On-Road Exposure to Particulate Matters in a Tier-II Indian City: A Case Study of Varanasi

Thesis submitted in partial fulfilment
for the Award of
DOCTOR OF PHILOSHPHY (PHD)
in
CIVIL ENGINEERING

by
Saroj Kanta Behera

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
BANARAS HINDU UNIVERSITY
VARANASI - 221 005

ROLL NUMBER
18061510

YEAR OF SUBMISSION
2024

I dedicate this thesis to all those who selflessly help others without expecting anything in return.

Certificate

It is certified that the work contained in this thesis entitled **"On-Road Exposure to Particulate Matters in a Tier-II Indian City: A Case Study of Varanasi"** by **Saroj Kanta Behera**, Roll Number **18061510**, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of **Ph.D. Degree** in **Civil Engineering**.

Abhisek Mudgal 11/11/24

Supervisor

Dr. Abhisek Mudgal

Department of Civil Engineering

Indian Institute of Technology (Banaras Hindu University)

Varanasi-221005

Dr. ABHISEK MUDGAL
Assistant Professor
Department of Civil Engineering
Indian Institute of Technology
(BHU), Varanasi-India-221005

Declaration

I, **Saroj Kanta Behera**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Dr. Abhisek Mudgal** from January 2019 to November 2024 at the **Department of Civil Engineering**, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers whenever and wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any others' work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

Saroj Kanta Behera

Date: 11/11/2024

Signature

(Saroj Kanta Behera)

Place: Varanasi

Certificate by the Supervisor

It is certified that the above statement made by the student is correct to the best of my knowledge.

Abhisek Mudgal 11/11/24

Supervisor

Dr. Abhisek Mudgal

Department of Civil Engineering

IIT (BHU)

Varanasi

11/11/24

Signature of the Head of the Department

(Civil Engineering)

Dr. ABHISEK MUDGAL
Assistant Professor
Department of Civil Engineering
Institute of Technology
Varanasi India-221005

विभागाध्यक्ष/HEAD
जानपद अभियांत्रिकी विभाग
Department of Civil Engineering
संस्थान (बी.एच.यू.)

Copyright Transfer Certificate

Title of the Thesis : **On-Road Exposure to Particulate Matters in a Tier-II Indian City: A Case Study of Varanasi**

Name of the Student : **Saroj Kanta Behera**

Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the **Doctor of Philosophy** in **Civil Engineering**.

Saroj Kanta Behera

Date: 11/11/2024 Signature

Place: Varanasi (Saroj Kanta Behera)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

Acknowledgements

With deep humility, misty eyes, and folded hands, I offer my heartfelt gratitude to the **Almighty** for showering blessings upon me throughout this journey. I express my profound thanks to the God of wisdom, knowledge, and prosperity, **Lord Ganesha Ji**, the great Lord of Varanasi, **Kashi Vishwanath Ji** and the Lord of the Universe, **Lord Jagannath Ji**, for their continuous grace and protection. Their divine presence infused me with the strength, focus, and determination needed to embark on and complete this work. This research would not have been possible without their boundless blessings. I pray that this divine force continues to guide me, providing the strength, courage, wisdom, and willpower to face all of life's challenges with unwavering faith.

My first and foremost heartfelt gratitude and deepest indebtedness are towards **Bharat Ratna Mahamana Pandit Madan Mohan Malviya Ji**, the visionary founder of Banaras Hindu University, for establishing this magnificent temple of learning. His dedication to the pursuit of knowledge and education has created an institution that continues to inspire and guide generations of scholars like me.

I want to express my deepest gratitude, appreciation, and indebtedness to my esteemed supervisor, **Dr. Abhisek Mudgal**, for his unwavering support, motivation, and immense knowledge throughout this journey. His guidance was instrumental in every aspect of this work, from conceptualization and experiment design to project investigation, supervision, data interpretation, and expert assistance in editing, drafting, and revisions. His professional insight, thoughtful and scholarly approach, and impeccable counseling were invaluable in helping me achieve my goals. **Dr. Mudgal**'s meticulous attention to detail, his ability to address every challenge, his constant involvement, and his tireless efforts, combined with his precious guidance and valued suggestions, were crucial in bringing this work to a successful conclusion. I am also sincerely thankful to him for providing the necessary facilities to carry out this research. I feel truly fortunate to have had the opportunity to be associated with and work under such an accomplished and inspiring mentor.

