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Seasonal analysis of particulate matter and its exposure on urban bikers in Nashik city, India

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ABSTRACT

Introduction: Exposure to Particulate Matter (PM) can cause ill health effects such as coughing, allergies, decreased lung function, chest discomfort and pain. The current study aims to monitor particulate matter concentrations on the highways in Nashik, India and to estimate its exposure to the bikers in the form of Respiratory Deposition Doses (RDDs) with its seasonal variation.
Materials and methods: Low-cost air quality monitor was mounted on the bike to measure Particulate Matter (PM_1, $PM_{2.5}$ and PM_{10}) concentrations at breathing level. Extensive mobile monitoring was performed on seven highway stretches passing through city limits at morning and evening peak hours for all the weekdays for three seasons.
Results: The PM concentrations differed on each route seasonally as well as at peak hours in morning and evening. The maximum PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 119.84 µg/m^3, 218.85 µg/m^3 and 239.25 µg/m^3 respectively on Route R3 in Winter morning. The maximum RDD_{HD} exposure on R5 and R3 in Winter mornings was due to PM_{10}. While maximum RDD_{TB} and RDD_{AL} exposure on R5 in Winter morning and evening was due to $PM_{2.5}$. Also, the seasonal and particle size effect on RDD has been studied which exhibits higher rise in exposure in Winter mornings due to $PM_{2.5}$.
Conclusion: This study reveals that maximum exposure was observed during Winter mornings. The results recommend that seasons have a substantial effect on PM concentrations and their exposure. The minimum exposure was observed in monsoon, followed by summer and the maximum exposure was seen in winters.

Introduction

Air quality in many cities in the world can be attributed to the amount of urbanisation and population growth that has happened in recent years consequently increasing the vehicular traffic, industries and use of energy [1, 2]. Human exposure to high levels of particulate matter has been associated with damaged

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airways, cardiovascular impairments, induction of diabetes mellitus, adverse effects in infancy and decreased life expectancy worldwide[3, 4]. On the highways, the PM pollution comes from vehicular exhausts, wear of brakes and tyres and re-suspension of road dust due to tyre pavement interaction [5]. Thus bikers can significantly be exposed to traffic related air pollution on highways during peak hour rush periods while commuting from home to work and from work to home each day, making it a long term exposure concern [3, 6].

Fifteen study participants were monitored for breathing zone Particulate Matter ($PM_{2.5}$) concentrations for a distance of 2.7 km while walking, biking, taking the bus, using the light rail system, driving the car with windows open and windows closed [3]. Exposure to PM was compared among the different modes of transports such as pedestrians, bicycle, motorbike, autorickshaw, car and buses on traffic and residential roads for morning and afternoons hours [7]. The effects of modes of transportation like bike, car and bus on commuter's exposure to $PM_{2.5}$ and NO_2 were studied [5].

In Indian cities most of the time traffic condition is heterogeneous and it is getting worse day by day due to large number of personal and public vehicles. The motorbikes are one of the most used vehicle in Indian cities like Nashik. The total registered two wheelers were 64,800 reported in Nashik city in 2022 as per the Times of India report. Due to large number of motorbikes the maximum emissions at morning peak period and evening peak periods were observed in Nashik city, which leads to exposure to the traffic related Particulate Matter pollution.

In this study, particulate matter was measured through mobile monitoring for seven highway stretches passing through Nashik city boundaries. The mobile monitoring was conducted for 49 days for each of the seasons viz. Summer, Monsoon and Winter, with an approximate 1,675 km of length monitored for each season making it about 5,025 km in total for all the three seasons. Also, the monitoring was performed at peak hours in the morning and repeated in the evening for the same route. It is very typical in India to have highways passing through urban agglomerations. The main purpose of mobile monitoring was to measure the exposure of particulate matter for each route. Further, analysis has been done to understand the biker's exposure concerning respiratory deposition doses and its seasonal variation.

Materials and methods

Study area

Nashik holds importance due to its mythology, history and culture. The city is situated on the banks of the rivers like Godavari and Nasardi. The city includes an industrial area, educational institutions, hospitals, and government Offices. This has triggered the growth of the city's population and infrastructure. Highways like NH-3, NH-848, NH-60, SH-17and SH-30 pass through the Nashik city municipal limits [8]. The location of the study region is shown in Fig. 1.

Route selection

As we can see in Fig. 1, all the roads seem to run radially outwards from the center of the city. The traffic moves towards the center of the city as well as away from the center of the city. So, it was decided to make round trips on the routes to obtain data for the traffic moving towards the center of the city and radially outwards. The mobile monitoring [9] on the highways was done by adhering to all driving related guidelines issued by traffic police and authorities.

