Chapter 5

Factors Affecting Average On-Road PM Exposure

This chapter analyses the effect of various factors on average PM concentrations in Varanasi city. The effect of factors such as meteorology factors (AT, RH), traffic factors (TT, PHT and OPHT), ventilatory factors (IR and ID), street configurations (LU) and ambient concentration (AC) are discussed in this chapter.

5.1 Background

The current study considered two prominent factors affecting PM exposure: traffic congestion and meteorological parameters. Delays, lower average speeds, and queuing of vehicles depict traffic congestion. Saksena et al. (2008) observed that the PM levels are higher during PHT than during OPHT in Delhi. A commuter in morning PHT was 1.8 times more exposed to PM in Vellore, India than one commuting in afternoon OPHT (Manojkumar et al., 2021). On the other hand, Hatzopoulou et al. (2013) observed that during morning trips ($PM_{2.5}$ = 10.4 µg m^{-3}), commuters were less exposed to PM than afternoon commuters ($PM_{2.5}$ = 11.1 µg m^{-3}) in Montreal (Canada). This contrast may be attributed to the difference in climate and driving behavior between developing and developed countries. Meteorological factors also impact commuters' exposure to PM concentration. Hatzopoulou et al. (2013) observed that AT, RH, and WS were positively associated with $PM_{2.5}$. In contrast, Manojkumar et al. (2021) observed that AT and WS were negatively associated with PM concentration, while RH was positively associated. Overall, these studies present contradictory findings regarding PM exposure concentration. A more detailed data collection accounting for variation in hourly AT and RH may be required to understand the exposure pattern. Most commuters in developing countries in Asia are motorcycle users who are also the most vulnerable to particulate pollution (Goel et al., 2015; Huy et al., 2022; Tsai et al., 2008). Minimal studies are available on PM exposure to motorcyclists compared to other transport microenvironments associated with walking, cycling, or riding a car, auto-rickshaw, bus, train, or tram. Table 5.1 shows the summary of PM exposure studies on motorcyclists around the world. Most of these studies were conducted during PHT or OPHT, which may not capture the hourly pattern of PM exposure concentration. The current study was conducted at various times of the day to record the exposure patterns more accurately. The study also focused on finding the impact of traffic and meteorological parameters on commuters' PM exposure.

5.2 Data Analysis

5.2.1 Spatial Analysis and Modeling

R was used for statistical computing and visualization of results, whereas QGIS (Quantum Geographic Information System) was used for geoprocessing and mapping. On-road PM concentration was compared with reference PM. The pre-trip reference concentration was compared with the first trip, and while post-trip reference concentration was compared with the last trip to minimize the difference in time of the day and meteorological parameters. The routes (R1, R2, R3, R4) were divided into 50 m segments. A rectangular buffer of 20 m width was constructed around each segment. The average $PM_{2.5}$ and PM_{10} concentrations were determined for each segment by aggregating data corresponding to GPS coordinates within a buffer. These average values were plotted on the map to visualize

Table 5.1 List of PM exposure studies carried out on motorcycles around the world.

Author	**N**	**Location**	**Period**	**Hour**	**PM$_{2.5}$ in µg m^{-3}**	**PM$_{10}$ in µg m^{-3}**
Tsai et al., 2008	16 trips	Taipei, Taiwan	January to April, 2005	07:00 – 09:00 and 17:00 – 19:00	67.5 (31.3)	112.8 (38.3)
Saksena et al., 2008	32 trips	Hanoi, Vietnam	October, 2006	–	–	580 (1.38*)
Wu et al., 2013	20 days	Foshan, China	March 5–10, March 28–April 3, and July 5–11 of 2011	07:00 – 12:00 and 14:00 – 19:00	77.1 (42.6)	–
Goel et al., 2015	21 trips	Delhi, India	April, 2014	08:00 – 13:00	207 (139)	–
Patel et al., 2016	–	Makassar, Indonesia	June, 2013	06:00 – 24:00	25 (34)	305 (598)
Ramos et al., 2016	15 trips	Lisbon, Portugal	December, 2013 to March, 2014	08:00, 11:00, 14:00, 17:30, and 21:00	39 - 91**	43 - 98**
Betancourt et al., 2017	12 trips	Bogota, Colombia	September to November, 2015	07:00 - 10:00	151***	–
Raj and Karthikeyan, 2020	36 trips	Chennai, India		08:00 – 11:00, 11:30 – 15:30, 17:30 – 20:30	251 (56)	–
Manojkumar et al., 2021	96 trips	Vellore, India	October, 2019 to February, 2020	07:30 – 10:00 and 13:00 – 15:00	144 (135)	–
Huy et al., 2022a	–	Ho Chi Minh, Vietnam	August to October, 2020	07:00 – 09:00	74.5 - 109.3**	171.3 - 239.6**
Huy et al., 2022b	–	Ho Chi Minh, Vietnam	July, 2020	06:30 and 12:00	77.2 (49.4)	243.1 (184.7)

Note: * Geometric standard deviation, ** reported in a range, *** median

PM hot spots. A one-way ANOVA was performed to investigate if there was a significant difference in PM concentrations between seasons. The effect of day of week and week type (weekdays or weekend) on on-road and reference PM concentration was explored. Correlation matrices were studied to find how PM concentration was correlated with meteorological parameters and traffic speed. The ratio of fine/coarse ($PM_{2.5}/PM_{10}$) PM concentrations was also studied. This ratio depicts the potential contribution of vehicle exhaust to PM concentration. Further, a linear regression model was fitted to investigate the relationship between on-road and reference PM concentration, on-road PM concentration and meteorological parameters. The inhaled dose of a motorcyclist was also estimated using the procedure already mentioned in Section 4.2.5.

5.3 Results and Discussion

5.3.1 Descriptive Statistics

Motorcycles are the city's most dominant mode of transportation, followed by auto-rickshaws, e-rickshaws, and walking. Thus, an exposure study was conducted for a typical motorcyclist. Data were collected during winter, spring, and summer seasons from 07:00 to 17:00 hours. The goal was to collect PM measurements and other related data to obtain representative samples of sufficient size. At least 30 minutes of cleaned data were available for each combination of route and hour of the day. Table 5.2 shows each route's extent and associated land use, along with a season-wise summary of trips, speed, temperature, and relative humidity. The route and season-wise distribution of speed, AT, and RH are presented in Fig. 5.1, 5.2, and 5.3, respectively. These box plots depict the values of different variable in concern along routes in different seasons. The 25th percentile, 50th percentile (median), 75th percentile, and range of PM concentrations are depicted.

The seasons were found to have no effect on speed on individual routes (Fig. 5.1). For example, the speed on R1 was found to be 17.2 kmph in winter, 17.8 kmph in spring, and 19.5 kmph in summer. The motorcycle was found to have a lower speed on R1 and R2 than on R3 and R4 due to frequent congestion.

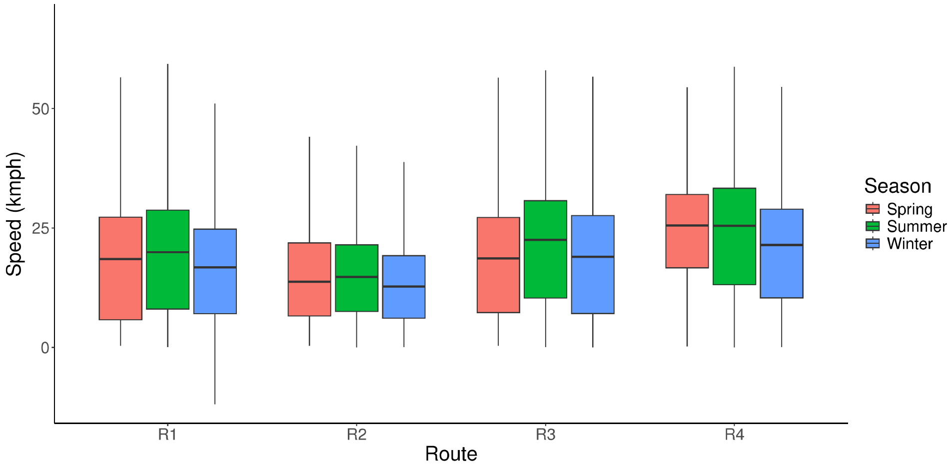

Fig. 5.1 Speed distribution on routes in different seasons.

Significant temperature difference was observed between winter and summer and between spring and summer on all routes (Fig. 5.2). Apart from R3 and R4, the significant difference in temperature between winter and spring on all routes (R1 and R2) was observed during the study. Again, the temperatures along the routes during a specific season is compared. No significant differences in temperature were observed among the routes during winter (22.7 – 26.3 °C) or summer (38.8 – 39.7 °C). During spring, the average temperature observed on R1 and R2 was 28.3 °C, while that on R3 and R4 was 35.6 and 36.0 °C, respectively. A greater number of trips with lower temperatures could have caused the lower average temperature on R1/R2 in spring. In this regard, it may be noted that data collection on a typical day was carried out either on R1 and R2 or R3 and R4.

The RH was observed compared to be higher in winter compared to other seasons (Fig. 5.3). A mixed trend of RH values was observed on the routes during summer and spring.

