

DISPERSION OF LINE SOURCE EXHAUST EMISSIONS USING AN INTEGRATED MODELLING APPROACH: A CASE STUDY OF DELHI CITY

ARCHANA CHAWLA



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2023**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2023

DISPERSION OF LINE SOURCE EXHAUST EMISSIONS USING AN INTEGRATED MODELLING APPROACH: A CASE STUDY OF DELHI CITY

by

ARCHANA CHAWLA

Department of Civil Engineering

Submitted

In the fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2023

Dedicated to

To

The one who persisted and persevered

**कर्मण्येवाधिकारस्ते मा फलेषु कदाचन।
मा कर्मफलहेतुर्भूर्मा ते सङ्गोऽस्त्वकर्मणि॥**

— श्रीमद्भगवद्गीता

CERTIFICATE

This is to certify that the thesis entitled “**Dispersion of Line Source Exhaust Emission using an Integrated Modelling Approach: A Case Study of Delhi City**”, being submitted by **Ms. Archana Chawla**, to the **Indian Institute of Technology Delhi** for the award of the degree of ‘**Doctor of Philosophy**’ in Department of Civil Engineering is a record of the bonafide research work carried out by her under my supervision and guidance. She has fulfilled the requirements for the submission of this thesis, which to the best of my knowledge has reached the requisite standard.

The material contained in the thesis has not been submitted in part or full to any other University or Institute for the award of any other degree or diploma.

Prof. Mukesh Khare

Department of Civil Engineering,
Indian Institute of Technology Delhi
New Delhi-110016, India

ACKNOWLEDGEMENTS

I feel deeply honoured to acknowledge the exceptional and unwavering support that my esteemed research supervisor, Prof. Mukesh Khare, has provided me throughout my PhD journey. His steady commitment to my academic growth and success has helped me to navigate the challenges and complexities of my research work with confidence and clarity. His valuable insights, fruitful discussions and innovative approach have allowed me to develop and explore new areas of knowledge and expertise that I would not have discovered on my own. I am truly grateful for all the opportunities you have bestowed on me which ultimately modelled myself to what I am today. Thank you so much for everything sir! You gave me the freedom to explore various avenues and to work independently, which has helped me to grow and thrive as a researcher. I am privileged to have had the opportunity to work with you and to learn from you, and I will always remember your contributions to my academic and overall development.

I am also thankful to my SRC members, Late Prof. K.C. Iyer, Prof. Dipti Ranjan Sahoo, Prof. Manju Mohan and Prof. Gazala Habib for rendering me their valuable comments, encouragement, and time towards my research. I would also like to thank Prof. A.K. Nema and Prof. N.K. Garg, faculty members of the Civil Engineering Department, for their kind support and encouragement. Thank you!

My sincere thanks to Dr. Harikishan Perugu, climate change data consultant, World Bank, Washington D.C. for his technical guidance and assistance to learn complex emission model and its application for Indian region, it has been of immense help in completing my thesis. I would convey my deep regards to Dr. Niraj Sharma, Scientist, CSIR-CRRI, New Delhi for helping me during traffic data collection and invaluable suggestions in my work.

I would also like to express my gratitude to Mr. Rajiv Sharma for his valuable support in the laboratory, along with Dr. Sanjay Gupta. My sincere gratitude goes to officials working with the Civil Engineering Department for their assistance. I express my deepest gratitude to my office in charge, Mr. Atul Chaturvedi, Superintendent Engineer, Rural Engineering Services, M.P. for going the extra mile and providing me with the flexibility to complete my thesis.

My genuine thanks to all my PhD seniors, especially Dr. Sunil Gulia, Dr. Sumanth Chinthala, Dr. Praveen B, and Dr. Isha Khanna and my dear colleagues Dr. Komal Shukla, Sasi Kumar N., Garima Gupta, Arpit Katiyar, Diljit Kumar Nayak, Gandham Phani Kumar, Paresh Parmar and Baby Keerthi. Special thanks to my lab friends Shiva Kumar Gummadavlli and Shubham Sharma for discussing and improving my work.

Some of my close friends have kept immense faith in me and made this journey a lot more enjoyable, Aparna Sharma, Swati Rani, Saif Khan, Srishti Bafna, Bhavya Parashar, Dr. Moulshree Tripathi, Dr. Sandhya Birla, Shikha Vats, Viswanath Velamuri and Dr. Sweetie Bairagi. Thank you for all the fun we had in institute in previous years! I would like to give a special thanks to my friend Kshitij Gupta for his constant support, improving my work, listening to me endlessly, and motivating me for the last five years. There are many unnamed here, what goes for *whole*, also goes for *parts*. I express my thankfulness for their, at present, seemingly, implicit help!