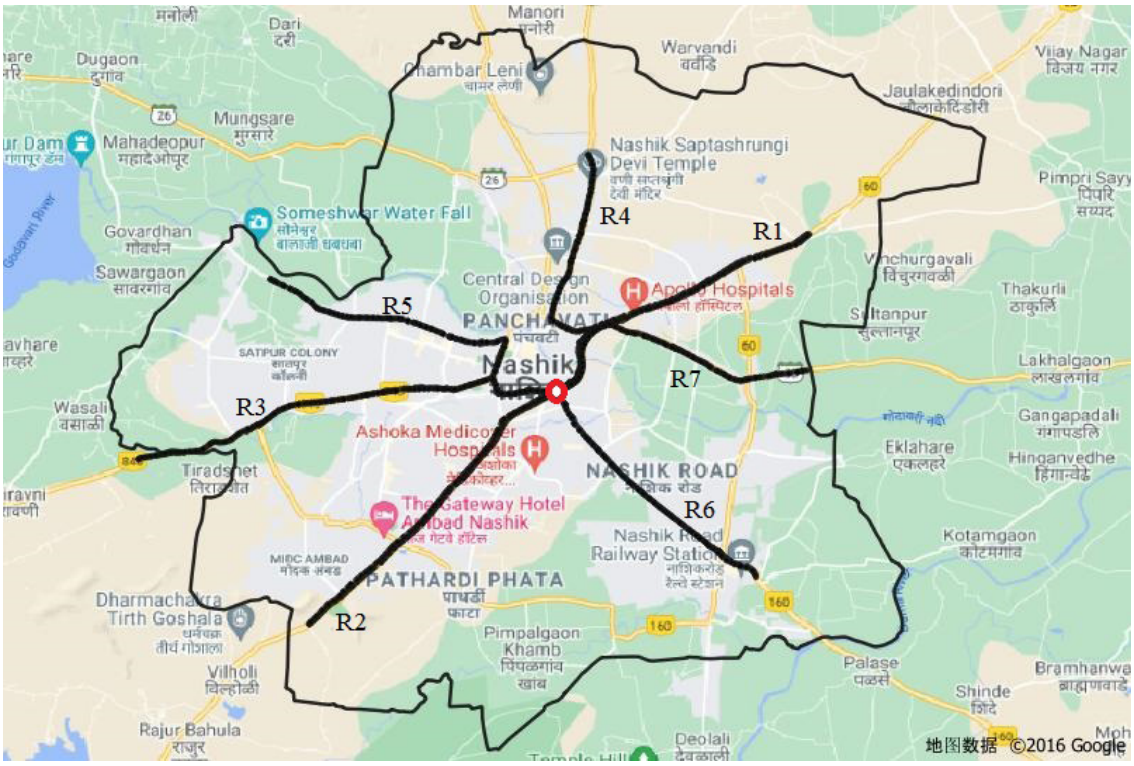

Fig. 1. Map of Nashik city showing selected routes for mobile monitoring

Table 1. Details of routes for mobile monitoring

Route	Route name	Characteristic activities	Road name and type	Approximate one-way length
R1	Dwarka Circle to Adgaon	Commercial, Educational, Residential	Mumbai Agra Highway NH-3	8.8 km
R2	Dwarka Circle to Nehru Van Udyan	Commercial, Connected to Ambad Industrial Area	Mumbai Agra Highway NH-3	9.7 km
R3	Dwarka Circle to Geeta Mandir	Commercial, Connected to Satpur Industrial Area	Nashik Trimbakeshwar Road NH-848	11.3 km
R4	Dwarka Circle to Mhasrul gaon	Commercial, Residential	Nashik Saputara Road SH-17	7.3 km
R5	Dwarka Circle to Someshwar Mandir	Commercial, Educational, Residential	Gangapur Road City Road	9.8 km
R6	Dwarka Circle to Nashik Road	Commercial, Educational, Residential	Nashik Pune Road NH-60	7.0 km
R7	Dwarka Circle to Madhsangvi via Aurangabad Naka	Commercial, Residential, Agricultural	Nashik Aurangabad Highway SH-30	5.9 km

Table 1 shows the details of all the seven routes on which mobile monitoring was performed. The schedule of monitoring was planned such that all seven routes are monitored for all seven days of the week making it 49 days for each season. The monitoring was done during peak hours in the morning and evening. The morning monitoring would start at 9:00 am from Dwarka Circle and would end after the round trip on the route back to Dwarka Circle. The same route was monitored for evening peak hours starting at 06:00 pm from Dwarka Circle and would end after the round trip on the route back to Dwarka Circle. The monitoring was done for all three seasons viz. Summer (24th February 2021 to 13th April 2021), Monsoon (11th August 2021 to 28th September 2021), and Winter (22nd December 2021 to 09th February 2022). An approximate 1,675 km of length was monitored for each season. The speed of the bike was kept as low as possible to obtain maximum data points.

Data collection through mobile monitoring

In this study, extensive mobile measurements of particulate matter on the highway stretches passing through the Nashik Municipal boundaries has been performed to demonstrate the feasibility of using low-cost air quality monitor to measure personal exposure to pollutants during peak hours.

Fig. 2. Deployment of ATMOS sensor platform on a fabricated frame on the bike

The low-cost sensor platform was deployed on a fabricated frame on a motorbike to be at a breathing level as shown in Fig. 2. The ATMOS sensor platform comes with a Plantower PM sensor, GPS module, and Temperature and Relative Humidity Sensor. These PM sensors use the laser-scattering technique to measure real-time mass concentrations of PM and apportion the corresponding laser scattering to PM_1, $PM_{2.5}$, and PM_{10} [10]. The sensor platform measures PM_1, $PM_{2.5}$, PM_{10}, Temperature, Relative Humidity, and Location for an averaging frequency of 10 seconds. The data obtained can be considered as personal exposure of the biker to the PM pollution.

Estimation of respiratory deposition doses

The RDDs can be estimated using concentrations of PM, the deposition factors DF, the amount of time T spent in each activity (Riding Bike), the respiratory frequency f, and Tidal Volume VT for the different activities. The RDDs value can be determined based on the DF value which decreases strongly with particle size and increases with VT.

The RDDs can be estimated using the following Eq. 1 from the International Commission on Radiological Protection (ICRP 1994) [11]. These equations have been used in many previous studies to estimate the RDDs [12–14].

$$\text{RDDs } (\mu g) = DFi \times VT\ (m^3/\text{breath}) \times f\ (\text{breath/min}) \times PMi\ (\mu g/m^3) \times T\ (\text{min}) \quad (1)$$

Where, DFi is a deposition fraction of a size fraction i, and PMi is the particulate matter mass concentration in different size ranges.

The deposition factors can be estimated using Eqs. 2 to 5.

The Deposition Factor for head airways DF_{HD} is calculated using the given equation,

$$DF_{HD} = IF\left(\frac{1}{1+\exp\,(6.84+1.183\ln\,(dp)} + \frac{1}{1+\exp\,(0.924-1.885\ln\,(dp)}\right) \quad (2)$$

Where dp is the particle size in µm and IF is the inhalable fraction given by,

$$IF = 1 - 0.5(1 - \frac{1}{1+0.00076dp^{2.8}}) \quad (3)$$

The Deposition Factor for the tracheobronchial region DF_{TB} is calculated using the given equation,

$$DF_{TB} = \left(\frac{0.00352}{(dp)}\right) \times [\exp(-0.234(\ln(dp) + 3.40)^2) + 63.9\exp(-0.819(\ln(dp) - 1.61)^2)] \quad (4)$$

The Deposition Factor for alveolar region DF_{AL} is calculated using the given equation,

$$DF_{AL} = \left(\frac{0.00155}{(dp)}\right) \times [\exp(-0.416(\ln(dp) + 2.84)^2) + 19.11\exp(-0.482(\ln(dp) - 13.62)^2)] \quad (5)$$

The tidal volume VT considered is 12.5×10^{-4} m^3/breath, and the respiratory frequency f is 20 breaths/min for a male adult. The exposure time T in minutes is the actual time of travel for the round trip [14].

Results and discussions

In this study, variation in the exposure of biker to particulate matter as RDDs with respect to each route, season and the size of the particle have been studied.

Route specific RDDs exposure

The seven routes were monitored for peak hours in the morning and evening for seven days of the week each for three seasons. The Respiratory Deposition Doses in head airways (RDD_{HD}), Tracheobronchial region (RDD_{TB}) and alveolar region (RDD_{AL}) were calculated for each route for all the seven days of the week for morning and evening. The average of these doses was considered as exposure to the biker for morning and evening peak hours.

Route R1

In summer the average concentrations of PM_1, $PM_{2.5}$ and PM_{10} during morning peak hours were 53.57 μg/m^3, 93.68 μg/m^3 and 106.14 μg/m^3 respectively however, during evening peak hours it was 42.23 μg/m^3, 71.49 μg/m^3 and 84.04 μg/m^3 respectively. In Monsoon the morning peak hour average PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 22.46 μg/m^3, 35.22 μg/m^3 and 42.25 μg/m^3 while the evening peak hour average concentrations were 53.00 μg/m^3, 40.67 μg/m^3 and 47.88 μg/m^3 respectively. In Winter the morning peak hour average PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 53.47 μg/m^3, 93.68 μg/m^3 and 106.14 μg/m^3 while in the evening peak hours 42.23 μg/m^3, 71.49 μg/m^3 and 84.04 μg/m^3 respectively.

