Exposure to particulate matter in different private commuting modes in Salem, India

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Abstract. In our modern world, peoples are spending more time inside the vehicles in urban areas. This study assessed one of the critical pollutant of particulate matter PM₁₀ (aerodynamic size ≤ 10 μm) in six private vehicles: hatchback car, sedan car, sports utility vehicle (SUV) car, multi utility vehicle (MUV) van, auto rickshaw, and motorcycle. PM pollutant in car and van transport modes evaluated under four different ventilation settings (air-conditioning (AC) ON/OFF; windows closed/open). In addition, air temperature (T) and relative humidity (RH) also assessed in six vehicles. The maximum PM exposure concentration was recorded in an auto-rickshaw, which is 4.28 times higher than the national pollution criteria. PM concentration lowered to 3.73, 1.94, and 1.53 times in hatchback, sedan and SUV transport modes, respectively while altering ventilation condition from windows open to windows closed (AC ON) settings. There is no statistical significant difference (p ˃ 0.05) between the transport modes of auto rickshaw-SUV, motorcycle-MUV, and motorcycle-sedan. All PM, T and RH parameters were correlated in car (AC ON) and auto-rickshaw transports.

1 Introduction
Indoor air quality (IAQ) generally describes the quality of air being in indoor buildings. However, in our today world peoples also spending more time in vehicles for a commute. Private vehicles have small spaces compared with buildings, so commuters can easily exposed to pollutant while travelling. IAQ is one of the comprised factors of indoor environmental quality (IEQ). IEQ includes thermal comfort (temperature and relative humidity (RH), lighting comfort, acoustic comfort, and IAQ. In this study, IAQ critical pollutant of particulate matter PM₁₀ were evaluated in six private transport modes. The aerodynamic size for PM₁₀ lies between 2.5 to 10 μm. Besides, thermal comfort parameters of temperature and RH also measured inside the vehicles.

The previous studies have shown that exposure to PM pollutants can cause cardiovascular diseases and respiratory problems [1, 2]. Only less number of studies are available related to particulate matter exposure concentration in vehicles [3-6]. PM₂.₅, ultrafine PM (particle number) and CO were measured in Jakarta, Indonesia, world largest pollutant traffic exposure, detected that mean concentration of pollutant was higher in public transport than the cars [7]. A study conducted in Seoul, Republic of Korea, the restaurant’s microenvironment had the highest particulate matters exposure than the offices, schools, buses and walking, as a result of cooking food in restaurants [8]. D.U Park et al. reported that PM₂.₅ and PM₁₀ are higher in trains than on platforms, owing to the absence of mechanical ventilation systems [9]. Table 1 summarizes the mean concentration of PM₁₀ in various location within the transports.

Most of the earlier studies of IAQ pollutants are carried out only in indoor buildings, and very least studies have been carried out in low volume space of indoor vehicles especially in India, which is third
largest pollution country in the world. The present study was measured the particulate matter PM$_{10}$ in various private vehicles. Also, evaluated the PM concentration under four different ventilation settings in four-wheeler transports (car and van). Independent 2 sample t-test was used to analyze the measured data.

**Table1.** Past studies mean PM$_{10}$ concentration in different transport modes with location.

| Past studies          | Transports          | PM$_{10}$ (μg/m$^3$ ± SD) | Location            |
|-----------------------|---------------------|---------------------------|---------------------|
| Park and Ha [9]       | Train               | 144 ± 13.1                | Seoul, Korea        |
| Chan et al. [10]      | Tram                | 175                       | Hong Kong, China    |
|                       | Bus (NAC)           | 112                       |                     |
|                       | Bus (AC)            | 74                        |                     |
|                       | Taxi                | 58                        |                     |
|                       | Ferry               | 81                        |                     |
| Strasser et al. [11]  | Bus                 | 41.4                      | Vienna, Austria     |
|                       | Tram                | 73.2                      |                     |
|                       | Bicycle             | 16.7                      |                     |
| Zagury et al. [12]    | Car                 | 168 ± 53                  | Paris, France       |
| Geiss et al. [13]     | Car                 | 48.6                      | Ispra, Italy        |

2 Experiments

2.1 Description of study location and routes

This study was carried out in the Salem urban, which is situated in the southern Indian state of Tamil Nadu. The city is located in latitude 11° 39' 51.5700'' North and longitude 78° 8' 45.6396'' East with an altitude of 278 m above sea level. Salem city is the 6th largest population (9,19,150) among the 32 urban agglomerations population of one lakh and above people in the state of Tamil Nadu, India [14].

