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# Atmospheric Pollution Research

## Analysis of various transport modes to evaluate personal exposure to PM<sub>2.5</sub> pollution in Delhi

--Manuscript Draft--

<b>Manuscript Number:</b>	APR-D-20-00942R1
<b>Article Type:</b>	Research Paper
<b>Keywords:</b>	Personal exposure; travel modes; air pollution; PM <sub>2.5</sub> ; Delhi
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<b>Abstract:</b>	<p>The data collection was carried out using a portable TSI SidePak Aerosol Monitor AM520, during February 2018. The results demonstrate that rickshaws (<math>266 \pm 159 \mu\text{g}/\text{m}^3</math>) and walking (<math>259 \pm 102 \mu\text{g}/\text{m}^3</math>) modes were exposed to significantly higher mean PM<sub>2.5</sub> levels, whereas AC cars (<math>89 \pm 30 \mu\text{g}/\text{m}^3</math>) and the metro (<math>72 \pm 11 \mu\text{g}/\text{m}^3</math>) had the lowest overall exposure rates. Buses (<math>113 \pm 14 \mu\text{g}/\text{m}^3</math>) and non-AC cars (<math>149 \pm 13 \mu\text{g}/\text{m}^3</math>) had average levels of exposure, but open windows and local factors caused surges in PM<sub>2.5</sub> for both transport modes. Closed air-conditioned transport modes were shown to be the best modes for avoiding high concentrations of PM<sub>2.5</sub>, 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 <math>84.7 \mu\text{g}/\text{km}</math>, <math>15.8 \mu\text{g}/\text{km}</math> and <math>9.7 \mu\text{g}/\text{km}</math> for walking, rickshaw and non-AC car transported mode of journey, respectively. Unless strong pollution control measures are taken, the high exposure to PM<sub>2.5</sub> 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.</p>
<b>Suggested Reviewers:</b>	Chinmoy Sarkar, PhD Professor, Hong Kong University: University of Hong Kong csarkar@hku.hk  Rajasekhar Balasubramanian, PhD Professor, National University of Singapore ceerbala@nus.edu.sg

	<p>Md. Aynul Bari, PhD  Assistant Professor, University at Albany State University of New York  mbari@albany.edu</p>
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	<p>Mary K Wolfe, PhD  Professor, University of Northern California  mkwolfe@unc.edu</p>
<b>Opposed Reviewers:</b>	
<b>Response to Reviewers:</b>	Please see the attachment.

Prof. Anil Namdeo and Dr. Kamal J. Maji  
Air Quality Research Group,  
Department of Geography and Environmental Sciences  
Northumbria University, United Kingdom

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<sub>2.5</sub> pollution in Delhi” for potential publication in Atmospheric Pollution Research.

This study provides a comparative assessment of on-road PM<sub>2.5</sub> 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 ( $266\pm 159 \mu\text{g}/\text{m}^3$ ) and walking ( $259\pm 102 \mu\text{g}/\text{m}^3$ ) modes were exposed to significantly higher mean PM<sub>2.5</sub> levels, whereas AC cars ( $89\pm 30 \mu\text{g}/\text{m}^3$ ) and the metro ( $72\pm 11 \mu\text{g}/\text{m}^3$ ) had the lowest overall exposure rates. Buses ( $113\pm 14 \mu\text{g}/\text{m}^3$ ) and non-AC cars ( $149\pm 13 \mu\text{g}/\text{m}^3$ ) had average levels of exposure, but open windows and local factors caused surges in PM<sub>2.5</sub> for both transport modes. Closed air-conditioned transport modes were shown to be the best modes for avoiding high concentrations of PM<sub>2.5</sub>, 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  $84.7\mu\text{g}/\text{km}$ ,  $15.8\mu\text{g}/\text{km}$  and  $9.7\mu\text{g}/\text{km}$  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 PM<sub>2.5</sub> pollution in Delhi**

Yours sincerely,

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

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

8

9 Yours sincerely,

10 Kamal Jyoti Maji

11

12

13 Editor and Reviewer comments:

14

15 Reviewer #1:

16

17 This manuscript was related to personal exposure to PM<sub>2.5</sub> in six different transportation modes  
18 in Delhi. The discussion was given in very detail but the number of data is limiting the  
19 evaluation of the manuscript. Generally, there is no statistically analyse results in the study.

20 My comments are given below:

21

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

23

24 Response: We would like to thank the reviewer for this comment and sorry for the typo.

25 A correction has made in the revised manuscript.

26

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

29

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

32

33 **3. Figure 4: The scale of Y axis is not satisfied the readers (up to 1500 µg/m<sup>3</sup>) for**  
34 **showing the trend of PM<sub>2.5</sub>. It can be good for rickshaw and walking, but for the**

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

37

38 Response: Thank you for your valuable suggestion.

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

41

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

45

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

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

49 Reference:

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

54 Lin, C., Hu, D., Jia, X., Chen, J., Deng, F., Guo, X., Heal, M.R., Cowie, H., Wilkinson,  
55 P., Miller, M.R., Loh, M., 2020. The relationship between personal exposure and  
56 ambient PM2.5 and black carbon in Beijing. Science of The Total Environment  
57 737, 139801. <https://doi.org/10.1016/j.scitotenv.2020.139801>

58

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

65

66 Response: Thank you for your suggestion. We have added PM<sub>2.5</sub> concentrations (Column:  
67 Ambient Concentration) from the monitoring stations in Table 2.

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

70 We have added the following sentence in the manuscript:

71 [During the study period \(2<sup>nd</sup> to 8<sup>th</sup> February 2018\), the average ambient PM<sub>2.5</sub>](#)  
72 [concentration was 146±53 µg/m<sup>3</sup>. Although, in the Panchkula \(PK\) monitoring site in](#)

73 Delhi, which is considered as an urban background site, observed a very low ambient  
74 PM<sub>2.5</sub> concentration during the study (average: 61±20 µg/m<sup>3</sup>; median: 60 µg/m<sup>3</sup>).  
75

76 **6. Line 187: 'the personal exposed PM<sub>2.5</sub> concentration and PM<sub>2.5</sub> in the**  
77 **microenvironment are the same,...'. authors mean walking mode.**

78  
79 Response: Sorry for the poor choice of the words. Here we want to say that in the present  
80 study, the time-weighted PM<sub>2.5</sub> concentration and the average concentration of PM<sub>2.5</sub> in  
81 the microenvironment are the same.

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

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

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

92  
93 **7. Line 226-238: Figure 1c is showing the data of typical urban traffic site. Actually,**  
94 **the meteorology, atmospheric conditions etc can affect the concentrations of the city,**  
95 **but this study has been made at the traffic microenvironment. So, in my opinion, the**  
96 **most reason of the difference between morning and afternoon could be the**  
97 **difference of the traffic load at the street. If possible, authors should give the number**  
98 **of vehicles on the study route in the morning and afternoon.**

99  
100 Response: Thank you for your comments and observation on the relevance of traffic  
101 volume in explaining the variations in the PM<sub>2.5</sub> concentrations during the morning and  
102 afternoon hours. Therefore, in section 3.2.2, we have added the following sentences.

103 Walking in the morning had a mean exposure to PM<sub>2.5</sub> of 379µg/m<sup>3</sup>, while in the  
104 afternoon the mean exposure was 166µg/m<sup>3</sup>. This suggests that, walking in the morning  
105 results in a 56% increase in exposure to PM<sub>2.5</sub> level compared to walking in the afternoon.  
106 The result is comparable with the difference in the diurnal variation of ambient PM<sub>2.5</sub>  
107 concentrations in the morning and afternoon. In between 08:00 to 10:00 am and 21:00 to  
108 23:00, the higher concentration of PM<sub>2.5</sub> is consistent with the morning and evening rush-

109 hour traffic pattern, respectively. The morning peak is followed by a gradual decrease in  
110 PM<sub>2.5</sub> concentrations through the afternoon. This feature might be explained in part by  
111 the growth of the mixing layer depths and stronger atmospheric ventilation during the  
112 afternoon. The morning peak might be associated with the fumigation effect in the  
113 boundary layer, which brings aerosols from the nocturnal residual layer shortly after the  
114 sunrise. As the day advances, increased solar heating leads to increase turbulent effects  
115 and a deeper boundary layer, leading to faster dispersion of aerosols and hence dilution  
116 of PM<sub>2.5</sub> concentration occurs near to the surface during the after 16:00 (late-afternoon).  
117 In the day of the study, the average ambient PM<sub>2.5</sub> concentration was 227µg/m<sup>3</sup> at  
118 morning 9:00, which was about 51% higher than the PM<sub>2.5</sub> concentration at 12:00.

119 We also feel that the vehicular numbers and PM<sub>2.5</sub> are highly correlated in this region.  
120 Therefore, we tried to collect the traffic flow data from the Traffic department in Delhi,  
121 but unfortunately, till now we have not been able to get any data on traffic volume.  
122

123 **8. What is the unit of journey time?**

124

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

127

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

129

130 Response: Sorry for the typo error. A correction has been made in the revised manuscript.  
131

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

134

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

137 Non-AC cars often have their windows kept open in Delhi and therefore PM<sub>2.5</sub>  
138 concentration was higher than that in the AC car.

139

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

143

144 Response: Thank you for your valuable suggestion.

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

148 These two references have been added to the revised manuscript.

149

150 References:

151 Kolluru, S.S.R., Patra, A.K., Dubey, R.S., 2019. In-vehicle PM<sub>2.5</sub> personal  
152 concentrations in winter during long distance road travel in India. *Science of The*  
153 *Total Environment* 684, 207–220. <https://doi.org/10.1016/j.scitotenv.2019.05.347>

154 Kumar, P., Rivas, I., Singh, A.P., Ganesh, V.J., Ananya, M., Frey, H.C., 2018.  
155 Dynamics of coarse and fine particle exposure in transport microenvironments.  
156 *npj Climate and Atmospheric Science* 1, 11. [https://doi.org/10.1038/s41612-018-](https://doi.org/10.1038/s41612-018-0023-y)  
157 [0023-y](https://doi.org/10.1038/s41612-018-0023-y)

158

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

161

162 Response: Thank you for your valuable comment.

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

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

169 However, the car used for the alternative route was using ‘fresh air’ (external circulation)  
170 without the recirculation mechanism of the AC. The effect of this was visible when the  
171 PM<sub>2.5</sub> levels did not fall during the journey, stabilising around the mean value (104±15  
172 µg/m<sup>3</sup>). These results confirmed that the different air ventilation settings of the cars can  
173 affect in-vehicle exposure levels.

174

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

177

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

183

184 **14. Line 293: ' The exposure levels in the metro predominantly were due to PM<sub>2.5</sub> levels**  
185 **from the metro station as well as from the metro carriage itself.' Maybe but there is**  
186 **no result or calculation? Additionally, there are three sources of PM in metro; (1)**  
187 **ventilation (2) movement of vagon in the tunnels (3) passengers. So, it's very difficult**  
188 **to explain the reason of the high concentration.**

189

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

194 *The PM<sub>2.5</sub> concentration in the metro predominantly was due to the PM<sub>2.5</sub> levels in the*  
195 *station, ventilation process, movement of the carriage in tunnels and number of*  
196 *passengers. Although, it's very difficult to explain the exact reason for the high*  
197 *concentration.*

198

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

201

202 Response: *Thank you for your suggestion. Section 4.1 (Open and Enclosed Transport)*  
203 *discusses PM<sub>2.5</sub> concentrations in the open and enclosed transport. We have analyzed and*  
204 *compared the ratio of PM<sub>2.5</sub> in open and enclosed transport in this section. We have moved*  
205 *the part in the result section 3.3.*

206

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

209

210 Response: Thank you for your comments. In the section 4.2, we characterise the PM<sub>2.5</sub>  
211 along the routes on different travel modes, showing the spatial variation, and compare  
212 these with previous studies. In the revised manuscript we have removed the duplication  
213 of the discussion from Section 3.

214

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

216

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

219 **Table 3** *Estimated respiratory deposition doses (RDDs) of PM<sub>2.5</sub> in multiple*  
220 *transport microenvironments in Delhi*

Mode of Transport	Total RDDs ( $\mu\text{g}$ )	Average RDDs/km journey ( $\mu\text{g}/\text{km}$ )
Rickshaw	205.8 $\pm$ 123	15.8 $\pm$ 9.5
AC Car	68.7 $\pm$ 23.2	5.8 $\pm$ 2.0
Non-AC Car	115.3 $\pm$ 10.1	9.7 $\pm$ 0.9
Metro	31.9 $\pm$ 4.9	3.0 $\pm$ 0.4
Bus	106.3 $\pm$ 13.2	7.4 $\pm$ 0.9
Walking	980 $\pm$ 386	84.7 $\pm$ 33.4

221

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

224

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

227 The study undertaken can be used to suggest several key areas where both research and  
 228 action will take steps forward in reducing PM<sub>2.5</sub> exposure in Delhi. Like, congestion  
 229 hotspots were proven to be areas where exposure levels were exceptionally high, limiting  
 230 congestion and number of vehicles may aid this. The possible implementation of  
 231 intelligent transport systems at the congested area can reduce levels of pollution (Díaz et  
 232 al., 2020). Education and information as to how to reduce exposure levels would go a  
 233 long way in protecting an individual from the effects of PM<sub>2.5</sub>, (i.e. wear a respirator  
 234 mask). Other methods to reduce exposure could be achieved through simple measures,  
 235 such as advising buses and cars to keep windows closed during high pollution episodes  
 236 and use of AC. Encouraging sustainable modes of transport such as electric vehicles and  
 237 the metro would help limit the generation of PM<sub>2.5</sub> on roads, effectively reducing ambient  
 238 levels.

239 The study has also outlined several areas where further research will help develop an  
 240 understanding of exposure levels of PM<sub>2.5</sub> and the effect different transport modes have.  
 241 Further research into the other areas will give more accurate data, further understanding  
 242 of what level people are exposed to daily. As well as this, research should be conducted  
 243 into other transport modes, such as cycling, trains, Light Goods Vehicles (LGVs) and  
 244 Heavy Goods Vehicles (HGVs). The frequency of door opening and passenger number  
 245 effects the PM<sub>2.5</sub> concentration in a bus need for further investigation. Whilst this study  
 246 focused on PM<sub>2.5</sub>, further research could monitor the personal exposure to different  
 247 pollutants, such as PM<sub>1</sub>, CO, NO<sub>2</sub> and VOCs, that have all been proven to be harmful to  
 248 human health. Health effects of the total exposure to all pollutants could then be assessed,  
 249 to investigate where and why pollution hotspots occur, and their detrimental effects.

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268 **Reviewer #2:**

269

270 The research "Analysis of various transport modes to evaluate personal 1 exposure to PM<sub>2.5</sub>  
271 pollution in Delhi" by Dr. Maji et al measured and compared real-time personal exposure to  
272 PM<sub>2.5</sub> at six travel modes in Delhi. Then it estimated respiratory deposition doses for different  
273 modes. The study is well written and interesting for heavy polluted regions. Some specific  
274 comments:

275

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

278

279 **1. Some external environments, such as wind and humidity of the experiments, are**  
280 **important factors affecting the PM<sub>2.5</sub> concentrations. They should be described to**  
281 **ensure that measurements for different travel modes comparable.**

282

283 Response: Thank you for your valuable suggestion. In our study, we had access to the  
284 wind speed data for the nearest air quality monitoring sites, although we could not obtain  
285 the relative humidity data either for the monitoring site or for inside environment of the

286 transport modes. The study was conducted with a short period in the winter month of  
287 February 2018 (2<sup>nd</sup> to 8<sup>th</sup>), so we can assume that the during the study period wind speed  
288 and humidity did not change dramatically. This can be a limitation of our study, and has  
289 been reported in the supplementary section.

290

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

294

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

297 **Thus, this will give a total RDDs of PM<sub>2.5</sub> per km journey in Delhi city and the resulted**  
298 **value was calculated for healthy adult population.**

299 The estimated value depends on the PM<sub>2.5</sub>, breath rate and the number of breath/min. In  
300 the present study, the only variable parameter is PM<sub>2.5</sub> concentration. We used the average  
301 value of PM<sub>2.5</sub> in this study. We have not calculated value with 95% CI. We added the  
302 standard deviation value in Table 3.

303

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

308

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

311

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320 **Analysis of various transport modes to evaluate personal exposure to PM<sub>2.5</sub>**  
321 **pollution in Delhi**

322

323 Kamal Jyoti Maji <sup>1,\*</sup>; Anil Namdeo <sup>1,\*</sup>; Dan Hoban <sup>2</sup>; Margaret Bell <sup>2</sup>; Paul Goodman <sup>2</sup>; S.M.  
324 Shiva Nagendra <sup>3</sup>; Jo Barnes <sup>4</sup>; Laura De Vito <sup>4</sup>; Enda Hayes <sup>4</sup>; James Longhurst <sup>4</sup>; ~~Virendra~~  
325 ~~Sethi~~<sup>5</sup>; Rakesh Kumar <sup>56</sup>; Niraj Sharma <sup>67</sup>; Sudheer Kumar Kuppili <sup>3</sup>; Dheeraj Alshetty <sup>3</sup>

326

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343

344 **Abstract**

345 Access to detailed comparisons of the air quality variations encountered when commuting  
346 through a city offers the urban traveller more informed choice on how to minimise personal  
347 exposure to inhalable pollutants. In this study we report on an experiment designed to compare  
348 atmospheric contaminants, in this case, PM<sub>2.5</sub> inhaled during rickshaw, bus, metro, non-air-  
349 conditioned car, air-conditioned (AC) car and walking journeys through the city of Delhi, India.  
350 The data collection was carried out using a portable TSI SidePak Aerosol Monitor AM520,  
351 during February 2018. The results demonstrate that rickshaws (266±159 µg/m<sup>3</sup>) and walking

352 (259±102 µg/m<sup>3</sup>) modes were exposed to significantly higher mean PM<sub>2.5</sub> levels, whereas AC  
353 cars (89±30 µg/m<sup>3</sup>) and the metro (72±11 µg/m<sup>3</sup>) had the lowest overall exposure rates. Buses  
354 (113±14 µg/m<sup>3</sup>) and non-AC cars (149±13 µg/m<sup>3</sup>) had average levels of exposure, but open  
355 windows and local factors caused surges in PM<sub>2.5</sub> for both transport modes. Closed air-  
356 conditioned transport modes were shown to be the best modes for avoiding high concentrations  
357 of PM<sub>2.5</sub>, however other factors (e.g. time of the day, window open or closed in the vehicles)  
358 affected exposure levels significantly. Overall, the highest total respiratory deposition doses  
359 (RDDs) values were estimated as 84.7µg/km, 15.8µg/km and 9.7µg/km for walking, rickshaw  
360 and non-AC car transported mode of journey, respectively. Unless strong pollution control  
361 measures are taken, the high exposure to PM<sub>2.5</sub> levels will continue causing serious short-term  
362 and long-term health concerns for the Delhi residents. Implementing integrated and intelligent  
363 transport systems and educating commuters on ways to reduce exposure levels and impacts on  
364 commuter's health are required.

365 Keywords: Personal exposure; travel modes; air pollution; PM<sub>2.5</sub>; Delhi

366

## 367 1. Introduction

368 Approximately 58% of districts in India recorded ambient particulate matter PM<sub>2.5</sub> (particulates  
369 with aerodynamic diameter ≤ 2.5 µm) pollution above the National Ambient Air Quality  
370 Standard (NAAQS) and 99% above the WHO guidelines in 2015 (Chowdhury et al., 2019).  
371 According to the recent Global Burden of Disease study, ambient PM<sub>2.5</sub> pollution in India was  
372 responsible for more than 673 thousand deaths in 2017 (Stanaway et al., 2018), although the  
373 newly developed Global Exposure Mortality Model (GEMM) reported much higher PM<sub>2.5</sub>-  
374 attributed deaths in India (2.219 million in 2015) (Burnett et al., 2018). According to the WHO  
375 Global Ambient Air Quality Database of PM<sub>2.5</sub> pollution levels in more than 1600 cities in the  
376 world in 2018, 13 Indian cities are among the 20 most polluted, with Delhi being the 6<sup>th</sup> most  
377 polluted city (annual average of 143 µg/m<sup>3</sup>) (World Health Organization, 2018). In winter, the  
378 annual average PM<sub>2.5</sub> concentration in 2018, reported by four air quality monitoring stations  
379 (Anand Vihar, Punjabi Bagh, RK Puram and Okhla) located across the city, was above 300  
380 µg/m<sup>3</sup>, which is approximately 5 times higher than the Indian NAAQS of 60 µg/m<sup>3</sup>, and 30  
381 times higher than the WHO guideline of 25 µg/m<sup>3</sup> (Nandi, 2018). Traditionally health risk  
382 analysis was conducted by assuming that the total population is exposed to the same average  
383 PM<sub>2.5</sub> concentration in city-level or gridded level (10km×10km or 1km×1km) (Maji, 2020),

384 although personal exposure monitoring campaigns in a city have indicated high space-time  
385 variation (Menon and Nagendra, 2018).

386 Epidemiological studies have linked exposure to PM<sub>2.5</sub> with various causes of premature  
387 mortality ~~, like ischemic heart disease (IHD), stroke (ischemic stroke and haemorrhagic stroke),~~  
388 ~~chronic obstructive pulmonary disease (COPD), lung cancer (LC) and lower respiratory~~  
389 ~~infections (LRIs) (in particular, pneumonia) and other cause of morbidity , such as Chronic~~  
390 ~~Kidney Disease, diabetes, Alzheimer's disease, mental and behavioural disorders, pneumonia~~  
391 (Bowe et al., 2019; Fu et al., 2019; Antonsen et al., 2020; Chen et al., 2017). Health risk studies  
392 assume equivalent toxicity for all chemical species in PM<sub>2.5</sub>, but there is considerable evidence  
393 that the chemical composition, and sources of PM<sub>2.5</sub> influence its health effects much more, e.g.  
394 traffic-related PM<sub>2.5</sub>, as vehicular exhausted PM<sub>2.5</sub> contain a high percentage of black carbon  
395 which has much more effects on human health (Matz et al., 2019; Costa et al., 2017; Jerrett et  
396 al., 2009; Monrad et al., 2017; Bowatte et al., 2017). In on-road microenvironments, due to the  
397 proximity of tailpipe emissions, exposure to traffic-related PM<sub>2.5</sub> concentration is higher than  
398 those in off-road locations (Chen et al., 2020). The travel-related exposure to on-road PM<sub>2.5</sub>  
399 pollution has been quantified by several studies for different microenvironments, classified as  
400 travel modes, ventilation status ~~(air conditioned or open windowed),~~ type of travel routes, and  
401 meteorological conditions. Table 1 summarizes ~~more than 16 past~~ **some of the key past** studies  
402 in various settings from across the world, analysing on-road exposure to PM<sub>2.5</sub> pollution. The  
403 range of concentrations in the table refers to the reported average values among all the  
404 microenvironments. There are only a few studies from India looking at exposure in three-  
405 wheeled auto-rickshaws (Apte et al., 2011; Goel et al., 2015). On-road high PM<sub>2.5</sub> concentration  
406 in vehicles are also observed in Indonesia (87-119 µg/m<sup>3</sup>), Turkey (30.6-120.4 µg/m<sup>3</sup>), and  
407 China (54.5-71.6 µg/m<sup>3</sup>), and the lowest values are from cleaner high-income settings in the  
408 USA (12-35 µg/m<sup>3</sup>), Europe (7.3-13.9 µg/m<sup>3</sup>) and Canada (8.6-71.9 µg/m<sup>3</sup>) (Table 1).

409 The cities in India differ significantly from the ~~high-income~~ **cities in developed countries**  
410 represented in Table 1. For instance, ambient PM<sub>2.5</sub> concentrations in Indian cities are 4–8 times  
411 higher than most high-income settings (Stanaway et al., 2018), and the traffic condition in  
412 metropolitan Indian cities is worsening daily due to increasing levels of vehicle ownership and  
413 a higher number of old vehicles (Transport Department Government of NCT of Delhi., 2018).

414 The rickshaw and bus are one of the most common forms of public transport in ~~Indian cities~~  
415 ~~like~~ Delhi, providing low-cost mobility and connecting travellers to mass transit. The rickshaw  
416 and bus sector provides a livelihood for some of India's poorest citizens and is easily available  
417 means of public transport in most of the cities (Choudhary and Gokhale, 2016). Relatively few

418 studies have investigated on-road exposures to PM<sub>2.5</sub> pollution, particularly whilst travelling on  
419 these modes, in developing-world megacities such as Delhi, where older vehicles are more  
420 common and high levels of congestion and travel times lead to higher personal exposure to  
421 PM<sub>2.5</sub> concentrations.

