carbon monoxide (CO) for commuting workers school children, and traffic police, in Jakarta, Indonesia. In total, we measured exposures for 36 individuals covering 93 days. Commuters in private cars experienced mean (st dev) exposures of 22 (9.4) ppm CO, 91 (38) μg/m^3 $PM_{2.5}$, and 290 (150)×10^3 particles cm^{-3}. Mean concentrations were higher in public transport than in private cars for $PM_{2.5}$ (difference in means: 22%) and particle counts (54%), but not CO, likely reflecting in-vehicle particle losses in private cars owing to air-conditioning. However, average commute times were longer for private car commuters than public transport commuters (in our sample, 24% longer: 3.0 vs. 2.3 h per day). Commute and traffic-related exposures experienced by Jakarta residents are among the highest in the world, owing to high on-road concentrations and multi-hour commutes.

1. Introduction

Jakarta, Indonesia, is among the most populated and polluted cities in the world, with especially high concentrations of particulate matter and carbon monoxide (Ananta and Anwar, 1995; Gurjar et al., 2008; Mage et al., 1996). Exposure to fine particulate matter is associated with an increase in allergic disorders, asthma, cognitive deficits, brain abnormalities, decreased lung function, cardiovascular disease, cardiopulmonary disease, and death (Brook et al., 2010; Brunekreef and Holgate, 2002; Calderon-Garciduenas et al., 2008; Dockery et al., 1993; Dockery and Stone, 2007; Padhi and Padhy, 2008; Pope, 2002; Samet et al., 2000; Zemp et al., 1999); exposure to CO is associated with an increase in mortality from cardiovascular disease (Allred et al., 1989; Samoli et al., 2007; Riojas-Rodríguez et al., 2006); exposure to ultrafine particles is associated with atherosclerosis, cardiovascular disease, and neurodegeneration (Delfino et al., 2005; Peters et al., 2006). Virtually no peer-reviewed studies have measured exposure to urban air pollution in Jakarta and relatively few in other developing country megacities, despite the fact that emissions and concentrations are typically much higher there than in the US and Europe (Apte et al., 2012; Duh et al., 2008; Gupta and Kumar, 2006; Apte et al., 2011; Han and Naeher, 2006; Hopke et al., 2008; Mage and Zali, 1992; Smith et al., 1994).

Jakarta is a coastal city, the capital of Indonesia, and the most populous city in Southeast Asia (Duh et al., 2008; United Nations, 2007). A comparison of available datasets suggests that Jakarta is between the 2nd and 12th most populous city in the world (Forstall et al., 2009). By U.S. standards, population densities in Jakarta are remarkable: 13,300 km^{-2} for the city of Jakarta ("DKI Jakarta"; 8.8 million people, 661 km^2) and 4400 km^{-2} for the region ("Jabodetabek"; 24 million people, 5500 km^2) (BPS DKI Jakarta, 2009). In contrast, among U.S. urban areas, median population density is 490 km^{-2} (Marshall, 2007). Population growth in Jakarta is ~1% annually,

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while the number of motor vehicles is growing ~9% annually (from 11 million in 2010 to an estimated 17 million in 2015) (Nugroho and Fujiwara, 2005). Citing statistics such as average traffic speed (8 km h^{-1}, "the equivalent of a light jog") and proportion of federal spending devoted to public works (8%, versus the 13% devoted to fuel subsidies), Foreign Policy magazine concluded, "Jakarta is the poster child for unsustainable urban development" (Terzis, 2010).

A 1998 study by the Asian Development Bank found that annual average PM_{10} concentration at Jakarta's six continuous monitoring stations was near or above the US-EPA standard of 50 μg m^{-3}, with two of the stations averaging approximately 80 μg m^{-3} (Syahril et al., 2002). All five stations frequently exceeded the local hourly CO standard (26 ppm), with one station exceeding the standard 619 of 724 h measured (Syahril et al., 2002). The World Bank (1994) estimated that in 1989 air pollution cost the city of Jakarta approximately US$220 million. Ostro (1994) estimated Jakarta meeting the Indonesian annual average TSP concentration standard (90 μg m^{-3}) would annually save 1200 lives and 6.3 million restricted activity days including work loss. Evidence suggests that policies that reduce air pollution in Jakarta also improve the income distribution (Resosudarmo and Thorbecke, 1996). Lower property values in Jakarta have been linked with higher levels of particulate matter (Yusuf and Resosudarmo, 2009).

High levels of ambient air pollution have been associated with anthropogenic sources such as industry, rubbish burning, and traffic (Lestiani and Santoso, 2011; Santosa et al., 2008; Santoso et al., 2008, 2011; Zou and Hooper, 1997). Jakarta has large numbers of highly polluting two-stroke engines, particularly three-wheel auto-rickshaws, which use converted motorcycle engines, often from the late 1960s, and large numbers of automobiles without catalytic converters (Santosa et al., 2008). Those factors lead to high levels on-roadway of CO and other combustion emissions. Furthermore, Jakarta has large numbers of high-emitting diesel trucks and light duty vehicles. Trucks generally run on high-sulfur diesel fuel, leading to high on-road concentrations of diesel PM and elemental or black carbon (BC). Though the production of leaded fuels was phased out in Indonesia as of July 2006, unleaded fuel has only recently (since 2001) been available in the country and while there is momentum for installing catalytic converters on taxis and public transportation, Syahril et al. (2002) in a study in 2002 found the overall number of catalytic converters remains relatively small. These conditions, combined with severe traffic congestion and long commute times (averaging >60 min per day (Forstall et al., 2009), more than the U.S. average of ~45 min per day (Hu and Reuscher, 2004)), produce high exposures for commuters and for workers such as professional drivers, near-roadway vendors, and traffic police (Knibbs and Morawska, 2012). Considering the large percentage of the world population that is found in the megacities of developing countries, it is surprising that nearly all exposure studies examining mode of transportation have been conducted in Europe and North America (see Table S1, which provides a literature review and summary of prior findings).

To characterize these high commuter exposures, this study measured exposure to $PM_{2.5}$ (particulate matter with mean aerodynamic diameter smaller than 2.5 μm), ultrafine PM (particulate matter smaller than 0.1 μm), and carbon monoxide for Jakartans while commuting, and during non-commuting periods at home, work or in school. We evaluated exposure differences by travel mode for adults, and compared to school children and to a high-exposure occupation (roadside traffic police), and estimated the contribution of commuting to overall pollutant exposures.