I want to thank my Research Progress Evaluation Committee (RPEC) members, **Dr. Ankit Gupta** (Associate Professor & MoRTH Chair Professor, Department of Civil Engineering, IIT (BHU) Varanasi) and **Dr. Amrendra Kumar** (Associate Professor, Department of Mining Engineering, IIT (BHU) Varanasi), for their valuable guidance, supervision, expert assistance, scientific inputs, and suggestions throughout my research.

I wish to convey my sincere gratitude to **Prof. Amit Patra**, Director, IIT (BHU) Varanasi, and **Prof. Promod Kumar Jain**, Ex-Director, IIT (BHU) Varanasi, for all the institutional support during this study. I want to thank **Prof. Devender Singh**, Dean of Academic Affairs and **Prof. Shyam Bihari Dwivedi**, former Dean of Academic Affairs, for their support. I express my gratitude to **Prof. Sasankasekhar Mandal**, Head, Department of Civil Engineering, IIT (BHU) Varanasi, for providing the necessary facilities and academic guidance during my Ph.D. work. I am immensely thankful to all former Head of the Department, **Prof. Prabhat Kumar Singh Dikshit** and **Prof. Prabhat Kumar Singh**, for their cooperation during my research work.

I express my gratitude to all the faculty of the Department of Civil Engineering: **Dr. Supriya Mohanty**, **Dr. Agnivesh P.**, and **Dr. Anshuman Sharma** for their cooperation and scientific suggestions during my research work. Without their precious support, it would not have been possible to execute this research work.

I want to especially thank my colleague, **Mr. Ashutosh Kumar**, and M.Tech Student, **Mr. Ankit Kumar Singh**, for their technical and analytical support during my research tenure. I am grateful for their guidance and support during data collection and curation, analysis, and paper publication processes.

My thankful regards to my batch mates **Dr. Parul Rawat**, **Dr. Amit Kumar Ram**, **Dr. Mayank Sukhija**, **Dr. Mohit Chaudhary**, **Dr. Supriya Chanda**, **Dr. Abhinav Kumar**, **Dr. Amit Singh**, **Dr. N. Sai Anuraag**, **Mr. Annadasu Nirmal Prasad Naidu**,

Mr. Ashish Kumar Chouksey, **Mr. Mayank Nishant**, and **Mr. Amardeep Pandey** for their pleasant company, cooperation, and help during research work.

I am also thankful to my respected seniors, **Dr. Jayvant Choudhary**, **Dr. Satyajit Mondal**, **Dr. Gaurav Verma**, **Dr. Amod Kashyap**, **Dr. Sourav Sarkar**, **Dr. Vishal Kumar Kushwaha**, **Mr. Ankit Tewari**, and beloved juniors, **Dr. Vivek Pratap Wagh**, **Mr. Rohit Rodhia**, **Mrs. Sadiya Shaikh**, **Mr. Abhijeet Babar**, **Mr. Aakash Singh**, **Mr. Ranveer Kumar**, **Mr. Shreyansh Mishra**, and **Mr. Sourav Chandra**, for their healthy company during my research tenure.

I am thankful to M.Tech students **Mr. Ananya Singh** and **Mr. Saurabh Dubey**, IDD student **Mr. Yash Pandey** and B.Tech students **Mr. Avyaya Perka**, **Mr. Abhijeet Kumar Gaurav**, **Mr. Ujjwal Kumar**, **Mr. Vedaant Gupta**, **Ms. Sneha Singh**, **Mr. Kunduru Sainath**, and **Mr. Nitin Sharma** for their help in the data curation process during the research work.

I extend my gratitude to the Department of Civil Engineering office staff **Mr. Kamalesh Kumar Yadav**, **Mr. Rajesh Prasad**, **Mr. Ajit Kumar**, and **Mr. Deepak Kharwar** for helping with official works and laboratory staff **Mr. Amit Kumar Singh** for helping with laboratory facilities.

I am very much thankful to all the members of the **Odia Society of Varanasi** (Varanaseya Utkal Samaj), especially **Prof. Gopabandhu Mishra**, **Prof. Pradosh Mishra**, **Prof. Kalyan Ghadei**, **Mrs. Smita Ghadei**, **Dr. Amiya Kumar Samal**, **Mrs. Sonali Mohapatra**, **Dr. Siva Prasad B N V**, **Mrs. Jhuna Rani Ojha**, **Dr. Soumya Ranjan Meher**, **Dr. Simanta Kumar Samal**, **Dr. Basant Sethi**, **Dr. Debadatta Mohapatra**, **Dr. Biswajit Mishra**, **Dr. Neha Pati**, **Dr. Sonali Mallick**, **Ms. Shravani Sahani**, **Er. Chandan Kumar Behera**, **Mr. Priyatosh Pradhan**, **Mr. Abhijeet Rana**, **Mr. Prabeen Kumar Sahu**, **Mr. Debasmit Mallick**, **Ms. Ananya Mishra**, **Mr. Ajaya Kumar Mahapatra**, **Mr. Ashirbad Lenka**, **Mr. Rabi Narayan Mohanty**, **Mr. Manoranjan Behera**, **Mr.**