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

## 427 **2. Methodology**

### 428 2.1 Study area and route selection

429 The study was carried out in Delhi, India, which has an area of 1,484 km<sup>2</sup> and around 16.3  
430 million inhabitants as per the latest census of 2011 (Government of India, 2020), making it one  
431 of the largest cities in Asia. In March 2018, Delhi had 10.8 million registered vehicles, including  
432 6.96 million motor-cycle/scooter and 3.1 million motor-car (private vehicles) (Transport  
433 Department Government of NCT of Delhi., 2018).

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

### 444 2.2 Measurements and sampling equipment

445 This work has focused on the assessment of personal exposure to PM<sub>2.5</sub>. We measured PM<sub>2.5</sub>  
446 concentrations using a portable SidePak<sup>TM</sup> Aerosol Monitor AM520 (TSI Inc., USA), which  
447 works on the principle of light scattering laser photometry for real-time concentration  
448 measurements of PM in the air. Different inlet options are available for the optics chamber to  
449 measure specific PM sizes, from PM<sub>1</sub> to PM<sub>10</sub>. For this study, the PM<sub>2.5</sub> inlet attachment was

450 used. The instrument measures between 0.001–100 mg/m<sup>3</sup>, so are well within the range of  
451 measurements for PM<sub>2.5</sub> in the micro-environments studied. ~~For further analysis, all the~~  
452 ~~readings were converted into µg/m<sup>3</sup>.~~ The Photometric Calibration Factor (PCF) in the device is  
453 set to 1.0 by default, however, the preliminary tests exhibited above normal PM values. Thus,  
454 as per the TSI guidelines for urban environments, the PCF was set to 0.38 ~~for urban areas~~. ~~This~~  
455 ~~factor is generally used for ambient aerosol in urban areas~~ (TSI., 2018). Usually, this equipment  
456 can have a flow rate up to 1.8 litres/minute, although for this experiment it was set to its default  
457 value of 1.7 litres/minute. The device was always calibrated to zero and was checked before  
458 every usage with the help of a supplied zero calibration attachment. A long interval of one  
459 second was considered to capture the fast-varying PM<sub>2.5</sub> levels encountered by a moving  
460 subject.

461 Qstarz™ Bluetooth-Q1000XT GPS Travel Recorder equipment was used to track the  
462 commuter's location (Qstarz., 2018). The travel recorder has an accuracy of 3m and can record  
463 up to 40 days' worth of data at a 1s interval. The Global Positioning System (GPS) device was  
464 calibrated before each test, by waiting 35 seconds after turning the device on ~~to allow it to~~  
465 ~~calibrate the location~~, as recommended by the Qstarz™ manual (Qstarz., 2018). Additionally,  
466 the QTravel™ is photo geotagging software for a computer that was used for quick  
467 visualisations of the routes chosen by the commuter on Google Earth/Google Map. ~~Also, this~~  
468 ~~software can sync with other software such as the SidePak™ AM520 and that will record the~~  
469 ~~exact geographical location with pollutants concentration on that particular location.~~

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

478 Six commuting modes of transport were selected in our study in between 2<sup>nd</sup> to 8<sup>th</sup> February  
479 2018, auto-rickshaw (three-wheelers) (three trips), bus (two trips), metro (one trip), non-air-  
480 conditioned (non-AC) car (one trip), air-conditioned (AC) car (two trips) and as a pedestrian  
481 (walking) (two trips). Visual representation of PM<sub>2.5</sub> levels on the different transport route was  
482 displayed on the maps by using various software such as RStudio®, [version 1.1.456](#) (R Core  
483 Team, 2017; [Rstudio Team, 2020](#)) and Stamen© map (Rodenbeck, 2018).

### 484 3. Results

#### 485 3.1. Ambient PM<sub>2.5</sub> concentration ~~in Delhi~~ during the study period

486 The personal exposure whilst travelling in transport modes in Delhi depends on factors such as  
487 season of the year and time of the day (for example in winter the PM<sub>2.5</sub> concentration is usually  
488 higher than other seasons) and whether the journey was conducted in the morning, afternoon or  
489 at night (traffic conditions can dictate the temporal variations) (Lin et al., 2020; Chaney et al.,  
490 2017). The ambient PM<sub>2.5</sub> concentrations are available from monitoring stations along the route  
491 and these have been analysed to understand how the background air quality changes over time.  
492 More specifically the continuous air-quality monitoring stations of Central Delhi, RK Puram  
493 (RKP) and Mandir Marg (MM), operated by the Delhi Pollution Control Committee (DPCC),  
494 were used as they were situated closer to the selected route (IIT Delhi to the Connaught Place).  
495 Daily-average PM<sub>2.5</sub> trends as well as a month- and hour specific averages for the three years  
496 were calculated. PM<sub>2.5</sub> has a significant seasonal variation in Delhi, with highest concentrations  
497 during winter months from November to February (123 to 235 µg/m<sup>3</sup>) which gradually decrease  
498 afterwards due to the winds and precipitation during the monsoon months from July through  
499 September (33.7 to 46.0 µg/m<sup>3</sup>). Some of the spikes of PM<sub>2.5</sub> were also observed in June and  
500 July probably due to low winds which would have helped the pollution to accumulate in the  
501 region. The diurnal profile of PM<sub>2.5</sub> showed the highest concentrations during late-evening  
502 hours (11 pm through midnight) and early morning and rush-hour period (8 am through 10 am).  
503 The levels were at their lowest during the afternoon hours (Figure 2). In winter the diurnal  
504 profile of PM<sub>2.5</sub> shows <200 µg/m<sup>3</sup> from 11.00 am to 7.00 pm, after which time the  
505 concentration rises to > 200 µg/m<sup>3</sup>. As the selected period of the current analysis was in early  
506 February, it was understood that the PM<sub>2.5</sub> levels were already at the higher side. ~~During the~~  
507 ~~study period (2<sup>nd</sup> to 8<sup>th</sup> February 2018), the average ambient PM<sub>2.5</sub> concentration was 146±53~~  
508 ~~µg/m<sup>3</sup>. Although, in the Panchkula (PK) monitoring site in Delhi, which is considered as an~~  
509 ~~urban background site observed a very low ambient PM<sub>2.5</sub> concentration during the study~~  
510 ~~(average: 61±20 µg/m<sup>3</sup>; median: 60 µg/m<sup>3</sup>). This was inferred using past data.~~

#### 511 3.2. PM<sub>2.5</sub> concentration in different modes of transport

512 Tables 2 summarise the PM<sub>2.5</sub> concentration during commuting by the six travel modes  
513 indicated earlier. In this study, the ~~time-weighted personal-exposed~~ PM<sub>2.5</sub> concentration and the  
514 ~~average of~~ PM<sub>2.5</sub> in ~~the-a~~ microenvironment ~~are~~ the same, as the Aerosol Monitor ~~measure~~  
515 ~~estimated PM<sub>2.5</sub>~~ concentration in every one second. It was noted that rickshaws were the most

516 exposed transport with the highest mean concentration of PM<sub>2.5</sub> of 266 µg/m<sup>3</sup>, followed by  
517 walking with an average of 258 µg/m<sup>3</sup>. The lowest exposed transport was in the metro and AC  
518 car with a mean of 72.0 µg/m<sup>3</sup> and 89.0 µg/m<sup>3</sup> respectively. The non-AC car and bus trips had  
519 PM<sub>2.5</sub> means of 149 µg/m<sup>3</sup> and 113 of PM<sub>2.5</sub> respectively. Figure 3 shows the spatial variations  
520 in the average PM<sub>2.5</sub> exposures for the six modes of travels.

### 521 3.2.1 PM<sub>2.5</sub> concentration in Rickshaws

522 The histogram in Figure S1a shows that the highest density of PM<sub>2.5</sub> level was observed around  
523 150µg/m<sup>3</sup>, the lower densities were observed in between ~300µg/m<sup>3</sup> and 550µg/m<sup>3</sup>. The three-  
524 day one-way trip average exposure level of PM<sub>2.5</sub> was 266±159µg/m<sup>3</sup> (median: 203µg/m<sup>3</sup>). The  
525 time-series plot of the exposure in the rickshaw for different days (Figure 4a) varied from each  
526 other probably due to several factors such as location, time of day and the nearby congestion.  
527 The figure shows that the levels on each day were very dissimilar with the fluctuating spikes of  
528 the pollution at different times. Also, it was noted that the pollution for 5<sup>th</sup> February 2018 was  
529 well over 1000µg/m<sup>3</sup> in the parts of routes which were known to be regularly congested. The  
530 higher PM emissions during periods of congestion are due to an increase in stop-start and idle  
531 times of high vehicle densities. A past study has established that vehicles fuel consumption and  
532 associated pollutants emitted during congestion are higher than the amount during free-flow  
533 traffic condition (Zhang et al., 2011).

### 534 3.2.2 PM<sub>2.5</sub> concentration during Walking

535 Whilst walking, exposure to concentrations of PM<sub>2.5</sub> is very high, with most exposure levels  
536 being between 165µg/m<sup>3</sup> and 304µg/m<sup>3</sup> (mean: 259±103µg/m<sup>3</sup>; median: 264µg/m<sup>3</sup>) (Figure  
537 S1b). This made it the second-highest exposed mode of transport during the study. A maximum  
538 value of 1280µg/m<sup>3</sup> was recorded during the survey, an exceptionally high reading when  
539 compared to the other results and compared to national and global standards. The exposure  
540 levels captured during walking were not examined on the same routes as other modes of  
541 transport, however, these higher levels were predominantly recorded around the periphery of  
542 IIT Delhi and Connaught Place. The histogram plot shows a multimodal distribution (Figure  
543 4b), with peak frequencies located at 150µg/m<sup>3</sup>, 290µg/m<sup>3</sup> and 375µg/m<sup>3</sup> with outliers  
544 concentrated around 550 µg/m<sup>3</sup>, culminating in very high levels of exposure to PM<sub>2.5</sub>. The time  
545 series for the morning were compared with the afternoon exposure. Time of travel is a major  
546 factor that affected all modes of transport but was particularly noticeable when walking. Fig.  
547 4b also displayed the stark difference between exposure in the morning at 09:15, and exposure

548 at noon, walking the same route from IIT Delhi Guest House to the Outer Ring Road. Walking  
549 in the morning had a mean exposure to PM<sub>2.5</sub> of 379µg/m<sup>3</sup>, while in the afternoon the mean  
550 exposure was 166µg/m<sup>3</sup>. This suggests that, walking in the morning results in a 56% increase  
551 in exposure to PM<sub>2.5</sub> level compared to walking in the afternoon.

552 The result is comparable with the difference in the diurnal variation of ambient PM<sub>2.5</sub>  
553 concentrations in the morning and afternoon. In between 08:00 to 10:00 am and 21:00 to 23:00,  
554 the higher concentration of PM<sub>2.5</sub> is consistent with the morning and evening rush-hour traffic  
555 pattern, respectively. ~~The morning peak is followed by a gradual decrease in PM<sub>2.5</sub>  
556 concentrations through the afternoon. This feature might be explained in part by the growth of  
557 the mixed layer depths and stronger atmospheric ventilation during the afternoon. The morning  
558 peak might be associated with the fumigation effect in the boundary layer, which brings  
559 aerosols from the nocturnal residual layer shortly after the sunrise. As the day advances,  
560 increased solar heating leads to increase turbulent effects and a deeper boundary layer, leading  
561 to faster dispersion of aerosols and hence dilution of PM<sub>2.5</sub> concentration occurs near to the  
562 surface during the after 16:00 (late afternoon). In the day of the study, †~~The average ambient  
563 PM<sub>2.5</sub> concentration was 227µg/m<sup>3</sup> at ~~morning~~ 09:00, which was about 51% higher than the  
564 PM<sub>2.5</sub> concentration at 12:00.

### 565 3.2.3 PM<sub>2.5</sub> concentration in nNon-AC car

566 PM<sub>2.5</sub> exposure was third highest in non-AC-car, where the majority of exposed PM<sub>2.5</sub>  
567 concentrations lies between 141 to 158µg/m<sup>3</sup>, showing a very small interquartile range with the  
568 results being relatively consistent (Figure S1c). While the maximum value was 206µg/m<sup>3</sup> and  
569 the minimum was 114µg/m<sup>3</sup>, with mean value was 149±13µg/m<sup>3</sup> (median: 149µg/m<sup>3</sup>). Non-  
570 AC cars often have their windows kept open in Delhi and this could be the reason why ~~therefore~~  
571 ~~PM<sub>2.5</sub> concentration for this mode than that in was higher than an AC car.~~ The average PM<sub>2.5</sub>  
572 concentration difference between AC car and non-AC car was around 61µg/m<sup>3</sup> on the same  
573 route of travel. The time-series plot in Figure 4c shows the wide distribution of the PM<sub>2.5</sub>  
574 exposure level in a non-AC car. It shows a relatively normal distribution around 145µg/m<sup>3</sup> of  
575 PM<sub>2.5</sub>. When compared to the AC car, the distribution begins at a much higher concentration  
576 (114µg/m<sup>3</sup> for the non-AC car and 35.0µg/m<sup>3</sup> for the AC car). The initial levels recorded by the  
577 two modes were around 150µg/m<sup>3</sup>, which gradually fluctuated along the route. This fluctuation,  
578 as observed for rickshaws, was mostly due to traffic congestion and the open window. This  
579 comparison has shown that exposed PM<sub>2.5</sub> concentration in the AC car was about 92% lower  
580 than that in a non-AC car.

### 581 3.2.4 PM<sub>2.5</sub> concentration in Bus

582 The bus was the fourth-highest exposed transport mode. The majority of the exposed PM<sub>2.5</sub>  
583 concentrations were between 104 to 120µg/m<sup>3</sup> (Figure 1Sd). The pollution levels inside the bus  
584 increased when the bus doors and windows were opened allowing the outside pollution from  
585 traffic on the road to infiltrate the bus. Average exposed PM<sub>2.5</sub> was 113±14µg/m<sup>3</sup> (range: 85 to  
586 226µg/m<sup>3</sup>; median: 111µg/m<sup>3</sup>) (Figure 4d). Most of the buses in Delhi, now are air-conditioned,  
587 however, due to the cold weather, it is a general practice to turn off the AC and open windows.  
588 Open windows combined with the frequent opening and closing of the bus doors resulted in  
589 high concentrations of PM<sub>2.5</sub> entering the bus from the outside environment. The main source  
590 of PM<sub>2.5</sub> at the kerbside is traffic-related the high pollution was associated with the office rush-  
591 hour congestion on the road, shown higher in the morning (155µg/m<sup>3</sup>) compared to the  
592 afternoon (89µg/m<sup>3</sup>) in the study day. The recorded PM<sub>2.5</sub> concentration on the bus routes  
593 illustrates that the exposure to PM<sub>2.5</sub> remains almost consistent but ~~s~~ except for the PM<sub>2.5</sub> peak  
594 level measured when the doors were open while the commuters were boarding the bus. These  
595 depended on the time of day and number of passengers boarding and alighting the bus (Kumar  
596 et al., 2018;) (Kolluru et al., 2019).

### 597 3.2.5 PM<sub>2.5</sub> concentration in Air-Conditioned Car

598 The air-conditioned car was the second-lowest mode of transport for PM<sub>2.5</sub> exposure. The  
599 frequency distribution slightly left-skewed distribution (Figure S1e) shows that most values lie  
600 around 45µg/m<sup>3</sup> and the mode is at 100µg/m<sup>3</sup>. The concentrations recorded had a range of  
601 35µg/m<sup>3</sup> to 177µg/m<sup>3</sup> (mean: 89±30µg/m<sup>3</sup>; median: 93µg/m<sup>3</sup>) and the mean was higher than  
602 the 24-hour NAAQS. One of the main reasons for the comparatively low PM<sub>2.5</sub> concentrations  
603 in the AC-cars was probably due to the microclimate created in the car by the air-conditioner,  
604 ~~as the air is usually set to the recirculation mode when AC is on the AC in the car work with~~  
605 ~~internal air recirculation condition.~~ The present study despite being conducted in the cold month  
606 of February, the air conditioning in the cars used was turned on at the beginning of the journey.  
607 Thus, it was also observed that the AC car showed initial higher levels of the pollution which  
608 then gradually kept decreasing to the lower concentration as the cleaner filtered out PM<sub>2.5</sub> air  
609 built-up inside the car.

610 The AC car route from Connaught Place to IIT Delhi, see time series (Figure 4e), shows that it  
611 took approximately 23 minutes for the pollution levels in the car to reduce to NAAQS of  
612 60µg/m<sup>3</sup>. Compared with the result obtained from the alternative by car route from the heavily

613 industrialized Okhla to IIT Delhi showed the  $PM_{2.5}$  levels inside the car with a concentration in  
614 the range around 90 to  $100\mu\text{g}/\text{m}^3$  after 10 minutes of the journey, although never achieved the  
615 NAAQS. The main reason behind this variance could be due to the significantly worst air  
616 quality in Okhla.

### 617 3.2.6 $PM_{2.5}$ concentration in Metro

618 The lowest exposure of the  $PM_{2.5}$  levels was found in the underground metro in Delhi. The  
619 lowest value of the pollution received was  $46.0\mu\text{g}/\text{m}^3$ , while the maximum level recorded for  
620 this mode of transport  $163\mu\text{g}/\text{m}^3$  (mean:  $72.0\pm 11.0\mu\text{g}/\text{m}^3$ ; median:  $71.0\mu\text{g}/\text{m}^3$ ). This maximum  
621 value was due to the opening of the metro door for the commuters to alight and enter. As the  
622 ventilation of the metro is similar to that of the AC cars, the pollution levels slowly decrease as  
623 the particulate matter (PM) is filtered out of the air. The  $PM_{2.5}$  emissions ~~concentration exposure~~  
624 ~~levels~~ in the metro predominantly ~~governed by were due to the  $PM_{2.5}$  levels in station,~~  
625 ~~ventilation process, the movement of carriages in tunnels, - and the movement of a large number~~  
626 ~~of commuters, and air-conditioning in the metro system~~ ~~number of passengers.  $PM_{2.5}$  levels from~~  
627 ~~the metro station as well as from the metro carriage itself.~~ Although, it's very difficult to  
628 precisely pinpoint ~~the explain~~ the exact reason for the high concentrations in the metro. Figure  
629 S1f showed a slightly skewed distribution of the exposure levels in Delhi. The high-frequency  
630 concentration is located between  $65.0\mu\text{g}/\text{m}^3$  and  $79.0\mu\text{g}/\text{m}^3$ , with no outliers being shown in the  
631 results, largely due to the more ambient nature of the outdoor pollution inside ventilated closed  
632 tunnels in which the metro runs. The resulting distribution substantially is below  $100\mu\text{g}/\text{m}^3$ ,  
633 making it the lowest distribution of  $PM_{2.5}$  exposure of all modes of transport.

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

### 644 3.34.1 Open and Enclosed Transport

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

#### 668 4. Discussion

669 The present study found that travelling by rickshaw exposed users to the highest concentrations  
670 of PM<sub>2.5</sub>, followed by walking. Also, it was observed that the high concentrations recorded in  
671 this investigation were similar to trends recorded in the previous study in Delhi (Goel et al.,  
672 2015). On the other hand, when travelling by metro and AC car, users were exposed to the  
673 lowest concentrations of PM<sub>2.5</sub> when compared with other modes. Exposure levels recorded on  
674 the bus relatively were lower than walking or by rickshaw, although higher when compared  
675 with the AC car or metro. Non-AC cars were ranked above the bus. In the present study, the  
676 PM<sub>2.5</sub> exposure in the metro and the bus were much lower than measured in the previous study  
677 by (Goel et al., 2015) conducted in Delhi during 2012-2014, this may be due to the recent clean

678 transport approach by the Government in Delhi which eventually reduce pollution from the  
679 transport sector (CII and NITI Aayog., 2018).

#### 680 ~~4.1 Open and Enclosed Transport~~

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

#### 703 4.1.2 Individual Transport Exposure Analysis [Along the Routes](#)

704 The varying differences in the exposure levels [along the routes](#) for transport modes studied in  
705 this research are now discussed.

##### 706 4.1.2.1 Exposure analysis in Rickshaws

707 In the present study, two different routes, the main (mean PM<sub>2.5</sub>: 598±51µg/m<sup>3</sup>; median:  
708 589µg/m<sup>3</sup>) and the alternative (mean PM<sub>2.5</sub>: 361±69µg/m<sup>3</sup>; median: 337µg/m<sup>3</sup>), were also

709 driven by the rickshaw (Figure S2 and S3). The high concentration was recorded around Deer  
710 Park, near IIT Delhi where higher traffic and higher congestion levels are the norms. The  
711 proximity to the vehicles in traffic would cause an increase in recorded levels, due to their  
712 exhausts and engines polluting directly into the open rickshaw. The maximum level was  
713 measured near Nehru Park, the proximity of three fuel stations within just 500m which have  
714 an additional contribution to the regular traffic and constitutes a possible explanation (Figure  
715 5). ~~The increased number of vehicles at slow speeds, stopping, starting and causing transients  
716 in the general flow of traffic on the road would contribute to emissions elevating local  
717 concentrations. Similar to the previous route, lower concentrations were noticed where there  
718 was decreased congestion or stretches of the road as in Connaught Place where the urban density  
719 is less.~~ The rickshaws travelled along the same stretch of Connaught Place on both routes but  
720 in different periods of the day ending at 10:00 AM and 11:00 AM. This one-hour difference  
721 reduced exposure levels by 200  $\mu\text{g}/\text{m}^3$ , as ~~the high levels were recorded from 9:00 to 10:00  
722 AM. Such a high value is consistent with the~~ high levels of concentrations measured during the  
723 early morning rush hours, due to congested related emissions coupled with the varying  
724 atmospheric mixing height which causes the levels of ambient  $\text{PM}_{2.5}$  to rise (Goel et al., 2015).  
725 ~~The findings that the rickshaw had the highest recorded levels of exposure, is in agreement with  
726 previous studies in Delhi (Kumar and Gupta, 2016) and Dhanbad (Gupta and Elumalai, 2019).~~  
727 This CNG operated open mode of transport is hugely exposed to the emissions from its engine  
728 and exhaust as well as other related road pollution sources often due to lengthy durations spent  
729 in Delhi congestion (Khan et al., 2015), although though a fair number of rickshaws (29% of  
730 the total rickshaw in 2018) had started to use electric, and therefore the exposure would be less.  
731 Research conducted by Reynolds et al., (2011) stated that not properly maintained CNG  
732 rickshaws was responsible for exceptionally high  $\text{PM}_{2.5}$  ( $3110 \mu\text{g}/\text{m}^3$ ). This is a worrying level  
733 of exposure, as it shows the high concentrations that commuters can be exposed to during day-  
734 to-day life in Delhi. The results obtained in the research reported in this manuscript ( $266 \pm 159$   
735  $\mu\text{g}/\text{m}^3$ ) are quite similar to the research conducted in Delhi (Goel et al., 2015), where the mean  
736 level was  $241 \pm 136 \mu\text{g}/\text{m}^3$  in February 2015. A study by Kumar and Gupta, (2016) also  
737 measured high mean levels of  $\text{PM}_{2.5}$  exposure in rickshaw of  $332.8 \pm 90.9 \mu\text{g}/\text{m}^3$  in March 2012,  
738 and whilst a lower value of lower value ( $200 \pm 46 \mu\text{g}/\text{m}^3$ ) was recorded by Apte et al., (2011) in  
739 2010, external factors such as different routes, time of day influence the results.