The names of my loved ones hold a special place in my heart, especially my parents Mrs. Kavita Chawla and Mr. Shyam Lal Chawla, who have played an integral role in shaping me into the person I am today. Without their love and unwavering support, I would not have come this far. My dear brother Dheeraj Chawla has been a constant pillar of strength since the beginning and guided me whenever I feel a little adrift during my journey, and my sister Tanuja Chawla has provided me with immense love and care in difficult times. My beloved husband Vikas Khatuja has been there for me through all the ups and downs, selflessly encouraging me every step of the way. I can truly say that this has been our journey together. My in-laws, Mrs. Kanchan Khatuja and Mr. Surendra Khatuja have shown me immense love and faith, and their support has made my journey much easier. The support of all these individuals has been and will always be crucial to my personal and professional growth.

Last but above all, I am grateful to Lord Hanuman ji, for everything while I write this!

Archana Chawla

ABSTRACT

Globally, vehicular emissions are recognized as the main source of air pollution in urban areas. The trend of urbanization has led to a surge in private vehicle ownership, particularly in metropolitan cities such as Delhi, India, resulting in significant growth of the automobile sector. Additionally, Delhi has experienced a considerable influx of people migrating from neighbouring states in the past decade, leading to higher demand for transportation facilities. The growing number of vehicles has a direct impact on air pollution by causing higher fuel consumption and increased traffic congestion. The activity of vehicles on congested roads, including sudden acceleration and deceleration, significantly affects emissions. As a result, precise estimation of vehicular emissions is critical in developing systematic pollution mitigation strategies.

In the present study, the analysis of emission measurement has focused on a heavy traffic road junction of Delhi city, which includes a mid-block signalized intersection. In the past, many modelling studies have used the average speed of vehicle for entire road segments that resulted in underestimation of emission. The relationship between vehicle operating characteristics, inter- and intra-vehicle fleet variability, driving behaviour, and traffic conditions have been investigated by developing an integrated modelling framework called VMIMD (VISSIM-MOVES Integration Model for Delhi city). The modelling framework serves as an interface between the VISSIM (traffic flow simulation) and MOVES (emission) models, allowing for the generation of operating condition-based emission factors (EFs) by considering VSP (vehicle specific power) and speed as an intermediate parameter. The revision of the MOVES default emission inventory has also been carried out using the correction factors developed specifically for India's emission standards. This modification has resulted in more precise emission estimates, and has improved the overall efficiency of the model for Indian conditions.

The analysis of results shows a strong correlation between time spent in each operating condition (idling, cruising, and braking) and emission generation. Heavy traffic hours have the highest percentage of distribution in braking/deceleration mode which reduces the speed of vehicles and increases power demand. As a result, the emission changes very rapidly as vehicles shift from cruising mode to braking mode. The study has found that HCVs and Buses are more sensitive to variations in speed than other types of vehicles, despite being a smaller proportion of the total traffic fleet. The impact of heavy traffic congestion on emission has also been found by analysing diurnal variation of EFs for HC, CO, NO_x and PM_{2.5} pollutants. All pollutants show the highest emission level from 0900 to 1100 hrs., which is the peak hour of traffic. The study also compares VMIMD generated EFs, and ARAI developed EFs and found a significant difference between emissions especially during peak hours. The ARAI developed EFs fail to consider the impact of real-world driving conditions. Further, the effect of fuel type on emission has also been evaluated in the study. The contributions of HC and CO pollutants are mainly from petrol-fuelled vehicles; while NO_x and PM_{2.5} are primarily contributed by diesel-fuelled vehicles. Additionally, CNG vehicles have also been found to contribute substantially to the levels of HC, CO, and NO_x emissions.

Further, the dispersion analysis of pollutants has been performed by using Gaussian based dispersion model, AERMOD. During winter months, the pollutants concentrations are found to be higher than summer months; besides, daytime, and night-time concentrations analysis have also been carried out. Temperature and wind speed have a positive impact on pollutant dispersion, while high relative humidity results in poor mixing and an increase in pollutant concentrations. Although, the maximum concentrations are observed at roadside near the source and most of the time the concentrations of pollutants are observed above the permissible limits. Moreover, the overall performance of integrated modelling approach has been evaluated by validating monitored (CPCB website) and predicted concentrations (using AERMOD) of

pollutants using statistical descriptors such as d, FB, NMSE, MG and VG. The statistical descriptors generally indicate satisfactory performance for both the summer and winter seasons.

