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Research Paper

Commuter exposure concentrations and inhalation doses in traffic and residential routes of Vellore city, India

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ABSTRACT

Commuting adds a significant proportion to the total $PM_{2.5}$ and PM_1 exposure concentration, especially in urban areas. However, spatial and inter-day variations of commuter exposure concentrations are rarely assessed in India. This study investigates the personal exposure concentration of $PM_{2.5}$ and PM_1 in Vellore city, India while commuting in active (pedestrian and bicycle) and motorized (motorbike, car, auto-rickshaw, and bus) transport modes. A total of 312 one-way trips were completed in urban traffic route and residential route during morning and afternoon periods to assess spatial and inter-day variations. The inhaled dose per trip and inhaled dose per kilometre travelled were also estimated using exposure concentrations, minute ventilation rates, travel time, and distance travelled. Irrespective of travel mode, $PM_{2.5}$ and PM_1 exposure concentrations in traffic route was consistently higher than the residential route. Morning trips were highly polluted than afternoon trips in traffic route, whereas afternoon trips registered marginally higher concentration than morning trips in the residential route. Motorized transport modes were observed with the highest exposure concentration compared to active commuters in both traffic and residential routes. Median $PM_{2.5}$ and PM_1 exposure concentration of motorized commuters across all routes and trips ranged from 54 to 202 and 21–153 μg m^{-3}. Car commuters experienced the highest $PM_{2.5}$ and PM_1 exposure concentration. Pedestrian and bicycle commuters registered maximum inhaled doses per trip in traffic and residential routes, respectively. Also, inhaled doses per kilometre travelled in active commuters were 4–8 times higher than motorized commutes. Motorbike commuters experienced the lowest doses among all six commutes.

1. Introduction

Road transport is found to be the primary source of air pollutants in the urban environment (Banerjee et al., 2015; Pokorná et al., 2015; Jithin et al., 2019). Among various pollutants emitted from road traffic, particulate matter with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) is considered as a crucial criteria pollutant. $PM_{2.5}$ physical properties such as mass, density, and morphology vary spatially and temporally (Pitz et al., 2008; Pipal et al., 2011; Javed et al., 2015; Pikridas et al., 2018; Yadav et al., 2020). Urban $PM_{2.5}$ is mainly composed of carbon compounds, ions, and elements, and these compositions are known to be originated from traffic related sources (tailpipe emissions, resuspended road dust, brake wear, and tyre wear), industrial emissions, biomass burning, and sea salt emissions. (Thorpe and Harrison, 2008; Srimuruganandam and Shiva Nagendra, 2012; Murillo et al., 2013; Cesari et al., 2016; Huamán et al., 2019; Pio et al., 2020; Sadeghi et al., 2020). $PM_{2.5}$ and PM_1 (aerodynamic diameter ≤ 1 μm) can easily enter the commuter respiratory tract and cause the onset of various health effects depending upon the amount of dose and deposited location in the lungs (Subramaniam et al., 2003; Manigrasso et al., 2017; Manojkumar et al., 2019). Epidemiological studies showed a strong association of traffic generated $PM_{2.5}$ and its components with short- and long-term health effects such as declined cognitive functions, respiratory hospital admissions, cardiovascular hospital admissions, respiratory mortality, lung cancer mortality and cardiovascular mortality (Brunekreef et al., 2009; Ostro et al., 2011; Heo et al., 2014; Atkinson et al., 2016; Samoli et al., 2016; Shehab and Pope, 2019). Therefore, assessment of commuter exposure concentration is essential for health effect studies and local policymaking.

Personal exposure studies conducted across different

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microenvironments (home, workplace, transit and outdoor) showed that commuting activity contributes a significant proportion to daily exposure (Fondelli et al., 2008; Pant et al., 2017; Carvalho et al., 2018; Koehler et al., 2019). Various travel modes such as pedestrian, cycling, car, bus, motorbike, train, and tram are adopted for measuring commuter exposure concentration (Chaney et al., 2017; Hernández--Paniagua et al., 2018; Kolluru et al., 2018; Borghi et al., 2019; Abbass et al., 2020; Torkmahalleh et al., 2020). Closer proximity to on-road air pollutants is found to be the major reason behind high exposure concentration (Kaur et al., 2007; Tsai et al., 2008; Ragettli et al., 2013; Jiao and Frey, 2014; Correia et al., 2020). Studies showed that commuters experienced unequal exposure to air pollutants due to the type of transport mode, route travelled, and fuel type used. For instance, car and bus commuters travelling with closed windows are protected from ambient pollution and experience less exposure concentration. In the case of active transport, the commuters are directly exposed to ambient pollutants. Thus, the transport mode plays a major role in daily personal exposure concentration (Suárez et al., 2014; Targino et al., 2018; Velasco et al., 2019). Also, commuters experience elevated exposure concentration in high traffic routes when compared to low traffic routes (McNabola et al., 2008; Liu et al., 2015). In the case of fuel type, the in-vehicle exposure concentration is observed higher in gasoline car when compared to diesel car (Zuurbier et al., 2010). Other influencing factors of personal exposure concentration are the time of travel (season and time of the day), characteristics of the travelled path (street or road configurations) and meteorological conditions (Betancourt et al., 2017; Onat et al., 2019; Polednik and Piotrowicz, 2019; Krecl et al., 2020). Further, among socio-economic groups, it is found that the most deprived income group experiences higher exposure concentration while commuting in London (Rivas et al., 2017).

According to the Exposure Factor Handbook of United States Environmental Protection Agency (US EPA, 2011) and China (Duan, 2013), people spend an average of 63–87.4 min in daily transit. Although the duration of commuter exposure is very short, the high exposure concentration will lead to maximum inhaled doses (Tsai et al., 2008; Yu et al., 2012). Thus, in addition to personal exposure concentration, many studies have quantified the inhaled doses. The inhaled doses are usually high in active commuters (walking and cycling) when compared to motorized commuting (car, bus and motorbikes) (Cepeda et al., 2016). This is because of higher tidal volume and breathing frequency in active commuters than motorized commuters (McNabola et al., 2008). This higher inhalation dose will result in maximum lung deposition, which leads to various diseases (Nyhan et al., 2013). Therefore, transport mode specific inhalation dose estimation is crucial for health assessment studies.

Despite knowing the importance of commuter exposure concentration and its inhalation doses, studies are limited in the Indian context. Especially, the most preferred means of commuting such as bicycle, motorbike, and auto-rickshaw are rarely assessed. Moreover, most of the earlier Indian studies are restricted to megacities viz., Delhi, Chennai, and Mumbai (Apte et al., 2011; Goel et al., 2015; Namdeo et al., 2016; Kumar and Gupta, 2016; Pant et al., 2017; Jain, 2017; Raj and Karthikeyan, 2019). Hence, this study aims to measure and compare the commuter exposure concentration and its inhalation doses in a medium-sized city (Vellore, Tamil Nadu state) while travelling in different transport modes viz., pedestrian, bicycle, motorbike, car, auto-rickshaw, and bus. Further, we assessed the variations experienced by commuters travelling in residential route (roads in the residential sector) and traffic route (major roads connecting essential places of city) during different times of the day (morning and afternoon).