#### 740 4.1.2.2 Exposure Analysis during Walking

741 Measurements were made whilst walking in the vicinity of IIT Delhi and Connaught Place due  
742 to safety concerns which made it impossible to conduct the study on the main route with  
743 rickshaw. ~~Walking was found to have the second-highest peak levels of PM<sub>2.5</sub> exposure with a~~  
744 ~~mean value of exposure (259±102 µg/m<sup>3</sup>) which was only slightly lower than the rickshaw~~  
745 ~~(266±159 µg/m<sup>3</sup>). The mean walking exposure value aligns with the study from Goel et al.,~~  
746 ~~(2015), who recorded a mean walking exposure of 278 µg/m<sup>3</sup> in February 2015. A study by~~  
747 ~~Saraswat et al., (2016) used models to simulate PM<sub>2.5</sub> exposure whilst walking in Delhi, but the~~  
748 ~~results compared to the measured values reported in this and previous studies seem to suggest~~  
749 ~~that the model underestimates, for example, the maximum mean winter exposure at 195 µg/m<sup>3</sup>~~  
750 ~~which is considerably lower than the observed values.~~ The results from the walk mode in this  
751 study suggested further that the pollution levels were increasing depending on the proximity to  
752 the main road and with the passage of heavily polluting vehicles such as HGVs close to the  
753 pavement. Also walking on the same route in the morning and afternoon showed variation in  
754 the different exposure levels. In general, the exposure levels for walking were high in the  
755 morning than in the afternoon. These results suggest that the high level of exposure in the  
756 morning could be avoided if pedestrians chose not to take walks during the peak hours of 8:00  
757 to 10:00 AM, however, that it is not a realistic option for most people. ~~However, raising~~  
758 ~~awareness of the general public to the health risks associated with exposure to peak hour~~  
759 ~~pollution levels along with advice to take short cuts along streets away from the main road~~  
760 ~~traffic would bring long term benefits.~~

#### 761 4.1.2.3 Exposure Analysis for Non-AC Cars

762 The analysis shows that the high level of PM<sub>2.5</sub> exposure was observed in Connaught Place, due  
763 to high congestion at the time, as well as in denser urban areas causing PM to be trapped in  
764 street canyons. As the open windows in the non-AC car, allowed PM<sub>2.5</sub> to enter directly into  
765 the car from nearby vehicles concentration spikes up to 206 µg/m<sup>3</sup> (Figure 7 and S6) were  
766 observed. The minimum exposure on this route was found near Delhi Racecourse, where the  
767 level of PM<sub>2.5</sub> reached its lowest level of 114 µg/m<sup>3</sup>, this trend was similar to that of the  
768 rickshaw main road exposure route. This drop-in level may be due to the open green area which  
769 provides an opportunity for natural ventilation reducing PM<sub>2.5</sub> exposure levels. ~~The other parts~~  
770 ~~of the route, such as Safdarjung area, high levels of congestion at an intersection of two major~~  
771 ~~roads were mainly responsible for the higher exposure levels. Levels also increased near IIT~~  
772 ~~Delhi, as recorded in the alternative route of rickshaw and AC car. This increase was due to an~~  
773 ~~increase in urban density coupled with increased congestion frequently observed in the area.~~

774 For the same route, the non-AC car was exposed to an average concentration of PM<sub>2.5</sub> 78 µg/m<sup>3</sup>  
775 higher than the AC car. ~~In the whole journey, the PM<sub>2.5</sub> results obtained from non-AC car was~~  
776 ~~92% higher than the AC car.~~ The difference that AC can make is evident when comparing the  
777 two modes of transport, with AC car being a much healthier commuter option than a non-AC  
778 car and rickshaw given the significant lower pollution exposure.

779 ~~This research also revealed that the non-AC car was the third most exposed travel mode with~~  
780 ~~the mean exposure of 149 µg/m<sup>3</sup> which was much lower than the levels of PM<sub>10</sub> of 311 µg/m<sup>3</sup>~~  
781 ~~reported by Namdeo et al., (2016) in Mumbai. The reported PM<sub>2.5</sub>/PM<sub>10</sub> ratio in Mumbai was~~  
782 ~~0.59 (Kothai et al., 2011), which implies that the concentration of PM<sub>2.5</sub> of 183.3 µg/m<sup>3</sup> for the~~  
783 ~~study in Mumbai, remains well above the concentration reported in this study.~~ Kumar and  
784 Gupta, (2016) also reported very high exposed PM<sub>2.5</sub> concentrations (332.4±137.5 µg/m<sup>3</sup>) in  
785 non-AC-car during morning peak-periods in Delhi. When comparing the exposure in the non-  
786 AC car to the ambient mean, the exposure in the car is only 3% greater than the observed daily  
787 ambient PM<sub>2.5</sub> during the study. However, compared to the rickshaw, the levels of exposure are  
788 much lower in the non-AC car, with a difference of 116 µg/m<sup>3</sup> between their mean exposure  
789 concentrations. This demonstrates that the physical barriers of the car, (i.e. windshield,  
790 windows and frame), play a major role in limiting the levels of PM<sub>2.5</sub> that can enter the vehicle.

#### 791 4.12.4 Exposure Analysis for Buses

792 The route followed by the bus was broadly similar to the alternative route of the rickshaw. The  
793 higher levels were recorded in Vasant Vihar IIT Delhi, (120–140 µg/m<sup>3</sup>) and these continued  
794 through the embassy area near Nehru Park, where the highest concentration of PM<sub>2.5</sub> was  
795 recorded at 226 µg/m<sup>3</sup> (Figure 8 and S7). ~~Of course, the pollution ingress increased as the dwell~~  
796 ~~times at bus stops increased which depended on the number of passengers alighting and~~  
797 ~~boarding.~~ The average recorded value in the bus ~~fourth highest exposure level was recorded in~~  
798 ~~the bus (113 µg/m<sup>3</sup>), which~~ was much lower when compared with the previous study in Delhi  
799 (Goel et al., 2015), ~~which recorded (278 µg/m<sup>3</sup>)~~ -at the same time of year in 2015. ~~Also, the~~  
800 ~~levels recorded by Namdeo et al., (2016) gave the highest levels for the buses in Mumbai (503~~  
801 ~~µg/m<sup>3</sup>). Taking the PM<sub>2.5</sub> to PM<sub>10</sub> concentration ratio factor of 0.59 reported by (Kothai et al.,~~  
802 ~~2011), this gives an average PM<sub>2.5</sub> concentration of 297 µg/m<sup>3</sup>, which remains significantly~~  
803 ~~higher than this study's results.~~ An explanation as to why the levels recorded was much lower  
804 than other studies may be because many buses in Delhi now use AC. With the Government of  
805 Delhi increasing the number of AC buses available in the city (Goswami, 2017), lower levels  
806 of exposure to PM<sub>2.5</sub> can be expected. A study in Ahmedabad (Swamy et al., 2015), found that

807 commuters in AC buses were exposed to approximately 40% less PM<sub>2.5</sub> than those in non-AC  
808 buses. The buses used during this study were AC, but like the AC cars, most of the AC units in  
809 buses were not activated initially because monitoring started in the winter months. Even when  
810 the AC was activated, some windows were left open on the bus, allowing ambient pollution to  
811 enter through the open windows. ~~The increased levels were also due to frequent opening of bus~~  
812 ~~doors, which allowed the entry of the outside pollution inside the bus and this was recorded by~~  
813 ~~the monitors.~~ Nevertheless, the overall results of the study show that buses were towards the  
814 lower end of exposure to PM<sub>2.5</sub> as a mode of transport. In general, travelling by bus had  
815 exposure levels 22% lower than the ambient air quality.

~~816 The route followed by the bus was broadly similar to the alternative route of the rickshaw. The~~  
817 ~~higher levels were recorded in Vasant Vihar IIT Delhi, (120–140 µg/m<sup>3</sup>) and these continued~~  
818 ~~through the embassy area near Nehru Park, where the highest concentration of PM<sub>2.5</sub> was~~  
819 ~~recorded at 226 µg/m<sup>3</sup> (Figure 8 and S7). Low levels were recorded towards Connaught Place,~~  
820 ~~India Gate. Consistent with earlier observations, the high levels were obtained near multiple~~  
821 ~~bus stops with additional stop, start, idling occurs and were interruptions with the main flow of~~  
822 ~~traffic occurs (Hess et al., 2010). The increased levels were also due to frequent opening of bus~~  
823 ~~doors, which allowed the entry of the outside pollution inside the bus and this was recorded by~~  
824 ~~the monitors. Of course, the pollution ingress increased as the dwell times at bus stops increased~~  
825 ~~which depended on the number of passengers alighting and boarding.~~

#### 826 4.1.2.5 Exposure Analysis for AC Cars

827 In this study, two routes were considered to record the PM<sub>2.5</sub> levels; the main route and the  
828 alternate route taken from the Okhla industrial estate (Figure S4 and S5). For both routes, high  
829 PM<sub>2.5</sub> values were recorded at the start of the journey and decreased once AC was switched on.  
830 In the case of the main route, the PM<sub>2.5</sub> concentrations (mean: 69±24 µg/m<sup>3</sup>) in AC vehicle  
831 continue to decrease throughout the journey and no surges were observed in the trend (Figure  
832 6). The levels recorded on the main route matched with the analysis of two previous studies  
833 (Namdeo et al., 2016; Goel et al., 2015). The alternative route was from the industrial area of  
834 Okhla to IIT Delhi. This route was deliberately selected to explore the changes occurring in the  
835 exposure levels due to travelling in the high pollution area in Okhla (Nandi, 2017). However,  
836 the car used for the alternative route was using ‘fresh air’ without the recirculation mechanism  
837 of the AC. The effect of this was visible when the PM<sub>2.5</sub> levels did not fall during the journey,  
838 stabilising around the mean value (104±15 µg/m<sup>3</sup>). These results confirmed that the different  
839 air ventilation settings of the cars can affect in-vehicle exposure levels. Towards and at the end

840 of the journey from Okhla to IIT Delhi showed high levels due to increased congestion and  
841 possibly coupled with high urban density. A study in Beijing (Yao et al., 2015) reported that  
842 urban areas were exposed to  $\sim 15 \mu\text{g}/\text{m}^3$  higher concentrations of  $\text{PM}_{2.5}$  compared to green and  
843 suburban areas. ~~This seems to be apparent in many of the routes studied in this research,  
844 because often PM levels increased when approaching a denser urban area, as PM becomes  
845 trapped, circulating in street canyons, causing higher ambient concentrations an observation  
846 consistent with (Namdeo et al., 1998; Abhijith and Kumar, 2019).~~

#### 847 4.12.6 Exposure Analysis for Metro

848 Travelling by metro proved to be the least exposed mode of transport studied in this research,  
849 with a mean exposure of  $\text{PM}_{2.5}$  of  $72 \mu\text{g}/\text{m}^3$ . These results were in the agreement with Goel et  
850 al., (2015) reporting an average exposure on the metro of  $87 \mu\text{g}/\text{m}^3$  in April 2015 and  $76 \mu\text{g}/\text{m}^3$   
851 in May 2015. However, these levels were recorded in the spring period when the pollution  
852 levels are already lower than in the winter consistent with measurements in another large city,  
853 ~~A study in Toronto recorded mean levels of  $100 \mu\text{g}/\text{m}^3$   $\text{PM}_{2.5}$  on the subway (Van Ryswyk et  
854 al., 2017). Another investigation in New York recorded  $\text{PM}_{2.5}$  levels which were double those  
855 in Toronto at ( $200.4 \mu\text{g}/\text{m}^3$ ) in one subway station (Vileassim, et al., 2014). In the London  
856 underground, the  $\text{PM}_{2.5}$  concentration (mean  $302 \mu\text{g}/\text{m}^3$ , median  $318 \mu\text{g}/\text{m}^3$ ) was approximately  
857 15 times greater than the surface ambient background (mean  $18 \mu\text{g}/\text{m}^3$ , median  $5 \mu\text{g}/\text{m}^3$ ) levels  
858 and roadside environments (mean  $26 \mu\text{g}/\text{m}^3$ , median  $22 \mu\text{g}/\text{m}^3$ ) in central London (Smith et al.,  
859 2020).~~ The newer and modern system adopted for Delhi metro, along with the use of AC in  
860 both the metro stations and carriages, reduced the  $\text{PM}_{2.5}$  level significantly.

861 The metro with around 2.7 million passengers daily (India Today, 2018), experiences exposure  
862 much lower when compared with that of the bus. However, the majority of Delhiites, around  
863 4.2 million commuters (Standard Business, 2018.), prefer travelling by bus due to the less  
864 expensive fares and wider coverage of areas served. Pollution levels in the station ~~, at the start  
865 of the survey,~~ were higher than those measured in the metro carriage. ~~Similar observations were  
866 recorded in Helsinki subway station in Finland (Aarnio et al., 2005).~~ The pollution levels within  
867 the metro were almost 51% less than the metro station. The monitors also recorded a slight rise  
868 in the  $\text{PM}_{2.5}$  concentrations (about  $20 \mu\text{g}/\text{m}^3$ ) at the locations ~~where and times~~ when the carriage  
869 doors opened to let passengers alight and board.

#### 870 4.23 Respiratory deposition doses (RDDs)

871 To accomplish a comprehensive study of the effects of this pollution on human health, the  
872 individual's inhalation or ventilation rate during the commute must be considered. Thus, this  
873 will give a total RDDs of PM<sub>2.5</sub> per km journey in Delhi city ~~and the resulted value was~~  
874 ~~calculated for healthy adult's population~~. The study by Gupta and Elumalai, (2019) calculated  
875 an inhalation rate of  $2.5 \times 10^{-2}$  m<sup>3</sup> per minute for light activity, and a deposition fraction factor  
876 for PM<sub>2.5</sub> of 0.87 (see supplementary material). Using these values with the average mean  
877 exposures, an estimated total RDDs per km was calculated for this study. As previously stated,  
878 walking and rickshaw have the highest inhaled PM<sub>2.5</sub> levels per km of ~~the~~ journey (Table 3).  
879 The total dosage received would be  $84.7 \pm 33.4$  µg/km with waking and  $15.8 \pm 9.5$  µg/km using  
880 a rickshaw. The total RDDs during the journey with a non-AC car and a bus were  $9.7 \pm 0.9$   
881 µg/km and  $7.4 \pm 0.9$  µg/km. The lowest RDDs were observed in AC-car ( $5.8 \pm 2.0$  µg/km) and  
882 metro ( $3.0 \pm 0.4$  µg/km). This is similar to the amount of PM<sub>2.5</sub> that a rickshaw driver inhaled in  
883 Dhanbad, India ( $19.4$  µg/m<sup>3</sup>) (Gupta and Elumalai, 2019). However, the study by Goel et al.,  
884 (2015) inferred that the total PM<sub>2.5</sub> dosage was much higher for all transport modes, which  
885 questions whether the estimated doses calculated in this study are underestimations.

#### 886 ~~4.4—Implications of the exposure results~~

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

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

## 903 5. Conclusion

904 The present study focusses on the different exposure levels recorded by commuters using six  
905 modes of transport in Delhi and the results showed that travellers in open modes of transport  
906 (rickshaws and walking) were exposed to the highest PM<sub>2.5</sub> concentrations. Inside enclosed  
907 modes of transports which used AC, including private cars and the metro, were found to have  
908 significantly lower PM<sub>2.5</sub> concentrations. The exposure levels for passengers on buses and  
909 travellers in non-AC cars were found to lie between fully closed and open transport modes.  
910 Nevertheless, open windows and the frequency of opening of, and duration with which the  
911 doors on buses opened resulted in ambient pollution (background plus that emitted by other  
912 vehicles) entering vehicles, thus increasing the concentrations to which travellers were exposed.  
913 ~~The exposure levels of rickshaws and walking were almost twice the ambient daily PM<sub>2.5</sub> mean.  
914 Travellers in AC cars, metro and buses all had mean exposures below the ambient level, whilst  
915 in non-AC cars, it was almost the same. This shows the effect different transport modes have  
916 on exposure, for example, commuting by metro would only be exposed to half the amount of  
917 PM<sub>2.5</sub> compared to ambient background levels in an urban area. But a similar commute by  
918 rickshaw a traveller would be exposed to 83% more PM<sub>2.5</sub> when compared to an ambient point.  
919 When compared to the metro's mean exposure, for this route the rickshaw commuter would be  
920 exposed to 3.7 times more PM<sub>2.5</sub>. Yet the results also showed that not one of the transport modes  
921 mean exposures met the Indian NAAQS and WHO Guidelines for PM<sub>2.5</sub>, with the closest being  
922 the metro. The variation in ambient pollution each day influenced the exposure levels greatly  
923 during the study. The lower atmospheric mixing height and high levels of traffic and congestion  
924 during the rush hours resulted in substantially higher PM<sub>2.5</sub> levels in the evenings and morning  
925 and reducing in the afternoons. This was suggested when the exposure levels measured for  
926 walking on the same route showed that there was 56% higher exposure in the morning  
927 compared to the afternoon. There was also a difference in the exposure levels in day to day  
928 analysis conducted for the rickshaw. Mean variations of >150 µg/m<sup>3</sup> showed that exposure can  
929 vary greatly for the same commute on a day to day basis. Delhi is one of the most polluted  
930 cities in the world and where about 20% of PM<sub>2.5</sub> in ambient air originates from primary PM<sub>2.5</sub>  
931 emissions from mobile sources. The current regulations are expected to decrease the  
932 contribution of primary PM<sub>2.5</sub> emitted in the transport sector by typically 40% in 2030,  
933 although, the absence of emission controls will increase the contributions by typically 50%  
934 (with the predicted growth in the number of vehicles in Delhi by 2030) (Purohit et al., 2019;~~

935 Goel and Guttikunda, 2015). If levels of PM<sub>2.5</sub> grow, the long-term PM<sub>2.5</sub> exposure-related  
936 premature deaths will most certainly increase in the upcoming years in Delhi.

937  
938 The findings of this study undertaken can be used to identify areas for further research and to  
939 shortlist the mitigation measures towards suggest several key areas where both research and  
940 action will take steps forward in reducing PM<sub>2.5</sub> exposure in Delhi. This study suggests that the  
941 identification of Like, the congestion hotspots is important as personal exposure is observed to  
942 be very high in these locations. were proven to be areas where exposure levels were  
943 exceptionally high, limiting congestion and number of vehicles may aid this. The possible  
944 implementation of intelligent transport systems at the congested area can reduce levels of  
945 pollution (Díaz et al., 2020). Education and information to the users of travel modes local people  
946 on to how to reduce their personal exposure levels would go a long way in protecting their  
947 health. an individual from the effects of PM<sub>2.5</sub>, (i.e. One of the solutions could be to wear a  
948 respirator mask) or avoid congestion hot spots if the route could be altered (e.g. when using  
949 rickshaws and private cars). Other methods to reduce exposure could be achieved through  
950 simple measures, such as advising buses and cars to keep windows closed during high pollution  
951 episodes and the use of AC. Encouraging sustainable modes of transport such as electric  
952 vehicles and the metro would reduce PM<sub>2.5</sub> emissions and help limit the generation of PM<sub>2.5</sub> on  
953 roads, effectively the reducing ambient levels consequently reducing the personal exposure.

954 The study has also outlined several areas where further research will help in developing a better  
955 n-understanding of the effect of traffic state (congestion vs. free-flowing), ventilation settings  
956 in vehicles (recirculation vs fresh-air; opening and closing of doors and windows) and metro  
957 stations. The frequency of door opening and passenger number effects the PM<sub>2.5</sub> concentration  
958 in a bus need for further investigation. Time spent travelling on a particular travel mode is also  
959 an important area to investigate. Apps could be developed to optimise for travel time and the  
960 lowest level of personal exposure on travel modes which will permit such changes. exposure  
961 levels of PM<sub>2.5</sub> and the effect different transport modes have. Further research into the other  
962 areas will give more accurate data, further understanding of what level people are exposed to  
963 daily. As well as this This research could be extended to include additional travel , research  
964 should be conducted into other transport modes, such as modes including walking, cycling and  
965 eyeling, local-trains, Light Goods Vehicles (LGVs) and Heavy Goods Vehicles (HGVs). The  
966 frequency of door opening and passenger number effects the PM<sub>2.5</sub> concentration in a bus need  
967 for further investigation. Whilst this study focused on PM<sub>2.5</sub>, further research could monitor the  
968 personal exposure to different pollutants, such as particle numbers, ultrafine particles, PM<sub>10</sub>, CO,

969 NO<sub>2</sub> and VOCs, that have all been proven to be harmful to human health. Health effects of the  
970 total exposure to all pollutants could then be assessed, to investigate where and why pollution  
971 hotspots occur, and their detrimental effects.

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993 **Reference:**

994 Antonsen, S., Mok, P.L.H., Webb, R.T., Mortensen, P.B., McGrath, J.J., Agerbo, E., Brandt, J.,  
995 Geels, C., Christensen, J.H., Pedersen, C.B., 2020. Exposure to air pollution during  
996 childhood and risk of developing schizophrenia: a national cohort study. *The Lancet*  
997 *Planetary Health* 4, e64–e73. [https://doi.org/10.1016/S2542-5196\(20\)30004-8](https://doi.org/10.1016/S2542-5196(20)30004-8)

998 Apte, J.S., Kirchstetter, T.W., Reich, A.H., Deshpande, S.J., Kaushik, G., Chel, A., Marshall,  
999 J.D., Nazaroff, W.W., 2011. Concentrations of fine, ultrafine, and black carbon particles  
1000 in auto-rickshaws in New Delhi, India. *Atmospheric Environment* 45, 4470–4480.

- 1001 <https://doi.org/10.1016/j.atmosenv.2011.05.028>
- 1002 Both, A.F., Westerdahl, D., Fruin, S., Haryanto, B., Marshall, J.D., 2013. Exposure to carbon  
1003 monoxide, fine particle mass, and ultrafine particle number in Jakarta, Indonesia: Effect  
1004 of commute mode. *Science of The Total Environment* 443, 965–972.  
1005 <https://doi.org/10.1016/j.scitotenv.2012.10.082>
- 1006 Bowatte, G., Erbas, B., Lodge, C.J., Knibbs, L.D., Gurrin, L.C., Marks, G.B., Thomas, P.S.,  
1007 Johns, D.P., Giles, G.G., Hui, J., Dennekamp, M., Perret, J.L., Abramson, M.J., Walters,  
1008 E.H., Matheson, M.C., Dharmage, S.C., 2017. Traffic-related air pollution exposure over  
1009 a 5-year period is associated with increased risk of asthma and poor lung function in  
1010 middle age. *European Respiratory Journal* 50, 1602357.  
1011 <https://doi.org/10.1183/13993003.02357-2016>
- 1012 Bowe, B., Xie, Y., Yan, Y., Al-Aly, Z., 2019. Burden of Cause-Specific Mortality Associated  
1013 With PM 2.5 Air Pollution in the United States. *JAMA Network Open* 2, e1915834.  
1014 <https://doi.org/10.1001/jamanetworkopen.2019.15834>
- 1015 Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C.A., Apte, J.S., Brauer,  
1016 M., Cohen, A., Weichenthal, S., Coggins, J., Di, Q., Brunekreef, B., Frostad, J., ~~et al., Lim,~~  
1017 ~~S.S., Kan, H., Walker, K.D., Thurston, G.D., Hayes, R.B., Lim, C.C., Turner, M.C., Jerrett,~~  
1018 ~~M., Krewski, D., Gapstur, S.M., Diver, W.R., Ostro, B., Goldberg, D., Crouse, D.L.,~~  
1019 ~~Martin, R. V., Peters, P., Pinault, L., Tjepkema, M., van Donkelaar, A., Villeneuve, P.J.,~~  
1020 ~~Miller, A.B., Yin, P., Zhou, M., Wang, L., Janssen, N.A.H., Marra, M., Atkinson, R.W.,~~  
1021 ~~Tsang, H., Quoc Thach, T., Cannon, J.B., Allen, R.T., Hart, J.E., Laden, F., Cesaroni, G.,~~  
1022 ~~Forastiere, F., Weinmayr, G., Jaensch, A., Nagel, G., Concini, H., Spadaro, J. V.,~~ 2018.  
1023 Global estimates of mortality associated with long-term exposure to outdoor fine  
1024 particulate matter. *Proceedings of the National Academy of Sciences* 115, 9592–9597.  
1025 <https://doi.org/10.1073/pnas.1803222115>
- 1026 Chaney, R.A., Sloan, C.D., Cooper, V.C., Robinson, D.R., Hendrickson, N.R., McCord, T.A.,  
1027 Johnston, J.D., 2017. Personal exposure to fine particulate air pollution while commuting:  
1028 An examination of six transport modes on an urban arterial roadway. *PLOS ONE* 12,  
1029 e0188053. <https://doi.org/10.1371/journal.pone.0188053>
- 1030 Chen, H., Kwong, J.C., Copes, R., Hystad, P., van Donkelaar, A., Tu, K., Brook, J.R., Goldberg,  
1031 M.S., Martin, R. V., Murray, B.J., Wilton, A.S., Kopp, A., Burnett, R.T., 2017. Exposure  
1032 to ambient air pollution and the incidence of dementia: A population-based cohort study.  
1033 *Environment International* 108, 271–277. <https://doi.org/10.1016/j.envint.2017.08.020>
- 1034 Chen, Y., Wild, O., Ryan, E., Sahu, S.K., Lowe, D., Archer-Nicholls, S., Wang, Y., McFiggans,  
1035 G., Ansari, T., Singh, V., Sokhi, R.S., Archibald, A., Beig, G., 2020. Mitigation of  
1036 PM<sub>2.5</sub> and ozone pollution in Delhi: a  
1037 sensitivity study during the pre-monsoon period. *Atmospheric Chemistry and Physics* 20,  
1038 499–514. <https://doi.org/10.5194/acp-20-499-2020>
- 1039 Choudhary, A., Gokhale, S., 2016. Urban real-world driving traffic emissions during  
1040 interruption and congestion. *Transportation Research Part D: Transport and Environment*  
1041 43, 59–70. <https://doi.org/10.1016/j.trd.2015.12.006>
- 1042 Chowdhury, S., Dey, S., Guttikunda, S., Pillarisetti, A., Smith, K.R., Di Girolamo, L., 2019.  
1043 Indian annual ambient air quality standard is achievable by completely mitigating

1044 emissions from household sources. *Proceedings of the National Academy of Sciences* 116,  
1045 10711–10716. <https://doi.org/10.1073/pnas.1900888116>

1046 CII and NITI Aayog., 2018. ACTION PLAN FOR CLEAN TRANSPORTATION: Report of  
1047 the Task Force on Clean Transportation. Delhi.

