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Analysis of various transport modes to evaluate personal exposure to $PM_{2.5}$ pollution in Delhi

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Abstract

Access to detailed comparisons of the air quality variations encountered when commuting through a city offers the urban traveller more informed choice on how to minimise personal exposure to inhalable pollutants. In this study we report on an experiment designed to compare atmospheric contaminants, in this case, $PM_{2.5}$ inhaled during rickshaw, bus, metro, non-air-conditioned car, air-conditioned (AC) car and walking journeys through the city of Delhi, India. The data collection was carried out using a portable TSI SidePak Aerosol Monitor AM520, during February 2018. The results demonstrate that rickshaws (266 ± 159 μg/m^3) and walking (259 ± 102 μg/m^3) modes were exposed to significantly higher mean $PM_{2.5}$ levels, whereas AC cars (89 ± 30 μg/m^3) and the metro (72 ± 11 μg/m^3) had the lowest overall exposure rates. Buses (113 ± 14 μg/m^3) and non-AC cars (149 ± 13 μg/m^3) had average levels of exposure, but open windows and local factors caused surges in $PM_{2.5}$ for both transport modes. Closed air-conditioned transport modes were shown to be the best modes for avoiding high concentrations of $PM_{2.5}$, however other factors (e.g. time of the day, window open or closed in the vehicles) affected exposure levels significantly. Overall, the highest total respiratory deposition doses (RDDs) values were estimated as 84.7 ± 33.4 μg/km, 15.8 ± 9.5 μg/km and 9.7 ± 0.9 μg/km for walking, rickshaw and non-AC car transported mode of journey, respectively. Unless strong pollution control measures are taken, the high exposure to $PM_{2.5}$ levels will continue causing serious short-term and long-term health concerns for the Delhi residents. Implementing integrated and intelligent transport systems and educating commuters on ways to reduce exposure levels and impacts on commuter's health are required.

Keywords: Personal exposure; Travel modes; Air pollution; $PM_{2.5}$; Delhi

1 Introduction

Approximately 58% of districts in India recorded ambient particulate matter $PM_{2.5}$ (particulates with aerodynamic diameter ≤ 2.5 μm) pollution above the National Ambient Air Quality Standard (NAAQS) and 99% above the WHO guidelines in 2015 (Chowdhury et al., 2019). According to the recent Global Burden of Disease study, ambient $PM_{2.5}$ pollution in India was responsible for more than 673 thousand deaths in 2017 (Stanaway et al., 2018), although the newly developed Global Exposure Mortality Model (GEMM) reported much higher $PM_{2.5}$-attributed deaths in India (2.219 million in 2015) (Burnett et al., 2018). According to the WHO Global Ambient Air Quality Database of $PM_{2.5}$ pollution levels in more than 1600 cities in the world in 2018, 13 Indian cities are among the 20 most polluted, with Delhi being the 6th most polluted city (annual average of 143 μg/m^3) (World Health Organization, 2018). In winter, the annual average $PM_{2.5}$ concentration in 2018, reported by four air quality monitoring stations (Anand Vihar, Punjabi Bagh, RK Puram and Okhla) located across the city, was above 300 μg/m^3, which is approximately 5 times higher than the Indian NAAQS of 60 μg/m^3, and 30 times higher than the WHO guideline of 25 μg/m^3 (Nandi, 2018). Traditionally health risk analysis was conducted by assuming that the total population is exposed to the same average $PM_{2.5}$ concentration in city-level or gridded level (10 km × 10 km or 1 km × 1 km) (Maji, 2020), although personal exposure monitoring campaigns in a city have indicated high space-time variation (Menon and Nagendra, 2018).

Epidemiological studies have linked exposure to $PM_{2.5}$ with various causes of premature mortality and morbidity (Bowe et al., 2019; Fu et al., 2019; Antonsen et al., 2020; Chen et al., 2017). Health risk studies assume equivalent toxicity for all chemical species in $PM_{2.5}$, but there is considerable evidence that the chemical composition, and sources of $PM_{2.5}$ influence its health effects much more, e.g. traffic-related $PM_{2.5}$, as vehicular exhausted $PM_{2.5}$ contain a high percentage of black carbon which has much more effects on human health (Matz et al., 2019; Costa et al., 2017; Jerrett et al., 2009; Monrad et al., 2017; Bowatte et al., 2017). In on-road microenvironments, due to the proximity of tailpipe emissions, exposure to traffic-related $PM_{2.5}$ concentration is higher than those in off-road locations (Chen et al., 2020). The travel-related exposure to on-road $PM_{2.5}$ pollution has been quantified by several studies for different microenvironments, classified as travel modes, ventilation status type of travel routes, and meteorological conditions. Table 1 summarizes some of the key past studies in various settings from across the world, analysing on-road exposure to $PM_{2.5}$ pollution. The range of concentrations in the table refers to the reported average values among all the microenvironments. There are only a few studies from India looking at exposure in three-wheeled auto-rickshaws (Apte et al., 2011; Goel et al., 2015). On-road high $PM_{2.5}$ concentration in vehicles are also observed in Indonesia (87–119 μg/m^3), Turkey (30.6–120.4 μg/m^3), and China (54.5–71.6 μg/m^3), and the lowest values are from cleaner high-income settings in the USA (12–35 μg/m^3), Europe (7.3–13.9 μg/m^3) and Canada (8.6–71.9 μg/m^3) (Table 1).

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Table 1

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Previous $PM_{2.5}$ exposure studies for transport micro-environments.

Location	Equipment	Monitoring Period	Mode of transport (mean ± SD)

			Rickshaw	Bus	Metro	Non-AC car	AC car	Walking
Delhi, India (Apte et al., 2011)	Optical aerosol monitor (DustTrak 8520, TSI Inc.)	February to May 2010	200 ± 46			170 ± 43	110 ± 36	
Delhi, India (Goel et al., 2015)	Optical aerosol monitor (DustTrak 8533, TSI Inc.),	January to May 2014	257 ± 295	140 ± 56	87 ± 141	180 ± 105	56 ± 44	234 ± 184
Delhi, India (morning) (Kumar and Gupta, 2016)	Aerosol spectrometer GRIMM Model, 1.108 (GRIMM Technologies Inc., Germany)	February to March 2012	332.8 ± 90.9	332.4 ± 137.5		320.4 ± 50.0		
Dhanbad, India (Gupta and Elumalai, 2019)	Aerosol spectrometer GRIMM Model, 1.109 (GRIMM Technologies Inc., Germany)	November 2015 to March 2016	345 ± 122					
Telangana, India (National Highway, inside city) (Kolluru et al., 2019a, 2019b)	Optical aerosol monitor (EPAM-5000; Environment Devices Corporation, USA)	July to September 2016		77 ± 18		113 ± 36	66 ± 21	
Barcelona, Spain (de Nazelle et al., 2012)	'Adams' high volume sampler	May 2009		25.9		35.5		21.6
Ispra, Italy (Geiss et al., 2010)	Optical particle counter, Grimm	–				26.9 ± 15.2		
Jakarta, Indonesia (Both et al., 2013)	Optical aerosol monitor (DustTrak 8520, TSI Inc.)	May to October 2005		119.0			87.0	
California, USA (Ham et al., 2017)	Optical aerosol monitor (DustTrak 8520, TSI Inc.)	April 2014–November 2015		7.47 ± 2	5.69 ± 2.1		7.1 ± 1.3	
Barcelona, Spain (Moreno et al., 2015)	Optical aerosol monitor (DustTrack 8533, TSI Inc.)	October to November 2014		45.0	43.0			32.0
Istanbul, Turkey (Onat and Stakeeva, 2013)	Optical aerosol monitor (pDR 1200 model, Thermo, USA)	October–November 2008		120.4 ± 73.5	45.4 ± 18.4	67.9 ± 25.1	30.6 ± 16.2	89.24 ± 8.6
London, UK (Rivas et al., 2017)	Aerosol spectrometer GRIMM EDM 107 (GRIMM Technologies Inc.)	February to June 2016		7.3 ± 2.0			13.9 ± 1.7	
Toronto, Canada (Van Ryswyk et al., 2017)	Optical aerosol monitor (DustTrak 8520, TSI Inc.)	Summer 2010			71.9			
York City, USA (Vilcassim et al., 2014)	Nephelometric-based real time DataRAM (PDR 1500, Thermo Scientific	January 2013 to March 2014			35.0–200.0			
Shanghai, China (Gong et al., 2019)	Optical aerosol monitor (DustTrak 8532, TSI Inc.)	March to October 2016			58.0			
Xi'an, China (Qiu et al., 2017)	Aerosol Monitor (Grimm spectrometer, Model 1.109)	May and June 2016		54.4			67.0	71.6
Ontario, Canada (Gilliland et al., 2019)	Nephelometric-based real time DataRAM (PDR 1500, Thermo Scientific).	February 2010		10.1			9.6	8.6
Singapore (Tan et al., 2017)	Optical aerosol monitor (DustTrak 8532, TSI Inc.)	April to June 2013		28.0 ± 6.0	26.0 ± 4.0		27.0 ± 7.0	36.0 ± 9.0