![Figure1. Map showing the measured routes of Salem city.](image)

All vehicle runs were start and end at the Sona College of Technology bus stop. Six traffic signals have on predefined routes: Hasthampatty Roundabout, ThiruvalluvarSillai, Four Roads, New Bus Stand, Three Roads and Railway Junction is shown in Figure 1. The routes covered a total distance of ~14 km
length. The selected route experiences a high flow of vehicles (~6000 vehicles per hour) during rush hours in Salem city on weekdays and background site includes both anthropogenic (malls, shops, schools, colleges, banks) and non-anthropogenic (parks, no land use) activities. All vehicles were measured during the winter month of November 2019 at evening peak hour. Because, PM concentrations are mostly high during evening period compared to morning [15]. A bridge construction work was undergone in predefined routes.

2.2 Measurements
A portable handheld instrument of IAQ 3007R (Rave Innovations, Noida, UP, IN) was used to measure PM, air temperature, and RH is shown in Figure 2. The maximum range of PM$_{10}$ can measure up to 1000 µg/m$^3$. IAQ 3007R device is working under the principle of light scattering method. Before the experiments, the instrument was calibrated by the manufactures. The device was set to record at a one-minute time interval, and soon after, the values were dragged to the data acquisition system (laptop).

This is the first study in Salem city regarding commuter exposure assessment in transport modes. The vehicles were chosen based upon easily available private transports: hatchback car, sedan car, sports utility vehicle (SUV) car, multi utility vehicle (MUV) van, auto-rickshaw and motorcycle. The typical specification of measured transport modes is given in Table 2. The selected vehicles were often using by inhabitants in predefined routes. Before the runs, ensured all vehicles usage were within two years from the delivery date. All vehicles are manufactured in the same local company except auto rickshaw. Because that renowned company not manufactured auto rickshaw. Car and van transports are right-side driving. All private transports tested with two passengers, including the driver. The portable PM sensing device was fixed at the backseat of car and van transport adjacent to a commuter. However, the device was engaged by hand itself in motorcycle and auto rickshaw.

![Image of indoor air quality monitor (IAQ 3007R).](image)

### Table 2. Measured transport modes.

| Transport       | Fuel type | Speedometer (km) | Air conditioned |
|-----------------|-----------|------------------|-----------------|
| Hatchback car   | Petrol    | 12805            | Yes             |
| Sedan car       | Petrol    | 8272             | Yes             |
| SUV car         | Diesel    | 22273            | Yes             |
| MUV van         | LPG       | 29320            | No              |
| Auto-rickshaw   | Diesel    | 11096            | No              |
| Motorcycle      | Petrol    | 3796             | No              |

2.3 Methods
Before testing the car and van transports, doors are opened for 10 min to equalise the outdoor environment concentrations to indoor vehicles. The portable device was started as early as 15 min ahead of commencing each test. In order to avoid the interruption during measuring, smoke-free drivers are supported throughout
the experiments. Therefore the drivers are fully aware of the target of the investigations. The following four feasible ventilation conditions are considered in air-conditioned cars:

- Windows open and fresh air supply mode (WO-FAS) with air-conditioning OFF
- Windows open and recirculation mode (WO-RC) with air-conditioning OFF
- Windows closed and fresh air supply mode (WC-FAS) with air-conditioning ON and
- Windows closed and recirculation mode (WC-RC) with air-conditioning ON

However, in non-air-conditioned MUV van, the above ventilation conditions are repeated without air conditioning mode. The fan speed was set to average for all the ventilation conditions. The ventilation conditions are successively changed to every 3.5 km in above order to track the sudden variations of PM concentrations for different settings. For the motorcycle and auto rickshaw transports, the ventilation conditions are inappropriate. Three test runs are carried out on each vehicles in different weekdays.

3 Results and discussion

3.1 Particulate Matter

For good health conditions, National Ambient Air Quality Standards (NAAQS) recommended the acceptable limit for coarse particle PM$_{10}$ is $100 \, \mu g/m^3$ [16]. The descriptive statistical data of PM$_{10}$ for the different transport modes is given in Table 3. The maximum PM exposure was obtained in an auto-rickshaw ($428.24 \, \mu g/m^3$), which is 4.28 times higher than the NAAQS. The auto-rickshaw have a vast opening in an enclosed compartment to ingress exhaust and non-exhaust particles compared to other transports.