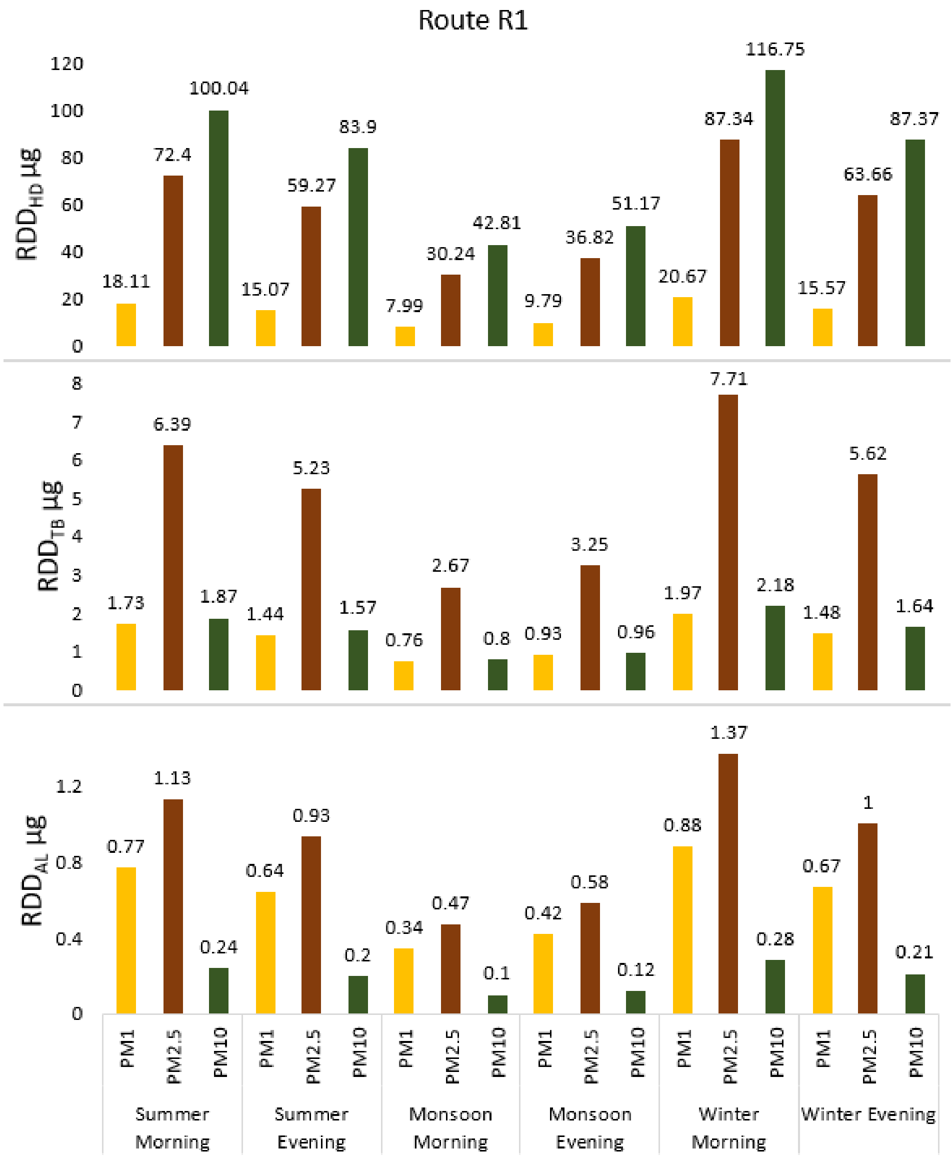

Fig. 3. Estimation of RDD_{HD}, RDD_{TB} and RDD_{AL} for Route R1

From Fig. 3, for Route R1, the maximum exposure as RDD_{HD} of 116.75 µg happened due to PM_{10} in Winter morning followed by 100.04 µg in Summer morning. The maximum exposure as RDD_{TB} of 7.71 µg was in the winter morning followed by 6.39 µg in summer morning due to $PM_{2.5}$. The maximum exposure as RDD_{AL} of 1.37 µg happened in the winter morning followed by 1.13 µg in the summer morning due to $PM_{2.5}$. The highest RDDs were observed at the morning peak hours of winter [12].

Route R2

In Summer, the average concentration of PM_1, $PM_{2.5}$ and PM_{10} monitored in the morning peak hour were as 43.61 µg/m³, 71.30 µg/m³ and 82.53 µg/m³ respectively and 30.16 µg/m³, 48.03 µg/m³ and 58.73 µg/m³ respectively in the monitored evening peak hours. In Monsoon the morning peak hour average PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 21.79 µg/m³, 33.58 µg/m³ and 39.70 µg/m³ while the evening peak hour average concentrations were 25.32 µg/m³, 39.64 µg/m³ and 46.80 µg/m³ respectively. In Winter the morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 50.93 µg/m³, 93.02 µg/m³ and 109.07 µg/m³ while the evening peak hours concentrations were 46.97 µg/m³, 82.50 µg/m³ and 96.68 µg/m³ respectively.