The cities in India differ significantly from the cities in developed countries represented in Table 1. For instance, ambient $PM_{2.5}$ concentrations in Indian cities are 4–8 times higher than most high-income settings (Stanaway et al., 2018), and the traffic condition in metropolitan Indian cities is worsening daily due to increasing levels of vehicle ownership and a higher number of old vehicles (Transport Department Government of NCT of Delhi., 2018). The rickshaw and bus are one of the most common forms of public transport in Delhi, providing low-cost mobility and connecting travellers to mass transit. The rickshaw and bus sector provides a livelihood for some of India's poorest citizens and is easily available means of public transport in most of the cities (Choudhary and Gokhale, 2016). Relatively few studies have investigated on-road exposures to $PM_{2.5}$ pollution, particularly whilst travelling on these modes, in developing-world megacities such as Delhi, where older vehicles are more common and high levels of congestion and travel times lead to higher personal exposure to $PM_{2.5}$ concentrations.

The objectives of this study are (a) to assess the on-road exposure to $PM_{2.5}$ in various travel modes, measured using an optical PM monitor, and (b) to estimate the total respiratory deposition doses (RDDs) of $PM_{2.5}$ in microenvironments in Delhi (more details in supplement material). The modes studied include auto-rickshaw (three-wheelers), bus, metro, non-air-conditioned (non-AC) car, air-conditioned (AC) car and walking.

2 Methodology

2.1 Study area and route selection

The study was carried out in Delhi, India, which has an area of 1484 km^2 and around 16.3 million inhabitants as per the latest census of 2011 (Goverment of India, 2011), making it one of the largest cities in Asia. In March 2018, Delhi had 10.8 million registered vehicles, including 6.96 million motor-cycle/scooter and 3.1 million motor-car (private vehicles) (Transport Department Government of NCT of Delhi., 2018).

For measuring on-road exposure of $PM_{2.5}$ in February 2018, we selected a route of 11 km length, between the Indian Institute of Technology Delhi campus (IIT Delhi) to the Connaught Place (Delhi's CBD), as shown in Fig. 1, with slight route deviations for rickshaw and bus. This variation in the route was due to the preference of the drivers and considered consistent to study the real-world micro-environments. The region from Prithviraj Road to Janpath Road is less populated and comprised of key government offices and embassies. The area between Janpath Road to Connaught Place is mainly of government authorities' structures, small retail infrastructures with a large hotel. The final part of the route, Connaught Place, is a series of ring roads which is surrounded by the central park and markets and is often congested due to large number rickshaws and cars using the area.

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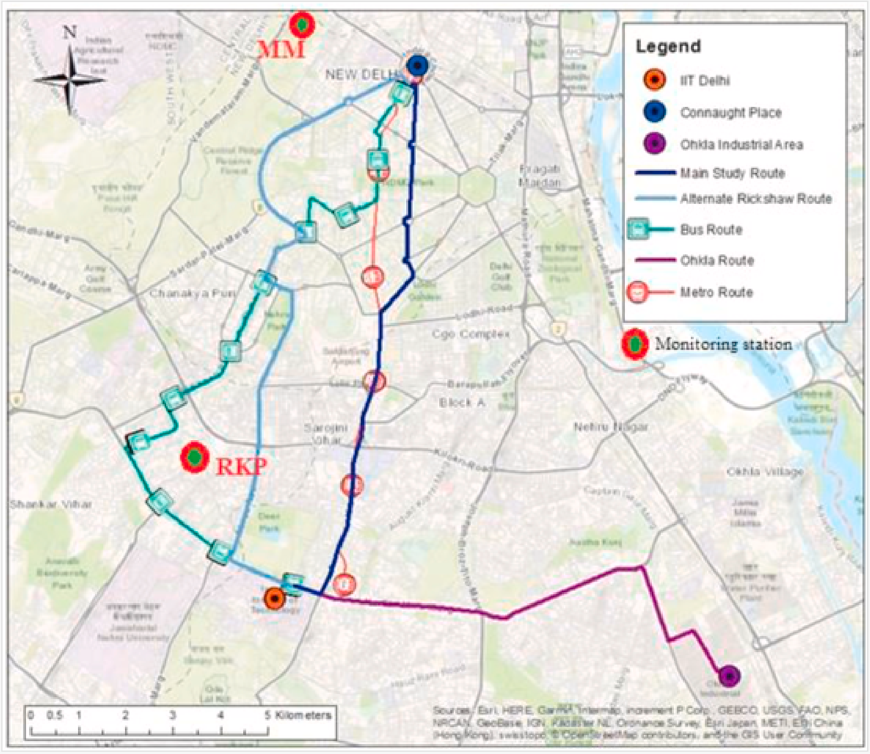
Fig. 1



Routes took by transport mode during the study (OpenStreetMap Contributors, 2017). Image produced using ArcMap™ Esri©.

2.2 Measurements and sampling equipment

This work has focused on the assessment of personal exposure to $PM_{2.5}$. We measured $PM_{2.5}$ concentrations using a portable SidePak™ Aerosol Monitor AM520 (TSI Inc., USA), which works on the principle of light scattering laser photometry for real-time concentration measurements of PM in the air. Different inlet options are available for the optics chamber to measure specific PM sizes, from PM_1 to PM_{10}. For this study, the $PM_{2.5}$ inlet attachment was used. The instrument measures between 0.001 and 100 mg/m^3, so are well within the range of measurements for $PM_{2.5}$ in the micro-environments studied. The Photometric Calibration Factor (PCF) in the device is set to 1.0 by default, however, the preliminary tests exhibited above normal PM values. Thus, as per the TSI guidelines for urban environments, the PCF was set to 0.38 for urban areas (TSI., 2018). Usually, this equipment can have a flow rate up to 1.8 L/min, although for this experiment it was set to its default value of 1.7 L/min. The device was always calibrated to zero and was checked before every usage with the help of a supplied zero calibration attachment. A long interval of 1 s was considered to capture the fast-varying $PM_{2.5}$ levels encountered by a moving subject.

Qstarz™ Bluetooth-Q1000XT GPS Travel Recorder equipment was used to track the commuter's location (Qstarz., 2018). The travel recorder has an accuracy of 3 m and can record up to 40 days' worth of data at a 1s interval. The Global Positioning System (GPS) device was calibrated before each test, by waiting 35 s after turning the device on, as recommended by the Qstarz™ manual (Qstarz., 2018). Additionally, the QTravel™ is photo geotagging software for a computer that was used for quick visualisations of the routes chosen by the commuter on Google Earth/Google Map.

The personal aerosol monitor AM520 was securely placed in a backpack to avoid any obstructions to the inlet, exhaust port and outlet. Besides, a tube was fixed to the inlet which then emerged from the backpack and was placed close to the commuter's breathing zone. Next, the travel recorder was turned on and calibrated and was placed in the side pouch of the backpack. The backpack was kept on the surveyors back as much as possible to simulate inhalation for the AM520 but was taken off for commuting on a rickshaw, in a car and on the bus. In such cases, the inlet tube was kept in proximity of the breathing zone.

Six commuting modes of transport were selected in our study in between 2nd to February 8, 2018, auto-rickshaw (three-wheelers) (three trips), bus (two trips), metro (one trip), non-air-conditioned (non-AC) car (one trip), air-conditioned (AC) car (two trips) and as a pedestrian (walking) (two trips). Visual representation of $PM_{2.5}$ levels on the different transport route was displayed on the maps by using various software such as RStudio®, version 1.1.456 (R Core Team, 2017; RStudio Team, 2020) and Q2 Stamen© map (Rodenbeck and Stamen, 2018).

