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Analysis of various transport modes to evaluate personal exposure to PM2.5 pollution in Delhi

--Manuscript Draft--

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Abstract:	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 84.7μg/km, 15.8μg/km and 9.7μg/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.
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Response to Reviewers:	Please see the attachment.

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To,
Editor in Chief,
Atmospheric Pollution Research

September 21, 2020

Dear Editor,

I am **resubmitting** herewith the manuscript entitled "Analysis of various transport modes to evaluate personal exposure to $PM_{2.5}$ pollution in Delhi" for potential publication in Atmospheric Pollution Research.

This study provides a comparative assessment of on-road $PM_{2.5}$ exposures in six transport microenvironments in Delhi. Novelty of this research is to identify the highest and the lowest exposure levels in different transport modes. The results will help to develop policies in future to reduce personal exposure in Delhi and many other metropolitan cities. 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 84.7μg/km, 15.8μg/km and 9.7μg/km for walking, rickshaw and non-AC car transported mode of journey, respectively.

I am looking forward to your favorable response in reviewing this submission.

Title: Analysis of various transport modes to evaluate personal exposure to PM2.5 pollution in Delhi

Yours sincerely,

Professor. Anil Namdeo and Dr. Kamal J. Maji
(Corresponding author)

Dear expert,

Thank you very much for giving us the opportunity to revise our manuscript. We are grateful for your comments and suggestions to improve our manuscript. We have studied your comments carefully and made relevant revisions and corrections which are marked in colour (Insertions are in Blue and Deletions are in Strikethrough Red colour) in the revised manuscript. Attached please find the responses to comments and the revised manuscript for your consideration.

Yours sincerely,

Kamal Jyoti Maji

Editor and Reviewer comments:

Reviewer #1:

This manuscript was related to personal exposure to PM2.5 in six different transportation modes in Delhi. The discussion was given in very detail but the number of data is limiting the evaluation of the manuscript. Generally, there is no statistically analyse results in the study.

My comments are given below:

1. Line 115: Figure 1 must change as Figure 2.

Response: We would like to thank the reviewer for this comment and sorry for the typo. A correction has made in the revised manuscript.

2. -Line 123: Is there any fixed air quality monitoring station? If yes please show it on the map (Figure 2).

Response: Thank you for your suggestion. Yes, there are two air quality monitoring stations in the study area. We have corrected the figure to reflect this.

3. Figure 4: The scale of Y axis is not satisfied the readers (up to 1500 µg/m3) for showing the trend of $PM_{2.5}$. It can be good for rickshaw and walking, but for the

others is not clear. The typical - short period fluctuations such as opening doors (especially in metro route) is not understandable.

Response: Thank you for your valuable suggestion.

Now, we have corrected Figure 4 in the revised manuscript to show appropriate Y axis scales.

4. **Line 164-167: The personal exposure whilst travelling depends on the seasons, time of the day..etc. Authors did not have any data about that within this study. Please give literature.**

Response: Thank you for asking the clarification. The following references have been added in the revised manuscript.

(Chaney et al., 2017)(Lin et al., 2020)

Reference:

Chaney, R.A., Sloan, C.D., Cooper, V.C., Robinson, D.R., Hendrickson, N.R., McCord, T.A., Johnston, J.D., 2017. Personal exposure to fine particulate air pollution while commuting: An examination of six transport modes on an urban arterial roadway. PLOS ONE 12, e0188053. https://doi.org/10.1371/journal.pone.0188053

Lin, C., Hu, D., Jia, X., Chen, J., Deng, F., Guo, X., Heal, M.R., Cowie, H., Wilkinson, P., Miller, M.R., Loh, M., 2020. The relationship between personal exposure and ambient PM2.5 and black carbon in Beijing. Science of The Total Environment 737, 139801. https://doi.org/10.1016/j.scitotenv.2020.139801

5. **Figure 1: Authors has given very detailed data for the annual and daily trend of PM2.5. It would be better if authors give the mean PM2.5 concentration at measurement day in table 2. The number of measurement days are very few. RK Puram and Mandir Marg stations are close to the study routes. Do you have any urban background station? If yes please mention the mean concentration at urban background station at these days.**

Response: Thank you for your suggestion. We have added $PM_{2.5}$ concentrations (Column: Ambient Concentration) from the monitoring stations in Table 2.

The Panchkula (PK) monitoring site in Delhi is considered as a background site for the Delhi city and a very low concentration was observed at the PK site.

We have added the following sentence in the manuscript:

During the study period (2nd to 8th February 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).

6. Line 187: 'the personal exposed PM2.5 concentration and PM2.5 in the microenvironment are the same,...'. authors mean walking mode.

Response: Sorry for the poor choice of the words. Here we want to say that in the present study, the time-weighted $PM_{2.5}$ concentration and the average concentration of $PM_{2.5}$ in the microenvironment are the same.

Personal exposure concentration is a function of the concentration within various microenvironments visited as well as the time spent in those microenvironments. It can be defined as by the following equation: $C_E = (\sum C_i t_i)/t$ (https://www.ncbi.nlm.nih.gov/books/NBK218147/).

where, C_E is the time-weighted concentration for personal exposure to a pollutant, C_i is the concentration of a pollutant in a microenvironment i, and t_i is the fraction of the modeled time spent in a microenvironment i. t is the total exposure time. The aerosol monitor AM520 measure $PM_{2.5}$ in every second, so the $C_E = (\sum C_i)/t$.

We have corrected the sentence accordingly and we added the explanation to the supplement.

7. Line 226-238: Figure 1c is showing the data of typical urban traffic site. Actually, the meteorology, atmospheric conditions etc can affect the concentrations of the city, but this study has been made at the traffic microenvironment. So, in my opinion, the most reason of the difference between morning and afternoon could be the difference of the traffic load at the street. If possible, authors should give the number of vehicles on the study route in the morning and afternoon.

Response: Thank you for your comments and observation on the relevance of traffic volume in explaining the variations in the $PM_{2.5}$ concentrations during the morning and afternoon hours. Therefore, in section 3.2.2, we have added the following sentences.

Walking in the morning had a mean exposure to $PM_{2.5}$ of 379μg/m^3, while in the afternoon the mean exposure was 166μg/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 am 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 morning peak is followed by a gradual decrease in $PM_{2.5}$ concentrations through the afternoon. This feature might be explained in part by the growth of the mixing layer depths and stronger atmospheric ventilation during the afternoon. The morning peak might be associated with the fumigation effect in the boundary layer, which brings aerosols from the nocturnal residual layer shortly after the sunrise. As the day advances, increased solar heating leads to increase turbulent effects and a deeper boundary layer, leading to faster dispersion of aerosols and hence dilution of $PM_{2.5}$ concentration occurs near to the surface during the after 16:00 (late-afternoon). In the day of the study, the average ambient $PM_{2.5}$ concentration was 227µg/m^3 at morning 9:00, which was about 51% higher than the $PM_{2.5}$ concentration at 12:00.

We also feel that the vehicular numbers and $PM_{2.5}$ are highly correlated in this region. Therefore, we tried to collect the traffic flow data from the Traffic department in Delhi, but unfortunately, till now we have not been able to get any data on traffic volume.

8. What is the unit of journey time?

Response:The journey times are shown in seconds. Although respiratory deposition doses (RDD) are calculated based on the journey times in minutes.

9. Line 240: ' ... third highest in Non-AC car..'

Response: Sorry for the typo error. A correction has been made in the revised manuscript.

10. Line 244: 'Non-AC cars often have their windows kept open in Delhi.' What about during measurement period?

Response: Yes, during the measurement period, the window was kept open in the non-AC car. The following sentence is added in the revised manuscript.

Non-AC cars often have their windows kept open in Delhi and therefore $PM_{2.5}$ concentration was higher than that in the AC car.

11. Line 267: ' These depended on the time of day and number of passengers boarding and alighting the bus.' There is no statistically evaluation in this study. Please add literature if you give a reason of the result.

Response: Thank you for your valuable suggestion.

Kumar et al., (2018) reported that particulate matter concentration in bus dependents on time of travel and frequency of descending from a bus, although that study was done in the UK. Kolluru et al., (2019) have conducted a similar study in India.

These two references have been added to the revised manuscript.