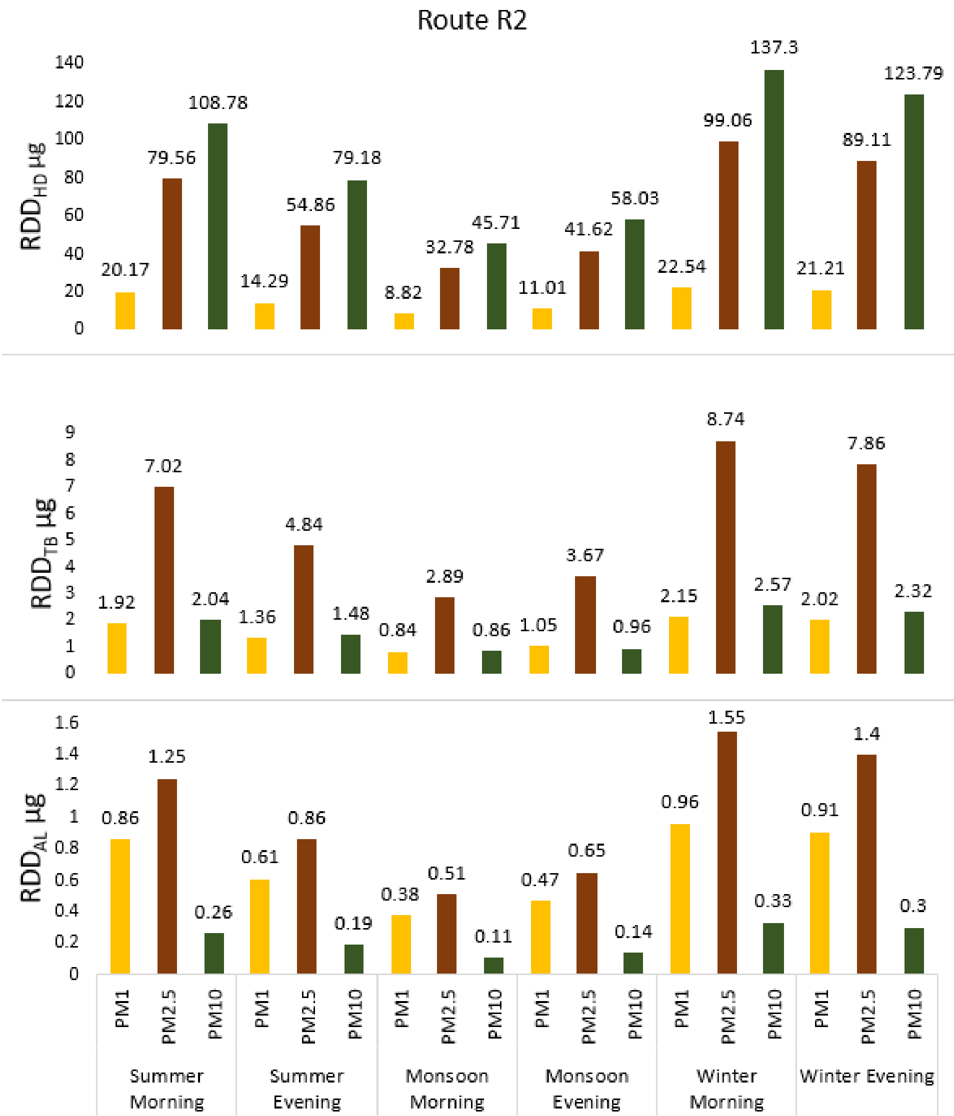

Fig. 4. Estimation of RDD_{HD}, RDD_{TB} and RDD_{AL} for Route R2

From Fig. 4, for Route R2, the maximum exposure as RDD_{HD} of 137.3 µg happened due to PM_{10} in Winter morning followed by 123.79 µg in Winter evening. The maximum exposure as RDD_{TB} of 8.74 µg was in the Winter morning followed by 7.86 µg in Winter evening due to $PM_{2.5}$. The maximum exposure as RDD_{AL} of 1.55 µg happened in the Winter morning followed by 1.4 µg in the Winter evening due to $PM_{2.5}$.

Route R3

In Summer, the average monitored morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations were 46.63 µg/m³, 75.61 µg/m³ and 86.10 µg/m³ respectively and 36.72 µg/m³, 58.76 µg/m³ and 67.49 µg/m³ respectively in the monitored evening peak hours. In Monsoon the morning peak hour average PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 28.42 µg/m³, 44.50 µg/m³ and 52.13 µg/m³ while the evening peak hour average concentrations were 29.26 µg/m³, 44.84 µg/m³ and 51.44 µg/m³ respectively. In Winter the morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 67.97 µg/m³, 121.37 µg/m³ and 135.55 µg/m³ while the evening peak hours concentrations were 58.59 µg/m³, 102.24 µg/m³ and 114.95 µg/m³ respectively.

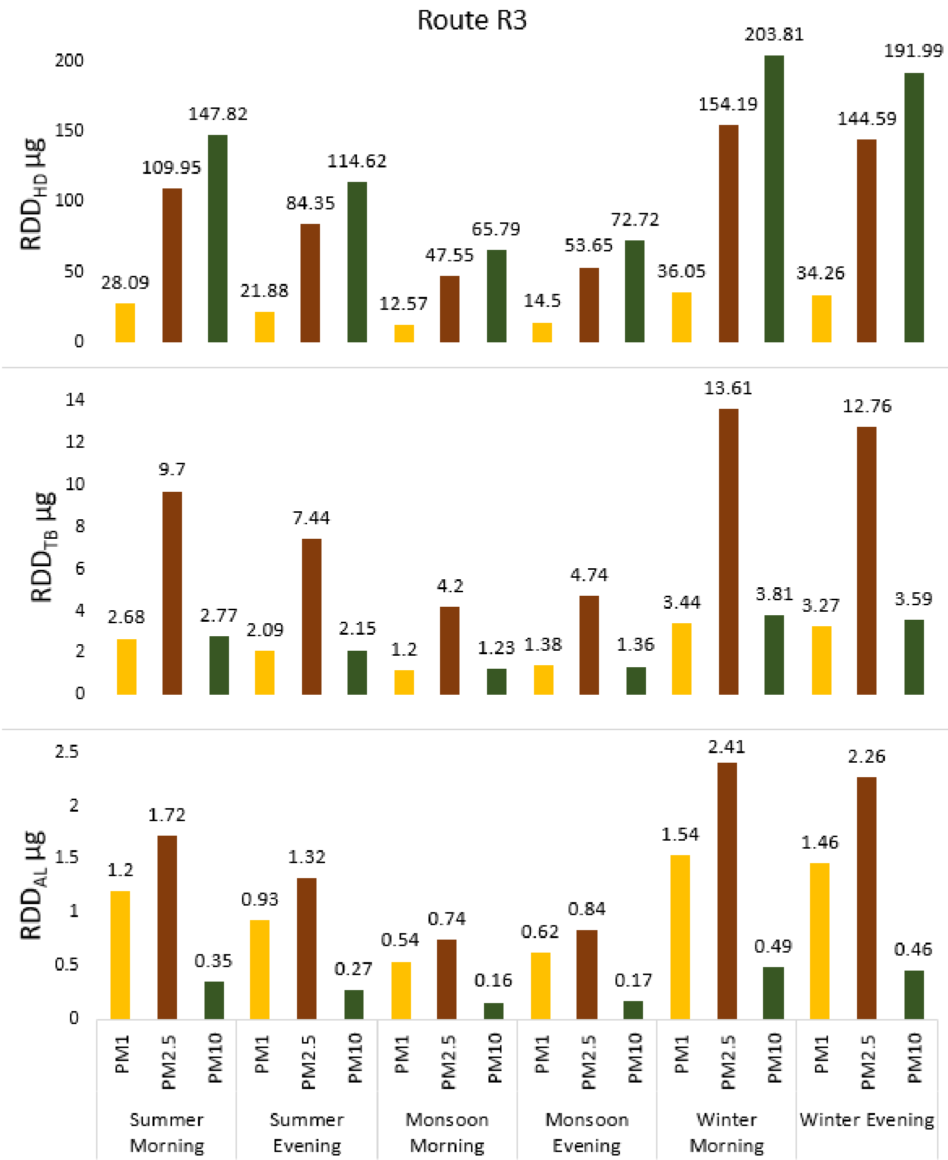

Fig. 5. Estimation of RDD_{HD}, RDD_{TB} and RDD_{AL} for Route R3

From Fig. 5, for Route R3, the maximum exposure as RDD_{HD} of 203.81 µg happened due to PM_{10} in Winter morning followed by 191.99 µg in Winter evening. The maximum exposure as RDD_{TB} of 13.61 µg was in the Winter morning followed by 12.76 µg in Winter evening due to $PM_{2.5}$. The maximum exposure as RDD_{AL} of 2.41 µg happened in the Winter morning followed by 2.26 µg in the Winter evening due to $PM_{2.5}$. As Route R3 is the longest route, the time required to cover the length increases. Hence, with the increased length and the exposure time, the RDDs show greater values [15].