1048 Costa, L.G., Cole, T.B., Coburn, J., Chang, Y.-C., Dao, K., Roqué, P.J., 2017. Neurotoxicity of  
1049 traffic-related air pollution. *NeuroToxicology* 59, 133–139.  
1050 <https://doi.org/10.1016/j.neuro.2015.11.008>

1051 de Nazelle, A., Fruin, S., Westerdahl, D., Martinez, D., Ripoll, A., Kubesch, N.,  
1052 Nieuwenhuijsen, M., 2012. A travel mode comparison of commuters' exposures to air  
1053 pollutants in Barcelona. *Atmospheric Environment* 59, 151–159.  
1054 <https://doi.org/10.1016/j.atmosenv.2012.05.013>

1055 Díaz, G., Macià, H., Valero, V., Boubeta-Puig, J., Cuartero, F., 2020. An Intelligent  
1056 Transportation System to control air pollution and road traffic in cities integrating CEP  
1057 and Colored Petri Nets. *Neural Computing and Applications* 32, 405–426.  
1058 <https://doi.org/10.1007/s00521-018-3850-1>

1059 Fu, P., Guo, X., Cheung, F.M.H., Yung, K.K.L., 2019. The association between PM2.5  
1060 exposure and neurological disorders: A systematic review and meta-analysis. *Science of*  
1061 *The Total Environment* 655, 1240–1248. <https://doi.org/10.1016/j.scitotenv.2018.11.218>

1062 Geiss, O., Barrero-Moreno, J., Tirendi, S., Kotzias, D., 2010. Exposure to Particulate Matter in  
1063 Vehicle Cabins of Private Cars. *Aerosol and Air Quality Research* 10, 581–588.  
1064 <https://doi.org/10.4209/aaqr.2010.07.0054>

1065 Gilliland, J., Maltby, M., Xu, X., Luginaah, I., Loebach, J., Shah, T., 2019. Is active travel a  
1066 breath of fresh air? Examining children's exposure to air pollution during the school  
1067 commute. *Spatial and Spatio-temporal Epidemiology* 29, 51–57.  
1068 <https://doi.org/10.1016/j.sste.2019.02.004>

1069 Goel, R., Gani, S., Guttikunda, S.K., Wilson, D., Tiwari, G., 2015. On-road PM2.5 pollution  
1070 exposure in multiple transport microenvironments in Delhi. *Atmospheric Environment*  
1071 123, 129–138. <https://doi.org/10.1016/j.atmosenv.2015.10.037>

1072 Gong, Y., Zhou, T., Zhao, Y., Xu, B., 2019. Characterization and Risk Assessment of  
1073 Particulate Matter and Volatile Organic Compounds in Metro Carriage in Shanghai, China.  
1074 *Atmosphere* 10, 302. <https://doi.org/10.3390/atmos10060302>

1075 Goswami, S., 2017. 10,000 cabs, 431 buses: New faces of Delhi's air-conditioned public  
1076 transport. [WWW Document]. *Hindustan Times*. URL  
1077 [https://www.hindustantimes.com/delhi-news/10-000-cabs-431-buses-new-faces-of-delhi-](https://www.hindustantimes.com/delhi-news/10-000-cabs-431-buses-new-faces-of-delhi-s-air-conditioned-public-transport/story-neNFaiY07oe85vFcUC75NM.html)  
1078 [s-air-conditioned-public-transport/story-neNFaiY07oe85vFcUC75NM.html](https://www.hindustantimes.com/delhi-news/10-000-cabs-431-buses-new-faces-of-delhi-s-air-conditioned-public-transport/story-neNFaiY07oe85vFcUC75NM.html)

1079 Government of India, C. 2011., 2020. Delhi City Census 2011 data. [WWW Document].  
1080 Government of India, Census 2011. URL [https://www.census2011.co.in/census/city/49-](https://www.census2011.co.in/census/city/49-delhi.html)  
1081 [delhi.html](https://www.census2011.co.in/census/city/49-delhi.html)

1082 Gupta, S.K., Elumalai, S.P., 2019. Exposure to traffic-related particulate matter and deposition  
1083 dose to auto rickshaw driver in Dhanbad, India. *Atmospheric Pollution Research* 10, 1128–

- 1084 1139. <https://doi.org/10.1016/j.apr.2019.01.018>
- 1085 Ham, W., Vijayan, A., Schulte, N., Herner, J.D., 2017. Commuter exposure to PM<sub>2.5</sub>, BC, and  
1086 UFP in six common transport microenvironments in Sacramento, California. *Atmospheric*  
1087 *Environment* 167, 335–345. <https://doi.org/10.1016/j.atmosenv.2017.08.024>
- 1088 India Today, n.d. Nearly 27 lakh commuters boarded Delhi Metro everyday in February,  
1089 ridership sees steady increase. [WWW Document]. 2018. URL  
1090 [https://www.indiatoday.in/india/story/delhi-metro-sees-steady-rise-in-daily-ridership-26-](https://www.indiatoday.in/india/story/delhi-metro-sees-steady-rise-in-daily-ridership-26-98-lakh-in-feb-1190516-2018-03-15)  
1091 [98-lakh-in-feb-1190516-2018-03-15](https://www.indiatoday.in/india/story/delhi-metro-sees-steady-rise-in-daily-ridership-26-98-lakh-in-feb-1190516-2018-03-15)
- 1092 Jerrett, M., Finkelstein, M.M., Brook, J.R., Arain, M.A., Kanaroglou, P., Stieb, D.M., Gilbert,  
1093 N.L., Verma, D., Finkelstein, N., Chapman, K.R., Sears, M.R., 2009. A Cohort Study of  
1094 Traffic-Related Air Pollution and Mortality in Toronto, Ontario, Canada. *Environmental*  
1095 *Health Perspectives* 117, 772–777. <https://doi.org/10.1289/ehp.11533>
- 1096 Khan, M.I., Yasmin, T., Shakoor, A., 2015. Technical overview of compressed natural gas  
1097 (CNG) as a transportation fuel. *Renewable and Sustainable Energy Reviews* 51, 785–797.  
1098 <https://doi.org/10.1016/j.rser.2015.06.053>
- 1099 Kolluru, S.S.R., Patra, A.K., Dubey, R.S., 2019a. In-vehicle PM<sub>2.5</sub> personal concentrations in  
1100 winter during long distance road travel in India. *Science of The Total Environment* 684,  
1101 207–220. <https://doi.org/10.1016/j.scitotenv.2019.05.347>
- 1102 Kolluru, S.S.R., Patra, A.K., Kumar, P., 2019b. Determinants of commuter exposure to PM<sub>2.5</sub>  
1103 and CO during long-haul journeys on national highways in India. *Atmospheric Pollution*  
1104 *Research* 10, 1031–1041. <https://doi.org/10.1016/j.apr.2019.01.012>
- 1105 Kumar, P., Gupta, N.C., 2016. Commuter exposure to inhalable, thoracic and alveolic particles  
1106 in various transportation modes in Delhi. *Science of The Total Environment* 541, 535–  
1107 541. <https://doi.org/10.1016/j.scitotenv.2015.09.076>
- 1108 Kumar, P., Rivas, I., Singh, A.P., Ganesh, V.J., Ananya, M., Frey, H.C., 2018. Dynamics of  
1109 coarse and fine particle exposure in transport microenvironments. *npj Climate and*  
1110 *Atmospheric Science* 1, 11. <https://doi.org/10.1038/s41612-018-0023-y>
- 1111 Lin, C., Hu, D., Jia, X., Chen, J., Deng, F., Guo, X., Heal, M.R., Cowie, H., Wilkinson, P.,  
1112 Miller, M.R., Loh, M., 2020. The relationship between personal exposure and ambient  
1113 PM<sub>2.5</sub> and black carbon in Beijing. *Science of The Total Environment* 737, 139801.  
1114 <https://doi.org/10.1016/j.scitotenv.2020.139801>
- 1115 Maji, K.J., 2020. Substantial changes in PM<sub>2.5</sub> pollution and corresponding premature deaths  
1116 across China during 2015–2019: A model prospective. *Science of The Total Environment*  
1117 729, 138838. <https://doi.org/10.1016/j.scitotenv.2020.138838>
- 1118 Matz, C.J., Egyed, M., Hocking, R., Seenundun, S., Charman, N., Edmonds, N., 2019. Human  
1119 health effects of traffic-related air pollution (TRAP): a scoping review protocol.  
1120 *Systematic Reviews* 8, 223. <https://doi.org/10.1186/s13643-019-1106-5>
- 1121 Menon, J.S., Nagendra, S.M.S., 2018. Personal exposure to fine particulate matter  
1122 concentrations in central business district of a tropical coastal city. *Journal of the Air &*  
1123 *Waste Management Association* 68, 415–429.

1124 <https://doi.org/10.1080/10962247.2017.1407837>

1125 Monrad, M., Sajadieh, A., Christensen, J.S., Ketzler, M., Raaschou-Nielsen, O., Tjønneland, A.,  
1126 Overvad, K., Loft, S., Sørensen, M., 2017. Long-Term Exposure to Traffic-Related Air  
1127 Pollution and Risk of Incident Atrial Fibrillation: A Cohort Study. *Environmental Health*  
1128 *Perspectives* 125, 422–427. <https://doi.org/10.1289/EHP392>

1129 Moreno, T., Reche, C., Rivas, I., Cruz Minguillón, M., Martins, V., Vargas, C., Buonanno, G.,  
1130 Parga, J., Pandolfi, M., Brines, M., Ealo, M., Sofia Fonseca, A., Amato, F., Sosa, G.,  
1131 Capdevila, M., de Miguel, E., Querol, X., Gibbons, W., 2015. Urban air quality  
1132 comparison for bus, tram, subway and pedestrian commutes in Barcelona. *Environmental*  
1133 *Research* 142, 495–510. <https://doi.org/10.1016/j.envres.2015.07.022>

1134 Namdeo, A., Ballare, S., Job, H., Namdeo, D., 2016. Commuter Exposure to Air Pollution in  
1135 Newcastle, U.K., and Mumbai, India. *Journal of Hazardous, Toxic, and Radioactive Waste*  
1136 20. [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000232](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000232)

1137 Nandi, J., 2018. 12 areas in Delhi where you can never breathe clean air [WWW Document].  
1138 The Times of India. URL [https://timesofindia.indiatimes.com/city/delhi/twelve-areas-in-](https://timesofindia.indiatimes.com/city/delhi/twelve-areas-in-delhi-where-you-can-never-breathe-clean-air/articleshow/62677188.cms)  
1139 [delhi-where-you-can-never-breathe-clean-air/articleshow/62677188.cms](https://timesofindia.indiatimes.com/city/delhi/twelve-areas-in-delhi-where-you-can-never-breathe-clean-air/articleshow/62677188.cms)

1140 Nandi, J., 2017. Delhi's new pollution hotspots are worse than Anand Vihar. [WWW  
1141 Document]. URL [https://timesofindia.indiatimes.com/city/delhi/delhis-new-pollution-](https://timesofindia.indiatimes.com/city/delhi/delhis-new-pollution-hotspots-are-worse-than-anand-vihar/articleshow/61537012.cms)  
1142 [hotspots-are-worse-than-anand-vihar/articleshow/61537012.cms](https://timesofindia.indiatimes.com/city/delhi/delhis-new-pollution-hotspots-are-worse-than-anand-vihar/articleshow/61537012.cms)

1143 Onat, B., Stakeeva, B., 2013. Personal exposure of commuters in public transport to PM2.5 and  
1144 fine particle counts. *Atmospheric Pollution Research* 4, 329–335.  
1145 <https://doi.org/10.5094/APR.2013.037>

1146 Qiu, Z., Song, J., Xu, X., Luo, Y., Zhao, R., Zhou, W., Xiang, B., Hao, Y., 2017. Commuter  
1147 exposure to particulate matter for different transportation modes in Xi'an, China.  
1148 *Atmospheric Pollution Research* 8, 940–948. <https://doi.org/10.1016/j.apr.2017.03.005>

1149 Qstarz., 2018. BT-Q1000XT GPS Travel Recorder. [WWW Document]. URL  
1150 [http://www.qstarz.com/Products/GPS Products/BT-Q1000XT-F.htm](http://www.qstarz.com/Products/GPS%20Products/BT-Q1000XT-F.htm)

1151 R Core Team, 2017. R: A Language and Environment for Statistical Computing R Foundation  
1152 for Statistical Computing, Vienna, Austria.

1153 [RStudio Team \(2020\). RStudio: Integrated Development Environment for R, Version 1.1.456](https://www.rstudio.com/)  
1154 [RStudio, PBC, Boston, MA URL. Available at: http://www.rstudio.com/.](https://www.rstudio.com/)

1155 Reynolds, C.C.O., Kandlikar, M., Badami, M.G., 2011. Determinants of PM and GHG  
1156 emissions from natural gas-fueled auto-rickshaws in Delhi. *Transportation Research Part*  
1157 *D: Transport and Environment* 16, 160–165. <https://doi.org/10.1016/j.trd.2010.10.004>

1158 Rivas, I., Kumar, P., Hagen-Zanker, A., 2017. Exposure to air pollutants during commuting in  
1159 London: Are there inequalities among different socio-economic groups? *Environment*  
1160 *International* 101, 143–157. <https://doi.org/10.1016/j.envint.2017.01.019>

1161 Rodenbeck, E., n.d. Stamen, San Francisco: Stamen Design LLC. [WWW Document]. 2018.  
1162 URL <https://stamen.com/>

1163 Stanaway, J.D., Afshin, A., Gakidou, E., Lim, S.S., Abate, D., Abate, K.H., Abbafati, C.,  
1164 Abbasi, N., Abbastabar, H., Abd-Allah, F., Abdela, J., Abdelalim, A., *et al.*, Abdollahpour,  
1165 I., Abdulkader, R.S., Abebe, M., Abebe, Z., Abera, S.F., Abil, O.Z., Abraha, H.N.,  
1166 Abrham, A.R., Abu-Raddad, L.J., Abu-Rmeileh, N.M., Accrombessi, M.M.K., Acharya,  
1167 D., Acharya, P., Adamu, A.A., Adane, A.A., Adebayo, O.M., Adedoyin, R.A.,  
1168 Adekanmbi, V., Ademi, Z., Adetokunboh, O.O., Adib, M.G., Admasie, A., Adsuar, J.C.,  
1169 Afanvi, K.A., Afarideh, M., Agarwal, G., Aggarwal, A., Aghayan, S.A., Agrawal, A.,  
1170 Agrawal, S., Ahmadi, A., Ahmadi, M., Ahmadi, H., Ahmed, M.B., Aichour, A.N.,  
1171 Aichour, I., Aichour, M.T.E., Akbari, M.E., Akinyemiju, T., Akseer, N., Al-Aly, Z., Al-  
1172 Eyadhy, A., Al-Mekhlafi, H.M., Alahdab, F., Alam, K., Alam, S., Alam, T., Alashi, A.,  
1173 Alavian, S.M., Alene, K.A., Ali, K., Ali, S.M., Alijanzadeh, M., Alizadeh Navaei, R.,  
1174 Aljunid, S.M., Alkerwi, A., Alla, F., Alsharif, U., Altirkawi, K., Alvis-Guzman, N.,  
1175 Amare, A.T., Ammar, W., Anber, N.H., Anderson, J.A., Andrei, C.L., Androudi, S.,  
1176 Animut, M.D., Anjomshoa, M., Ansha, M.G., Antó, J.M., Antonio, C.A.T., Anwari, P.,  
1177 Appiah, L.T., Appiah, S.C.Y., Arabloo, J., Aremu, O., Ärnlov, J., Artaman, A., Aryal,  
1178 K.K., Asayesh, H., Ataro, Z., Ausloos, M., Avokpaho, E.F.G.A., Awasthi, A., Ayala  
1179 Quintanilla, B.P., Ayer, R., Ayuk, T.B., Azzopardi, P.S., Babazadeh, A., Badali, H.,  
1180 Badawi, A., Balakrishnan, K., Bali, A.G., Ball, K., Ballew, S.H., Banach, M., Banoub,  
1181 J.A.M., Barac, A., Barker-Collo, S.L., Bärnighausen, T.W., Barrero, L.H., Basu, S.,  
1182 Baune, B.T., Bazargan-Hejazi, S., Bedi, N., Beghi, E., Behzadifar, Masoud, Behzadifar,  
1183 Meysam, Béjot, Y., Bekele, B.B., Bekru, E.T., Belay, E., Belay, Y.A., Bell, M.L., Bello,  
1184 A.K., Bennett, D.A., Bensenor, I.M., Bergeron, G., Berhane, A., Bernabe, E., Bernstein,  
1185 R.S., Beuran, M., Beyranvand, T., Bhala, N., Bhalla, A., Bhattarai, S., Bhutta, Z.A.,  
1186 Biadgo, B., Bijani, A., Bikbov, B., Bilano, V., Bililign, N., Bin-Sayeed, M.S., Bisanzio,  
1187 D., Biswas, T., Björge, T., Blacker, B.F., Bleyer, A., Borschmann, R., Bou-Orm, I.R.,  
1188 Boufous, S., Bourne, R., Brady, O.J., Brauer, M., Brazinova, A., Breitborde, N.J.K.,  
1189 Brenner, H., Briko, A.N., Britton, G., Brugha, T., Buchbinder, R., Burnett, R.T., Busse,  
1190 R., Butt, Z.A., Cahill, L.E., Cahuana-Hurtado, L., Campos-Nonato, I.R., Cárdenas, R.,  
1191 Carreras, G., Carrero, J.J., Carvalho, F., Castañeda-Orjuela, C.A., Castillo-Rivas, J.,  
1192 Castro, F., Catalá-López, F., Causey, K., Cerey, K.M., Cerin, E., Chaiah, Y., Chang, H.-  
1193 Y., Chang, J.-C., Chang, K.-L., Charlson, F.J., Chattopadhyay, A., Chattu, V.K., Chee,  
1194 M.L., Cheng, C.-Y., Chew, A., Chiang, P.P.-C., Chimed-Oehir, O., Chin, K.L., Chitbeer,  
1195 A., Choi, J.-Y.J., Chowdhury, R., Christensen, H., Christopher, D.J., Chung, S.-C.,  
1196 Cicuttini, F.M., Cirillo, M., Cohen, A.J., Collado-Mateo, D., Cooper, C., Cooper, O.R.,  
1197 Coresh, J., Cornaby, L., Cortesi, P.A., Cortinovis, M., Costa, M., Cousin, E., Criqui, M.H.,  
1198 Cromwell, E.A., Cundiff, D.K., Daba, A.K., Dachew, B.A., Dadi, A.F., Damasceno,  
1199 A.A.M., Dandona, L., Dandona, R., Darby, S.C., Dargan, P.I., Daryani, A., Das-Gupta,  
1200 Rajat, Das-Neves, J., Dasa, T.T., Dash, A.P., Davitoiu, D.V., Davletov, K., De-la-Cruz-  
1201 Góngora, V., De-La-Hoz, F.P., De-Leo, D., De-Neve, J.-W., Degenhardt, L., Deiparine, S.,  
1202 Dellavalle, R.P., Demoz, G.T., Denova-Gutiérrez, E., Deribe, K., Derveniz, N.,  
1203 Deshpande, A., Des-Jarlais, D.C., Dessie, G.A., Deveber, G.A., Dey, S., Dharmaratne,  
1204 S.D., Dhimal, M., Dinberu, M.T., Ding, E.L., Diro, H.D., Djalalinia, S., Do, H.P., Dokova,  
1205 K., Doku, D.T., Doyle, K.E., Driscoll, T.R., Dubey, M., Dubljanin, E., Duken, E.E.,  
1206 Duncan, B.B., Duraes, A.R., Ebert, N., Ebrahimi, H., Ebrahimpour, S., Edvardsson, D.,  
1207 Effiong, A., Eggen, A.E., El-Beheraoui, C., El-Khatib, Z., Elyazar, I.R., Enayati, A.,  
1208 Endries, A.Y., Er, B., Erskine, H.E., Eskandarich, S., Esteghamati, A., Estep, K., Fakhim,  
1209 H., Faramarzi, M., Fareed, M., Farid, T.A., Farinha, C.S.E. Sá, Farioli, A., Faro, A., Farvid,  
1210 M.S., Farzaei, M.H., Fatima, B., Fay, K.A., Fazaeli, A.A., Feigin, V.L., Feigl, A.B.,  
1211 Fereshtehnejad, S. M., Fernandes, E., Fernandes, J.C., Ferrara, G., Ferrari, A.J., Ferreira,  
1212 M.L., Filip, I., Finger, J.D., Fischer, F., Foigt, N.A., Foreman, K.J., Fukumoto, T.,  
1213 Fullman, N., Fürst, T., Furtado, J.M., Futran, N.D., Gall, S., Gallus, S., Gamkrelidze, A.,

1214 Ganji, M., Garcia Basteiro, A.L., Gardner, W.M., Gebre, A.K., Gebremedhin, A.T.,  
1215 Gebremichael, T.G., Gelano, T.F., Geleijnse, J.M., Geramo, Y.C.D., Gething, P.W.,  
1216 Gezae, K.E., Ghadimi, R., Ghadiri, K., Ghasemi Falavarjani, K., Ghasemi Kasman, M.,  
1217 Ghimire, M., Ghosh, R., Ghoshal, A.G., Giampaoli, S., Gill, P.S., Gill, T.K., Gillum, R.F.,  
1218 Ginawi, I.A., Giussani, G., Gnedovskaya, E. V., Godwin, W.W., Goli, S., Gómez Dantés,  
1219 H., Gona, P.N., Gopalani, S.V., Goulart, A.C., Grada, A., Grams, M.E., Grosso, G.,  
1220 Gugnani, H.C., Guo, Y., Gupta, Rahul, Gupta, Rajeev, Gupta, T., Gutiérrez, R.A.,  
1221 Gutiérrez Torres, D.S., Haagsma, J.A., Habtewold, T.D., Hachinski, V., Hafezi Nejad, N.,  
1222 Hagos, T.B., Hailegiyorgis, T.T., Hailu, G.B., Haj-Mirzaian, Arvin, Haj-Mirzaian, Arya,  
1223 Hamadeh, R.R., Hamidi, S., Handal, A.J., Hankey, G.J., Hao, Y., Harb, H.L.,  
1224 Harikrishnan, S., Haro, J.M., Hassankhani, H., Hassen, H.Y., Havmoeller, R., Hawley,  
1225 C.N., Hay, S.I., Hedayatzadeh Omran, A., Heibati, B., Heidari, B., Heidari, M., Hendrie,  
1226 D., Henok, A., Heredia Pi, I., Herteliu, C., Heydarpour, F., Heydarpour, S., Hibstu, D.T.,  
1227 Higazi, T.B., Hilawe, E.H., Hoek, H.W., Hoffman, H.J., Hole, M.K., Homaie Rad, E.,  
1228 Hoogar, P., Hosgood, H.D., Hosseini, S.M., Hosseinzadeh, M., Hostiue, M., Hostiue, S.,  
1229 Hoy, D.G., Hsairi, M., Hsiao, T., Hu, G., Hu, H., Huang, J.J., Hussien, M.A., Huynh, C.K.,  
1230 Iburg, K.M., Ikeda, N., Ilesanmi, O.S., Iqbal, U., Irvani, S.S.N., Irvine, C.M.S., Islam,  
1231 S.M.S., Islami, F., Jackson, M.D., Jacobsen, K.H., Jahangiry, L., Jahanmehr, N., Jain,  
1232 S.K., Jakovljevic, M., James, S.L., Jassal, S.K., Jayatilleke, A.U., Jeemon, P., Jha, R.P.,  
1233 Jha, V., Ji, J.S., Jonas, J.B., Jonnagaddala, J., Jorjoran Shushtari, Z., Joshi, A., Jozwiak,  
1234 J.J., Jürisson, M., Kabir, Z., Kahsay, A., Kalani, R., Kanehan, T., Kant, S., Kar, C., Karami,  
1235 M., Karami Matin, B., Karch, A., Karema, C., Karimi, N., Karimi, S.M., Kasaeian, A.,  
1236 Kassa, D.H., Kassa, G.M., Kassa, T.D., Kassebaum, N.J., Katikireddi, S.V., Kaul, A.,  
1237 Kawakami, N., Kazemi, Z., Karyani, A.K., Kefale, A.T., Keiyoro, P.N., Kemp, G.R.,  
1238 Kengne, A.P., Keren, A., Kesavachandran, C.N., Khader, Y.S., Khafaei, B., Khafaie,  
1239 M.A., Khajavi, A., Khalid, N., Khalil, I.A., Khan, G., Khan, M.S., Khan, M.A., Khang,  
1240 Y. H., Khater, M.M., Khazaie, M., Khazaie, H., Khoja, A.T., Khosravi, A., Khosravi,  
1241 M.H., Kiadaliri, A.A., Kiirithio, D.N., Kim, C. I., Kim, D., Kim, Y. E., Kim, Y.J.,  
1242 Kimokoti, R.W., Kinfu, Y., Kisa, A., Kissimova Skarbek, K., Kivimäki, M., Knibbs, L.D.,  
1243 Knudsen, A.K.S., Kochhar, S., Kokubo, Y., Kolola, T., Kopee, J.A., Kosen, S., Koul, P.A.,  
1244 Koyanagi, A., Kravchenko, M.A., Krishan, K., Krohn, K.J., Kromhout, H., Kuate Defo,  
1245 B., Kueuk Bicer, B., Kumar, G.A., Kumar, M., Kuzin, I., Kyu, H.H., Lachat, C., Lad, D.P.,  
1246 Lad, S.D., Lafranconi, A., Lalloo, R., Lallukka, T., Lami, F.H., Lang, J.J., Lansingh, V.C.,  
1247 Larson, S.L., Latifi, A., Lazarus, J. V., Lee, P.H., Leigh, J., Leili, M., Leshargie, C.T.,  
1248 Leung, J., Levi, M., Lewycka, S., Li, S., Li, Y., Liang, J., Liang, X., Liao, Y., Liben, M.L.,  
1249 Lim, L. L., Linn, S., Liu, S., Lodha, R., Logroscino, G., Lopez, A.D., Lorkowski, S.,  
1250 Lotufo, P.A., Lozano, R., Lucas, T.C.D., Lunevicius, R., Ma, S., Macarayan, E.R.K.,  
1251 Machado, Í.E., Madotto, F., Mai, H.T., Majdan, M., Majdzadeh, R., Majeed, A.,  
1252 Malekzadeh, R., Malta, D.C., Mamun, A.A., Manda, A. L., Manguerra, H., Mansournia,  
1253 M.A., Mantovani, L.G., Maravilla, J.C., Marenes, W., Marks, A., Martin, R. V., Martins,  
1254 S.C.O., Martins Melo, F.R., März, W., Marzan, M.B., Massenburg, B.B., Mathur, M.R.,  
1255 Mathur, P., Matsushita, K., Maulik, P.K., Mazidi, M., McAlinden, C., McGrath, J.J.,  
1256 McKee, M., Mehrotra, R., Mehta, K.M., Mehta, V., Meier, T., Mekonnen, F.A., Melaku,  
1257 Y.A., Melese, A., Melku, M., Memiah, P.T.N., Memish, Z.A., Mendoza, W., Mengistu,  
1258 D.T., Mensah, G.A., Mensink, G.B.M., Mereta, S.T., Meretoja, A., Meretoja, T.J.,  
1259 Mestrovic, T., Mezgebe, H.B., Miazgowski, B., Miazgowski, T., Millear, A.I., Miller,  
1260 T.R., Miller Petrie, M.K., Mini, G.K., Mirarefin, M., Mirica, A., Mirrakhimov, E.M.,  
1261 Misganaw, A.T., Mitiku, H., Moazen, B., Mohajer, B., Mohammad, K.A., Mohammadi,  
1262 M., Mohammadifard, N., Mohammadnia Afrouzi, M., Mohammed, S., Mohebi, F.,  
1263 Mokdad, A.H., Molokhia, M., Momeniha, F., Monasta, L., Moodley, Y., Moradi, G.,  
1264 Moradi Lakeh, M., Moradinazar, M., Moraga, P., Morawska, L., Morgado Da Costa, J.,

