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On-road $PM_{2.5}$ pollution exposure in multiple transport microenvironments in Delhi

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HIGHLIGHTS

- Measurements of on-road $PM_{2.5}$ exposures in 11 transport microenvironments in Delhi.
- Traveling in auto rickshaw leads to 30% higher exposure rate than in an off-road location.
- Inside air-conditioned cars and metro carriages, the exposure rate is the lowest.
- $PM_{2.5}$ mass inhaled per km is 9 times for cycling compared to inside of an AC car.

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ABSTRACT

$PM_{2.5}$ pollution in Delhi averaged 150 μg/m^3 from 2012 through 2014, which is 15 times higher than the World Health Organization's annual-average guideline. For this setting, we present on-road exposure of $PM_{2.5}$ concentrations for 11 transport microenvironments along a fixed 8.3-km arterial route, during morning rush hour. The data collection was carried out using a portable TSI DustTrak DRX 8433 aerosol monitor, between January and May (2014). The monthly-average measured ambient concentrations varied from 130 μg/m^3 to 250 μg/m^3. The on-road $PM_{2.5}$ concentrations exceeded the ambient measurements by an average of 40% for walking, 10% for cycle, 30% for motorised two wheeler (2W), 30% for open-windowed (OW) car, 30% for auto rickshaw, 20% for air-conditioned as well as for OW bus, 20% for bus stop, and 30% for underground metro station. On the other hand, concentrations were lower by 50% inside air-conditioned (AC) car and 20% inside the metro rail carriage. We find that the percent exceedance for open modes (cycle, auto rickshaw, 2W, OW car, and OW bus) reduces non-linearly with increasing ambient concentration. The reduction is steeper at concentrations lower than 150 μg/m^3 than at higher concentrations. After accounting for air inhalation rate and speed of travel, $PM_{2.5}$ mass uptake per kilometer during cycling is 9 times of AC car, the mode with the lowest exposure. At current level of concentrations, an hour of cycling in Delhi during morning rush-hour period results in $PM_{2.5}$ dose which is 40% higher than an entire-day dose in cities like Tokyo, London, and New York, where ambient concentrations range from 10 to 20 μg/m^3.

1. Introduction

Majority of the population in Indian subcontinent is exposed to ambient particulate matter (PM) pollution levels much higher than World Health Organization (WHO) guidelines (Dey et al., 2012). According to Global Burden of Disease 2010 study, ambient PM pollution in India resulted in more than 600,000 deaths in 2010 (Lim et al., 2013). According to a database of PM_{10} (PM with aerodynamic diameter < 10 μm) pollution levels in more than 1600 cities in the world in 2014, more than 40 cities from India are among the 100 most polluted, with Delhi being the most polluted of all (WHO, 2014). The annual average $PM_{2.5}$ concentration for the period 2012 through 2014, reported by three air quality monitoring stations located across the city, was 150 μg/m^3, which is

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approximately 4 times (hereafter indicated by ×) higher than the national ambient standard and 15× higher than the WHO guideline.

The direct links between emissions, outdoor air pollution, and human health have been extensively documented (IHME, 2013). Epidemiological studies have also linked $PM_{2.5}$ as the robust indicator of adverse (mortality) impacts, and also the pollutant most linked to the vehicular exhaust emissions (Brauer et al., 2012). The negative health effects of traffic-related air pollution are also well documented (HEI, 2010). In on-road microenvironments, due to vicinity to tailpipe emissions, exposure to traffic-related PM is higher than those in off-road locations (Kaur et al., 2007). The travel-related exposure to on-road PM pollution has been quantified for different microenvironments, classified as travel modes, ventilation status (air conditioned or open windowed), type of travel routes, and meteorological conditions. Table 1 summarizes more than 20 studies in various settings from across the world, analyzing on-road exposure to $PM_{2.5}$ pollution. The range of concentrations in the table refers to the minimum and maximum reported average values among all the microenvironments (including on-road modes and ambient location, and excluding underground rail). Apte et al. (2011) is the only study from India looking at exposure in three-wheeled auto rickshaws, and most studies are from cleaner high-income settings in the USA and the Europe. The average ambient concentrations in these studies varied from 10 to 70 $\mu g/m^3$.

The cities in India differ significantly from the cities represented in Table 1. For instance, ambient $PM_{2.5}$ concentrations in Indian cities are 4–8 times higher than most high-income settings (Dey et al., 2012; WHO, 2014), and vehicle ownership levels, expressed as number of vehicles per 1000 persons, are at least an order of magnitude lower (IMF, 2005; MoRTH, 2012). In case of Delhi, this means, a majority of trips are carried out using non-motorised modes, 2W, and bus-based public transportation (Pucher et al., 2007; RITES, 2010), leading to higher exposure rates compared to cities represented in Table 1, for the same amount of travel. However, available literature has not adequately addressed the on-road exposure of these modes in Indian cities.

In this paper, we present an approach to assess the on-road exposure in various modes, analysis of the on-road exposure to $PM_{2.5}$ concentrations measured using optical PM monitor, and estimates of inhaled doses of $PM_{2.5}$ in 11 transport microenvironments – covering all motorised passenger-travel modes, walking, and cycling in Delhi.

2. Data and methods

2.1. $PM_{2.5}$ pollution in Delhi

A summary of $PM_{2.5}$ concentrations for years 2012 through 2014, reported by three continuous air-quality monitoring stations – Punjabi Bagh, Mandir Marg, and R K Puram – operated by the Delhi Pollution Control Committee (DPCC), is presented in Fig. 1. The figure shows daily-average trend as well as month- and hour-specific averages for the three-year period. The locations of the three stations are shown in Fig. 2. The particulate pollution in Delhi has a significant seasonal variation with highest concentrations during winter months from November through February (monthly average range– 200–250 $\mu g/m^3$), and the lowest during monsoon months from July through September (70–100 $\mu g/m^3$). The diurnal distribution of pollution shows the highest concentrations during late night hours (10 PM through midnight) and early morning and rush-hour period (8 AM through 10 AM), and the lowest during the afternoon hours.

2.2. Study route

For measuring on-road exposure of $PM_{2.5}$, we selected a route between Indian Institute of Technology Delhi campus (IIT), located in the southern part of the city at Aurobindo Marg, and Union Public Service Commission office (UPSC), located at Shahjahan Road (see Fig. 2). The two end points for the study route were a bus stop in front of IIT located at the southbound approach of Aurobindo Marg, and the bus stop in front of UPSC at the southbound approach of Shahjahan Road. The total distance covered was 8.1 km; 5.6 km was traveled on Aurobindo Marg, 1.7 km on Prithviraj Road, and 0.8 km on Shahjahan Road. Along the route, ward-level built-up density is ~200 persons per hectare (pph), compared to Delhi's overall density of 260 pph. Aurobindo Marg is one of the major arterial roads in Delhi running north-south, and caters to both inter-city as well as

Table 1

$PM_{2.5}$ exposure studies for transport microenvironments (AR = auto rickshaw).