2. Methods

2.1. Sampling design

Our study investigated pollution exposures for four population groups in Jakarta in 2005, from May through October. (Table 1): school children using a variety of transport modes, adult commuters using private cars, adult commuters using public transportation (buses, minibusses), and traffic police officers who spent time in or near traffic impacted locations. We recruited a convenience sample of 36 non-smokers and measured a total of 93 days of exposure concentrations. All subjects worked or attended school in Jakarta and lived in Jakarta or surrounding suburbs. Our recruitment aimed to be representative within each population group, though the four groups studied were not necessarily representative of the greater population's commute mode choices. For example, private car commuters are over-represented in our 36-person sample relative to the population as a whole (Fig. 1). Many commutes involved multiple modes (e.g., walk from home to bus stop/bus from bus stop to transit station/3-wheeler from transit station to office); modes delineated here reflect the majority mode.

2.2. Equipment

All monitoring instruments used were battery powered, logged data as one-minute average concentrations, and were lightweight and portable. A photometer (DustTrak 8520, TSI Inc., Shoreview, MN), fitted with a $PM_{2.5}$ inlet, estimated $PM_{2.5}$ mass concentrations based on light scattering. To avoid humidity-induced overestimation of mass (Laulainen, 1993), we used a silica-filled diffusion dryer upstream of the DustTrak inlet (Chakrabarti et al., 2004; Day and Malm, 2001; Donateo et al., 2006).

An electrochemical sensor (Q-TRAK 8552, TSI Inc., Shoreview, MN) measured carbon monoxide (CO; mechanism: electrochemical cell), carbon dioxide (CO_2; non-dispersive infrared), temperature, and relative humidity. The CO cells were calibrated by the vendor immediately prior to our use; we conducted additional checks of the calibration against a standard gas at the Environmental Monitoring Center (EMC) in Serpong, Indonesia. Ultrafine number concentrations were measured using a condensation particle counter (CPC Model 3007, TSI Inc., Shoreview, MN), which detects particles of size 0.01 μm to 1 μm. Number concentrations are dominated by ultrafine particles ($PM_{0.1}$, diameter less than 0.1 μm). Particle number concentrations in Jakarta routinely exceeded the CPC measurement range suggested by the manufacturer (up to 10^5 cm^{-3}); to address this issue, a diluter was installed upstream of the CPC, thereby reducing concentrations in sampled air by a factor of 9.8 — a sufficient amount to reduce values to levels not needing correction for coincidence counting problems (Knibbs et al., 2007). The degree of dilution was checked prior to each sample trip, and observed concentrations were multiplied by the dilution factor. At concentrations above ~10^5 cm^{-3}, the CPC 3007 linear counting efficiency degrades; thus without this dilution the instrument would under-report true concentrations.

In addition to the silica-filled diffusion dryer upstream of the DustTrak, a further step was required to assure that the DustTrak reported reliable $PM_{2.5}$ measurements. The DustTrak is calibrated against Arizona Road Dust and requires comparison to an accepted local mass monitor to establish a calibration correction factor that accounts for the unique characteristics of PM in Jakarta. For this study we compared the data from a dryer-equipped DustTrak with an E-BAM (MetOne, Grants Pass, OR) that was operated as part of near-roadway monitoring conducted by our group. The E-BAM was fitted with a $PM_{2.5}$ cyclone inlet. An E-BAM, which operates on the principal of beta radiation attenuation, maintains

Table 1
Study population groups.

Group	Number of subjects	Total days of monitoring		
		CO	$PM_{2.5}$	CPC
School children	8	16	19	8
Car commuters	9	25	25	11
Public transit commuters	9	26	26	16
Traffic police	10	26	26	0

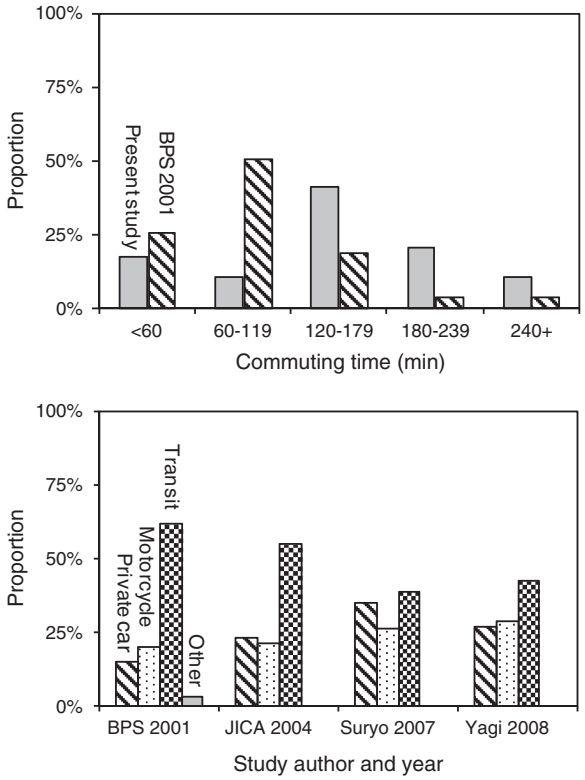

Fig. 1. Roundtrip commute time (upper plot) and mode of commute (lower plot): comparisons to earlier studies.

humidity of the airstream by heating the inlet and reports data with one-hour resolution. Importantly for our study, the MetOne beta attenuation monitor (BAM) is listed by the EPA as an automated equivalent method (EQPM-0798-122; the 'E' in 'E-BAM' refers to the 'environmental' enclosure protecting the BAM), meaning that the E-BAM is equivalent to the reference method. A USDA Forest Service report (Trent, 2003) reported that all observed correlation coefficients between the E-BAM and the Federal Reference Methods were > 0.99.

The two instruments (DustTrak; E-BAM) were co-located at a residential reference site, approximately 20 m from a busy roadway in central Jakarta. The site, which was selected for instrument security, was one floor above ground level, in a high-income neighborhood consisting of single-family detached houses.

2.3. Field study set-up

During exposure measurements, students from the University of Indonesia traveled with the subjects, carrying equipment and checking it as needed. Subjects were instructed not to modify their activities as a result of the presence of the data collection teams. Although some modification may have occurred despite these instructions, self-reported major aspects of subjects' activities (commute mode and work, home and school locations) remained unchanged. Questionnaires were distributed and filled in by the subjects (or guardian, for school children) recording demographic attributes (age, sex). Police exposure data were collected as they performed their work (routine observation and traffic control while on foot). Police were monitored for PM and CO exposure, but not for ultrafine counts. Two or three 1-day measurements were made for each subject (average monitoring time [hours] per day: 21 for children, 24 for adults commuting via private car, 12 for adults commuting via public transport, 6 for traffic police). There were approximately half as many days of monitoring for particle counts as for CO and $PM_{2.5}$ because the study employed one CPC, two DustTraks, and two Q-Traks. The duration of sampling for traffic police (~6 h) reflects the duration of time that they spend working on-roadway each day.