सारांश

विश्व स्तर पर, वाहनों से होने वाले उत्सर्जन को शहरी क्षेत्रों में वायु प्रदूषण का मुख्य स्रोत माना जाता है। शहरीकरण की प्रवृत्ति के कारण निजी वाहनों के स्वामित्व में वृद्धि हुई है, विशेष रूप से महानगरीय शहरों जैसे दिल्ली, जो कि भारत में स्थित है, जिसके परिणामस्वरूप ऑटोमोबाइल क्षेत्र में उल्लेखनीय वृद्धि हुई है। इसके अतिरिक्त, पिछले एक दशक में दिल्ली में पड़ोसी राज्यों से बड़ी संख्या में लोग पलायन कर रहे हैं, जिससे परिवहन सुविधाओं की मांग बढ़ गई है। वाहनों की बढ़ती संख्या का ईंधन की अधिक खपत और यातायात की भीड़ में वृद्धि के कारण वायु प्रदूषण पर सीधा प्रभाव पड़ता है। भीड़भाड़ वाली सड़कों पर वाहनों की गतिविधि, जिसमें अचानक तेजी और मंदी शामिल है, उत्सर्जन को महत्वपूर्ण रूप से प्रभावित करती है। परिणामस्वरूप, नियमित प्रदूषण शमन की योजनाओं को विकसित करने में वाहन उत्सर्जन का सटीक अनुमान महत्वपूर्ण है।

वर्तमान अध्ययन में, उत्सर्जन माप के विश्लेषण के लिए दिल्ली शहर के भारी यातायात वाले सड़क जंक्शन पर अध्ययन केंद्रित किया है, जिसमें एक मध्य-ब्लॉक सिग्नलयुक्त चौराहा भी शामिल है। विगत वर्षों में कई मॉडलिंग अध्ययनों ने पूरे सड़क खंडों के लिए वाहन की औसत गति का उपयोग किया है जिसके परिणामस्वरूप उत्सर्जन का अनुमान कम हुआ है। VMIMD (दिल्ली शहर के लिए VISSIM-MOVES इंटीग्रेशन मॉडल) नामक एक एकीकृत मॉडलिंग

सरंचना विकसित करके वाहन परिचालन विशेषताओं जैसे अंतर- और अन्तः वाहनों की परिवर्तनशीलता, ड्राइविंग व्यवहार और यातायात स्थितियों के बीच संबंधों की जांच की गई है। मॉडलिंग सरंचना VMIMD, VISSIM (यातायात प्रवाह सिमुलेशन) और MOVES (उत्सर्जन) मॉडल के बीच एक अंतरापृष्ठ के रूप में कार्य करता है, जो VSP (वाहन विशिष्ट शक्ति) और गति को एक मध्यवर्ती मापदण्ड के रूप में विचार करके प्रेषण स्थिति-आधारित उत्सर्जन कारकों (EFs) को मापने में सहयोग करता है। भारत के उत्सर्जन मानकों के लिए विशेष रूप से विकसित सुधार कारकों का उपयोग करके MOVES, default उत्सर्जन की सूची का संशोधन भी इस अध्ययन में किया गया है। इस संशोधन के परिणामस्वरूप अधिक सटीक उत्सर्जन अनुमान प्राप्त हुए हैं, और भारतीय परिस्थितियों के लिए मॉडल की समग्र दक्षता में सुधार हुआ है।

परिणामों का विश्लेषण प्रत्येक परिचालन स्थिति (निष्क्रिय, परिभ्रमण और ब्रेक लगाना) और उत्सर्जन प्रक्रिया में बिताए गए समय के बीच एक मजबूत संबंध दिखाता है। **व्यस्त** यातायात घंटों के दौरान, ब्रेकिंग/मंदी में वितरण का प्रतिशत सबसे अधिक होता है जिससे वाहनों की गति कम हो जाती है और वाहन की मोटर शक्ति की मांग बढ़ जाती है। परिणामस्वरूप, जैसे ही वाहन क्रूज़िंग मोड से ब्रेकिंग मोड में स्थानांतरित होते हैं, उत्सर्जन बहुत तेज़ी से बदलता है। अध्ययन में पाया गया है कि कुल यातायात सरंचना का एक छोटा अनुपात होने के बावजूद, भारी वाहन और बसें अन्य प्रकार के वाहनों की तुलना में गति में भिन्नता के प्रति अधिक