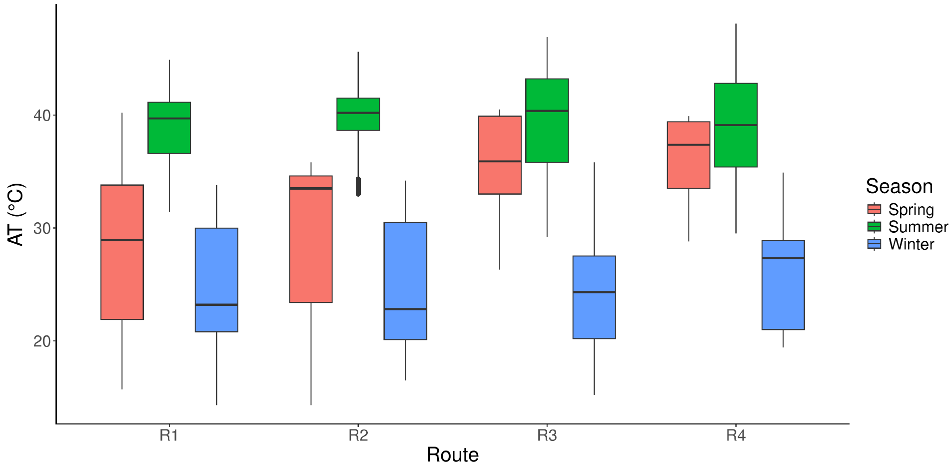

Fig. 5.2 AT distribution on routes in different seasons.

Higher RH was observed on R1 and R2 during spring compared to summer, while slightly higher RH was observed on R3 and R4 during summer compared to spring.

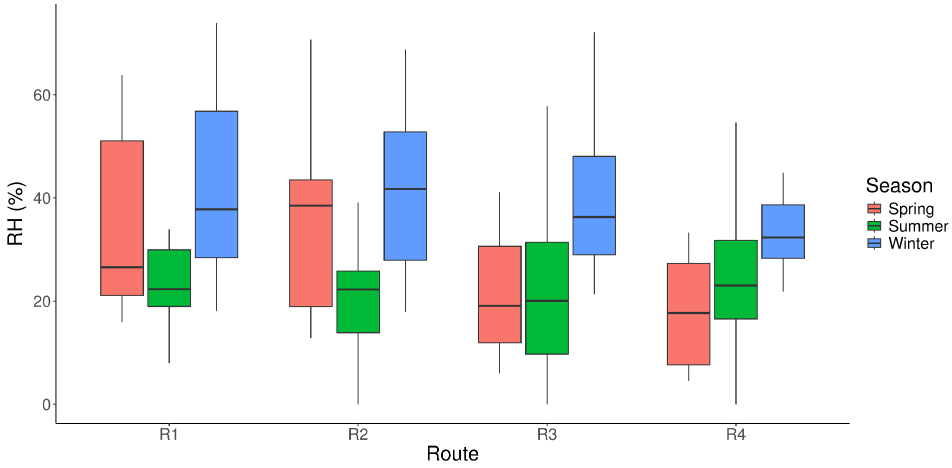

Fig. 5.3 RH distribution on routes in different seasons.

Table 5.3 and 5.4 (Fig. 5.4) summarizes the on-road PM concentrations for each route and season. During the winter, mean and median $PM_{2.5}$ and PM_{10} concentrations along all routes were significantly higher. During the winter, the average $PM_{2.5}$ concentration was 1.72 – 2.00 times that during the summer. Likewise, the average PM_{10} was 1.36 – 1.47 times the summer concentration. Similarly, the average $PM_{2.5}$ and PM_{10} concentrations

Table 5.2 Summary of the trip and trip-related information.

Route	**Season**	**Trips**	**Speed in kmph**	**AT in °C**		**RH in %**	
				Mean (SD)	**Min-Max**	**Mean (SD)**	**Min-Max**
R1	Winter	22	17.2	22.7 (6.64)	12.1 – 33.8	44.5 (15.6)	18.1 – 73.9
	Spring	12	17.8	28.3 (7.64)	15.7 – 40.2	35.1 (16.3)	15.9 – 63.8
	Summer	16	19.5	38.8 (3.31)	31.4 – 44.9	23.4 (6.65)	8.00 – 33.9
R2	Winter	20	13.6	23.3 (6.94)	12.2 – 34.2	44.7 (14.6)	17.9 – 68.8
	Spring	12	14.9	28.3 (7.22)	14.3 – 35.8	37.0 (18.1)	12.8 – 70.7
	Summer	20	15.6	39.7 (3.12)	33.0 – 45.6	21.9 (6.44)	9.30 – 39.1
R3	Winter	22	18.1	24.5 (4.87)	15.1 – 35.8	40.2 (14.4)	21.3 – 72.1
	Spring	10	18.4	35.6 (4.51)	26.3 – 40.5	20.7 (10.6)	6.00 – 41.1
	Summer	20	21.3	39.5 (5.28)	29.2 – 46.9	25.2 (17.7)	3.20 – 57.8
R4	Winter	22	20.0	26.3 (4.23)	19.4 – 34.9	35.1 (10.2)	21.8 – 65.0
	Spring	10	23.7	36.0 (3.75)	28.8 – 39.9	17.8 (9.55)	4.64 – 33.3
	Summer	24	24.7	38.2 (5.42)	29.5 – 48.1	26.8 (15.2)	4.00 – 58.1

in spring varied from 0.84 – 1.64 and 0.76 – 1.40 times summer PM concentrations, respectively. In winter, mean (Standard Deviation or SD) $PM_{2.5}$ values for R1, R2, R3, and R4 were 176 (76), 193 (82), 171 (73), 163 (73) µg m^{-3}, respectively, while the mean (SD) PM_{10} values on those routes were 269 (111), 308 (114), 296 (124), 291 (119) µg m^{-3} respectively. Except for R4, PM concentrations were higher in the spring than in the summer. The reason for such an anomaly could be the lack of a significant difference in average temperature between spring (36.0 °C) and summer (38.2 °C) along R4 (Table 5.2). The exposure study on pedestrians performed by Polednik and Piotrowicz (2020) in Lublin also supported this exposure trend (winter > spring > summer). Similarly, a motorcyclist's exposure to $PM_{2.5}$ during spring (84.1 µg m^{-3}) was found to be significantly higher than in summer (59.6 µg m^{-3}) in Foshan, China (Wu et al., 2013). However, Christopher Frey et al. (2020) discovered that average $PM_{2.5}$ concentrations for North Carolina pedestrians were higher in the summer than in the spring and winter.

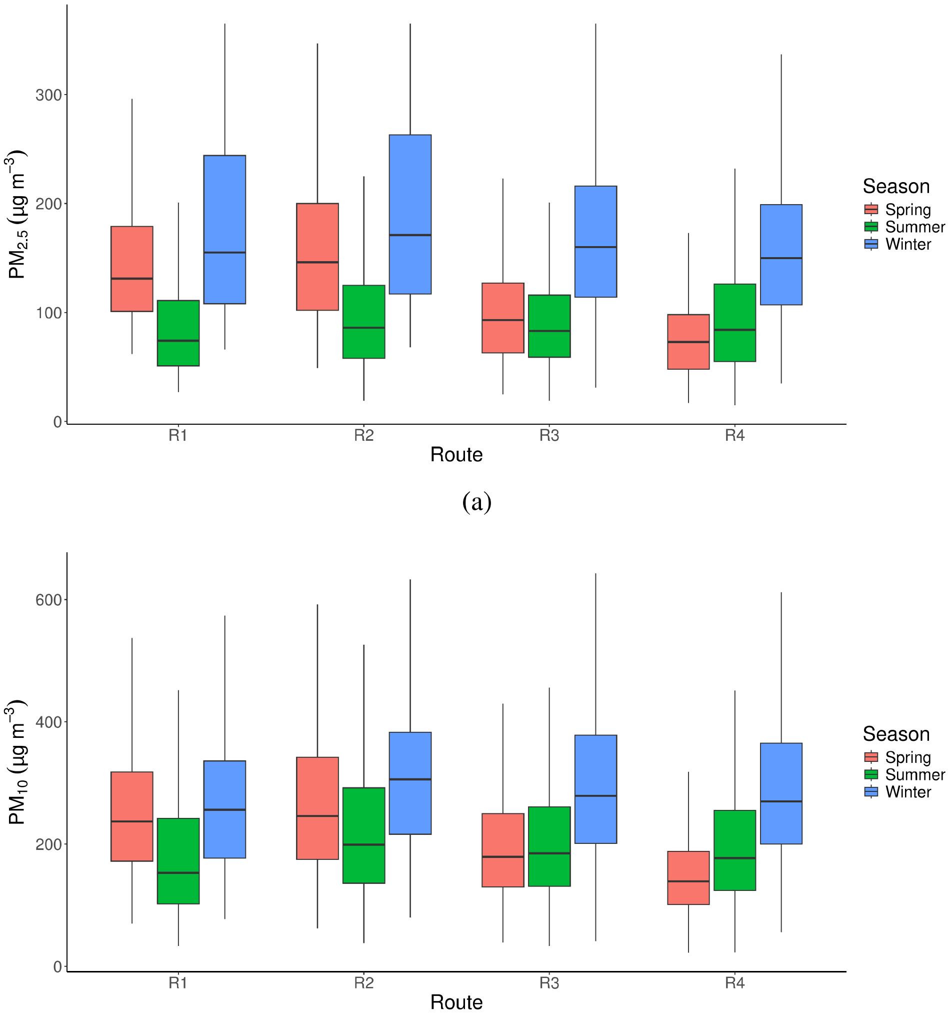

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Fig. 5.4 On-road (a) PM$_{2.5}$ and (b) PM$_{10}$ exposure on routes in different seasons.

