

Chapter 3

Study Design and Data Collection

This chapter covers the demographic details of the study area, selection of study routes and traffic intersections. It also outlines the instrument details and data collection procedures. In addition, the chapter explains the data processing methods employed to prepare the data for various analyses to meet the study objectives.

3.1 Study Area

Varanasi city is in the northern part of the country, India, covering an area of 82 km². The study area is also one of the world's oldest inhabited cities, renowned for its rich cultural heritage and devoutness (Nandi et al., 2017; Verma et al., 2007). The city has a dry tropical monsoon climate with three distinct seasons: summer (March to June), rainy (July to October), and winter (November to February) (Pandey et al., 1992; Tiwari et al., 2008). The transition period between winter and summer, specifically February and March, was considered as the spring season in the study. In the winter, the temperature drops to as low as 5°C. It could be due to cold waves coming from the Himalayan region. The atmosphere becomes dry in the summer, and the temperature regularly exceeds 40°C. It is exacerbated by hot winds that blow during the day. According to the Census conducted by the Government of India, around 1.20 million people resided in the city in 2011 (GoI, 2015). The population of the city was estimated to be 1.72 million in 2022 (WPR, 2024). In addition, the city attracts around 6 – 7 million tourists each year (UPT, 2022). As a result, the city is densely inhabited, with close to 21 thousand people residing in a 1 km² area.

The traffic in the study area is contributed by both the residents of the city and the pilgrims arriving at the location. Motorcycles alone contribute 65% (median value) of the vehicular traffic in the study area. Thus, frequent congestion is observed at different routes and intersections in the city due to various human (local and tourist) activities. Several major railway stations, government offices, hospitals, shopping complexes, religious places, and educational institutions, including a renowned university with a capacity for 50 thousand students, contribute significantly to the traffic in the city. Thus, Varanasi is among the congested Indian cities, including Mumbai, Delhi, Kolkata, Bangalore, Surat, and Pune (Meena et al., 2023). For Varanasi, the air quality index (AQI) on 197 days (60.2%) out of 327 monitored days was poor to severe. However, the % of days with poor to severe AQI was lower in other Tier-II cities such as Agra (20.3%), Ajmer (0.2%), Amritsar (8.5%), Jaipur (5.2%), Kanpur (31.9%), Lucknow (42.0%), and Nagpur (6.5%). Ghaziabad is an exception with 59% days poor to severe AQI (CPCB, 2021).”

3.2 Routes and Traffic Intersections

The data collection was carried out along four city routes (Fig. 3.1): R1 (Saket Nagar to Lanka via. Sankat Mochan and IP Vijaya), R2 (Bhelupur to Girja Ghar via. Rathyatra), R3 (Mahmoorganj to Rathyatra via. Lahartara and Varanasi Junction), and R4 (Naria to Mahmoorganj via. Bhikharipur). These routes consisted of 36 traffic intersections that spread throughout the city. Routes were made up of various sections with a variety of land uses. The routes were chosen to represent various land use types, such as commercial, educational, and residential areas. Near R1, there are residential areas, eateries or restaurants, on-street vendors, and various shops. The presence of a university campus (Banaras Hindu University-BHU), a hospital (Sir Sunderlal Hospital) on the campus, and a Trauma center is the primary reason for traffic on R1. The traffic pattern of the route is influenced by university students and staff arriving for classes and office work, as well as patients