References:

Kolluru, S.S.R., Patra, A.K., Dubey, R.S., 2019. In-vehicle PM2.5 personal concentrations in winter during long distance road travel in India. Science of The Total Environment 684, 207–220. https://doi.org/10.1016/j.scitotenv.2019.05.347

Kumar, P., Rivas, I., Singh, A.P., Ganesh, V.J., Ananya, M., Frey, H.C., 2018. Dynamics of coarse and fine particle exposure in transport microenvironments. npj Climate and Atmospheric Science 1, 11. https://doi.org/10.1038/s41612-018-0023-y

12. Line 269: What is the mode of the AC circulation? What is the circulation type? internal or external?

Response: Thank you for your valuable comment.

Most of the AC cars in Delhi keep air to recirculation mode to conserve the energy and to keep the in-cabin temperature cooler. This reduces the intake of fresh, polluted outside air, and at the same time recirculation through AC filters. This in turn reduces internal PM levels.

Results of the scenario when external air is drawn are reported in the manuscript in the discussion section (4.2.5).

However, the car used for the alternative route was using ‘fresh air’ (external circulation) 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.

13. Generally, there is no information about the features of vehicles; the model, year, fuel type etc.

Response: Detailed information about the vehicle make and model was not deemed essential for this manuscript, hence omitted. In terms of the fuel used: buses and autorickshaws use CNG, private cars used petrol and metro uses electricity. Autorickshaw, cars and buses used in this study represented a typical average vehicle age profile in Delhi (5-10 years)

14. Line 293: ' The exposure levels in the metro predominantly were due to PM2.5 levels from the metro station as well as from the metro carriage itself.' Maybe but there is no result or calculation? Additionally, there are three sources of PM in metro; (1) ventilation (2) movement of vagon in the tunnels (3) passengers. So, it's very difficult to explain the reason of the high concentration.

Response: We would like to thank the reviewer for highlighting this aspect. Your view regarding the pollution concentration in the metro is correct. Unfortunately, we do not know the relative contribution of each of these factors hence will not be able to expand more. However, we have refkected this difficulty in the revised sentence shown below:

The $PM_{2.5}$ concentration in the metro predominantly was due to the $PM_{2.5}$ levels in the station, ventilation process, movement of the carriage in tunnels and number of passengers. Although, it's very difficult to explain the exact reason for the high concentration.

15. Line 322: This title and explanation is not necessary. Authors did not give a different result or analyze. Authors can discuss in Part 3.

Response: Thank you for your suggestion. Section 4.1 (Open and Enclosed Transport) discusses $PM_{2.5}$ concentrations in the open and enclosed transport. We have analyzed and compared the ratio of $PM_{2.5}$ in open and enclosed transport in this section. *We have moved the part in the result section 3.3.*

16. Part 4.2: I could not understand the difference between the part 3 and part 4.2. The same concentration results were discussed.

Response: Thank you for your comments. In the section 4.2, we characterise the $PM_{2.5}$ along the routes on different travel modes, showing the spatial variation, and compare these with previous studies. In the revised manuscript we have removed the duplication of the discussion from Section 3.

17. Part 4.3. It should be better if authors give the RDDs results in a Table.

Response: Thank you for your suggestion. We have added the following table in the revised manuscript.

Table 3 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

18. Conclusion is very long. The findings must be given shortly and the solutions/suggestions and the future studies must be mentioned.

Response: We would like to thank the reviewer for this comment and agree with it. We have shortened the conclusion section as whoen below:

The study undertaken can be used to suggest several key areas where both research and action will take steps forward in reducing $PM_{2.5}$ exposure in Delhi. Like, congestion hotspots were proven to be areas where exposure levels were exceptionally high, limiting congestion and number of vehicles may aid this. The possible implementation of intelligent transport systems at the congested area can reduce levels of pollution (Díaz et al., 2020). Education and information as to how to reduce exposure levels would go a long way in protecting an individual from the effects of $PM_{2.5}$, (i.e. wear a respirator mask). 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 use of AC. Encouraging sustainable modes of transport such as electric vehicles and the metro would help limit the generation of $PM_{2.5}$ on roads, effectively reducing ambient levels.

The study has also outlined several areas where further research will help develop an understanding of exposure levels of $PM_{2.5}$ and the effect different transport modes have. Further research into the other areas will give more accurate data, further understanding of what level people are exposed to daily. As well as this, research should be conducted into other transport modes, such as cycling, trains, Light Goods Vehicles (LGVs) and Heavy Goods Vehicles (HGVs). The frequency of door opening and passenger number effects the $PM_{2.5}$ concentration in a bus need for further investigation. Whilst this study focused on $PM_{2.5}$, further research could monitor the personal exposure to different pollutants, such as PM_1, 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.

Reviewer #2:

The research "Analysis of various transport modes to evaluate personal 1 exposure to PM2.5 pollution in Delhi" by Dr. Maji et al measured and compared real-time personal exposure to PM2.5 at six travel modes in Delhi. Then it estimated respiratory deposition doses for different modes. The study is well written and interesting for heavy polluted regions. Some specific comments:

Response: Thank you for your positive response and giving us the opportunity to improve the manuscript.

1. **Some external environments, such as wind and humidity of the experiments, are important factors affecting the $PM_{2.5}$ concentrations. They should be described to ensure that measurements for different travel modes comparable.**

Response: Thank you for your valuable suggestion. In our study, we had access to the wind speed data for the nearest air quality monitoring sites, although we could not obtain the relative humidity dataeither for the monitoring site or for inside environment of the transport modes. The study was conducted with a short period in the winter month of February 2018 (2^{nd} to 8^{th}), so we can assume that the during the study period wind speed and humidity did not change dramatically. This can be a limitation of our study, and has been reported in the supplementary section.

2. The respiratory deposition dose might be varied between different people, such as children/ young/old. It's not clear the estimated value in the manuscript is applicable for which group. A 95% confidence interval is also welcome.

Response: Thank you for your suggestion. The respiratory deposition dose was calculated for healthy adults. The correction has been made in the revised manuscript.

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 population**.

The estimated value depends on the $PM_{2.5}$, breath rate and the number of breath/min. In the present study, the only variable parameter is $PM_{2.5}$ concentration. We used the average value of $PM_{2.5}$ in this study. We have not calculated value with 95% CI. We added the standard deviation value in Table 3.

3. The citation of RStudio might be incorrect. Please refer the following citation supplied by the function "RStudio.Version()" in the software: RStudio Team (2020). RStudio: Integrated Development Environment for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/.

Response: Thank you for your valuable input. We have corrected the RStudio reference in the revised manuscript.

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 84.7μg/km, 15.8μg/km and 9.7μg/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 (10km×10km or 1km×1km) (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 ~~, like ischemic heart disease (IHD), stroke (ischemic stroke and haemorrhagic stroke), chronic obstructive pulmonary disease (COPD), lung cancer (LC) and lower respiratory infections (LRIs) (in particular, pneumonia)~~ and ~~other cause of~~ morbidity ~~, such as Chronic Kidney Disease, diabetes, Alzheimer's disease, mental and behavioural disorders, pneumonia~~ (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 ~~(air-conditioned or open windowed),~~ type of travel routes, and meteorological conditions. Table 1 summarizes ~~more than 16past~~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 $\mu g/m^3$), Turkey (30.6-120.4 $\mu g/m^3$), and China (54.5-71.6 $\mu g/m^3$), and the lowest values are from cleaner high-income settings in the USA (12-35 $\mu g/m^3$), Europe (7.3-13.9 $\mu g/m^3$) and Canada (8.6-71.9 $\mu g/m^3$) (Table 1).

The cities in India differ significantly from the ~~high-income~~ 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 ~~Indian cities like~~ 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 1,484 km^2 and around 16.3 million inhabitants as per the latest census of 2011 (Government of India, 2020), 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 11km length, between the Indian Institute of Technology Delhi campus (IIT Delhi) to the Connaught Place (Delhi's CBD), as shown in Figure 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.

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^{TM} 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 0.001–100 mg/m^3, so are well within the range of measurements for $PM_{2.5}$ in the micro-environments studied. ~~For further analysis, all the readings were converted into µg/m^3.~~ 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 ~~. This factor is generally used for ambient aerosol in urban areas~~ (TSI., 2018). Usually, this equipment can have a flow rate up to 1.8 litres/minute, although for this experiment it was set to its default value of 1.7 litres/minute. 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 one second 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 3m 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 seconds after turning the device on ~~to allow it to calibrate the location~~, 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. ~~Also, this software can sync with other software such as the SidePak™ AM520 and that will record the exact geographical location with pollutants concentration on that particular location.~~

The personal aerosol monitor AM520 was securely placed in a backpack to avoid any obstructions to the inlet, exhaust port and outlet. ~~Improper placement of the monitor can cause blockages and failure in the device.~~ 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 8th February 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 Stamen© map (Rodenbeck, 2018).