Table 5.3 Summary of on-road $PM_{2.5}$ (µg m^{-3}) concentrations during different seasons.

Route	Season	Mean (SD)	Median	Min-Max
R1	Winter	176 (76)	155	66 – 365
	Spring	144 (56)	131	62 – 365
	Summer	88 (48)	74	27 – 362
R2	Winter	193 (82)	171	68 – 365
	Spring	158 (69)	146	49 – 365
	Summer	97 (51)	86	19 – 364
R3	Winter	171 (73)	160	31 – 365
	Spring	103 (54)	93	25 – 365
	Summer	94 (49)	83	19 – 364
R4	Winter	163 (73)	150	35 – 365
	Spring	80 (45)	73	17 – 363
	Summer	95 (53)	84	15 – 361
Study Area	Winter	174 (76)	157	31 – 365
	Spring	124 (64)	110	17 – 365
	Summer	94 (50)	82	15 – 364
Study Area	All	132 (74)	114	15 – 365

In this study, the average $PM_{2.5}$ exposure during winter in Varanasi (174 ± 76 µg m^{-3}) was found to be significantly higher than that reported by Manojkumar et al. (2021) in Vellore (India) (144 ± 135 µg m^{-3}). During the summer, motorcyclists in Delhi (India) were exposed to higher $PM_{2.5}$ concentrations (207 ± 139 µg m^{-3}) than in the Varanasi (94 ± 50 µg m^{-3}) (Goel et al., 2015). Again, most motorcyclists in Varanasi are exposed to higher fine ($PM_{2.5}$) particulate matters than those reported in Asian cities (Huy et al., 2022; Patel et al., 2016; Tsai et al., 2008; Wu et al., 2013) such as Ho Chi Minh (Vietnam) (77.2 ± 49.4 µg m^{-3}), Makassar (Indonesia) (25 ± 34 µg m^{-3}), Taipei (Taiwan) (67.5 ± 31.3 µg m^{-3}), and Foshan (China) (77.1 ± 42.6 µg m^{-3}). However, PM_{10} concentration was lower than that reported by other studies (Huy et al., 2022; Patel et al., 2016; Saksena et al., 2008) for all seasons. The PM_{10} concentration in the following cities was measured as follows: Ho Chi Minh (Vietnam) (243.1 ± 184.7 µg m^{-3}), Makassar (Indonesia) (305 ± 598 µg m^{-3}),

Table 5.4 Summary of on-road PM_{10} (µg m^{-3}) concentrations during different seasons.

Route	Season	Mean (SD)	Median	Min-Max
R1	Winter	269 (111)	256	77 – 645
	Spring	257 (112)	237	70 – 645
	Summer	183 (108)	153	33 – 645
R2	Winter	308 (114)	306	80 – 646
	Spring	268 (120)	246	62 – 645
	Summer	226 (119)	199	38 – 646
R3	Winter	296 (124)	279	41 – 646
	Spring	204 (104)	179	39 – 646
	Summer	210 (110)	185	33 – 646
R4	Winter	291 (119)	270	56 – 646
	Spring	152 (80)	139	22 – 628
	Summer	201 (108)	177	23 – 645
Study Area	Winter	291 (119)	277	41 – 646
	Spring	226 (115)	201	22 – 646
	Summer	207 (112)	181	23 – 646
Study Area	All	243 (122)	221	22 – 646

and Hanoi (Vietnam) (580 ± 1.38 µg m^{-3}). Several factors influence pollutant exposure concentration in different cities. Meteorology and traffic patterns vary from city to city, resulting in different PM concentrations. The current study discovered that motorcyclists in Varanasi are likely to have worse health effects than those in other cities due to higher fine particulate concentrations ($PM_{2.5}$).

Both $PM_{2.5}$ and PM_{10} concentrations followed a similar trend, with those values being highest during the winter, followed by spring and summer (Table 5.3 and 5.4). The observed difference was statistically significant at a 5% level of significance (Table 5.5 and 5.6). The PM exposure concentration was higher in winter than in other seasons for all hours of the day. Mixed trends were observed during spring and summer. The PM concentration was higher in spring between 07:00 – 12:00 hours and higher in summer between 16:00 – 17:00 hours.

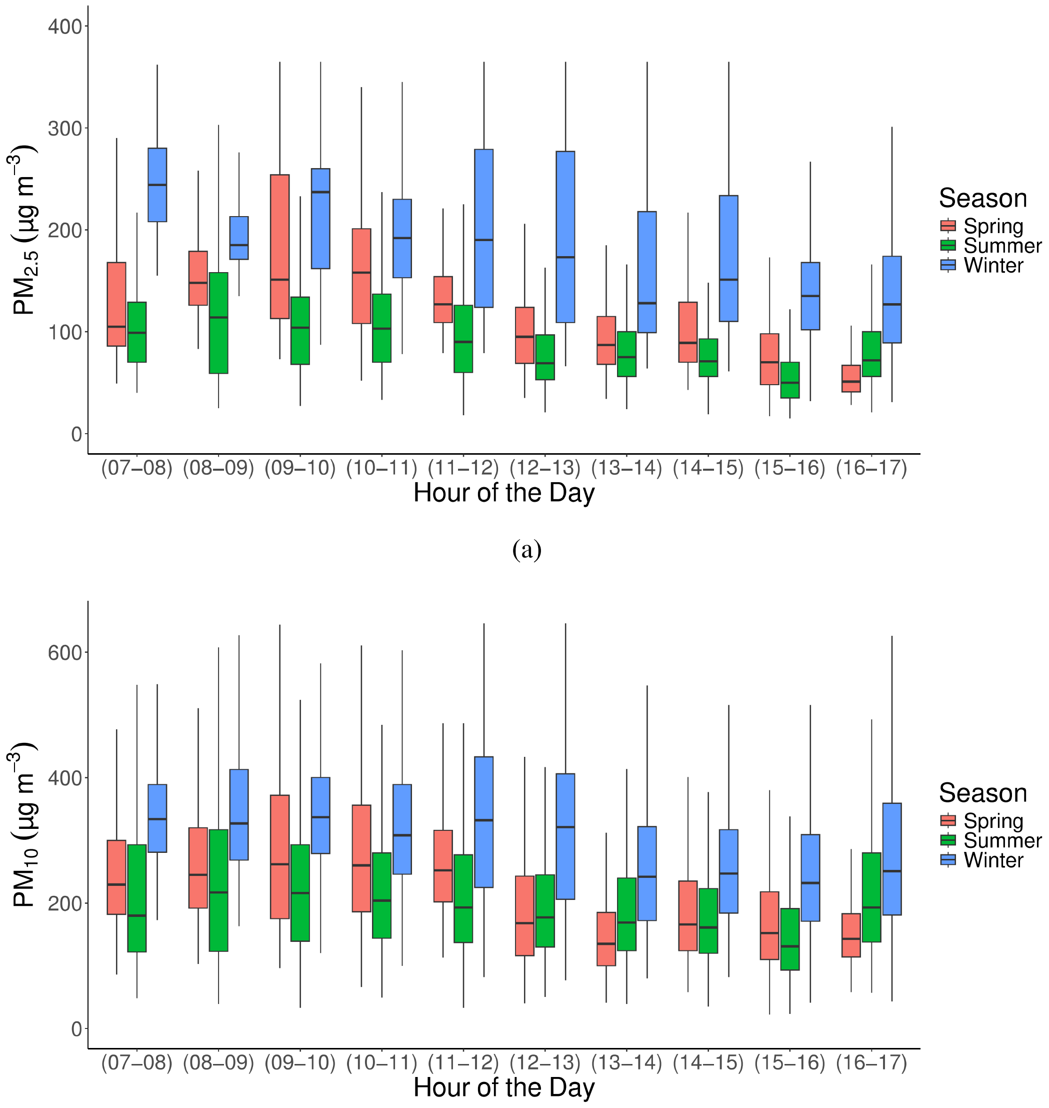

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Fig. 5.5 On-road (a) PM$_{2.5}$ and (b) PM$_{10}$ exposure during different seasons and hours of the day.

Table 5.5 One-way ANOVA between season-wise PM$_{2.5}$ concentrations.

Seasons	**Difference in μg m^{-3}**	**Lower Value in μg m^{-3}**	**Upper Value in μg m^{-3}**	**Adjusted P**
Spring-Summer	31	29	31	0
Winter-Spring	50	49	68	0
Winter-Summer	81	78	81	0

Table 5.6 One-way ANOVA between season-wise PM_{10} concentrations.