Study	Study year	City	Walk	Cycle	2W	Car	AR	Bus	Train	Tram	$PM_{2.5}$ ($\mu g/m^3$)
Rodes et al. (1999)	1997	Sacramento and Los Angeles (USA)				*		*			2–89
Pfeifer et al. (1999)	1996	London (UK)				*			*		24–33
Adams et al. (2001)	1999–2000	Central London (UK)		*		*		*	*		13–39
Chan et al. (2002a)	1999–2000	Hong Kong						*	*	*	33–97
Chan et al. (2002b)	2001	Guangzhou (China)				*		*	*		73–145
Riediker et al. (2003)	2001	North Carolina (USA)				*					22–24
Gomez-Perales et al. (2004)	2002	Mexico City (Mexico)						*	*		68–71
Gulliver and Briggs (2004)	1999–2000	Northampton (UK)	*			*					15–55
Chertok et al. (2004)	2002	Sydney (Australia)				*					8–30
Kaur et al. (2005)	2003	Central London (UK)	*	*		*		*			10–42
Aarnio et al. (2005)	2004	Helsinki (Finland)							*		10–17
Fondelli et al. (2008)	2004	Florence (Italy)				*		*			19–60
Fruin et al. (2008)	2003	Los Angeles (USA)				*					8–110
McNabola et al. (2008)	2005–2006	Dublin (Ireland)	*	*		*		*			63–128
Briggs et al. (2008)	2005	London (UK)	*			*					3–13
Tsai et al. (2008)	2005	Taipei (Taiwan)			*	*		*	*		22–68
Boogaard et al. (2009)	2006	Various cities (Netherlands)		*		*					6–122
Morabia et al. (2009)	2007–2008	New York (USA)	*			*			*		13–24
Zuurbier et al. (2010)	2007–2008	Arnhem (Netherlands)		*		*		*			34–115
Apte et al. (2011)	2010	Delhi (India)				*	*				110–170
de Nazelle et al. (2012)	2009	Barcelona (Spain)	*	*		*		*			21–35
Quiros et al. (2013)	2011	California (USA)	*	*		*					3–11
Weichenthal et al. (2015)	2010–2013	Montreal and Vancouver (Canada)				*					1–56

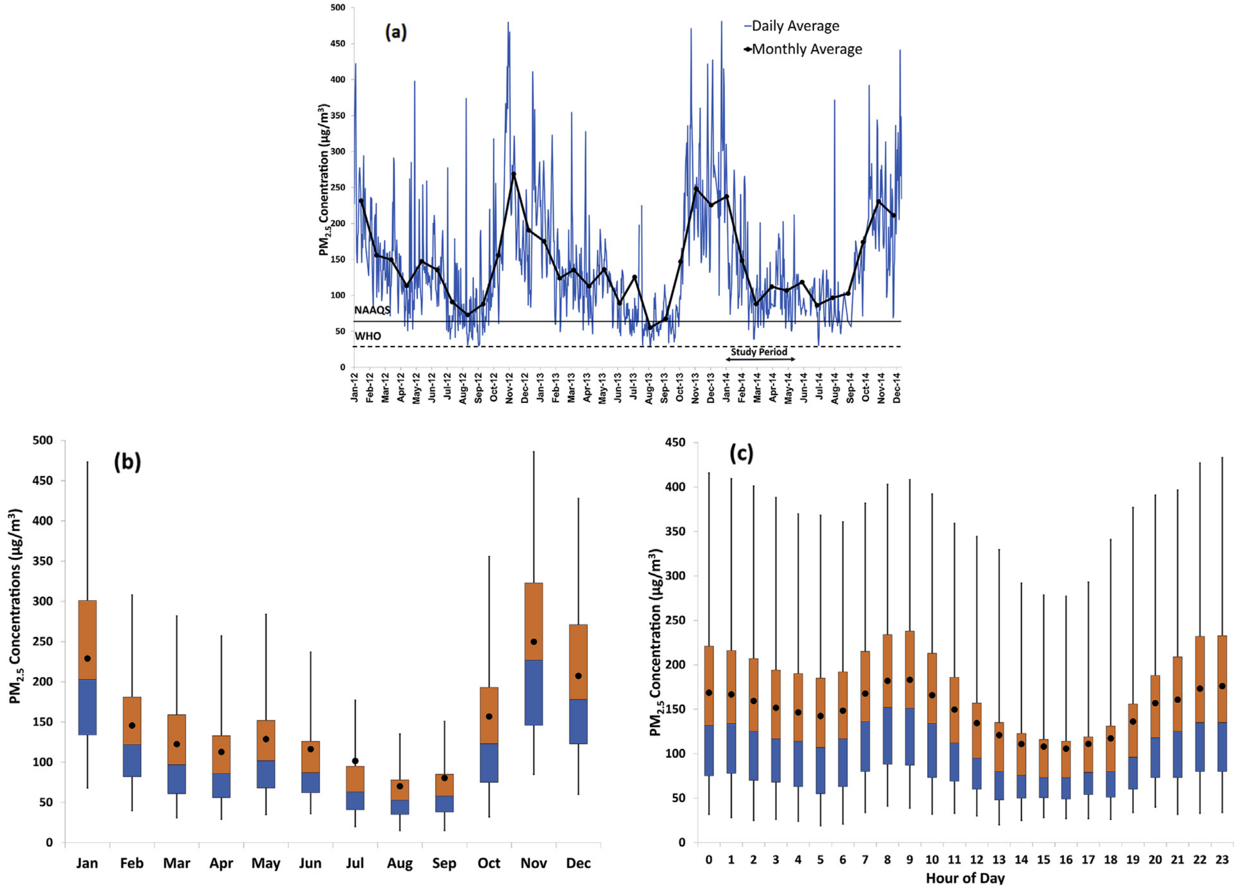

Fig. 1. (a) Daily and monthly average $PM_{2.5}$ concentrations between January 2012 and December 2014 (b) Monthly variation in $PM_{2.5}$ concentrations in 2012, 2013, and 2014 (c) Diurnal variation in $PM_{2.5}$ concentrations in 2012, 2013, and 2014. For (b) and (c), the dot represents the mean; box plot represents 25th and 75th percentile, with median at the break; and whiskers represent the 5th and 95th.

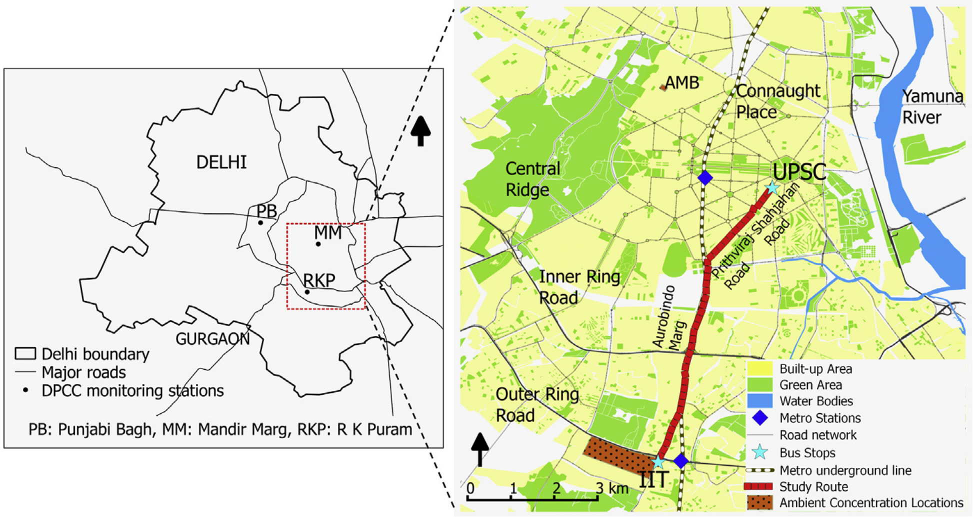

Fig. 2. DPCC ambient air quality monitoring stations and on-road pollution exposure study route in Delhi.

intra-city traffic. The road connects Delhi with Gurgaon, the satellite city to the south of Delhi, and passes through highly dense residential areas within southern part of Delhi. Thus the selected route is likely representative of the daily traffic conditions experienced by a traveler in Delhi region.