Soumya Ranjan Mohapatra, **Ms. Lopamudra Samal**, **Ms. Sougandhika Mohapatra**, **Ms. Lipsa Badu**, **Mrs. Sukanya Patra**, **Mr. Anirbana Parida**, **Ms. Twinkle Pradhan**, **Ms. Sushree Sangita Mohapatra**, **Ms. Akankshya Sunani**, **Ms. Sobhana Sahoo**, **Mr. Chinmay Chiranjeeb Nayak**, **Ms. Jyotirmayee**, **Mr. Abhijit Sahoo**, **Mr. Balaram Sahoo**, **Ms. Sarita Lenka**, **Mr. Ananga Udaya Bhoi**, **Ms. Suprava Mishra**, **Ms. Suchismita Satapathy**, **Ms. Niharika Samantaray**, **Ms. Bhubaneswari Sahoo**, **Ms. Saswati Dehury**, **Ms. Soumyashree Meher**, **Ms. Adyasha Samal**, **Mr. Subrat Sahani**, **Mr. Manoranjan Bijuliseth**, **Ms. Renubala Bhoi**, **Ms. Purnima Jain**, **Ms. Kanchan Kumari Sriwas**, **Ms. Soujanya Sa**, **Mr. Vineet Bharadwaj**, **Mr. Shivashish Priyadarshi Mohanta**, **Ms. Anuska Beura**, **Mr. Tikun Dhal**, **Ms. Ankita Nayak**, **Ms. Baishnabi Kishan**, **Mr. Gopal Krishna Pradhan**, **Mr. Soumya Ranjan Sahoo**, **Ms. Aishwarya Rath**, **Ms. Niharika Mishra**, **Ms. Swetasoma Nayak**, **Mr. Bikash Behera**, **Mr. Nimain Biswaranjan Behera**, **Ms. Anwesha Patnaik**, **Ms. Sonali Priyadarsini Sahoo**, **Mr. Ritik Roshan Parida**, **Mr. Pratik Kumar Biswal**, **Mr. Abhinandan Sahoo**, **Mr. Krishna Sahoo**, **Ms. Subhalaxmi Sahoo**, and **Mr. Priyaranjan Jena** for their care, affection, and moral support like my family members.

I am grateful to my school teacher, **Mr. Manoj Kumar Pradhan**, for his immense contribution to both my career and character development. I owe the journey to the completion of my PhD to him. I am also thankful to **Kalinga Abasika Vidyalaya, Kendrapara** and its faculty members **Mrs. Bijaylaxmi Mohanty**, **Mr. Anil Dash**, and **Mrs. Damayanti Swain** for providing quality education during my schooling.

Finally, I will always remain deeply thankful and indebted to my grandparents, **Late Mr. Natabar Behera** and **Late Mrs. Jemadei Behera**, as well as to my parents, **Mr. Balaram Behera** and **Mrs. Rajani Behera**, for their unconditional love, unwavering support, and countless sacrifices. I also extend my heartfelt gratitude to my sister, **Mrs. Maninilata Behera**; my brother-in-law, **Mr. Sukanta Kumar Behera**; my brother, **Er.**

Khageswar Behera; and my sister-in-law, **Mrs. Sumitra Behera**, for their continuous strength, cooperation, and selfless encouragement throughout this journey. This work could not have been completed without their blessings and support, for which I have no words to express my gratitude. I will always remain thankful to my nephew, **Mr. Ashutosh Behera**, and my niece, **Ms. Bisweswaree Behera**, for their love and affection, which lightened my path during this endeavor.

Last but not least, I am deeply grateful and would like to **thank everyone** who, in one way or another, contributed to this research and motivated me to overcome the hurdles along this journey.

The financial assistance for this work provided as a scholarship to me by the **Ministry of Education (MoE), Government of India**, is highly acknowledged.

Ultimately, I would like to bow down and pray to the **Almighty** for always giving me enough strength and courage to fulfill all my dreams and goals.