1265 Morrison, S.D., Moschos, M.M., Mouodi, S., Mousavi, S.M., Mozaffarian, D., Mruts,  
1266 K.B., Muche, A.A., Muchie, K.F., Mueller, U.O., Muhammed, O.S., Mukhopadhyay, S.,  
1267 Muller, K., Musa, K.I., Mustafa, G., Nabhan, A.F., Naghavi, M., Naheed, A., Nahvijou,  
1268 A., Naik, G., Naik, N., Najafi, F., Nangia, V., Nansseu, J.R., Nascimento, B.R., Neal, B.,  
1269 Neamati, N., Negoi, I., Negoi, R.I., Neupane, S., Newton, C.R.J., Ngunjiri, J.W., Nguyen,  
1270 A.Q., Nguyen, G., Nguyen, Ha Thu, Nguyen, H.L.T., Nguyen, Huong Thanh, Nguyen,  
1271 M., Nguyen, N.B., Nichols, E., Nie, J., Ningrum, D.N.A., Nirayo, Y.L., Nishi, N., Nixon,  
1272 M.R., Nojomi, M., Nomura, S., Norheim, O.F., Noroozi, M., Norrving, B., Noubiap, J.J.,  
1273 Nouri, H.R., Nourollahpour Shiadeh, M., Nowroozi, M.R., Nsoesie, E.O., Nyasulu, P.S.,  
1274 Obermeyer, C.M., Odell, C.M., Ofori Asenso, R., Ogbo, F.A., Oh, I. H., Oladimeji, O.,  
1275 Olagunju, A.T., Olagunju, T.O., Olivares, P.R., Olsen, H.E., Olusanya, B.O., Olusanya,  
1276 J.O., Ong, K.L., Ong, S.K., Oren, E., Orpana, H.M., Ortiz, A., Ota, E., Otstavnov, S.S.,  
1277 Øverland, S., Owolabi, M.O., P A, M., Pacella, R., Pakhare, A.P., Pakpour, A.H., Pana,  
1278 A., Panda Jonas, S., Park, E. K., Parry, C.D.H., Parsian, H., Patel, S., Pati, S., Patil, S.T.,  
1279 Patle, A., Patton, G.C., Paudel, D., Paulson, K.R., Paz Ballesteros, W.C., Pearce, N.,  
1280 Pereira, A., Pereira, D.M., Perico, N., Pesudovs, K., Petzold, M., Pham, H.Q., Phillips,  
1281 M.R., Pillay, J.D., Piradov, M.A., Pirsaeheb, M., Pischon, T., Pishgar, F., Plana Ripoll, O.,  
1282 Plass, D., Polinder, S., Polkinghorne, K.R., Postma, M.J., Poulton, R., Pourshams, A.,  
1283 Poustehi, H., Prabhakaran, D., Prakash, S., Prasad, N., Purcell, C.A., Purwar, M.B.,  
1284 Qorbani, M., Radfar, A., Rafay, A., Rafiei, A., Rahim, F., Rahimi, Z., Rahimi Movaghar,  
1285 A., Rahimi Movaghar, V., Rahman, M., Rahman, M.H. ur, Rahman, M.A., Rai, R.K.,  
1286 Rajati, F., Rajsic, S., Raju, S.B., Ram, U., Ranabhat, C.L., Ranjan, P., Rath, G.K., Rawaf,  
1287 D.L., Rawaf, S., Reddy, K.S., Rehm, C.D., Rehm, J., Reiner, R.C., Reitsma, M.B.,  
1288 Remuzzi, G., Renzaho, A.M.N., Resnikoff, S., Reynales Shigematsu, L.M., Rezaei, S.,  
1289 Ribeiro, A.L.P., Rivera, J.A., Roba, K.T., Rodriguez Ramirez, S., Roever, L., Román, Y.,  
1290 Ronfani, L., Roshandel, G., Rostami, A., Roth, G.A., Rothenbacher, D., Roy, A.,  
1291 Rubagotti, E., Rushton, L., Sabanayagam, C., Sachdev, P.S., Saddik, B., Sadeghi, E.,  
1292 Saeedi Moghaddam, S., Safari, H., Safari, Y., Safari Faramani, R., Safdarian, M., Safi, S.,  
1293 Safiri, S., Sagar, R., Sahebkar, A., Sahraian, M.A., Sajadi, H.S., Salam, N., Salamati, P.,  
1294 Saleem, Z., Salimi, Y., Salimzadeh, H., Salomon, J.A., Salvi, D.D., Salz, I., Samy, A.M.,  
1295 Sanabria, J., Sanchez-Niño, M.D., Sánchez-Pimienta, T.G., Sanders, T., Sang, Y.,  
1296 Santomauro, D.F., Santos, I.S., Santos, J.V., Santric Milicevic, M.M., Sao Jose, B.P.,  
1297 Sardana, M., Sarker, A.R., Sarmiento Suárez, R., Sarrafzadegan, N., Sartorius, B., Sarvi,  
1298 S., Sathian, B., Satpathy, M., Sawant, A.R., Sawhney, M., Saylan, M., Sayyah, M.,  
1299 Schaeffner, E., Schmidt, M.I., Schneider, I.J.C., Schöttker, B., Schutte, A.E., Schwebel,  
1300 D.C., Schwendicke, F., Scott, J.G., Seedat, S., Sekerija, M., Sepanlou, S.G., Serre, M.L.,  
1301 Serván-Mori, E., Seyedmousavi, S., Shabaninejad, H., Shaddick, G., Shafieesabet, A.,  
1302 Shahbazi, M., Shaheen, A.A., Shaikh, M.A., Shamah Levy, T., Shams Beyranvand, M.,  
1303 Shamsi, M., Sharafi, H., Sharafi, K., Sharif, M., Sharif Alhoseini, M., Sharifi, H., Sharma,  
1304 J., Sharma, M., Sharma, R., She, J., Sheikh, A., Shi, P., Shibuya, K., Shiferaw, M.S.,  
1305 Shigematsu, M., Shin, M. J., Shiri, R., Shirkoobi, R., Shiue, I., Shokraneh, F., Shoman,  
1306 H., Shrimme, M.G., Shupler, M.S., Si, S., Siabani, S., Sibai, A.M., Siddiqi, T.J., Sigfusdottir,  
1307 I.D., Sigurvinsdottir, R., Silva, D.A.S., Silva, J.P., Silveira, D.G.A., Singh, J.A., Singh,  
1308 N.P., Singh, V., Sinha, D.N., Skiadaresi, E., Skirbekk, V., Smith, D.L., Smith, M., Sobaih,  
1309 B.H., Sobhani, S., Somayaji, R., Soofi, M., Sorensen, R.J.D., Soriano, J.B., Soyiri, I.N.,  
1310 Spinelli, A., Sposato, L.A., Sreeramareddy, C.T., Srinivasan, V., Starodubov, V.I.,  
1311 Steckling, N., Stein, D.J., Stein, M.B., Stevanovic, G., Stockfelt, L., Stokes, M.A., Sturua,  
1312 L., Subart, M.L., Sudaryanto, A., Sufiyan, M.B., Sulo, G., Sunguya, B.F., Sur, P.J., Sykes,  
1313 B.L., Szoeki, C.E.I., Tabarés-Seisdedos, R., Tabuchi, T., Tadakamadla, S.K., Takahashi,  
1314 K., Tandon, N., Tassew, S.G., Tavakkoli, M., Taveira, N., Tehrani Banihashemi, A.,  
1315 Tekalign, T.G., Tekelemedhin, S.W., Tekle, M.G., Temesgen, H., Temsah, M. H.,

1316 ~~Temsah, O., Terkawi, A.S., Tessema, B., Teweldemedhin, M., Thankappan, K.R., Theis,~~  
1317 ~~A., Thirunavukkarasu, S., Thomas, H.J., Thomas, M.L., Thomas, N., Thurston, G.D.,~~  
1318 ~~Tilahun, B., Tillmann, T., To, Q.G., Tobollik, M., Tonelli, M., Topor Madry, R., Torre,~~  
1319 ~~A.E., Tortajada-Girbés, M., Touvier, M., Tovani-Palone, M.R., Towbin, J.A., Tran, B.X.,~~  
1320 ~~Tran, K.B., Truelsen, T.C., Truong, N.T., Tsadik, A.G., Tudor Car, L., Tuzcu, E.M.,~~  
1321 ~~Tymeson, H.D., Tyrovolas, S., Ukwaja, K.N., Ullah, I., Updike, R.L., Usman, M.S.,~~  
1322 ~~Uthman, O.A., Vaduganathan, M., Vaezi, A., Valdez, P.R., Van Donkelaar, A.,~~  
1323 ~~Varavikova, E., Varughese, S., Vasankari, T.J., Venkateswaran, V., Venketasubramanian,~~  
1324 ~~N., Villafaina, S., Violante, F.S., Vladimirov, S.K., Vlassov, V., Vollset, S.E., Vos, T.,~~  
1325 ~~Vosoughi, K., Vu, G.T., Vujeic, I.S., Wagnew, F.S., Waheed, Y., Waller, S.G., Walson,~~  
1326 ~~J.L., Wang, Yafeng, Wang, Yanping, Wang, Y. P., Weiderpass, E., Weintraub, R.G.,~~  
1327 ~~Weldegebreal, F., Werdecker, A., Werkneh, A.A., West, J.J., Westerman, R., Whiteford,~~  
1328 ~~H.A., Widecka, J., Wijeratne, T., Winkler, A.S., Wiyeh, A.B., Wiysonge, C.S., Wolfe,~~  
1329 ~~C.D.A., Wong, T.Y., Wu, S., Xavier, D., Xu, G., Yadgir, S., Yadollahpour, A.,~~  
1330 ~~Yahyazadeh Jabbari, S.H., Yamada, T., Yan, L.L., Yano, Y., Yaseri, M., Yasin, Y.J.,~~  
1331 ~~Yeshaneh, A., Yimer, E.M., Yip, P., Yisma, E., Yonemoto, N., Yoon, S.-J., Yotebieng,~~  
1332 ~~M., Younis, M.Z., Yousefifard, M., Yu, C., Zaidi, Z., Zaman, S. Bin, Zamani, M., Zavala-~~  
1333 ~~Arciniega, L., Zhang, A.L., Zhang, H., Zhang, K., Zhou, M., Zimsen, S.R.M., Zodpey, S.,~~  
1334 ~~Murray, C.J.L., 2018. Global, regional, and national comparative risk assessment of 84~~  
1335 ~~behavioural, environmental and occupational, and metabolic risks or clusters of risks for~~  
1336 ~~195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of~~  
1337 ~~Disease Stu. The Lancet 392, 1923–1994. [https://doi.org/10.1016/S0140-6736\(18\)32225-](https://doi.org/10.1016/S0140-6736(18)32225-6)~~  
1338 ~~6~~

1339 Standard Business, 2018n.d. Upswing in DTC,Cluster buses daily ridership, 41.90 passengers  
1340 carried per day: Sisodia. [WWW Document]. 2018. URL [https://www.business-](https://www.business-standard.com/article/pti-stories/upswing-in-dtc-cluster-buses-daily-ridership-41-90-passengers-carried-per-day-sisodia-118032101391_1.html)  
1341 [standard.com/article/pti-stories/upswing-in-dtc-cluster-buses-daily-ridership-41-90-](https://www.business-standard.com/article/pti-stories/upswing-in-dtc-cluster-buses-daily-ridership-41-90-passengers-carried-per-day-sisodia-118032101391_1.html)  
1342 [passengers-carried-per-day-sisodia-118032101391\\_1.html](https://www.business-standard.com/article/pti-stories/upswing-in-dtc-cluster-buses-daily-ridership-41-90-passengers-carried-per-day-sisodia-118032101391_1.html)

1343 Swamy, S., Pai, M., Kulshrestha, S., 2015. Impact Of Bus Rapid Transit On Urban Air  
1344 Pollution: Commuter’S Exposure To PM2.5 In Ahmedabad, Ahmedabad.

1345 Tan, S.H., Roth, M., Velasco, E., 2017. Particle exposure and inhaled dose during commuting  
1346 in Singapore. Atmospheric Environment 170, 245–258.  
1347 <https://doi.org/10.1016/j.atmosenv.2017.09.056>

1348 Transport Department Government of NCT of Delhi., 2018. Total Vehical Registered uoto  
1349 31.03.2018. [WWW Document]. Transport Department, ARTMENT Government of NCT  
1350 of Delhi. URL <https://transport.delhi.gov.in/content/statistics-0>

1351 TSI., 2018. SIDEPAK PERSONAL AEROSOL MONITOR AM520. [WWW Document].  
1352 URL [https://tsi.com/products/aerosol-and-dust-monitors/dust-monitors/sidepak-personal-](https://tsi.com/products/aerosol-and-dust-monitors/dust-monitors/sidepak-personal-aerosol-monitor-am520/)  
1353 [aerosol-monitor-am520/](https://tsi.com/products/aerosol-and-dust-monitors/dust-monitors/sidepak-personal-aerosol-monitor-am520/)

1354 Van Ryswyk, K., Anastasopoulos, A.T., Evans, G., Sun, L., Sabaliauskas, K., Kulka, R.,  
1355 Wallace, L., Weichenthal, S., 2017. Metro Commuter Exposures to Particulate Air  
1356 Pollution and PM 2.5 -Associated Elements in Three Canadian Cities: The Urban  
1357 Transportation Exposure Study. Environmental Science & Technology 51, 5713–5720.  
1358 <https://doi.org/10.1021/acs.est.6b05775>

1359 Vilcassim, M.J.R., Thurston, G.D., Peltier, R.E., Gordon, T., 2014. Black Carbon and  
1360 Particulate Matter (PM 2.5 ) Concentrations in New York City’s Subway Stations.

1361 Environmental Science & Technology 48, 14738–14745.  
1362 <https://doi.org/10.1021/es504295h>

1363 World Health Organization, 2018. WHO Global Ambient Air Quality Database (update 2018)  
1364 [WWW Document]. URL <https://www.who.int/airpollution/data/cities/en/>

1365 Yao, L., Lu, N., Yue, X., Du, J., Yang, C., 2015. Comparison of Hourly PM<sub>2.5</sub> Observations  
1366 Between Urban and Suburban Areas in Beijing, China. International Journal of  
1367 Environmental Research and Public Health 12, 12264–12276.  
1368 <https://doi.org/10.3390/ijerph121012264>

1369 Zhang, K., Batterman, S., Dion, F., 2011. Vehicle emissions in congestion: Comparison of work  
1370 zone, rush hour and free-flow conditions. Atmospheric Environment 45, 1929–1939.  
1371 <https://doi.org/10.1016/j.atmosenv.2011.01.030>

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1395 **Number of Tables**

1396

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1401 Table 3 Estimated respiratory deposition doses (RDDs) of PM<sub>2.5</sub> in multiple transport  
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- Figure 1. Routes took by transport mode during the study (OpenStreetMap Contributors, 2017). Image produced using ArcMap™ Esri©.
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**Number of Tables**

- ~~Table 1—Previous PM<sub>2.5</sub>-exposure studies for transport micro-environments~~
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1442 ~~Figure 1.—(a) Daily and monthly average PM<sub>2.5</sub> concentrations between January 2016 and~~  
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1451 ~~Figure 4.—PM<sub>2.5</sub> concentration levels in different transport modes (a) Rickshaw, (b) Walk (c)~~  
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1453 ~~Figure 5.—Rickshaw map exposure route monitored during study (a) main route (b) alternative~~  
1454 ~~route~~

1455 ~~Figure 6.—AC car map exposure route monitored during study (a) main route (b) alternative~~  
1456 ~~route~~

1457 ~~Figure 7.— Non AC car map exposure route monitored during the study~~

1458 ~~Figure 8.— Bus map exposure route monitored during the study~~

1459

## **Highlight**

- On-road PM<sub>2.5</sub> exposures in six transport microenvironments are 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<sub>2.5</sub> mass inhaled/km is 28.2 and 5.3 times for walking and rickshaw compared to that for a metro.

# 1 **Analysis of various transport modes to evaluate personal exposure to PM<sub>2.5</sub>** 2 **pollution in Delhi**

3

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5 Shiva Nagendra <sup>3</sup>; Jo Barnes <sup>4</sup>; Laura De Vito <sup>4</sup>; Enda Hayes <sup>4</sup>; James Longhurst <sup>4</sup>; Rakesh  
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22

## 23 **Abstract**

24 Access to detailed comparisons of the air quality variations encountered when commuting  
25 through a city offers the urban traveller more informed choice on how to minimise personal  
26 exposure to inhalable pollutants. In this study we report on an experiment designed to compare  
27 atmospheric contaminants, in this case, PM<sub>2.5</sub> inhaled during rickshaw, bus, metro, non-air-  
28 conditioned car, air-conditioned (AC) car and walking journeys through the city of Delhi, India.  
29 The data collection was carried out using a portable TSI SidePak Aerosol Monitor AM520,  
30 during February 2018. The results demonstrate that rickshaws (266±159 µg/m<sup>3</sup>) and walking  
31 (259±102 µg/m<sup>3</sup>) modes were exposed to significantly higher mean PM<sub>2.5</sub> levels, whereas AC  
32 cars (89±30 µg/m<sup>3</sup>) and the metro (72±11 µg/m<sup>3</sup>) had the lowest overall exposure rates. Buses

33 (113±14 µg/m<sup>3</sup>) and non-AC cars (149±13 µg/m<sup>3</sup>) had average levels of exposure, but open  
34 windows and local factors caused surges in PM<sub>2.5</sub> for both transport modes. Closed air-  
35 conditioned transport modes were shown to be the best modes for avoiding high concentrations  
36 of PM<sub>2.5</sub>, however other factors (e.g. time of the day, window open or closed in the vehicles)  
37 affected exposure levels significantly. Overall, the highest total respiratory deposition doses  
38 (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  
39 walking, rickshaw and non-AC car transported mode of journey, respectively. Unless strong  
40 pollution control measures are taken, the high exposure to PM<sub>2.5</sub> levels will continue causing  
41 serious short-term and long-term health concerns for the Delhi residents. Implementing  
42 integrated and intelligent transport systems and educating commuters on ways to reduce  
43 exposure levels and impacts on commuter's health are required.

44 Keywords: Personal exposure; travel modes; air pollution; PM<sub>2.5</sub>; Delhi

45

## 46 1. Introduction

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

65 Epidemiological studies have linked exposure to PM<sub>2.5</sub> with various causes of premature  
66 mortality and morbidity (Bowe et al., 2019; Fu et al., 2019; Antonsen et al., 2020; Chen et al.,  
67 2017). Health risk studies assume equivalent toxicity for all chemical species in PM<sub>2.5</sub>, but there  
68 is considerable evidence that the chemical composition, and sources of PM<sub>2.5</sub> influence its  
69 health effects much more, e.g. traffic-related PM<sub>2.5</sub>, as vehicular exhausted PM<sub>2.5</sub> contain a high  
70 percentage of black carbon which has much more effects on human health (Matz et al., 2019;  
71 Costa et al., 2017; Jerrett et al., 2009; Monrad et al., 2017; Bowatte et al., 2017). In on-road  
72 microenvironments, due to the proximity of tailpipe emissions, exposure to traffic-related PM<sub>2.5</sub>  
73 concentration is higher than those in off-road locations (Chen et al., 2020). The travel-related  
74 exposure to on-road PM<sub>2.5</sub> pollution has been quantified by several studies for different  
75 microenvironments, classified as travel modes, ventilation status type of travel routes, and  
76 meteorological conditions. Table 1 summarizes some of the key past studies in various settings  
77 from across the world, analysing on-road exposure to PM<sub>2.5</sub> pollution. The range of  
78 concentrations in the table refers to the reported average values among all the  
79 microenvironments. There are only a few studies from India looking at exposure in three-  
80 wheeled auto-rickshaws (Apte et al., 2011; Goel et al., 2015). On-road high PM<sub>2.5</sub> concentration  
81 in vehicles are also observed in Indonesia (87-119 µg/m<sup>3</sup>), Turkey (30.6-120.4 µg/m<sup>3</sup>), and  
82 China (54.5-71.6 µg/m<sup>3</sup>), and the lowest values are from cleaner high-income settings in the  
83 USA (12-35 µg/m<sup>3</sup>), Europe (7.3-13.9 µg/m<sup>3</sup>) and Canada (8.6-71.9 µg/m<sup>3</sup>) (Table 1).  
84 The cities in India differ significantly from the cities in developed countries represented in  
85 Table 1. For instance, ambient PM<sub>2.5</sub> concentrations in Indian cities are 4–8 times higher than  
86 most high-income settings (Stanaway et al., 2018), and the traffic condition in metropolitan  
87 Indian cities is worsening daily due to increasing levels of vehicle ownership and a higher  
88 number of old vehicles (Transport Department Government of NCT of Delhi., 2018). The  
89 rickshaw and bus are one of the most common forms of public transport in Delhi, providing  
90 low-cost mobility and connecting travellers to mass transit. The rickshaw and bus sector  
91 provides a livelihood for some of India's poorest citizens and is easily available means of public  
92 transport in most of the cities (Choudhary and Gokhale, 2016). Relatively few studies have  
93 investigated on-road exposures to PM<sub>2.5</sub> pollution, particularly whilst travelling on these modes,  
94 in developing-world megacities such as Delhi, where older vehicles are more common and high  
95 levels of congestion and travel times lead to higher personal exposure to PM<sub>2.5</sub> concentrations.  
96 The objectives of this study are (a) to assess the on-road exposure to PM<sub>2.5</sub> in various travel  
97 modes, measured using an optical PM monitor, and (b) to estimate the total respiratory  
98 deposition doses (RDDs) of PM<sub>2.5</sub> in microenvironments in Delhi (more details in supplement

99 material). The modes studied include auto-rickshaw (three-wheelers), bus, metro, non-air-  
100 conditioned (non-AC) car, air-conditioned (AC) car and walking.

