Chapter 1

Introduction

This chapter includes a brief overview of air pollution, particulate matter (PM) and its sources, on-road PM exposure, the health effects of pollution, the motivation for this work, research objectives, and the scope of work. This chapter also presents an organization of the rest of the chapters of the thesis.

1.1 Background

Commuting is an important human activity. It refers to the process of traveling from one location to another for different purposes such as work, education, social or cultural events, shopping, recreation, health and sports. Commuting can be divided into different types by mode of transportation, distance, and frequency. The mode of transportation includes private vehicles such as motorcycles and cars, public transit such as buses, trains, trams, and subways, cycling, walking, and carpooling or ridesharing. The distance traveled during commuting depends on the trip purpose pertaining to work, education, sports and recreation, health, social or cultural events, and shopping. Commuters are directly exposed to various hazardous on-road pollutants, raising the risk of mortality and morbidity (Gurjar et al., 2010). No other activity could pose as much risk to health as traveling on the road (Pant et al., 2017). Furthermore, on-road exposure is often more severe than off-road exposure due to the contribution of vehicular exhaust emissions (Kaur et al., 2007).

1.2 Air Pollution

Air Pollution refers to the presence of harmful pollutants or substances in the air that can negatively impact living organisms, ecosystems, and the climate. Depending on the process of formation these pollutants are categorized as primary and secondary pollutants. Primary pollutants such as PM, sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), ammonia (NH_3), hydrocarbons (HC_x) and volcanic organic compounds (VOC_s) are emitted directly from a source. Secondary pollutants such as secondary PM (formed by chemical reactions between SO_2, NO_x, and NH_3), ozone (O_3), smog, peroxyacetyl nitrate (PAN), and acid rain are formed in the atmosphere by chemical reactions. These pollutants come from both natural sources and anthropogenic activities. The natural sources can be volcanic eruptions, wildfires, dust storms, and biological decay, while the anthropogenic sources can be transportation, industrial activities, agriculture, coal combustion, and solid waste.

There were several instances around the world when the concentration of pollutants peaked, resulting in emergencies such as increased hospital admissions, deaths, and the closing of schools, offices, and other non-essential activities. Various pollution events in different parts of the world, such as Meuse Valley (1930), Donora (1948), and London (1952), are remembered for their lethal effects (Bell et al., 2004; Logan, 1953; Nemery et al., 2001). These events resulted in a significant increase in fatalities and hospital admissions, especially for those with respiratory and cardiovascular ailments. In recent years, elevated air pollution levels have been observed throughout the year in prominent cities in India like Agra, Ahmedabad, Amritsar, Bengaluru, Chandigarh, Delhi, Dhanbad, Guwahati, Hyderabad, Jodhpur, Kanpur, Kolkata, Mumbai, Raipur, and Varanasi (Dutta and Jinsart, 2021). Longer exposure to elevated pollutant concentrations deteriorates the health of living organisms. Thus, the concentration of pollutants must be forecasted for public safety, awareness, and abatement measures. PM is one of the major pollutants affecting human health and other living organisms. The introduction about PM, on-road PM exposure and its sources, and mortality and morbidity associated with PM exposure are presented in the following sections.

1.3 Particulate Matter

Particulate matter (PM) is a complex mixture of particles and droplets in the air that includes organic chemicals, metals, acids, soil, or dust (Ciencewicki and Jaspers, 2007; USEPA, 1996). The PM also contains inorganic components such as calcium, potassium, silica, sodium, aluminum, iron, and magnesium, with minor constituents such as arsenic, selenium, zinc, and lead. Primary PM is released directly into the atmosphere by natural sources or anthropogenic activities, while physical and chemical reaction processes generate secondary PM. Generally, PM of varying composition and sizes is suspended in the air. Some particles, such as dust, soot, or smoke, are large or dark enough to be seen with the naked eye, whereas others are so minute that they can only be detected with an electron microscope. The size of PM is significantly smaller than even the human hair (diameter). Particle sizes are primarily categorized into two major categories based on their aerodynamic particle diameter: fine and coarse PM. Fine PM ($PM_{2.5}$) has an average aerodynamic diameter of less than 2.5 µm. Likewise, coarse PM (PM_{10}) is defined as the PM with an average aerodynamic diameter $<$ 10 µm. The average diameter of both the PMs is smaller than the diameter of a human hair (50 – 70 µm) and fine beach sand (90 µm) as depicted in Fig. 1.1 (USEPA, 1996).