3. Results and discussion

Adult commute times and distances (Fig. 2) were relatively long: median (interquartile range) round-trip values are 66 (20–80) km and 3.0 (2.8–3.5) hours for private car commuters, versus 70 (50–80) km and 2.3 (2.1–3.5) hours for public transport commuters. The median school commute was notably shorter (3 km [IQR: 2–17]; 0.8 h [IQR: 0.5–1.4]) since children typically attend local/nearby schools. For comparison, the average roundtrip commute in the U.S. in 2001 was 24 km (0.8 h) (Hu and Reuscher, 2004). The maximum commute length among the 20 adults we sampled was 200 km round-trip (5.0 h). Comparison to prior studies (BPS DKI Jakarta, 2001) suggests that private car commuters with long commute times are over-sampled in our cohort; or, the longer commute times in our study (see Fig. 1) may partially reflect changes in traffic congestion from 2001 to 2005. In either case, our results and the previous research both indicate comparatively long commutes: the vast majority (78%) of Jakartans commute for more than 1 h (BPS DKI Jakarta, 2001). Median time near road traffic during the work shift for traffic police was 6.3 (IQR: 6.2–6.3) h per day.

3.1. Photometer correction

Fig. 3 presents the DustTrak-E–BAM comparison. The two monitors agreed well ($R^2 = 0.96$); accordingly, the DustTrak was adjusted using a simple linear expression (corrected $PM_{2.5}$ = [DustTrak-recorded $PM_{2.5}$]/2.77). All DustTrak data reported in this paper are E-BAM-adjusted values. Because the E-BAM is not portable, a limitation of our calibration is that it represents outdoor air in one near-roadway residential location; we were unable to generate separate calibration factors for each microenvironment.

3.2. Exposure measurements

Fig. 4 illustrates an example monitoring period for CO from a private car commuter. On-road exposures are routinely above 40 ppm CO, 75 μg m^{-3} $PM_{2.5}$, and 100,000 particles cm^{-3}. For CO and UFP, there was little difference between morning and afternoon on-road concentrations, despite increases in wind speed and mixing height from morning to afternoon, suggesting that a large fraction of in-vehicle exposures are attributable to nearby vehicles rather than regional pollution. Available data from NASA's Global Modeling and Assimilation Office (GMAO, 2011) indicate that the annual harmonic mean surface boundary layer in Jakarta is approximately 2.5 times greater in the afternoon (1120 m during 14:00–16:00 for 2005–2007) than in the morning (460 m during 5:00–9:00). CO and $PM_{2.5}$ concentrations reported here are many times higher than typical on-road concentrations in developed country cities. For example, Riediker et al. (2003) reported mean on-road concentrations of 2.6 ppm CO and 23 μg m^{-3} $PM_{2.5}$, in Raleigh, NC, US. Westerdahl et al. (2005) reported mean on-road concentrations of 1.9 to 2.7 ppm CO on Los Angeles freeways, depending on the freeway segment. In contrast, UFP concentrations reported here are approximately within a factor of ~2 to 3 of typical values measured on-roads in developed country mega-cities. For example, Westerdahl et al. (2005) reported UFP number concentrations of 47,000 to 210,000 cm^{-3} on different Los Angeles freeways. A literature review by Knibbs et al. (2011), not limited to megacities, reported mean UFP number concentrations of 34,000 to 57,000 cm^{-3}, depending on commute mode. The reason why UFP concentrations in Jakarta are not as unusually high as the other pollutants may be attributable to enhanced adsorption of semi-volative vapors onto available $PM_{2.5}$ particle surface area, thereby reducing the formation

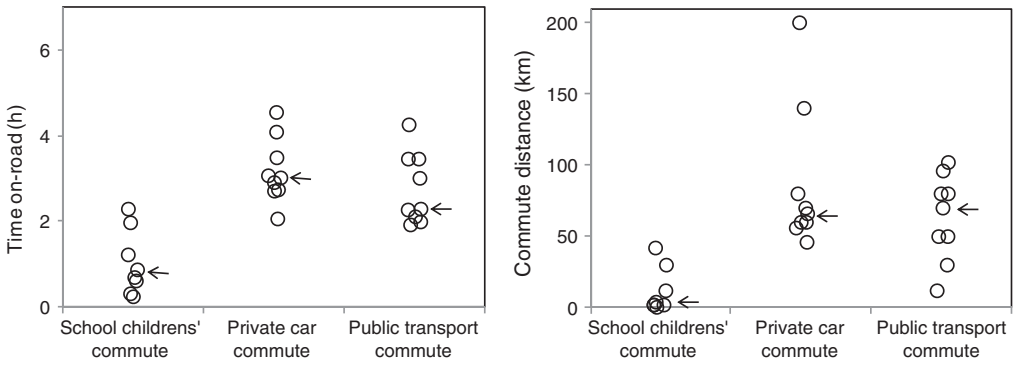

Fig. 2. Average roundtrip commute time (left panel) and distance (right panel) per person, for the participants enrolled in the study. Arrows indicate median values.

of UFP by homogeneous nucleation (Biswas and Wu, 2005). Clean air dilution on- and near-roadway impacts the size distribution and the number concentration, and near-roadway UFP concentrations exhibit strong spatial gradients (Zhang and Wexler, 2004; Zhang et al., 2004, 2005).

Exposure data, as shown in Fig. 5, are segregated by subject group and by location: (1) at home, (2) on the road, or (3) at work/school. Work and school exposure concentrations were similar. CO concentrations were 180%–700% greater on-road than elsewhere. Median on-road CO concentrations were approximately 22 ppm (IQR: 15–28) for public transport users, with little variability between air-conditioned (AC) and non AC public transport. Median CO exposures at home and work were less than 3 ppm. CO exposure concentrations on-road for private car commuters were similar to public transport commuters, ~200% higher than for school children and traffic police.

