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

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

by

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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.

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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 योजनाओ 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 घंटो 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 प्रदूषको

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 विवरणकों 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 है।

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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_2H_4O	Acetaldehyde
C_4H_6	1,3-Butadiene
C_6H_6	Benzene
$C_8H_{20}Pb$	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_2O	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
FORTRAN	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 traffic 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_2O	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-Destinantion
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 Politechnica 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