3 Results

3.1 Ambient $PM_{2.5}$ concentration during the study period

The personal exposure whilst travelling in transport modes in Delhi depends on factors such as season of the year and time of the day (for example in winter the $PM_{2.5}$ concentration is usually higher than other seasons) and whether the journey was conducted in the morning, afternoon or at night (traffic conditions can dictate the temporal variations) (Lin et al., 2020; Chaney et al., 2017). The ambient $PM_{2.5}$ concentrations are available from monitoring stations along the route and these have been analysed to understand how the background air quality changes over time. More specifically the continuous air-quality monitoring stations of Central Delhi, RK Puram (RKP) and Mandir Marg (MM), operated by the Delhi Pollution Control Committee (DPCC), were used as they were situated closer to the selected route (IIT Delhi to the Connaught Place). Daily-average $PM_{2.5}$ trends as well as a month- and hour specific averages for the three years were calculated. $PM_{2.5}$ has a significant seasonal variation in Delhi, with highest concentrations during winter months from November to February (123–235 µg/m^3) which gradually decrease afterwards due to the winds and precipitation during the monsoon months from July through September (33.7–46.0 µg/m^3). Some of the spikes of $PM_{2.5}$ were also observed in June and July probably due to low winds which would have helped the pollution to accumulate in the region. The diurnal profile of $PM_{2.5}$ showed the highest concentrations during late-evening hours (11 p.m. through midnight) and early morning and rush-hour period (8 a.m. through 10 a.m.). The levels were at their lowest during the afternoon hours (Fig. 2). In winter the diurnal profile of $PM_{2.5}$ shows <200 µg/m^3 from 11.00 a.m. to 7.00 p.m., after which time the concentration rises to >200 µg/m^3. As the selected period of the current analysis was in early February, it was understood that the $PM_{2.5}$ levels were already at the higher side. During the study period (2nd to February 8, 2018), the average ambient $PM_{2.5}$ concentration was 146 ± 53 µg/m^3. Although, in the Panchkula (PK) monitoring site in Delhi, which is considered as an urban background site observed a very low ambient $PM_{2.5}$ concentration during the study (average: 61 ± 20 µg/m^3; median: 60 µg/m^3).

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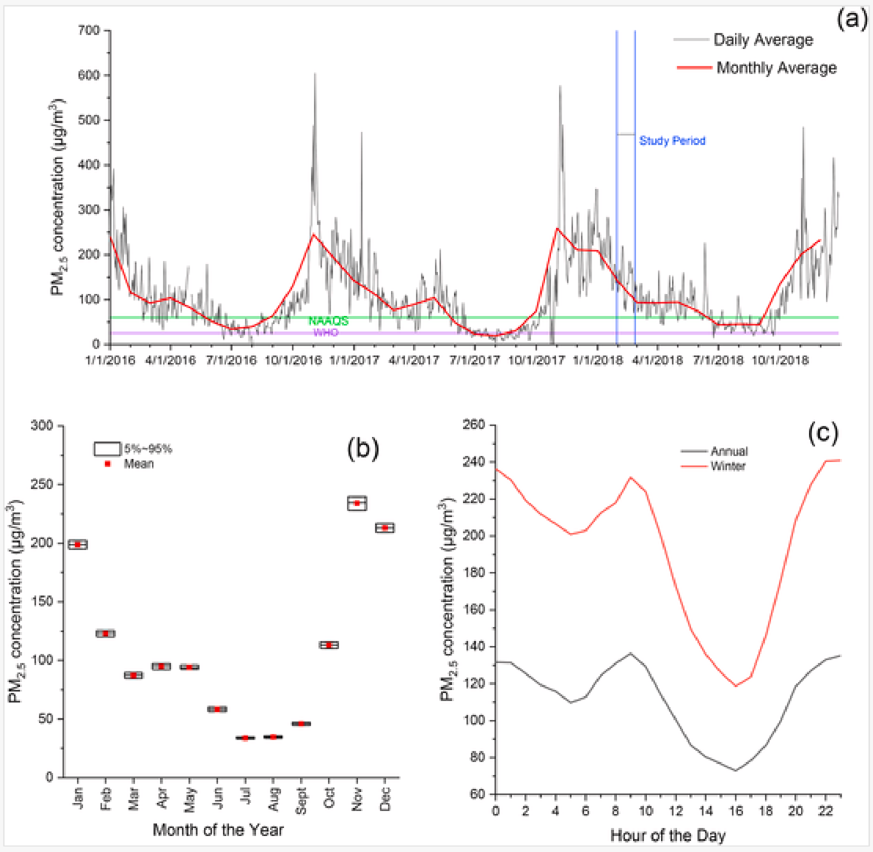
Fig. 2



(a) Daily and monthly average PM$_{2.5}$ concentrations between January 2016 and December 2018 for RK Puram and Mandir Marg monitoring stations (b) Monthly variation in PM$_{2.5}$ concentrations in 2016–2018 (c) Diurnal variation in PM$_{2.5}$ concentrations in 2016–2018 for all year and winter season. For (b) the red square represents the mean; the box plot represents 5th and 95th percentile. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2 PM$_{2.5}$ concentration in different modes of transport

Table 2 summarise the PM$_{2.5}$ concentration during commuting by the six travel modes indicated earlier. In this study, the time-weighted PM$_{2.5}$ concentration and the average of PM$_{2.5}$ in a microenvironment are the same, as the Aerosol Monitor measure concentration in every 1 s. It was noted that rickshaws were the most exposed transport with the highest mean concentration of PM$_{2.5}$ of 266 μg/m^3, followed by walking with an average of 258 μg/m^3. The lowest exposed transport was in the metro and AC car with a mean of 72.0 μg/m^3 and 89.0 μg/m^3 respectively. The non-AC car and bus trips had PM$_{2.5}$ means of 149 μg/m^3 and 113 of PM$_{2.5}$ respectively. Fig. 3 shows the spatial variations in the average PM$_{2.5}$ exposures for the six modes of travels.

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Table 2

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Statistical analysis of the PM$_{2.5}$ levels for different transport modes.

Level of PM$_{2.5}$ exposure (μg/m^3)	Ambient concentration	Mode of Transport					
		Rickshaw	AC Car	Non-AC Car	Metro	Bus	Walking
Minimum	42	96	35	114	46	85	73
1st Quartile	103	143	63	141	65	104	165
Mean (±SD)	146 ± 53	266 ± 159	89 ± 30	149 ± 13	72 ± 11	113 ± 14	259 ± 102
Median	141	203	93	149	71	111	264
Median absolute deviation (MAD)	40	76	21	9	7	8	85
3rd Quartile	185	331	106	158	79	120	304
Maximum	295	3110	177	206	163	226	1280

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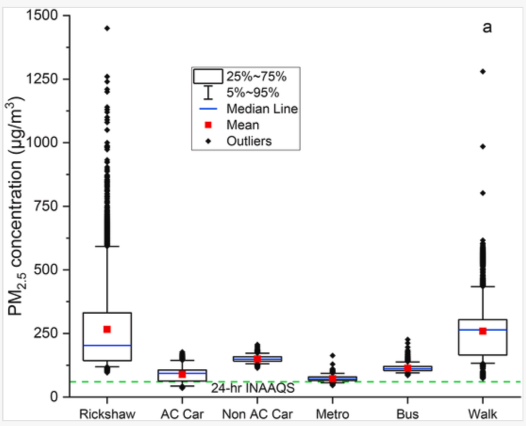
Fig. 3



Boxplot of different transport modes exposure results. The outliers are below 5th and above 95th percentiles.