The average number of vehicles operating on Aurobindo Marg from 8 AM to noon is 5100 per hour, with 52% cars, 27% 2W, 18% auto rickshaws, 2% buses and mini-buses, and less than 1% of light commercial vehicles with no 2-axle or multi-axle trucks (CRRI, 2012). The absence of trucks in the vehicular mix is because heavy-duty diesel-based trucks are allowed to operate within the city only from 9 PM to 6 AM. On Prithviraj Road and Shahjahan Road, no commercial goods vehicles are allowed as they are located under the jurisdiction of New Delhi Municipal Corporation (NDMC), which disallows the movement of commercial vehicles throughout the day. The first 4.1 km of the route north of IIT is heavily populated and has commercial land-use along the roadside – mostly retail shops. The rest of the route northward lies within the jurisdiction of NDMC, is much less populated, and has federal government offices and residential settlements for their staff members, with almost no commercial land-use along the route.

2.3. Data collection

Our data collection spanned from January through May 2014, and was carried out over 41 days during the five-month period. For on-road travel, we recorded $PM_{2.5}$ concentrations, along with relative humidity (RH), geographical location, as well as speed of travel. The study months were selected as they cover a wide range of $PM_{2.5}$ concentrations, from very high in January to comparatively lower in May (see Fig. 1b). Also, this time of year has no rainfall which is required for the ease of data collection. Only a single instrument was used for measuring $PM_{2.5}$ concentrations, therefore, simultaneous measurements of ambient and in-vehicle concentrations were not possible. Thus, ambient $PM_{2.5}$ concentrations were measured at the beginning and the end of the on-road trips.

We define a trip as a one-way journey between IIT and UPSC, regardless of the direction. The group of consecutive trips between the two sets of ambient concentration measurements will be referred to as a tour. We made a total of 75 tours, consisting of 150 trips, from 8 AM to 1 PM, with 27 of those trips lasting past noon. The time period was selected to capture the rush hour traffic movement. Among all the tours, 6 included more than 2 trips, and the rest included 2 or fewer. We started most tours from IIT, in which case we measured ambient concentrations in a green space in IIT campus at the beginning as well as at the end of the tour. For a few tours with only one trip, on one end, we measured ambient concentrations at a house (second floor, balcony, height ~ 6 m) in a residential locality within 3 km of UPSC (see AMB in Fig. 2), and on the other end, at IIT. Except for 12 tours, we used only one mode of travel. For 34 out of 75 tours, we measured ambient concentrations only in the beginning or in the end. We did not consider the trips that were discontinued in the middle due to long traffic jams, road-closures, or bus-route detours.

The measurements were made in a total of 11 different types of microenvironments, covering all motorised passenger travel-modes operating in Delhi. This included 8 travel modes – cycle, 2W, open-windowed car (OW car), air-conditioned car (AC car), auto rickshaw, open-windowed bus (OW bus), air-conditioned bus (AC bus), and metro. The air-conditioners of cars were set to recycled air mode. For metro, we traveled on the Yellow line from Hauz Khas station (closest to IIT) to Udyog Bhawan station (closest to UPSC), which is the underground line parallel to study route. The metro platforms, as well as the coaches, are air-conditioned. Out of ~190 km of existing Delhi metro network, 48 km is underground, while the rest is elevated. The two stations are shown in Fig. 2. There are no bicycle lanes along the study route.

Rest of the 3 microenvironments are walk, and two types of public transport (PT) stops – bus stops (close to IIT and UPSC), and metro station. Unlike other modes, walking was carried out only for traveling to bus stops and crossing the road. The measurements for bus stops and metro stations were carried out for the duration of waiting for bus and metro, respectively.

2.4. Instruments

We measured $PM_{2.5}$ concentrations using a portable DustTrak (DT) DRX Aerosol Monitor (Model 8533, TSI Inc., USA), which employs light scattering for real-time mass determination (TSI, 2012). The instrument has factory calibration of A1 Arizona ultrafine test dust (ISO 12103-1), at a relative humidity (RH) of 29%. Average RH values for the days of our data collection are – 62% (January), 45% (February), 45% (March), 36% (April), and 31% (May). Comparison of RH and wind speed values to those of previous years show that meteorological conditions are representative of this time of year in Delhi (see Supplementary Material (SI)). In order to account for the error in the measurement of the instrument due to RH, we used the correction reported by Ramachandran et al. (2003), also used by Apte et al. (2011) for their $PM_{2.5}$ exposure study in Delhi. The corrected $PM_{2.5}$ reading is referred to as $PM_{2.5\text{RH-corrected}}$. In addition, we calibrated the DT using gravimetric sampling, in which we co-located the gravimetric sampler (cyclone and filter) at IIT campus and a roadside location. The description of the calibration process is provided in the SI. The calibration factor was generated to correct the RH-corrected readings from DT. The RH-correction and the calibration equation are shown in equations (1) and (2).

$$PM2.5_{RH-Corrected} = \frac{PM2.5_{DT}}{1 + 0.25\,\frac{RH^2}{1-RH}} \tag{1}$$

$$PM2.5 = 1.34\ (PM2.5_{RH-Corrected})^{0.93} \tag{2}$$

To measure RH, we used a portable instrument (HOBO, Model U10-003, Onset Computer Corporation, Massachusetts, USA). For logging time stamp, geographic location (latitude and longitude), and speed of movement, we used a GPS unit (Model AGL3080, AMOD Technology Company, Taipei, Taiwan). The GPS device is based on SiRF-III technology and has a positional accuracy of 10 m. We used a frequency of 1 Hz for the three instruments and synchronized the data. The three instruments were carried by a volunteer using a backpack. The DT was kept in the backpack with the inlet of the conductive tube set at the breathing level of the volunteer. Further, the DT was padded inside the backpack to avoid sudden jerks during the movement of volunteer. The RH instrument and GPS unit were strapped to the outside of the backpack. All volunteers who contributed to data collection for this study were non-smokers.

2.5. Data analysis

2.5.1. In-vehicle and ambient concentrations

Out of 75 tours, we measured ambient concentrations on both ends of the tours for 41 tours, and for the rest, we measured ambient concentrations at either the beginning or the end of the tour. Note that a tour may have more than one microenvironment. For the cases when ambient concentrations were measured at both ends of a tour, we averaged the concentration readings at the two ends, and considered those as ambient concentrations corresponding to the on-road measurements. To give equal weightage to the concentration readings for the two ends, we considered equal duration of measurement on both ends (average total duration of measurements at the two ends ~7 min; average difference between the two sets of measurements ~70 min). For the cases when ambient concentrations were measured only at the beginning or at the end of the tours ($n = 34$), we used a correction factor to account for the missing concentration on one end (see SI).

2.6. Ratio of in-vehicle and ambient concentrations (Υ)

We calculated the ratio of average in-vehicle concentrations to the average ambient concentrations, referred to as ϒ. Thus, ϒ-1 indicates the fraction by which in-vehicle concentrations exceeds ambient concentrations. For each mode, number of ratios calculated is equal to the number of tours made using that mode. Table 2 shows duration of measurement as well as overall average concentration values for different microenvironments, classified by month, and Table 3 presents the number of tours and number of one-way trips for each microenvironment.