3. Results

3.1. Ambient $PM_{2.5}$ concentration ~~in Delhi~~ 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 to 235 μg/m³) which gradually decrease afterwards due to the winds and precipitation during the monsoon months from July through September (33.7 to 46.0 μg/m³). 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 pm through midnight) and early morning and rush-hour period (8 am through 10 am). The levels were at their lowest during the afternoon hours (Figure 2). In winter the diurnal profile of $PM_{2.5}$ shows <200 μg/m³ from 11.00 am to 7.00 pm, after which time the concentration rises to > 200 μg/m³. 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 8th February 2018), the average ambient $PM_{2.5}$ concentration was 146±53 μg/m³. 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/m³; median: 60 μg/m³). ~~This was inferred using past data.~~

3.2. $PM_{2.5}$ concentration in different modes of transport

Tables 2 summarise the $PM_{2.5}$ concentration during commuting by the six travel modes indicated earlier. In this study, the time-weighted ~~personal exposed~~ $PM_{2.5}$ concentration and the average of $PM_{2.5}$ in ~~the~~ a microenvironment are~~are~~ the same, as the Aerosol Monitor measure ~~estimated $PM_{2.5}$~~ concentration in every one second. 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. Figure 3 shows the spatial variations in the average $PM_{2.5}$ exposures for the six modes of travels.

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 150μg/m^3, the lower densities were observed in between ~300μg/m^3 and 550μg/m^3. The three-day one-way trip average exposure level of $PM_{2.5}$ was 266±159μg/m^3 (median: 203μg/m^3). The time-series plot of the exposure in the rickshaw for different days (Figure 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 5th February 2018 was well over 1000μg/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).

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 165μg/m^3 and 304μg/m^3 (mean: 259±103μg/m^3; median: 264μg/m^3) (Figure S1b). This made it the second-highest exposed mode of transport during the study. A maximum value of 1280μg/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 (Figure 4b), with peak frequencies located at 150μg/m^3, 290μg/m^3 and 375μg/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 379µg/m^3, while in the afternoon the mean exposure was 166µg/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 am 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 morning peak is followed by a gradual decrease in PM2.5 concentrations through the afternoon. This feature might be explained in part by the growth of the mixed layer depths and stronger atmospheric ventilation during the afternoon. The morning peak might be associated with the fumigation effect in the boundary layer, which brings aerosols from the nocturnal residual layer shortly after the sunrise. As the day advances, increased solar heating leads to increase turbulent effects and a deeper boundary layer, leading to faster dispersion of aerosols and hence dilution of PM2.5 concentration occurs near to the surface during the after 16:00 (late-afternoon). In the day of the study, t~~The average ambient $PM_{2.5}$ concentration was 227µg/m^3 at ~~morning ~~09:00, which was about 51% higher than the $PM_{2.5}$ concentration at 12:00.

3.2.3 $PM_{2.5}$ concentration in n~~N~~on-AC car

$PM_{2.5}$ exposure was third highest in non-AC-car, where the majority of exposed $PM_{2.5}$ concentrations lie~~s~~ between 141 to 158µg/m^3, showing a very small interquartile range with the results being relatively consistent (Figure S1c). While the maximum value was 206µg/m^3 and the minimum was 114µg/m^3, with mean value was 149±13µg/m^3 (median: 149µg/m^3). Non-AC cars often have their windows kept open in Delhi and this could be the reason why ~~therefore~~ $PM_{2.5}$ concentration for this mode than that in ~~was higher than ~~an AC car. The average $PM_{2.5}$ concentration difference between AC car and non-AC car was around 61µg/m^3 on the same route of travel. The time-series plot in Figure 4c shows the wide distribution of the $PM_{2.5}$ exposure level in a non-AC car. It shows a relatively normal distribution around 145µg/m^3 of $PM_{2.5}$. When compared to the AC car, the distribution begins at a much higher concentration (114µg/m^3 for the non-AC car and 35.0µg/m^3 for the AC car). The initial levels recorded by the two modes were around 150µg/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 to 120µg/m^3 (Figure 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±14µg/m^3 (range: 85 to 226µg/m^3; median: 111µg/m^3) (Figure 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 (155µg/m^3) compared to the afternoon (89µg/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~~s~~ 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., 2019).

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 45µg/m^3 and the mode is at 100µg/m^3. The concentrations recorded had a range of 35µg/m^3 to 177µg/m^3 (mean: 89±30µg/m^3; median: 93µg/m^3) and the mean was higher than the 24-hour 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. AC in the car work with internal air recirculation condition.~~ 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 (Figure 4e), shows that it took approximately 23 minutes for the pollution levels in the car to reduce to NAAQS of 60µg/m^3. Compared with the result obtained from the alternative by car route from the heavily industrialized Okhla to IIT Delhi showed thePM$_{2.5}$ levels inside the car with a concentration in the range around 90 to 100µg/m^3 after 10 minutes 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 46.0µg/m^3, while the maximum level recorded for this mode of transport 163µg/m^3 (mean: 72.0±11.0µg/m^3'; median: 71.0µg/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 ~~concentration exposure levels~~ in the metro predominantly governed by ~~were due to the PM$_{2.5}$ levels in station, ventilation process,~~ the movement of carriages in tunnels,~~-~~ ~~and~~ the movement of a large number of commuters, and air-conditioning in the metro system~~number of passengers~~. ~~PM$_{2.5}$ levels from the metro station as well as from the metro carriage itself.~~ Although, it's very difficult to precisely pinpoint ~~the explain~~ 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 65.0µg/m^3 and 79.0µg/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 100µg/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 Figure 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~~4.1~~ 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 ug/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).

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4.1~~2~~ 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~~2~~.1 Exposure analysis in Rickshaws

In the present study, two different routes, the main (mean $PM_{2.5}$: 598±51μg/m^3; median: 589μg/m^3) and the alternative (mean $PM_{2.5}$: 361±69μg/m^3; median: 337μg/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 500m which~~ill~~ have an additional contribution to the regular traffic ~~and constitutes a possible explanation~~ (Figure 5). ~~The increased number of vehicles at slow speeds, stopping, starting and causing transients in the general flow of traffic on the road would contribute to emissions elevating local concentrations. Similar to the previous route, lower concentrations were noticed where there was decreased congestion or stretches of the road as in Connaught Place where the urban density is less.~~ 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 one-hour difference reduced exposure levels by 200 µg/m^3, as ~~the high levels were recorded from 9:00 to 10:00 AM. Such a high value is consistent with the~~ 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). ~~The findings that the rickshaw had the highest recorded levels of exposure, is in agreement with previous studies in Delhi (Kumar and Gupta, 2016) and Dhanbad (Gupta and Elumalai, 2019).~~ 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~~.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. ~~Walking was found to have the second-highest peak levels of $PM_{2.5}$ exposure with a mean value of exposure (259±102 μg/m^3) which was only slightly lower than the rickshaw (266±159 μg/m^3). The mean walking exposure value aligns with the study from Goel et al., (2015), who recorded a mean walking exposure of 278 μg/m^3 in February 2015. A study by Saraswat et al., (2016) used models to simulate $PM_{2.5}$ exposure whilst walking in Delhi, but the results compared to the measured values reported in this and previous studies seem to suggest that the model underestimates, for example, the maximum mean winter exposure at 195 μg/m^3 which is considerably lower than the observed values.~~ 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. ~~However, raising awareness of the general public to the health risks associated with exposure to peak-hour pollution levels along with advice to take short cuts along streets away from the main-road traffic would bring long-term benefits.~~

4.1~~2~~.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 (Figure 7 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. ~~The other parts of the route, such as Safdarjung area, high levels of congestion at an intersection of two major roads were mainly responsible for the higher exposure levels. Levels also increased near IIT Delhi, as recorded in the alternative route of rickshaw and AC car. This increase was due to an increase in urban density coupled with increased congestion frequently observed in the area.~~

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. ~~In the whole journey, the $PM_{2.5}$ results obtained from non-AC car was 92% 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.

