Investigating Car User's Exposure to Traffic Congestion-Induced Fine Particles in Megacity Delhi

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Abstract Air pollution and traffic congestion have become a significant concern for all urban cities. This study aims to find a relationship between the congestion zone and the Particle Number Concentration (PNC) of Fine Particulates. During the study, a direct relation was observed between traffic densities, congestion, and the PNC. Heavy congestion causes an average increase of 3×10^5 to 6×10^5 #/cc in PNC, while the light congestion zone causes an average growth of 1.3×10^5 to 1.8×10^5 #/cc. A relation between the traffic signal duration and PNC was also observed. Shorter duration signals resulted in negligible impact, while longer duration signals have a noticeable impact on PNC.

Keywords Air pollution · Commuter exposure · Fine particles · Particulate matter · qUFP · Traffic congestion

1 Introduction

Traffic congestion and commuter exposure to Particulate Matter (PM) are becoming new norms, and while both are related to each other in one way or another, not much study has been done to understand how the two are related to each other. This study aims to analyse better how traffic congestion impacts the in-cabin concentration of fine particulate matter in cars and determine the risk of commuter exposure.

The seriousness of this issue can be understood by the fact that in recent years, commuter exposure to air pollution has become a topic of concern across the globe [1–3]. Developing countries like India [4] witness rapid urbanization and industrialization. India has a large number of urban cities facing overcrowding and severe air pollution, resulting in many Indian cities regularly featuring in the list of most polluted (9 cities in the list of 10 most polluted cities in the world [5]) and congested cities (4 out of 10 most congested cities [6]) in the world.

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On average, Indians spend 7% of their day commuting to the office [7], while the situation is much worse in Delhi. As per a report [6] published in Delhi, the average commuting time is increased by 56% due to traffic congestion, while in terms of air pollution, bad and severe Air Quality Index (AQI) days have become the new normal in the city, while good air days have become rare occurrences [3, 5, 8]. As a result, people living in Delhi are at greater risk of commuter exposure to air pollution.

Amongst the various pollutants, PMs have become a significant concern amongst people due to serious health risks like respiratory allergies, asthmas, and bronchitis [9]. As per World Health Organization's (WHO) latest report [10], 9 out of 10 people living in urban areas are exposed to PM2.5, while almost 4.5 million premature deaths are attributed to PM exposure. Also, almost 2.7% of global illnesses can be linked to respirable PM [11].

Amongst the various PMs, fine particles (dp < 1 μm) have recently become particularly interesting as they contribute to up to 70–80% of the total particle number in the ambient air [12, 13]. Fine particles tend to have a varying chemical composition and very small size, which allows them to remain in the air for a long period and penetrate deep into the respiratory tract and have profound implications (directly as well as indirectly) on the health and contributing to issues like arrhythmia, hypertension, reduced lung function, etc. [14–16]. Exposure to fine particles is a well-known risk [17–19], and the risk increases further while commuting [8, 20, 21].

Fine particles, quasi-Ultra Fine Particles (qUFP), and Ultra Fine Particles (UFP) are a sub-fraction of PM 2.5, contributing up to 90% of total Particle Number Concentration (PNC, i.e., the total number of particles present per unit volume of air) of PM2.5 [13]. While fine particles are defined as particles having a size less than 1000 nm, at the moment, there is a lack of agreement amongst scholars regarding the definition of the UFP and qUFP; as a result, the boundary conditions are not well established. Over the years, various researchers have used different meanings for these particles. For this study, we have considered UFP as particulate matter with at least one dimension less than 100 nm [13] and qUFP particles as particulates in a size range of 100–360 nm [22].

In Indian urban areas, people spend a considerably large amount of time commuting from one place to another place. Most of the Indian metro cities are highly congested and regularly ranked very high on the list of cities with the most polluted air, which translates to the fact that people living in Indian metro cities (especially Delhi) are at a relatively higher risk of facing serious health implications (directly and indirectly) related to air pollution due to increased risk of commuter exposure.