3.2.1 PM$_{2.5}$ concentration in rickshaws

The histogram in Figure S1a shows that the highest density of PM$_{2.5}$ level was observed around 150 μg/m^3, the lower densities were observed in between ~300 μg/m^3 and 550 μg/m^3. The three-day one-way trip average exposure level of PM$_{2.5}$ was 266 ± 159 μg/m^3 (median: 203 μg/m^3). The time-series plot of the exposure in the rickshaw for different days (Fig. 4a) varied from each other probably due to several factors such as location, time of day and the nearby congestion. The figure shows that the levels on each day were very dissimilar with the fluctuating spikes of the pollution at different times. Also, it was noted that the pollution for February 5, 2018 was well over 1000 μg/m^3 in the parts of routes which were known to be regularly congested. The higher PM emissions during periods of congestion are due to an increase in stop-start and idle times of high vehicle densities. A past study has established that vehicles fuel consumption and associated pollutants emitted during congestion are higher than the amount during free-flow traffic condition (Zhang et al., 2011).

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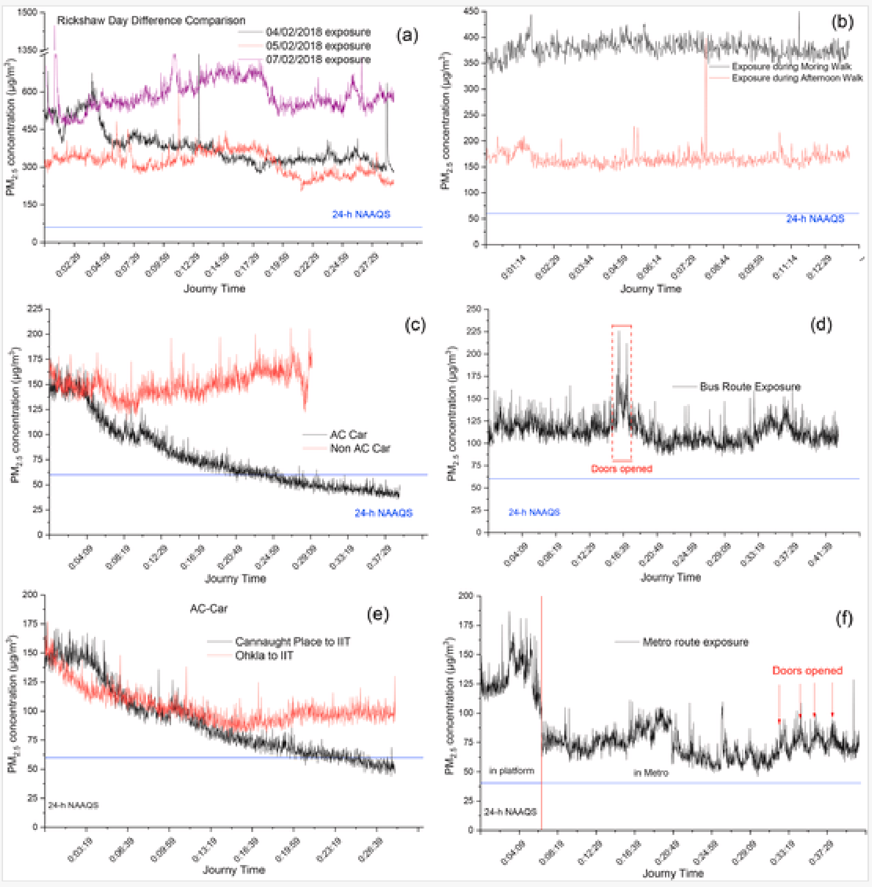
Fig. 4



$PM_{2.5}$ concentration levels in different transport modes (a) Rickshaw, (b) Walk (c) non-AC-Car, (d) Bus, (e) AC-Car and (f) Metro.

3.2.2 $PM_{2.5}$ concentration during walking

Whilst walking, exposure to concentrations of $PM_{2.5}$ is very high, with most exposure levels being between 165 µg/m^3 and 304 µg/m^3 (mean: 259 ± 103 µg/m^3; median: 264 µg/m^3) (Figure S1b). This made it the second-highest exposed mode of transport during the study. A maximum value of 1280 µg/m^3 was recorded during the survey, an exceptionally high reading when compared to the other results and compared to national and global standards. The exposure levels captured during walking were not examined on the same routes as other modes of transport, however, these higher levels were predominantly recorded around the periphery of IIT Delhi and Connaught Place. The histogram plot shows a multimodal distribution (Fig. 4b), with peak frequencies located at 150 µg/m^3, 290 µg/m^3 and 375 µg/m^3 with outliers concentrated around 550 µg/m^3, culminating in very high levels of exposure to $PM_{2.5}$. The time series for the morning were compared with the afternoon exposure. Time of travel is a major factor that affected all modes of transport but was particularly noticeable when walking. Fig. 4b also displayed the stark difference between exposure in the morning at 09:15, and exposure at noon, walking the same route from IIT Delhi Guest House to the Outer Ring Road. Walking in the morning had a mean exposure to $PM_{2.5}$ of 379 µg/m^3, while in the afternoon the mean exposure was 166 µg/m^3. This suggests that, walking in the morning results in a 56% increase in exposure to $PM_{2.5}$ level compared to walking in the afternoon.

The result is comparable with the difference in the diurnal variation of ambient $PM_{2.5}$ concentrations in the morning and afternoon. In between 08:00 to 10:00 a.m. and 21:00 to 23:00, the higher concentration of $PM_{2.5}$ is consistent with the morning and evening rush-hour traffic pattern, respectively. The average ambient $PM_{2.5}$ concentration was 227 µg/m^3 at 09:00, which was about 51% higher than the $PM_{2.5}$ concentration at 12:00.

3.2.3 $PM_{2.5}$ concentration in non-AC car

$PM_{2.5}$ exposure was third highest in non-AC-car, where the majority of exposed $PM_{2.5}$ concentrations lie between 141 and 158 µg/m^3, showing a very small interquartile range with the results being relatively consistent (Figure S1c). While the maximum value was 206 µg/m^3 and the minimum was 114 µg/m^3, with mean value was 149 ± 13 µg/m^3 (median: 149 µg/m^3). Non-AC cars often have their windows kept open in Delhi and this could be the reason why $PM_{2.5}$ concentration for this mode than that in an AC car. The average $PM_{2.5}$ concentration difference between AC car and non-AC car was around 61 µg/m^3 on the same route of travel. The time-series plot in Fig. 4c shows the wide distribution of the $PM_{2.5}$ exposure level in a non-AC car. It shows a relatively normal distribution around 145 µg/m^3 of $PM_{2.5}$. When compared to the AC car, the distribution begins at a much higher concentration (114 µg/m^3 for the non-AC car and 35.0 µg/m^3 for the AC car). The initial levels recorded by the two modes were around 150 µg/m^3, which gradually fluctuated along the route. This fluctuation, as observed for rickshaws, was mostly due to traffic congestion and the open window. This comparison has shown that exposed $PM_{2.5}$ concentration in the AC car was about 92% lower than that in a non-AC car.

3.2.4 $PM_{2.5}$ concentration in bus

The bus was the fourth-highest exposed transport mode. The majority of the exposed $PM_{2.5}$ concentrations were between 104 and 120 µg/m^3 (Fig. 1Sd). The pollution levels inside the bus increased when the bus doors and windows were opened allowing the outside pollution from traffic on the road to infiltrate the bus. Average exposed $PM_{2.5}$ was 113 ± 14 µg/m^3 (range: 85–226 µg/m^3; median: 111 µg/m^3) (Fig. 4d). Most of the buses in Delhi, now are air-conditioned, however, due to the cold weather, it is a general practice to turn off the AC and open windows. Open windows combined with the frequent opening and closing of the bus doors resulted in high concentrations of $PM_{2.5}$ entering the bus from the outside environment. The main source of $PM_{2.5}$ at the kerbside is traffic-related the high pollution was associated with the office rush-hour congestion on the road, shown higher in the morning (155 µg/m^3) compared to the afternoon (89 µg/m^3) in the study day. The recorded $PM_{2.5}$ concentration on the bus routes illustrates that the exposure to $PM_{2.5}$ remains almost consistent but except for the $PM_{2.5}$ peak level measured when the doors were open while the commuters were boarding the bus. These depended on the time of day and number of passengers boarding and alighting the bus (Kumar et al., 2018; Kolluru et al., 2019a, 2019b).