Median CO concentrations seen while commuting in Jakarta are among the highest reported in the world, although such studies are uncommon and instruments used have varied (see Table S1). To our knowledge, the highest on-road CO values previously reported in the literature are 32–63, 26–38, and 17–25 ppm in minibusses, buses, and the metro, respectively, in Mexico City, in the winter of 1991 (Fernandez-Bremauntz and Ashmore, 1995) although the values measured in the Spring of 2002 averaged 5, 2, and 7 ppm, respectively for the same vehicle modes (Gomez-Perales et al., 2004), reflecting improved air quality and perhaps better dilution during spring conditions. Also, the instrumentation in those studies changed from a General Electric COED-1 CO monitor (electrochemical) to a Langan Model T15 (infrared). Measured values of similar magnitude are rare: in Guangzhou, 24 and 9 ppm CO, respectively, were measured on taxis and buses during summer 2002 (Chan et al., 2002) using an Intersan Co. Model 4148 (electrochemical); in Athens, 21 and 10 ppm CO, respectively, was measured in cars and busses during winter 1998–1999 (Duci et al., 2003) using a Solomat MPM 4100 portable CO monitor. Other developing cities with lower on-road or in-vehicle CO values include Tehran, Bangkok, three cities in Guatemala, and Ankara (Abdollahi et al., 1998; Atimtay et al., 2000; Han and Naeher, 2006; Leong et al., 2001; Shendell and Naeher, 2002). Considering that our values were measured in 2005, when much of the developing world had already reduced traffic CO through tailpipe controls, concentrations reported here are high.

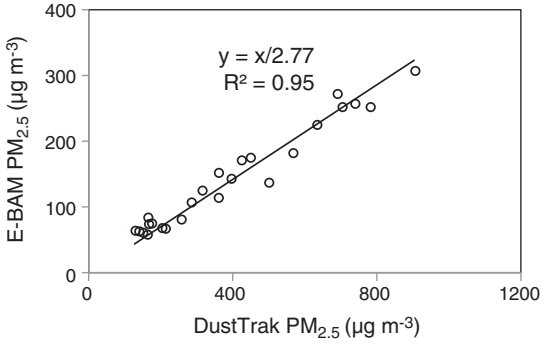

Fig. 3. Comparison of $PM_{2.5}$ measurements by two instruments (E-BAM, DustTrak) for a near-traffic residential location. These results, which indicate a high correlation, were used to derive the correction factor to convert DustTrak-reported concentration into reference method –equivalent values.

The situation for on-road and in-vehicle $PM_{2.5}$ concentrations in Jakarta is similar to CO. $PM_{2.5}$ exposures were 30%–200% higher while on-road than not on-road. Concentrations at home and at school/office were fairly consistent across the subject groups (median: 42 μg m^{-3}). On-road median $PM_{2.5}$ concentrations for school children, private car commuters, and public transport commuters, respectively, were 56 (IQR: 49–75), 87 (IQR: 61–116) and 119 (IQR: 104–122) μg m^{-3}. These concentrations are more than twice the on-road concentrations seen in developed countries (Adams et al., 2001) and are among the higher reported values in the world. Comparable values in the literature for on-road or in-vehicle $PM_{2.5}$ include a reported near-traffic $PM_{2.5}$ concentration of 423 μg m^{-3} near roadways in Nanjing China (Wang et al., 2003) using an Anderson GT22001 HiVol and a reported mean exposure concentration of 190 μg m^{-3} for passengers of auto-rickshaws in New Delhi in the spring of 2010 (Apte et al., 2011) using a DustTrak. Similarly high values reported were in Guangzhou during the summer of 2001 and were 73, 101, 106, and 145 μg m^{-3} $PM_{2.5}$ in AC taxis, AC buses, non-AC taxis, and non-AC buses, respectively, (Chan et al., 2002) using a DustTrak and in Quetzaltenango and Guatemala City, Guatemala, in the summer of 1997 and were 120 and 150 μg m^{-3} in (Shendell and Naeher, 2002) using an Adams sampler (gravimetric measures on a PUF substrate). Reported near-roadway $PM_{2.5}$ concentrations in Bangalore, India, estimated using a filter-corrected nephelometer, were 56 and 68 μg m^{-3} in a middle- and low-income community, respectively (Both et al., 2011).

Vehicle air-conditioning appeared to yield only modest (6–15%) reductions in on-road $PM_{2.5}$ relative to non-AC vehicles. The median on-road concentration for traffic police was 78 (IQR: 61–92) μg m^{-3}. While exposure concentrations are less for traffic police than most commuters, police officers spend more than twice as long on the road since their entire 6-hour shift is on-road directing traffic. Exposures by traffic police during their commutes were not measured here.

Median particle counts were 30%–300% higher on-road than not on-road, similar to or slightly larger than the 30%–200% difference seen with $PM_{2.5}$. Particle counts were similar for public transportation commuters (AC and non-AC) and for private car commuters without AC (approximately 400,000 cm^{-3}). School children using a variety of transport modes and private car commuters with AC experienced similar median particle concentrations (approximately 140,000 cm^{-3}). CPC measurements at home or at the office/school were typically around 100,000 cm^{-3}, however the measurements were taken