संवेदनशील हैं। HC, CO, NO_x और PM_{2.5} प्रदूषकों के लिए उत्सर्जन कारकों की दैनिक भिन्नता का विश्लेषण करके उत्सर्जन पर भारी यातायात भीड़ का प्रभाव अध्ययन दौरान पाया गया है। सभी प्रदूषक 0900 से 1100 बजे तक उच्चतम उत्सर्जन स्तर दिखाते हैं, जो यातायात का चरम समय होता है। अध्ययन में VMIMD द्वारा उत्पन्न उत्सर्जन कारक और ARAI द्वारा विकसित उत्सर्जन कारक की भी तुलना की गई और विशेष रूप से अति व्यस्त समय के दौरान उत्सर्जन के बीच महत्वपूर्ण अंतर पाया गया। ARAI द्वारा विकसित उत्सर्जन कारक वास्तविक दुनिया की ड्राइविंग स्थितियों के प्रभाव पर विचार करने में विफल रहते हैं। इसके अलावा, अध्ययन में उत्सर्जन पर ईंधन के प्रकार के प्रभाव का भी मूल्यांकन किया गया है। HC और CO प्रदूषकों का योगदान मुख्य रूप से पेट्रोल-ईंधन वाले वाहनों से होता है; जबकि NO_x और PM_{2.5} का योगदान मुख्य रूप से डीजल-ईंधन वाले वाहनों द्वारा होता है। इसके अतिरिक्त, CNG वाहनों को HC, CO, NO_x के उत्सर्जन स्तर में भी महत्वपूर्ण योगदान देते पाया गया है।

इसके अलावा Gaussian आधारित प्रसार मॉडल, AERMOD का उपयोग करके प्रदूषकों का वायु में प्रसार का विश्लेषण भी किया गया है। सर्दियों के महीनों के दौरान, प्रदूषकों की सांद्रता गर्मियों के महीनों की तुलना में अधिक पाई जाती है; इसके अलावा, दिन और रात के समय की सांद्रता का विश्लेषण भी किया गया है। तापमान और हवा की गति का प्रदूषक के प्रसार पर सकारात्मक प्रभाव पड़ता है, जबकि उच्च सापेक्ष आर्द्रता के परिणामस्वरूप वायु में प्रदूषकों

का प्रसार बाध्य होता है और प्रदूषक सांद्रता में वृद्धि होती है। हालाँकि, अध्ययन के दौरान अधिकतम सांद्रता स्रोत के पास सड़क किनारे देखी गयी है और अधिकांश समय प्रदूषकों की सांद्रता अनुमेय सीमा से ऊपर पायी गई है। इसके अलावा, एकीकृत मॉडलिंग दृष्टिकोण के समग्र प्रदर्शन का मूल्यांकन d, FB, NMSE, MG और VG जैसे सांख्यिकीय विवरणों का उपयोग करके प्रदूषकों की परिविक्षित सांद्रता (CPCB वेबसाइट) और अनुमानित सांद्रता (AERMOD का उपयोग करके) की तुलना करके किया गया है। अध्ययन के दौरान सामान्यतः सभी सांख्यिकीय विवरक गर्मी और सर्दी दोनों मौसमों के लिए संतोषजनक प्राप्त हुए हैं।

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS.....	ii
ABSTRACT.....	iv
TABLE OF CONTENTS.....	vii
LIST OF FIGURES	xi
LIST OF TABLES.....	xvi
ABBREVIATIONS	xviii
 Chapter 1 Introduction	 1
1.1 Background	1
1.2 Need of the study.....	8
1.3 Scope of the study	10
1.4 Objectives of the Study	10
1.5 Thesis Outline	10
 Chapter 2 Vehicular air pollution	 12
2.1 Vehicular pollution in Delhi.....	12
2.1.1 Scenario of vehicular pollutants in Delhi city.....	15
2.1.2 Implemented mitigation policies.....	17
2.2 Factor affecting vehicular air pollution.....	22
2.2.1 Vehicle characteristics	22
2.2.2 Vehicle operating characteristics	23
2.2.3 Driving behaviour	24
2.2.4 Traffic flow characteristics	24
2.2.5 Road Characteristics	25

2.2.6	Environmental parameters	26
2.3	Health effect of vehicular air pollution	26
Chapter 3 Review of literature		30
3.1	Vehicular emission measurement studies	30
3.1.1	Remote Sensing	32
3.1.2	Plume Chase.....	33
3.1.3	Tunnel measurement.....	33
3.1.4	Portable emission measurement system (PEMS)	35
3.2	Vehicular exhaust emission models	37
3.2.1	Average speed-based models	38
3.2.2	Instantaneous speed models	39
3.2.3	Multi-scale models.....	41
3.3	Traffic flow simulation models	46
3.3.1	Macroscopic models	47
3.3.2	Microscopic models	50
3.3.3	Mesosopic models	53
3.4	Line source dispersion models	58
3.4.1	Deterministic models	58
3.4.2	Stochastic based models	62
3.5	Integrated modelling approach.....	67
3.6	Summary	74
Chapter 4 Methodology and modelling approach.....		77
4.1	Site selection and description.....	77
4.2	Data acquisition.....	81