Seasons	**Difference in µg m^{-3}**	**Lower Value in µg m^{-3}**	**Upper Value in µg m^{-3}**	**Adjusted P**
Spring-Summer	19	18	21	0
Winter-Spring	65	64	67	0
Winter-Summer	85	83	86	0

In most cases, spring and summer PM concentration was comparable between 12:00 – 16:00 hours. The morning and evening PHT were observed to be 09:00 – 10:00 and 16:00 – 17:00, respectively. During the spring and summer seasons, PM concentration increased from around 7:00 AM, reaching peak values during the morning PHT. Also, peak PM concentration was observed between 16:00 – 17:00 hours during spring and summer. Ramos et al. (2016) observed peak PM exposure during PHT (08:00 hour) in all transport modes (bus, car, motorcycle, bicycle) except the metro. Patel et al. (2016) observed higher PM_{10} levels during PHT than during OPHT. The difference was, however, not statistically significant.

In contrast, during the winter, the peak PM concentration was observed during the mid-day non-rush hour (12:00 – 13:00 hours). The difference in trends was caused by dispersion and dilution. Wind speed aids in dispersion, while temperature aids in dilution (Kgabi and Mokgwetsi, 2009). Because of higher temperatures and wind speed in the spring and summer, emissions from on-road vehicles are easily diluted and dispersed. However, due to low temperatures and wind speed during winter, it takes longer for PM concentration to get diluted and dispersed in the atmosphere. As a result, PM produced by the vehicles accumulates, and the peak PM level is observed during OPHT.

5.3.2 Day of Week Exposure

Fig. 5.6 depicts the average PM concentrations on various days of the week. The study observed a bimodal pattern of exposure for both $PM_{2.5}$ and PM_{10}. The PM exposure started increasing on Monday, reaching a peak on Wednesday. It then began to rise again on Thursday, peaking on Saturday. The precise cause of this pattern might be the result of specific traffic conditions on particular days of the week and during certain hours of the day. The effect of traffic state or composition on PM exposure during different hours of the day, days of the week and season are discussed later in upcoming chapter.

Weekends see less traffic than weekdays. Past studies reveal that a reduction in road traffic can significantly reduce PM concentrations (Gopalaswami, 2016; Yuval and Broday, 2008). Because of reduced human activity on weekends, pollutant concentrations were predicted to be lower than on weekdays. In this study, Saturdays are treated as other weekdays. Fig. 5.7 represents the temporal (weekdays and weekends) PM concentrations in the study area. The Tukey multiple comparisons of means with a 95% family-wise confidence level found that the difference between weekdays and weekend both $PM_{2.5}$ and PM_{10} exposure concentrations was highly significant (adjusted p-value $< .001$) in all seasons. The comparison found difference in $PM_{2.5}$ concentrations between weekdays and weekend to be 17.4 µg m^{-3} in winter, 15.9 µg m^{-3} in summer, and 3.9 µg m^{-3} in spring. Though the difference was significant but the difference in $PM_{2.5}$ exposure in spring very small (3.9 µg m^{-3}). Similarly, the comparison found difference in PM_{10} concentrations between weekdays and weekend to be 32.5 µg m^{-3} in winter, 20.1 µg m^{-3} in summer, and 21.6 µg m^{-3} in spring. On weekends, the study area experienced lesser traffic flow, resulting in lower pollution levels. The observation is corroborated by previous studies (Lonati et al., 2006; Song et al., 2020).

5.3.3 Exposure Maps

Exposure maps were used to visualize the spatial variability of PM ($PM_{2.5}$ and PM_{10}) concentrations and PM exposure hot spots along the study routes (Fig. 5.8). Such maps could assist the commuters in choosing environmentally friendly routes by avoiding PM

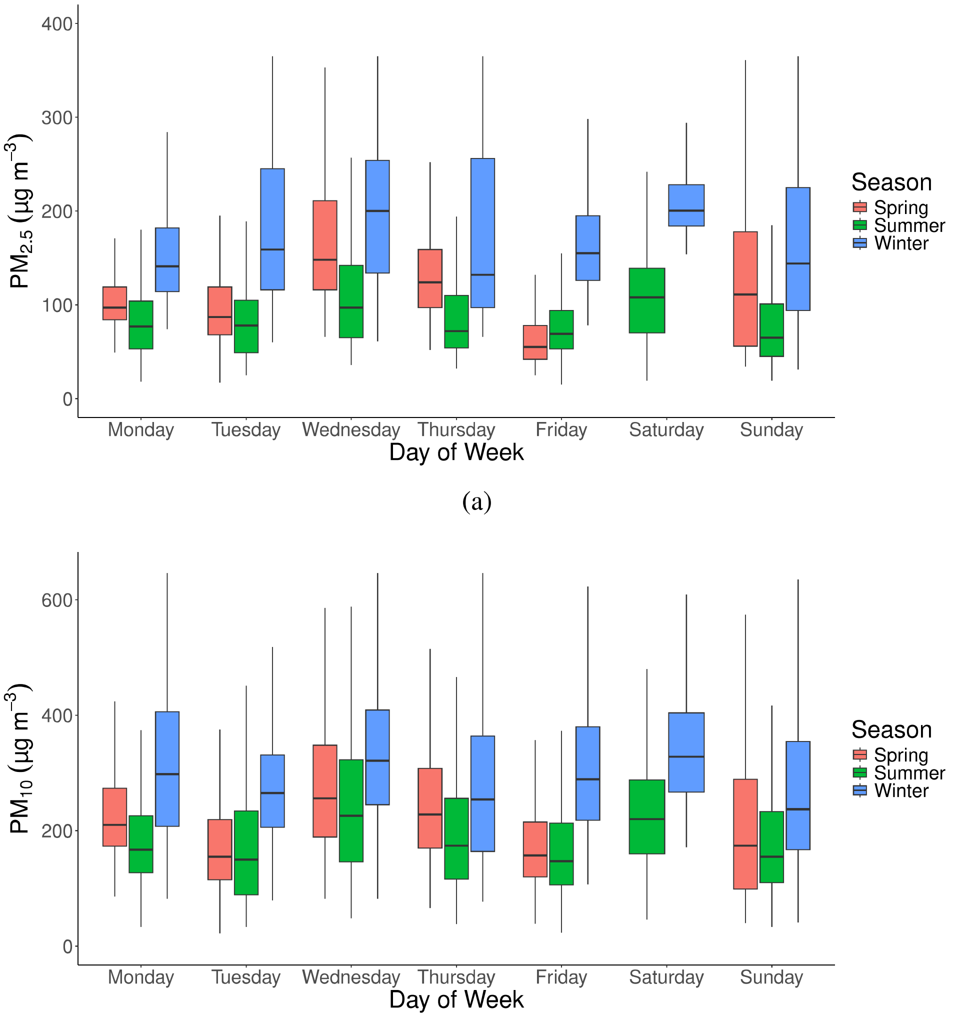

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Fig. 5.6 PM exposure during different day of week and seasons.