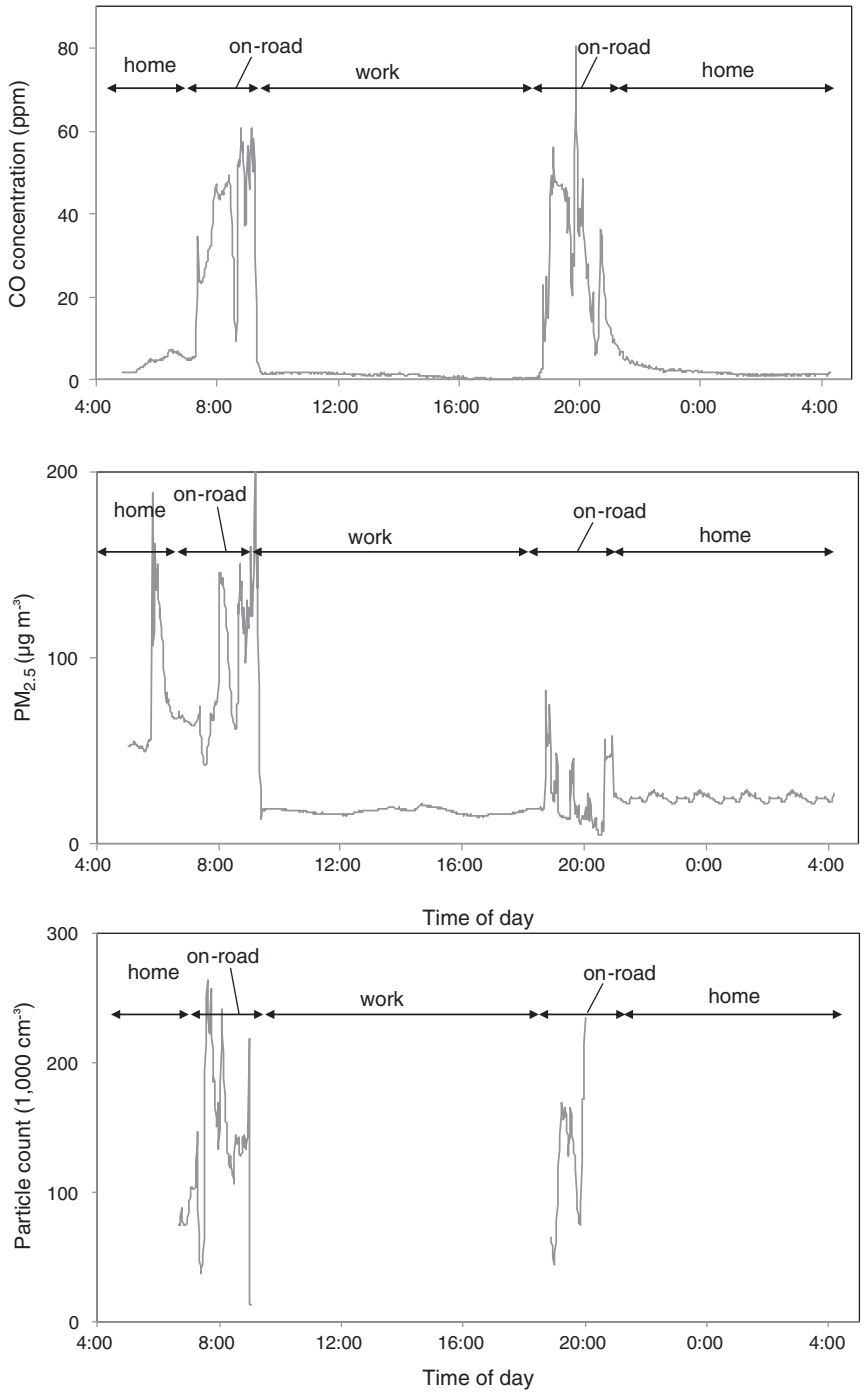

Fig. 4. Sample 1-day data for CO, $PM_{2.5,}$ and particle count in a private car commuter with AC on June 7th showing subject location.

immediately before or after the commute, and thus the recorded concentrations may not represent an average of all time spent in these locations. Air-conditioning had a substantial effect for private car commuters, reducing particle counts by 60%, while having only a minor effect for public transport commuters. Ventilation settings in a vehicle have been shown to have a strong effect on UFP exposure (Hudda et al., 2011; Knibbs et al., 2010; Zhu et al., 2007).

Mann–Whitney U tests (Fig. 6) indicate that commuting exposure for public transport users are significantly higher ($p<0.05$) than for private car commuters ($PM_{2.5}$), for school children (all three pollutants), and for traffic police (CO, $PM_{2.5}$ [no police CPC data]). Subject groups without a statistically significant difference in Fig. 6 are labeled with the same letter (a, b, or c) above the column. Fig. 6 compares the straightforward measurements per person, without attempting to correct for day-to-day differences in regional ambient concentrations. Because measurement days for each sub-group were scattered randomly throughout the study, we do not consider this aspect to be a major limitation in interpreting Fig. 6 (i.e., based on the study design, it is unlikely that differences in Fig. 6 merely reflect random variation in regional pollution and do not point to true differences among the subgroups studied).

3.3. Population exposure estimates

Time spent on-road (Fig. 2) appears to be a strong contributor to subjects' daily exposures. Although in-vehicle concentrations were

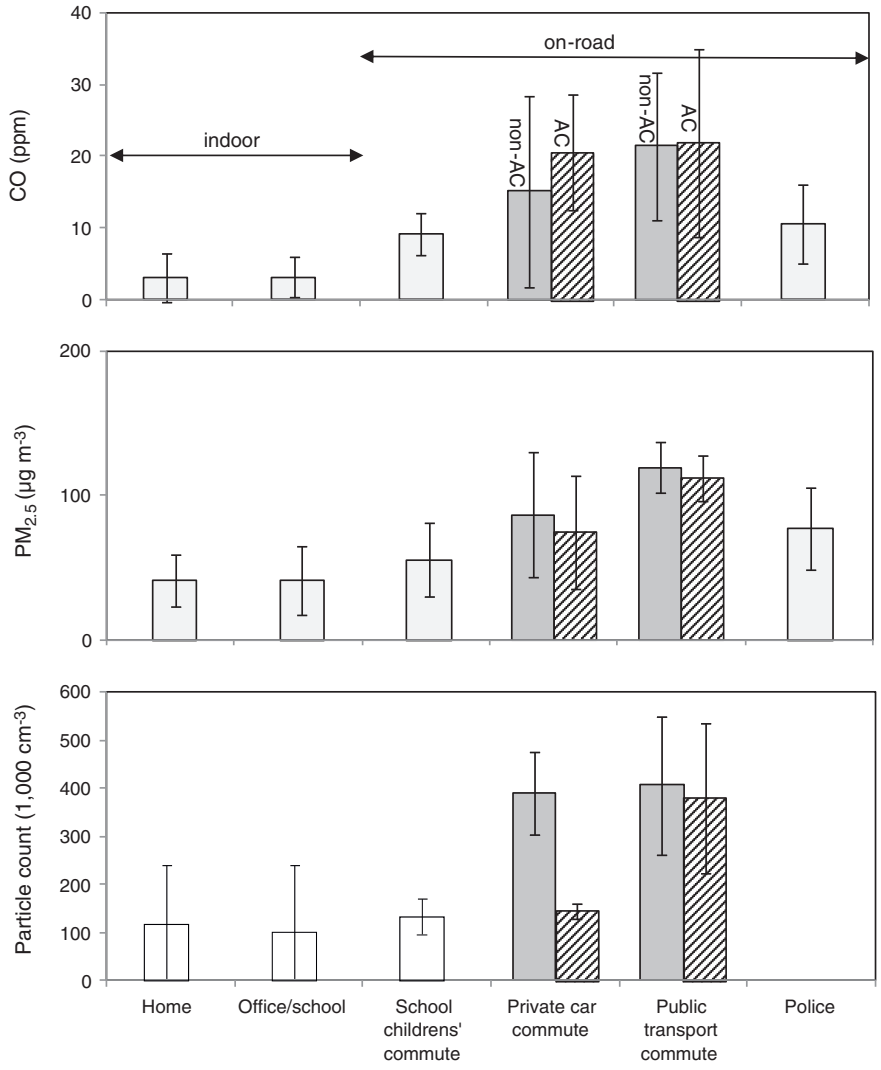

Fig. 5. Median exposure by subject group and location for CO (upper plot), $PM_{2.5}$ (middle plot), and particle counts (lower plot). Error bars represent one standard deviation.