2.6.1. Inhaled dose

For inter-modal comparisons, concentrations are not sufficient to evaluate the full extent of the differences between the mass of pollutants inhaled by different road-user types. This is because pollution dose, i.e. the mass of pollutant inhaled, is also dependent on the minute ventilation rates (VR), which is a measure of amount of air inhaled per unit time, expressed in litres/minute. To estimate inhaled doses in various travel modes, we used distance-based and duration-based approaches. In the former, doses are estimated for a given distance, which takes speed of travel in to account, and in the latter, dose is estimated for a given duration of on-road travel. For both approaches, we estimated the dose for 5 km of travel, and for the former, expressed it as per km and, for the latter, as per 15-min duration. For these estimates, we assumed an ambient concentration of 165 μg/m^3, which is the annual average concentration from 8 AM through 12 noon. The average travel speed calculated from GPS data and VR values for each microenvironment reported by USEPA (2011) are presented in Table 3. For PT modes (bus and metro), we also assumed 15-min out-of-vehicle movement of passengers – 10 min of walking for access and egress, and 5 min of waiting at bus stops and metro stations, respectively. The detailed equations for calculation of inhaled dose are provided in SI.

3. Results and discussion

3.1. Seasonal variation of ambient and in-vehicle concentrations

Our data collection includes winter (January), spring (February–March), and summer (April–May) seasons (see Table 2). The measured average (±standard deviation) ambient $PM_{2.5}$ concentration during March through May (150 ± 109 μg/m^3) was significantly lower than that in January and February (231 ± 113 μg/m^3). The variation of $PM_{2.5}$ concentrations over months can also be observed for different on-road microenvironments. Average in-vehicle concentrations for AC bus vary from 315 μg/m^3 in January to 140 μg/m^3 in April. Similar findings of seasonal variation of in-vehicle exposure of $PM_{2.5}$ in Delhi were reported by Apte et al. (2011). The large variation over the months is due to the significant effect of meteorology on PM pollution in Delhi (Guttikunda and Gurjar, 2012). The seasonal variation is more significant in some modes than others. This is because not all modes were studied simultaneously, and, even during summer months, some days have ambient concentrations as high as during winters.

3.2. Ratio of in-vehicle and ambient concentrations (ϒ)

The average ϒ values along with their 95% confidence intervals are shown in Fig. 3. AC car has the lowest average value of 0.5, followed by metro's 0.8, and for all other microenvironments, average values vary from 1.1 to 1.4. The ratios can be interpreted for inter modal comparisons. For instance, average ratios indicate that a 2W rider is exposed to 2.6× higher concentrations than a passenger in an AC car. We compared the average ϒ values estimated for cases in which ambient concentration measurements were done on both ends of the tours with the cases with ambient concentration only on one end (see SI). We found that the two sets of estimates differ by 10–20%.

The value of ϒ estimated for open modes in this study (1.3) is similar to the ratio (1.5) reported by Apte et al. (2011), also for Delhi, and to the ratio of near-road to off-road locations (1.1), in Bangalore (2011 population– 8.5 million, located in southern part of India), reported by Both et al. (2011). Among the studies presented in Table 1, we reviewed studies which reported concentrations for on-road microenvironments as well as ambient location, and calculated corresponding ϒ values. For cycling, ϒ varied from 1.5 to 3.4 with an average of 2.0 (Adams et al., 2001; de Nazelle et al., 2012; Fondelli et al., 2008; McNabola et al., 2008; Zuurbier et al., 2010),

Table 2
Duration of measurement in minutes and $PM_{2.5}$ concentrations (average, median, 5th percentile and 95th percentile) in μg/m^3 for different microenvironments (AR = auto rickshaw; MS = metro station).

Month	Location	Ambient	Walk	Cycle	2W	OW car	AC car	AR	OW bus	AC bus	Bus stop	Metro	MS
January	Duration	79	35	139	–	–	–	22	72	89	132	–	–
	Average (SD)	253 (80)	231 (72)	347 (94)	–	–	–	255 (139)	295 (62)	315 (105)	248 (94)	–	–
	Median	217	208	338	–	–	–	240	284	319	205	–	–
	p5	180	175	263	–	–	–	178	220	136	166	–	–
	p95	380	333	442	–	–	–	328	399	470	383	–	–
February	Duration	183	79	630	–	–	–	346	190	147	280	–	–
	Average (SD)	220 (121)	278 (223)	285 (141)	–	–	–	241 (136)	293 (131)	278 (143)	301 (141)	–	–
	Median	211	248	270	–	–	–	236	280	247	319	–	–
	P5	66	104	129	–	–	–	87	87	128	98	–	–
	P95	425	491	509	–	–	–	430	492	517	482	–	–
March	Duration	65	53	–	–	–	–	240	106	150	127	–	–
	Average (SD)	132 (71)	149 (102)	–	–	–	–	159 (113)	187 (173)	132 (118)	176 (105)	–	–
	Median	93	117	–	–	–	–	137	160	102	158	–	–
	P5	50	59	–	–	–	–	58	79	50	57	–	–
	P95	270	315	–	–	–	–	318	350	284	311	–	–
April	Duration	209	82	–	529	385	501	28	24	45	112	85	27
	Average (SD)	157 (122)	234 (184)	–	207 (139)	180 (105)	56 (44)	257 (295)	277 (77)	140 (56)	195 (87)	87 (141)	141 (29)
	Median	116	186	–	162	164	49	207	277	129	178	83	141
	P5	48	84	–	78	68	18	96	207	88	89	56	97
	P95	380	485	–	519	308	123	431	348	218	325	110	186
May	Duration	18	4	–	–	–	–	39	–	27	32	66	43
	Average (SD)	133 (51)	159 (122)	–	–	–	–	187 (330)	–	113 (35)	120 (38)	76 (20)	142 (41)
	Median	130	127	–	–	–	–	146	–	109	116	74	140
	P5	73	101	–	–	–	–	85	–	84	94	60	73
	P95	195	334	–	–	–	–	325	–	153	154	100	195

Table 3
Summary of trips for different microenvironments.

Microenvironment	Number of tours	Number of one-way trips	Average travel time for one-way trip (minutes)	Speed (km/h)	Minute ventilation (Litres/minute)
Cycle	12	24	28	17	35
2W	12	21	20	24	10
OW Car	8	16	24	20	10
AC Car	10	20	24	20	10
Auto rickshaw	16	27	22	22	10
OW Bus	12	15	28	14	10
AC Bus	14	18	24	20	10
Metro	5	9	14	32	10
Walk	50	–	–	4	15
Bus stop	46	–	–		10
Metro station	6	–	–		10

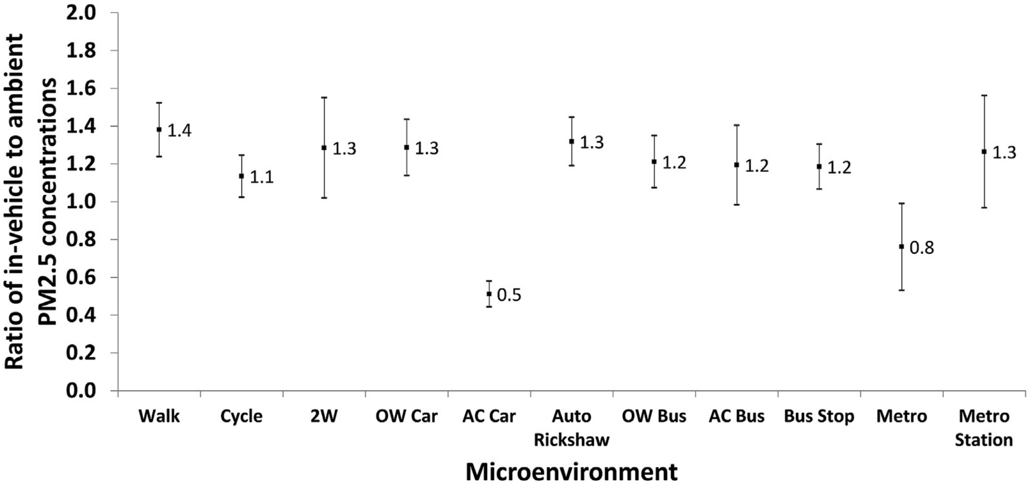

Fig. 3. Ratio of in-vehicle and ambient $PM_{2.5}$ measurements during the on-road exposure study in multiple transport micro-environments in Delhi.