Date: 09/11/2024

Place: Varanasi **Saroj Kanta Behera**

Table of contents

List of figures **xxvii**

List of tables **xxxi**

1 Introduction **1**

1.1 Background 1

1.2 Air Pollution 2

1.3 Particulate Matter 3

1.4 Sources of PM in Indian Cities 4

1.5 The Health Effects 5

1.6 Effectiveness of Interventions or Policies 6

1.7 Motivation for This Work 8

1.8 Research Objectives and Problem Statement 9

1.9 Research Scopes 9

1.10 Organization of This Thesis 10

2 Literature Review **13**

2.1 Factors affecting Commuters' PM Exposure 13

2.1.1 Meteorology Factors 15

2.1.2 Traffic Factors 17

2.1.3 Ventilatory Factors 19

2.1.4 Street Configurations 20

2.1.5 Ambient Concentration (AC) 21

2.2 Recent Advancements in Air Quality Monitoring 22

2.2.1 Satellite-Based Air Quality Monitoring 22

2.2.2 Continuous (Stationary) Ambient Air Quality Monitoring 24
2.2.3 On-Road (Mobile) Air Quality Monitoring 25
2.3 Research Gaps 29

3 Study Design and Data Collection 31
3.1 Study Area 31
3.2 Routes and Traffic Intersections 32
3.3 Instrumentation 34
3.4 Data Collection 36
3.5 Data Processing and QA/QC 37

4 Comparison of PM Exposure: Within BHU Campus and On-Roads in Varanasi City 41
4.1 Background 41
4.2 Methodology 43
4.2.1 Study Area and Routes 43
4.2.2 Instrumentation and Data Collection 45
4.2.3 Exploratory Data Analysis and Data Visualization 45
4.2.4 Pollution Exposure Mapping 45
4.2.5 Inhaled Dose Estimation 46
4.3 Results and Discussion 48
4.3.1 Summary Statistics 48
4.3.2 Difference in PM Exposure 50
4.3.3 Effect of Day Type on PM Exposure 52
4.3.4 Effect of Hour of the Day on PM Exposure 54
4.3.5 Exposure Maps 56
4.3.6 Relationships between Inside and Outside PM Exposures 59

4.3.7 Inhaled Doses 60
4.4 Summary 61

5 Factors Affecting Average On-Road PM Exposure 63

5.1 Background 63
5.2 Data Analysis 64
5.2.1 Spatial Analysis and Modeling 64
5.3 Results and Discussion 66
5.3.1 Descriptive Statistics 66
5.3.2 Day of Week Exposure 74
5.3.3 Exposure Maps 75
5.3.4 PM Concentration Ratio 78
5.3.5 On-Road and Reference PM Exposure Ratio 82
5.3.6 Effect of RH and AT on On-road PM Exposure 82
5.3.7 On-Road PM Exposure as a Function of Reference PM 84
5.3.8 PM Inhaled Dose 85
5.4 Summary 87

6 Study of Extreme PM Exposure at Traffic Intersections 93

6.1 Background 93
6.1.1 Extreme Exposure 94
6.1.2 Bayesian Hierarchical Modeling 96
6.2 Data Analysis 97
6.2.1 Zone of Influence (ZoI) 97
6.2.2 Analysis of Extreme Levels of PM 98
6.2.3 Exposure Hotspot Maps 105
6.3 Results and Discussion 105

6.3.1 Descriptive Statistics 105
6.3.2 Peak-Over Threshold Models 108
6.3.3 Prediction of Extreme Exposure 111
6.3.4 Extreme Exposure Hotspots 116
6.4 Summary 116

7 Modeling the Effect of Traffic Count on Commuters' Exposure to PM 119

7.1 Background 119
7.2 Data Analysis 120
7.2.1 Vehicle Detection 120
7.2.2 Manual Vehicle Detection 120
7.2.3 Automatic Vehicle Detection 122
7.2.4 Statistical Analysis 127
7.3 Results and Discussion 127
7.3.1 Section-Wise PM Exposure Summary Statistics 127
7.3.2 Performance Evaluation of PM Exposure Models using Section-Wise Traffic Count 128
7.3.3 Performance Evaluation of PM Exposure Models using Real-Time Traffic Count 135
7.4 Summary 138

8 Conclusions 139

8.1 Background 139
8.2 Key Findings 140
8.3 Key Contributions 140
8.4 Policy Implications 141
8.5 Limitations and Future Scopes 142