22% ($PM_{2.5}$) and 54% (particle counts) higher for public transport commuters than for private car commuters, the private car commuters typically spent 25% more time on the road than public transport commuters (3 h vs. 2.3 h), potentially increasing the amount of pollution inhaled.

Typical commute modes are given in Fig. 1. Many commuters (39–63%, among surveys in Fig. 1) use some form of public transit (trains, busses, small busses, three-wheelers). Only 15–35% use motorcycles or private cars. Private car use is the only mode of commuting that is increasing in proportion to the other categories and is projected to more than double from 2000 to 2020 (JICA and NDPI, 2004).

Based on our measurements, we estimated daily exposures for the 24-hour monitoring groups (school children; private car commuters) in terms of exposure multiplied by time ("time-exposure"). These estimates were derived straightforwardly: mean pollutant concentrations for each individual were multiplied by the mean time spent on-road and at-work. Remaining time was assumed to be at home. Findings are shown in Fig. 7. Relative to school children, private car commuters had a higher daily time-exposure for all three pollutants, and a higher percentage of time-exposure from commute for all three pollutants (117% higher for CO, 50% higher for $PM_{2.5}$; 88% higher for particle count). For $PM_{2.5}$ and UFP, the fraction of total time-exposure due to commuting was 25%, which is in the range of estimates for the United States and Europe. Wallace and Ott (2011) calculated an in-vehicle time-exposure contribution of 17% for a range of city-to-city trips on both coasts, taking other microenvironments into account, while Fruin et al. (2008) similarly estimated 36% for urban Los Angeles. Dons et al. (2011) estimated for participants in a Belgian study that transport/commute was responsible for 26% of their daily time-exposure to black carbon. Therefore, despite the very high in-vehicle concentrations, the concentrations of $PM_{2.5}$ and UFP outdoors and inside homes or offices are also proportionately higher in Jakarta. However, the nearly 60% of CO time-exposure coming from the commute for private car owners is an unexpectedly high fraction.

4. Summary and conclusions

This study provides real-time measurements for a variety of micro-environments in an area of the world seeing unprecedented growth in population, traffic, and air pollution. Travel mode, high micro-environmental concentrations, and travel time, as well as time at work, school or home, all contribute to overall exposure. For all three pollutants (CO, $PM_{2.5}$, particle counts), concentrations were higher in public transport than in private cars; however, private car commuters traveled different routes (i.e., different distances) and spent a substantially longer time on-road. The net result was that on-road exposure was greater for private car commuters than for

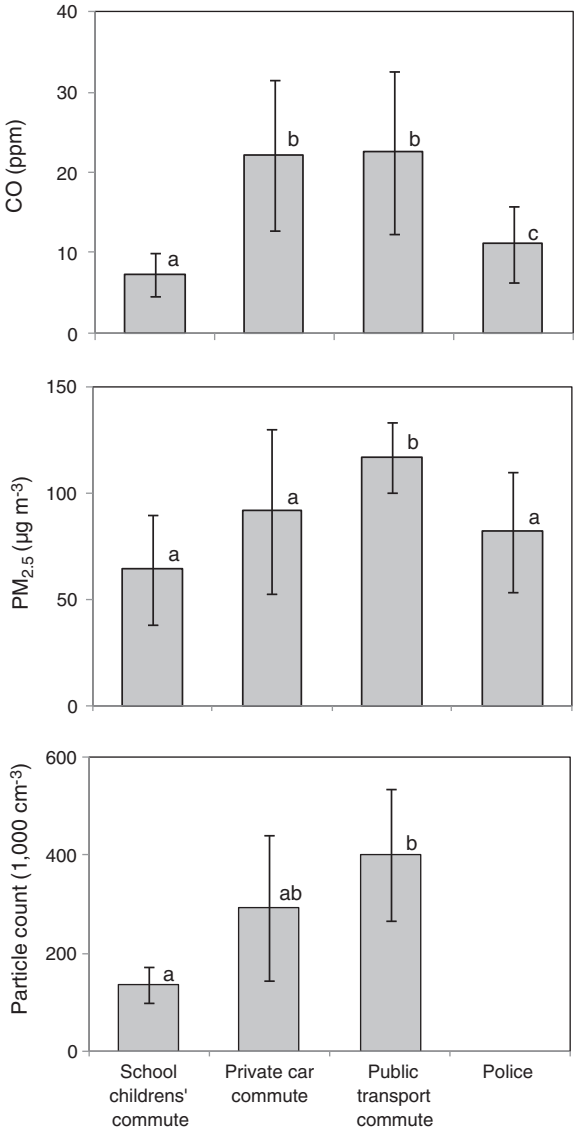

Fig. 6. Mean on-road concentrations by subject group and location for CO (upper plot), $PM_{2.5}$ (middle plot), and particle counts (lower plot). Error bars represent one standard deviation. Letters denote significant difference (Mann–Whitney [$p<0.05$]). For example, in the bottom panel, the first and last bars exhibit a statistically significant difference from each other, and the middle bar ("Private car commute") is not statistically different from the first or the last bars.