2 Methodology

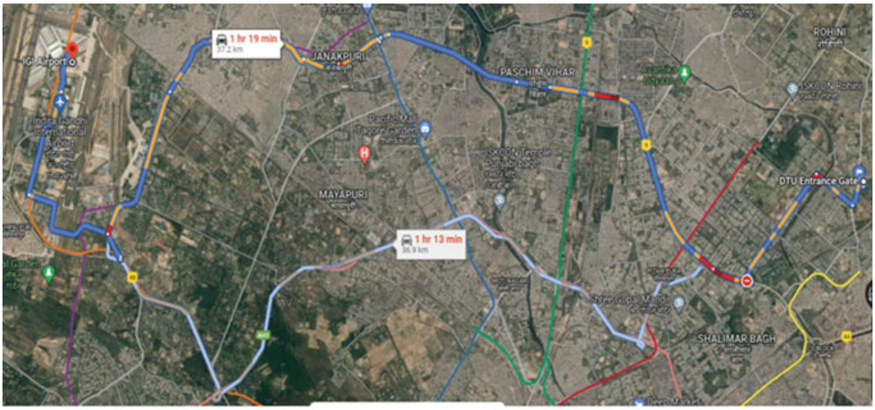
2.1 Route Selection

The study was conducted on two different routes located in the National Capital Territory (NCT) of Delhi; both routes were selected to provide a realistic representation of the traffic scenario NCT of Delhi and contain different traffic densities. Both routes were similar in length; route-1 was from Delhi Technological University (DTU) to Indira Gandhi International (IGI) airport Terminal-2 (Fig. 1a), a 37 km long route connecting North Delhi to South West Delhi. This route had a variable traffic density and contained more greenery and less unplanned stoppage and congestion zone as it included the open area near the airport. The route-2 covered a 36 km long stretch from Mohan Nagar metro station to DTU (Fog 1b), connecting North Delhi with East Delhi, and Ghaziabad. This route included the Kashmiri Gate Inter-State Bus Terminus (ISBT) area, one of the busiest terminus in Delhi, the industrial area of Mohan Nagar/Sahibabad, and covers parts of Grand Trunk (GT) road. The route has a high traffic density and unplanned stoppage while also including the crossing of the river Yamuna. The average duration of both the routes was around 2 h 45 min for a round trip.

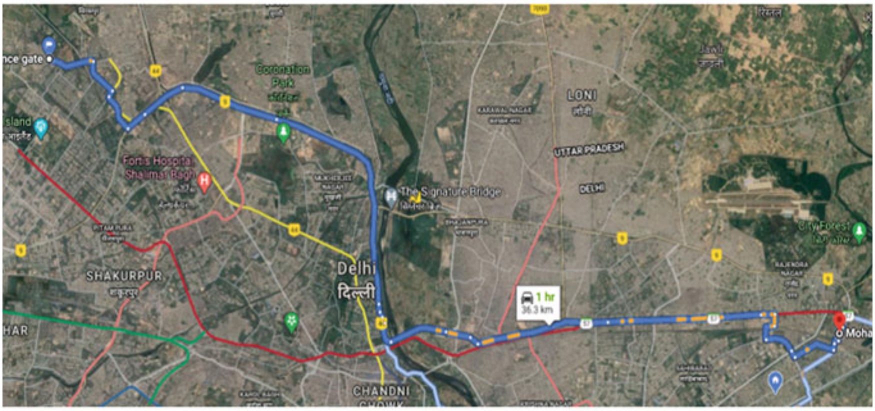
2.2 Instrumentation

The sampling was done inside the vehicle (car) using "GRIMM Technik, model 11-A portable aerosol spectrometer", a portable Optical Particle Counter (OPC) (refer to Table 1[1] for technical specs). For this study, 12 particulate-size channel bins (corresponding to <1 µm particle size) were used, i.e., <0.25 µm, 0.25–0.28µ, 0.28–0.30 µm, 0.30–0.35 µm, 0.35–0.40 µm, 0.40–0.45 µm, 0.45–0.50 µm, 0.50–0.58 µm, 0.58–0.65 µm, 0.65–0.7 µm, 0.7–0.8 µm, and 0.8–1.0 µm, while the reading interval was set to 6 s (the least frequency). The vehicle used was a 2010 model, white Maruti Suzuki Dzire, with a working AC (non-HEPA air filter); the vehicle underwent servicing a week before sampling and was in excellent condition. The instrument and the sampling probe were set up on the front passenger seat next to the driver (as shown in Fig. 2) at a distance similar to the passenger breathing zone (although the height of the sampling probe was lower) to measure the driver exposure.

[1] https://pdf.directindustry.com/pdf/grimm-aerosol-technik/model-11-a/69071-654475.html".



a) Route 1- DTU to IGI T2 parking



b) Route 2- DTU to Mohan Nagar

Fig. 1 Route used for the data collection

2.3 Sampling Protocols

The data was collected twice each day during morning and evening peak hours for two days on each route (one working day and one non-working day). The peak hours were selected based on Delhi's traffic flow data [6], with morning peak hours being 9 AM to 11 AM and 11 AM to 1 PM, while evening peak hours were 5 PM to 8 PM and 4 PM to 7 PM, respectively for weekdays and weekends.