101

102

[Insert Table 1]

103

## 104 2. Methodology

### 105 2.1 Study area and route selection

106 The study was carried out in Delhi, India, which has an area of 1,484 km<sup>2</sup> and around 16.3  
107 million inhabitants as per the latest census of 2011 (Government of India, 2020), making it one  
108 of the largest cities in Asia. In March 2018, Delhi had 10.8 million registered vehicles, including  
109 6.96 million motor-cycle/scooter and 3.1 million motor-car (private vehicles) (Transport  
110 Department Government of NCT of Delhi., 2018).

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

121

122

[Insert Figure 1]

123

### 124 2.2 Measurements and sampling equipment

125 This work has focused on the assessment of personal exposure to PM<sub>2.5</sub>. We measured PM<sub>2.5</sub>  
126 concentrations using a portable SidePak<sup>TM</sup> Aerosol Monitor AM520 (TSI Inc., USA), which  
127 works on the principle of light scattering laser photometry for real-time concentration  
128 measurements of PM in the air. Different inlet options are available for the optics chamber to  
129 measure specific PM sizes, from PM<sub>1</sub> to PM<sub>10</sub>. For this study, the PM<sub>2.5</sub> inlet attachment was  
130 used. The instrument measures between 0.001–100 mg/m<sup>3</sup>, so are well within the range of

131 measurements for PM<sub>2.5</sub> in the micro-environments studied. The Photometric Calibration Factor  
132 (PCF) in the device is set to 1.0 by default, however, the preliminary tests exhibited above  
133 normal PM values. Thus, as per the TSI guidelines for urban environments, the PCF was set to  
134 0.38 for urban areas (TSI., 2018). Usually, this equipment can have a flow rate up to 1.8  
135 litres/minute, although for this experiment it was set to its default value of 1.7 litres/minute.  
136 The device was always calibrated to zero and was checked before every usage with the help of  
137 a supplied zero calibration attachment. A long interval of one second was considered to capture  
138 the fast-varying PM<sub>2.5</sub> levels encountered by a moving subject.

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

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

153 Six commuting modes of transport were selected in our study in between 2<sup>nd</sup> to 8<sup>th</sup> February  
154 2018, auto-rickshaw (three-wheelers) (three trips), bus (two trips), metro (one trip), non-air-  
155 conditioned (non-AC) car (one trip), air-conditioned (AC) car (two trips) and as a pedestrian  
156 (walking) (two trips). Visual representation of PM<sub>2.5</sub> levels on the different transport route was  
157 displayed on the maps by using various software such as RStudio®, version 1.1.456 (R Core  
158 Team, 2017; Rstudio Team, 2020) and Stamen© map (Rodenbeck, 2018).

### 159 3. Results

#### 160 3.1. Ambient PM<sub>2.5</sub> concentration during the study period

161 The personal exposure whilst travelling in transport modes in Delhi depends on factors such as  
162 season of the year and time of the day (for example in winter the PM<sub>2.5</sub> concentration is usually

163 higher than other seasons) and whether the journey was conducted in the morning, afternoon or  
164 at night (traffic conditions can dictate the temporal variations) (Lin et al., 2020; Chaney et al.,  
165 2017). The ambient PM<sub>2.5</sub> concentrations are available from monitoring stations along the route  
166 and these have been analysed to understand how the background air quality changes over time.  
167 More specifically the continuous air-quality monitoring stations of Central Delhi, RK Puram  
168 (RKP) and Mandir Marg (MM), operated by the Delhi Pollution Control Committee (DPCC),  
169 were used as they were situated closer to the selected route (IIT Delhi to the Connaught Place).  
170 Daily-average PM<sub>2.5</sub> trends as well as a month- and hour specific averages for the three years  
171 were calculated. PM<sub>2.5</sub> has a significant seasonal variation in Delhi, with highest concentrations  
172 during winter months from November to February (123 to 235 µg/m<sup>3</sup>) which gradually decrease  
173 afterwards due to the winds and precipitation during the monsoon months from July through  
174 September (33.7 to 46.0 µg/m<sup>3</sup>). Some of the spikes of PM<sub>2.5</sub> were also observed in June and  
175 July probably due to low winds which would have helped the pollution to accumulate in the  
176 region. The diurnal profile of PM<sub>2.5</sub> showed the highest concentrations during late-evening  
177 hours (11 pm through midnight) and early morning and rush-hour period (8 am through 10 am).  
178 The levels were at their lowest during the afternoon hours (Figure 2). In winter the diurnal  
179 profile of PM<sub>2.5</sub> shows <200 µg/m<sup>3</sup> from 11.00 am to 7.00 pm, after which time the  
180 concentration rises to > 200 µg/m<sup>3</sup>. As the selected period of the current analysis was in early  
181 February, it was understood that the PM<sub>2.5</sub> levels were already at the higher side. During the  
182 study period (2<sup>nd</sup> to 8<sup>th</sup> February 2018), the average ambient PM<sub>2.5</sub> concentration was 146±53  
183 µg/m<sup>3</sup>. Although, in the Panchkula (PK) monitoring site in Delhi, which is considered as an  
184 urban background site observed a very low ambient PM<sub>2.5</sub> concentration during the study  
185 (average: 61±20 µg/m<sup>3</sup>; median: 60 µg/m<sup>3</sup>).

186

187

**[Insert Figure 2]**

188

189 3.2. PM<sub>2.5</sub> concentration in different modes of transport

190 Tables 2 summarise the PM<sub>2.5</sub> concentration during commuting by the six travel modes  
191 indicated earlier. In this study, the time-weighted PM<sub>2.5</sub> concentration and the average of PM<sub>2.5</sub>  
192 in a microenvironment are the same, as the Aerosol Monitor measure concentration in every  
193 one second. It was noted that rickshaws were the most exposed transport with the highest mean  
194 concentration of PM<sub>2.5</sub> of 266 µg/m<sup>3</sup>, followed by walking with an average of 258 µg/m<sup>3</sup>. The  
195 lowest exposed transport was in the metro and AC car with a mean of 72.0 µg/m<sup>3</sup> and 89.0

196  $\mu\text{g}/\text{m}^3$  respectively. The non-AC car and bus trips had  $\text{PM}_{2.5}$  means of  $149 \mu\text{g}/\text{m}^3$  and  $113$  of  
197  $\text{PM}_{2.5}$  respectively. Figure 3 shows the spatial variations in the average  $\text{PM}_{2.5}$  exposures for the  
198 six modes of travels.

199

200

**[Insert Table 2]**

201

202

**[Insert Figure 3]**

203

### 204 3.2.1 $\text{PM}_{2.5}$ concentration in Rickshaws

205 The histogram in Figure S1a shows that the highest density of  $\text{PM}_{2.5}$  level was observed around  
206  $150\mu\text{g}/\text{m}^3$ , the lower densities were observed in between  $\sim 300\mu\text{g}/\text{m}^3$  and  $550\mu\text{g}/\text{m}^3$ . The three-  
207 day one-way trip average exposure level of  $\text{PM}_{2.5}$  was  $266\pm 159\mu\text{g}/\text{m}^3$  (median:  $203\mu\text{g}/\text{m}^3$ ). The  
208 time-series plot of the exposure in the rickshaw for different days (Figure 4a) varied from each  
209 other probably due to several factors such as location, time of day and the nearby congestion.  
210 The figure shows that the levels on each day were very dissimilar with the fluctuating spikes of  
211 the pollution at different times. Also, it was noted that the pollution for 5<sup>th</sup> February 2018 was  
212 well over  $1000\mu\text{g}/\text{m}^3$  in the parts of routes which were known to be regularly congested. The  
213 higher PM emissions during periods of congestion are due to an increase in stop-start and idle  
214 times of high vehicle densities. A past study has established that vehicles fuel consumption and  
215 associated pollutants emitted during congestion are higher than the amount during free-flow  
216 traffic condition (Zhang et al., 2011).

217

218

**[Insert Figure 4]**

219

### 220 3.2.2 $\text{PM}_{2.5}$ concentration during Walking

221 Whilst walking, exposure to concentrations of  $\text{PM}_{2.5}$  is very high, with most exposure levels  
222 being between  $165\mu\text{g}/\text{m}^3$  and  $304\mu\text{g}/\text{m}^3$  (mean:  $259\pm 103\mu\text{g}/\text{m}^3$ ; median:  $264\mu\text{g}/\text{m}^3$ ) (Figure  
223 S1b). This made it the second-highest exposed mode of transport during the study. A maximum  
224 value of  $1280\mu\text{g}/\text{m}^3$  was recorded during the survey, an exceptionally high reading when  
225 compared to the other results and compared to national and global standards. The exposure  
226 levels captured during walking were not examined on the same routes as other modes of

227 transport, however, these higher levels were predominantly recorded around the periphery of  
228 IIT Delhi and Connaught Place. The histogram plot shows a multimodal distribution (Figure  
229 4b), with peak frequencies located at  $150\mu\text{g}/\text{m}^3$ ,  $290\mu\text{g}/\text{m}^3$  and  $375\mu\text{g}/\text{m}^3$  with outliers  
230 concentrated around  $550\mu\text{g}/\text{m}^3$ , culminating in very high levels of exposure to  $\text{PM}_{2.5}$ . The time  
231 series for the morning were compared with the afternoon exposure. Time of travel is a major  
232 factor that affected all modes of transport but was particularly noticeable when walking. Fig.  
233 4b also displayed the stark difference between exposure in the morning at 09:15, and exposure  
234 at noon, walking the same route from IIT Delhi Guest House to the Outer Ring Road. Walking  
235 in the morning had a mean exposure to  $\text{PM}_{2.5}$  of  $379\mu\text{g}/\text{m}^3$ , while in the afternoon the mean  
236 exposure was  $166\mu\text{g}/\text{m}^3$ . This suggests that, walking in the morning results in a 56% increase  
237 in exposure to  $\text{PM}_{2.5}$  level compared to walking in the afternoon.  
238 The result is comparable with the difference in the diurnal variation of ambient  $\text{PM}_{2.5}$   
239 concentrations in the morning and afternoon. In between 08:00 to 10:00 am and 21:00 to 23:00,  
240 the higher concentration of  $\text{PM}_{2.5}$  is consistent with the morning and evening rush-hour traffic  
241 pattern, respectively. The average ambient  $\text{PM}_{2.5}$  concentration was  $227\mu\text{g}/\text{m}^3$  at 09:00, which  
242 was about 51% higher than the  $\text{PM}_{2.5}$  concentration at 12:00.

### 243 3.2.3 $\text{PM}_{2.5}$ concentration in non-AC car

244  $\text{PM}_{2.5}$  exposure was third highest in non-AC-car, where the majority of exposed  $\text{PM}_{2.5}$   
245 concentrations lie between  $141$  to  $158\mu\text{g}/\text{m}^3$ , showing a very small interquartile range with the  
246 results being relatively consistent (Figure S1c). While the maximum value was  $206\mu\text{g}/\text{m}^3$  and  
247 the minimum was  $114\mu\text{g}/\text{m}^3$ , with mean value was  $149\pm 13\mu\text{g}/\text{m}^3$  (median:  $149\mu\text{g}/\text{m}^3$ ). Non-  
248 AC cars often have their windows kept open in Delhi and this could be the reason why  $\text{PM}_{2.5}$   
249 concentration for this mode than that in an AC car. The average  $\text{PM}_{2.5}$  concentration difference  
250 between AC car and non-AC car was around  $61\mu\text{g}/\text{m}^3$  on the same route of travel. The time-  
251 series plot in Figure 4c shows the wide distribution of the  $\text{PM}_{2.5}$  exposure level in a non-AC  
252 car. It shows a relatively normal distribution around  $145\mu\text{g}/\text{m}^3$  of  $\text{PM}_{2.5}$ . When compared to the  
253 AC car, the distribution begins at a much higher concentration ( $114\mu\text{g}/\text{m}^3$  for the non-AC car  
254 and  $35.0\mu\text{g}/\text{m}^3$  for the AC car). The initial levels recorded by the two modes were around  
255  $150\mu\text{g}/\text{m}^3$ , which gradually fluctuated along the route. This fluctuation, as observed for  
256 rickshaws, was mostly due to traffic congestion and the open window. This comparison has  
257 shown that exposed  $\text{PM}_{2.5}$  concentration in the AC car was about 92% lower than that in a non-  
258 AC car.

### 259 3.2.4 PM<sub>2.5</sub> concentration in Bus

260 The bus was the fourth-highest exposed transport mode. The majority of the exposed PM<sub>2.5</sub>  
261 concentrations were between 104 to 120µg/m<sup>3</sup> (Figure 1Sd). The pollution levels inside the bus  
262 increased when the bus doors and windows were opened allowing the outside pollution from  
263 traffic on the road to infiltrate the bus. Average exposed PM<sub>2.5</sub> was 113±14µg/m<sup>3</sup> (range: 85 to  
264 226µg/m<sup>3</sup>; median: 111µg/m<sup>3</sup>) (Figure 4d). Most of the buses in Delhi, now are air-conditioned,  
265 however, due to the cold weather, it is a general practice to turn off the AC and open windows.  
266 Open windows combined with the frequent opening and closing of the bus doors resulted in  
267 high concentrations of PM<sub>2.5</sub> entering the bus from the outside environment. The main source  
268 of PM<sub>2.5</sub> at the kerbside is traffic-related the high pollution was associated with the office rush-  
269 hour congestion on the road, shown higher in the morning (155µg/m<sup>3</sup>) compared to the  
270 afternoon (89µg/m<sup>3</sup>) in the study day. The recorded PM<sub>2.5</sub> concentration on the bus routes  
271 illustrates that the exposure to PM<sub>2.5</sub> remains almost consistent but except for the PM<sub>2.5</sub> peak  
272 level measured when the doors were open while the commuters were boarding the bus. These  
273 depended on the time of day and number of passengers boarding and alighting the bus (Kumar  
274 et al., 2018; Kolluru et al., 2019).

### 275 3.2.5 PM<sub>2.5</sub> concentration in Air-Conditioned Car

276 The air-conditioned car was the second-lowest mode of transport for PM<sub>2.5</sub> exposure. The  
277 frequency distribution slightly left-skewed distribution (Figure S1e) shows that most values lie  
278 around 45µg/m<sup>3</sup> and the mode is at 100µg/m<sup>3</sup>. The concentrations recorded had a range of  
279 35µg/m<sup>3</sup> to 177µg/m<sup>3</sup> (mean: 89±30µg/m<sup>3</sup>; median: 93µg/m<sup>3</sup>) and the mean was higher than  
280 the 24-hour NAAQS. One of the main reasons for the comparatively low PM<sub>2.5</sub> concentrations  
281 in the AC-cars was probably due to the microclimate created in the car by the air-conditioner,  
282 as the air is usually set to the recirculation mode when AC is on The present study despite being  
283 conducted in the cold month of February, the air conditioning in the cars used was turned on at  
284 the beginning of the journey. Thus, it was also observed that the AC car showed initial higher  
285 levels of the pollution which then gradually kept decreasing to the lower concentration as the  
286 cleaner filtered out PM<sub>2.5</sub> air built-up inside the car.

287 The AC car route from Connaught Place to IIT Delhi, see time series (Figure 4e), shows that it  
288 took approximately 23 minutes for the pollution levels in the car to reduce to NAAQS of  
289 60µg/m<sup>3</sup>. Compared with the result obtained from the alternative by car route from the heavily  
290 industrialized Okhla to IIT Delhi showed the PM<sub>2.5</sub> levels inside the car with a concentration in

291 the range around 90 to 100 $\mu\text{g}/\text{m}^3$  after 10 minutes of the journey, although never achieved the  
292 NAAQS. The main reason behind this variance could be due to the significantly worst air  
293 quality in Okhla.

### 294 3.2.6 PM<sub>2.5</sub> concentration in Metro

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

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

### 319 3.3 Open and Enclosed Transport

320 The results demonstrate that enclosed transport, such as metro and AC car, was the best option  
321 for travel compared with the open modes (e.g. walking, rickshaw, motorised vehicles with open  
322 windows) because travelling in the enclosed commute mode received the lowest mean exposure

323 PM<sub>2.5</sub> levels. Air- conditioning played an important role in AC cars and metro compartments,  
324 as they helped to filter out the outdoor PM ingress. The average exposure levels in rickshaws  
325 and walking were approximately 3.7 and 3 times greater than the metro and AC car respectively.  
326 The rickshaws recorded an exceptionally high level of PM<sub>2.5</sub> (>1000 ug/m<sup>3</sup>). This was due to  
327 the rickshaws' open interior, with travellers being affected by the rickshaw's own as well as  
328 being much closer to the effects of other vehicle exhaust during congestion and compounded  
329 with the re-suspended PM being closer to the road surface (Choudhary and Gokhale, 2016).  
330 Consistently open forms of transport whether buses or non-AC car exhibited mean exposure  
331 levels that are higher than the closed modes. Even if technically these commutes have enclosed  
332 spaces (AC buses and metros), the air inside the transport is continuously circulated and doors  
333 have to be opened periodically to allow passengers to alight and board the vehicle. Although,  
334 the enclosed structure quintessentially constrains the higher levels of PM<sub>2.5</sub>. This was  
335 demonstrated by the results which clearly show that whilst the rickshaw had respectively a  
336 mean exposure level of 1.8 and 2.4 times higher than the non-AC car and bus and the maximum  
337 levels measured were 15.1 and 13.8 times higher, respectively. Also, the mean exposure levels  
338 of non- AC car were around 1.3 times greater than that of the bus. The current study was  
339 conducted in February, the cold month of the year, AC in the buses was turned off and some of  
340 the windows were open, including the driver's window. Thus, this would have affected the  
341 results of this study.

#### 342 4. Discussion

343 The present study found that travelling by rickshaw exposed users to the highest concentrations  
344 of PM<sub>2.5</sub>, followed by walking. Also, it was observed that the high concentrations recorded in  
345 this investigation were similar to trends recorded in the previous study in Delhi (Goel et al.,  
346 2015). On the other hand, when travelling by metro and AC car, users were exposed to the  
347 lowest concentrations of PM<sub>2.5</sub> when compared with other modes. Exposure levels recorded on  
348 the bus relatively were lower than walking or by rickshaw, although higher when compared  
349 with the AC car or metro. Non-AC cars were ranked above the bus. In the present study, the  
350 PM<sub>2.5</sub> exposure in the metro and the bus were much lower than measured in the previous study  
351 by (Goel et al., 2015) conducted in Delhi during 2012-2014, this may be due to the recent clean  
352 transport approach by the Government in Delhi which eventually reduce pollution from the  
353 transport sector (CII and NITI Aayog., 2018).

##### 354 4.1 Individual Transport Exposure Analysis Along the Routes

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

#### 357 4.1.1 Exposure analysis in Rickshaws

358 In the present study, two different routes, the main (mean  $PM_{2.5}$ :  $598\pm 51\mu g/m^3$ ; median:  
359  $589\mu g/m^3$ ) and the alternative (mean  $PM_{2.5}$ :  $361\pm 69\mu g/m^3$ ; median:  $337\mu g/m^3$ ), were also  
360 driven by the rickshaw (Figure S2 and S3). The high concentration was recorded around Deer  
361 Park, near IIT Delhi where higher traffic and higher congestion levels are the norms. The  
362 proximity to the vehicles in traffic would cause an increase in recorded levels, due to their  
363 exhausts and engines polluting directly into the open rickshaw. The maximum level was  
364 measured near Nehru Park, the proximity of three fuel stations within just 500m which have an  
365 additional contribution to the regular traffic (Figure 5). The rickshaws travelled along the same  
366 stretch of Connaught Place on both routes but in different periods of the day ending at 10:00  
367 AM and 11:00 AM. This one-hour difference reduced exposure levels by  $200\mu g/m^3$ , as high  
368 levels of concentrations measured during the early morning rush hours, due to congested related  
369 emissions coupled with the varying atmospheric mixing height which causes the levels of  
370 ambient  $PM_{2.5}$  to rise (Goel et al., 2015).

371 This CNG operated open mode of transport is hugely exposed to the emissions from its engine  
372 and exhaust as well as other related road pollution sources often due to lengthy durations spent  
373 in Delhi congestion (Khan et al., 2015), although though a fair number of rickshaws (29% of  
374 the total rickshaw in 2018) had started to use electric, and therefore the exposure would be less.  
375 Research conducted by Reynolds et al., (2011) stated that not properly maintained CNG  
376 rickshaws was responsible for exceptionally high  $PM_{2.5}$  ( $3110\mu g/m^3$ ). This is a worrying level  
377 of exposure, as it shows the high concentrations that commuters can be exposed to during day-  
378 to-day life in Delhi. The results obtained in the research reported in this manuscript ( $266\pm 159$   
379  $\mu g/m^3$ ) are quite similar to the research conducted in Delhi (Goel et al., 2015), where the mean  
380 level was  $241\pm 136\mu g/m^3$  in February 2015. A study by Kumar and Gupta, (2016) also  
381 measured high mean levels of  $PM_{2.5}$  exposure in rickshaw of  $332.8\pm 90.9\mu g/m^3$  in March 2012,  
382 and whilst a lower value of lower value ( $200\pm 46\mu g/m^3$ ) was recorded by Apte et al., (2011) in  
383 2010, external factors such as different routes, time of day influence the results.

384

385

**[Insert Figure 5]**

386

#### 387 4.1.2 Exposure Analysis during Walking

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

#### 398 4.1.3 Exposure Analysis for Non-AC Cars

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

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

419

420

**[Insert Figure 6]**

421

#### 422 4.1.4 Exposure Analysis for Buses

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

439

440 **[Insert Figure 7]**

441

#### 442 4.1.5 Exposure Analysis for AC Cars

443 In this study, two routes were considered to record the  $\text{PM}_{2.5}$  levels; the main route and the  
444 alternate route taken from the Okhla industrial estate (Figure S4 and S5). For both routes, high  
445  $\text{PM}_{2.5}$  values were recorded at the start of the journey and decreased once AC was switched on.  
446 In the case of the main route, the  $\text{PM}_{2.5}$  concentrations (mean:  $69 \pm 24 \mu\text{g}/\text{m}^3$ ) in AC vehicle  
447 continue to decrease throughout the journey and no surges were observed in the trend (Figure  
448 8). The levels recorded on the main route matched with the analysis of two previous studies  
449 (Namdeo et al., 2016; Goel et al., 2015). The alternative route was from the industrial area of  
450 Okhla to IIT Delhi. This route was deliberately selected to explore the changes occurring in the  
451 exposure levels due to travelling in the high pollution area in Okhla (Nandi, 2017). However,  
452 the car used for the alternative route was using ‘fresh air’ without the recirculation mechanism

453 of the AC. The effect of this was visible when the PM<sub>2.5</sub> levels did not fall during the journey,  
454 stabilising around the mean value (104±15 µg/m<sup>3</sup>). These results confirmed that the different  
455 air ventilation settings of the cars can affect in-vehicle exposure levels. Towards and at the end  
456 of the journey from Okhla to IIT Delhi showed high levels due to increased congestion and  
457 possibly coupled with high urban density. A study in Beijing (Yao et al., 2015) reported that  
458 urban areas were exposed to ~15µg/m<sup>3</sup> higher concentrations of PM<sub>2.5</sub> compared to green and  
459 suburban areas.

460

461

**[Insert Figure 8]**

462

#### 463 4.1.6 Exposure Analysis for Metro

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

471 The metro with around 2.7 million passengers daily (India Today, 2018), experiences exposure  
472 much lower when compared with that of the bus. However, the majority of Delhiites, around  
473 4.2 million commuters (Standard Business, 2018.), prefer travelling by bus due to the less  
474 expensive fares and wider coverage of areas served. Pollution levels in the station were higher  
475 than those measured in the metro carriage. The pollution levels within the metro were almost  
476 51% less than the metro station. The monitors also recorded a slight rise in the PM<sub>2.5</sub>  
477 concentrations (about 20 µg/m<sup>3</sup>) at the locations when the carriage doors opened to let  
478 passengers alight and board.