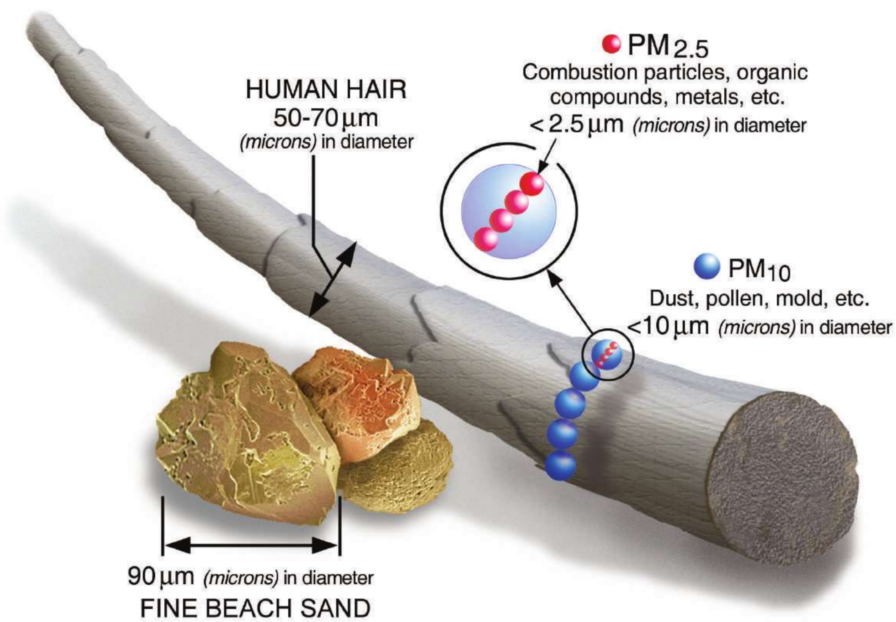

Fig. 1.1 Size comparison of particulate matters. Source: US EPA (United States Environmental Protection Agency).

1.4 Sources of PM in Indian Cities

The on-road PMs are generated from a variety of sources such as vehicle exhaust, soil or road dust, domestic fuel, municipal solid waste burning, construction materials, and industries (CPCB, 2022). Das et al. (2015) discovered that vehicle exhaust, road dust, industrial emissions, and coal combustion were the primary contributors to the on-road PM levels in Kolkata. A receptor modeling for Hyderabad found road dust, vehicle exhaust, biomass and coal burning, and secondary sulfates and nitrates were the main reasons behind the pollution in the city (Guttikunda and Gurjar, 2012). In various source apportionment studies, vehicle exhaust was found to be the major contributor to particulate pollution. Motor vehicle exhaust contains hazardous pollutants such as benzene, CO, Lead (Pb), NO_x, PM, polycyclic aromatic hydrocarbons (PAH_s), and SO_2 (Westerholm and Egeback, 1994). According to two source apportionment studies, vehicles contribute 26% of PM_{10} and 14

– 18% of $PM_{2.5}$ emissions in Indian cities (Karar and Gupta, 2007; Pant et al., 2015). In another multi-city study, Chowdhury et al. (2007) observed that the contribution of vehicle exhaust to ambient $PM_{2.5}$ varied with the season in Delhi (20 – 25%), Kolkata (27 – 52%), and Mumbai (20 – 27%). Source apportionment study in the urban areas of Mangalore found that vehicular emissions contribute 70% of total pollution (Kalaiarasan et al., 2018). The study also found that heavy vehicles and diesel vehicle emissions contributed 37% and 42%, respectively, of $PM_{2.5}$ in industrial areas and city centers. Also, older vehicles (pre-2005) account for 70% of particulate pollution, while heavy commercial vehicles are the largest source of PM emissions (Adak et al., 2016; Kumar et al., 2017, 2011; Pandey and Venkataraman, 2014). Apart from vehicle exhaust, soil or road dust is also a major contributor to particulate pollution. In Mangalore city, the unpaved road dust and paved road dust contributed around 36% and 47%, respectively (Kalaiarasan et al., 2018). Nagpure et al. (2016) found road dust to contribute 42 – 73% of total PM_{10} emissions in Delhi between 1991 and 2011. Gopalaswami (2016) found that road dust contribute to 38% and 56% of $PM_{2.5}$ and PM_{10} in Delhi during 2015. The source apportionment study in Mumbai found that road dust contributed 40% of the total particulate pollution in traffic junctions (Kumar et al., 2001).