The car was vacuum cleaned before starting each trip, and OPC was calibrated and allowed to warm up for 15 min before the trip. The sampling was done with closed windows (as it is the most common setting in winter), while the ventilation setting used were fan—off, re-circulation (RC)—off, and AC—off as this was found to be the highest exposure setting with windows closed [23]. The same driver drove the

Table 1 Technical specification of GRIMM Technik, model 11-A portable aerosol. spectrometer

Technical parameter	Range
Supply voltage	18–24 VDC
Maximum current	2.5 A
Temperature range (operating)	0 to + 40 °C
Max relative humidity (operating)	r.H. < 95% (not condensing)
Sample air temperature	0 to 40 °C
Laser	Wavelength: $\lambda = 600$ nm, Power $P_{max} = 40$ mW
Size channel (μm)	31 channels: 0.25/0.28/0.3/0.35/0.4/0.45/0.5/0.58/0.65/0.7/0.8/1.0/1.3/1.6/2/2.5/3/3.5/4/5/6.5/7.5/8.5/10/12.5/15/17.5/20/25/30/32
Particle concentration	1 to 3,000,000 particles/litter
Sample flow rate	1.2 l/min, ±5% constantly through control
Dust collection	47 mm PTFE filter (without supporting tissue)

Fig. 2 GRIMM Technik, model 11-A portable aerosol spectrometer

car to minimize the variation due to the driver's behaviour. Also, efforts were made to avoid any sudden acceleration or deceleration of the vehicle, while top speed was limited to 50kmph to maintain a constant wind flow inside the car [24–26]. Also, the traffic congestion zone was monitored and marked visually and using Google Maps, while the traffic behaviour was also observed visually. The congestion zones were divided into three categories:

(a) Planned congestion zone (grey columns in Fig. 4): they include traffic signals or manually controlled intersections where the local authorities regulate the traffic stoppage in a planned way.

b) The orange congestion zone (orange columns in Fig. 4): it includes the zone where traffic density was high and the vehicles were moving at a speed below 30 kmph.
c) The red congestion zone (red columns in Fig. 4) includes the zones where the traffic density was dense and the vehicles were halted completely or were moving below 10 kmph.

Both the Orange congestion zone and the Red congestion zone were unplanned zones, and the study only included the unplanned congestion zones having a duration of more than 60 s. The data was collected in the form of PNC as a number per cm^3 from the aerosol spectrometer and stored in an MS Excel spreadsheet. All the data was filtered, sorted, and analysed using the analysis tools of MS Excel, while data interpretation was made using a visual interpretation of the graph.