Route R4

In Summer, the average s morning peak hour PM_1, $PM_{2.5}$ and PM_{10} concentrations were 47.15 µg/m^3, 74.65 µg/m^3 and 84.91 µg/m^3 respectively and 34.11 µg/m^3, 52.96 µg/m^3 and 63.05 µg/m^3 respectively in the monitored evening peak hours. In Monsoon the morning peak hour average PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 22.62 µg/m^3, 34.66 µg/m^3 and 41.03 µg/m^3 while the evening peak hour average concentrations were 28.15 µg/m^3, 44.23 µg/m^3 and 51.95 µg/m^3 respectively. In Winter the morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 65.51 µg/m^3, 114.55 µg/m^3 and 127.49 µg/m^3 while the evening peak hours concentrations were 53.89 µg/m^3, 93.31 µg/m^3 and 104.94 µg/m^3 respectively.

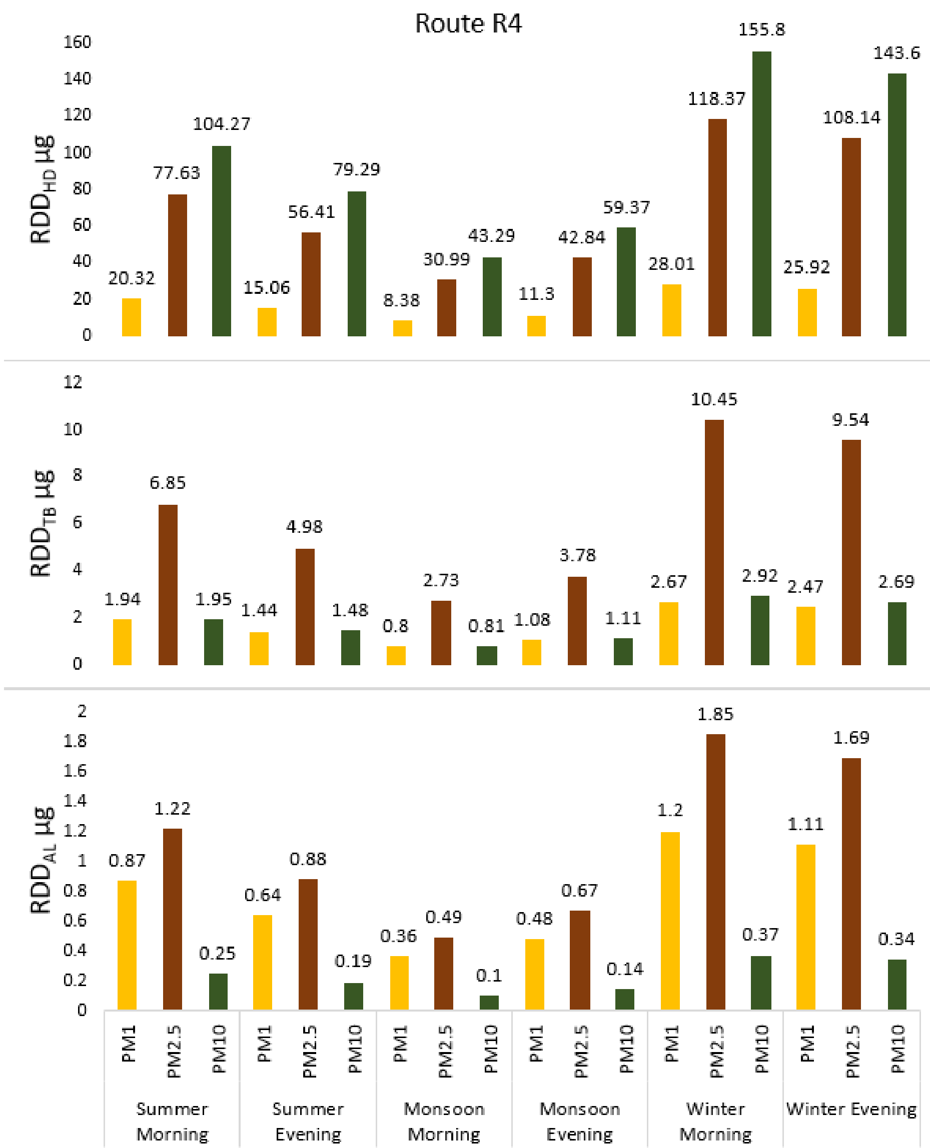

Fig. 6. Estimation of RDD_{HD}, RDD_{TB} and RDD_{AL} for Route R4

From Fig. 6, for Route R4, the maximum exposure as RDD_{HD} of 155.8 µg happened due to PM_{10} in Winter morning followed by 143.6 µg in Winter evening. The maximum exposure as RDD_{TB} of 10.45 µg was in the Winter morning followed by 9.54 µg in Winter evening due to $PM_{2.5}$. The maximum exposure as RDD_{AL} of 1.85 µg happened in the Winter morning followed by 1.69 µg in the Winter evening due to $PM_{2.5}$.

Route R5

In Summer the average monitored morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations were 46.40 µg/m³, 73.76 µg/m³ and 83.29 µg/m³ respectively and 37.31 µg/m³, 58.56 µg/m³ and 68.89 µg/m³ respectively in the monitored evening peak hours. In Monsoon the morning peak hour average PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 23.46 µg/m³, 36.17 µg/m³ and 42.45 µg/m³ while the evening peak hour average concentrations were 28.87 µg/m³, 44.71 µg/m³ and 51.25 µg/m³ respectively. In Winter the morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 78.03 µg/m³, 136.96 µg/m³ and 149.67 µg/m³ while the evening peak hours concentrations were 61.10 µg/m³, 107.56 µg/m³ and 119.28 µg/m³ respectively.