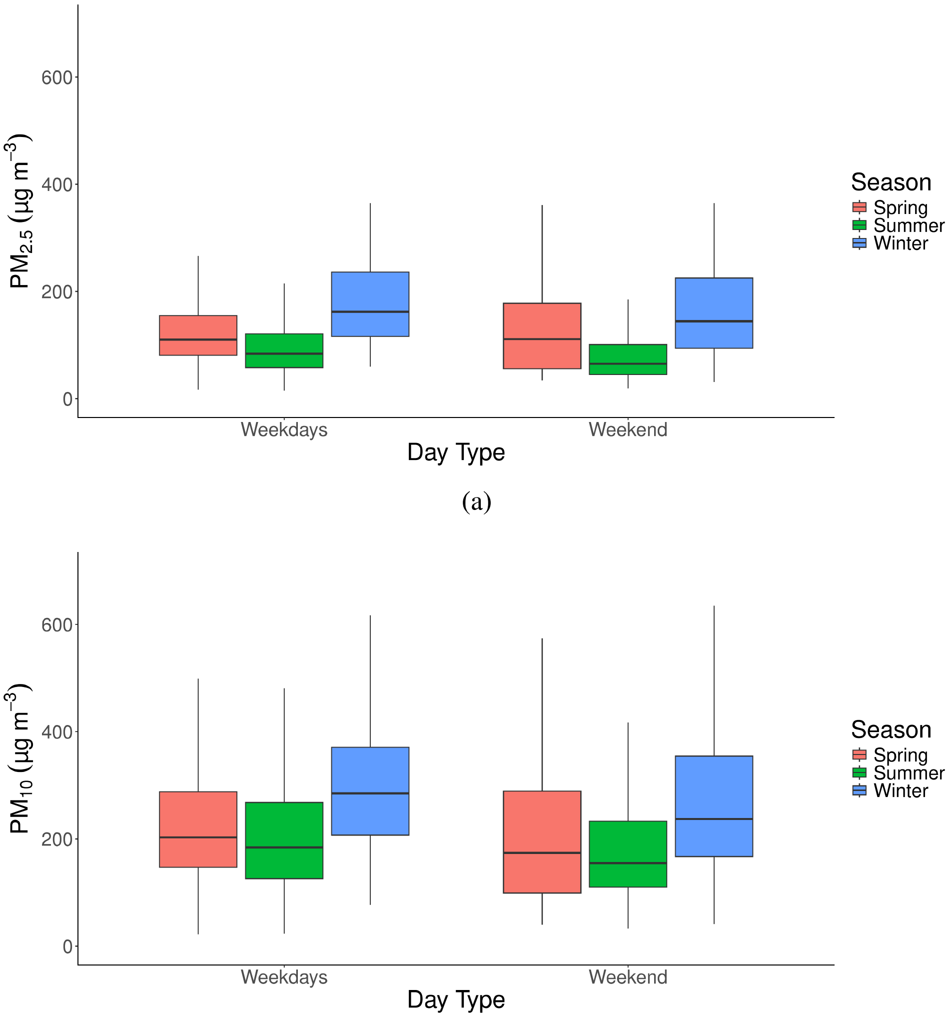

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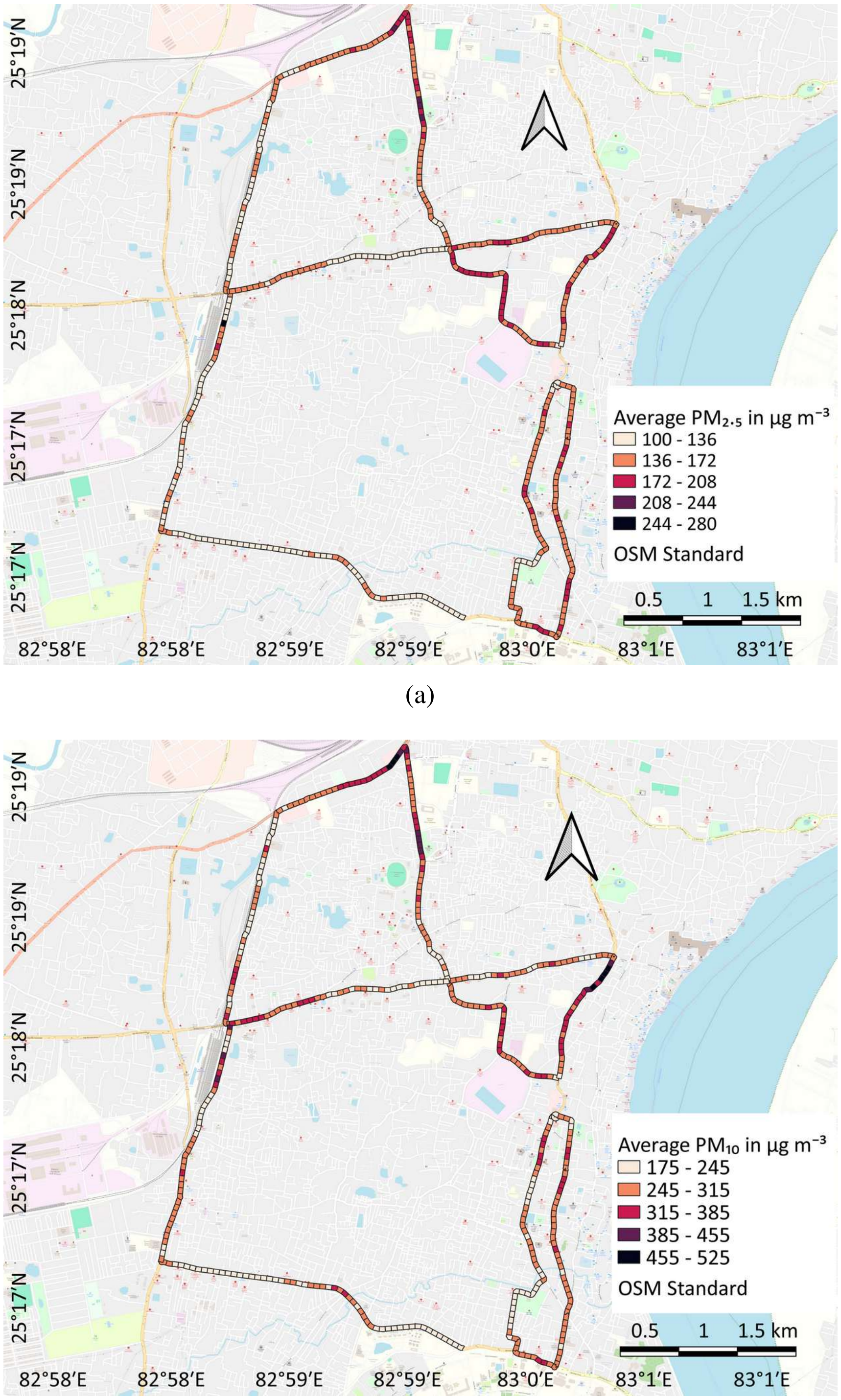
Fig. 5.7 Weekdays vs weekend PM exposure during different seasons.

hotspots. Also, such maps could help the government agency take appropriate measures to reduce pollution at appropriate locations. The measures may include introducing hybrid electric vehicles and increasing the frequency and mobility of public transportation (Xu et al., 2022).

As described, each route was divided into 50.0 m segments, and average PM concentrations were computed for each segment. $PM_{2.5}$ and PM_{10} concentration values were divided into bins of size 36 and 70 µg m^{-3}, respectively. Each bin was color coded (light brown to dark brown) such that segments with higher values appeared darker. R1 and R2 were at higher exposure levels than R3 and R4. $PM_{2.5}$ and PM_{10} concentrations were extremely high along most R1 and R2 routes. Along R1 and R2, $PM_{2.5}$ and PM_{10} ranged from 136 – 244 and 245 – 525 µg m^{-3}, respectively. $PM_{2.5}$ and PM_{10} levels on R3 ranged from 100 – 280 µg m^{-3} and 175 – 525 µg m^{-3}, respectively. R4 was the least polluted route, with most segments exposed to 70.0 – 120 µg m^{-3} of $PM_{2.5}$ and 175 – 315 µg m^{-3} of PM_{10} concentrations. On-road PM concentrations are greatly influenced by road type and traffic characteristics (Huy et al., 2022). The details of each route in terms of land use, traffic congestion (average speed), and weather conditions (temperature and humidity) are depicted in Table 5.2. The combined effect of these factors determines the pollution level of each route. The primary reasons for deteriorated air quality on R1 and R2 could be high traffic volume and more frequent congestion caused by on-street parking, road encroachment by street vendors, and pedestrian walking on the road. Dons et al. (2013) also discovered that high traffic volume increases exposure concentration.

5.3.4 PM Concentration Ratio

Both vehicular exhaust emissions and non-exhaust emissions contribute to on-road pollution. Vehicle exhaust emissions are the primary reason for generating fine particles, whereas non-exhaust emissions generate coarse particles (Harrison et al., 1997). More



(a)

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Fig. 5.8 Spatial variability of (a) $PM_{2.5}$ and (b) PM_{10} on different routes during the study period.

than 60% of PM_{10} in urban areas is due to road dust (Guttikunda et al., 2013; Kalaiarasan et al., 2018). Tire and road wear particles only constitute 0.27% of total $PM_{2.5}$ (Panko et al., 2019). These results imply that road dust is typically coarser. Coarse particles result from wearing brakes, tires, and road surfaces (Lawrence et al., 2013). These particles get resuspended due to the movement of the vehicles (Kolluru et al., 2019; Panko et al., 2019).

The fine/coarse PM concentration ratio ($PM_{2.5}/PM_{10}$) was calculated for each route and its associated reference values. The seasonal variation in the PM ratio along each route was studied (Table 5.7 and Fig. 5.9). The on-road PM ratio was 0.45 – 0.67, while reference PM ratios ranged from 0.49 – 0.83. Tsai et al. (2008) reported the PM ratio for motorcyclists in Taipei to be 0.60, while Huy et al. (2022) found it to be 0.51 ± 0.15 for motorcyclists in Ho Chi Minh. A higher $PM_{2.5}/PM_{10}$ ratio indicates a higher proportion of fine particles in PM_{10}.