and for cars, from 0.7 to 3.8 with an average of 2.1 (Adams et al., 2001; de Nazelle et al., 2012; McNabola et al., 2008; Riediker et al., 2003; Zuurbier et al., 2010) in the cities of high-income European countries and the USA. In these settings, average ambient concentrations varied from 10 to 70 $\mu g/m^3$, compared to monthly averages of 130–250 $\mu g/m^3$ over the period of our study. The values of Υ estimated in our study (1.1 for cyclists and 0.5 for AC car) are clearly much lower. This indicates a higher correlation between in-vehicle and ambient concentrations in Delhi than in cleaner settings. However, even with lower difference between ambient and on-road concentrations, in-vehicle exposure in Delhi is an order of magnitude higher than those reported from the cleaner settings.

Higher values of Υ in high-income countries with low pollution levels are likely because air in those settings may be polluted largely along the roads and much cleaner otherwise. This is in contrast with low-income countries, such as India, where share of emissions from non-vehicular sources is also significant, resulting in high background concentrations. For instance, for a highly-trafficked location in Delhi, Pant et al. (2015) reported 16–19% of $PM_{2.5}$ concentrations attributed to primary vehicular exhaust. On the other hand, for major urban settings in France and the UK, share of traffic-related sources to PM pollution has been reported to be higher than 40% (AIRPARIF, 2012; Lawrence et al., 2013). This is because, in high-income countries, industrial emissions have reduced as a result of stringent emission standards, domestic emissions as a result of universal use of gas-based fuels or electricity, and diesel-generator emissions as a result of adequate power availability. All these sources, on the other hand, continue to be significant contributors to PM pollution in Indian cities (Guttikunda et al., 2014).

We found that the underground rail (metro) has 20% lower $PM_{2.5}$ concentrations than the ambient location. In contrast, studies from London, Stockholm, and New York have reported up to 5× to 20× higher $PM_{2.5}$ concentrations in the underground rail than the outside levels (Adams et al., 2001; Johansson and Johansson, 2003; Vilcassim et al., 2014). This difference between the concentrations in metro systems is possible due to difference in the material of the wheels, ventilation levels, and breaking systems (Nieuwenhuijsen et al., 2007).

3.2.1. *Relationship with ambient concentrations*

For the open modes, we calculated average Υ classified by four ranges of corresponding ambient concentrations – lower than 100, 100–200, 200–300, and higher than 300 $\mu g/m^3$. For this analysis, we excluded walk, as its exposure was not measured along the route, unlike other modes. The average Υ values for the four categories are 1.6, 1.3, 1.1, and 1.0, respectively. A plot of Υ values and ambient concentrations is presented in Fig. 4, with a logarithmic curve fitted over the data points ($n = 60$). The ratios reduce non-linearly as the ambient concentrations increase, with steeper reduction at concentrations lower than 150 $\mu g/m^3$ than at higher concentrations. This trend is likely to arise if the concentrations contributed by vehicles are largely constant and, as the background concentrations increase, the percent share of concentrations contributed by vehicles reduces. This is also indicated by the seasonal differences in the source-apportionment of $PM_{2.5}$ in Delhi. For instance, during winter months, concentrations increase due to additional PM sources such as burning of wood and biomass for heating purposes, as well as operations of brick kilns and, as a result, share of vehicular exhaust in overall PM pollution reduces

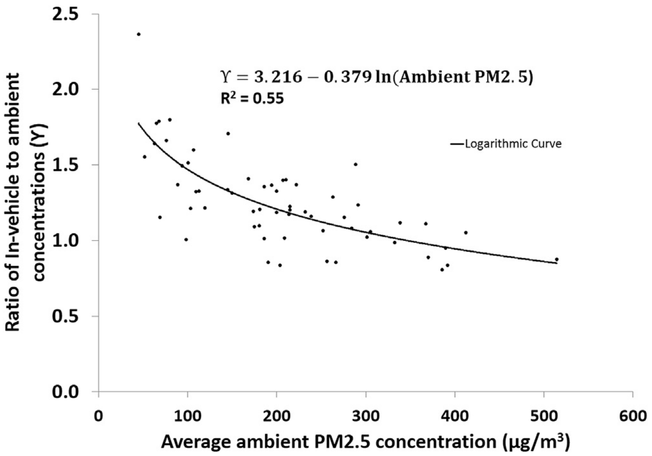

Fig. 4. Variation between the ratio of in-vehicle to ambient $PM_{2.5}$ measurements for all open modes and ambient $PM_{2.5}$ measurements in Delhi.

(Chowdhury et al., 2007; Guttikunda and Calori, 2013; Pant et al., 2015).

The variation of ϒ with ambient concentration is likely to have an effect on the representativeness of our results, as the measurements for different modes were not carried out simultaneously, and, as a result, ambient concentrations varied significantly for different modes (see Table 1). The scatter plot of ϒ and ambient concentrations, classified by mode, has been presented in the SI. In order to control for the differences in the ambient concentration levels for different modes, we calculated mode-specific average ϒ values classified by two levels of ambient concentration – <150 μg/m^3 and >150 μg/m^3 (see Table 4). For all travel modes, average values of ϒ are higher in the former category (<150 μg/m^3) than those in the latter, except AC car with equal values for the two categories. The largest difference in ϒ values between the two categories is for 2W (1.0 versus 1.7), while all other modes differ within a range of 0.1–0.3. For the four microenvironments – cycle, auto rickshaw, AC bus, and OW bus, significantly higher number of trips were carried out for >150 μg/m^3 than for <150 μg/m^3 (see Table 4). Given that the differences lie within 0.1–0.3, ϒ values for the four microenvironments is only moderately underestimated.

3.2.2. Differences due to driving behavior

Cycles and 2W have no enclosure compared to any other travel mode, except walking. An interesting finding is that cycle, though completely unenclosed, does not have significantly higher ratios than other open modes. This is likely because, unlike auto rickshaws, cars, and buses, cyclists often travel on the left-most part of the carriageway (traffic movement in India is left-hand) and also move ahead of the queued-up vehicles at a traffic signal, or during congestion. The effect of lateral position of cyclists on their exposure to pollution have been highlighted earlier by various other studies as reported in a review by Bigazzi and Figliozzi (2014).

Similar to cyclists, 2W drivers also move ahead of the queued-up traffic. However, unlike cyclists, 2W are driven within the stream of traffic, due to their ability to move as fast as other motorized modes. For concentrations lower than 150 μg/m^3, 2W has the highest ϒ value, while for the concentrations higher than 150 μg/m^3, ϒ value is within the same range as other modes. Thus, between cyclists and 2W drivers, lateral position of the former contributes significantly in their reduction of exposure. For Taiwan, Tsai et al. (2008) also reported the highest exposure to PM by motorcyclists (average ~ 68 μg/m^3) compared to bus commuters, rail users, and car drivers.