4.2.1	Traffic data collection	82
4.2.2	Age and fuel distribution of vehicles	86
4.2.3	Road geometry and signalling	87
4.2.4	Descriptive analysis of air pollutants	88
4.3	Traffic flow simulation model: VISSIM	92
4.3.1	Road network formation in VISSIM	92
4.3.2	Calibration of VISSIM model	94
4.3.3	Model validation	97
4.4	Emission model: MOVES	99
4.4.1	MOVES Modelling setup	99
4.4.2	Vehicle specific power (VSP)	104
4.4.3	Operating mode ID	106
4.5	VISSIM-MOVES Integration Model for Delhi city (VMIMD)	107
4.6	Dispersion model: AERMOD	109
Chapter 5 Result and Discussions		110
5.1	Characterisation of vehicle activity data	110
5.1.1	Traffic flow simulations	111
5.1.2	Instantaneous speed and acceleration/deceleration	115
5.2	Incorporation of simulated vehicle trajectory data into MOVES	118
5.2.1	VSP distribution	119
5.2.2	Generation of operating mode distribution	122
5.2.3	Modification of default emission inventory by applying correction factor	131
5.3	Emission load estimation by MOVES model	134
5.3.1	Speed dependent EF	134
5.3.2	Correlation between EFs and average speed of vehicles	136

5.3.3	Hourly variation in EFs for different vehicle categories	143
5.3.4	Weekend and weekday emission variation	146
5.3.5	Comparison between modelled EFs and emission standards	149
5.3.6	Fuel based pollutant contribution.....	156
5.3.7	Comparison of EFs with previous Indian studies	157
5.4	Dispersion modelling	160
5.4.1	Meteorological parameters and air quality	160
5.4.2	AERMOD result analysis	167
5.4.3	Performance evaluation and validation.....	170
Chapter 6 Conclusions		176
6.1	Summary	176
6.2	Contribution of the present study	180
6.3	Scope for future work.....	181
REFERENCES		184
APPENDIX I Descriptive Statistics.....		226
APPENDIX II Models descriptions.....		228
APPENDIX III Supplementary Data		234
APPENDIX IV Default data modification in MOVES		239
APPENDIX V VMIMD Code		241
APPENDIX VI Background Concentration		244
APPENDIX VII Statistical descriptors		245
Curriculum Vitae		247

LIST OF FIGURES

Figure 1.1 Global, CO ₂ emission from transport sector.....	3
Figure 1.2 Distribution of road network in India.....	4
Figure 1.3 Growth of registered vehicle with road length.....	5
Figure 1.4 Category wise vehicle distribution in India.....	6
Figure 1.5 Status of registered vehicle in million plus cities.....	6
Figure 1.6 Percentage emissions contribution from different vehicle categories in India.....	8
Figure 2.1 Vehicular growth in Delhi.....	13
Figure 2.2 Summary of emission loads contribution by various sources in Delhi	14
Figure 2.3 Percentage wise vehicle distribution in year 2019-2020.....	14
Figure 2.4 Emission load contribution by vehicle category	17
Figure 2.5 Locations of air quality monitoring station in Delhi	18
Figure 2.6 Speed vs Accessibility.....	25
Figure 2.7 Short- and long-term effects of vehicular emission	27
Figure 2.8 Size distribution of particulate matter	28
Figure 3.1 (a) Eulerian grid, (b) Lagrangian grid	48
Figure 3.2 Integrated traffic emission modelling framework	69
Figure 3.3 Literature review framework and classification of models	76
Figure 4.1 Location map of Delhi city and study site.....	79
Figure 4.2 Study location near CRRI gate	79
Figure 4.3 Research methodology framework.....	80