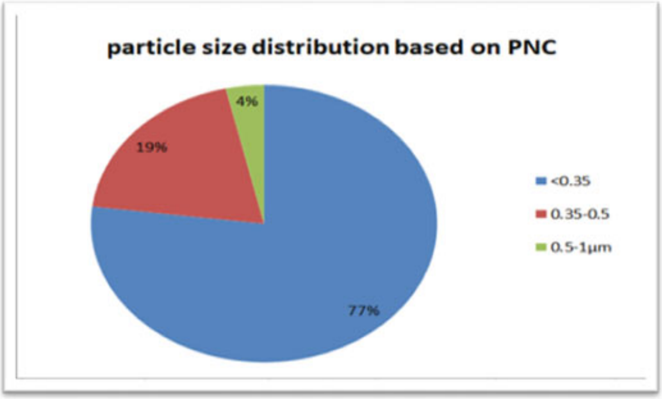
3 Results and Discussions

3.1 Particle Size Distribution

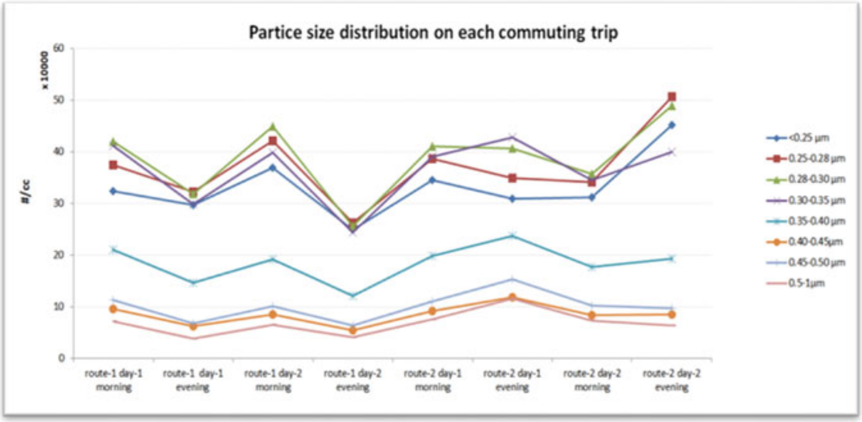
The PNC data was collected for different size bins which were <0.25 µm, 0.25–0.28 µm,0.28–0.30 µm, 0.30–0.35 µm, 0.35–0.40 µm, 0.40–0.45 µm, 0.45–0.50 µm, 0.50–0.58 µm, 0.58–0.65 µm, 0.65–0.7 µm, 0.7–0.8 µm, and 0.8–1.0 µm. Inside the cabin, it was found that the particle size distribution for PM 1 was dominated by the quasi-UFP, contributing nearly 74–80% of the PNC, while the particles having Dp < 0.5 contributed 96–98% of total PNC for PM-1 (as shown in Fig. 3a). This can be attributed to the fact that the smaller size particles are more capable of infiltrating the vehicle cabin [27] and are also in accordance with the general fact that smaller particles make up the bulk of PNC in total PMs [13, 27]. The dominance of small particles in heavy traffic density can also be attributed to the fact that, in Indian metropolitan cities like Delhi, people tend to drive bumper to bumper and as per a study by Xu et al. in 2020, the PNC of smaller particles is higher near the vehicle exhaust and reduces as we move further away [28]. In the study, it was also noticed that the particles having a size range of <0.25 µm, 0.25–0.28 µm, 0.28–0.30 µm, and 0.30–0.35 µm follow a similar trend (as shown in Fig. 3b) and hence they were combined to form a single bin range of <0.35 µm.

3.2 Impact of Traffic Congestion

A direct impact of the congestion zone on the PNC can be seen in Fig. 4a and 4b. During the study, the average PNC was found to be relatively high when the traffic density was high. As per Fig. 4b, Higher PNC was found on weekdays (high traffic density) compared to weekends (low traffic density). A direct link between



a) Particle size contribution based on PNC

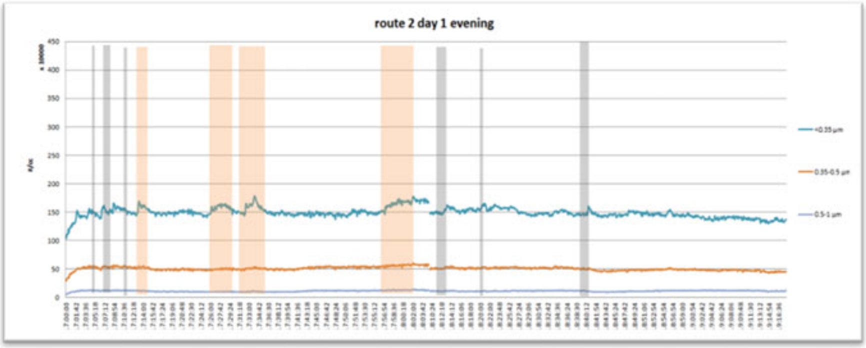


b) Particle size distributions on each commuting trip

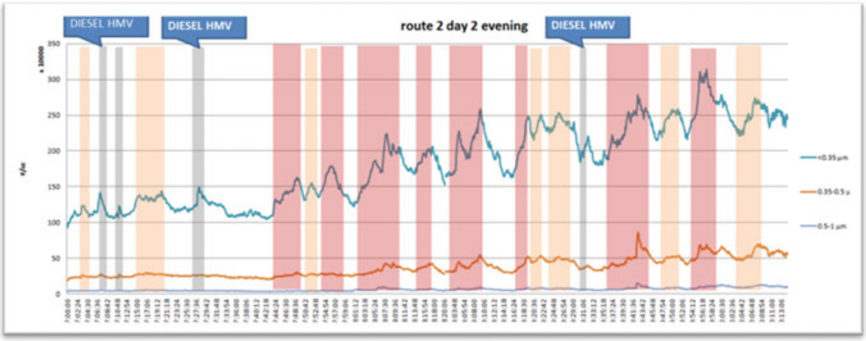
Fig. 3 Particle size distribution

the traffic congestion zone and PNC was observed. It was also observed that the traffic congestion could cause a sudden increase in PNC concentration for quasi-UFP having a size of <0.35 μm. Higher traffic congestion has resulted in higher variation in PNC for qUFP with a standard deviation being as high as 6.6×10^5 #/cc on weekdays while on weekends, the standard deviation was found to be 1.1×10^5 #/cc.