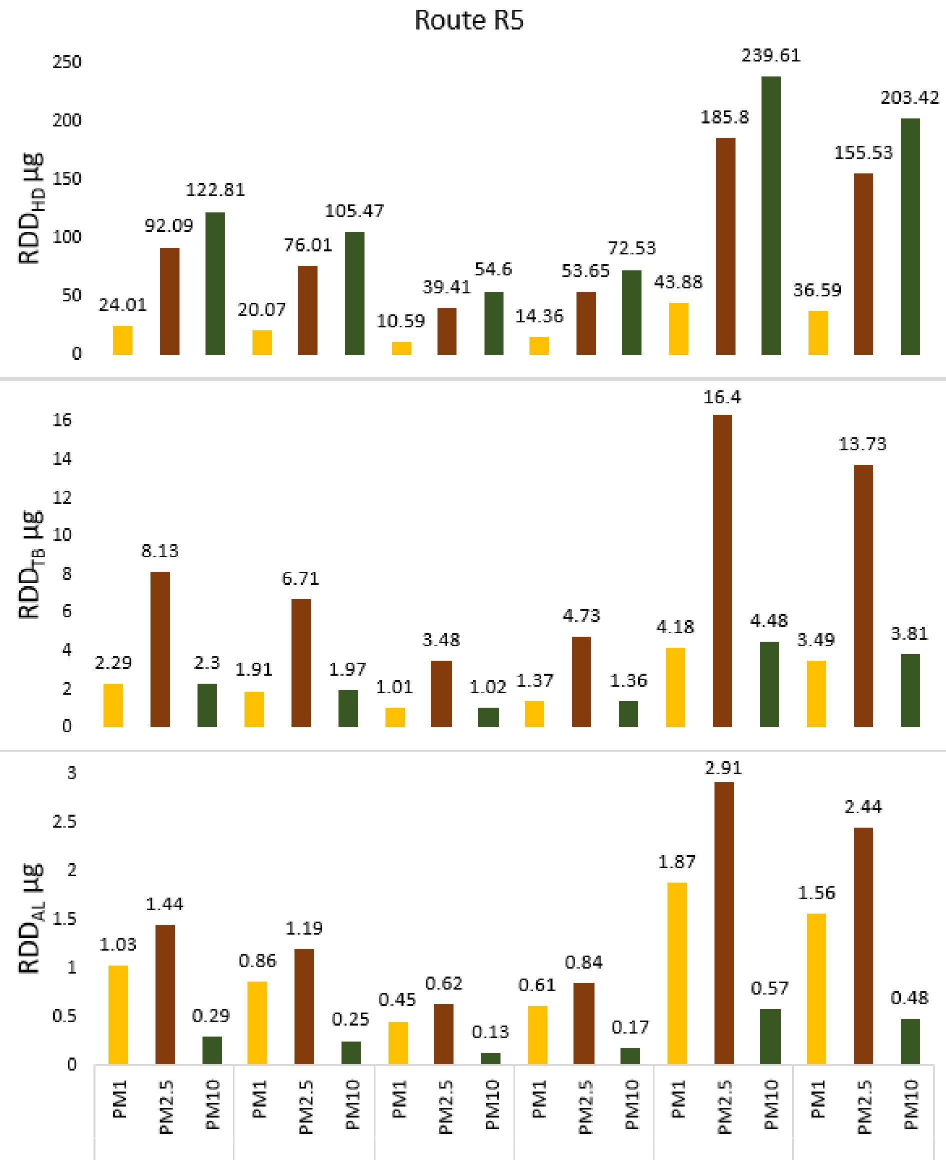

Fig. 7. Estimation of RDD_{HD}, RDD_{TB} and RDD_{AL} for Route R5

From Fig. 7, for Route R5, the maximum exposure as RDD_{HD} of 239.61 µg happened due to PM_{10} in Winter morning followed by 203.42 µg in Winter evening. The maximum exposure as RDD_{TB} of 16.4 µg was in the Winter morning followed by 13.73 µg in Winter evening due to $PM_{2.5}$. The maximum exposure as RDD_{AL} of 2.91 µg happened in the Winter morning followed by 2.44 µg in the Winter evening due to $PM_{2.5}$. The exposure on Route R5 is higher as compared to other routes, as it has higher traffic density and major signalised intersections [7].

Route R6

In Summer the average monitored morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations were 52.31 µg/m³, 84.01 µg/m³ and 94.68 µg/m³ respectively and 37.92 µg/m³, 59.84 µg/m³ and 70.06 µg/m³ respectively in the monitored evening peak hours. In Monsoon the morning peak hour average PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 27.26 µg/m³, 42.06 µg/m³ and 49.67 µg/m³ while the evening peak hour average concentrations were 30.56 µg/m³, 48.14 µg/m³ and 55.84 µg/m³ respectively. In Winter the morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 73.22 µg/m³, 127.99 µg/m³ and 139.57 µg/m³ while the evening peak hours concentrations were 55.56 µg/m³, 93.98 µg/m³ and 108.37 µg/m³ respectively.