Figure 4.4 Traffic volume count survey	83
Figure 4.5 Diurnal traffic flow for both days.....	83
Figure 4.6 Fleet wise diurnal traffic flow for (a) Weekday and (b) Weekend.....	85
Figure 4.7 Fuel Distribution of vehicles	87
Figure 4.8 Layout of Mid-block road section	88
Figure 4.9 Box plot and histogram of CO, NO _x and PM _{2.5} concentration for summer period	90
Figure 4.10 Box plot and histogram of CO, NO _x and PM _{2.5} concentration for winter period	91
Figure 4.11 Road network generated in VISSIM for study site	93
Figure 4.12 Simulation process in 2D and 3D animation.....	93
Figure 4.13 Framework for traffic simulation model calibration	95
Figure 4.14 VMIMD framework	108
Figure 4.15 Flowchart of data processing in AERMOD model	109
Figure 5.1 Comparison of simulated (calibrated and default) and observed traffic flow for weekday	112
Figure 5.2 Comparison of simulated (calibrated and default) and observed traffic flow for weekend	113
Figure 5.3 Linear regression between observed and simulated traffic flow for weekday and weekend	115
Figure 5.4 Simulated speed and acceleration profile of individual vehicle.....	116
Figure 5.5 Average speed versus distance during (a) Peak hour and (b) Non-peak hour.....	117
Figure 5.6 Comparison of VSP distribution for peak and non-peak hour	120
Figure 5.7 Comparison of VSP distribution for peak and non-peak hour	121

Figure 5.8 Percentage distribution of opModeID for (a) 0100-0200 hrs, (b) 0200-0300 hrs, (c) 0300-0400 hrs and 0400-05000 hrs	125
Figure 5.9 Percentage distribution of opModeID for (a) 0500-0600 hrs, (b) 0600-0700 hrs, (c) 0700-0800 hrs and 0800-0900 hrs	126
Figure 5.10 Figure 5.10 Percentage distribution of opModeID for (a) 0900-1000 hrs, (b) 1000-1100 hrs, (c) 1100-1200 hrs and 1200-1300 hrs.....	127
Figure 5.11 Percentage distribution of opModeID for (a) 1300-1400 hrs, (b) 1400-1500 hrs, (c) 1500-1600 hrs and 1600-1700 hrsFi.....	128
Figure 5.12 Percentage distribution of opModeID for (a) 1700-1800 hrs, (b) 1800-1900 hrs, (c) 1900-2000 hrs and 2000-2100 hrs	129
Figure 5.13 Percentage distribution of opModeID for (a) 2100-2200 hrs, (b) 2200-2300 hrs, (c) 2300-2400 hrs and 2400-0100 hrs	130
Figure 5.14 Correction factor development methodology	132
Figure 5.15 Diurnal variation between speed and EFs of (a) HC, (b) CO, (c) NO _x and (d) PM _{2.5}	135
Figure 5.16 Correlation between average speed and relative EFs of HC for (a) 2W, (b) 3W, (c) 4W, (d) LCV, (e) HCV and (f) Bus.....	138
Figure 5.17 Correlation between average speed and relative EFs of CO for (a) 2W, (b) 3W, (c) 4W, (d) LCV, (e) HCV and (f) Bus.....	139
Figure 5.18 Correlation between average speed and relative EFs of NO _x for (a) 2W, (b) 3W, (c) 4W, (d) LCV, (e) HCV and (f) Bus.....	140
Figure 5.19 Correlation between average speed and relative EFs of PM _{2.5} for (a) 2W, (b) 3W, (c) 4W, (d) LCV, (e) HCV and (f) Bus	141
Figure 5.20 Vehicle based hourly EFs of (a) HC, (b) CO, (c) NO _x and (d) PM _{2.5}	145
Figure 5.21 Weekday and weekend emission variation of pollutants for winter season	147

Figure 5.22 Weekday and weekend emission variation of pollutants for summer season	148
Figure 5.23 Comparison of modelled EFs and emission standards for 2Ws and 3Ws (a) HC, (b) CO, (c) NO _x and (d) PM _{2.5}	151
Figure 5.24 Comparison of modelled EFs and emission standards for 4Ws (a) HC, (b) CO, (c) NO _x and (d) PM _{2.5}	152
Figure 5.25 Comparison of modelled EFs and emission standards for LCVs (a) HC, (b) CO, (c) NO _x and (d) PM _{2.5}	153
Figure 5.26 Comparison of modelled EFs and emission standards for Buses (a) HC, (b) CO, (c) NO _x and (d) PM _{2.5}	154
Figure 5.27 Comparison of modelled EFs and emission standards for HCVs (a) HC, (b) CO, (c) NO _x and (d) PM _{2.5}	155
Figure 5.28 Emission contribution based on fuel	156
Figure 5.29 Diurnal variation of CO with temperature, relative humidity, and wind speed during (a) Summer and (b) Winter season.....	162
Figure 5.30 Diurnal variation of NO _x with temperature, relative humidity, and wind speed during (a) Summer and (b) Winter season.....	163
Figure 5.31 Diurnal variation of PM _{2.5} with temperature, relative humidity, and wind speed during (a) Summer and (b) Winter season.....	164
Figure 5.32 Wind class frequency distribution and wind rose diagram for summer season .	165
Figure 5.33 Wind class frequency distribution and wind rose diagram for winter season	166
Figure 5.34 AERMOD output of CO during (a) Summer and (b) Winter.....	167
Figure 5.35 AERMOD output of NO _x during (a) summer and (b) winter.....	168
Figure 5.36 AERMOD output of PM _{2.5} during (a) summer and (b) winter.....	169
Figure 5.37 Monitored and predicted concentration of CO pollutant during (a) Summer and (b) Winter season	172