The larger particles (having size > 0.5 μm), on the other hand, show a negligible relationship with traffic congestion as they show a maximum standard deviation of 3.5×10^4 #/cc. This discrepancy between the finer and coarse particles may be due to the different penetration abilities of both particles [29] as well as the fact that in



a) Route-2 evening weekend



b) Route-2 evening weekday

Fig. 4 Impact of traffic congestion zone on PNC (#/cc) weekday versus weekend

the near exhaust environment, the particles emitted from the vehicular exhaust are finer [30, 31].

3.3 Impact of Congestion Zones

For this study, we categorize the congestion zones into three categories, i.e., red zone, orange zone, and planned congestion zone (i.e., traffic signal). During the study, it was observed that amongst the planned and unplanned (red and orange) congestion zones, the planned congestion zone showed a slight increase (i.e., 0.5×10^5–1.5×10^5 #/cc) in the PNC, while the unplanned congestion zone contributed to a significant increase (4×10^5 to 6×10^5 for red zone and 2×10^5 for orange zone) in the PNC of qUFP.

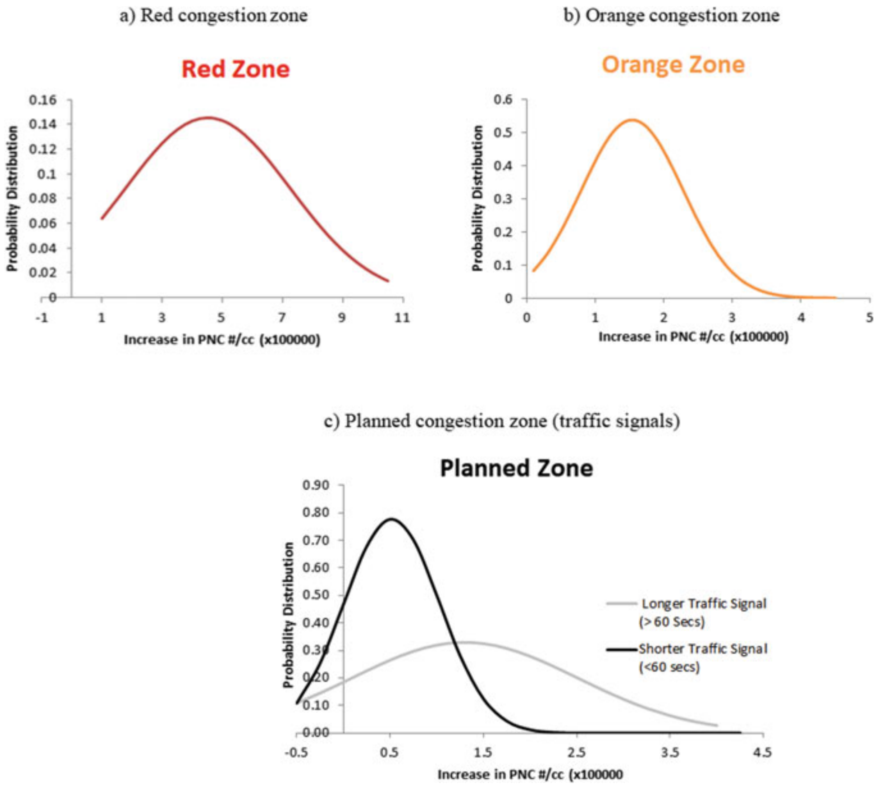


Fig. 5 Probability Distribution of Increase in PNC in different congestion zones

3.3.1 Impact of Red Zones

During the red zone, a quite significant increase was observed in the concentration of qUFP, with an increase as high as 75%, while in terms of PNC, the peak concentration of 3.1×10^6 #/cc was observed during a single red zone. The maximum increase of PNC was noted to be 1×10^6 #/cc, while as Fig. 5a shows, an average increase in the order of 4×10^5 to 6×10^5 #/cc (25–30%) was observed during the red zone. This high increase may be due to the slow speed of vehicles (which contributes to higher PNC formation [32] coupled with the stop-start movement of cars during the red zone and bumper-to-bumper driving) (Rodriguez et al. 2020).

3.3.2 Impact of Orange Zones

A moderate increase was observed during the orange zone in the qUFP concentration. As shown in Fig. 5 b, an average rise of 1.5×10^5 to 2×10^5 #/cc was observed in the orange zone, which was lower than the increase during the red zone. The lower intensity of growth can be attributed to the fact that traffic density was still moving at some pace in the orange zone and there was a relative distance between the vehicles, which allowed for some degree of dilution of particles [33, 34].