3.2.5 $PM_{2.5}$ concentration in air-conditioned car

The air-conditioned car was the second-lowest mode of transport for $PM_{2.5}$ exposure. The frequency distribution slightly left-skewed distribution (Figure S1e) shows that most values lie around 45 µg/m^3 and the mode is at 100 µg/m^3. The concentrations recorded had a range of 35 µg/m^3 to 177 µg/m^3 (mean: 89 ± 30 µg/m^3; median: 93 µg/m^3) and the mean was higher than the 24-h NAAQS. One of the main reasons for the comparatively low $PM_{2.5}$ concentrations in the AC-cars was probably due to the microclimate created in the car by the air-conditioner, as the air is usually set to the recirculation mode when AC is on The present study despite being conducted in the cold month of February, the air conditioning in the cars used was turned on at the beginning of the journey. Thus, it was also observed that the AC car showed initial higher levels of the pollution which then gradually kept decreasing to the lower concentration as the cleaner filtered out $PM_{2.5}$ air built-up inside the car.

The AC car route from Connaught Place to IIT Delhi, see time series (Fig. 4e), shows that it took approximately 23 min for the pollution levels in the car to reduce to NAAQS of 60 μg/m^3. Compared with the result obtained from the alternative by car route from the heavily industrialized Okhla to IIT Delhi showed the$PM_{2.5}$ levels inside the car with a concentration in the range around 90–100 μg/m^3 after 10 min of the journey, although never achieved the NAAQS. The main reason behind this variance could be due to the significantly worst air quality in Okhla.

3.2.6 $PM_{2.5}$ concentration in metro

The lowest exposure of the $PM_{2.5}$ levels was found in the underground metro in Delhi. The lowest value of the pollution received was 46.0 μg/m^3, while the maximum level recorded for this mode of transport 163 μg/m^3 (mean: 72.0 ± 11.0 μg/m^3'; median: 71.0 μg/m^3). This maximum value was due to the opening of the metro door for the commuters to alight and enter. As the ventilation of the metro is similar to that of the AC cars, the pollution levels slowly decrease as the particulate matter (PM) is filtered out of the air. The $PM_{2.5}$ emissions in the metro predominantly governed by the movement of carriages in tunnels, the movement of a large number of commuters, and air-conditioning in the metro system. Although, it's very difficult to precisely pinpoint the exact reason for the high concentrations in the metro. Figure S1f showed a slightly skewed distribution of the exposure levels in Delhi. The high-frequency concentration is located between 65.0 μg/m^3 and 79.0 μg/m^3, with no outliers being shown in the results, largely due to the more ambient nature of the outdoor pollution inside ventilated closed tunnels in which the metro runs. The resulting distribution substantially is below 100 μg/m^3, making it the lowest distribution of $PM_{2.5}$ exposure of all modes of transport.

Notwithstanding, there was a noticeable difference in the results between the pollution exposure levels at the metro station exposure compared to the inside of the metro carriage. This difference is illustrated in Fig. 4f, with a significant drop in $PM_{2.5}$ levels, when the metro was boarded at the station. An immediate 29% reduction in $PM_{2.5}$ concentration levels is observed, with an overall 51% total lower exposure on the metro compared to being on the station platform. While the metro and metro station could have been recorded as separate exposures as in other studies (Goel et al., 2015), this was out of the scope of this study. Any commute using the metro would have to travel through the metro station, thus experiencing the exposure whilst walking in the station, however, this study is focused on the effect on exposure inside the vehicle when the metro is stopped at stations.

3.3 Open and enclosed transport

The results demonstrate that enclosed transport, such as metro and AC car, was the best option for travel compared with the open modes (e.g. walking, rickshaw, motorised vehicles with open windows) because travelling in the enclosed commute mode received the lowest mean exposure $PM_{2.5}$ levels. Air-conditioning played an important role in AC cars and metro compartments, as they helped to filter out the outdoor PM ingress. The average exposure levels in rickshaws and walking were approximately 3.7 and 3 times greater than the metro and AC car respectively. The rickshaws recorded an exceptionally high level of $PM_{2.5}$ (>1000 μg/m^3). This was due to the rickshaws' open interior, with travellers being affected by the rickshaw's own as well as being much closer to the effects of other vehicle exhaust during congestion and compounded with the re-suspended PM being closer to the road surface (Choudhary and Gokhale, 2016). Consistently open forms of transport whether buses or non-AC car exhibited mean exposure levels that are higher than the closed modes. Even if technically these commutes have enclosed spaces (AC buses and metros), the air inside the transport is continuously circulated and doors have to be opened periodically to allow passengers to alight and board the vehicle. Although, the enclosed structure quintessentially constrains the higher levels of $PM_{2.5}$. This was demonstrated by the results which clearly show that whilst the rickshaw had respectively a mean exposure level of 1.8 and 2.4 times higher than the non-AC car and bus and the maximum levels measured were 15.1 and 13.8 times higher, respectively. Also, the mean exposure levels of non- AC car were around 1.3 times greater than that of the bus. The current study was conducted in February, the cold month of the year, AC in the buses was turned off and some of the windows were open, including the driver's window. Thus, this would have affected the results of this study.

4 Discussion

The present study found that travelling by rickshaw exposed users to the highest concentrations of $PM_{2.5}$, followed by walking. Also, it was observed that the high concentrations recorded in this investigation were similar to trends recorded in the previous study in Delhi (Goel et al., 2015). On the other hand, when travelling by metro and AC car, users were exposed to the lowest concentrations of $PM_{2.5}$ when compared with other modes. Exposure levels recorded on the bus relatively were lower than walking or by rickshaw, although higher when compared with the AC car or metro. Non-AC cars were ranked above the bus. In the present study, the $PM_{2.5}$ exposure in the metro and the bus were much lower than measured in the previous study by (Goel et al., 2015) conducted in Delhi during 2012–2014, this may be due to the recent clean transport approach by the Government in Delhi which eventually reduce pollution from the transport sector (CII and NITI Aayog., 2018).

4.1 Individual transport exposure analysis along the routes

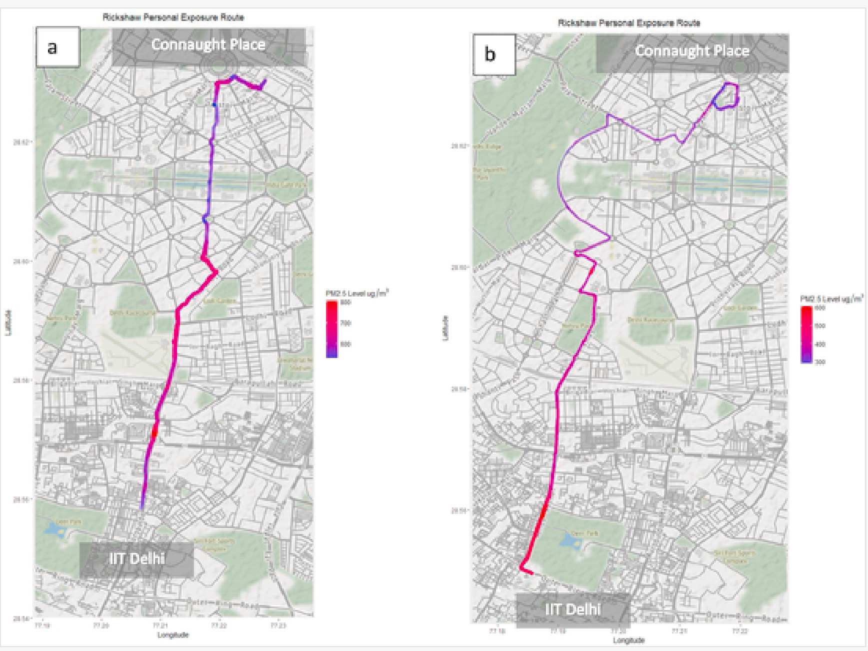
The varying differences in the exposure levels along the routes for transport modes studied in this research are now discussed.