Appendix A List of Publications **143**

A.1 Journal Publications 143

A.2 Conference Publications 143

Appendix B Illustration of Raw Data Set **145**

References **147**

List of figures

1.1 Size comparison of particulate matters. Source: US EPA (United States Environmental Protection Agency). 4

2.1 Factors considered in various PM exposure studies around the world. . . . 14

2.2 Schematic diagram of continuous pollution monitoring process. 26

2.3 Schematic diagram of on-road pollution monitoring process. 29

3.1 PM data collection on routes and traffic intersections in Varanasi, India. . 33

3.2 Land use details of the study area 34

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. 35

3.4 Number of trips made on routes in different seasons. 37

3.5 Overall flowchart of analysis, results, discussion, and findings of the four objectives of the study. 39

4.1 Monitoring locations of air pollutants inside and outside the university campus. 44

4.2 Process of mapping on-road pollution exposure. 47

4.3 Ratio of PM exposure outside to inside campus. 53

4.4 Comparison of inside and outside PM (μg m^{-3}) exposure during weekdays and weekends. 54

4.5 Comparison of the effect of day of the week on trips to outside university locations. 55
4.6 Comparison of PM levels at different hours of the day. 57
4.7 Inside and outside $PM_{2.5}$ and PM_{10} exposure maps of the university campus. 58
4.8 Linear relationship between exposure to particulate matter inside and outside the campus. 59

5.1 Speed distribution on routes in different seasons. 67
5.2 AT distribution on routes in different seasons. 68
5.3 RH distribution on routes in different seasons. 68
5.4 On-road (a) $PM_{2.5}$ and (b) PM_{10} exposure on routes in different seasons. . 70
5.5 On-road (a) $PM_{2.5}$ and (b) PM_{10} exposure during different seasons and hours of the day. 73
5.6 PM exposure during different day of week and seasons. 76
5.7 Weekdays vs weekend PM exposure during different seasons. 77
5.8 Spatial variability of (a) $PM_{2.5}$ and (b) PM_{10} on different routes during the study period. 79
5.9 Ratio of fine and coarse PM for on-road and reference locations. 81
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. 83
5.11 Correlation among on-road and reference PM concentration, traffic speed, and meteorological parameters. 84
5.12 Quantification of on-road PM concentrations during (a) winter, (b) spring, (c) summer using reference PM concentrations. 86
5.13 PM inhaled dose per trip on routes during different seasons. 88
5.14 PM inhaled dose per km on routes during different seasons. 89

6.1 Computation of zone of influence (ZoI) and extraction of intersection PM data. 99
6.2 Identification of the Zone of Influence (ZoI) at an Intersection. 100
6.3 Threshold stability plot for $PM_{2.5}$ observed during (a) Summer, (b) Spring and (c) Winter season. 109
6.4 Posterior distribution of parameters for (a) $PM_{2.5}$ and (b) PM_{10} during different seasons. 110
6.5 Monthly return levels of (a) $PM_{2.5}$ and (b) PM_{10} during different seasons. 112
6.6 The probability of observing severe PM levels in Delhi's smog event. . . . 113
6.7 Trace plot for model checking for (a) $PM_{2.5}$ and (b) PM_{10}. 114
6.8 Posterior predictive check for (a) $PM_{2.5}$ and (b) PM_{10}. 115
6.9 Sensitivity analysis of (a) $PM_{2.5}$ and (b) PM_{10} return levels with different thresholds. 115
6.10 Average (a) $PM_{2.5}$ and (b) PM_{10} extreme pollution hotspots at traffic intersections during winter. 117

7.1 Representation of study routes in terms of various sections. 121
7.2 Steps for manual vehicle counting. 122
7.3 Example of an extracted raw image using Python. 123
7.4 Performance evaluation YOLOv5 by confusion matrix. 124
7.5 Performance evaluation of YOLOv5 by Precision-Recall Curve. 125
7.6 Vehicle classification by YOLOv5. 126
7.7 Steps involved in automated vehicle counting. 126
7.8 Average (a) $PM_{2.5}$ and (b) PM_{10} exposure along different sections of the study routes. 131

List of tables

2.1 List of air pollution regulatory and control boards across different countries. 23
2.2 List of major pollutants' satellite monitoring instruments and their spatiotemporal resolutions (Adopted from: AbdelSattar, 2019). 24
2.3 Working principles and pollutants monitored by various CAAQMS. . . . 26
2.4 Specification of instruments used for in-vehicle pollution monitoring (Adopted from: Kumar et al., 2011). 28