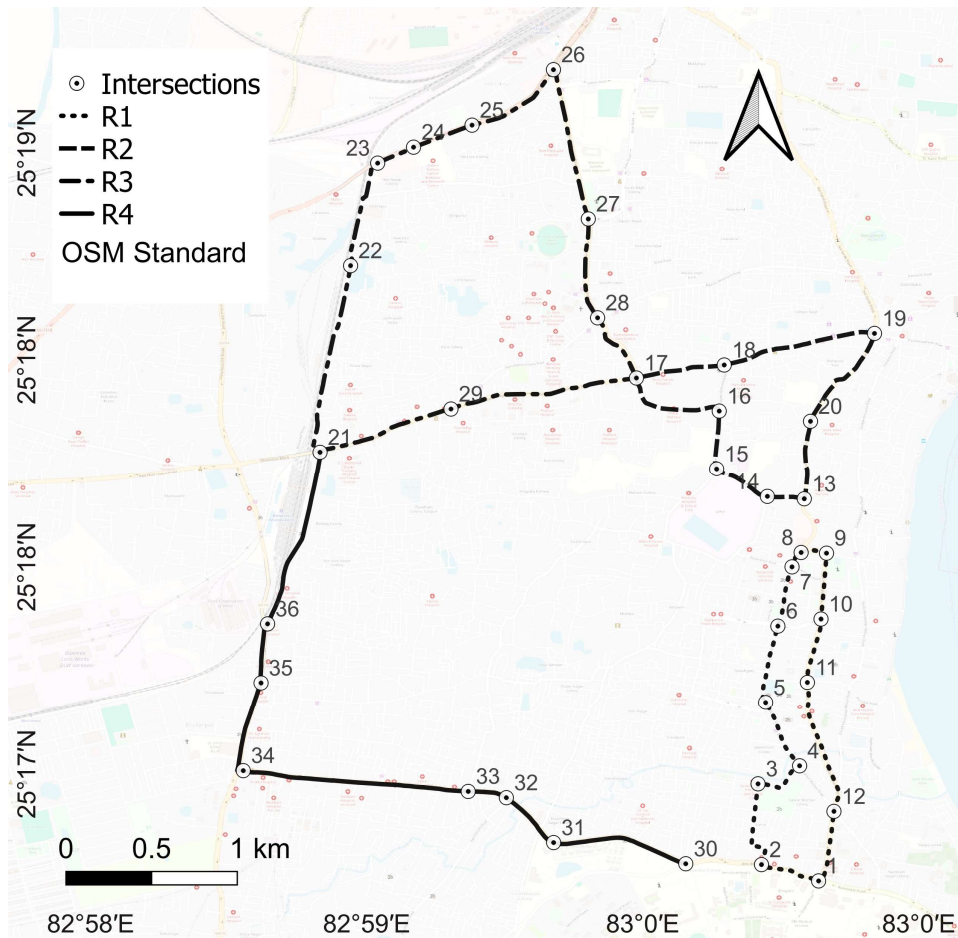


Fig. 3.1 PM data collection on routes and traffic intersections in Varanasi, India.

arriving for treatment at the hospital. R2 is made up of clothing stores, government offices, a wholesale market, and devotees visiting the famous temple. Traffic congestion occurs as a result of unrestricted pedestrian movement and on-street parking in the most congested segments of R1 and R2. The presence of a railway station, schools, and a passport office generates traffic on R3. R4 traffic is generated by the railway station, diesel locomotive (train engine) factory, and various roadside shops. However, the more detailed land uses of all the routes are presented in Fig. 3.2.