4.1.1 Exposure analysis in rickshaws

In the present study, two different routes, the main (mean $PM_{2.5}$: 598 ± 51 μg/m^3; median: 589 μg/m^3) and the alternative (mean $PM_{2.5}$: 361 ± 69 μg/m^3; median: 337 μg/m^3), were also driven by the rickshaw (Figure S2 and S3). The high concentration was recorded around Deer Park, near IIT Delhi where higher traffic and higher congestion levels are the norms. The proximity to the vehicles in traffic would cause an increase in recorded levels, due to their exhausts and engines polluting directly into the open rickshaw. The maximum level was measured near Nehru Park, the proximity of three fuel stations within just 500 m which have an additional contribution to the regular traffic (Fig. 5). The rickshaws travelled along the same stretch of Connaught Place on both routes but in different periods of the day ending at 10:00 AM and 11:00 AM. This 1-h difference reduced exposure levels by 200 μg/m^3, as high levels of concentrations measured during the early morning rush hours, due to congested related emissions coupled with the varying atmospheric mixing height which causes the levels of ambient $PM_{2.5}$ to rise (Goel et al., 2015).

alt-text: Fig. 5

Fig. 5



Rickshaw map exposure route monitored during study (a) main route (b) alternative route.

This CNG operated open mode of transport is hugely exposed to the emissions from its engine and exhaust as well as other related road pollution sources often due to lengthy durations spent in Delhi congestion (Khan et al., 2015), although though a fair number of rickshaws (29% of the total rickshaw in 2018) had started to use electric, and therefore the exposure would be less. Research conducted by Reynolds et al. (2011) stated that not properly maintained CNG rickshaws was responsible for exceptionally high $PM_{2.5}$ (3110 µg/m^3). This is a worrying level of exposure, as it shows the high concentrations that commuters can be exposed to during day-to-day life in Delhi. The results obtained in the research reported in this manuscript (266 ± 159 µg/m^3) are quite similar to the research conducted in Delhi (Goel et al., 2015), where the mean level was 241 ± 136 µg/m^3 in February 2015. A study by Kumar and Gupta (2016) also measured high mean levels of $PM_{2.5}$ exposure in rickshaw of 332.8 ± 90.9 µg/m^3 in March 2012, and whilst a lower value of lower value (200 ± 46 µg/m^3) was recorded by Apte et al. (2011) in 2010, external factors such as different routes, time of day influence the results.

4.1.2 Exposure analysis during walking

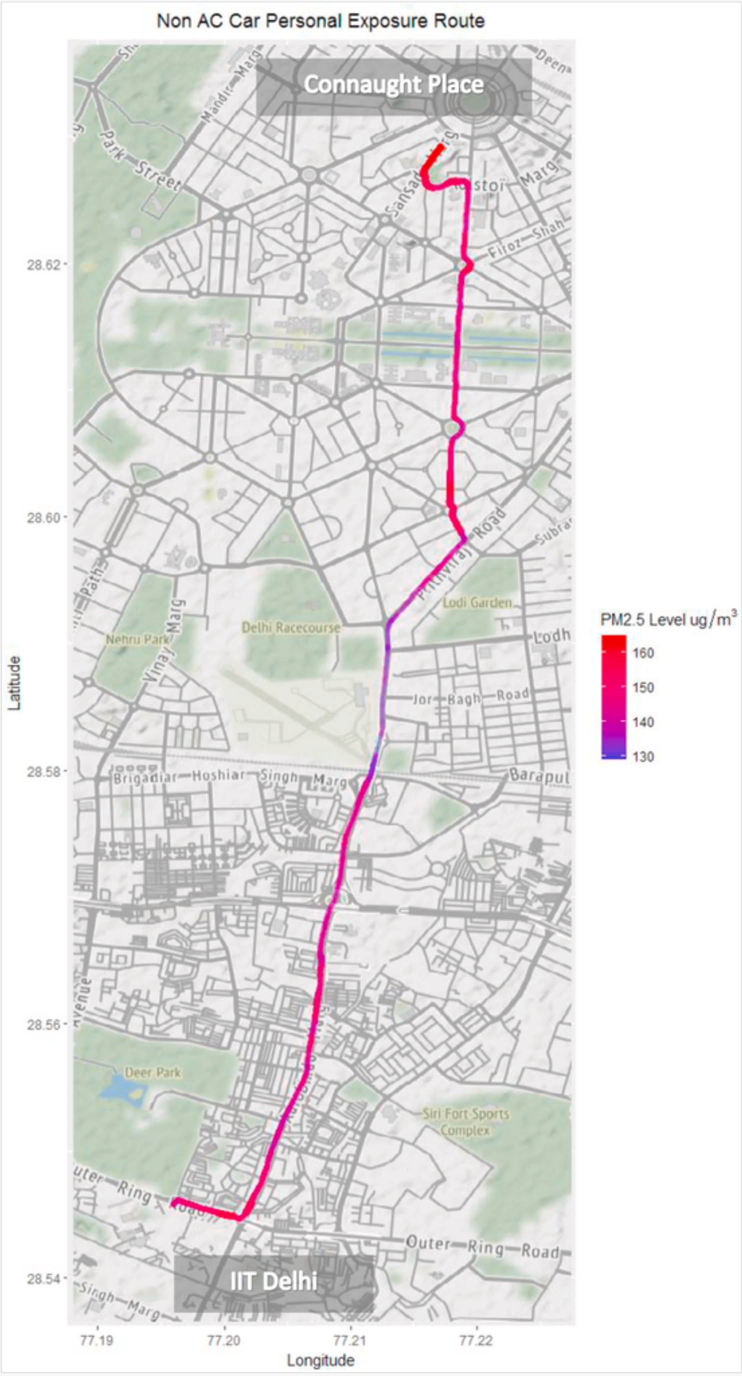
Measurements were made whist walking in the vicinity of IIT Delhi and Connaught Place due to safety concerns which made it impossible to conduct the study on the main route with rickshaw. The results from the walk mode in this study suggested further that the pollution levels were increasing depending on the proximity to the main road and with the passage of heavily polluting vehicles such as HGVs close to the pavement. Also walking on the same route in the morning and afternoon showed variation in the different exposure levels. In general, the exposure levels for walking were high in the morning than in the afternoon. These results suggest that the high level of exposure in the morning could be avoided if pedestrians chose not to take walks during the peak hours of 8:00 to 10:00 AM, however, that it is not a realistic option for most people.

4.1.3 Exposure analysis for Non-AC cars

The analysis shows that the high level of $PM_{2.5}$ exposure was observed in Connaught Place, due to high congestion at the time, as well as in denser urban areas causing PM to be trapped in street canyons. As the open windows in the non-AC car, allowed $PM_{2.5}$ to enter directly into the car from nearby vehicles concentration spikes up to 206 µg/m^3 (Fig. 6 and S6) were observed. The minimum exposure on this route was found near Delhi Racecourse, where the level of $PM_{2.5}$ reached its lowest level of 114 µg/m^3, this trend was similar to that of the rickshaw main road exposure route. This drop-in level may be due to the open green area which provides an opportunity for natural ventilation reducing $PM_{2.5}$ exposure levels. For the same route, the non-AC car was exposed to an average concentration of $PM_{2.5}$ 78 µg/m^3 higher than the AC car. The difference that AC can make is evident when comparing the two modes of transport, with AC car being a much healthier commuter option than a non-AC car and rickshaw given the significant lower pollution exposure.

alt-text: Fig. 6

Fig. 6



Non-AC car map exposure route monitored during the study.

Kumar and Gupta (2016) also reported very high exposed $PM_{2.5}$ concentrations (332.4 ± 137.5 µg/m^3) in non-AC-car during morning peak-periods in Delhi. When comparing the exposure in the non-AC car to the ambient mean, the exposure in the car is only 3% greater than the observed daily ambient $PM_{2.5}$ during the study. However, compared to the rickshaw, the levels of exposure are much lower in the non-AC car, with a difference of 116 µg/m^3 between their mean exposure concentrations. This demonstrates that the physical barriers of the car, (i.e. windshield, windows and frame), play a major role in limiting the levels of $PM_{2.5}$ that can enter the vehicle.