1.5 The Health Effects

Air pollution is regarded as one of the most serious environmental threats to human health. The emissions generated from various sources affect air quality. Humans inhale the hazardous pollutants that eventually affects their health (Bigazzi and Figliozzi, 2014; Bigazzi and Rouleau, 2017). According to the World Health Organization (WHO), ambient (outdoor) air pollution causes 4.2 million premature deaths each year in both cities and rural regions globally, with exposure to $PM_{2.5}$ being the primary cause of death (WHO, 2022). As a result of its adverse health effects, airborne PM is a major worldwide concern (Mohanraj and Azeez, 2004). Indoor air pollution is also one of the most serious environmental threats to the health of occupants (Gaur et al., 2018). About 2.4 billion people suffer from major health consequences from indoor smoke produced by cooking and heating homes with biomass, coal, kerosene, and fuel oill (WHO, 2022).

Human exposure to PM is a prominent concern in pollution exposure investigations. PM can easily penetrate the lungs, heart, and bloodstream. Therefore, long-term exposure to PM causes breathing and respiratory issues, aggravation of pre-existing respiratory and cardiovascular disease, alterations in the body's defensive mechanisms against foreign chemicals, lung tissue damage, carcinogenesis, and premature mortality (Li et al., 2019; TDT, 2015). An epidemiological study revealed that ambient PM causes increased stress levels. The study discovered that each increment of 10 µg m^{-3} in $PM_{2.5}$ exposure increased the levels of cortisol and cortisone stress hormones by 7.79% and 3.7% respectively (Li et al., 2017). PM exposure has also been associated with higher levels of increased anxiety, depression, and stress (Azhdari et al., 2022; Kuo et al., 2018). Ambient PM exposure impairs lung function (Raz-Maman et al., 2022). Peak Expiratory Flow (PEF) is a measurement of lung function. An increase in 10 µg m^{-3} of short-term $PM_{2.5}$ exposure was responsible for the change of -2.09 L min^{-1} in students' evening PEF (Zhang et al., 2015). In China, pneumonia hospital admission risks were 1.044 and 1.009, corresponding to an escalation in 10 µg m^{-3} of $PM_{2.5}$ and PM_{10} respectively (Jin et al., 2022).

1.6 Effectiveness of Interventions or Policies

There have been various studies on the policy and mitigation strategies to reduce human exposure to poor air quality. Various researchers reviewed these studies and elaborated on intervention measures and how they help reduce pollution exposure (Bigazzi and Rouleau, 2017; Burns et al., 2020; Henschel et al., 2012; Sanchez et al., 2020; van Erp et al., 2012). Henschel et al. (2012) studied intervention studies (n=28) from 1960 to 2010 and found evidence of a decrease in pollution levels along with improvement in health. van Erp et al. (2012) found that using intelligent transport systems, such as providing information to the public about congestion, alternate routes and parking places, decreased pollution. The study also reviewed a number of changes in traffic management (changes in traffic light phases) and public vehicle fleet (new buses with better emission standards, increased bus frequency, particle traps in diesel buses) that significantly reduced vehicular emissions and improved ambient air quality. Bigazzi and Rouleau (2017) reviewed 30 studies that found the effectiveness of 22 traffic management strategies (TMS) for reducing emissions, ambient concentrations, human exposure, and related health effects. Entry restrictions and pricing, lane management, speed management, traffic flow control, and trip reduction strategies were divided into 22 TMS. However, the study reviewed the effects of TMS on traffic emissions by 19 studies and found it effective in reducing traffic emissions. However, the effect of TMS on ambient air quality (6 out of 30 TMS studies) and human exposure was not well-studied (0 out of 30 TMS studies). Burns et al. (2020) reviewed 42 studies assessing 38 unique interventions. The interventions such as industrial sources (n = 5, e.g., fuel change), residential sources (n=7, e.g., coal ban), vehicular sources (n=22, e.g., low emission zones), multiple sources (n = 4. e.g., measures during international sporting events). The review did not arrive at an overall conclusion regarding the significant effectiveness of interventions toward air quality or health. However, the study found evidence that some interventions improved air quality and health. Generally, interventions did not degrade the air quality. Sanchez et al. (2020) reviewed intervention studies from 2000 to 2020 and provided a system evidence map that can be implemented at the urban level. Interventions help reduce human exposure and adverse health impacts. However, it is important to quantify the pollution caused by PM to evaluate any intervention measures. Some interventions need not be in place throughout the day or week or year. For example, some interventions may not be needed on rainy days in comparison to the winter season due to significant differences in pollution levels between both seasons. Similarly, the pollution might be lower during late night hours, so interventions such as traffic signal timing and vehicle operating restrictions might not be necessary during those hours. Thus, along with the air quality measurements, factors affecting the pollutant concentrations should be measured or noted for further analysis. Interventions that would work for a particular day of the week or season may be identified.