#### 479 4.2 Respiratory deposition doses (RDDs)

480 To accomplish a comprehensive study of the effects of this pollution on human health, the  
481 individual's inhalation or ventilation rate during the commute must be considered. Thus, this  
482 will give a total RDDs of PM<sub>2.5</sub> per km journey in Delhi city and the resulted value was  
483 calculated for healthy adult's population. The study by Gupta and Elumalai, (2019) calculated  
484 an inhalation rate of 2.5×10<sup>-2</sup> m<sup>3</sup> per minute for light activity, and a deposition fraction factor

485 for PM<sub>2.5</sub> of 0.87 (see supplementary material). Using these values with the average mean  
486 exposures, an estimated total RDDs per km was calculated for this study. As previously stated,  
487 walking and rickshaw have the highest inhaled PM<sub>2.5</sub> levels per km of the journey (Table 3).  
488 The total dosage received would be 84.7±33.4 µg/km with waking and 15.8±9.5 µg/km using  
489 a rickshaw. The total RDDs during the journey with a non-AC car and a bus were 9.7±0.9  
490 µg/km and 7.4±0.9 µg/km. The lowest RDDs were observed in AC-car (5.8±2.0 µg/km) and  
491 metro (3.0±0.4 µg/km). This is similar to the amount of PM<sub>2.5</sub> that a rickshaw driver inhaled in  
492 Dhanbad, India (19.4 µg/m<sup>3</sup>) (Gupta and Elumalai, 2019). However, the study by Goel et al.,  
493 (2015) inferred that the total PM<sub>2.5</sub> dosage was much higher for all transport modes, which  
494 questions whether the estimated doses calculated in this study are underestimations.

495  
496 **[Insert Table 3]**  
497

## 498 **5. Conclusion**

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

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

518 Encouraging sustainable modes of transport such as electric vehicles and the metro would  
519 reduce PM<sub>2.5</sub> emissions and the ambient levels consequently reducing the personal exposure.  
520 The study has also outlined several areas where further research will help in developing a better  
521 understanding of the effect of traffic state (congestion vs. free-flowing), ventilation settings in  
522 vehicles (recirculation vs fresh-air; opening and closing of doors and windows) and metro  
523 stations. The frequency of door opening and passenger number effects the PM<sub>2.5</sub> concentration  
524 in a bus need for further investigation. Time spent travelling on a particular travel mode is also  
525 an important area to investigate. Apps could be developed to optimise for travel time and the  
526 lowest level of personal exposure on travel modes which will permit such changes. This  
527 research could be extended to include additional travel modes including cycling and local-  
528 trains. Whilst this study focused on PM<sub>2.5</sub>, further research could monitor the personal exposure  
529 to different pollutants, such as particle numbers, ultrafine particles, CO, NO<sub>2</sub> and VOCs, that  
530 have all been proven to be harmful to human health. Health effects of the total exposure to all  
531 pollutants could then be assessed, to investigate where and why pollution hotspots occur, and  
532 their detrimental effects.

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551 **Reference:**

- 552 Antonsen, S., Mok, P.L.H., Webb, R.T., Mortensen, P.B., McGrath, J.J., Agerbo, E., Brandt, J.,  
553 Geels, C., Christensen, J.H., Pedersen, C.B., 2020. Exposure to air pollution during  
554 childhood and risk of developing schizophrenia: a national cohort study. *The Lancet*  
555 *Planetary Health* 4, e64–e73. [https://doi.org/10.1016/S2542-5196\(20\)30004-8](https://doi.org/10.1016/S2542-5196(20)30004-8)
- 556 Apte, J.S., Kirchstetter, T.W., Reich, A.H., Deshpande, S.J., Kaushik, G., Chel, A., Marshall,  
557 J.D., Nazaroff, W.W., 2011. Concentrations of fine, ultrafine, and black carbon particles  
558 in auto-rickshaws in New Delhi, India. *Atmospheric Environment* 45, 4470–4480.  
559 <https://doi.org/10.1016/j.atmosenv.2011.05.028>
- 560 Both, A.F., Westerdahl, D., Fruin, S., Haryanto, B., Marshall, J.D., 2013. Exposure to carbon  
561 monoxide, fine particle mass, and ultrafine particle number in Jakarta, Indonesia: Effect  
562 of commute mode. *Science of The Total Environment* 443, 965–972.  
563 <https://doi.org/10.1016/j.scitotenv.2012.10.082>
- 564 Bowatte, G., Erbas, B., Lodge, C.J., Knibbs, L.D., Gurrin, L.C., Marks, G.B., Thomas, P.S.,  
565 Johns, D.P., Giles, G.G., Hui, J., Dennekamp, M., Perret, J.L., Abramson, M.J., Walters,  
566 E.H., Matheson, M.C., Dharmage, S.C., 2017. Traffic-related air pollution exposure over  
567 a 5-year period is associated with increased risk of asthma and poor lung function in  
568 middle age. *European Respiratory Journal* 50, 1602357.  
569 <https://doi.org/10.1183/13993003.02357-2016>
- 570 Bowe, B., Xie, Y., Yan, Y., Al-Aly, Z., 2019. Burden of Cause-Specific Mortality Associated  
571 With PM 2.5 Air Pollution in the United States. *JAMA Network Open* 2, e1915834.  
572 <https://doi.org/10.1001/jamanetworkopen.2019.15834>
- 573 Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C.A., Apte, J.S., Brauer,  
574 M., Cohen, A., Weichenthal, S., Coggins, J., Di, Q., Brunekreef, B., Frostad, J., et al.,  
575 2018. Global estimates of mortality associated with long-term exposure to outdoor fine  
576 particulate matter. *Proceedings of the National Academy of Sciences* 115, 9592–9597.  
577 <https://doi.org/10.1073/pnas.1803222115>
- 578 Chaney, R.A., Sloan, C.D., Cooper, V.C., Robinson, D.R., Hendrickson, N.R., McCord, T.A.,  
579 Johnston, J.D., 2017. Personal exposure to fine particulate air pollution while commuting:  
580 An examination of six transport modes on an urban arterial roadway. *PLOS ONE* 12,  
581 e0188053. <https://doi.org/10.1371/journal.pone.0188053>
- 582 Chen, H., Kwong, J.C., Copes, R., Hystad, P., van Donkelaar, A., Tu, K., Brook, J.R., Goldberg,  
583 M.S., Martin, R. V., Murray, B.J., Wilton, A.S., Kopp, A., Burnett, R.T., 2017. Exposure  
584 to ambient air pollution and the incidence of dementia: A population-based cohort study.  
585 *Environment International* 108, 271–277. <https://doi.org/10.1016/j.envint.2017.08.020>
- 586 Chen, Y., Wild, O., Ryan, E., Sahu, S.K., Lowe, D., Archer-Nicholls, S., Wang, Y., McFiggans,  
587 G., Ansari, T., Singh, V., Sokhi, R.S., Archibald, A., Beig, G., 2020. Mitigation of  
588 PM<sub>2.5</sub> and ozone pollution in Delhi: a  
589 sensitivity study during the pre-monsoon period. *Atmospheric Chemistry and Physics* 20,  
590 499–514. <https://doi.org/10.5194/acp-20-499-2020>

- 591 Choudhary, A., Gokhale, S., 2016. Urban real-world driving traffic emissions during  
592 interruption and congestion. *Transportation Research Part D: Transport and Environment*  
593 43, 59–70. <https://doi.org/10.1016/j.trd.2015.12.006>
- 594 Chowdhury, S., Dey, S., Guttikunda, S., Pillarisetti, A., Smith, K.R., Di Girolamo, L., 2019.  
595 Indian annual ambient air quality standard is achievable by completely mitigating  
596 emissions from household sources. *Proceedings of the National Academy of Sciences* 116,  
597 10711–10716. <https://doi.org/10.1073/pnas.1900888116>
- 598 CII and NITI Aayog., 2018. ACTION PLAN FOR CLEAN TRANSPORTATION: Report of  
599 the Task Force on Clean Transportation. Delhi.
- 600 Costa, L.G., Cole, T.B., Coburn, J., Chang, Y.-C., Dao, K., Roqué, P.J., 2017. Neurotoxicity of  
601 traffic-related air pollution. *NeuroToxicology* 59, 133–139.  
602 <https://doi.org/10.1016/j.neuro.2015.11.008>
- 603 de Nazelle, A., Fruin, S., Westerdahl, D., Martinez, D., Ripoll, A., Kubesch, N.,  
604 Nieuwenhuijsen, M., 2012. A travel mode comparison of commuters' exposures to air  
605 pollutants in Barcelona. *Atmospheric Environment* 59, 151–159.  
606 <https://doi.org/10.1016/j.atmosenv.2012.05.013>
- 607 Díaz, G., Macià, H., Valero, V., Boubeta-Puig, J., Cuartero, F., 2020. An Intelligent  
608 Transportation System to control air pollution and road traffic in cities integrating CEP  
609 and Colored Petri Nets. *Neural Computing and Applications* 32, 405–426.  
610 <https://doi.org/10.1007/s00521-018-3850-1>
- 611 Fu, P., Guo, X., Cheung, F.M.H., Yung, K.K.L., 2019. The association between PM2.5  
612 exposure and neurological disorders: A systematic review and meta-analysis. *Science of*  
613 *The Total Environment* 655, 1240–1248. <https://doi.org/10.1016/j.scitotenv.2018.11.218>
- 614 Geiss, O., Barrero-Moreno, J., Tirendi, S., Kotzias, D., 2010. Exposure to Particulate Matter in  
615 Vehicle Cabins of Private Cars. *Aerosol and Air Quality Research* 10, 581–588.  
616 <https://doi.org/10.4209/aaqr.2010.07.0054>
- 617 Gilliland, J., Maltby, M., Xu, X., Luginaah, I., Loebach, J., Shah, T., 2019. Is active travel a  
618 breath of fresh air? Examining children's exposure to air pollution during the school  
619 commute. *Spatial and Spatio-temporal Epidemiology* 29, 51–57.  
620 <https://doi.org/10.1016/j.sste.2019.02.004>
- 621 Goel, R., Gani, S., Guttikunda, S.K., Wilson, D., Tiwari, G., 2015. On-road PM2.5 pollution  
622 exposure in multiple transport microenvironments in Delhi. *Atmospheric Environment*  
623 123, 129–138. <https://doi.org/10.1016/j.atmosenv.2015.10.037>
- 624 Gong, Y., Zhou, T., Zhao, Y., Xu, B., 2019. Characterization and Risk Assessment of  
625 Particulate Matter and Volatile Organic Compounds in Metro Carriage in Shanghai, China.  
626 *Atmosphere* 10, 302. <https://doi.org/10.3390/atmos10060302>
- 627 Goswami, S., 2017. 10,000 cabs, 431 buses: New faces of Delhi's air-conditioned public  
628 transport. [WWW Document]. *Hindusthan Times*. URL  
629 [https://www.hindustantimes.com/delhi-news/10-000-cabs-431-buses-new-faces-of-delhi-](https://www.hindustantimes.com/delhi-news/10-000-cabs-431-buses-new-faces-of-delhi-s-air-conditioned-public-transport/story-neNFaiY07oe85vFcUC75NM.html)  
630 [s-air-conditioned-public-transport/story-neNFaiY07oe85vFcUC75NM.html](https://www.hindustantimes.com/delhi-news/10-000-cabs-431-buses-new-faces-of-delhi-s-air-conditioned-public-transport/story-neNFaiY07oe85vFcUC75NM.html)

- 631 Government of India, C. 2011., 2020. Delhi City Census 2011 data. [WWW Document].  
632 Government of India, Census 2011. URL [https://www.census2011.co.in/census/city/49-](https://www.census2011.co.in/census/city/49-delhi.html)  
633 [delhi.html](https://www.census2011.co.in/census/city/49-delhi.html)
- 634 Gupta, S.K., Elumalai, S.P., 2019. Exposure to traffic-related particulate matter and deposition  
635 dose to auto rickshaw driver in Dhanbad, India. *Atmospheric Pollution Research* 10, 1128–  
636 1139. <https://doi.org/10.1016/j.apr.2019.01.018>
- 637 Ham, W., Vijayan, A., Schulte, N., Herner, J.D., 2017. Commuter exposure to PM<sub>2.5</sub>, BC, and  
638 UFP in six common transport microenvironments in Sacramento, California. *Atmospheric*  
639 *Environment* 167, 335–345. <https://doi.org/10.1016/j.atmosenv.2017.08.024>
- 640 India Today, n.d. Nearly 27 lakh commuters boarded Delhi Metro everyday in February,  
641 ridership sees steady increase. [WWW Document]. 2018. URL  
642 [https://www.indiatoday.in/india/story/delhi-metro-sees-steady-rise-in-daily-ridership-26-](https://www.indiatoday.in/india/story/delhi-metro-sees-steady-rise-in-daily-ridership-26-98-lakh-in-feb-1190516-2018-03-15)  
643 [98-lakh-in-feb-1190516-2018-03-15](https://www.indiatoday.in/india/story/delhi-metro-sees-steady-rise-in-daily-ridership-26-98-lakh-in-feb-1190516-2018-03-15)
- 644 Jerrett, M., Finkelstein, M.M., Brook, J.R., Arain, M.A., Kanaroglou, P., Stieb, D.M., Gilbert,  
645 N.L., Verma, D., Finkelstein, N., Chapman, K.R., Sears, M.R., 2009. A Cohort Study of  
646 Traffic-Related Air Pollution and Mortality in Toronto, Ontario, Canada. *Environmental*  
647 *Health Perspectives* 117, 772–777. <https://doi.org/10.1289/ehp.11533>
- 648 Khan, M.I., Yasmin, T., Shakoor, A., 2015. Technical overview of compressed natural gas  
649 (CNG) as a transportation fuel. *Renewable and Sustainable Energy Reviews* 51, 785–797.  
650 <https://doi.org/10.1016/j.rser.2015.06.053>
- 651 Kolluru, S.S.R., Patra, A.K., Dubey, R.S., 2019a. In-vehicle PM<sub>2.5</sub> personal concentrations in  
652 winter during long distance road travel in India. *Science of The Total Environment* 684,  
653 207–220. <https://doi.org/10.1016/j.scitotenv.2019.05.347>
- 654 Kolluru, S.S.R., Patra, A.K., Kumar, P., 2019b. Determinants of commuter exposure to PM<sub>2.5</sub>  
655 and CO during long-haul journeys on national highways in India. *Atmospheric Pollution*  
656 *Research* 10, 1031–1041. <https://doi.org/10.1016/j.apr.2019.01.012>
- 657 Kumar, P., Gupta, N.C., 2016. Commuter exposure to inhalable, thoracic and alveolic particles  
658 in various transportation modes in Delhi. *Science of The Total Environment* 541, 535–  
659 541. <https://doi.org/10.1016/j.scitotenv.2015.09.076>
- 660 Kumar, P., Rivas, I., Singh, A.P., Ganesh, V.J., Ananya, M., Frey, H.C., 2018. Dynamics of  
661 coarse and fine particle exposure in transport microenvironments. *npj Climate and*  
662 *Atmospheric Science* 1, 11. <https://doi.org/10.1038/s41612-018-0023-y>
- 663 Lin, C., Hu, D., Jia, X., Chen, J., Deng, F., Guo, X., Heal, M.R., Cowie, H., Wilkinson, P.,  
664 Miller, M.R., Loh, M., 2020. The relationship between personal exposure and ambient  
665 PM<sub>2.5</sub> and black carbon in Beijing. *Science of The Total Environment* 737, 139801.  
666 <https://doi.org/10.1016/j.scitotenv.2020.139801>
- 667 Maji, K.J., 2020. Substantial changes in PM<sub>2.5</sub> pollution and corresponding premature deaths  
668 across China during 2015–2019: A model prospective. *Science of The Total Environment*  
669 729, 138838. <https://doi.org/10.1016/j.scitotenv.2020.138838>
- 670 Matz, C.J., Egyed, M., Hocking, R., Seenundun, S., Charman, N., Edmonds, N., 2019. Human

- 671 health effects of traffic-related air pollution (TRAP): a scoping review protocol.  
672 *Systematic Reviews* 8, 223. <https://doi.org/10.1186/s13643-019-1106-5>
- 673 Menon, J.S., Nagendra, S.M.S., 2018. Personal exposure to fine particulate matter  
674 concentrations in central business district of a tropical coastal city. *Journal of the Air &*  
675 *Waste Management Association* 68, 415–429.  
676 <https://doi.org/10.1080/10962247.2017.1407837>
- 677 Monrad, M., Sajadieh, A., Christensen, J.S., Ketzel, M., Raaschou-Nielsen, O., Tjønneland, A.,  
678 Overvad, K., Loft, S., Sørensen, M., 2017. Long-Term Exposure to Traffic-Related Air  
679 Pollution and Risk of Incident Atrial Fibrillation: A Cohort Study. *Environmental Health*  
680 *Perspectives* 125, 422–427. <https://doi.org/10.1289/EHP392>
- 681 Moreno, T., Reche, C., Rivas, I., Cruz Minguillón, M., Martins, V., Vargas, C., Buonanno, G.,  
682 Parga, J., Pandolfi, M., Brines, M., Ealo, M., Sofia Fonseca, A., Amato, F., Sosa, G.,  
683 Capdevila, M., de Miguel, E., Querol, X., Gibbons, W., 2015. Urban air quality  
684 comparison for bus, tram, subway and pedestrian commutes in Barcelona. *Environmental*  
685 *Research* 142, 495–510. <https://doi.org/10.1016/j.envres.2015.07.022>
- 686 Namdeo, A., Ballare, S., Job, H., Namdeo, D., 2016. Commuter Exposure to Air Pollution in  
687 Newcastle, U.K., and Mumbai, India. *Journal of Hazardous, Toxic, and Radioactive Waste*  
688 20. [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000232](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000232)
- 689 Nandi, J., 2018. 12 areas in Delhi where you can never breathe clean air [WWW Document].  
690 *The Times of India*. URL [https://timesofindia.indiatimes.com/city/delhi/twelve-areas-in-](https://timesofindia.indiatimes.com/city/delhi/twelve-areas-in-delhi-where-you-can-never-breathe-clean-air/articleshow/62677188.cms)  
691 [delhi-where-you-can-never-breathe-clean-air/articleshow/62677188.cms](https://timesofindia.indiatimes.com/city/delhi/twelve-areas-in-delhi-where-you-can-never-breathe-clean-air/articleshow/62677188.cms)
- 692 Nandi, J., 2017. Delhi's new pollution hotspots are worse than Anand Vihar. [WWW  
693 Document]. URL [https://timesofindia.indiatimes.com/city/delhi/delhis-new-pollution-](https://timesofindia.indiatimes.com/city/delhi/delhis-new-pollution-hotspots-are-worse-than-anand-vihar/articleshow/61537012.cms)  
694 [hotspots-are-worse-than-anand-vihar/articleshow/61537012.cms](https://timesofindia.indiatimes.com/city/delhi/delhis-new-pollution-hotspots-are-worse-than-anand-vihar/articleshow/61537012.cms)
- 695 Onat, B., Stakeeva, B., 2013. Personal exposure of commuters in public transport to PM<sub>2.5</sub> and  
696 fine particle counts. *Atmospheric Pollution Research* 4, 329–335.  
697 <https://doi.org/10.5094/APR.2013.037>
- 698 Qiu, Z., Song, J., Xu, X., Luo, Y., Zhao, R., Zhou, W., Xiang, B., Hao, Y., 2017. Commuter  
699 exposure to particulate matter for different transportation modes in Xi'an, China.  
700 *Atmospheric Pollution Research* 8, 940–948. <https://doi.org/10.1016/j.apr.2017.03.005>
- 701 Qstarz., 2018. BT-Q1000XT GPS Travel Recorder. [WWW Document]. URL  
702 [http://www.qstarz.com/Products/GPS Products/BT-Q1000XT-F.htm](http://www.qstarz.com/Products/GPS%20Products/BT-Q1000XT-F.htm)
- 703 R Core Team, 2017. R: A Language and Environment for Statistical Computing R Foundation  
704 for Statistical Computing, Vienna, Austria.
- 705 RStudio Team (2020). RStudio: Integrated Development Environment for R, Version 1.1.456  
706 RStudio, PBC, Boston, MA URL. Available at: <http://www.rstudio.com/>.
- 707 Reynolds, C.C.O., Kandlikar, M., Badami, M.G., 2011. Determinants of PM and GHG  
708 emissions from natural gas-fueled auto-rickshaws in Delhi. *Transportation Research Part*  
709 *D: Transport and Environment* 16, 160–165. <https://doi.org/10.1016/j.trd.2010.10.004>
- 710 Rivas, I., Kumar, P., Hagen-Zanker, A., 2017. Exposure to air pollutants during commuting in

- 711 London: Are there inequalities among different socio-economic groups? *Environment*  
712 *International* 101, 143–157. <https://doi.org/10.1016/j.envint.2017.01.019>
- 713 Rodenbeck, E., n.d. Stamen, San Francisco: Stamen Design LLC. [WWW Document]. 2018.  
714 URL <https://stamen.com/>
- 715 Stanaway, J.D., Afshin, A., Gakidou, E., Lim, S.S., Abate, D., Abate, K.H., Abbafati, C.,  
716 Abbasi, N., Abbastabar, H., Abd-Allah, F., Abdela, J., Abdelalim, A., et al., 2018. Global,  
717 regional, and national comparative risk assessment of 84 behavioural, environmental and  
718 occupational, and metabolic risks or clusters of risks for 195 countries and territories,  
719 1990–2017: a systematic analysis for the Global Burden of Disease Stu. *The Lancet* 392,  
720 1923–1994. [https://doi.org/10.1016/S0140-6736\(18\)32225-6](https://doi.org/10.1016/S0140-6736(18)32225-6)
- 721 Standard Business, 2018. Upswing in DTC, Cluster buses daily ridership, 41.90 passengers  
722 carried per day: Sisodia. [WWW Document]. 2018. URL [https://www.business-](https://www.business-standard.com/article/pti-stories/upswing-in-dtc-cluster-buses-daily-ridership-41-90-passengers-carried-per-day-sisodia-118032101391_1.html)  
723 [standard.com/article/pti-stories/upswing-in-dtc-cluster-buses-daily-ridership-41-90-](https://www.business-standard.com/article/pti-stories/upswing-in-dtc-cluster-buses-daily-ridership-41-90-passengers-carried-per-day-sisodia-118032101391_1.html)  
724 [passengers-carried-per-day-sisodia-118032101391\\_1.html](https://www.business-standard.com/article/pti-stories/upswing-in-dtc-cluster-buses-daily-ridership-41-90-passengers-carried-per-day-sisodia-118032101391_1.html)
- 725 Swamy, S., Pai, M., Kulshrestha, S., 2015. Impact Of Bus Rapid Transit On Urban Air  
726 Pollution: Commuter’S Exposure To PM2.5 In Ahmedabad, Ahmedabad.
- 727 Tan, S.H., Roth, M., Velasco, E., 2017. Particle exposure and inhaled dose during commuting  
728 in Singapore. *Atmospheric Environment* 170, 245–258.  
729 <https://doi.org/10.1016/j.atmosenv.2017.09.056>
- 730 Transport Department Government of NCT of Delhi., 2018. Total Vehical Registered upto  
731 31.03.2018. [WWW Document]. Transport Department, ARTMENT Government of NCT  
732 of Delhi. URL <https://transport.delhi.gov.in/content/statistics-0>
- 733 TSI., 2018. SIDEPAK PERSONAL AEROSOL MONITOR AM520. [WWW Document].  
734 URL [https://tsi.com/products/aerosol-and-dust-monitors/dust-monitors/sidepak-personal-](https://tsi.com/products/aerosol-and-dust-monitors/dust-monitors/sidepak-personal-aerosol-monitor-am520/)  
735 [aerosol-monitor-am520/](https://tsi.com/products/aerosol-and-dust-monitors/dust-monitors/sidepak-personal-aerosol-monitor-am520/)
- 736 Van Ryswyk, K., Anastasopoulos, A.T., Evans, G., Sun, L., Sabaliauskas, K., Kulka, R.,  
737 Wallace, L., Weichenthal, S., 2017. Metro Commuter Exposures to Particulate Air  
738 Pollution and PM 2.5 -Associated Elements in Three Canadian Cities: The Urban  
739 Transportation Exposure Study. *Environmental Science & Technology* 51, 5713–5720.  
740 <https://doi.org/10.1021/acs.est.6b05775>
- 741 Vilcassim, M.J.R., Thurston, G.D., Peltier, R.E., Gordon, T., 2014. Black Carbon and  
742 Particulate Matter (PM 2.5 ) Concentrations in New York City’s Subway Stations.  
743 *Environmental Science & Technology* 48, 14738–14745.  
744 <https://doi.org/10.1021/es504295h>
- 745 World Health Organization, 2018. WHO Global Ambient Air Quality Database (update 2018)  
746 [WWW Document]. URL <https://www.who.int/airpollution/data/cities/en/>
- 747 Yao, L., Lu, N., Yue, X., Du, J., Yang, C., 2015. Comparison of Hourly PM2.5 Observations  
748 Between Urban and Suburban Areas in Beijing, China. *International Journal of*  
749 *Environmental Research and Public Health* 12, 12264–12276.  
750 <https://doi.org/10.3390/ijerph121012264>