~~This research also revealed that the non-AC car was the third most exposed travel mode with the mean exposure of 149µg/m^3 which was much lower than the levels of PM_{10} of 311µg/m^3 reported by Namdeo et al., (2016) in Mumbai. The reported $PM_{2.5}$/PM_{10} ratio in Mumbai was 0.59 (Kothai et al., 2011), which implies that the concentration of $PM_{2.5}$ of 183.3 µg/m^3 for the study in Mumbai, remains well above the concentration reported in this 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~~2~~.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 µg/m^3) and these continued through the embassy area near Nehru Park, where the highest concentration of $PM_{2.5}$ was recorded at 226 µg/m^3 (Figure 8 and S7). ~~Of course, the pollution ingress increased as the dwell times at bus stops increased which depended on the number of passengers alighting and boarding.~~ The average recorded value in the bus ~~fourth highest exposure level was recorded in the bus~~ (113 µg/m^3) ~~, which~~ was much lower when compared with the previous study in Delhi (Goel et al., 2015)~~, which recorded~~ (278 µg/m^3) at the same time of year in 2015. ~~Also, the levels recorded by Namdeo et al., (2016) gave the highest levels for the buses in Mumbai (503 µg/m^3). Taking the $PM_{2.5}$ to PM_{10} concentration ratio factor of 0.59 reported by (Kothai et al., 2011), this gives an average $PM_{2.5}$ concentration of 297 µg/m^3, which remains significantly higher than this study's results.~~ 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. ~~The increased levels were also due to frequent opening of bus doors, which allowed the entry of the outside pollution inside the bus and this was recorded by the monitors.~~ 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.

~~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 μg/m³) and these continued through the embassy area near Nehru Park, where the highest concentration of PM2.5 was recorded at 226 μg/m³ (Figure 8 and S7). Low levels were recorded towards Connaught Place, India Gate. Consistent with earlier observations, the high levels were obtained near multiple bus stops with additional stop, start, idling occurs and were interruptions with the main flow of traffic occurs (Hess et al., 2010). The increased levels were also due to frequent opening of bus doors, which allowed the entry of the outside pollution inside the bus and this was recorded by the monitors. Of course, the pollution ingress increased as the dwell times at bus stops increased which depended on the number of passengers alighting and boarding.~~

4.1~~2~~.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 μg/m^3) in AC vehicle continue to decrease throughout the journey and no surges were observed in the trend (Figure 6). 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 μg/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 ~15µg/m^3 higher concentrations of $PM_{2.5}$ compared to green and suburban areas.~~. This seems to be apparent in many of the routes studied in this research, because often PM levels increased when approaching a denser urban area, as PM becomes trapped, circulating in street canyons, causing higher ambient concentrations an observation consistent with (Namdeo et al., 1998; Abhijith and Kumar, 2019).~~

4.1~~2~~.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, ~~A study in Toronto recorded mean levels of 100µg/m^3 $PM_{2.5}$ on the subway (Van Ryswyk et al., 2017). Another investigation in New York recorded $PM_{2.5}$ levels which were double those in Toronto at (200.4µg/m^3) in one subway station (Vilcassim, et al., 2014). In the London underground, the $PM_{2.5}$ concentration (mean 302 µg/m^3, median 318 µg/m^3) was approximately 15 times greater than the surface ambient background (mean 18 µg/m^3, median 5 µg/m^3) levels and roadside environments (mean 26 µg /m^3, median 22 µg/m^3) in central London (Smith et al., 2020).~~ 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 ~~, at the start of the survey,~~ were higher than those measured in the metro carriage. ~~Similar observations were recorded in Helsinki subway station in Finland (Aarnio et al., 2005).~~ 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 ~~where and times~~ when the carriage doors opened to let passengers alight and board.

4.2~~3~~ 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.

~~4.4 Implications of the exposure results~~

~~It was clear from this research that the recorded $PM_{2.5}$ levels by the monitors for all the selected transport modes of Delhi were exceptionally higher than both advised national limits for India and WHO guideline. Another important observation was that travellers in open modes (where door and windows are mostly kept open to air) of transport were exposed more to $PM_{2.5}$ than in enclosed ones such as car or metro. While the exposure levels of $PM_{2.5}$ are dependent on the different modes of transport used, there was also evidence of the links between congestion and $PM_{2.5}$ levels. The results from this study showed that prevalence of congestion caused greater levels of exposure in open transport modes, due to the increased $PM_{2.5}$ sources from nearby vehicles, and the higher exposures occurred when vehicles were delayed for longer. This is in agreement with other studies, that all showed that exposure in congestion is higher when compared to ambient exposure (Bigazzi et al., 2015; Zhang and Batterman, 2013). Thus, this research has shown that Delhiites by raising awareness should be advised to choose AC-Car or metro to protect themselves from such a high level of pollution to reduce the risk of developing harmful health effects. Although, fuel consumption in an AC-Car in higher than a non-AC Car, and have different environmental effects.~~

~~The present study has some limitations which reported in Supplementary Material.~~

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 ~~of, and duration with which the~~ doors on buses ~~opened~~ resulted in ambient pollution (background plus that emitted by other vehicles) entering vehicles, thus increasing the concentrations to which travellers were exposed. ~~The exposure levels of rickshaws and walking were almost twice the ambient daily $PM_{2.5}$ mean. Travellers in AC cars, metro and buses all had mean exposures below the ambient level, whilst in non-AC cars, it was almost the same. This shows the effect different transport modes have on exposure, for example, commuting by metro would only be exposed to half the amount of $PM_{2.5}$ compared to ambient background levels in an urban area. But a similar commute by rickshaw a traveller would be exposed to 83% more $PM_{2.5}$ when compared to an ambient point. When compared to the metro's mean exposure, for this route the rickshaw commuter would be exposed to 3.7 times more $PM_{2.5}$. Yet the results also showed that not one of the transport modes mean exposures met the Indian NAAQS and WHO Guidelines for $PM_{2.5}$, with the closest being the metro. The variation in ambient pollution each day influenced the exposure levels greatly during the study. The lower atmospheric mixing height and high levels of traffic and congestion during the rush hours resulted in substantially higher $PM_{2.5}$ levels in the evenings and morning and reducing in the afternoons. This was suggested when the exposure levels measured for walking on the same route showed that there was 56% higher exposure in the morning compared to the afternoon. There was also a difference in the exposure levels in day to day analysis conducted for the rickshaw. Mean variations of >150 µg/m^3 showed that exposure can vary greatly for the same commute on a day-to-day basis. Delhi is one of the most polluted cities in the world and where about 20% of $PM_{2.5}$ in ambient air originates from primary $PM_{2.5}$ emissions from mobile sources. The current regulations are expected to decrease the contribution of primary $PM_{2.5}$ emitted in the transport sector by typically 40% in 2030, although, the absence of emission controls will increase the contributions by typically 50% (with the predicted growth in the number of vehicles in Delhi by 2030) (Purohit et al., 2019;~~

~~Goel and Guttikunda, 2015). If levels of $PM_{2.5}$ grow, the long-term $PM_{2.5}$ exposure-related premature deaths will most certainly increase in the upcoming years in Delhi.~~

The findings of this -study ~~undertaken~~ can be used to identify areas for further research and to shortlist the mitigation measures towards ~~suggest several key areas where both research and action will take steps forward in~~ reducing $PM_{2.5}$ exposure in Delhi. This study suggests that the identification of ~~Like,~~ the congestion hotspots is important as personal exposure is observed to be very high in these locations. ~~were proven to be areas where exposure levels were exceptionally high, limiting congestion and number of vehicles may aid this.~~ 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 ~~local people~~ on ~~to~~ how to reduce their ~~personal~~ exposure levels would go a long way in protecting their health. ~~an individual from the effects of $PM_{2.5}$, (i.e.~~ 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 ~~help limit the generation of $PM_{2.5}$ on roads, effectively~~ the ~~reducing~~ ambient levels consequently reducing the personal exposure.
The study has also outlined several areas where further research will help in developing a better ~~n~~ 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. ~~exposure levels of $PM_{2.5}$ and the effect different transport modes have. Further research into the other areas will give more accurate data, further understanding of what level people are exposed to daily. As well as this~~ This research could be extended to include additional travel ~~, research should be conducted into other transport modes, such as~~ modes including ~~walking,~~ cycling and ~~cycling,~~ local-trains.~~, Light Goods Vehicles (LGVs) and Heavy Goods Vehicles (HGVs).~~ ~~The frequency of door opening and passenger number effects the $PM_{2.5}$ concentration in a bus need for further investigation.~~ Whilst this study focused on $PM_{2.5}$, further research could monitor the personal exposure to different pollutants, such as particle numbers, ultrafine particles,~~PM_1,~~ 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.