Figure 5.38 Monitored and predicted concentration for NO _x pollutant during (a) Summer and (b) Winter season	173
---	-----

Figure 5.39 Monitored and predicted concentrations for PM _{2.5} pollutant during (a) Summer and (b) Winter season	174
--	-----

LIST OF TABLES

Table 1.1 Consumption pattern of petroleum products in India	3
Table 2.1 Summary of various mitigation strategies implemented in Delhi	20
Table 2.2 Revised NAAQM standards (2009).....	28
Table 2.3 Sources and major effects of vehicular air pollution	29
Table 3.1 Summary of emission models.....	44
Table 3.2 Summary and application of traffic flow simulation models	55
Table 3.3 Summary of features and limitations of various line source models.....	65
Table 3.4 Integrated modelling studies.....	70
Table 4.1 Input data required for the study.....	81
Table 4.2 Comparison of traffic fleet distribution	84
Table 4.3 Percentage wise age distribution of vehicles	86
Table 4.4 Statistics of 1-hour average pollutants concentration for summer and winter periods	89
Table 4.5 List of selected parameters	95
Table 4.6 Parameters with ANOVA results.....	96
Table 4.7 Calibrated values of sensitive parameters.....	97
Table 4.8 VISSIM model validation results	98
Table 4.9 MOVES default vehicle type (source type).....	100
Table 4.10 Summary of BS-IV and MOVES default fuel characteristics	102
Table 4.11 Characteristics of source use type.....	105
Table 4.12 List of operating mode ID.....	106

Table 5.1 Statistical analysis of observed and simulated traffic flow.....	114
Table 5.2 Illustration of MOVES default EFs, BS-IV standards, and CFs	133
Table 5.3 Vehicle wise speed-dependent fitting functions for EFs of HC, CO, NO _x and PM _{2.5} with correlation coefficient	142
Table 5.4 Comparison of estimated EFs with previous studies from India	158
Table 5.5 Statistical descriptor for one hour average concentration.....	171

ABBREVIATIONS

ABL	Atmospheric Boundary Layer
ADMS	Atmospheric Dispersion Modeling System
AEMS	Aerosol Emission Measurement System;
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
AIMSUN	Advanced Interactive Microscopic Simulation Model
ANFIS	Adaptive Beuro-Fuzzy Inference System
ANN	Artificial Neural Networks
ANOVA	Analysis of Variance
AOD	Aerosol Optical Depth
ARAI	Automotive Research Association of India
ARIMA	Autoregressive Integrated Moving Average
AVFT	Alternate Vehicle and Fuel Technology
BS	Bharat Stage
C ₂ H ₄ O	Acetaldehyde
C ₄ H ₆	1,3-Butadiene
C ₆ H ₆	Benzene
C ₈ H ₂₀ Pb	Tetraethyl lead
CALINE	California Line Source
CAR	Calculation of Air Pollution from Road Traffic
CARB	California Air Resource Board
CARSIM	Car-following model
CF	Correction Factor
CH ₂ O	Formaldehyde
CH ₄	Methane
CMEM	Comprehensive Modal Emissions Model
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO ₂	Carbon-di-oxide
CONTRAM	Continuous Traffic Assignment Model
COPERT	Computer Program for Estimating Emissions from Road Transport

CORFLO	Corridor Flow model
CORQ	Corridor Queuing
CORSIM	Corridor Simulation Model
COVID-19	Coronavirus
CPCB	Central Pollution Control Board
CRRI	Central Road Research Institute
DFLSM	Delhi Finite Line Source Model
DPCC	Delhi Pollution Control Committee
DYNAMIT	Dynamic Network Assignment Management of Information to Travelers
DYNASMART	Dynamic Network Assignment-Simulation Model for Advanced Road Telematics
DYNEMO	Dynamic Network Modeler
EEA	European Environment Agency
EF	Emission Factor
EMPA	Eidgenössische Materialprüfungs- und Forschungsanstalt (Swiss Federal Laboratories for Materials Science and Technology)
EPCC	Edinburgh Parallel Computing Centre
FHWA	Federal Highway Administration
FHWA	Federal Highway Administration
FLT	Fuzzy Logic Theory
FMI	Finish Meteorological Institute
FORTTRAN	Formula Translation
FREFLO	Freeway Flow
FRESIM	Freeway Simulation Model
FTP	Federal Test Procedure
FTP	Federal Test Procedure
GA	Genetic Algorithm
GEH	Geoffrey E. Heaver
GFSLM	General Finite Line Source Model
GLO	Ground Level Ozone
GM	General Motors
GRAL	Graz Lagrange Model