2. Methodology

2.1. Study area and route description

Vellore city covers an area of 87.92 Km^2 with a population of 1,85,803 people. Recently, this city is selected under the Smart Cities Mission by the Ministry of Housing and Urban Affairs, Government of India (SCM, 2017). Our study area is located in the northernmost part of Tamil Nadu state and share its border with the adjacent state Andhra Pradesh. Hence in addition to city traffic, Vellore receives additional traffic from Andhra Pradesh state. Measurements were carried out in traffic and residential routes to assess the variation of commuter exposure concentration in different urban environments, as shown in Fig. 1. The traffic route is 8 km long, and it starts from city railway junction and ends near Vellore corporation office. Traffic route runs through the city's major road intersections, Vellore fort (tourist place), museum, two bus stations, hospital (largest in the state), and commercial locations. The traffic route has four lanes with 13 traffic signals and 16 bus stops. Also, the selected traffic route is the only way vehicles can enter or leave the Vellore from nearby states and cities. The residential route is 3 km long and covers Gandhi Nagar (one of the residential areas) in Vellore. The selected road segments in the residential route are two-lane and have several street intersections. Public bus services are not available to cover the whole residential route. Hence, people in this locality mostly prefer private transportation and auto-rickshaws.

2.2. Instrumentation

$PM_{2.5}$ and PM_1 were measured using a portable SidePak aerosol monitoring instrument (AM520, TSI Inc., USA). Several studies used this instrument previously (Fan et al., 2009; Molle et al., 2013; Chaney et al., 2017; Zhang et al., 2018). It measures real-time $PM_{2.5}$ and PM_1 mass concentration by light-scattering laser photometer technology. AM520 can measure particle mass concentration in the range of 0.001–100 mg m^{-3}. The instrument's operating relative humidity and temperature range from 0 to 95% and 0–50 °C, respectively. The instrument was zero calibrated every day before sampling and at the time of changing impactor using zero filter. Flowmeter (Make: TSI, Model: 4146) was used periodically for ensuring the constant flow rate of 1.7 L per minute. The instrument was enabled to log minute wise data continuously throughout the trip. AM520 was factory calibrated to the respirable fraction of ISO 12103–1, A1 Test Dust. However, the optical properties of ambient aerosol are usually different from A1 test dust resulting in overestimation of ambient concentration (Jiang et al., 2011; Yun et al., 2015). Hence a calibration factor should be used for reporting measured values. Since we did not perform gravimetric measurements, an ambient calibration factor was chosen based on the suggestions given by instrument manufacturer (TSI-Inc, 2013). This calibration factor was derived from the relationship established by Wallace et al. (2011). The relative humidity is also known to cause overestimation of ambient aerosol concentration due to the uptake of water vapor by particles (Chakrabarti et al., 2004). Thus, the effect of relative humidity was corrected by using the approach (Eq. (1)) given in Ramachandran et al. (2003). This equation was adopted in earlier exposure concentration studies (Apte et al., 2011; Goel et al., 2015; Tan et al., 2017; Yang et al., 2019).

$$\text{Correction factor} = 1 + \frac{0.25^{*}\,\textit{Relative Humidity}^2}{1 - \textit{Relative Humidity}} \tag{1}$$

Meteorological data such as relative humidity, temperature, and wind speed during all sampling trips were collected from the nearby weather station (Table 1).

2.3. Sampling protocol

Commuter exposure was measured in six transport modes viz., walking, cycling, motorbike (Hero Honda Splendor-NxG, and petrol engine), car (Chevrolet Tavera, 2015 model and diesel engine), auto-rickshaw (Bajaj-RE, 2017 model and petrol engine) and bus. Sampling in car and bus were taken under non-air conditioned and open window

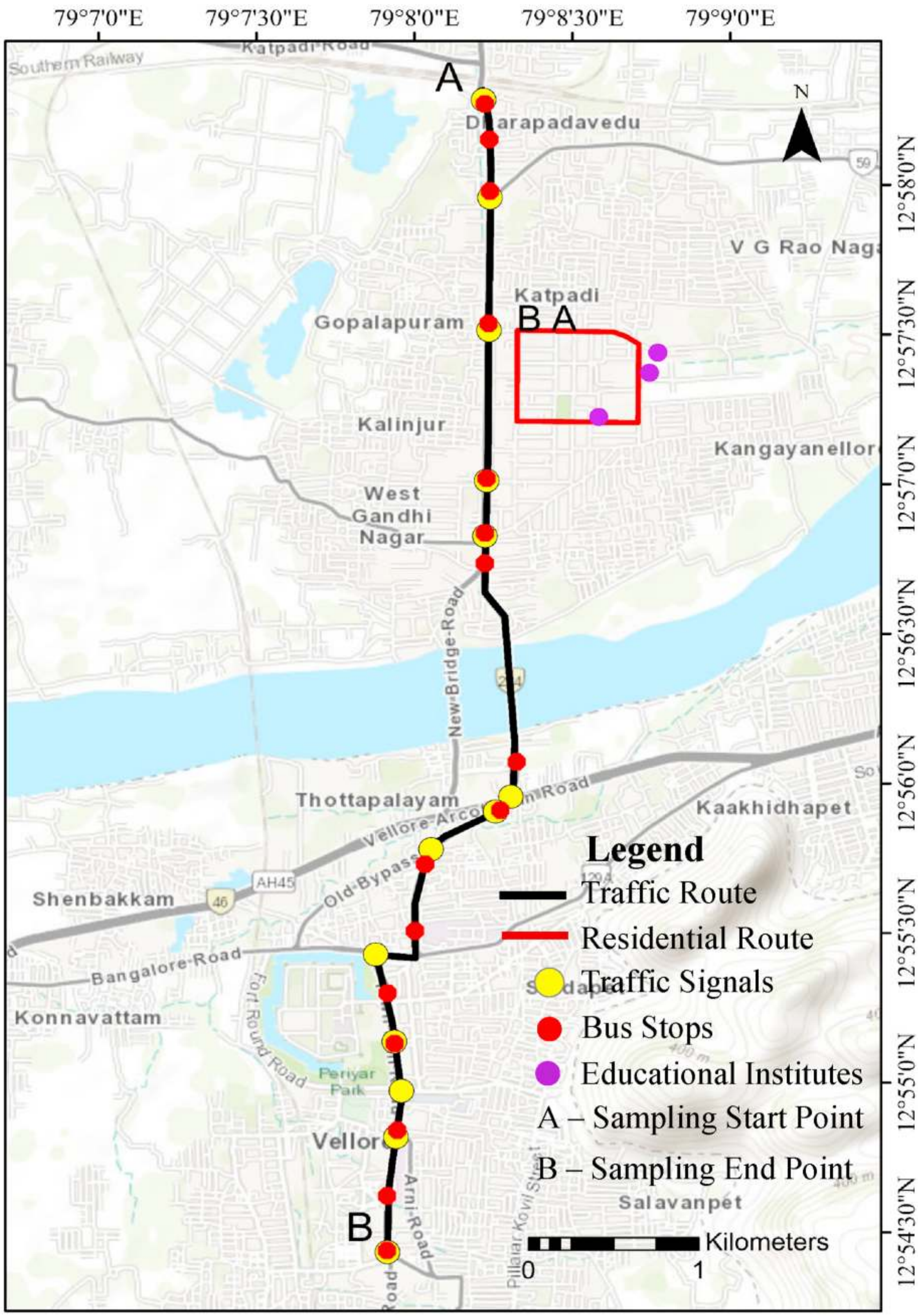

Fig. 1. Map showing traffic and residential routes.

Table 1
Summary of meteorological parameters recorded during commuting.