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Number of Tables

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~~Figure 1. (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.~~

~~Figure 2. Routes took by transport mode during the study (OpenStreetMap Contributors, 2017). Image produced using ArcMap™ Esri©.~~

~~Figure 3. Boxplot of different transport modes exposure results. The outliers are below 5th and above 95th percentiles.~~

~~Figure 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~~

~~Figure 5. Rickshaw map exposure route monitored during study (a) main route (b) alternative route~~

~~Figure 6. AC car map exposure route monitored during study (a) main route (b) alternative route~~

~~Figure 7. Non-AC car map exposure route monitored during the study~~

~~Figure 8. Bus map exposure route monitored during the study~~

Highlight

- On-road $PM_{2.5}$ exposures in six transport microenvironments ae measured in Delhi.
- Traveling in auto rickshaws and walking leads to higher exposure.
- Traveling 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.

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 (10km×10km or 1km×1km) (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 $\mu g/m^3$), Turkey (30.6-120.4 $\mu g/m^3$), and China (54.5-71.6 $\mu g/m^3$), and the lowest values are from cleaner high-income settings in the USA (12-35 $\mu g/m^3$), Europe (7.3-13.9 $\mu g/m^3$) and Canada (8.6-71.9 $\mu g/m^3$) (Table 1).

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.

[Insert Table 1]

2. Methodology

2.1 Study area and route selection

The study was carried out in Delhi, India, which has an area of 1,484 km^2 and around 16.3 million inhabitants as per the latest census of 2011 (Government of India, 2020), 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 11km length, between the Indian Institute of Technology Delhi campus (IIT Delhi) to the Connaught Place (Delhi's CBD), as shown in Figure 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.

[Insert Figure 1]

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 0.001–100 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 litres/minute, although for this experiment it was set to its default value of 1.7 litres/minute. 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 one second 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 3m 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 seconds 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 8th February 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 Stamen© map (Rodenbeck, 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 to 235 µg/m^3) which gradually decrease afterwards due to the winds and precipitation during the monsoon months from July through September (33.7 to 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 pm through midnight) and early morning and rush-hour period (8 am through 10 am). The levels were at their lowest during the afternoon hours (Figure 2). In winter the diurnal profile of $PM_{2.5}$ shows <200 µg/m^3 from 11.00 am to 7.00 pm, 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 8th February 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).

[Insert Figure 2]

3.2. $PM_{2.5}$ concentration in different modes of transport

Tables 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 one second. 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. Figure 3 shows the spatial variations in the average $PM_{2.5}$ exposures for the six modes of travels.

[Insert Table 2]

[Insert Figure 3]

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 150μg/m^3, the lower densities were observed in between ~300μg/m^3 and 550μg/m^3. The three-day one-way trip average exposure level of $PM_{2.5}$ was 266±159μg/m^3 (median: 203μg/m^3). The time-series plot of the exposure in the rickshaw for different days (Figure 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 5th February 2018 was well over 1000μg/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).

[Insert Figure 4]

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 165μg/m^3 and 304μg/m^3 (mean: 259±103μg/m^3; median: 264μg/m^3) (Figure S1b). This made it the second-highest exposed mode of transport during the study. A maximum value of 1280μg/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 (Figure 4b), with peak frequencies located at 150μg/m^3, 290μg/m^3 and 375μg/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 379μg/m^3, while in the afternoon the mean exposure was 166μg/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 am 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 227μg/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 to 158μg/m^3, showing a very small interquartile range with the results being relatively consistent (Figure S1c). While the maximum value was 206μg/m^3 and the minimum was 114μg/m^3, with mean value was 149±13μg/m^3 (median: 149μg/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 61μg/m^3 on the same route of travel. The time-series plot in Figure 4c shows the wide distribution of the $PM_{2.5}$ exposure level in a non-AC car. It shows a relatively normal distribution around 145μg/m^3 of $PM_{2.5}$. When compared to the AC car, the distribution begins at a much higher concentration (114μg/m^3 for the non-AC car and 35.0μg/m^3 for the AC car). The initial levels recorded by the two modes were around 150μg/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 to 120μg/m^3 (Figure 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±14μg/m^3 (range: 85 to 226μg/m^3; median: 111μg/m^3) (Figure 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 (155μg/m^3) compared to the afternoon (89μg/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., 2019).

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 45μg/m^3 and the mode is at 100μg/m^3. The concentrations recorded had a range of 35μg/m^3 to 177μg/m^3 (mean: 89±30μg/m^3; median: 93μg/m^3) and the mean was higher than the 24-hour 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 (Figure 4e), shows that it took approximately 23 minutes for the pollution levels in the car to reduce to NAAQS of 60μg/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 to 100µg/m^3 after 10 minutes 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 46.0µg/m^3, while the maximum level recorded for this mode of transport 163µg/m^3 (mean: 72.0±11.0µg/m^3'; median: 71.0µg/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 65.0µg/m^3 and 79.0µg/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 100µg/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 Figure 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 ug/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±51µg/m^3; median: 589µg/m^3) and the alternative (mean $PM_{2.5}$: 361±69µg/m^3; median: 337µg/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 500m which have an additional contribution to the regular traffic (Figure 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 one-hour 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).

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.

[Insert Figure 5]

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 (Figure 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.

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.

[Insert Figure 6]

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 µg/m^3) and these continued through the embassy area near Nehru Park, where the highest concentration of $PM_{2.5}$ was recorded at 226 µg/m^3 (Figure 7 and S7). The average recorded value in the bus (113 µg/m^3) was much lower when compared with the previous study in Delhi (Goel et al., 2015) (278 µg/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.

[Insert Figure 7]

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 µg/m^3) in AC vehicle continue to decrease throughout the journey and no surges were observed in the trend (Figure 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 µg/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 ~15µg/m^3 higher concentrations of $PM_{2.5}$ compared to green and suburban areas.

[Insert Figure 8]

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.

[Insert Table 3]

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.

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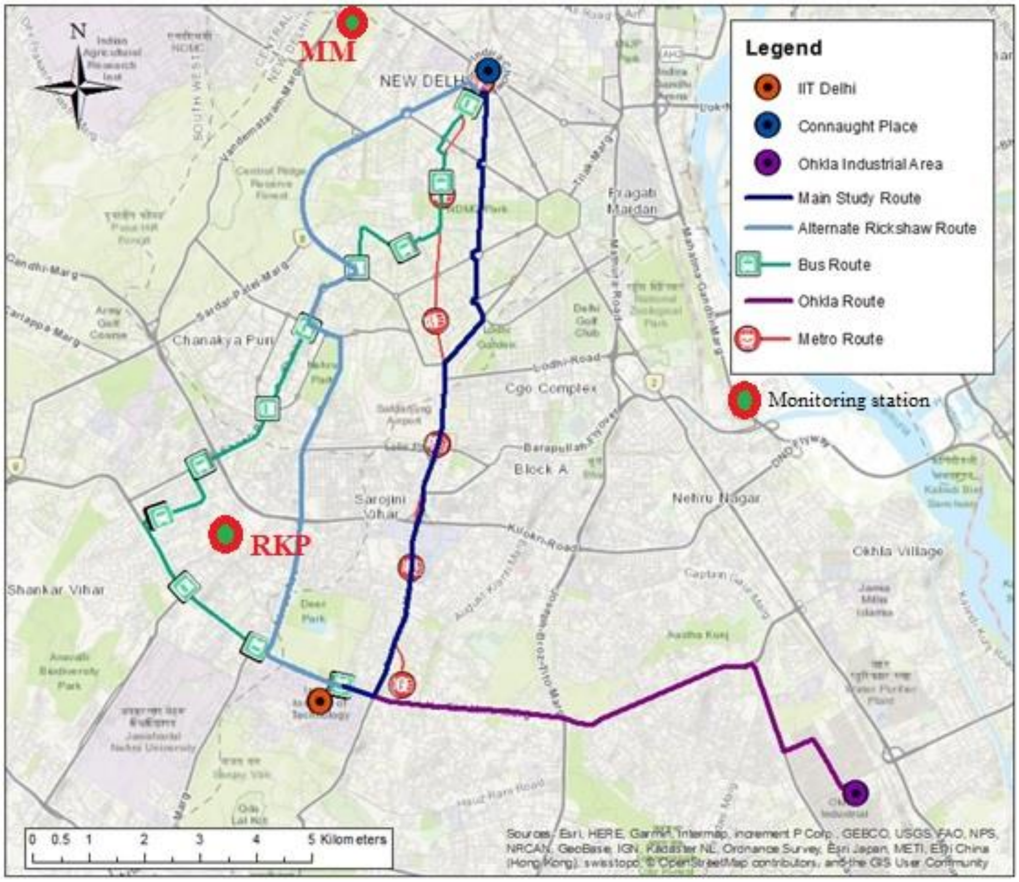