3.3.3 Impact of Planned Congestion Zone (Traffic Signals)

A relationship between traffic signal duration and PNC was observed during the study. Traffic signals with a short duration (less than 60 s) show a minor or negligible impact on PNC, as can be seen in Fig. 5c, with a shorter duration signal having a sharper peak and resulting in an average increase of just 0.5×10^5 #/cc. On the other hand, in the case of traffic signals with longer duration (>60 secs), the peak is much damper and, on the right, the average measurable increase in PNC was observed in the order of 1.5×10^5 to 2×10^5 #/cc (Fig. 5 c). A similar rise in PNC was also found by Wang et al. [35].

3.4 Impact of Leading Vehicle or Nearby Vehicles

During the study, a strong relationship was noticed between the increase in PNC and the characteristics of the leading vehicle (i.e., the vehicle in front of the test car) as well as that of nearby vehicles. It was observed that when a large diesel Heavy Motor Vehicle (HMV) like a truck or tractor was present in the vicinity of the test vehicle, it caused a sudden increase in the PNC of quasi-fine particles. An average spike of 20–40% was observed during the study. This can be attributed to diesel engines generating more PNC due to the high sulphur content in diesel [30]. The max increase observed was 75% (9×10^5 #/cc) on the 18th morning. This high peak may be due to the combined effect of the Red zone and the presence of HMV. A similar trend was also observed in the study conducted by [36, 37]. While all the vehicles resulted in some increase in PNC, E-vehicles show the most negligible impact on the PNC, which can be attributed to the fact that E-Vehicle has zero direct emissions.

4 Conclusion

Various studies have shown that whenever a person commutes and spends only a small portion of his daytime, it can contribute up to 50% of their daily fine particle exposure. As per the study conducted by [38], one hour of in-cabin commuting can contribute to up to 50% of fine particle exposure, while a study by [39] in LA found a similar result in which 33–45% of daily fine particle exposure can be linked directly to time spent in commuting (6% of day which is less than Indian average of 7%). This exposure can further increase during congestion, as congestion increases commuting time. This study established a direct relation between congestion and in-cabin concentration of qUFP. During the investigation, it was observed that the PNC was higher (with peak concentration 3.1×10^6 #/cc) on route 2, which has higher traffic density and more congestion zone. Impact on PNC was also found higher (almost 10 times more deviation) on a working day than on a non-working day. The study revealed that unplanned congestion zones (red congestion zone) cause a more potent increase (15% more average increase) in PNC as compared to planned congestion zones. A secondary relationship between the duration of the planned zone was also discovered, with traffic signal having short duration (<60 s) showing a negligible or low impact on PNC of qUFP, while long duration signals (>60 s) showing a visible increase. The impact of the type of nearby vehicle was also visible in the study as the presence of diesel HMV resulted in a massive and sharp spike in PNC for qUFP. Based on the study outcomes, it can be concluded that by reducing the congestion zones and having shorter duration traffic signals, we can reduce the commuter exposure to qUFP by a great extent. During this study, it has been found that the traffic congestion mainly affected the smaller size particles ($D_p < 0.35$ μm) while having no or negligible impact on larger size particles ($D_p > 0.5$ μm).

Due to the limitation of the monitoring instrument, this study focuses on particles up to the range of qUFP, while the Covid conditions limited the sample size to just 1 season. Furthermore, the study's scope was limited to studying the impact of congestion only, and the impact of vehicle condition and driving behaviour were kept constant. Based on the trend observed in this study, it can be assumed that traffic congestion could have a significant impact on the concentration of UFP, further research studying the impact of traffic zone on UFP is needed to be carried out.