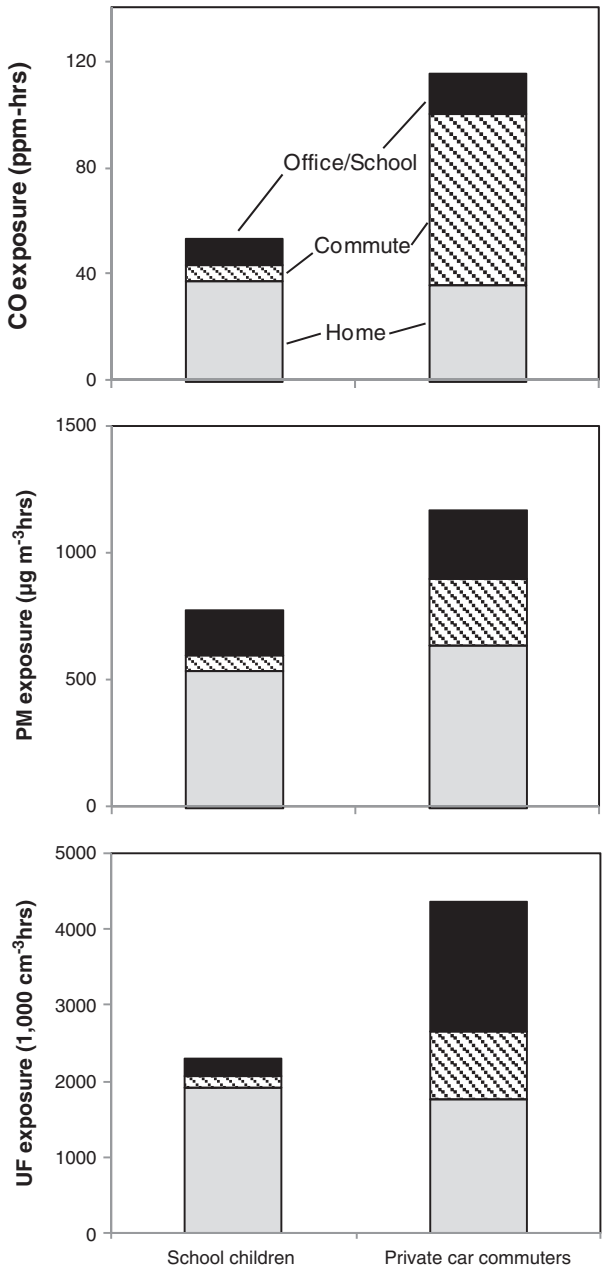

Fig. 7. Estimated daily exposure for the 24-hour monitoring groups, represented here as exposure times time.

public transport commuters. The police officers' exposures are especially of note because they spend 2–3 times more time on or near roads as commuters in this study. The findings of this study suggest that pollution exposures in Jakarta represent a health concern for school children and adults based on the relatively high concentrations and the amounts of time spent in and near vehicles.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2012.10.082.

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k) supplementary data

This online supplement contains one figure, showing raw data (mean concentrations) for each of the subjects.

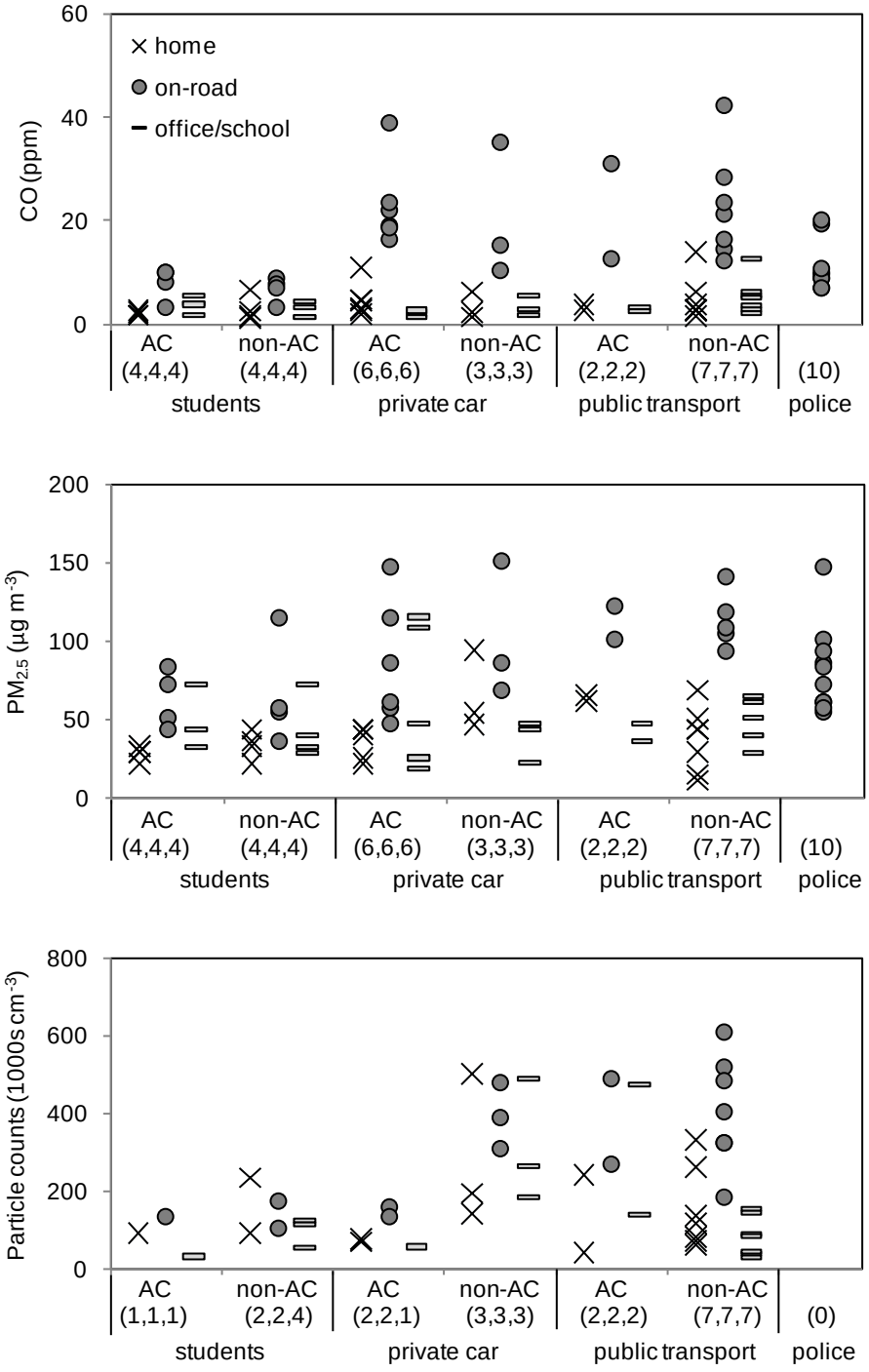

Fig. S1. Mean individual concentration for CO (upper plot), $PM_{2.5}$ (middle plot), and particle counts (lower plot) by subject group and location. AC refers to subjects with air-conditioning during their commute. Number of monitored subjects in parentheses.