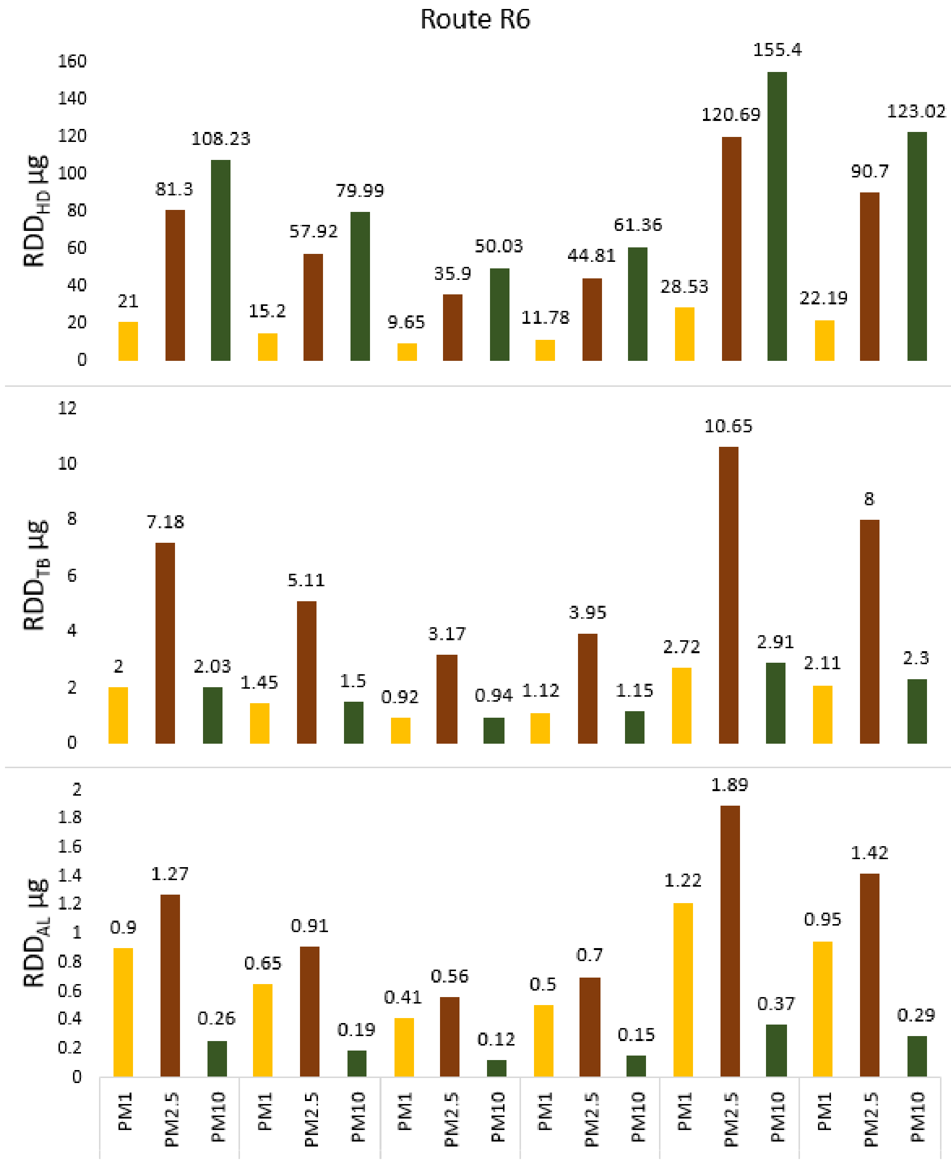

Fig. 8. Estimation of RDD_{HD}, RDD_{TB} and RDD_{AL} for Route R6

From Fig. 8, for Route R6, the maximum exposure as RDD_{HD} of 155.4 µg happened due to PM_{10} in Winter morning followed by 123.02 µg in Winter evening. The maximum exposure as RDD_{TB} of 10.65 µg was in the Winter morning followed by 8.0 µg in Winter evening due to $PM_{2.5}$. The maximum exposure as RDD_{AL} of 1.89 µg happened in the Winter morning followed by 1.42 µg in the Winter evening due to $PM_{2.5}$.

Route R7

In Summer, the average monitored morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations were 42.33 µg/m³, 68.70 µg/m³ and 79.90 µg/m³ respectively and 30.80 µg/m³, 49.85 µg/m³ and 60.45 µg/m³ respectively in the monitored evening peak hours. In Monsoon the morning peak hour average PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 21.07 µg/m³, 32.84 µg/m³ and 39.05 µg/m³ while the evening peak hour average concentrations were 23.44 µg/m³, 38.43 µg/m³ and 45.79 µg/m³ respectively. In Winter the morning peak hours PM_1, $PM_{2.5}$ and PM_{10} concentrations monitored were 70.05 µg/m³, 123.09 µg/m³ and 135.68 µg/m³ while the evening peak hours concentrations were 48.34 µg/m³, 83.38 µg/m³ and 94.24 µg/m³ respectively.

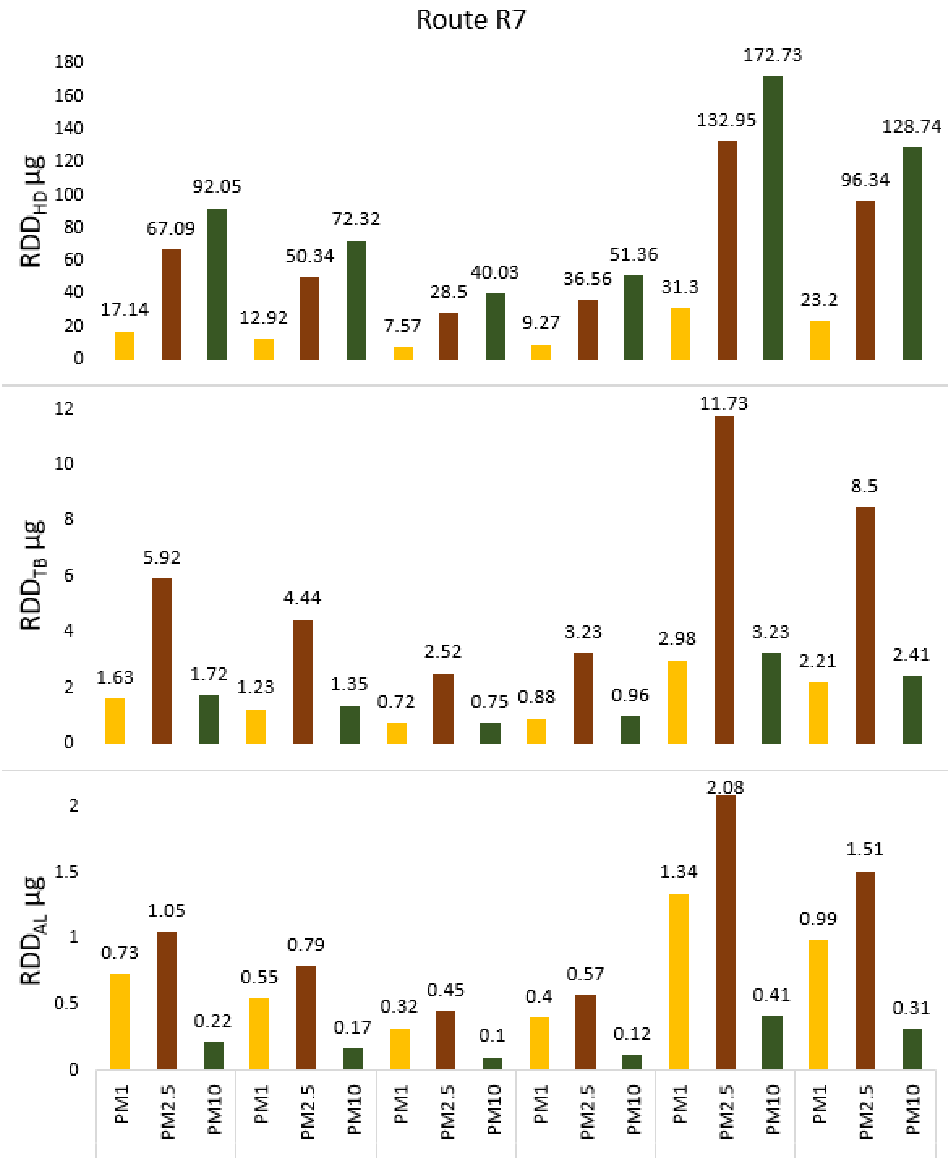

Fig. 9. Estimation of RDD_{HD}, RDD_{TB} and RDD_{AL} for Route R7

From Fig. 9, for Route R7, the maximum exposure as RDD_{HD} of 172.73 µg happened due to PM_{10} in Winter morning followed by 132.95 µg in Winter morning due to $PM_{2.5}$. The maximum exposure as RDD_{TB} of 11.73 µg was in the Winter morning followed by 8.5 µg in Winter evening due to $PM_{2.5}$. The maximum exposure as RDD_{AL} of 2.08 µg happened in the Winter morning followed by 1.51 µg in the Winter evening due to $PM_{2.5}$.