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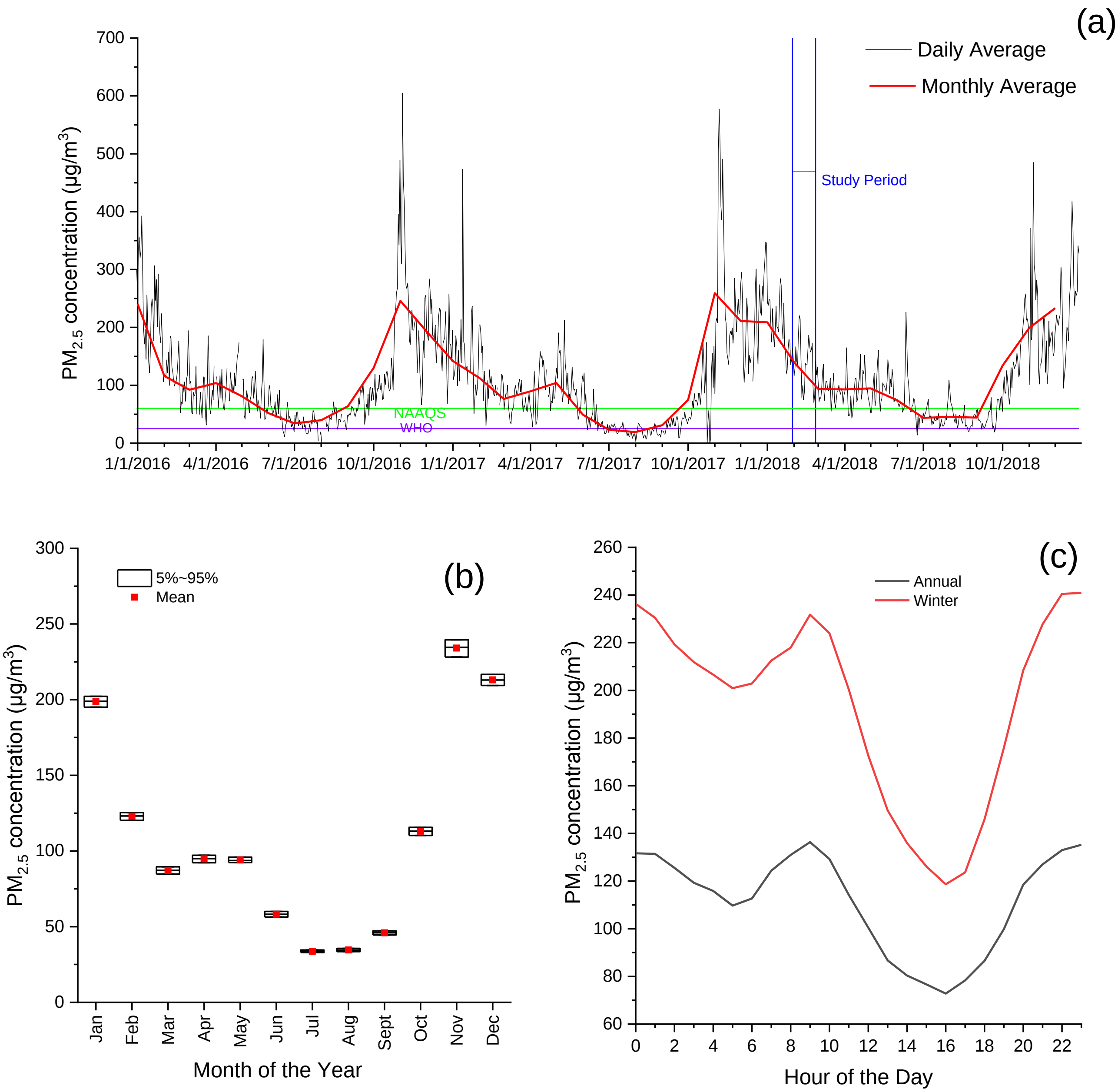

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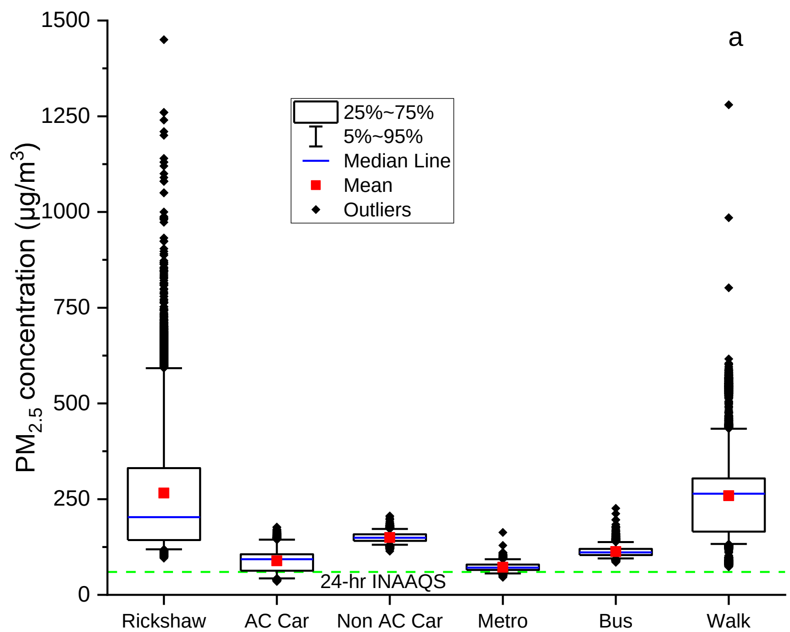

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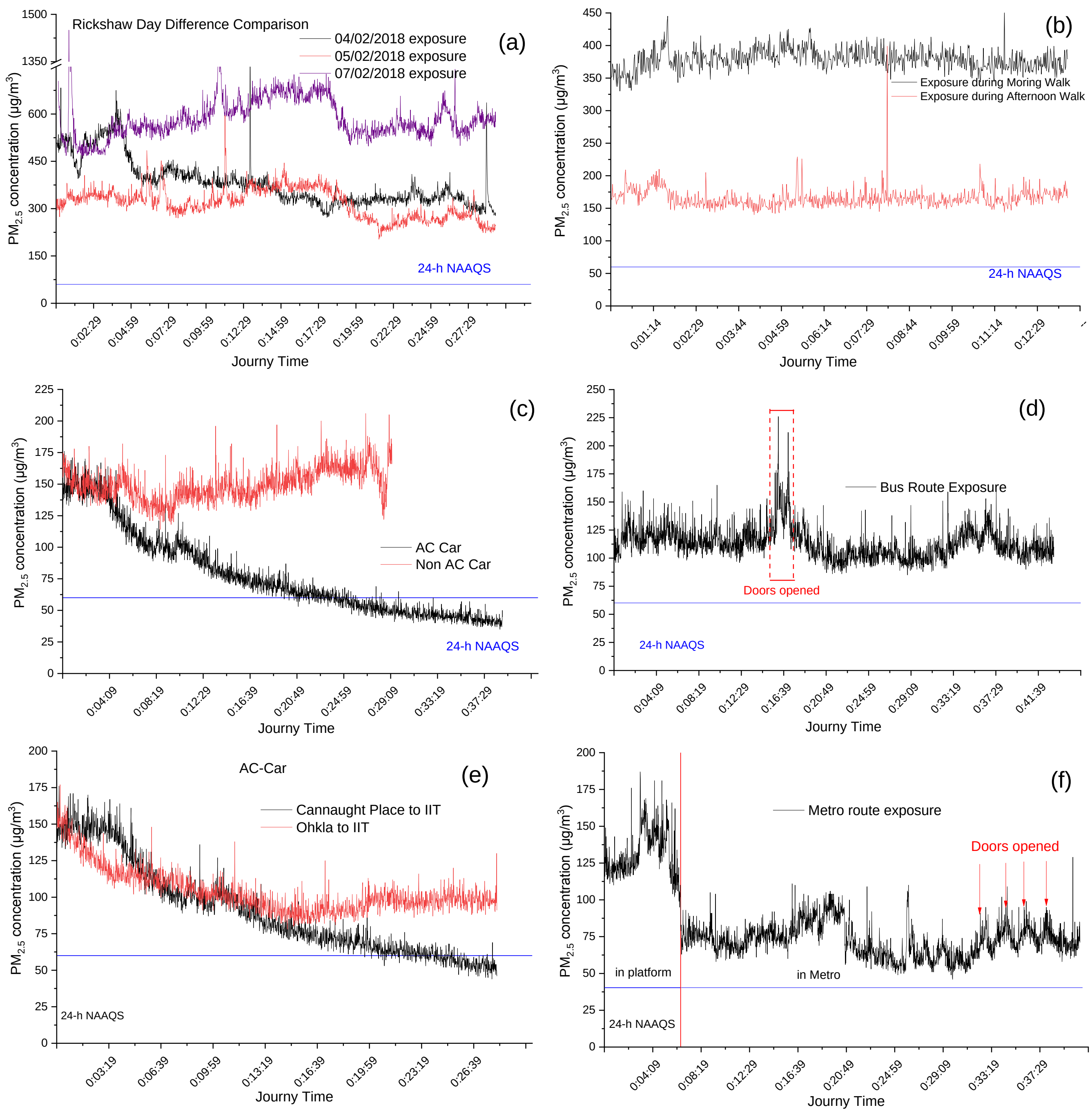