4.1.4 Exposure analysis for buses

The route followed by the bus was broadly similar to the alternative route of the rickshaw. The higher levels were recorded in Vasant Vihar IIT Delhi, (120–140 $\mu g/m^3$) and these continued through the embassy area near Nehru Park, where the highest concentration of $PM_{2.5}$ was recorded at 226 $\mu g/m^3$ (Fig. 7 and S7). The average recorded value in the bus (113 $\mu g/m^3$) was much lower when compared with the previous study in Delhi (Goel et al., 2015) (278 $\mu g/m^3$) at the same time of year in 2015. An explanation as to why the levels recorded was much lower than other studies may be because many buses in Delhi now use AC. With the Government of Delhi increasing the number of AC buses available in the city (Goswami, 2017), lower levels of exposure to $PM_{2.5}$ can be expected. A study in Ahmedabad (Swamy et al., 2015), found that commuters in AC buses were exposed to approximately 40% less $PM_{2.5}$ than those in non-AC buses. The buses used during this study were AC, but like the AC cars, most of the AC units in buses were not activated initially because monitoring started in the winter months. Even when the AC was activated, some windows were left open on the bus, allowing ambient pollution to enter through the open windows. Nevertheless, the overall results of the study show that buses were towards the lower end of exposure to $PM_{2.5}$ as a mode of transport. In general, travelling by bus had exposure levels 22% lower than the ambient air quality.

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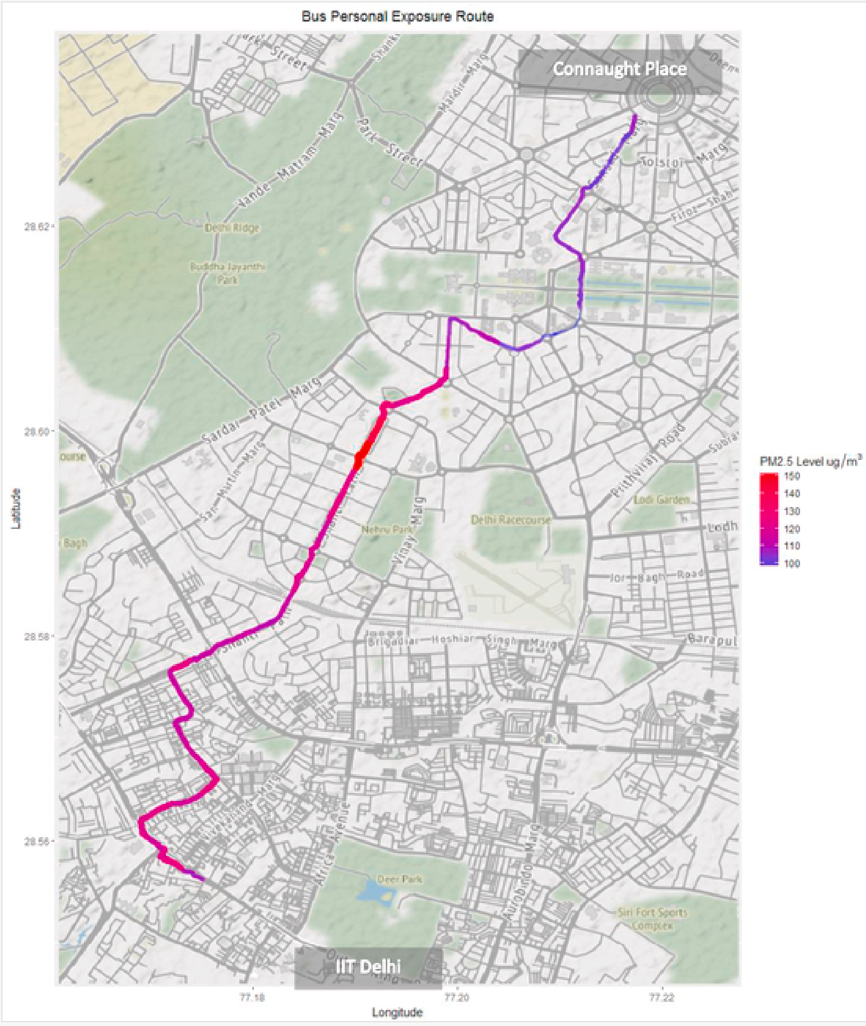
Fig. 7



Bus map exposure route monitored during the study.

4.1.5 Exposure analysis for AC cars

In this study, two routes were considered to record the $PM_{2.5}$ levels; the main route and the alternate route taken from the Okhla industrial estate (Figure S4 and S5). For both routes, high $PM_{2.5}$ values were recorded at the start of the journey and decreased once AC was switched on. In the case of the main route, the $PM_{2.5}$ concentrations (mean: 69 ± 24 $\mu g/m^3$) in AC vehicle continue to decrease throughout the journey and no surges were observed in the trend (Fig. 8). The levels recorded on the main route matched with the analysis of two previous studies (Namdeo et al., 2016; Goel et al., 2015). The alternative route was from the industrial area of Okhla to IIT Delhi. This route was deliberately selected to explore the changes occurring in the exposure levels due to travelling in the high pollution area in Okhla (Nandi, 2017). However, the car used for the alternative route was using 'fresh air' without the recirculation mechanism of the AC. The effect of this was visible when the $PM_{2.5}$ levels did not fall during the journey, stabilising around the mean value (104 ± 15 $\mu g/m^3$). These results confirmed that the different air ventilation settings of the cars can affect in-vehicle exposure levels. Towards and at the end of the journey from Okhla to IIT Delhi showed high levels due to increased congestion and possibly coupled with high urban density. A study in Beijing (Yao et al., 2015) reported that urban areas were exposed to ~15 $\mu g/m^3$ higher concentrations of $PM_{2.5}$ compared to green and suburban areas.

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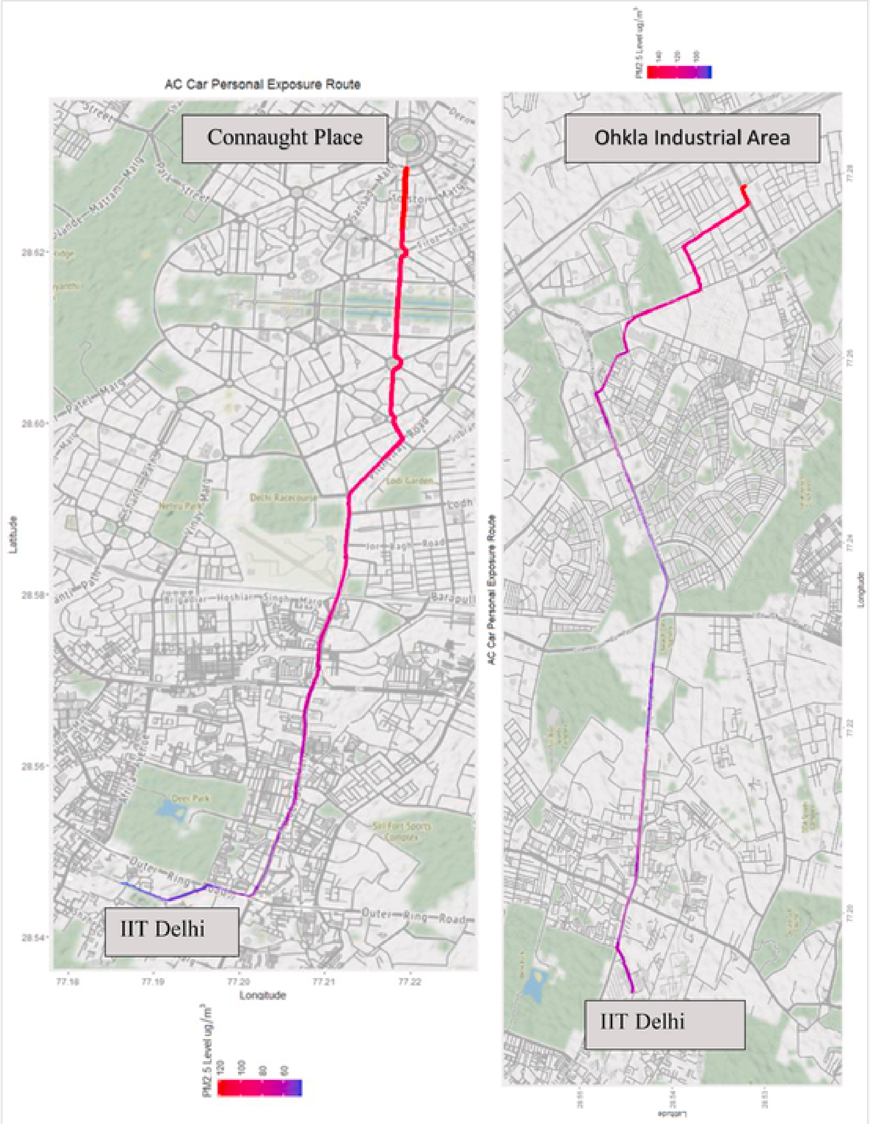
Fig. 8



AC-car map exposure route monitored during study (a) main route (b) alternative route.