References

1. Health Effects Institute. State of Global Air 2019. Heal Eff Institute 24 (2019). https://www.stateofglobalair.org/sites/default/files/soga_2019_report.pdf
2. Kumar P, Robins A, Vardoulakis S, Britter R (2010) A review of the characteristics of nanoparticles in the urban atmosphere and the prospects for developing regulatory controls. Atmos Environ 44:5035–5052. https://doi.org/10.1016/j.atmosenv.2010.08.016
3. IQAir. World Air Quality Report (2019) 2019. World Air Qual Rep 1–35
4. Beig G, Ghude SD, Deshpande A (2010) Scientific evaluation of air quality standards and defining air quality index for India. Indian Inst Trop Meteorol 1–31
5. IQAir. World Air Quality Report (2020) 2020, World Air Qual Rep 1–35
6. Tomtom (2019) Traffic Index results. https://www.tomtom.com/traffic-index/ranking
7. MoveInSync (2019) Indians Spend 7% of Their Day in Office Commute. Travel Time Rep Q1 2019 vs Q1 2018 8
8. Mishra RK, Mishra AR, Pandey A (2020) Commuters' exposure to fine particulate matter in Delhi City. Lect Notes Civ Eng 69:369–377. https://doi.org/10.1007/978-981-15-3742-4_23
9. Nagar J, Akolkar A, Kumar R (2014) A review on airborne particulate matter and its sources, chemical composition and impact on human respiratory system. Int J Environ Sci 5:447–463. https://doi.org/10.6088/ijes.2014050100039
10. World health statistics (2019) WHO world heatlh statistics 2019, 2019th ed. WHO
11. Junaid M, Syed JH, Abbasi NA, Hasmi MZ, Malik RN, Pei DS (2018) Status of indoor air pollution (IAP) through particulate matter (PM) emissions and associated health concerns in South Asia. Chemosphere 191:651–663. https://doi.org/10.1016/j.chemosphere.2017.10.097

12. Hussein T, Hämeri K, Aalto PP, Paatero P, Kulmala M (2005) Modal structure and spatial-temporal variations of urban and suburban aerosols in Helsinki - Finland. Atmos Environ 39:1655–1668. https://doi.org/10.1016/j.atmosenv.2004.11.031
13. Air Quality Expert Group (2018) Ultrafine Particles (UFP) in the UK. 96. https://uk-air.defra.gov.uk
14. Kelly FJ, Fussell JC (2015) Air pollution and public health: emerging hazards and improved understanding of risk. Environ Geochem Health 37:631–649. https://doi.org/10.1007/s10653-015-9720-1
15. Franchini M, Mannucci PM (2007) Short-term effects of air pollution on cardiovascular diseases: Outcomes and mechanisms. J Thromb Haemost 5:2169–2174. https://doi.org/10.1111/j.1538-7836.2007.02750.x
16. Delfino RJ, Sioutas C, Malik S (2005) Potential role of ultrafine particles in associations between airborne particle mass and cardiovascular health. Environ Health Perspect 113:934–946. https://doi.org/10.1289/ehp.7938
17. Das A, Kumar A, Habib G, Vivekanandan P (2020) Insights on the biological role of ultrafine particles of size PM<0.25: A prospective study from New Delhi. Environ Pollut 268:115638. https://doi.org/10.1016/j.envpol.2020.115638
18. Sotty J, Kluza J, Sousa C De, Tardivel M, Antherieu S, Alleman LY, Canivet L, Perdrix E, Loyens A, Marchetti P, Guidice JM Lo, Gorcon G (2020) Mitochondrial alterations triggered by repeated exposure to fine (PM2.5-0.18) and quasi-ultrafine (PM0.18) fractions of ambient particulate matter. Environ Int 142:105830. https://doi.org/10.1016/j.envint.2020.105830
19. Chen R, Hu B, Liu Y, Xu Z, Yang G, Xu D, Chen C (2016) Beyond PM2.5: The role of ultrafine particles on adverse health effects of air pollution. Biochim Biophys Acta – Gen Subj 1860:2844–2855. https://doi.org/10.1016/j.bbagen.2016.03.019
20. Pant P, Habib G, Marshall JD, Peltier RE (2017) PM2.5 exposure in highly polluted cities: A case study from New Delhi, India. Environ Res 156:167–174. https://doi.org/10.1016/j.envres.2017.03.024
21. Onat, B., Şahin, Ü.A., Uzun, B., Akin, U., Özkaya, F., Ayvaz, C.,: Determinants of exposure to ultrafine particulate matter, black carbon, and PM2.5 in common travel modes in Istanbul. Atmos Environ 206:258–270 (2019). https://doi.org/10.1016/j.atmosenv.2019.02.015
22. Li F, Kreis JS, Cyrys J, Wolf K, Karg E, Gu J, Orasche J, Abbaszade G, Peters A, Zimmermann R (2018) Spatial and temporal variation of sources contributing to quasi-ultrafine particulate matter PM0.36 in Augsburg, Germany. Sci Total Environ 631–632:191–200. https://doi.org/10.1016/j.scitotenv.2018.03.041
23. Leavey A, Reed N, Patel S, Bradley K, Kulkarni P, Biswas P (2017) Comparing on-road real-time simultaneous in-cabin and outdoor particulate and gaseous concentrations for a range of ventilation scenarios. Atmos Environ 166:130–141. https://doi.org/10.1016/j.atmosenv.2017.07.016
24. Zhu S, Marshall JD, Levinson D (2016) Population exposure to ultrafine particles: Size-resolved and real-time models for highways. Transp Res Part D Transp Environ 49:323–336. https://doi.org/10.1016/j.trd.2016.09.010
25. Chawla, K., Singh, R., Singh, J (2020) Segregation and recycling of plastic solid waste: a review. In: Lecture Notes in Mechanical Engineering. pp 205–221
26. Campagnolo D, Cattaneo A, Corbella L, Borghi F, Buono LD, Rovelli S, Spinazzé A, Cavallo DM (2019) In-vehicle airborne fine and ultra-fine particulate matter exposure: The impact of leading vehicle emissions. Environ Int 123:407–416. https://doi.org/10.1016/j.envint.2018.12.020
27. Knibbs LD, de Dear RJ, Morawska L (2010) Effect of cabin ventilation rate on ultrafine particle exposure inside automobiles. Environ Sci Technol 44:3546–3551. https://doi.org/10.1021/es9038209
28. Xu G, Wang J, Qiao X (2020) Numerical study on evolution of ultrafine particles emitted from vehicle exhaust with multi-dynamical behaviors. Atmos Environ 244:117916. https://doi.org/10.1016/j.atmosenv.2020.117916