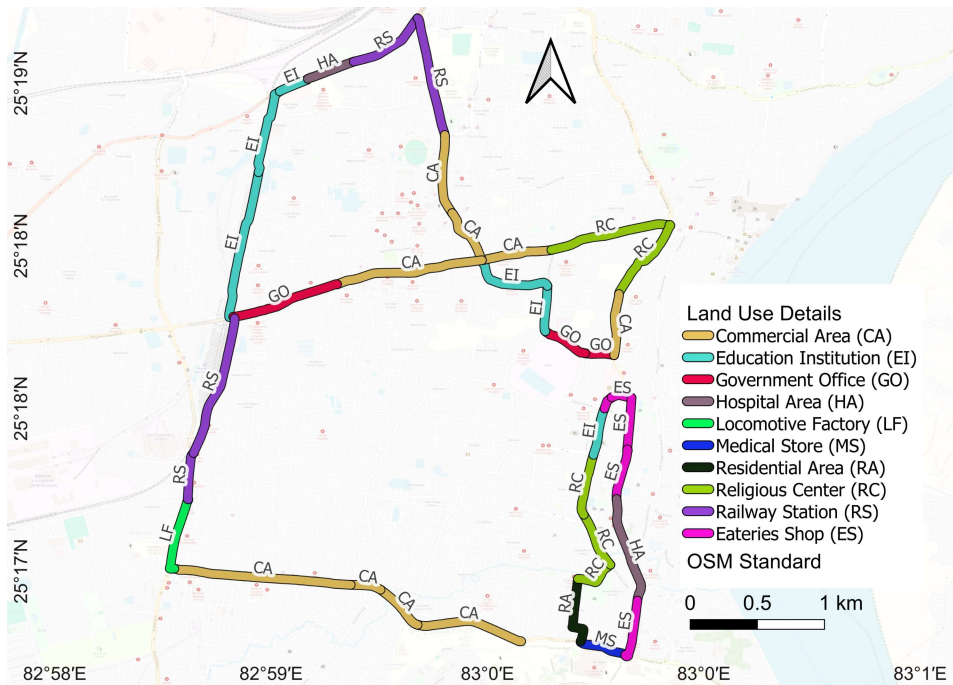


Fig. 3.2 Land use details of the study area

3.3 Instrumentation

Various instruments were employed for collecting data, including measurements of PM concentration, global positioning systems (GPS), temperature, humidity, and traffic video. The instruments so chosen are capable of providing real-time data at reasonable accuracy. The specifications of these instruments are presented in Table 3.1. A portable aerosol monitor (DustTrak, Model: 8533) and a GPS receiver (Garmin, Model: eTrex 22X) were used for collecting PM and GPS data at 1-Hz frequency, respectively. A temperature and humidity data logger (HTC, Model: EasyLog) was used for collecting AT and RH at 10-s intervals. Action cameras (Osmo Action, Model: AC001 and GoPro, Model: Hero 8) were used for traffic data collection. The instrument set-up is shown in Fig. 3.3. The action camera was attached to the motorcycle's handle. Garmin receiver and HTC data logger were kept in the side pocket of the backpack, while the DustTrak was kept inside the



Fig. 3.3 Instrumentation setup: (a) DustTrak aerosol monitor for collecting PM concentration data; (b) Garmin device for GPS coordinates; (c) HTC data logger for RH and AT logging; (d) an action video camera (e) backpack with aerosol monitor, GPS receiver, and RH & AT data logger; (f) motorcycle fitted with action camera.

backpack. One end of the sampling tube of the DustTrak was connected to the monitor's inlet and another end was attached to the handle of the backpack.

Table 3.1 Specification of instruments used during the field study.

Instruments	Name/Model	Range	Log interval	Resolution
Portable Aerosol Monitor	DustTrak 8533	0.01 – 15 μm	1 s to 1 h	$\pm 0.1\%$ or or 0.001 mg m^{-3}
GPS Receiver	Garmin eTrex 22X		1 s	3 m
Temperature and Humidity Data Logger	HTC EasyLog	- 40 to 70°C,	1 s to 24 h 0 to 100% RH	0.1°C and 0.1% RH
Video Camera	Osmo Action AC001	10 m	1 s	1080 pixels
	GoPro Hero 8	10 m	1 s	1080 pixels

3.4 Data Collection

Before making a trip for data collection, the DustTrak was zero-calibrated using a zero filter. A reference location was selected inside the IIT BHU campus such that there is no direct influence of vehicular traffic or any other primary source of particulate matter. Reference data (PM concentration, RH, and AT) were taken at the reference location for 10 minutes using the same set of equipment (DustTrak and HTC data loggers). Reference data were collected twice, one within 30 minutes before the trip and another within 30 minutes after the end of the trip. The mean value of the reference PM concentration was used as a reference concentration. An action camera (Osmo Action) embedded with an image stabilization accelerometer was mounted on the motorcycle's handlebar, as shown in Fig. 3.3(f) with image stabilization technology, it was possible to capture stable videos that were useful in assessing a qualitative measure of congestion (rush hours or non-rush hours). The motorcycle was ridden close to the road median so that exposure due to traffic moving in both directions could be captured. A surveyor carried the backpack on the motorcycle in such a way that the inlet pipe was positioned at breathing level. The surveyor rode along the four selected routes in the study area. Data was collected on non-rainy days from January to June 2022 and November to December 2022. The survey was carried out during five 2-hr intervals starting from 7 am to 5 pm (07:00 – 09:00, 09:00 – 11:00, 11:00 – 13:00, 13:00 – 15:00, 15:00 – 17:00). During one day, data collection was carried out in one of these time intervals along either R1 and R2 or R3 and R4. A total of 210 trips were collected over 8-month periods. At least 10 trips were made on each route in spring, while at least 15 trips were made in summer and winter Fig. 3.4. In terms of traffic demand, the morning peak hours, mid-day off-peak hours and evening peak hours are observed from 09:00 – 10:00, 12:00 – 13:00, and 16:00 – 17:00, respectively.