3.1 Specification of instruments used during the field study. 35

4.1 Summary of studies on PM exposure in various outdoor environments of university campuses. 42
4.2 Average (SD) PM exposure for trips from the campus to key locations. . . 50
4.3 Comparison of PM exposure (µg m^{-3}) between trip portions outside and inside the campus. 51
4.4 Ratio and percentage share of aggregate concentrations for trip portions inside and outside the campus. 52
4.5 PM dose (µg) inhaled during Weekday (Weekend) trips to destinations outside the campus. 60
4.6 Difference in PM doses between trip portions inside and outside the university campus. 61

5.1 List of PM exposure studies carried out on motorcycles around the world. 65
5.2 Summary of the trip and trip-related information. 69
5.3 Summary of on-road $PM_{2.5}$ (µg m^{-3}) concentrations during different seasons. 71
5.4 Summary of on-road PM_{10} (µg m^{-3}) concentrations during different seasons. 72

5.5 One-way ANOVA between season-wise $PM_{2.5}$ concentrations. 73
5.6 One-way ANOVA between season-wise PM_{10} concentrations. 74
5.7 PM ratio (Fine/coarse ratio or $PM_{2.5}/PM_{10}$ ratio during various seasons. . 81
5.8 Summary of inhaled doses by the motorcyclists in Varanasi. 87

6.1 Summary of PM extreme value analyses conducted at various cities around the world. 95
6.2 Seasonal $PM_{2.5}$ concentration (µg m^{-3}) at traffic intersections and mid-block sections in Varanasi. 106
6.3 Seasonal PM_{10} concentration (µg m^{-3}) at traffic intersections and mid-block sections in Varanasi. 106
6.4 Thresholds to segregate extreme PM concentrations (µg m^{-3}) observed in various seasons. 109
6.5 Estimate of model parameters for $PM_{2.5}$ (µg m^{-3}) by hierarchical modeling for different seasons. 110
6.6 Estimate of model parameters for PM_{10} (µg m^{-3}) by hierarchical modeling for different seasons. 111

7.1 Summary of on-road $PM_{2.5}$ concentration across all route sections (µg m^{-3}). 129
7.2 Summary of on-road PM_{10} concentration across all route sections (µg m^{-3}). 130
7.3 Linear regression for section-wise $PM_{2.5}$ exposure models. 132
7.4 Linear regression for section-wise PM_{10} exposure models. 132
7.5 Mixed-effect linear regression for section-wise $PM_{2.5}$ exposure models (fixed effects). 133
7.6 Mixed-effect linear regression for section-wise $PM_{2.5}$ exposure models (random effects). 134
7.7 Mixed-effect linear regression for section-wise PM_{10} exposure models (fixed effects). 134

7.8 Mixed-effect linear regression for section-wise PM_{10} exposure models (random effects). 134

7.9 Linear regression for real-time $PM_{2.5}$ exposure models. 135

7.10 Linear regression for real-time PM_{10} exposure models. 136

7.11 Mixed-effect linear regression for real-time log$PM_{2.5}$ exposure models (fixed effects). 136

7.12 Mixed-effect linear regression for real-time log$PM_{2.5}$ exposure models (random effects). 137

7.13 Mixed-effect linear regression for real-time logPM_{10} exposure models (fixed effects). 137

7.14 Mixed-effect linear regression for real-time logPM_{10} exposure models (random effects). 137

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 $PM_{2.5}$ (PM_{10}) 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}, PM_{10}: 100 μg m^{-3}) set by National Ambient Air Quality Standards (NAAQS). The on-road $PM_{2.5}$ (PM_{10}) concentrations during winter were 2.36 (1.69) times that of summer. In contrast, the average $PM_{2.5}$ (PM_{10}) 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 PM_{10}. This is because the PM_{10} settles to the ground within 6 – 8 min of generation, while $PM_{2.5}$ remains suspended longer and propagates to other locations more easily (Cheriyan 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 $PM_{2.5}$ (PM_{10}) 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 PM_{10} levels would exceed that of the Delhi smog event (585 and 989 μg m^{-3} of $PM_{2.5}$ 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 $PM_{2.5}$: 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 $PM_{2.5}$ (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. $PM_{2.5}/PM_{10}$ 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 $PM_{2.5}$ and PM_{10} levels were significantly higher in winter due to lower mixing height (Tiwari et al., 2013). Also, a higher $PM_{2.5}/PM_{10}$ ratio (0.49 – 0.74) was observed during winter, implying that PM was mostly composed of fine particles. As $PM_{2.5}$ 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.