Table 3. Descriptive statistical data of particulate matter PM$_{10}$ for the different transport modes.

| Transport | Ventilation condition | Min$^*$ (µg/m$^3$) | Max$^*$ (µg/m$^3$) | Mean (µg/m$^3$) | SD$^*$ (µg/m$^3$) | CV$^*$ (%) |
|-----------|-----------------------|---------------------|---------------------|-----------------|-----------------|-----------|
| Motorcycle| -                     | 52.68               | 334.35              | 126.07          | 67.51           | 53.55     |
| Auto-rickshaw | -                   | 178.63              | 428.24              | 266.07          | 54.28           | 20.4      |
| Hatchback | WO-FAS                | 43.52               | 155.73              | 99.31           | 35.02           | 35.26     |
|           | WO-RC                 | 50.39               | 148.86              | 101.69          | 33.5            | 32.95     |
|           | WC-FAS                | 38.94               | 160.31              | 69.09           | 33.15           | 47.99     |
|           | WC-RC                 | 16.04               | 45.81               | 27.24           | 10.65           | 39.09     |
| Sedan     | WO-FAS                | 183.21              | 281.68              | 238.17          | 36.02           | 15.12     |
|           | WO-RC                 | 167.18              | 293.13              | 212.98          | 43.48           | 20.41     |
|           | WC-FAS                | 158.02              | 258.78              | 198.41          | 30.11           | 15.17     |
|           | WC-RC                 | 61.84               | 178.63              | 109.24          | 37.64           | 34.46     |
| SUV       | WO-FAS                | 194.66              | 380.15              | 275.64          | 53.58           | 19.44     |
|           | WO-RC                 | 231.3               | 370.99              | 297.25          | 51.76           | 17.41     |
|           | WC-FAS                | 215.27              | 350.38              | 266.22          | 36.1            | 13.56     |
|           | WC-RC                 | 146.57              | 270.23              | 193.52          | 45.12           | 23.32     |
| MUV       | WO-FAS                | 77.87               | 139.7               | 97.97           | 20.6            | 21.03     |
|           | WO-RC                 | 96.19               | 183.21              | 118.4           | 26.92           | 22.74     |
|           | WC-FAS                | 98.48               | 139.7               | 112.98          | 13.84           | 12.25     |
|           | WC-RC                 | 91.61               | 153.44              | 114.51          | 20.61           | 18        |

*Min - minimum; Max - maximum; SD - standard deviation; CV - coefficient of variation.

The lowest mean PM concentration of hatchback, sedan and SUV were $27.24 \pm 10.65 \, \mu g/m^3$, $109.24 \pm 37.64 \, \mu g/m^3$ and $193.52 \pm 45.12 \, \mu g/m^3$, respectively under WC-RC ventilation mode. Except hatchback, other two car transport (sedan and SUV) mean PM concentration exceeds the NAAQS limit. Figure 3 depicted the boxplot of PM$_{10}$ concentration for the six private vehicles. The middle line of the boxes represents mean PM exposure. From figure 3, it is noticed that hatchback only the transport meets
the PM standards (<100 μg/m$^3$) of NAAQS. The mean PM levels of motorcycle and auto rickshaw were 1.26 and 2.66 times higher than the national standards, respectively.

![Box plot of particulate matter PM$_{10}$ for the six different transport modes.](image)

**Figure 3.** Box plot of particulate matter PM$_{10}$ for the six different transport modes.

World health organization (WHO) recommended 24-h exposure limit is 50 μg/m$^3$ [17]. According to WHO, hatchback transport meets the requirements under windows closed recirculation mode ventilation settings. When comparing the cabins of hatchback, sedan, SUV, and MUV, hatchback car have a low volume interior space. It means occupants PM exposure concentration get higher when the volume of vehicle compartments higher. SUV, auto rickshaw, and sedan mean PM concentration were 2.35, 2.11, and 1.88 times higher than the motorcycle concentrations, respectively. However, hatchback and MUV mean PM concentration were 1.23 and 1.01 times lower than the motorcycle.