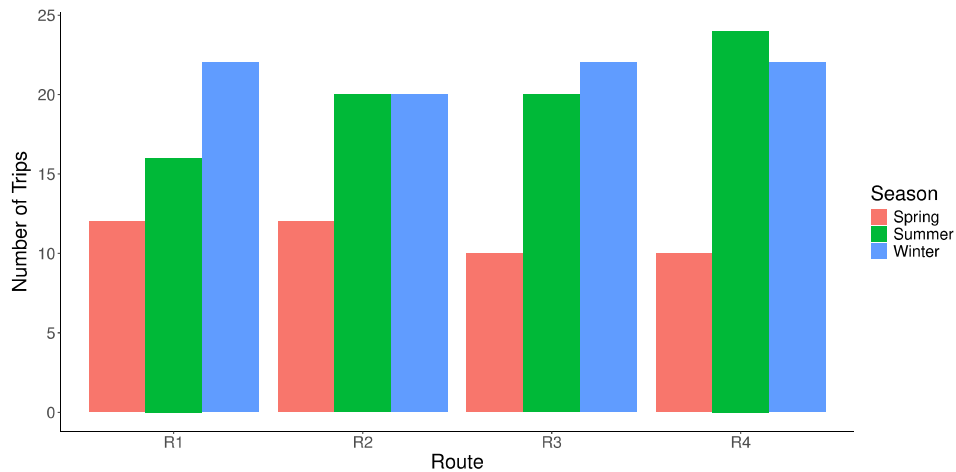


Fig. 3.4 Number of trips made on routes in different seasons.

3.5 Data Processing and QA/QC

The DustTrak was factory calibrated to ISO 12103-1, A1 Arizona test dust. However, the study location's dust or particle properties differ from the test dust. So, the DustTrak may overestimate the particulate concentrations (Yun et al., 2015). Hence, the instrument should be calibrated against the dust properties of the study location. The instrument was calibrated with a Photometer (PH-5) in the laboratory at RH and AT of 51% and 25.1°C, respectively. A satisfactory percentage deviation (- 1.27 to 1.90%) between the DustTrak and Photometer was observed. The DustTrak works on the principle of light scattering. Hygroscopic development and agglomeration of aerosol particles due to changing humidity (RH) conditions may affect the accuracy of light scattering principle-based instruments (Han et al., 2020). The RH effect on DustTrak can be corrected by using the correction factor (CF) approach considered by Laulainen (1993), as shown in Eq. 3.1 and Eq. 3.2. This correction factor has been used in past studies on PM exposure (Apte et al., 2011; Goel et al., 2015; Ramachandran et al., 2003). The correction factor is typically applied when RH exceeds 65.0% (Adeniran et al., 2017). The 95th percentile value of RH was less than 65.0%. Therefore, no RH correction was applied.

$$PM_{2.5 \text{ RH corrected}} = \frac{PM_{2.5 \text{ Raw}}}{CF} \quad (3.1)$$

$$CF = 1 + \frac{0.25 \times RH^2}{1 - RH} \quad (3.2)$$

The clock in various devices used for data collection drifted with time. Data were synchronized, taking the drift into account. For example, the observation that DustTrak lagged by about 2 seconds per day was incorporated into the data fusion process. Data corresponding to malfunctioning devices were removed. Furthermore, outliers were eliminated from the data before performing further statistical analyses. Data falling outside the interquartile range were removed. The instantaneous speed at every second was calculated using the synchronized GPS coordinates. November -January, February - March, and April - June were taken as part of the winter, spring, and summer seasons, respectively. The final dataset included cleaned data on PM concentration, GPS coordinates, meteorological parameters (AT and RH), instantaneous speed, and traffic congestion level (rush hours and non-rush hours) for various routes, seasons, directions of travel, and hours of the day. The final data set was used to analyze average, extreme and real-time PM exposure concentrations.