The maximum RDD_{HD} exposure due to PM_{10} can be seen on R5 morning (239.610 µg) > R3 morning (203.81 µg) > R5 evening (203.42 µg) > R3 evening (191.99 µg). The maximum RDD_{TB} exposure due to $PM_{2.5}$ can be seen on R5 morning (16.4 µg) > R5 evening (13.73 µg) > R3 morning (13.61 µg) > R3 evening (12.76 µg). The maximum RDD_{AL} exposure due to $PM_{2.5}$ can be seen on R5 morning (2.91 µg) > R5 evening (2.44 µg) > R3 morning (2.41 µg) > R3 evening (2.26 µg). The Routes R3 and R5 show maximum exposure as these routes have the maximum one side lengths of 11.3 km and 9.8 km respectively consequently increasing the travel time and exposure time of the biker.

Effect of seasonal variation on exposure

Seasonal variation has a significant impact on air pollution levels in Indian cities. The city of Nashik experiences distinct seasons throughout the year, including winter, summer and monsoon. These seasons are characterized by various meteorological and environmental factors that influence the dispersion of air pollution in different ways. The RDD_{HD} due to PM_{10} exposure in Summer morning decreased by 56.34% in Monsoon morning and increased by 245.17% in Winter Morning as compared to Monsoon morning while the RDD_{HD} due to PM_{10} exposure in Summer evening decreased by 29.4% in Monsoon evening and increased by 141.4% in Winter evening as compared to Monsoon evening. The RDD_{TB} and RDD_{AL} due to $PM_{2.5}$ exposure in Summer morning decreased by 57.7% in Monsoon morning and increased by 266.1% in Winter morning as compared to Monsoon morning while the RDD_{TB} and RDD_{AL} due to $PM_{2.5}$ exposure in Summer evening decreased by 29.5% in Monsoon evening and increased by 141.6% in Winter morning as compared to Monsoon evening. The summer season is characterized by hot and dry conditions, which increase the prevalence of winds. The monsoon season brings rainfall which helps in reducing air pollution levels by effectively washing out pollutants from the atmosphere, leading to improved air quality [16]. While the overall air quality improves during the monsoon, there can still be localized pollution events due to increased humidity, stagnant conditions, and the recirculation of pollutants, high vehicular traffic and industrial activities. Increased pollution levels: During winter pollution levels tend to rise significantly due to the combined effects of meteorological conditions, increased emissions, and regional sources such as crop residue burning and industrial pollution. The phenomenon known as "temperature inversion" occurs, where a layer of cold air gets trapped close to the ground, preventing the dispersion of pollutants and leading to the formation of smog and high levels of particulate matter [17].

Effect of particle size on region of deposition

The size of particulate matter plays a significant role in determining the region of deposition within the lungs. The respiratory system consists of various airways of different sizes, ranging from the large conducting airways to the smaller respiratory bronchioles and alveoli. Inhalable particles generally refer to particles with aerodynamic diameters less than 100 µm to greater than 10 µm. These particles can be inhaled into the respiratory system but tend to deposit mainly in the upper airways (nasopharyngeal region, trachea) [18]. Due to their relatively larger size, they are not capable of penetrating deep into the lungs and are typically captured by the body's natural defence mechanisms like mucociliary clearance and sneezes.

Table 2. Mass deposition and percentage deposition for route R1 in Winter morning

Winter morning									
Route	PM_{10}			$PM_{2.5}$			PM_1		
R1	RDD_{HD}	RDD_{TB}	RDD_{AL}	RDD_{HD}	RDD_{TB}	RDD_{AL}	RDD_{HD}	RDD_{TB}	RDD_{AL}
Mass Deposition (µg)	116.75	2.18	0.28	87.34	7.71	1.37	20.67	1.97	0.88
Deposition (%)	97.93	1.83	0.23	90.59	7.99	1.42	87.87	8.37	3.75

Thoracic particles are those with aerodynamic diameters less than 10 µm to 4 µm. They have the potential to reach the uppermost part of lower respiratory system, including the bronchioles and the beginning of the alveolar region. As seen in Table 2, The mass deposition in the head airways RDD_{HD} follows a trend of PM_{10}>$PM_{2.5}$>PM_1. These particles can undergo deposition through impaction and sedimentation. Impaction occurs when particles are unable to follow the curved airways and impact on the walls due to their inertia. Sedimentation refers to the gravitational settling of particles in the airways. These particles are more likely to deposit in the bronchial region and the upper parts of the alveolar region [19].

Respirable particles have aerodynamic diameters less than 4 µm, allowing them to penetrate deep into the lung's lower regions, specifically the alveoli. From Table 2, it can be observed that the mass deposition in the tracheobronchial region RDD_{TB} follows trend of $PM_{2.5}$>PM_{10}>PM_1. The RDD_{TB} due to PM_{10} and PM_1 differs slightly. The mass deposition in the alveolar region RDD_{AL} follows trend of $PM_{2.5}$>PM_1>PM_{10}. Due to their small size, these particles can evade impaction in the larger airways and instead follow the airstream into the alveolar region. Within the alveoli, they can deposit through mechanisms such as diffusion and sedimentation. Diffusion causes particles to collide with gas molecules and move toward the alveolar surfaces, while sedimentation occurs as particles settle under the influence of gravity. As a result, respirable particles have a higher likelihood of reaching the gas-exchange regions of the lungs and potentially causing adverse health effects [20].

While considering the percentage deposition, it can be seen from Table 2, that the highest deposition in Head Airways RDD_{HD} happens due to PM_{10} as 97.93%. The maximum deposition in tracheobronchial region RDD_{TB} happens due to PM_1 as 8.37% and due to $PM_{2.5}$ as 7.99% with a slight difference. The maximum deposition in the alveolar region RDD_{AL} is maximum due to PM_1 as 3.75%.

Conclusion

The PM_1, $PM_{2.5}$ and PM_{10} concentrations vary spatially in Indian cities. Hence to present the seasonal variation, the mobile monitoring has been performed on seven highway stretches passing through Nashik city. The monitoring has been performed for morning and evening peak hours of all the weekdays. The maximum RDD_{HD} exposure was observed on routes R5 and R3 in the winter mornings. The maximum RDD_{TB} and RDD_{AL} exposure can be observed on route R5 in winter morning as well as evening. The Routes R3 and R5 show maximum exposure as these routes have the maximum one side lengths of 11.3 km and 9.8 km respectively consequently increasing the travel time and exposure time of the biker. The seasonal variation has a substantial effect on PM concentrations and their exposure. The minimum exposure was observed in monsoon, followed by summer and the maximum exposure was observed in winters. The PM particle size plays an important role in the depositions in the respiratory tract. The maximum mass deposition of RDD_{HD} is higher due to PM_{10}, while RDD_{TB} and RDD_{AL} are higher due to $PM_{2.5}$.

Recommendations and future scope

The findings of this study suggest that there is high exposure on the highways, making it advisable to use alternate routes. To protect oneself from exposure it can be advised to use respiratory masks while riding the bike. Also, the same study can be carried out on arterial roads connecting these highways as well as for last mile delivery partners.

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Competing interests

The authors declare they have no conflicts of interest or competing interests.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely observed by the authors.

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