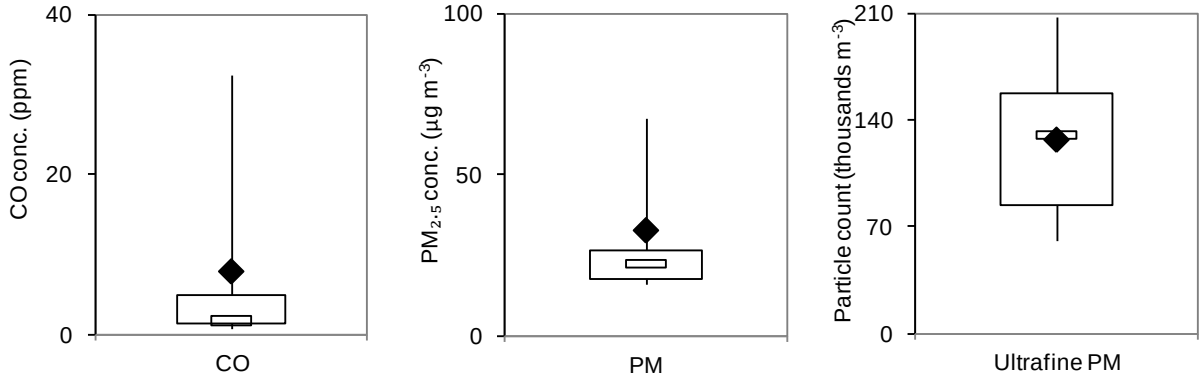

Fig. S2. Box plot of CO, $PM_{2.5,}$ and particle count of a private car commuter with AC on June 7th. Box plot displays 10th, 25th, 75th, and 90th percentile as well as mean (diamond) and median (rectangle) of data set.

1 k) Supplemental Information- Table S1

Author	Location	Pollutant	Mode of transport	Mean exposure	
Flachsbart et al. (1987)	Washington, USA	CO	Bus	4-8	ppm
			Train	2-5	ppm
Dor et al. (1995)	Paris, France	CO	Bus	4	ppm
			Subway	2	ppm
Fernandez-Bremauntz and Ashmore (1995)	Mexico City, Mexico	CO	Bus	21-41	ppm
			Metro	17-27	ppm
Praml and Schierl (2000)	Munich, Germany	PM_{10}	Bus	110-165	µg/m³
			Tram	161	µg/m³
Adams et al. (2001)	London, UK	$PM_{2.5}$	*Summer*		
			Cycling	35	µg/m³
			Bus	39	µg/m³
			Car	38	µg/m³
			Winter		
			Cycling	24	µg/m³
			Bus	39	µg/m³
			Car	34	µg/m³
Chan et al. (2002a)	Hong Kong	$PM_{2.5}$	Non-AC Bus	93	µg/m³
			AC Bus	51	µg/m³
Chan et al. (2002b)	Guangzhou, China	$PM_{2.5}$	Non-AC Bus	145	µg/m³
			Taxi	90	µg/m³
			AC Bus	106	µg/m³
			Subway	44	µg/m³
Dennekamp et al. (2002)	Aberdeen, UK	$PM_{2.5}$	Walking	median ~22	µg/m³
			Bus	median ~38	µg/m³
			Car	median ~11	µg/m³

Author	Location	Pollutant	Mode of transport	Mean exposure	
Levy et al. (2002)	Boston, USA	$PM_{2.5}$	Bus	median ~100	$\mu g\ m^{-3}$
			Car	median ~100	$\mu g\ m^{-3}$
Gomez-Perales et al. (2004)	Mexico City, Mexico	$PM_{2.5}$	Minibus	68	$\mu g\ m^{-3}$
			Bus	71	$\mu g\ m^{-3}$
Gulliver and Briggs (2004)	Northampton, UK	$PM_{2.5}$	Walking	15	$\mu g\ m^{-3}$
			Car	16	$\mu g\ m^{-3}$
Kaur et al. (2005b)	London, UK	$PM_{2.5}$	Walking	28	$\mu g\ m^{-3}$
			Cycling	34	$\mu g\ m^{-3}$
			Bus	35	$\mu g\ m^{-3}$
			Car	38	$\mu g\ m^{-3}$
			Taxi	43	$\mu g\ m^{-3}$
Gomez-Perales (2007)	Mexico City, Mexico	$PM_{2.5}$	Minibus	38	$\mu g\ m^{-3}$
			Bus	40	$\mu g\ m^{-3}$
Briggs et al. (2008)	London, UK	UFP	Car	21,600	$\#\ cm^{-3}$
		UFP	Walking	30,000	$\#\ cm^{-3}$
Weichenthal et al. (2008)	Montreal, Canada	UFP	Car	35,000	$\#\ cm^{-3}$
		UFP	Bus	25,300	$\#\ cm^{-3}$
		UFP	Walking	20,500	$\#\ cm^{-3}$
Boogaard et al. (2009)	Various, Netherlands	$PM_{2.5}$	Car	49.4	$\mu g\ m^{-3}$
		$PM_{2.5}$	Cycling	44.5	$\mu g\ m^{-3}$
		UFP	Car	24,300	$\#\ cm^{-3}$
		UFP	Cycling	24,300	$\#\ cm^{-3}$
Cattaneo et al. (2009)	Milan, Italy	UFP	Car	107,000	$\#\ cm^{-3}$
		UFP	Bus	117,600	$\#\ cm^{-3}$
		UFP	Walking	100,200	$\#\ cm^{-3}$

Author	Location	Pollutant	Mode of transport (sample size)	Mean exposure	
Int Panis et al. (2010)	Brussels, Belgium	PM_{10}	Cycling	62	µg m^{-3}
		PM_{10}	Car	35	µg m^{-3}
		UFP	Cycling	31,000	# cm^{-3}
		UFP	Car	30,000	# cm^{-3}
Knibbs and de Dear (2010)	Sydney, Australia	$PM_{2.5}$	Car	27.3	µg m^{-3}
		$PM_{2.5}$	Ferry	58.3	µg m^{-3}
		$PM_{2.5}$	Bus	33.4	µg m^{-3}
		$PM_{2.5}$	Train	35.8	µg m^{-3}
		UFP	Car	89,000	# cm^{-3}
		UFP	Ferry	55,000	# cm^{-3}
		UFP	Bus	105,000	# cm^{-3}
		UFP	Train	46,000	# cm^{-3}
Zuurbier et al. (2010)	Arnhem, Netherlands	UFP	Car	39,000	# cm^{-3}
		UFP	Bus	36,000	# cm^{-3}
		UFP	Cycling	44,300	# cm^{-3}
Apte et al. (2011)	New Delhi, India	$PM_{2.5}$	AC Car	110	µg m^{-3}
		$PM_{2.5}$	Non-AC	170	µg m^{-3}
		$PM_{2.5}$	Auto-Rickshaw	170	µg m^{-3}
		UFP	AC Car	100,000	# cm^{-3}
		UFP	Non-AC	180,000	# cm^{-3}
		UFP	Auto-Rickshaw	230,000	# cm^{-3}
This article	Jakarta, Indonesia	$PM_{2.5}$	Car	91	µg m^{-3}
		$PM_{2.5}$	Bus	117	µg m^{-3}
		CO	Car	22	ppm
		CO	Bus	23	ppm
		UFP	Car	294,000	# cm^{-3}
		UFP	Bus	401,000	# cm^{-3}

2