4.1.6 Exposure analysis for metro

Travelling by metro proved to be the least exposed mode of transport studied in this research, with a mean exposure of $PM_{2.5}$ of 72 μg/m^3. These results were in the agreement with Goel et al. (2015) reporting an average exposure on the metro of 87 μg/m^3 in April 2015 and 76 μg/m^3 in May 2015. However, these levels were recorded in the spring period when the pollution levels are already lower than in the winter consistent with measurements in another large city, The newer and modern system adopted for Delhi metro, along with the use of AC in both the metro stations and carriages, reduced the $PM_{2.5}$ level significantly.

The metro with around 2.7 million passengers daily (India Today, 2018), experiences exposure much lower when compared with that of the bus. However, the majority of Delhiites, around 4.2 million commuters (Standard Business, 2018.), prefer travelling by bus due to the less expensive fares and wider coverage of areas served. Pollution levels in the station were higher than those measured in the metro carriage. The pollution levels within the metro were almost 51% less than the metro station. The monitors also recorded a slight rise in the $PM_{2.5}$ concentrations (about 20 μg/m^3) at the locations when the carriage doors opened to let passengers alight and board.

4.2 Respiratory deposition doses (RDDs)

To accomplish a comprehensive study of the effects of this pollution on human health, the individual's inhalation or ventilation rate during the commute must be considered. Thus, this will give a total RDDs of $PM_{2.5}$ per km journey in Delhi city and the resulted value was calculated for healthy adult's population. The study by Gupta and Elumalai (2019) calculated an inhalation rate of 2.5×10^{-2} m^3 per minute for light activity, and a deposition fraction factor for $PM_{2.5}$ of 0.87 (see supplementary material). Using these values with the average mean exposures, an estimated total RDDs per km was calculated for this study. As previously stated, walking and rickshaw have the highest inhaled $PM_{2.5}$ levels per km of the journey (Table 3). The total dosage received would be 84.7 ± 33.4 μg/km with waking and 15.8 ± 9.5 μg/km using a rickshaw. The total RDDs during the journey with a non-AC car and a bus were 9.7 ± 0.9 μg/km and 7.4 ± 0.9 μg/km. The lowest RDDs were observed in AC-car (5.8 ± 2.0 μg/km) and metro (3.0 ± 0.4 μg/km). This is similar to the amount of $PM_{2.5}$ that a rickshaw driver inhaled in Dhanbad, India (19.4 μg/m^3) (Gupta and Elumalai, 2019). However, the study by Goel et al. (2015) inferred that the total $PM_{2.5}$ dosage was much higher for all transport modes, which questions whether the estimated doses calculated in this study are underestimations.

alt-text: Table 3

Table 3

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Estimated respiratory deposition doses (RDDs) of $PM_{2.5}$ in multiple transport microenvironments in Delhi.

Mode of Transport	Total RDDs (μg)	Average RDDs/km journey (μg/km)

Rickshaw	205.8 ± 123	15.8 ± 9.5
AC Car	68.7 ± 23.2	5.8 ± 2.0
Non-AC Car	115.3 ± 10.1	9.7 ± 0.9
Metro	31.9 ± 4.9	3.0 ± 0.4
Bus	106.3 ± 13.2	7.4 ± 0.9
Walking	980 ± 386	84.7 ± 33.4

5 Conclusion

The present study focusses on the different exposure levels recorded by commuters using six modes of transport in Delhi and the results showed that travellers in open modes of transport (rickshaws and walking) were exposed to the highest $PM_{2.5}$ concentrations. Inside enclosed modes of transports which used AC, including private cars and the metro, were found to have significantly lower $PM_{2.5}$ concentrations. The exposure levels for passengers on buses and travellers in non-AC cars were found to lie between fully closed and open transport modes. Nevertheless, open windows and the frequency of opening doors on buses resulted in ambient pollution (background plus that emitted by other vehicles) entering vehicles, thus increasing the concentrations to which travellers were exposed.

The findings of this study can be used to identify areas for further research and to shortlist the mitigation measures towards reducing $PM_{2.5}$ exposure in Delhi. This study suggests that the identification of the congestion hotspots is important as personal exposure is observed to be very high in these locations. The possible implementation of intelligent transport systems at the congested area can reduce levels of pollution (Díaz et al., 2020). Education and information to the users of travel modes on how to reduce their exposure levels would go a long way in protecting their health. One of the solutions could be to wear a respirator mask or avoid congestion hot spots if the route could be altered (e.g. when using rickshaws and private cars). Other methods to reduce exposure could be achieved through simple measures, such as advising buses and cars to keep windows closed during high pollution episodes and the use of AC. Encouraging sustainable modes of transport such as electric vehicles and the metro would reduce $PM_{2.5}$ emissions and the ambient levels consequently reducing the personal exposure.

The study has also outlined several areas where further research will help in developing a better understanding of the effect of traffic state (congestion vs. free-flowing), ventilation settings in vehicles (recirculation vs fresh-air; opening and closing of doors and windows) and metro stations. The frequency of door opening and passenger number effects the $PM_{2.5}$ concentration in a bus need for further investigation. Time spent travelling on a particular travel mode is also an important area to investigate. Apps could be developed to optimise for travel time and the lowest level of personal exposure on travel modes which will permit such changes. This research could be extended to include additional travel modes including cycling and local-trains. Whilst this study focused on $PM_{2.5}$, further research could monitor the personal exposure to different pollutants, such as particle numbers, ultrafine particles, CO, NO_2 and VOCs, that have all been proven to be harmful to human health. Health effects of the total exposure to all pollutants could then be assessed, to investigate where and why pollution hotspots occur, and their detrimental effects.

Credit author statement

K. J. Maji: Formal analysis, Data curation, Software, Validation, Writing-original draft, Writing - review & editing. **A. N~~ma~~amdeo**: Methodology, Resources, Conceptualization, Data curation, Visualization, Writing - review & editing, Supervision, Funding acquisition, Project administration. **D. Hoban**: Methodology, Software, Validation, Formal analysis, Investigation. **M. Bell**: Methodology, Resources, Conceptualization, Writing - review & editing, Supervision, Investigation. **P. Goodman**: Software, Writing - review & editing. **S.M.S. Nagendra:** Resources, Data curation. **J. Barnes**: Writing - review & editing, Visualization. **L. D Vito**: Writing - review & editing. **E. Hayes**: Writing - review & editing. **J. Longhurst**: Writing - review & editing. **R. Kumar**: Resources, Data curation. **N. Sharma**: Resources, Data curation. **S.K. Kuppili**: Resources. **D. Alshetty**: Resources, Data curation.

Declaration of competing interest

Kamal Jyoti Maji and Anil Namdeo declares that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We~~I~~ confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of the authors, and there is no conflict of interest.

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Appendix A Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2020.12.003.

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The corrections made in this section will be reviewed and approved by a journal production editor. The newly added/removed references and its citations will be reordered and rearranged by the production team.

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Footnotes

Article Footnotes

Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.

Highlights

- On-road $PM_{2.5}$ exposures in six transport microenvironments ae measured in Delhi.
- Travelling in auto rickshaws and walking leads to higher exposure.
- Travelling in AC-cars and the metro had the lowest overall exposure.
- $PM_{2.5}$ mass inhaled/km is 28.2 and 5.3 times for walking and rickshaw compared to that for a metro.

Appendix A Supplementary data

The following is the Supplementary data to this article:

Multimedia Component 1

Multimedia component 1

alt-text: Multimedia component 1

Queries and Answers

Q1

Query: Please confirm that the provided emails “kamal.maji@northumbria.ac.uk, anil.namdeo@northumbria.ac.uk” are the correct address for official communication, else provide an alternate e-mail address to replace the existing one, because private e-mail addresses should not be used in articles as the address for communication.

Answer: Correct

Q2

Query: The citation 'Rodenbeck, 2018' has been changed to match the author name in the reference list. Please check here and in subsequent occurrences.

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Q4

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