

Abstract

Commuting is an important human activity that links activities related to work, education, health, social or cultural events, recreation, or sports. Commuters are exposed to elevated pollutant concentrations. The mortality and morbidity rates associated with Particulate Matter (PM) are substantially higher than other pollutants. The commuters' exposure to PM depends upon various factors such as pollutant concentrations, the breathing level of commuters, the position of the vehicle with respect to the road, traffic conditions, and meteorological conditions. The meteorology factors consist of atmospheric temperature (AT), relative humidity (RH), season of the year, wind direction (WD), and wind speed (WS), while traffic factors consist of position of vehicle on the road (PVR), off-peak hour traffic (OPHT), peak hour traffic (PHT), traffic count (TC) and travel time or travel mode (TT/TM). The ventilatory factors include the presence/absence of a facemask, inhalation rate (IR) and inhaled dose (ID), while street configurations consist of land use (LU) and road geometry (RG). Additionally, the background or ambient concentration of pollutants is an important factor affecting the on-road pollutant concentration. Past studies considered these factors while modeling on-road PM levels. However, a few studies considered the effect of traffic composition, the combined impact of seasons and traffic congestion levels, and meteorological parameters on PM concentration. This study attempted to model average, extreme, and real-time on-road PM levels as a function of these factors.

Varanasi, a densely populated Tier-II city, was selected as the case study. The city is located in the northern part of India at an elevation of 76.2 m from the mean sea level. Four routes, namely R1, R2, R3, and R4, were selected for the exposure study. These routes are 4 to 7.4 km long and pass through diverse land use that affect traffic characteristics and vehicle-generated pollution. PM concentrations ($PM_{2.5}$ and PM_{10}) were measured near the typical breathing zone of commuters who traveled along the four designated routes. Instruments used for data collection were DustTrak for PM data, Garmin device for location data, HTC data logger for temperature and humidity data, Osmo and GoPro action camera for traffic video recordings and motorcycle for data collection while traversing

along the routes. Data were collected from January to December 2022 between 07:00 and 17:00 hours. R was used for statistical analysis and visualization of PM data and model fitting. Q-GIS was used for geoprocessing of data and visualization of spatial patterns of PM exposure. Exploratory analysis such as summary statistics, ANOVA, comparison of on-road and off-road PM levels and combined effect of season and traffic congestion level were carried out. Linear regression, mixed-effect models, extreme value theory and Bayesian hierarchical models were fitted to the data. The hotspot maps of average and extreme PM exposure on various parts of the routes, were also created.

The average PM_{2.5} (PM₁₀) values were 205 (324), 118 (213) and 87 (96) in winter, spring and summer, respectively. The PM levels exceeded the daily limits (PM_{2.5}: 60 µg m⁻³, PM₁₀: 100 µg m⁻³) set by National Ambient Air Quality Standards (NAAQS). The on-road PM_{2.5} (PM₁₀) concentrations during winter were 2.36 (1.69) times that of summer. In contrast, the average PM_{2.5} (PM₁₀) concentrations during spring were 1.35 (1.12) times that of summer. PM_{2.5} correlated much more with relative humidity and atmospheric temperature than PM₁₀. This is because the PM₁₀ settles to the ground within 6 – 8 min of generation, while PM_{2.5} remains suspended longer and propagates to other locations more easily (Cheriyana et al., 2020).

Higher PM concentration was recorded in peak hour traffic (09:00 – 10:00) during spring and summer. However, PM concentration in winter was highest during off-peak hours (12:00 – 13:00) instead of peak hours. This opposite trend (compared to spring and summer) in winter happened because PM particles took longer to spread and disperse. Also, a higher proportion of PM_{2.5} (0.49 – 0.74) was observed on routes in winter. Analysis of extreme PM exposure revealed that the monthly return level for PM_{2.5} (PM₁₀) was 589 (1127), 474 (961), and 429 (902) µg m⁻³ during winter, spring, and summer, respectively. The probability that during winter, PM_{2.5} and PM₁₀ levels would exceed that of the Delhi

smog event (585 and 989 $\mu\text{g m}^{-3}$ of $\text{PM}_{2.5}$ and PM_{10}) was estimated to be 0.72% and 1.47%, respectively.

Linear regression was fit to route aggregated PM concentration (R^2 value for $\text{PM}_{2.5}$: 0.78 to 0.93 and for PM_{10} : 0.69 to 0.78). The ambient PM concentration was found to be strongly correlated (r-value: 0.83 to 0.96) with route aggregated PM concentration, followed by temperature (r-value: -0.56 to -0.69) and humidity (r-value: 0.50 to 0.65). Routes were further divided into sections (the distance between two traffic intersections), and section-wise PM exposure was estimated. Both section-wise and real-time PM were modeled using linear regression and mixed-effect models, keeping traffic counts as fixed effects. The mixed-effect models better fit the PM exposure compared to conventional linear regression. The conditional R^2 value for section-wise and real-time mixed effect models for $\text{PM}_{2.5}$ (PM_{10}) were found to be 0.700 (0.434) and 0.548 (0.313), respectively. The Bayesian inference was found suitable for modeling monthly return levels and predicting the probability of extreme pollution events as it appropriately addressed the heterogeneity in data. $\text{PM}_{2.5}/\text{PM}_{10}$ ratio during summer was estimated to be between 0.45 and 0.51, implying that about half of the PM were coarse particles. The reason behind this is the re-suspension of road dust caused by dry conditions. Therefore, road dust should be removed regularly to reduce the coarse particulate concentrations, especially in summer. Both $\text{PM}_{2.5}$ and PM_{10} levels were significantly higher in winter due to lower mixing height (Tiwari et al., 2013). Also, a higher $\text{PM}_{2.5}/\text{PM}_{10}$ ratio (0.49 – 0.74) was observed during winter, implying that PM was mostly composed of fine particles. As $\text{PM}_{2.5}$ poses greater health risks compared to PM_{10} , commuters should avoid using routes with high PM exposure especially in winter.

Hotspot maps can be proactively shared with the public so that they become aware of the locations with higher pollution and make decisions regarding the choice of routes. Commuters should be advised to use masks while traveling, especially during high-polluting

days or hours. This study discovered that commuters in Varanasi are likely to be exposed to worse air quality than in other Tier-II cities, especially in spring and winter. The findings of the study could help public administrations and urban planners to devise abatement measures for reducing pollutant concentrations. Some of these abatement measures are better traffic management, vehicle scrappage programs, intelligent transport systems, road dust cleaning, and awareness programs for commuters to use public transit, electric vehicles and non-motorized modes of transportation.