Transport Mode	Relative humidity (%)	Temperature (°C)	Wind speed (m s^{-1})
Pedestrian	59.1 ± 10.9	29.1 ± 2.7	1.5 ± 0.7
Bicycle	63.3 ± 8.3	28.2 ± 3.5	0.8 ± 0.7
Motorbike	66.1 ± 9.6	28.6 ± 2.3	1.1 ± 0.7
Auto-rickshaw	53.6 ± 18.6	28.2 ± 3.8	0.9 ± 0.5
Car	54.9 ± 10.9	28.3 ± 3.2	0.6 ± 0.6
Bus	58.3 ± 13.6	27.9 ± 3.2	0.7 ± 0.6

conditions. Buses were powered by diesel fuel and it offered service only in the traffic route. Thus, except bus, all other commuter modes were completed in the residential route. All six modes of commute were completed in the traffic route. The measurements were taken during the morning (7.30–10.00 a.m.) and afternoon (1.00–3.00 p.m.) hours of the day under non-smoking conditions to assess personal commuters carried AM520 instrument in a backpack, and the instrument inlet was kept near to breathing zone during sampling. The backpack was held on the commuter lap while commuting in car, auto-rickshaw, and bus. Commuters were seated behind the driver during car and auto-rickshaw commutes. As the buses were always crowded, it was hard for commuters to take sampling in the same location. Thus, commuters seated or stood in available places while travelling in buses. All measurements were taken between October 2019 and February 2020. A total of 40, 96, 96, 32, 32 and 16 one-way trips were completed during weekdays in pedestrian, bicycle, motorbike, auto-rickshaw, car, and bus transport modes, respectively.

2.4. Dose estimation

Inhalation dose can be estimated by knowing the values of exposure concentration (C in μg m^{-3}), minute ventilation (MV in m^{-3} min^{-1}), sampling trip duration (T in minutes) and distance travelled (D in Km). The following equations (Eq. (2) and Eq. (3)) were used for estimating inhaled dose per trip and inhaled dose per kilometre travelled.

$$\text{Inhaled dose per trip } (\mu g) = C * MV * T \quad (2)$$

$$\text{Inhaled dose per kilometre travelled } (\mu g\ Km^{-1}) = \frac{(C * MV * T)}{D} \quad (3)$$

These equations were widely adopted in recent studies (Ramos et al., 2017; Ham et al., 2017; Betancourt et al., 2017). Also, the trip-averaged concentrations were used for estimating inhaled dose per trip and inhaled dose per kilometre travelled. Minute ventilation rates suggested by the Exposure Factors Handbook of United States Environmental Protection Agency were utilized in this study (U.S. EPA, 2011). Minute ventilation rate in all motorized commutes was selected as 0.01 m^3 min^{-1}, whereas for active commuters, 0.015 and 0.035 m^3 min^{-1} were considered for pedestrian and bicycle mode, respectively. An earlier Indian study adopted similar values for estimating inhaled doses (Goel et al., 2015).

2.5. Statistical analysis

Two non-parametric tests viz., Kruskal Wallis test and Mann-Whitney *U* test were performed at $p < 0.05$ and 95% confidence interval to evaluate the presence of statistically significant differences of exposure concentration among different travel modes and travel time. Correlation analysis was performed to identify the association between meteorological variables (viz., relative humidity, temperature, and wind speed) with exposure concentration and inhaled dose. IBM SPSS software (V22.0, IBM, NY, USA) was used for all statistical analyses.

3. Results and discussion

3.1. Summary of traffic survey

The summary of traffic volume survey and the average time taken for completing one trip (from point A to B in Fig. 1) in both routes are presented in Table 2. All transport modes in traffic route registered a higher traffic volume during morning trips than afternoon trips. Motorbike registered the higher contribution to traffic followed by auto-rickshaw, car, bus, and bicycle modes. Trucks and minivans in traffic route contributed less than 1% to total traffic during morning and afternoon trips. Motorbike in the residential route had a maximum contribution of 84–85% to total traffic. Further, the traffic volume of motorbike, auto-rickshaw and car in the residential route was higher during afternoon than morning trips. Minivans in the residential route contributed 2% and 1% to morning and afternoon traffic, respectively.

3.2. Exposure concentration

$PM_{2.5}$ and PM_1 exposure concentration in various transport micro-environments are shown as boxplots in Figs. 2 and 3, respectively. Measurements from all trips in the respective commutes were used for plotting these figures. Centreline and solid square symbol inside the interquartile range (IQR) box represent the median and arithmetic mean values. The top and bottom of the box represent upper (75th percentile) and lower quartiles (25th percentile), respectively. It can be observed that $PM_{2.5}$ and PM_1 exposure concentrations were positively skewed in all modes of transport. Hence median exposure concentrations are presented in this study. In addition to this, trip averaged $PM_{2.5}$ and PM_1 concentrations are also discussed separately. Further, a comparison of these study results with recent studies (published between 2015 and 2020) is done and presented in Table 3.

3.2.1. Pedestrian

Median (IQR) $PM_{2.5}$ exposure concentration of pedestrian in traffic and residential route during morning trips were 118 (83–154) and 59 (48–76) μg m^{-3}, respectively. In the case of afternoon, $PM_{2.5}$ exposure concentration dropped in both traffic and residential routes. Traffic commutes registered 1.6–2 times higher $PM_{2.5}$ exposure concentration than residential commutes. Among active commuting modes, the pedestrian was found with the highest $PM_{2.5}$ median exposure concentration during the traffic route's morning route. The lowest $PM_{2.5}$ exposure concentration in this study was recorded during pedestrian's afternoon trips in traffic and residential routes. Trip-averaged $PM_{2.5}$ exposure concentration ranged from 88 to 161, 76–128, 50–78 and 47–61 μg m^{-3} in the traffic morning, traffic afternoon, residential morning, and residential afternoon trips, respectively. Median (IQR) PM_1 exposure concentration of pedestrian in the traffic morning, traffic afternoon, residential morning, and residential afternoon commutes were 50 (35–71), 44 (28–63), 15 (11–25) and 12 (9–17) μg m^{-3}, respectively. Like $PM_{2.5}$, the median PM_1 exposure concentration of traffic commute was higher than the residential route. Also, morning commutes in traffic and residential routes were up to 12 and 20% higher PM_1 exposure concentration than afternoon trips. Trip-averaged PM_1 exposure concentration ranged from 51 to 64, 45–59, 17–52 and 9–17 μg m^{-3} in the traffic morning, traffic afternoon, residential morning, and residential afternoon, respectively. Among six commuting modes, the lowest PM_1 exposure concentration and trip-averages were observed in pedestrian commute across all trips and routes.

In the present study, pedestrian $PM_{2.5}$ exposure concentration values were lower than megacity Delhi (Goel et al., 2015). However, $PM_{2.5}$ exposure concentration was higher than values reported in Sydney, Australia (Greaves et al., 2008), Raleigh, USA (Jiao and Frey, 2014), Seattle, USA (Bae and Sinha, 2016), Xi'an, China (Qiu et al., 2017), Guildford, UK (Kumar et al., 2018), and Mexico (Velasco et al., 2019). PM_1 results in traffic route were comparable to values reported in

Table 2
Summary of sampling trips and traffic survey.

Transport mode	Traffic route								Residential route							
	Total trips (Nos)		Average ± SD trip time (Minutes)		Traffic volume (Vehicles per hour)		Contribution to traffic (%)		Total trips (Nos)		Average ± SD trip time (Minutes)		Traffic volume (Vehicles per hour)		Contribution to traffic (%)	
	M	A	M	A	M	A	M	A	M	A	M	A	M	A	M	A
Pedestrian	8	8	96 ± 2	96 ± 2	–	–	–	–	12	12	32 ± 1	32 ± 1	–	–	–	–
Bicycle	24	24	38 ± 2	37 ± 2	51	45	1	2	24	24	14 ± 2	14 ± 2	18	6	3	1
Motorbike	24	24	21 ± 2	21 ± 2	2088	1572	59	54	24	24	9 ± 1	9 ± 1	576	732	84	85
Auto	8	8	22 ± 3	19 ± 3	768	765	22	26	8	8	8 ± 1	7 ± 1	42	48	6	6
Car	8	8	23 ± 4	21 ± 2	468	426	13	15	8	8	7 ± 1	7 ± 1	36	72	5	7
Bus	8	8	27 ± 2	27 ± 2	132	72	4	2	–	–	–	–	–	–	–	–

Note: SD = Standard Deviation; M = Morning; A = Afternoon.