3.2.3. Differences due to ventilation conditions

The modes of transportation considered in this study can be classified as open and closed, based on the type of their enclosure. Open modes are those which have surrounding air circulating in the vehicles – walk, cycle, 2W, OW car, auto rickshaw, and OW bus. The closed modes are AC car, AC bus, and metro. It can be seen that, in general, open modes have higher ϒ values than closed ones (see Fig. 3 and Table 4). In case of cars, the ventilation status resulted in the exposure difference between an AC and OW car by a factor of more than two (average ϒ of 0.5 and 1.3, respectively). We found no difference between exposure of auto rickshaw and OW car. This is similar to the findings reported by Apte et al. (2011) for the two travel modes.

In case of buses, ventilation status results in no difference, which is likely because of opening and closing of bus doors at bus stops. These findings are different from those reported from other settings. For instance, the studies carried out in Hong Kong (Chan et al., 2002a) and Guangzhou, China (Chan et al., 2002b) showed a significant effect of ventilation condition on $PM_{2.5}$ exposure in a bus. The studies showed that OW buses have an average $PM_{2.5}$ concentration up to 40–50% higher than AC buses. The difference between the findings is likely because of other factors which have not been accounted for, such as air circulation system of air-conditioners in the buses, according to which air intake from outside the bus may vary, leading to intake of $PM_{2.5}$ from outside. During our data collection in AC buses, volunteers observed that the window next to the driver was often open, which drivers used for hand signals. The two studies from Hong Kong and Guangzhou also mentioned the same observation.

Table 4
Average in-vehicles to ambient PM2.5 concentrations classified by ambient concentration value.

Microenvironment	Average ϒ (number of tours)	
	Ambient concentration > 150 μg/m^3	Ambient concentration ≤ 150 μg/m^3
Cycle	1.1 (11)	1.2 (1)
2W	1.0 (7)	1.7 (5)
OW car	1.1 (4)	1.4 (4)
AC car	0.5 (2)	0.5 (8)
Auto rickshaw	1.2 (10)	1.5 (6)
OW bus	1.2 (9)	1.4 (3)
AC bus	1.2 (11)	1.3 (3)
Metro	0.5 (2)	0.9 (3)
Walk	1.2 (26)	1.6 (22)
Bus stop	1.1 (29)	1.3 (13)
Metro station	0.9 (2)	1.5 (3)

3.3. Inhaled dose

Fig. 5 presents distance-based and duration-based inhaled dose of $PM_{2.5}$. The dose estimates show higher inter-modal differences for distance-based estimates than duration-based, as the former also takes speed of travel into account, which varies over different modes. According to distance-based estimates, walk has the highest dose per km, followed by cycle and bus, while AC car has the lowest, followed by metro. For buses, more than half of the total intake dose is contributed from out-of-vehicle movement, while in the case of metro, up to 80%. For a given distance, $PM_{2.5}$ dose inhaled during cycling is 4× of 2W, 9× of AC car, and 4× of auto rickshaw and, for a given duration, these ratios are 10×, 20× and 9×, respectively. Active travel modes (walking and cycling) have lower travel speeds and their users have higher inhalation rates, as compared to their non-active counterparts (2W, cars, auto rickshaw, etc.) (see Table 3). This contributes to significantly higher inhaled dose for the active-mode users, even after controlling for the exposed concentrations. For instance, even with similar value of Υ, per-km inhaled dose of cycling will be 4× higher than an AC car.

4. Implications

For ambient concentration of 20 $\mu g/m^3$ in the Netherlands, de Hartog et al. (2010) estimated a dose of 35 μg for one hour of cycling and 24-h dose of 274 μg. According to our estimates, just an hour of cycling in Delhi contributes to a dose of 393 μg (11× of 35 μg and 1.4× of 274 μg). Thus, with an annual average $PM_{2.5}$ concentration of ~150 $\mu g/m^3$, an individual in Delhi inhales more $PM_{2.5}$ during less than an hour of cycling (representing two 30-min trips) than an individual inhales during the entire day in cities like Tokyo, Copenhagen (in Netherlands), London, New York, and Los Angeles, which have $PM_{2.5}$ concentrations ranging from 10 to 20 $\mu g/m^3$ (Hara et al., 2014; GLA, 2014; NYC, 2013). As another example, an individual carrying out household cooking using biomass or coal burning is exposed to a concentration of 330 $\mu g/m^3$ (Burnett et al., 2014) and, with an inhalation rate of 10 L per minute, inhales a dose of 200 μg in an hour. A cyclist in Delhi inhales twice that dose for the same duration on the road.

The results of this study highlighted that the risk of travel-related pollution exposure, when expressed in terms of inhaled dose, is the lowest for cars and the highest for active modes of transportation, followed by PT modes which also involve walking for a part of the trip. This implies socio-economic inequality of travel-related pollution exposure, as those using cars in Delhi are likely to have higher socio-economic status than those using non-motorised modes or PT. In 2011, only 20% of the households in Delhi owned a car (Census-India, 2012) and, in 2007, less than 10% of the total trips in Delhi were reported to be traveled by car (RITES, 2010). The inequality of pollution exposure will be much less for high-income countries, such as the USA and the UK, where 70% and 90% of all the households, respectively, own at least one car (Giuliano and Dargay, 2006).

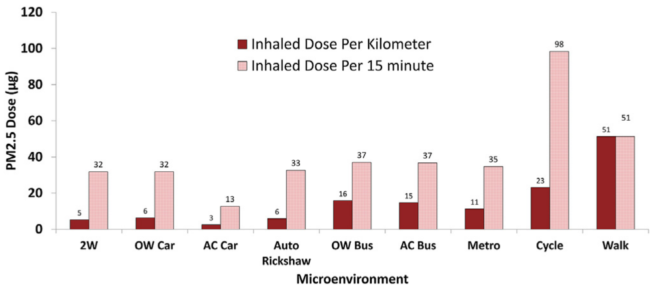

Fig. 5. Estimated inhaled dose of $PM_{2.5}$ in multiple transport micro-environments in Delhi.

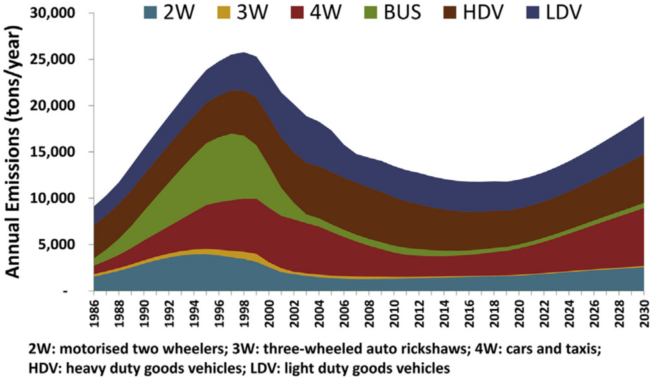

Fig. 6. Estimated annual $PM_{2.5}$ emissions from on-road transport in Delhi (Goel and Guttikunda, 2015).

In the next 15 years, from 2015 through 2030, in-use fleet of 2W is estimated to grow by 2.5× and that of cars by 3× and, in the business-as-usual scenario, the particulate emissions are estimated to increase by 1.5× (see Fig. 6). With an inevitable increase in vehicle ownership, policies need to be formulated to control the growth of on-road emissions by setting higher emission standards for vehicles, and to curb the growing use of vehicles, through bolstering of public transport services, higher parking charges, and mixed land-use development. If the current levels of pollution levels persist on road, individuals who can afford to, are likely to shift away from active modes as well as from PT. A comparatively low value of Υ indicates that on-road concentrations of $PM_{2.5}$ are largely contributed by non-vehicular sources. Thus, higher exposure of pollution during traveling in Indian cities should be seen within the broader framework of overall air pollution problem and not from vehicular perspective alone, and the former is a result of multiple sectors in Indian cities other than road transport (Guttikunda et al., 2014). Therefore, policies aimed at reducing pollution from brick kilns, power plants, industries, and diesel generator sets are as important as policies for reducing vehicular pollution, for reducing travel-related hazard of air pollution.