In this study, independent 2 sample t-test was used to find PM exposure difference between the vehicles with a 95% confidence level. Completely fifteen t-tests were carried out among the six vehicles. The independent 2 sample t-test between the transport modes is given in Table 4. For our climatic conditions, usually, car occupants are approach windows closed (AC ON) ventilation settings and Non AC van occupants approach windows open ventilation settings. The above two settings of samples are taken for t-test to the corresponding vehicles. There is no statistically significant difference between the auto rickshaw-SUV, motorcycle-MUV, and motorcycle-sedan (p > 0.05) at 95% confidence level. It shows that auto-rickshaw and SUV commuters are exposed to the same level of PM$_{10}$ concentrations. Similarly, between motorcycle/MUV and motorcycle/sedan transports.

While there is a significant difference between AC mode and non AC mode ventilation settings in car transports for PM exposure is shown in Figure 4. It is clearly shown that PM exposure was lower during AC ON setting (windows closed) than the AC OFF (windows open). Even PM concentration are lowered from fresh air supply mode (FAS) to recirculation mode (RC) ventilation settings in car transports. PM levels were 3.73, 1.94, and 1.53 times lowered in hatchback, sedan and SUV, respectively, when car settings altered from windows open to windows closed. In MUV van transport mode, the mean PM$_{10}$ was 108.72 ± 25.71 μg/m$^3$ and 113.75 ± 17.05 μg/m$^3$ for windows open and windows closed, respectively. Therefore, it is concluded that PM exposure in Non AC MUV vehicles acts consistently on both windows opened and windows closed settings.
Table 4. Independent 2 sample t-test for particulate matter PM$_{10}$ between the transport modes.

| t-test | Transports      | Mean (µg/m$^3$) | SD (µg/m$^3$) | Mean difference (µg/m$^3$) | t     | p-value |
|--------|-----------------|-----------------|---------------|-----------------------------|-------|---------|
| 1      | Motorcycle      | 128.4           | 69.5          | -137.7                      | -9.63 | < 0.001 |
|        | Auto rickshaw   | 266.1           | 54.3          | -137.7                      | -9.63 | < 0.001 |
| 2      | Motorcycle      | 126             | 65.4          | 74.8                        | 4.67  | < 0.001 |
|        | Hatchback       | 51.2            | 33.2          | 2                         | 0.119*|
| 3      | Motorcycle      | 126             | 65.4          | 24.6                        | 0.136*|
|        | Sedan           | 155.9           | 56.3          | -29.9                       | -1.59 | 0.119* |
| 4      | Motorcycle      | 129.6           | 64.9          | 24.6                        | 0.136*|
|        | SUV             | 237.1           | 53.3          | -107.5                      | -5.73 | < 0.001 |
| 5      | Motorcycle      | 133.3           | 64.4          | 24.6                        | 0.136*|
|        | MUV             | 108.7           | 25.7          | 17.06                       | < 0.001|
| 6      | Auto rickshaw   | 261.9           | 45.9          | 201.7                       | 17.06 | < 0.001|
| 7      | Auto rickshaw   | 261.9           | 45.9          | 106                         | 6.69  | < 0.001|
| 8      | Auto rickshaw   | 262.4           | 47            | 25.3                        | 1.59  | 0.12*   |
| 9      | Auto rickshaw   | 262             | 48.3          | 25.3                        | 1.59  | 0.12*   |
|        | MUV             | 108.7           | 25.7          | 153.3                       | 12.22 | < 0.001|
| 10     | Hatchback       | 51.2            | 33.2          | -104.7                      | -7.35 | < 0.001|
|        | Sedan           | 155.9           | 56.3          | -73.5                       | < 0.001|
| 11     | Hatchback       | 45.7            | 22.4          | -191.44                     | -14.81| < 0.001|
|        | SUV             | 237.1           | 53.3          | -191.44                     | -14.81| < 0.001|
| 12     | Hatchback       | 43.04           | 19.5          | 65.66                       | -8.88 | < 0.001|
|        | MUV             | 108.7           | 25.7          | 46.1                        | 3.11  | 0.005   |
| 13     | Sedan           | 155.8           | 57.8          | 3                     | 0.005 |
|        | SUV             | 237.1           | 53.3          | -81.3                       | -4.62 | < 0.001|
| 14     | Sedan           | 154.8           | 59.2          | 46.1                        | 3.11  | 0.005   |
|        | MUV             | 108.7           | 25.7          | 122.5                       | 9.9   | < 0.001|

*no significant difference (p > 0.05)
3.2 Air temperature

The maximum air temperature of 39.9°C has obtained in the Non AC (windows closed) MUV transport mode. Temperature difference for the different transport modes is shown in Figure 5. The minimum temperature of 24.5°C was obtained in AC sedan transport under WC-RC ventilation condition. According to the ASHRAE, the indoor thermal comfort air temperature could range from 19.6°C to 27.9°C [18]. The sedan and hatchback vehicles were achieved the ASHRAE limit under WC-RC condition. Compared the sedan minimum temperature to other vehicles minimum temperature, the differences were 3.3°C, 4.4°C, 8.7°C, 8.1°C, and 10°C for the hatchback, SUV, motorcycle, auto-rickshaw and MUV, respectively.