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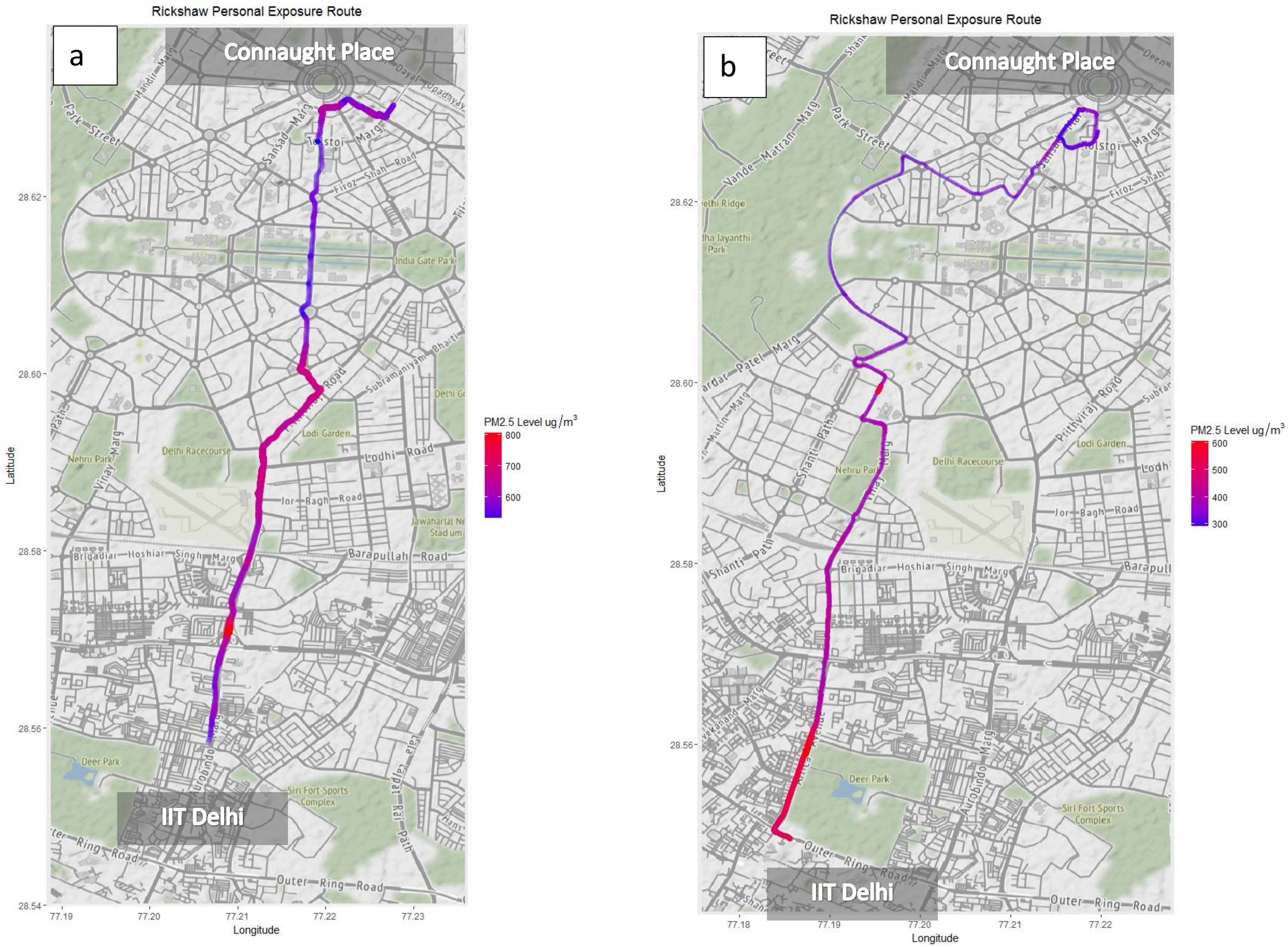

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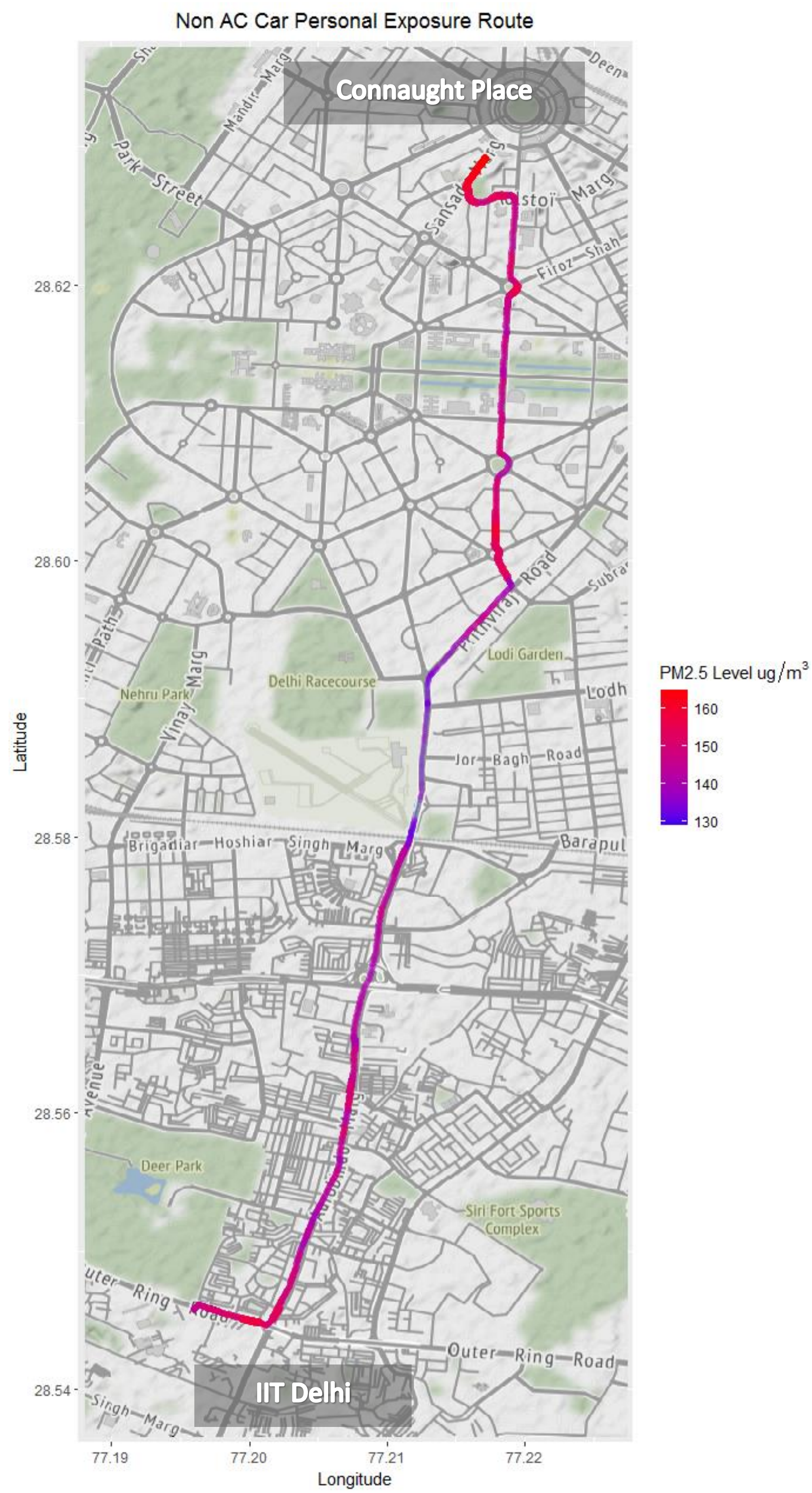