GRAL	Graz Lagrange Model
GRAP	Graded Response Action Plan
HC	Hydrocarbon
HCN	Hydrogen Cyanide
HCV	Heavy Commercial Vehicle
HDV	Heavy Duty Vehicle
I/M	Inspection and maintenance
IDC	Indian Driving Cycle (IDC)
IITLS	IIT Line Source model
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
INRETS	The French National Institute for Transport and Safety Research
INTRAS	Interactive Network for Traffic Analysis and Simulation
IR	Infrared
ISBT	Inter State Bus Terminus
ISC3	Industrial Source Complex Model
ITS	Institute of Transportation Studies
ITS	Institute for Transport Studies
IVE	International Vehicle Emissions
LCV	Light Commercial Vehicle
LDV	Light Duty Vehicle
LHS	Latin Hypercube Sampling
LPG	Liquefied Petroleum Gas
LWR	Lighthill-Whitham and Richards
MAPE	Mean Absolute Percentage Error
METANET	Modèle d'écoulement du trafic sur autoroutes (Traffic Flow Model on Transport Networks)
MIT	Massachusetts Institute of Technology
MODEM	Modeling of Emissions and Consumption
MoRTH	Ministry of Road Transport & Highways
MOVES	Motor Vehicle Emission Simulator
N ₂ O	Nitrous Oxide
NAAQS	National Ambient Air Quality Standards

NCR	National Capital Region
NCT	National Capital Territory
NETFLO	Network Traffic Flow
NETSIM	Network Simulation
NH	National Highway
NH ₃	Ammonia
NMVOC	Non-methane Volatile Organic Compound
NO	Nitric Oxide
NO ₂	Nitrogen dioxide
NO _x	Oxides of Nitrogen
NRC	National Research Council
O ₃	Ozone
OD	Origin-Destination
OMD	Operating Mode Distribution
PAH	Polycyclic Aromatic Hydrocarbons
PARAMICS	Parallel Microscopic Traffic Simulator
Pb	Lead
PBL	Planetary Boundary Layer
PCRA	Pollution Conservation Research Association
PCs	Personal Cars
PDF	Probability Density Function
PEMS	Portable Emission Measurement System
PHEM	Passenger Car and Heavy-Duty Emission Model
PM ₁₀	Particulate Matter with diameter less than 10 microns
PM _{2.5}	Particulate Matter with diameter less than 2.5 microns
PTV	Planung Transport Verkehr (Planning Transport Traffic)
RMSE	Root Mean Square Error
SAFAR	System of Air Quality and Weather Forecasting and Research
SATURN	Simulation and Assignment of Traffic in Urban Road Network
SCOT	Simulation of Corridor Traffic
SF ₆	Sulphur hexafluoride
SO ₂	Sulfur dioxide
SO ₃	Sulphur trioxide

TGM	Total Gaseous Mercury
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzo (Netherlands Organisation for Applied Scientific Research)
TRANSYT	Traffic Network Study Tool
TRL	Transport Research Laboratory
TRRL	Transport and Road Research Laboratory
TUM	Technical University of Munich
TÜV	Technical Inspection Association
UC	University of California
UC	University of California
UCR	University of California Riverside
UF	University of Florida
UK	United Kingdom
UMTRI	University of Michigan Transportation Research Institute
UPC	Universitat Politecnica de Catalunya (Polytechnic University of Catalonia)
USA	United States of America
USEPA	United States Environmental Protection Agency
UTCS	Urban Community Simulation
UV	Ultra-violate
VAPI	Vehicular Air Pollution Emission Inventory
VISSIM	Verkehr In Städten–SIMulationsmodell (Traffic in Cities - Simulation Model)
VKT	Vehicle Kilometres Travelled
VMIMD	VISSIM-MOVES Integration Model for Delhi city
VOCs	Volatile Organic Compounds
VSP	Vehicle Specific Power
VT-Micro	Virginia Tech Microscopic vehicle fuel consumption and emission
WATSIM	Wide Area Traffic Simulation Model
WEAVSIM	Weaving sections model
WHO	World health organization
WRF	Weather Research and Forecasting