The following four chapters describe the analysis, results, discussion and findings corresponding to the four objectives of the study. Then, the next chapter depicts the overall findings and the concluding remarks. Fig. 3.5 shows the flow chart representing each analysis and how they are connected.

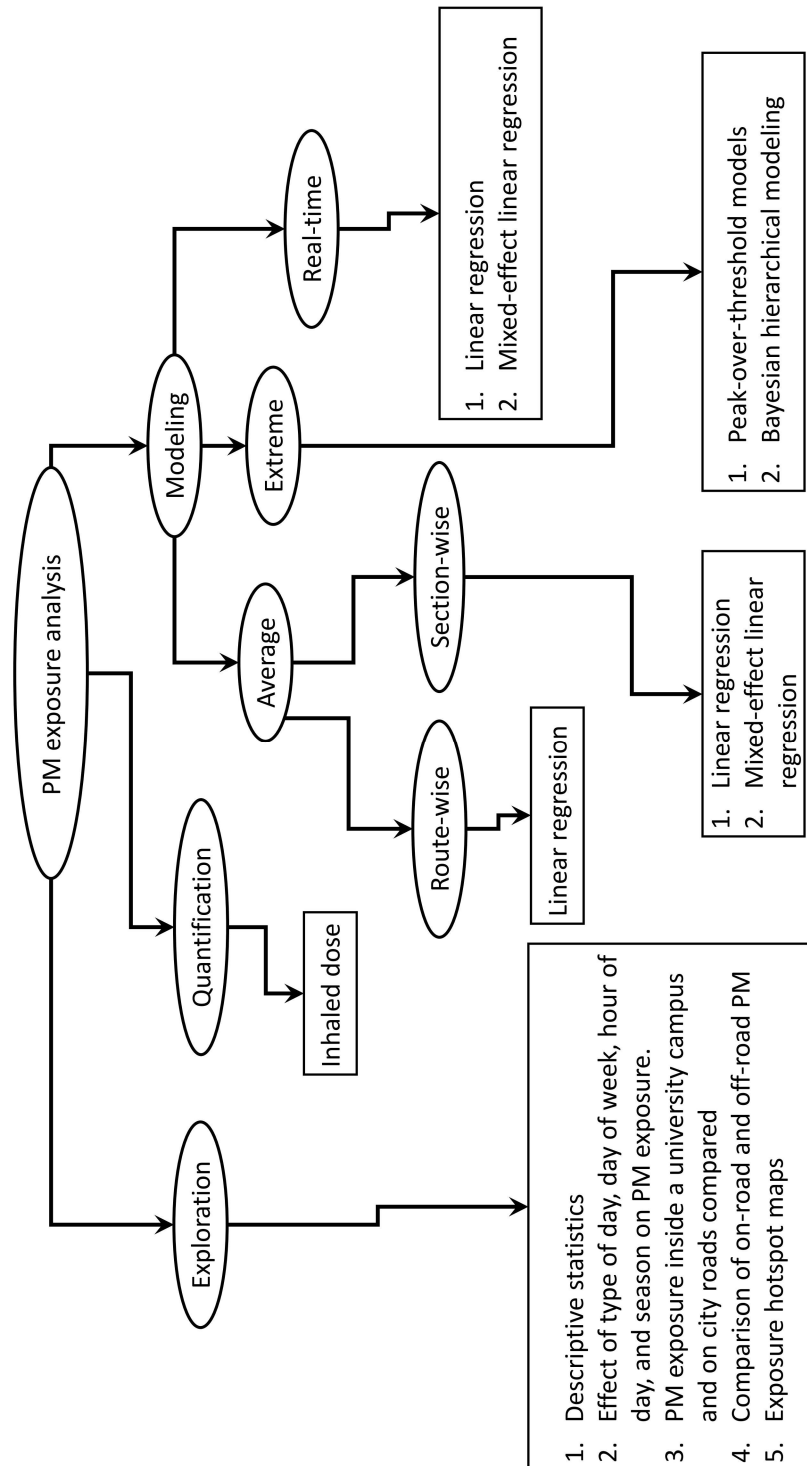


Fig. 3.5 Overall flowchart of analysis, results, discussion, and findings of the four objectives of the study.