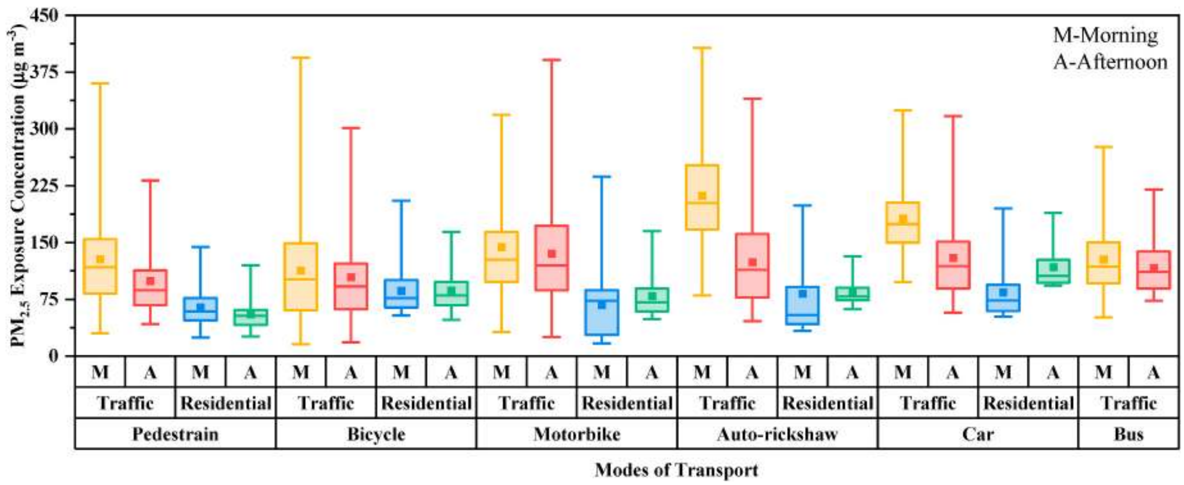

Fig. 2. $PM_{2.5}$ exposure concentration in all modes of transport.

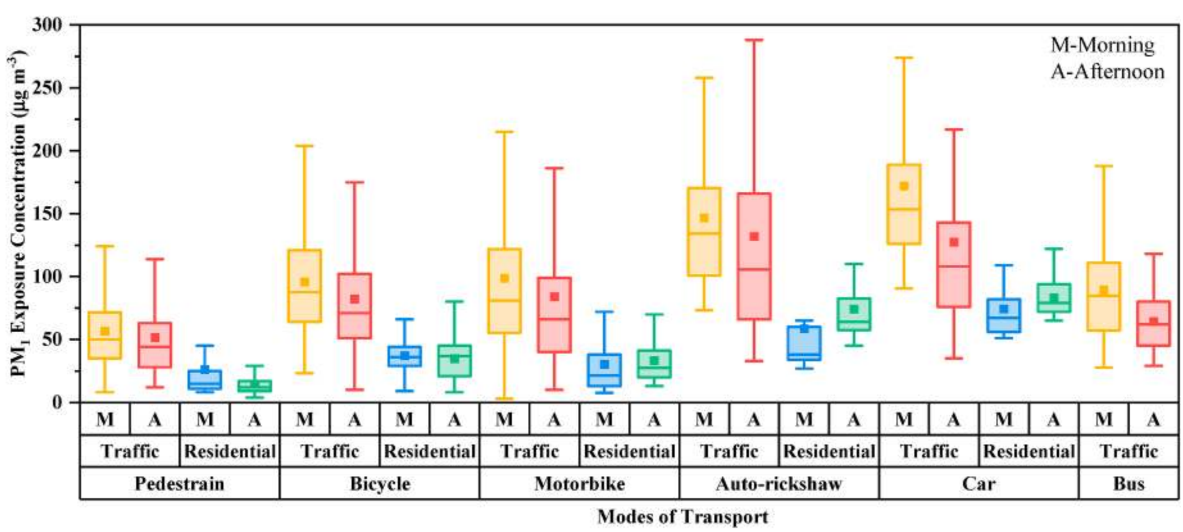

Fig. 3. PM_1 exposure concentration in all modes of transport.

Nanjing (Shen and Gao, 2019) but lower than Shanghai (Yu et al., 2012). PM_1 concentration of residential route was nearer to values reported in Milan (Lonati et al., 2011). In conclusion, the pedestrian exposure concentration was lower than megacities but higher than European and American countries. The pedestrian paths and roads in Vellore are not separated by a barrier. Hence pedestrians are directly exposed to fresh vehicle emissions and this could be a reason for high exposure concentrations especially during morning and afternoon trips in traffic route.

The maximum peaks in Fig. 4. (a) and (g) indicates the elevated $PM_{2.5}$ and PM_1 concentrations near the major intersections and traffic signals during traffic route commute. Similar observations of high exposure concentration near intersections and low concentration away from intersections were reported in Polednik and Piotrowicz (2019). A maximum peak $PM_{2.5}$ concentration of 360, 344, 341, and 159 μg m^{-3} was recorded for a short duration in one of the traffic mornings, traffic afternoon, residential morning, residential afternoon trips, respectively.

Table 3
Comparison of present study results with earlier commuter exposure concentration studies.