For each route, the PM ratio was higher for reference readings than for on-road measurements. This observation could be because the reference location was free from sweeping, vehicle movement, and road construction activities that generate coarser particles. In both reference and on-road locations, the PM ratio was higher in winter and lower in summer. Harrison et al. (1997) reported a similar trend in Birmingham. Dry conditions aid in the resuspension of road dust (coarser particulate matter) during summer (Adeniran et al., 2017). As a result, the proportion of coarser particles is higher in summer, resulting in a lower PM ratio. The mixing height has a significant impact on pollutant dispersion. The mixing height is defined as the height of the atmospheric layer up to which various pollutants enter and disperse within one hour by convection or mechanical turbulence (Beyrich, 1997; Roy et al., 2012; Seibert et al., 2000). The mixing height depends on meteorological parameters like AT, RH, WS, WD, solar radiation, and rainfall. During the winter, WS is low, resulting in a smaller mixing height. Therefore, it takes longer for $PM_{2.5}$ to disperse, resulting in a higher PM ratio (fine/coarse) (Guttikunda and Gurjar,

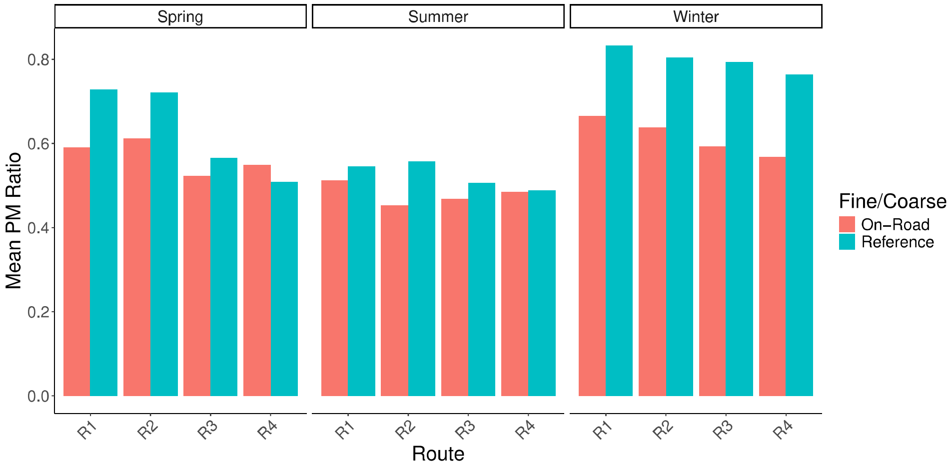


Fig. 5.9 Ratio of fine and coarse PM for on-road and reference locations.

2012). In contrast, the high temperature during the summer results in increased mixing height that expedites the vertical dispersion of pollutants, resulting in a lower PM ratio (Huy et al., 2022).

Table 5.7 PM ratio (Fine/coarse ratio or $PM_{2.5}/PM_{10}$ ratio during various seasons.

Route	**Season**	**On-Road $PM_{2.5}/PM_{10}$**	**Reference $PM_{2.5}/PM_{10}$**
R1	Spring	0.59	0.73
	Summer	0.51	0.55
	Winter	0.67	0.83
R2	Spring	0.61	0.72
	Summer	0.45	0.56
	Winter	0.64	0.80
R3	Spring	0.52	0.57
	Summer	0.47	0.51
	Winter	0.59	0.79
R4	Spring	0.55	0.51
	Summer	0.49	0.49
	Winter	0.57	0.76

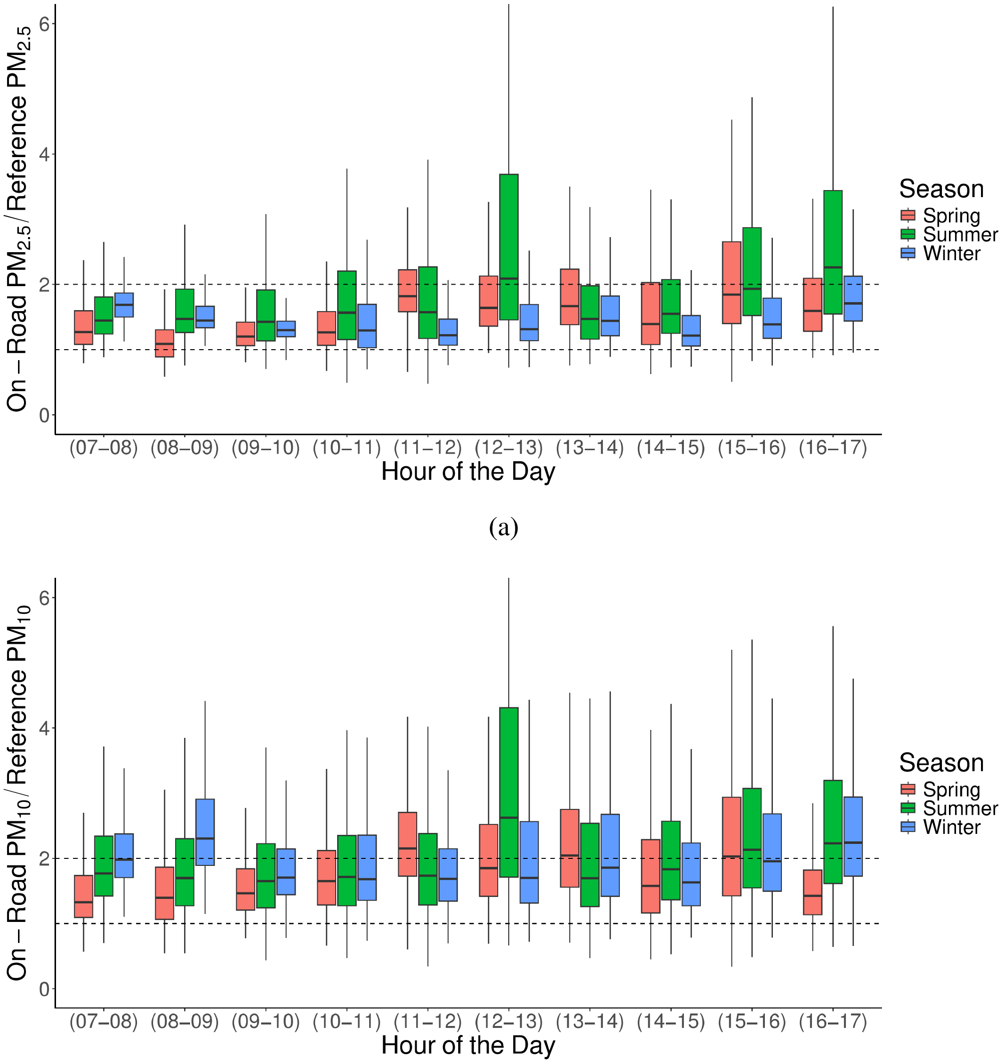
5.3.5 On-Road and Reference PM Exposure Ratio

On-road PM exposure was higher than off-road PM exposure in various transport microenvironments (Goel et al., 2015; Kaur et al., 2007; Kingham et al., 2013). The ratio of on-road and reference readings is presented in Fig. 5.10.A ratio greater than 1 implies that on-road PM concentration is higher than off-road concentration. For $PM_{2.5}$, the ratio almost always ranged from 1 to 2. The only exception occurred between 09:00 and 11:00 hours during the winter when this ratio was less than one. The reason for this could not be ascertained. Goel et al. (2015) found that on-road $PM_{2.5}$ was 1.3 times more than off-road $PM_{2.5}$ in Delhi. The on-road to reference concentration ratio for PM_{10} was between 1 and 2. Overall, in almost all cases, higher PM concentration was observed on the road than at the reference (off-road) location.

5.3.6 Effect of RH and AT on On-road PM Exposure

The current study attempted to contrast on-road PM exposure with reference (or off-road) exposure for various weather conditions. The relationship between daily average PM concentration (on-road and reference), traffic speed, and meteorological factors was studied using Pearson's correlation coefficient, r (Fig. 5.11). Daily average On-road PM concentration was highly correlated to reference PM concentration, with the r values ranging from 0.84 to 0.95. Huy et al. (2022) also discovered (r = 0.81) that $PM_{2.5}$ exposure concentration for motorcycle commuters was correlated with concentration recorded at urban monitoring stations

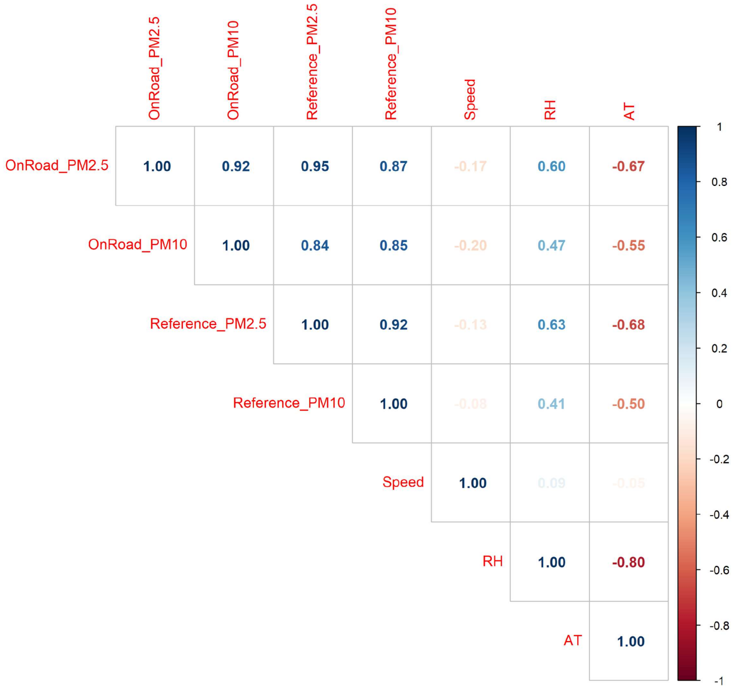
Both on-road and reference $PM_{2.5}$ were moderately correlated with RH with r value 0.60 and and 0.63, respectively. Again, Both on-road and reference $PM_{2.5}$ were also moderately correlated with AT with r value -0.67 and and -0.68, respectively. Wu et al. (2013) found that $PM_{2.5}$ was comparatively less correlated to RH (0.35) and AT (-0.39).