5. Conclusions

We carried out measurements of in-vehicle exposure of $PM_{2.5}$ concentrations for 11 different transport microenvironments, on a major arterial road in Delhi. Compared to all the studies presented in Table 1 with a mix of low-, middle- and high-income settings, we observed that on-road modes in Delhi experience the highest concentrations. Among various travel modes, walking, cycling, and use of PT result in the highest dose of particulate pollution, estimated for a unit of distance, or time, whereas traveling in an AC car leads to the least amount of dose. We find that, on an average, unenclosed travel modes in Delhi experience 10–40% higher $PM_{2.5}$ concentration than an ambient location. We reported a non-linear relationship between Υ and ambient concentration, and the latter has a strong seasonal variation in Delhi (see Fig. 1). This implies that the relative difference between ambient and on-road concentration is season dependent. This also underscores that, for settings such as Delhi, results of on-road exposure studies can differ considerably depending on the season during which the study is conducted.

We estimated that the ratios of on-road to ambient concentrations are much lower in Delhi than those reported from settings in high-income countries with much cleaner air. However, even with lower difference between in-vehicle and ambient concentrations, in-vehicle concentrations in Delhi are still an order of magnitude higher than high-income settings due to high ambient/background concentration of the former. We attributed the reason for low ratios to moderate contribution of traffic sources to $PM_{2.5}$ pollution in Delhi, as reported by source-apportionment studies. PM pollution in most Indian cities is a multi-sectoral problem, with transport contributing a smaller fraction (Guttikunda et al., 2014) compared to cleaner settings. Thus, in-vehicle to ambient concentration ratios estimated in this study are equally likely to be applicable in other major Indian settings with high pollution levels. In addition, the low values of ratio also indicate a higher correlation between on-road and background concentrations. Thus, ambient concentration is a better surrogate of on-road exposure for open modes in Indian cities, than it is for cleaner high-income settings.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.10.037.

References

Aarnio, P., Yli-Tuomi, T., Kousa, A., Mäkelä, T., Hirsikko, A., Hämeri, K., , et al.Jantunen, M., 2005. The concentrations and composition of and exposure to fine particles ($PM_{2.5}$) in the Helsinki subway system. Atmos. Environ. 39 (28), 5059–5066.

Adams, H.S., Nieuwenhuijsen, M.J., Colvile, R.N., 2001. Fine particle ($PM_{2.5}$) personal exposure levels in transport microenvironments, London, UK. Sci. Total Environ. 279 (1), 29–44.

AIRPARIF, 2012. Source Apportionment of Airborne Particles in the Ile-De-France Region. Final Report. AIRPAIF, Paris, France.

Apte, Joshua S., Kirchstetter, Thomas W., Reich, Alexander H., Deshpande, Shyam J., Kaushik, Geetanjali, Chel, Arvind, Marshall, Julian D., Nazaroff, William W., 2011. Concentrations of fine, ultrafine, and black carbon particles in auto rickshaws in New Delhi, India. Atmos. Environ. 45 (26), 4470–4480.

Bigazzi, A.Y., Figliozzi, M.A., 2014. Review of urban bicyclists' intake and uptake of traffic-related air pollution. Transp. Rev. 34 (2), 221–245.

Boogaard, H., Borgman, F., Kamminga, J., Hoek, G., 2009. Exposure to ultrafine and fine particles and noise during cycling and driving in 11 Dutch cities. Atmos. Environ. 43 (27), 4234–4242.

Both, A.F., Balakrishnan, A., Joseph, B., Marshall, J.D., 2011. Spatiotemporal aspects of real-time PM2. 5: low-and middle-income neighborhoods in Bangalore, India. Environ. Sci. Technol. 45 (13), 5629–5636.

Brauer, M., Amann, M., Burnett, R.T., Cohen, A., Dentener, F., Ezzati, M., et al., 2012. Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. Environ. Sci. Technol. 46 (2), 652–660.

Briggs, D.J., de Hoogh, K., Morris, C., Gulliver, J., 2008. Effects of travel mode on exposures to particulate air pollution. Environ. Int. 34 (1), 12–22.

Burnett, R.T., Pope, C.A., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., et al., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ. Health Perspect. 122 (4), 397–403.

Census-India, 2012. Census of India, 2011. The Government of India, New Delhi, India.

Chan, L.Y., Lau, W.L., Lee, S.C., Chan, C.Y., 2002a. Commuter exposure to particulate matter in public transportation modes in Hong Kong. Atmos. Environ. 36 (21), 3363–3373.

Chan, L.Y., Lau, W.L., Zou, S.C., Cao, Z.X., Lai, S.C., 2002b. Exposure level of carbon monoxide and respirable suspended particulate in public transportation modes while commuting in urban area of Guangzhou, China. Atmos. Environ. 36 (38), 5831–5840.

Chertok, M., Voukelatos, A., Sheppeard, V., Rissel, C., 2004. Comparison of air pollution exposure for five commuting modes in Sydney-car, train, bus, bicycle and walking. Health Promot. J. Aust. 15 (1), 63–67.

Chowdhury, Z., Zheng, M., Schauer, J.J., Sheesley, R.J., Salmon, L.G., Cass, G.R., Russell, A.G., 2007. Speciation of ambient fine organic carbon particles and source apportionment of $PM_{2.5}$ in Indian cities. J. Geophys. Res. Atmos. (1984–2012) 112, D15.

CRRI, 2012. Personal Communications with Neelam Gupta. Central Road Research Institute, Delhi.

de Hartog, J.J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 1109–1116.

de Nazelle, A., Fruin, S., Westerdahl, D., Martinez, D., Ripoll, A., Kubesch, N., Nieuwenhuijsen, M., 2012. A travel mode comparison of commuters' exposures to air pollutants in Barcelona. Atmos. Environ. 59, 151–159.

Dey, S., Di Girolamo, L., van Donkelaar, A., Tripathi, S.N., Gupta, T., Mohan, M., 2012. Variability of outdoor fine particulate ($PM_{2.5}$) concentration in the Indian subcontinent: a remote sensing approach. Remote Sens. Environ. 127, 153–161.

Fondelli, M.C., Chellini, E., Yli-Tuomi, T., Cenni, I., Gasparrini, A., Nava, S., , et al.Jantunen, M., 2008. Fine particle concentrations in buses and taxis in Florence, Italy. Atmos. Environ. 42 (35), 8185–8193.

Fruin, S., Westerdahl, D., Sax, T., Sioutas, C., Fine, P.M., 2008. Measurements and predictors of on-road ultrafine particle concentrations and associated pollutants in Los Angeles. Atmos. Environ. 42 (2), 207–219.

GLA, 2014. Average Air Quality Levels, Greater London Authority [computer file], accessed from. https://www.london.gov.uk/priorities/environment/consultations/air-quality.

Goel, R., Guttikunda, S.K., 2015. Evolution of On-Road Vehicle Exhaust Emissions in Delhi. Atmospheric Environment.

Gomez-Perales, J.E., Colvile, R.N., Nieuwenhuijsen, M.J., Fernandez-Bremauntz, A., Gutierrez-Avedoy, V.J., Paramo-Figueroa, V.H., , et al.Ortiz-Segovia, E., 2004. Commuters' exposure to $PM_{2.5}$, CO, and benzene in public transport in the metropolitan area of Mexico City. Atmos. Environ. 38 (8), 1219–1229.