29. Lee ES, Stenstrom MK, Zhu Y (2015) Ultrafine particle infiltration into passenger vehicles. Part I: Experimental evidence. Transp Res Part D Transp Environ 38:156–165. https://doi.org/10.1016/j.trd.2015.04.025
30. Banerjee T, Christian RA (2018) A review on nanoparticle dispersion from vehicular exhaust: Assessment of Indian urban environment. Atmos Pollut Res 9:342–357. https://doi.org/10.1016/j.apr.2017.10.009
31. Zhong J, Nikolova I, Cai X, MacKenzie AR, Harrison RM (2018) Modelling traffic-induced multicomponent ultrafine particles in urban street canyon compartments: Factors that inhibit mixing. Environ Pollut 238:186–195. https://doi.org/10.1016/j.envpol.2018.03.002
32. Bhardawaj A, Habib G, Kumar A, Singh S, Nema AK (2017) A review of ultrafine particle-related pollution during vehicular motion, health effects and control. J Environ Sci Public Heal 01:268–288. https://doi.org/10.26502/jesph.96120024
33. Chang VWC, Hildemann LM, Chang CH (2009) Dilution rates for tailpipe emissions: Effects of vehicle shape, tailpipe position, and exhaust velocity. J Air Waste Manag Assoc 59:715–724. https://doi.org/10.3155/1047-3289.59.6.715
34. Rodriguez R, Murzyn F, Mehel A, Larrarte F (2020) Dispersion of ultrafine particles in the wake of car models: A wind tunnel study. J Wind Eng Ind Aerodyn 198:104109. https://doi.org/10.1016/j.jweia.2020.104109
35. Wang Y, Zhu Y, Salinas R, Ramirez D, Karnae S, John K (2008) Roadside measurements of ultrafine particles at a busy urban intersection. J Air Waste Manag Assoc 58:1449–1457. https://doi.org/10.3155/1047-3289.58.11.1449
36. Strawa AW, Kirchstetter TW, Hallar AG, Ban-Weiss GA, McLaughlin JP, Harley RA, Lunden MM (2010) Optical and physical properties of primary on-road vehicle particle emissions and their implications for climate change. J Aerosol Sci 41:36–50. https://doi.org/10.1016/j.jaerosci.2009.08.010
37. Tsang H, Kwok R, Miguel AH (2008) Pedestrian exposure to ultrafine particles in Hong Kong under heavy traffic conditions. Aerosol Air Qual Res 8:19–27. https://doi.org/10.4209/aaqr.2007.09.0041
38. Zhu Y, Eiguren-Fernandez A, Hinds WC, Miguel AH (2007) In-cabin commuter exposure to ultrafine particles on Los Angeles freeways. Environ Sci Technol 41:2138–2145. https://doi.org/10.1021/es0618797
39. Fruin S, Westerdahl D, Sax T, Sioutas C, Fine PM (2008) Measurements and predictors of on-road ultrafine particle concentrations and associated pollutants in Los Angeles. Atmos Environ 42:207–219. https://doi.org/10.1016/j.atmosenv.2007.09.057