(a)

(b)

Fig. 5.10 Comparison of on-road and reference (a) $PM_{2.5}$ and (b) PM_{10} exposure on different routes during different seasons and hours of the day.



	OnRoad_PM2.5	OnRoad_PM10	Reference_PM2.5	Reference_PM10	Speed	RH	AT
OnRoad_PM2.5	1.00	0.92	0.95	0.87	-0.17	0.60	-0.67
OnRoad_PM10		1.00	0.84	0.85	-0.20	0.47	-0.55
Reference_PM2.5			1.00	0.92	-0.13	0.63	-0.68
Reference_PM10				1.00	-0.08	0.41	-0.50
Speed					1.00	0.09	-0.05
RH						1.00	-0.80
AT							1.00

Fig. 5.11 Correlation among on-road and reference PM concentration, traffic speed, and meteorological parameters.

No stronger correlation was found between meteorological parameters and PM_{10}. The current study found vehicle speed to be weekly correlated to on-road PM concentration (-0.20 to -0.08). A link between vehicle speed and on-road PM concentrations was not apparent.

5.3.7 On-Road PM Exposure as a Function of Reference PM

The city of Varanasi has only 3 ambient monitoring stations. They have good temporal resolution and accuracy but lack spatial coverage. Also, the instruments are placed 3 – 10 m above ground to avoid pollutant contributions from ground zero objects such as vehicle exhaust and soil dust re-suspension. But the motorcycle riders' breathing zone is around an adult's height (1.6 – 1.7 m). Many monitors are needed to get better spatial coverage of PM measures. That could be very expensive. The cost of monitoring may be significantly reduced if a relationship between on-road PM and reference PM concentrations could be established. A linear regression line between on-road PM exposure and reference measurements was fitted for various seasons (Fig. 5.12). The linear regression line of on-road $PM_{2.5}$ had a good fit (adj $R^2 = 0.88 – 0.93$), while that of PM_{10} had a moderate fit (adj $R^2 = 0.76 – 0.89$). Tsai et al. (2008) modeled motorcyclists' PM exposure concentration with reference monitors in Taipei. They found that the coefficient of determination of the linear model with $PM_{2.5}$ was 0.64, while that of PM_{10} was 0.13. PM_{10} returns to the ground within 6 – 8 minutes of generation, while $PM_{2.5}$ remains suspended longer and propagates to other locations more easily (Cheriyan et al., 2020). Therefore, PM_{10} particles are confined to a local area. Consequently, predicting on-road PM_{10} using reference monitoring data is challenging compared to $PM_{2.5}$.

5.3.8 PM Inhaled Dose

The inhaled dose per trip (µg) and inhaled dose per kilometer (µg km^{-1}) for each season and along each route are shown in Fig. 5.13 and 5.14, respectively. The motorcyclists were exposed to the highest inhaled dose during winter for all routes. In contrast, they were exposed to the lowest inhaled dose during summer for R1, R2, and R3. The motorcyclists experienced the highest inhaled dose per km and inhaled dose per trip along R2. This finding could be because of the high exposure concentration (Table 5.8) and the lowest speed on this route (Table 5.2). The highest (7.0 µg km^{-1}) and the lowest (3.8 µg km^{-1}) $PM_{2.5}$ inhaled dose per kilometer was measured on R2 and R4, respectively (Table 5.8). Goel et al. (2015) found that, on average, motorcycle riders inhaled 5 µg km^{-1} dose of $PM_{2.5}$ in Delhi. However, the motorcyclists in Vellore's residential routes inhaled as low as 2 to 3 µg km^{-1} of $PM_{2.5}$ dose (Manojkumar et al., 2021). Likewise, the highest (34.3 µg) and the lowest (18.8 µg) $PM_{2.5}$ inhaled dose per trip was measured on R3 and R4, respectively. Except for R4, the average PM_{10} dose per trip ranged from 48.8 to 63.0 µg.

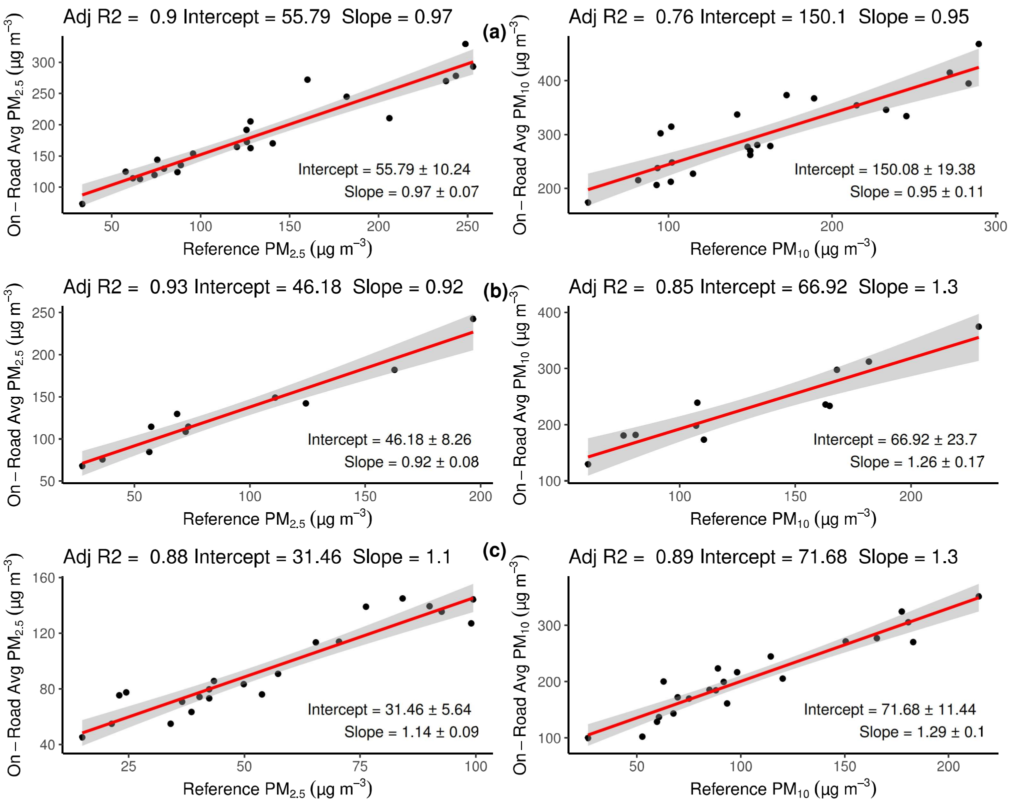


Fig. 5.12 Quantification of on-road PM concentrations during (a) winter, (b) spring, (c) summer using reference PM concentrations.

The average PM_{10} dose per kilometer (7.2 - 12.6 µg km^{-1}) varied significantly across all four routes. Motorcyclists' on R3 and R4 had lower inhaled dose per kilometer ($PM_{2.5}$: 3.68 and PM_{10}: 7.72 µg km^{-1}) than that estimated in Ho Chi Minh city (Vietnam) (Huy et al., 2022). Since the trip length on each route was fixed, the inhaled dose per kilometer (Fig. 5.14) had the same pattern as the corresponding PM exposure concentration (Table 5.3 and 5.4). However, the inhaled dose per trip (Fig. 5.13) did not follow the same pattern due to traffic conditions and travel time fluctuations. A recent study in India also found that inhaled doses did not follow the corresponding PM exposure patterns (Manojkumar et al., 2021). Compared to motorcyclists, bicyclists are exposed to the open atmosphere and have their noses at similar heights. Consequently, a bicyclist moving at a considerably lower speed (than a motorcyclist) could also be exposed to a similar level of PM concentration for a longer time. Therefore, bicyclists are likely to have higher inhaled PM doses than motorcyclists.