Giuliano, G., Dargay, J., 2006. Car ownership, travel and land use: a comparison of the US and Great Britain. Transp. Res. Part A Policy Pract. 40 (2), 106–124.

Gulliver, J., Briggs, D.J., 2004. Personal exposure to particulate air pollution in transport microenvironments. Atmos. Environ. 38 (1), 1–8.

Guttikunda, S.K., Gurjar, B.R., 2012. Role of meteorology in seasonality of air pollution in megacity Delhi, India. Environ. Monit. Assess. 184 (5), 3199–3211.

Guttikunda, S.K., Calori, G., 2013. A GIS based emissions inventory at 1 km × 1 km spatial resolution for air pollution analysis in Delhi, India. Atmos. Environ. 67, 101–111.

Guttikunda, S.K., Goel, R., Pant, P., 2014. Nature of air pollution, emission sources, and management in the Indian cities. Atmos. Environ. 95, 501–510.

Hara, K., et al., 2014. Difference in concentration trends of airborne particulate matter during rush hour on weekdays and sundays in Tokyo, Japan. J. Air Waste Manag. Assoc. 64 (9), 1045–1053.

Health Effects Institute (HEI), 2010. Traffic-related Air Pollution: a Critical Review of the Literature on Emissions, Exposure, and Health Effects (Special Report 17). Health Effects Institute, Boston, MA.

IHME, 2013. GBD Arrow Diagram. Institute for Health Metrics and Evaluation, University of Washington, Seattle, WA. Available from: http://vizhub.healthdata.org/irank/arrow.php (accessed 10.11.14.).

IMF, 2005. Will the oil continue to be tight?. In: World Economic Outlook, Global and External Imbalances. International Monetary Fund, Washington D.C., US, pp. 157–183.

Johansson, C., Johansson, P.-Å., 2003. Particulate matter in the underground of Stockholm. Atmos. Environ. 37 (1), 3–9.

Kaur, S., Nieuwenhuijsen, M.J., Colvile, R.N., 2007. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmos. Environ. 41 (23), 4781–4810.

Kaur, S., Nieuwenhuijsen, M., Colvile, R., 2005. Personal exposure of street canyon intersection users to $PM_{2.5}$, ultrafine particle counts and carbon monoxide in Central London, UK. Atmos. Environ. 39 (20), 3629–3641.

Lawrence, S., Sokhi, R., Ravindra, K., Mao, H., Prain, H.D., Bull, I.D., 2013. Source apportionment of traffic emissions of particulate matter using tunnel measurements. Atmos. Environ. 77, 548–557.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., , et al.Davis, A., 2013. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380 (9859), 2224–2260.

McNabola, A., Broderick, B.M., Gill, L.W., 2008. Relative exposure to fine particulate matter and VOCs between transport microenvironments in Dublin: personal exposure and uptake. Atmos. Environ. 42 (26), 6496–6512.

Morabia, A., Amstislavski, P.N., Mirer, F.E., Amstislavski, T.M., Eisl, H., Wolff, M.S., Markowitz, S.B., 2009. Air pollution and activity during transportation by car, subway, and walking. Am. J. Prev. Med. 37 (1), 72–77.

MoRTH, 2012. Road Transport Year Book (2011-12). Transport Research Wing, Ministry of Road Transport and Highways, Government of India, New Delhi.

Nieuwenhuijsen, M., et al., 2007. Levels of particulate air pollution, its elemental composition, determinants and health effects in metro systems. Atmos. Environ. 41 (37), 7995–8006.

NYC, 2013. New York City Trends in Air Quality Pollution and its Health Consequences. NYC Health, City of New York, USA.

Pant, P., Shukla, A., Kohl, S.D., Chow, J.C., Watson, J.G., Harrison, R.M., 2015. Characterization of ambient $PM_{2.5}$ at a pollution hotspot in New Delhi, India and inference of sources. Atmos. Environ. 109, 178–189.

Pfeifer, G.D., Harrison, R.M., Lynam, D.R., 1999. Personal exposures to airborne metals in London taxi drivers and office workers in 1995 and 1996. Sci. Total Environ. 235 (1), 253–260.

Pucher, J., Peng, Z.R., Mittal, N., Zhu, Y., Korattyswaroopam, N., 2007. Urban transport trends and policies in China and India: impacts of rapid economic growth. Transp. Rev. 27 (4), 379–410.

Quiros, D.C., Lee, E.S., Wang, R., Zhu, Y., 2013. Ultrafine particle exposures while walking, cycling, and driving along an urban residential roadway. Atmos. Environ. 73, 185–194.

Ramachandran, G., Adgate, J.L., Pratt, G.C., Sexton, K., 2003. Characterizing indoor and outdoor 15 minute average $PM_{2.5}$ concentrations in urban neighborhoods. Aerosol Sci. Technol. 37 (1), 33–45.

Riediker, M., Williams, R., Devlin, R., Griggs, T., Bromberg, P., 2003. Exposure to particulate matter, volatile organic compounds, and other air pollutants inside patrol cars. Environ. Sci. Technol. 37 (10), 2084–2093.

RITES, 2010. Transport Demand Forecast Study and Development of an Integrated Road Cum Multi-modal Public Transport Network for NCT of Delhi. Household Interview Survey Report, Chapter-4, Travel Characteristics. RITES Ltd.

Rodes, C., Sheldon, L., Whitaker, D., Clayton, A., Fitzgerald, K., 1999. Measuring Concentrations of Selected Air Pollutants inside California Vehicles. Final Report (No. PB—99—161028/XAB). Research Triangle Inst., Research Triangle Park, NC (US). Sierra Research, Inc., Sacramento, CA (US); Aerosol Dynamics, Inc., Berkeley, CA (US); Nevada Univ. System, Reno, NV (US); California State Air Resources Board, Sacramento, CA (US); Research Triangle Inst., Durham, NC (US).

Tsai, D.H., Wu, Y.H., Chan, C.C., 2008. Comparisons of commuter's exposure to particulate matters while using different transportation modes. Sci. Total Environ. 405 (1), 71–77.

TSI, 2012. DUSTTRAK DRX Aerosol Monitor- Theory of Operation. TSI Incorporated, USA.

U.S. Environmental Protection Agency (USEPA), 2011. Exposure Factors Handbook, 2011 Edition. National Center for Environmental Assessment, Washington, DC. EPA/600/R-09/052F. Available from: the National Technical Information Service, Springfield, VA, and online at. http://www.epa.gov/ncea/efh.

Vilcassim, M.R., Thurston, G.D., Peltier, R.E., Gordon, T., 2014. Black carbon and particulate matter ($PM_{2.5}$) concentrations in New York City's subway stations. Environ. Sci. Technol. 48 (24), 14738–14745.

Weichenthal, S., Van Ryswyk, K., Kulka, R., Sun, L., Wallace, L.A., Joseph, L., 2015. In-vehicle exposures to particulate air pollution in Canadian metropolitan areas: the Urban Transportation Exposure Study. Environmental Science & Technology.

WHO, 2014. Outdoor Air Pollution in the World Cities. World Health Organization, Geneva, Switzerland.

Zuurbier, M., Hoek, G., Oldenwening, M., Lenters, V.C., Meliefste, K., Hazel, P., Brunekreef, B., 2010. Commuters' exposure to particulate matter air pollution is affected by mode of transport, fuel type, and route. Environ. Health Perspect. 118 (6), 783–789.