3.3 Relative humidity (RH)

Generally, acceptable RH is < 65% recommended by ASHRAE, because more than that can lead to microbial growth [19]. The RH may well change influenced by the air temperature. However, RH was below the ASHRAE standards in all the transport modes is shown in Figure 6. RH gradually

Figure 4. Boxplot of particulate matter PM$\text{_{10}}$ exposure between AC and Non AC ventilation mode in car transports.

Figure 5. Temperature difference obtained in six transport modes.
increased when the ventilation condition changed from WC-FAS to WC-RC. The RH difference was 3%, 8% and 13% attained for the motorcycle, auto rickshaw and MUV transport modes, respectively.

Figure 6. Maximum relative humidity obtained in six transport modes.

3.4 Correlation between PM$_{10}$, air temperature (T), and relative humidity (RH)

The correlation analysis shows any relation among the parameters of PM, T and RH in different modes of transport. Pearson correlation between PM, T and RH of six vehicles at 95% confidence level is given in Table 5. As like before, for correlation analysis also windows closed (AC ON) sample were taken for car transport and windows open sample were considered for van. All parameters are correlated in AC cars and auto-rickshaw vehicles. As we know that, temperature and RH parameters are always correlated. According to that in all transport modes, T/RH was correlated with p-value $\leq$ 0.001. However, for MUV van PM$_{10}$/T and PM$_{10}$/RH parameters are not correlated due to windows open and Non AC vehicle. Similarly, PM$_{10}$/T and PM$_{10}$/RH parameters are not correlated for motorcycle due to directly exposure to outdoor concentrations.

Table 5. Pearson correlation between the PM$_{10}$, air temperature (T), and relative humidity (RH) in six vehicles.

| Transport       | PM$_{10}$/T Pearson Correlation (r) | P-value | PM$_{10}$/RH Pearson Correlation (r) | P-value | T/RH Pearson Correlation (r) | P-value |
|-----------------|-----------------------------------|---------|------------------------------------|---------|-----------------------------|---------|
| Hatchback car   | 0.918                             | <0.001  | -0.745                             | <0.001  | -0.931                      | <0.001  |
| Sedan car       | 0.755                             | <0.001  | -0.719                             | <0.001  | -0.896                      | <0.001  |
| SUV car         | 0.881                             | <0.001  | -0.690                             | <0.001  | -0.722                      | <0.001  |
| MUV van         | 0.409                             | 0.092*  | -0.448                             | 0.062*  | -0.862                      | <0.001  |
| Auto rickshaw   | 0.529                             | 0.001   | -0.350                             | 0.031   | -0.684                      | <0.001  |
| Motorcycle      | -0.222                            | 0.164*  | -0.309                             | 0.052*  | -0.486                      | 0.001   |

* no significant correlation (p$>$0.05)

4 Conclusions

The mean PM exposure in hatchback, sedan, SUV, MUV, auto rickshaw, and motorcycle transport were 27.24 (WC-RC), 109.24 (WC-RC), 193.52 (WC-RC), 97.97 (WO-FAS), 266.07, and 126.07 µg/m$^3$, respectively. The least PM concentration obtained in hatchback (16.04 µg/m$^3$) under windows closed recirculation mode (AC ON) condition. PM exposure concentration was increased according to the indoor volume of car vehicles increased. Occupants are exposed to high PM concentration during windows open than the windows closed (AC ON). The independent 2 sample t-test showed no statistically significant
difference (p > 0.05) between the auto rickshaw-SUV, motorcycle-MUV, and motorcycle-sedan. All measured parameters of PM, air temperature (T), RH were significantly correlated (P ≤ 0.001) in the car and auto-rickshaw vehicles. Finally, suggesting the commuters operate vehicles under air-conditioning mode to expose below acceptable limit of pollutant.

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