Region	Reference	City, Country	Pollutant	Instrument Used	Descriptive	Route	Trip	Pedestrian	Cycling	Motorbike	Car	AR	Bus
Asia	Present study	Vellore, India	$PM_{2.5}$	SidePak AM520, TSI	Median	T	M (A)	118 (87)	101 (92)	127 (119)	174 (119)	202 (114)	118 (111)
						R	M (A)	59 (53)	76 (80)	73 (71)	74 (106)	54 (79)	
					Mean	T	M (A)	128 (99)	113 (103)	144 (135)	182 (130)	212 (124)	127 (116)
						R	M (A)	64 (55)	86 (87)	67 (79)	84 (118)	82 (83)	
			PM_1		Median	T	M (A)	50 (44)	88 (71)	81 (66)	153 (108)	134 (106)	85 (62)
						R	M (A)	15 (12)	36 (37)	21 (28)	67 (79)	38 (64)	
					Mean	T	M (A)	57 (52)	96 (82)	99 (84)	172 (127)	147 (132)	89 (64)
						R	M (A)	26 (15)	37 (35)	30 (34)	74 (83)	59 (74)	
	Torkmahalleh et al. (2020)	Nur-Sultan, Kazakhstan	PM_1	DustTrak DRX 8533, TSI	Mean	T	E						11–99
	Kolluru and Kumar (2020)	Vijayawada to Guntur, India	$PM_{2.5}$	Model 1.108, GRIMM	Mean	H	M & A				29		37
			PM_1		Mean	H	M & A				16		18
	Shen and Gao (2019)	Nanjing, China	PM_1	DustTrak II	Mean	T	M,A&E	60	59				56
			$PM_{2.5}$	8532, TSI	Mean	T		80	79				75
	Qiu et al. (2019)	Xi'an, China	PM_1	Model 11-A, GRIMM	Mean	T	M,A&E		14–18				
			$PM_{2.5}$		Mean	T			13–22				
	Raj and Karthikeyan (2019)	Chennai, India	$PM_{2.5}$	PCXR-8, SKC	Mean	T	M,A&E			251			225
	Kolluru et al. (2018)	Vijayawada, India	$PM_{2.5}$	EPAM-5000, EDC	Mean	H	M (E)				85 (92)		75 (67)
	Qiu et al. (2017)	Xi'an, China	$PM_{2.5}$	Model 1.109, GRIMM	Mean	T	M (A)	72 (66)					-(59)
			PM_1		Mean	T	M (A)	57 (54)					-(41)
	Goel et al. (2015)	Delhi, India	$PM_{2.5}$	DustTrak DRX 8533, TSI	Mean	T	M & A	278	347	207	180	257	295
					Median	T	M & A	248	338	162	164	240	284
	Swamy et al. (2015)	Ahmedabad, India	$PM_{2.5}$	DustTrak II	Median	T	M,A&E			300	383	328	
				8532, TSI	Mean	T	M,A&E			359	414	385	
Europe	Correia et al. (2020)	Lisbon, Portugal	$PM_{2.5}$	Personal Exposure Monitor, SKC	Mean	R&T	M,A&E		30		34		28
	Polednik and Piotrowicz (2019)	Lublin, Poland	$PM_{2.5}$	DustTrak DRX 8533, TSI	Mean	T	M (N)	78 (71)					
					Median	T	M (N)	66 (83)					
	Borghi et al. (2019)	Milan, Italy	$PM_{2.5}$	GK2.05 sampler, BGI	Mean	T	–	15	19				
			PM_1		Mean	T	–	13	15				
North America	Hernández-Paniagua et al. (2018)	Mexico City, Mexico	$PM_{2.5}$	pDR-1500, Thermo Scientific	Median	T	M & A	15	82		27		
					Mean	T		16	82		28		
	Ham et al. (2017)	Sacramento, USA	$PM_{2.5}$	DustTrak 8520, TSI	Mean	T	M & E		9.56				
	Chaney et al. (2017)	Salt Lake City, USA	$PM_{2.5}$	SidePak AM520, TSI	Mean	T		12.21	12.62		15.21		13.03
South America	Krecl et al. (2020)	Curitiba, Brazil	$PM_{2.5}$	DustTrak 8520, TSI	Mean	T	M & E	33					
					Median	T	M & E	30					
	Betancourt et al. (2017)	Bogota, Colombia	$PM_{2.5}$	DustTrak 8520 and DustTrak DRX, TSI	Median	T	M	68	77	151	131		
Other	Abbass et al. (2020)	Cairo, Egypt	$PM_{2.5}$	Series 500, Aeroqual	Mean	T	M (E)				47 (33)		
	Onat et al. (2019)	Istanbul, Turkey	$PM_{2.5}$	pDR-1200, Thermo-Fisher Scientific	Median	T	M & A				31		31
					Mean	T	M & A				36		37

Note: AR- Auto-rickshaw, T-Traffic, R-Residential, H-Highway, M-Morning, A-Afternoon, E-Evening, N-Night, M&E-Mean/Median of morning and evening, M&A- Mean/Median of morning and afternoon, M,A&E– Mean/Median of morning, afternoon and evening.

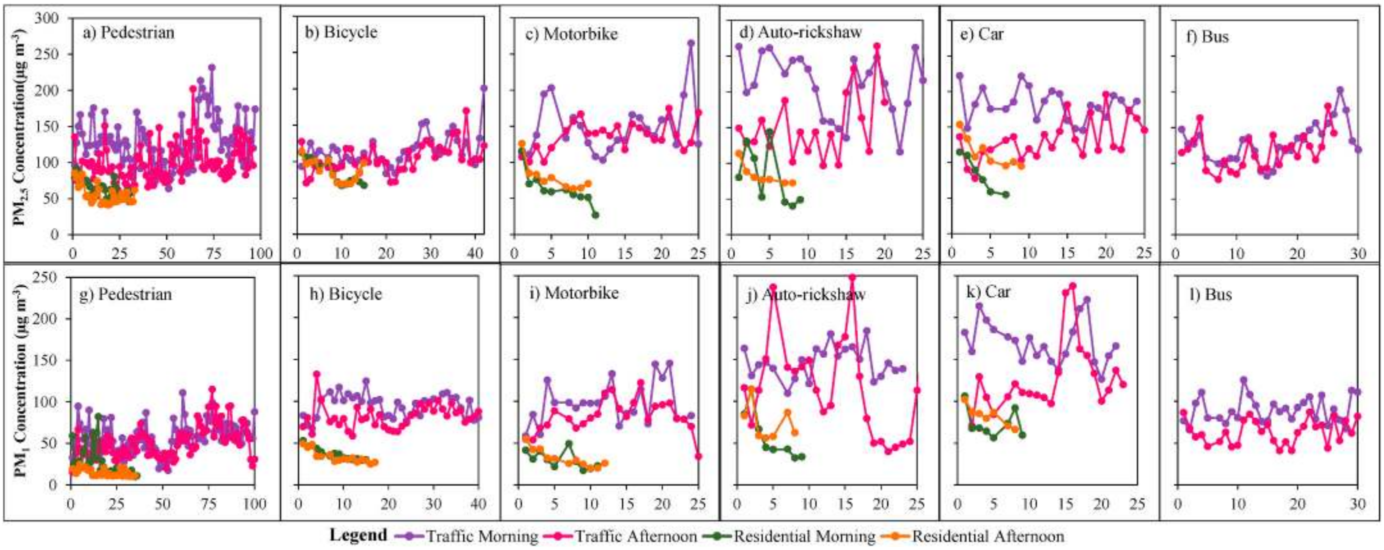

Fig. 4. Time series plot of $PM_{2.5}$ and PM_1 exposure concentration in different travel modes.

A similar peak concentration of 360 μg m^{-3} was reported in Omaha, USA (Bereitschaft, 2015). Kruskal Wallis test results indicated that pedestrian $PM_{2.5}$ and PM_1 exposure concentration in traffic and residential routes were significantly different ($p < 0.05$) from other transport modes. This shows pedestrian exposure levels were not the same as other modes of transport.

3.2.2. Bicycle

Vellore does not have a separate lane for bicycle commuters. Thus, like other bicycle commuters, all sampling trips were completed by travelling at the lane's edge. $PM_{2.5}$ median (IQR) exposure concentration in the traffic morning, traffic afternoon, residential morning, and residential afternoon commutes were 101 (61–149), 92 (62–122), 76 (64–100), and 80 (67–98) μg m^{-3}, respectively. Similarly, for PM_1 these values were 88 (64–121), 71 (51–102), 36 (29–44), and 37 (22–45) μg m^{-3}, respectively. Except for traffic morning trips, bicycle commuting registered higher median $PM_{2.5}$ exposure concentration when compared to pedestrian commutes. Also, the residential morning trip of bicycle commute was found with the highest median $PM_{2.5}$ concentration among active and motorized commutes. Trip-averaged $PM_{2.5}$ exposure concentration of bicycle commuters ranged from 46 to 194, 60–170, 66–114, and 60–120 μg m^{-3} in traffic morning, traffic afternoon, residential morning, and residential afternoon, respectively. Similarly, for PM_1 these figures were 64–147, 69–96, 13–50, and 14–51 μg m^{-3}, respectively. Statistical analysis showed that $PM_{2.5}$ exposure concentration of bicycle commute in the traffic route was not significantly different from the car (residential route, $p = 0.74$) commute. All other $PM_{2.5}$ and PM_1 commutes were significantly different ($p < 0.05$) from bicycle commutes.