1.7 Motivation for This Work

Commuters' exposure to PM concentrations is affected by various factors, including route and travel mode, traffic volume and composition, the emission factors, ventilation inside the vehicles (open or closed window vehicles), position (center line or edge line) of a commuter on the road, meteorological parameters (atmospheric temperature, relative humidity, wind speed and wind direction, season), the position of breathing zone (depends on the height and seating position of the commuters), breathing rate and tidal volume (Knibbs et al., 2011; Kumar et al., 2018; Singh et al., 2021). These factors can be utilized for estimating the on-road PM concentrations. Various PM exposure studies have been conducted to explore the effects of these factors (Betancourt et al., 2017; Goel et al., 2015; Huy et al., 2022; Manojkumar et al., 2021; Patel et al., 2016; Raj and Karthikeyan, 2020; Saksena et al., 2008; Swamy et al., 2015; Tsai et al., 2008; Wu et al., 2013). However, only a few studies have modeled PM exposure using these factors (Goel et al., 2015; Huy et al., 2022; Tsai et al., 2008; Wu et al., 2013). Almost all of the studies have used data from stationary monitoring stations to predict average on-road PM concentrations. The study by Huy et al. (2022) and Wu et al. (2013) used meteorological parameters to predict on-road PM concentrations. No study considered the effect of traffic composition, the combined effect of seasons and traffic congestion levels and meteorological parameters in PM modeling processes. In addition, no studies were found that model the extreme and real-time (second-by-second) exposure of commuters to PM. Essentially, this study tried to utilize these factors to model average, extreme and real-time on-road particulate concentrations. The results of the study will benefit the public for their safety and awareness of air pollution and help public administrations and urban planners to implement abatement measures.

1.8 Research Objectives and Problem Statement

The study proposed to analyze (1) average, (2) extreme, and (3) real-time on-road PM to investigate commuter's exposure to it more comprehensively. The effect of meteorological and traffic parameters on these measures was also explored. The following list depicts the primary objectives of the study:

1. to compare PM concentration inside a university campus and on the city roads,
2. to investigate factors that affect on-road PM exposure,
3. to study extreme PM exposure at traffic intersections, and
4. to model the effect of traffic composition on commuters' exposure to PM.

The following chapters focus on each of these objectives.

1.9 Research Scopes

The study aimed to explore the effect of various factors on commuters' exposure to PM concentration. This study utilized a mobile data collection methodology approach for collecting PM, GPS location, traffic video, and temperature and humidity data along a set of routes in a Tier-II city covering various land uses. The study was conducted in various seasons, such as winter, spring and summer. The study was not conducted in the rainy season since the functioning of the instruments may be compromised. Also, there were spatial irregularities in rain over the study routes and quantifying this was beyond the scope of this study.

1.10 Organization of This Thesis

This thesis is organized into eight Chapters. The chapter-wise organization of the thesis is described below.

Chapter 1 (this chapter) includes an introduction to the research area, motivation for the research, research objectives and problem statement, research scopes and the overview of the thesis.

Chapter 2 presents literature reviews of factors affecting commuters' PM exposure and of recent advances in pollution monitoring. This chapter also presents a list of research gaps in each subsection.

Chapter 3 explains the study area, instrumentation, data collection and pre-processing, quality control and quality assurance (QA/QC). This chapter explains why Varanasi city was chosen for this study.

Chapter 4 compares the PM levels inside the Banaras Hindu University (BHU) campus and on the roads in Varanasi city.

Chapter 5 presents the effect of various factors on average on-road PM concentrations in the study area. This chapter describes the factors that are more suitable for modeling on-road PM levels.

Chapter 6 describes the study of extreme PM exposure at traffic intersections using extreme value theory and the Bayesian hierarchical approach. This chapter describes the effect of seasons on monthly PM return levels and the probability of attaining extreme PM concentration or any pollution event that happened in India.

Chapter 7 discusses various approaches for modeling on-road PM levels using traffic composition as the primary factor.

Chapter 8 provides the conclusion of the thesis work with key findings, policy implications, limitations and future scopes of this work.