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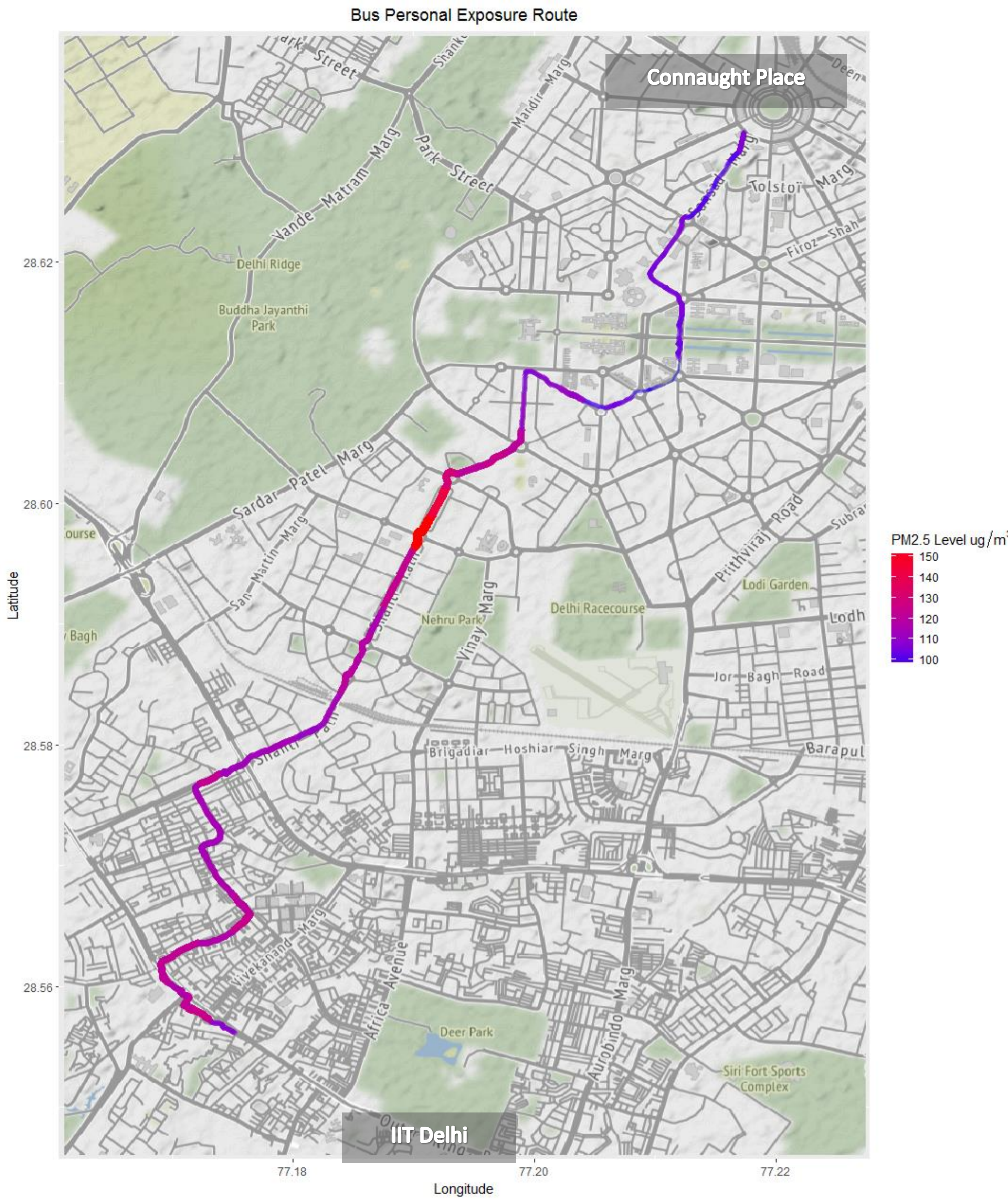

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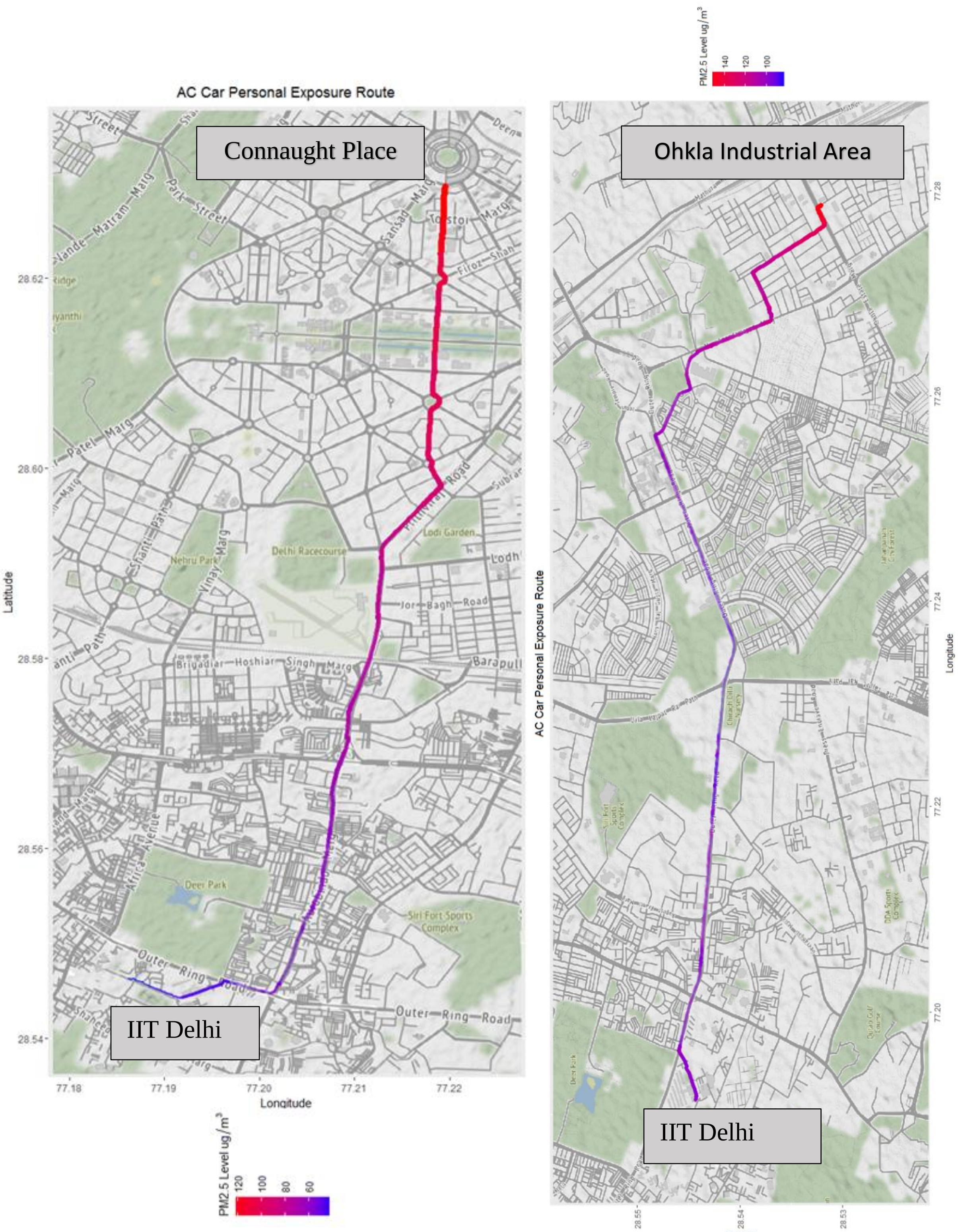

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Declaration of competing interest:

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. 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.

Credit Author Statement:

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