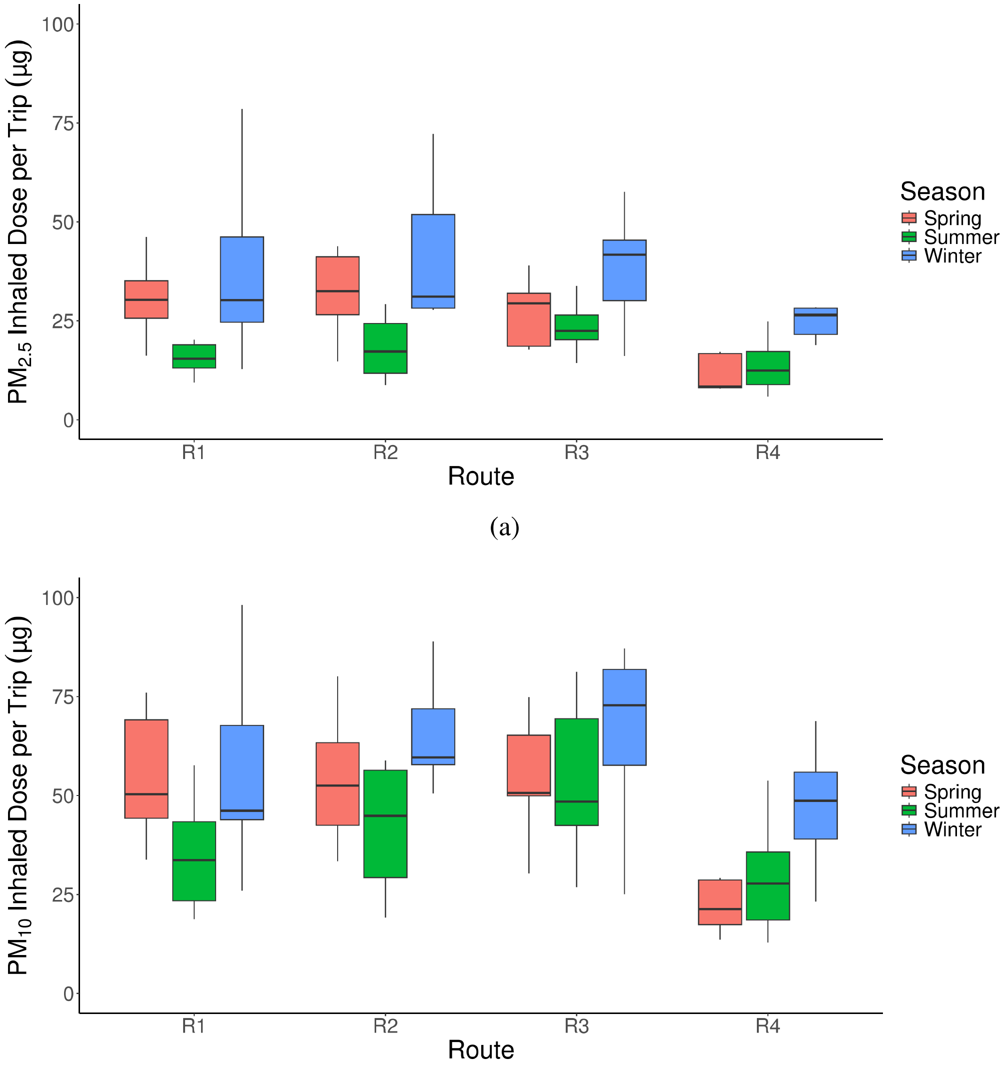
Table 5.8 Summary of inhaled doses by the motorcyclists in Varanasi.

Route	**$PM_{2.5}$ per trip** in µg	**$PM_{2.5}$ per km** in µg km^{-1}	**PM_{10} per trip** in µg	**PM_{10} per km** in µg km^{-1}
R1	28.7 (80.9 - 9.8)	5.5 (15.4 - 1.9)	48.8 (101.1 - 19.2)	9.3 (19.3 - 3.7)
R2	29.5 (74.5 - 8.8)	7.0 (17.6 - 2.1)	53.1 (91.8 - 19.2)	12.6 (21.7 - 4.5)
R3	34.3 (99.6 - 5.9)	4.7 (13.8 - 0.8)	63.0 (137.4 - 8.9)	8.7 (19.0 - 1.2)
R4	18.8 (50.0 - 5.9)	3.8 (10.1 - 1.2)	35.4 (71.8 - 12.9)	7.2 (14.6 - 2.6)

Note: Inhaled doses are presented in the format of mean (maximum - minimum) values

5.4 Summary

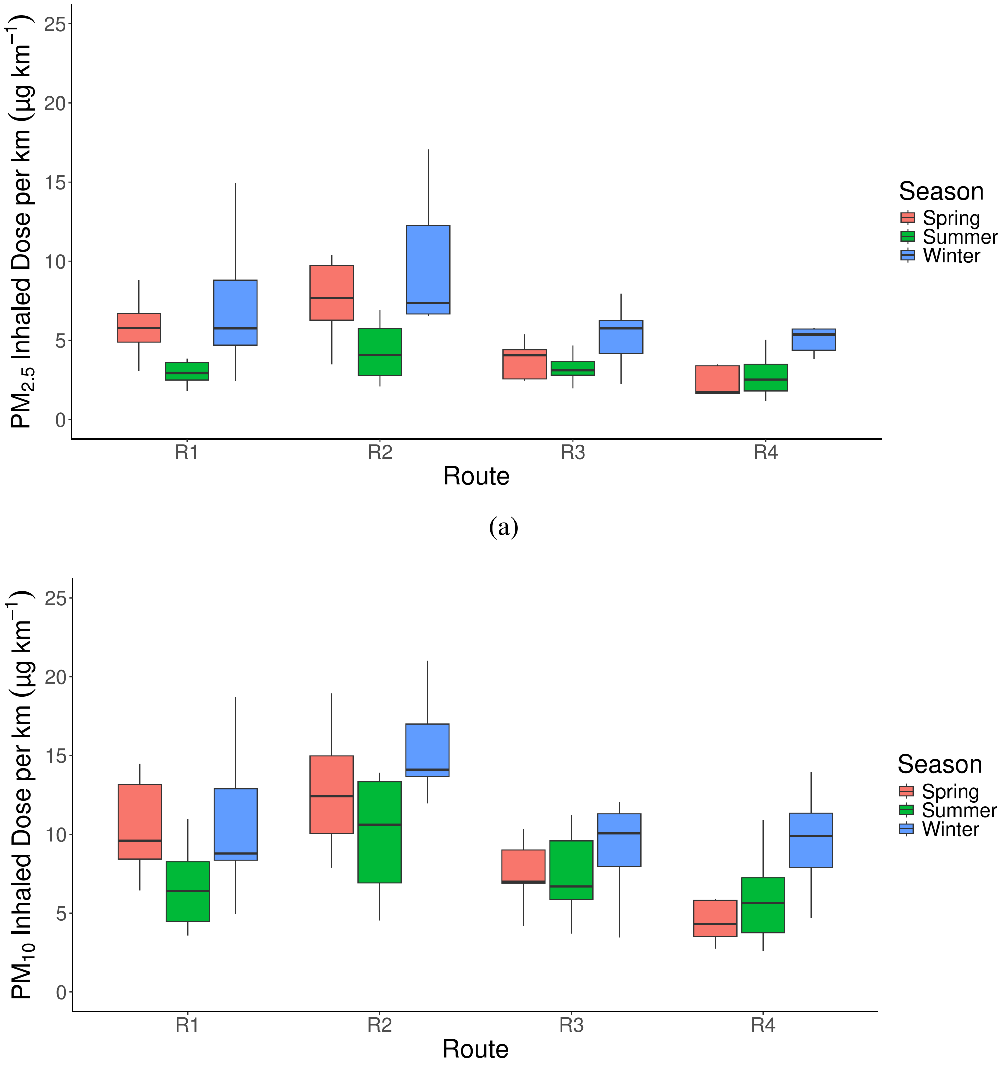
The study's primary aim was to investigate how exposure of motorcyclists to particulate matter (PM) varied with the hour of the day, days of the week, season, meteorological factors and traffic congestion level. PM measurements were taken using a portable PM monitor placed in the motorcycle rider's backpack. The study was conducted on four



(a)

(b)

Fig. 5.13 PM inhaled dose per trip on routes during different seasons.



(a)

(b)

Fig. 5.14 PM inhaled dose per km on routes during different seasons.

routes in Varanasi (a densely populated city in India) at different hours of the day (07:00 to 17:00). Other data included GPS coordinates and temperature and humidity recorder. Variation in atmospheric temperature and relative humidity was captured by collecting data during three seasons: winter, spring, and summer. Through the use of ANOVA, fine and coarse PM ratio, exposure maps, and linear regression with reference PM concentration, and dose estimation, it was possible to

1. identify the possible contribution of vehicular exhaust emission to on-road pollution,
2. study the effect of PHT on PM exposure level,
3. statistically test whether PM concentration depends on the season,
4. and investigate the possibility of modeling $PM_{2.5}$ and PM_{10} from reference measurements.

Based on data exploration and analysis, the following conclusions were derived:

1. $PM_{2.5}$ and PM_{10} concentrations during winter were 1.85 and 1.41 times that of summer. In contrast, $PM_{2.5}$ and PM_{10} concentrations during spring were 1.32 and 1.10 times that of summer, respectively.
2. $PM_{2.5}$ concentration was positively (0.60) associated with relative humidity (RH) and negatively (0.67) associated with atmospheric temperature (AT). In contrast, PM_{10} concentration was moderately associated with both the meteorological parameters. A possible reason for this finding is that PM_{10} settles to the ground much sooner than $PM_{2.5}$, which can be dispersed by the wind and temperature difference. Consequently, PM_{10} pollution spreads locally, making it challenging to predict on-road exposure using PM_{10} reference measurements on monitoring stations.
3. Commuters are exposed to significantly higher PM_{10} concentrations on the road than off-road locations. PM concentration on all routes exceeded the daily limits ($PM_{2.5}$:

60 µg m^{-3}, PM_{10}: 100 µg m^{-3}) established by NAAQS. A bicyclist moves slower than a motorcyclist but is exposed to the open atmosphere and has a breathing zone at a similar height as a motorcyclist. Consequently, a bicyclist would be exposed to high PM concentrations for longer, resulting in even higher inhaled doses.

4. With a few exceptions, the proportion of $PM_{2.5}$ in PM_{10} was at least 50%. This finding illustrates the significant contribution of vehicle exhaust emissions to on-road pollution. Frequent traffic congestion on routes R1 and R2 during the day makes them less healthy to travel than routes R3 and R4.