Bicycle $PM_{2.5}$ exposure concentration in Delhi was 2.7–4.2 times higher than Vellore (Goel et al., 2015). Bicycle commute in traffic route was found with higher mean $PM_{2.5}$ exposure concentration when compared to cities like Santiago, Chile (50.9 ± 18.8 μg m^{-3}) (Suárez et al., 2014), Lisbon, Portugal (85 ± 66 μg m^{-3}) (Ramos et al., 2016), Nanjing, China (79 ± 45.7 μg m^{-3}) (Shen and Gao, 2019), and Curitiba, Brazil (33.22 ± 25.64 μg m^{-3}) (Krecl et al., 2020). Median PM_1 concentration in residential route was higher than Mol city, Belgium (Berghmans et al., 2009). However, $PM_{2.5}$ and PM_1 values were lower than those values reported in Chengdu, and Shanghai, China (Yu et al., 2012; Liu et al., 2019). Peak $PM_{2.5}$ and PM_1 exposure concentration as seen in Fig. 4. (b) and (h) correspond to $PM_{2.5}$ (PM_1) concentration of 201 (130), and 170 (132) μg m^{-3} during morning and afternoon trips of traffic routes, respectively. These peaks were found near bus stops. As there is no separate parking space, all buses will stop on the main road for boarding and deboarding of passengers at every bus stops. This leads to congestion and idling of vehicles behind the bus and hence increasing the exposure concentration. Bicyclists travelling in traffic route (high traffic volume) were identified with higher exposure concentration than residential route (low traffic volume). This was in accordance with earlier study results (Weichenthal et al., 2011; Jarjour et al., 2013). Morning trips in traffic route were highly polluted than afternoon trips. A similar trend of having higher $PM_{2.5}$ and PM_1 concentrations during morning trips than afternoon trips were observed in earlier studies (Berghmans et al., 2009; Hatzopoulou et al., 2013; Hankey and Marshall, 2015). However, afternoon exposure concentration was marginally higher than morning trips in the residential route. This can be related to higher traffic volume during the afternoon period in the residential route. Bicyclists experienced higher exposure concentration than pedestrians in most of the trips. This can be explained by the fact that bicyclists travel very nearer to the traffic than pedestrians, therefore exposes them to the maximum on-road tailpipe emissions, tyre wear, resuspended road dust and brake dust (Huang et al., 2012).

3.2.3. Motorbike

Motorbike is the most used private transport mode in Vellore. Median (IQR) $PM_{2.5}$ values of traffic morning, traffic afternoon, residential morning and residential afternoon were 127 (98–164), 119 (87–172), 73 (28–87), and 71 (59–89) μg m^{-3}, whereas PM_1 values were 81 (55–122), 66 (40–99), 21 (13–37), and 28 (20–41) μg m^{-3}, respectively. Exposure concentration during the traffic afternoon trip was the highest among all six commutes. Median $PM_{2.5}$ exposure concentration in traffic afternoon trip was 1.37, 1.30, 1.05, and 1.08 times higher than pedestrian, bicycle, auto-rickshaw, bus commutes but similar to car commute. However, among motorized commute, the motorbike commutes registered the lowest PM_1 exposure concentration in traffic morning, residential morning, and residential afternoon trips. Trip-averaged $PM_{2.5}$ (PM_1) concentration in traffic and residential routes were in the range of 71–251 (42–151) and 28–112 (15–75) μg m^{-3}, respectively. Motorbike commuters registered the highest trip-averaged concentration during morning and afternoon trips in the traffic route. Except for motorbike trips in the residential route ($p = 0.49$), the $PM_{2.5}$ exposure concentration in motorbike commute was significantly different from all other modes ($p < 0.05$). In the case of PM_1, the motorbiker's exposure concentration in traffic route was like bus (traffic route, $p = 0.72$) and car (residential route, $p = 0.39$) commutes.

$PM_{2.5}$ exposure concentration in motorbike was lower than other

Indian cities viz., Ahmedabad (300 μg m^{-3}) (Swamy et al., 2015), Chennai (251 μg m^{-3}) (Raj and Karthikeyan, 2019) and Delhi (162 μg m^{-3}) (Goel et al., 2015). However, another study in Delhi reported lower $PM_{2.5}$ values (55 μg m^{-3}) than the present study (Pant et al., 2017). Also, PM_1 exposure concentration registered during traffic trips were in the range of values (38–89), as reported by Ramos et al. (2016). Trip-average values of this study were higher than Taipei, Taiwan ($PM_{2.5}$ = 67.5 μg m^{-3} and PM_1 = 48.4 μg m^{-3}) (Tsai et al., 2008). Morning trips of motorbike were found to have higher exposure concentration than afternoon and this was in accordance with earlier observations in Delhi (Jain, 2017). Distinct peak concentrations in Fig. 4 (c) and (i) were recorded near bus stops and traffic signals. Peak $PM_{2.5}$ (PM_1) during traffic morning and traffic afternoon morning was 251 (151) and 198 (120) μg m^{-3}, respectively. Motorbike $PM_{2.5}$ exposure concentration in traffic route was higher than pedestrian and bicycle commutes. This finding was consistent with the study by (Betancourt et al., 2017).

3.2.4. Auto-rickshaw

The public bus transport in Vellore is restricted to selected routes that connect important places of the city. This forced people to prefer other means of public transport such as auto-rickshaw. Many people choose auto-rickshaw because it is frequently available, moderate cost and provides door to door services. A total of 8418 auto-rickshaws are available for public transport in Vellore. The traffic morning, traffic afternoon, residential morning, and residential afternoon commutes registered $PM_{2.5}$ median (IQR) concentration of 202 (168–252), 114 (77–161), 54 (43–90), 79 (74–90) μg m^{-3}, respectively. Morning trips in traffic and residential routes were found with the highest and lowest $PM_{2.5}$ exposure concentration among six commutes. $PM_{2.5}$ median exposure concentration in traffic morning was 1.7, 2, 1.6, 1.2, 1.7 times higher than pedestrian, bicycle, motorbike, car, and bus commutes, respectively. PM_1 median exposure concentration in traffic and residential routes ranged from 106 to 134 and 38–64 μg m^{-3}, respectively.

Trip-averaged $PM_{2.5}$ (PM_1) concentration in traffic and residential routes ranged from 99 to 227 (110–169) and 78–90 (39–88) μg m^{-3}, respectively. The PM_1 trip-average in residential route was 1.5–2.9 times lower than the traffic route. Trip-average $PM_{2.5}$ during morning traffic was 1.2–1.7 times higher than the traffic afternoon commutes. However, morning and afternoon residential trips were found to have similar trip averaged $PM_{2.5}$ concentrations. Morning trips of traffic route had 1.1 to 1.2 times higher PM_1 trip-average than afternoon trips whereas, in the case of residential route, afternoon trips registered 1.4–1.6 times higher than morning trips. The Kruskal Wallis test results indicated that auto-rickshaw commuters in the residential route experienced similar $PM_{2.5}$ exposure concentration of bicycle (residential route, $p = 0.14$) commute. Also, auto-rickshaw in traffic route had similar PM_1 exposure concentration of car commute (traffic route, $p = 0.3$). This was in accordance with an earlier study in Delhi (Jain, 2017). The highest peaks seen in Fig. 4 (d) during morning and afternoon traffic trips correspond to $PM_{2.5}$ concentration of 263 and 264 μg m^{-3}, whereas in Fig. 4 (j) the peak PM_1 concentrations were 174 and 250 μg m^{-3}, respectively. Earlier studies in Delhi showed lower PM_1 and $PM_{2.5}$ concentration when compared to the present study (Jain, 2017; Pant et al., 2017). Another study in Delhi was found to have a similar trip-average $PM_{2.5}$ exposure concentration (Apte et al., 2011). However, other studies conducted in India cities viz., Dhanbad and Ahmedabad reported higher trip-average and median exposure concentrations than the present study (Swamy et al., 2015; Gupta and Elumalai, 2019).