751 Zhang, K., Batterman, S., Dion, F., 2011. Vehicle emissions in congestion: Comparison of work  
752 zone, rush hour and free-flow conditions. Atmospheric Environment 45, 1929–1939.  
753 <https://doi.org/10.1016/j.atmosenv.2011.01.030>

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**Number of Tables**

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**Number of Figures**

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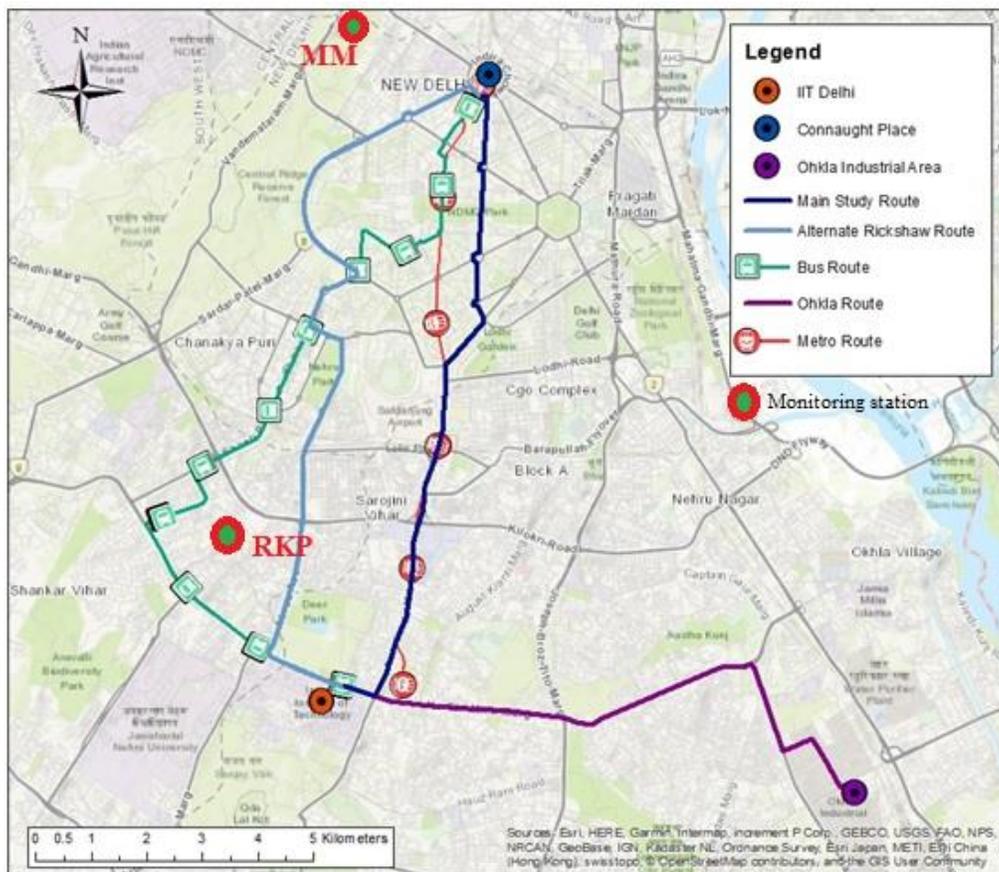


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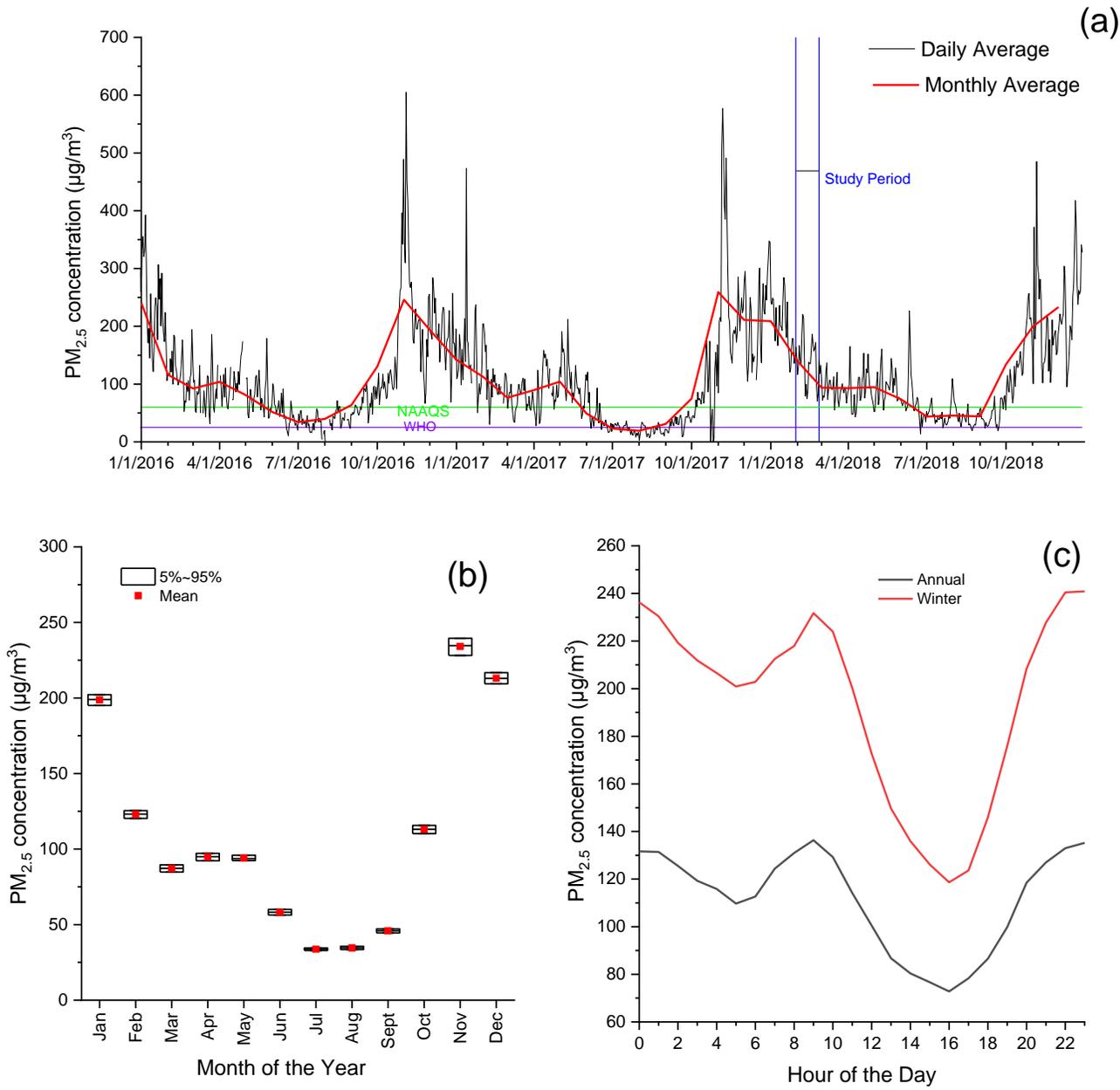


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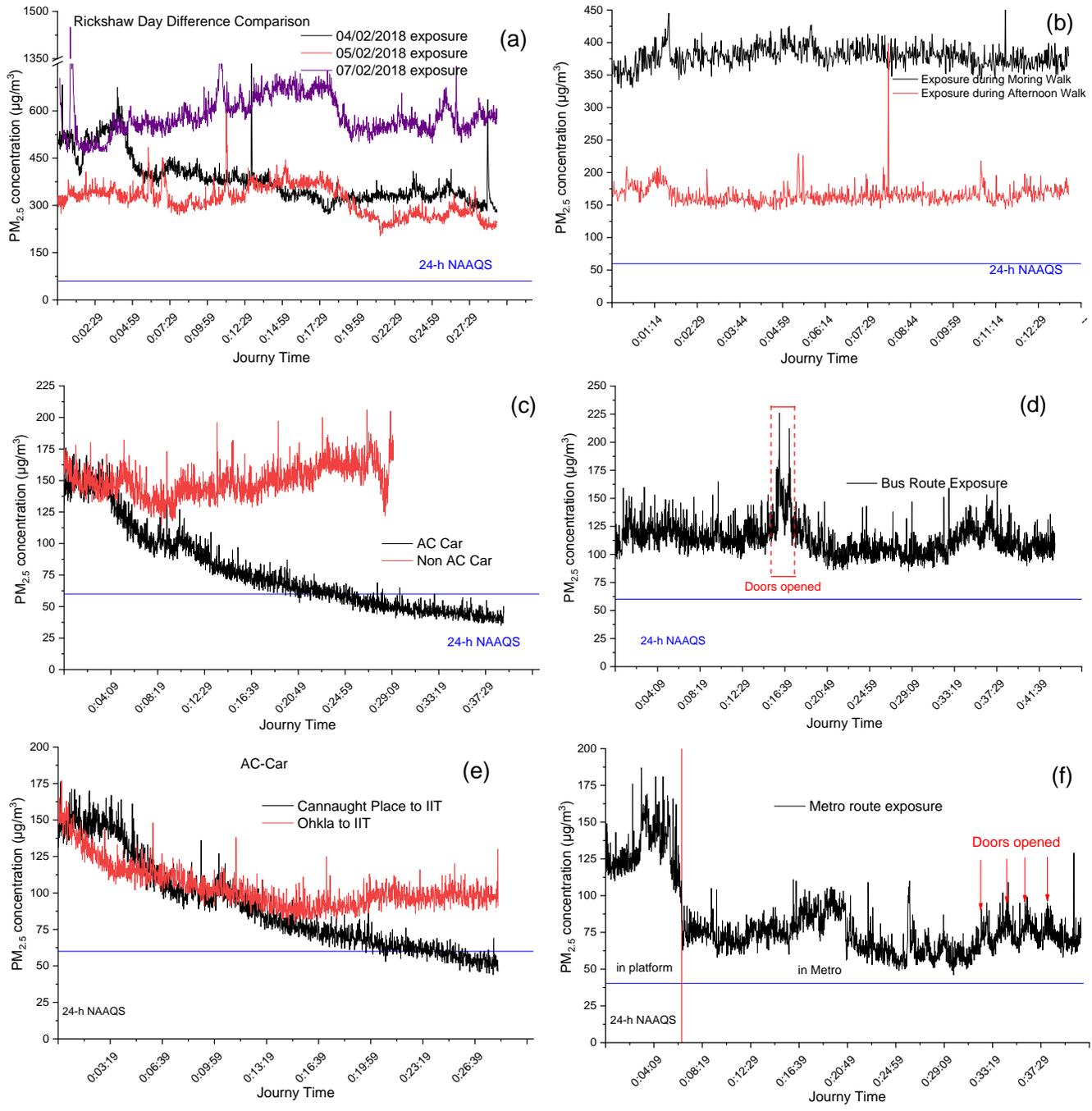


Figure 4  $PM_{2.5}$  concentration levels in different transport modes (a) Rickshaw, (b) Walk (c) non-AC-Car, (d) Bus, (e) AC-Car and (f) Metro

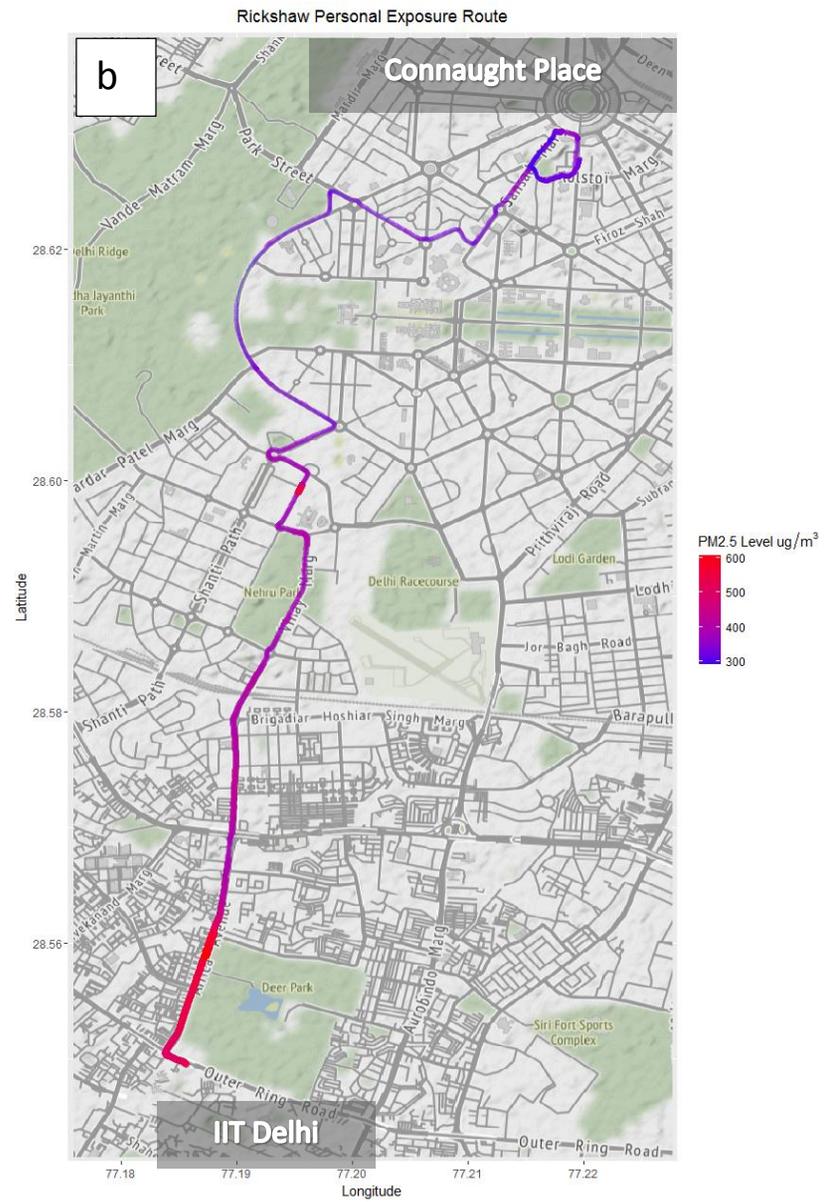
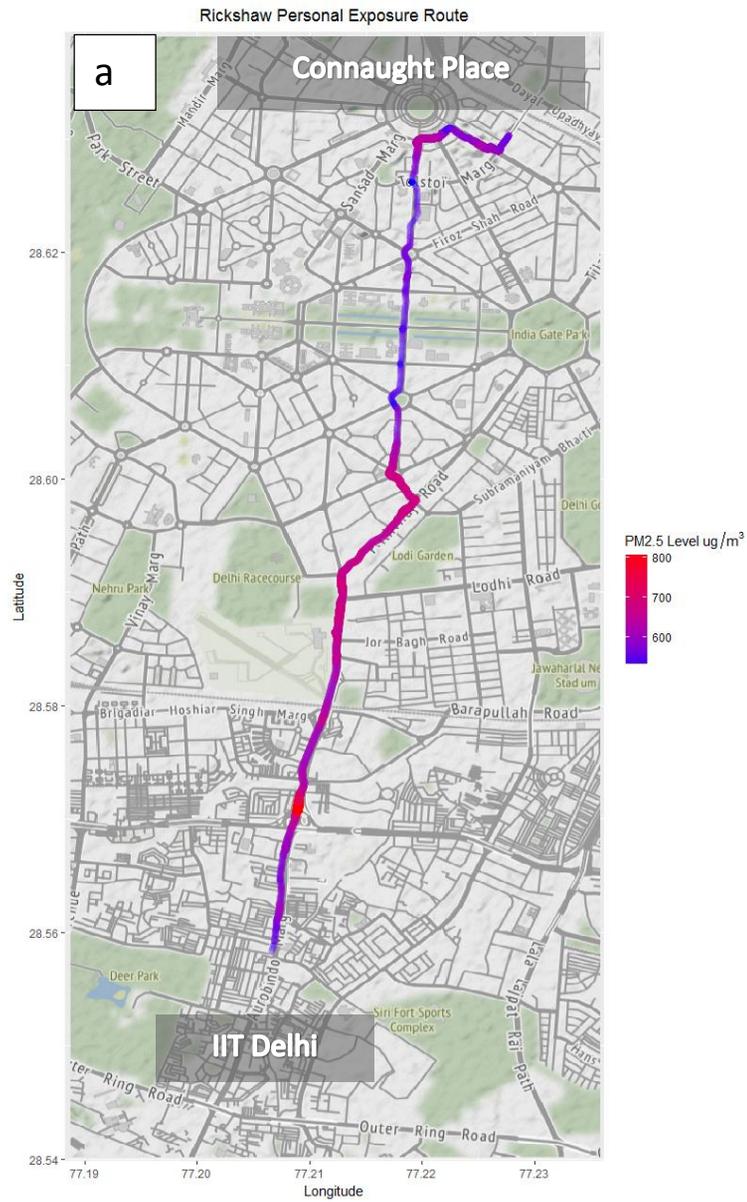


Figure 5 Rickshaw map exposure route monitored during study (a) main route (b) alternative route

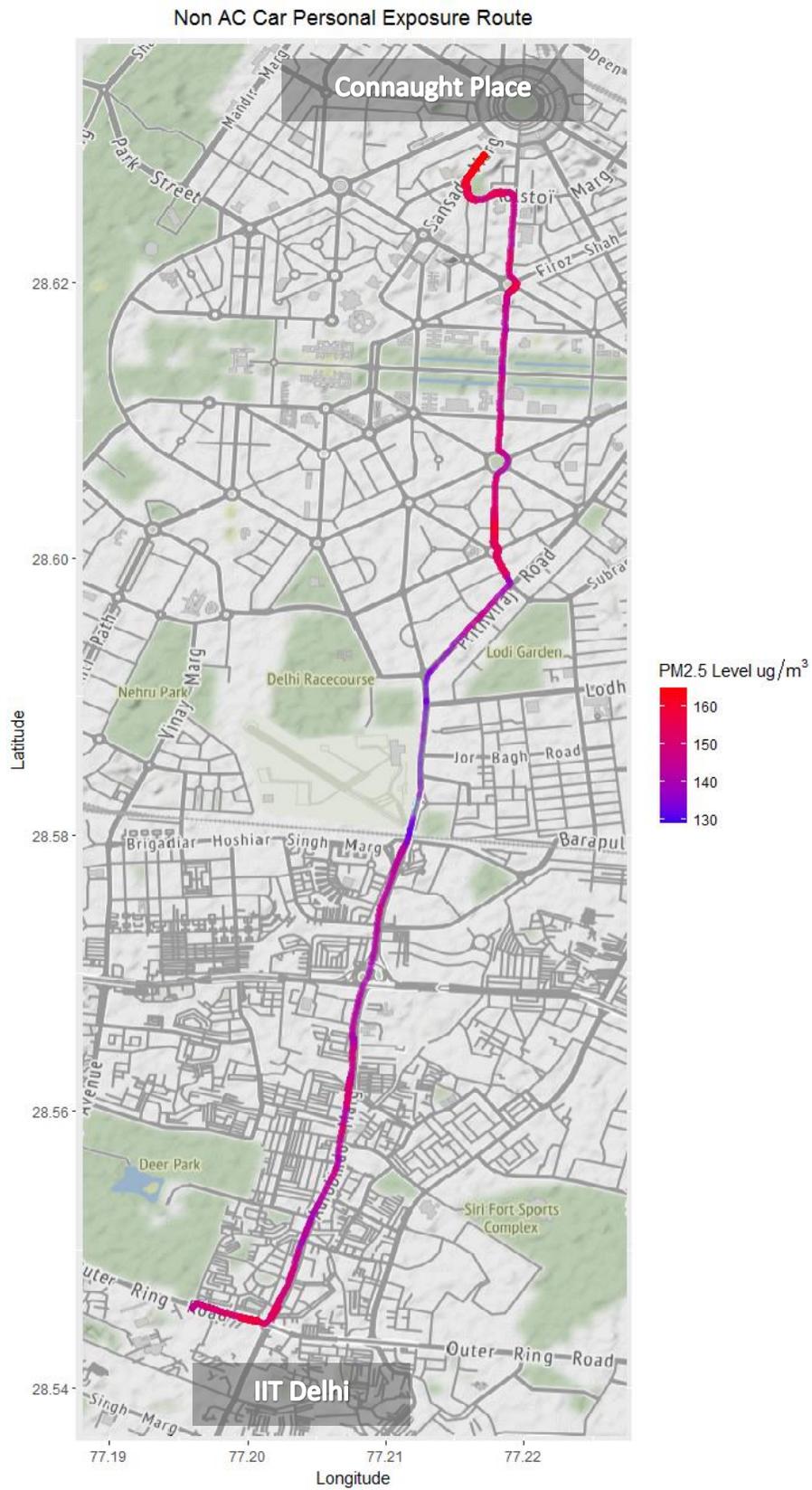


Figure 6. Non-AC car map exposure route monitored during the study



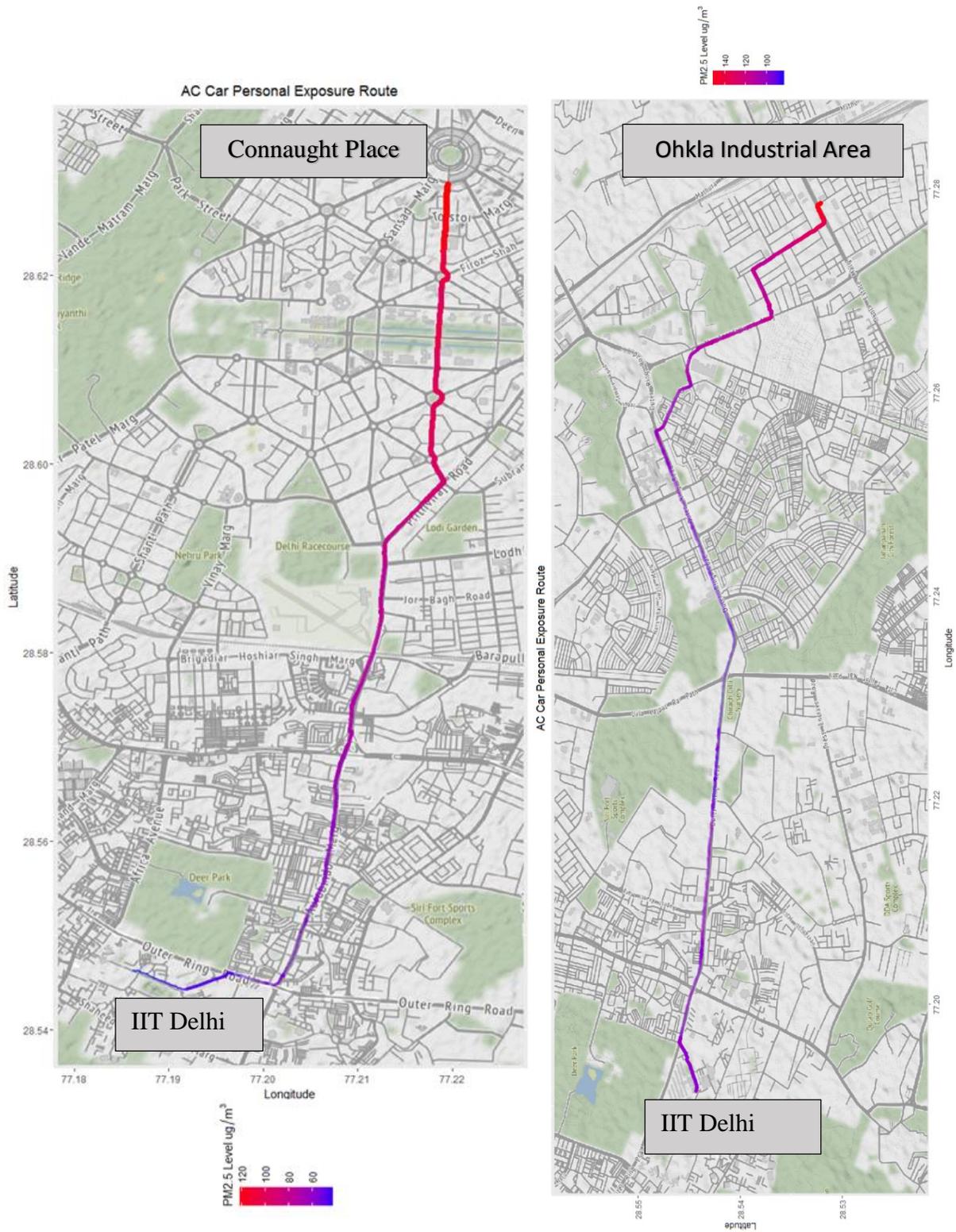


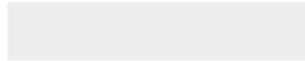
Figure 8. AC-car map exposure route monitored during study (a) main route (b) alternative route



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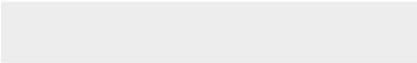
**Table**

4\_Table\_Final version\_R1.docx





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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:**

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