3.2.5. Car

Driving a car with an open window is a common setting among Vellore people. Hence in this study, all measurements were taken under open window settings. $PM_{2.5}$ median (IQR) exposure concentration during traffic morning, traffic afternoon, residential morning, residential afternoon trips were 174 (150–202), 119 (90–151), 74 (60–94), and 106 (97–126) μg m^{-3}, respectively. The trip-averaged $PM_{2.5}$ concentration in traffic and residential routes ranged from 98 to 206 and 72–135 μg m^{-3}, respectively. The highest median PM_1 concentration was recorded in traffic route (morning = 153 μg m^{-3} and afternoon = 108 μg m^{-3}) followed by residential route (afternoon = 79 μg m^{-3} and morning = 67 μg m^{-3}). Trip-averaged PM_1 exposure concentration ranged from 128 to 234, 99–169, 64–87, and 75–94 μg m^{-3} in the traffic morning, traffic afternoon, residential morning, and residential afternoon commutes, respectively. $PM_{2.5}$ exposure concentration of car commute in traffic and residential routes were not significant with auto-rickshaw (traffic route, $p = 0.62$) and pedestrian (traffic route, $p = 0.49$), respectively. In the case of PM_1 exposure, car commute in the residential route is similar to bicycle commute (traffic route, $p = 0.73$).

Peak $PM_{2.5}$ (PM_1) concentration in Fig. 4 (e) and (k) correspond to 222 (221) μg m^{-3}in traffic morning and 196 (238) μg m^{-3} in traffic afternoon. Car commuting was found to be most polluted in terms of $PM_{2.5}$ during afternoon trips in both traffic and residential routes. $PM_{2.5}$ median concentration in traffic and residential afternoon was 1–1.4 and 1.3–2 times higher than other modes, respectively. Also, $PM_{2.5}$ values in the residential morning were closer to the highest median concentration registered in bicycle commute. Further, median PM_1 concentration in car commute across all trips and routes were the highest among all six commutes. PM_1 concentration experienced by car commuters were 1.1–3.1, 1.02–2.5, 1.8–4.5, 1.2–6.6 times higher than other commutes during traffic morning, traffic afternoon, residential morning, and residential afternoon, respectively. Recent studies from Indian cities also found that car commuting is more polluted than other commuting modes (Swamy et al., 2015; Kolluru et al., 2019). However, some studies showed lower exposure concentrations in car commute when compared to other transport modes (Panis et al., 2010; Jiao and Frey, 2014; Good et al., 2016). This inconsistency can be due to variations in fuel quality, traffic volume, idling time in traffic, vehicle technology, and proximity to sources (Boogaard et al., 2009). The $PM_{2.5}$ exposure concentration in morning trips of traffic and residential route agrees with previous commuter study in Delhi, India and Arnhem, Netherlands, respectively (Zuurbier et al., 2010; Goel et al., 2015). $PM_{2.5}$ values were at least 2.4 times higher than $PM_{2.5}$ concentration values registered in Helsinki, Rotterdam and Thessaloniki cities (Okokon et al., 2017). Also, PM_1 exposure concentrations were higher than the values registered in Frankfurt am Main, Germany (Dröge et al., 2018).

3.2.6. Bus

The bus commute is the cheapest public transport available in Vellore. Since bus services were not available to complete the selected residential route, measurements were taken only in the traffic route. The median $PM_{2.5}$ concentration during morning and afternoon trips were 118 (96–150) and 111 (89–138) μg m^{-3}, respectively. PM_1 median concentration was 85 (57–117) μg m^{-3} in the morning and 62 (45–80) μg m^{-3} in the afternoon. Maximum trip-averaged concentrations of $PM_{2.5}$ and PM_1 during morning (afternoon) route were 167 (130) and 110 (66) μg m^{-3}, respectively. Kruskal Wallis test indicated that bus commuters experienced similar $PM_{2.5}$ exposure concentration as car commuters in traffic route ($p = 0.49$) whereas PM_1 exposure was similar to the bicycle (traffic route, $p = 0.22$) and car (residential route, $p = 0.57$) commuters.

Peak $PM_{2.5}$ (PM_1) concentrations near traffic signal and bus stop (refer Fig. 4 (f) and (l)) were recorded to be 203 (125) and 180 (118) μg m^{-3} in morning afternoon trips, respectively. Present study PM_1 and $PM_{2.5}$ values were found to be higher than exposure concentrations reported in India and Brazil (Kolluru and Kumar, 2020; Targino et al., 2020). However, $PM_{2.5}$ exposure concentration was lower than other Indian cities viz., Chennai and Ahmedabad (Goel et al., 2015; Swamy et al., 2015; Raj and Karthikeyan, 2019). Among motorized commute, the bus commute registered lowest median $PM_{2.5}$ exposure concentration during morning and afternoon trips in traffic route. However, $PM_{2.5}$ exposure concentration was higher than the active commuters. PM_1

concentration during afternoon trip in residential route was lowest among motorized commutes. These findings are consistent with previous studies in Lisbon, Portugal and Barcelona, Spain (De Nazelle et al., 2012; Correia et al., 2020). Both $PM_{2.5}$ and PM_1 values were higher in the morning trip than afternoon trip. Similar results of having high concentration in morning trips were observed in previous studies (Shen and Gao, 2019; Kumar et al., 2018). Among motorized travel modes, the lowest $PM_{2.5}$ and PM_1 trip-average concentrations were recorded in bus commute.

3.3. Inhaled dose

Fig. 5 shows the inhaled dose per trip (μg) and inhaled dose per kilometre travelled (μg Km^{-1}) for all transport modes. From Fig. 5, it can be noted that inhaled dose trend differs from corresponding exposure concentration. Similar results were reported in Lisbon, Portugal (Correia et al., 2020). All transport modes experienced the highest and lowest $PM_{2.5}$ inhalation dose while travelling in traffic route and residential route, respectively. Also, morning trips in traffic route were found to have maximum $PM_{2.5}$ inhaled dose irrespective of transport mode. Pedestrian and bicycle commuters experienced maximum $PM_{2.5}$ inhaled dose in traffic and residential routes, respectively. Similar results of having higher inhaled doses in active commuters were reported in India and Italy (Goel et al., 2015; Borghi et al., 2020). The higher dose in active commuters is because of higher minute ventilation rate when compared to motorized commuters (Zuurbier et al., 2009). Median $PM_{2.5}$ dose per kilometre travelled of pedestrian, bicycle, motorbike, car, auto-rickshaw and bus commuters in all trips and routes ranged from 8 to 21, 12–17, 2–3, 2–6, 2–5, 3–4 μg km^{-1}, respectively. $PM_{2.5}$ inhaled dose per trip among active commutes ranged from 136 to 165, 116–126, 26–37, and 23–37 μg in traffic morning, traffic afternoon, residential morning, and residential afternoon, respectively, whereas in motorized commutes these figures were 27–45, 24–32, 4.7–5.4, 5.6–7.4 μg, respectively. Present study inhaled dose in traffic route was higher than previous studies conducted in China and Colombia, Ireland, and Spain (De Nazelle et al., 2012; Nyhan et al., 2013; Betancourt et al., 2017; Shen and Gao, 2019). However, bicyclist inhaled dose per trip in traffic route was similar to reported results in Mexico (Hernández-Paniagua et al., 2018). Pedestrian $PM_{2.5}$ inhaled dose during the residential afternoon was comparable to Singapore studies (Tan et al., 2017; Velasco et al., 2019). Also, Residential route $PM_{2.5}$ inhaled dose in pedestrian and bicycle were 2–3 and 6–9 times higher than the previous study conducted in urban residential roadway, Santa Monica, USA (Quiros et al., 2013). Among the motorized transport modes, auto-rickshaw and bus registered highest $PM_{2.5}$ inhaled dose in traffic morning and afternoon trips, respectively, whereas, in the residential route, the car commutes registered highest $PM_{2.5}$ dose in both morning and afternoon trips.

In terms of PM_1, bicycle commute registered the highest inhaled dose in all trips and routes. Median inhalation dose per trip (dose per kilometre travelled) during bicycle commuting ranged from 94 to 122 μg (12–15 μg km^{-1}) in traffic route and 15–16 μg (5.2–5.4 μg km^{-1}) in residential route. PM_1 ($PM_{2.5}$) dose in bicycle commuters was 3–7 (3–5), 4–6 (4–5), 3–8 (7–8), 3–6 (5–7) times higher than motorized commute during the traffic morning, traffic afternoon, residential morning, and residential afternoon trips, respectively. PM_1 inhaled dose per trip and dose per kilometre travelled were higher than Xi'an, China (Qiu et al., 2019). However, bicycle PM_1 inhaled dose was in the range (15–27 μg km^{-1}) of previous study results (Ramos et al., 2016). Next to bicycle, pedestrian commute registered the highest median PM_1 inhaled dose across all trips and routes. Among the motorized transport, the car and motorbike commuters experienced maximum and lowest PM_1 doses, respectively. Except for bus, all other modes in traffic route registered higher PM_1 inhaled dose than the Shanghai study (Yu et al., 2012).

3.4. Influence of meteorology and trip time on commuter exposure concentration and inhaled dose

Correlation matrix of exposure concentration and inhaled dose with meteorological parameters (relative humidity, temperature, and wind speed) are given in Supplementary Table 1. Relative humidity was positively correlated with exposure concentration and inhaled dose in most of the commuting modes. Relative humidity was moderately correlated with auto-rickshaw exposure concentration (Pearson correlation coefficient (r) = 0.54, $p < 0.01$) and inhaled dose (r = 0.56, $p < 0.01$). All other commutes were weakly correlated with relative humidity. Temperature and wind speed were negatively correlated with exposure concentration and inhaled dose in all commuting modes. The temperature was moderately correlated with exposure concentration experienced by car (r = −0.51, $p < 0.01$) and auto-rickshaw (r = −0.58, $p < 0.01$) commuters, whereas wind speed was moderately correlated with pedestrian (r = −0.65, $p < 0.01$) commuter exposure concentration. Also, the inhaled dose in auto-rickshaw was moderately correlated with temperature (r = −0.57, $p < 0.01$). Exposure concentration and inhaled dose in all other commutes were weakly correlated with temperature and wind speed. Although most of the commuting modes were weakly correlated with meteorology, the significance levels ($p < 0.01$ and $p < 0.05$) showed that correlation coefficients were significant. Mann-Whitney *U* test results showed that traffic route trips in the morning have significantly different $PM_{2.5}$ (p = 0.50) and PM_1 (p =

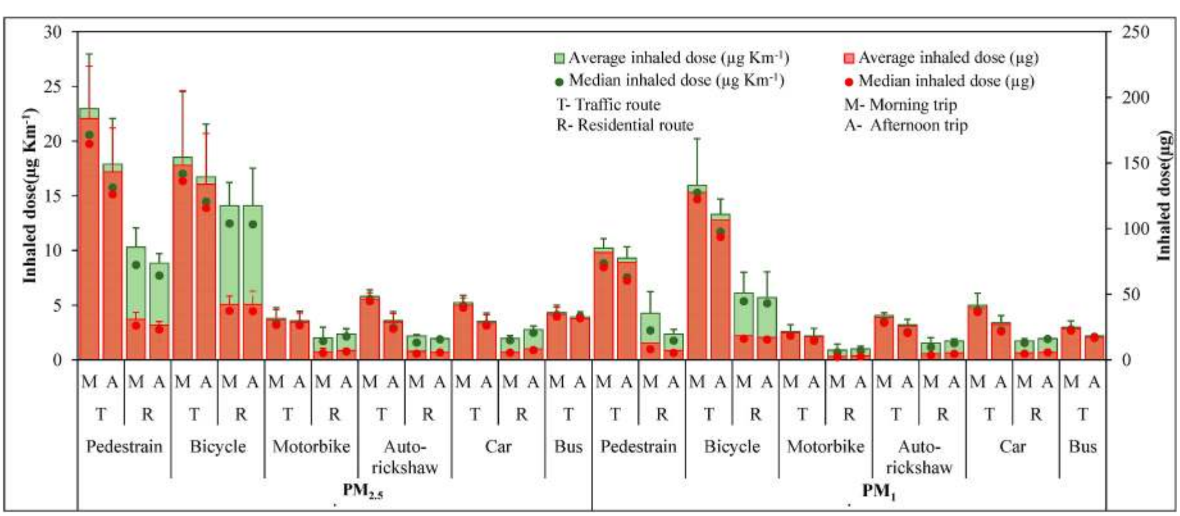

Fig. 5. Route and trip specific $PM_{2.5}$ and PM_1 inhaled doses.

0.056) exposure concentrations from afternoon trips. However, morning and afternoon trips in residential route were not significantly different ($p < 0.05$). It can be noted that from Table 3, except few modes, the morning and afternoon trip median exposure concentration in the residential route was nearer to each other. Thus, commuters travelling during morning and afternoon trips in the residential route may experience similar exposure concentration.

4. Conclusion

This study assessed the exposure concentration and inhaled dose of commuters travelling in different modes and routes. A total of 125 h (88 h in traffic route and 37 h in residential route) of measurements were taken using the portable aerosol monitor. Results showed that commuter exposure concentration significantly varies between travel modes. Commuters travelling in traffic route had 1.1–3.9 times higher exposure concentration than the residential route. Morning trips in traffic route registered up to 1.8 times higher exposure concentration than afternoon trips. However, the afternoon trips in residential route registered marginally higher exposure concentration than morning trips and this was due to increased traffic volume in the afternoon period. Among six modes, travelling in car was found to be the most polluted commute. Also, the exposure concentration of auto-rickshaw and car commuters in Vellore was similar to Delhi but lower than Chennai. Thus, more studies should be carried out to conclude that commuter exposure concentrations in mid-sized cities are similar to megacities. Peak exposure concentration in traffic route was located near bus stops, major road intersections, and traffic signals. Providing separate parking space at bus stops and better traffic management practices would substantially reduce the commuter exposure concentration in Vellore.

Except for few trips, meteorological parameters were weak but significantly correlated with exposure concentration and inhaled doses. Inhaled $PM_{2.5}$ (PM_1) dose in active commute was 5–8 (2–4) times higher than motorized commutes. Despite experiencing lower exposure concentration, the larger travel time and higher physical activity lead to elevated inhaled dose levels in active commuters. Motorbike commutes registered the lowest inhaled dose per trip and inhaled dose per kilometre travelled. This was due to lower travel time and minute ventilation rates. We utilized the published inhalation rates for estimating inhaled doses. Hence in future, the use of measured inhalation rate values would yield more accurate results. Further, the impact of long-range transported aerosols on commuter exposure concentration can be assessed to understand local and regional contributions.

5. Credit author statement

N. Manojkumar – Conceptualization, Investigation, Visualization, Writing - Original Draft. M. Monishraj – Investigation, Visualization. B. Srimuruganandam – Conceptualization, Resources, Supervision, Writing - Review & Editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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