

**EMISSIONS OF AEROSOL AND GASES FROM ON-ROAD
LIGHT DUTY VEHICLES**

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

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by

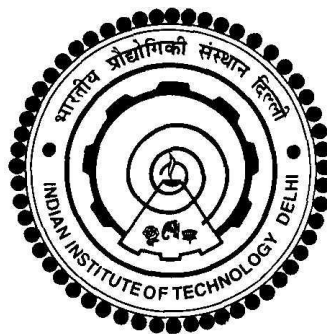
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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2017

Dedicated to

**My Father (Shukhdeo Prasad)
&
My Beloved Daughter (Navya)**

CERTIFICATE

This is to certify that the thesis entitled “**Emissions of Aerosol and Gases from On-Road Light Duty Vehicles**” being submitted by **Mr. Jai Prakash** to the **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy** is a record of the original bonafide research work carried out by him under my guidance and supervision. The thesis work, in my opinion, has reached the requisite standards fulfilling the requirement for the Degree of Doctor of Philosophy.

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

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Jai Prakash

ABSTRACT

This study reports the design and evaluation of portable dilution system (PDS) for emission measurement of stationary and mobile sources. The PDS consists of portable dilution tunnel, heated duct and particle sampling probe, zero air assembly, multi-stream particle sampler, flue gas analyzer, relative humidity and temperature sensors, vane probe velocity meter and power supply unit. The system mounted on trolley was used for measurement of aerosol and gaseous pollutants during on-road operation of light duty vehicles powered by diesel, gasoline, and compressed natural gas (CNG). The vehicles were selected on the basis of Bharat Stage categories-II, III, and IV. The distance and fuel based emission factors of climate relevant pollutants including organic and elemental carbon, water soluble ions, trace elements, and gaseous pollutants (CO, CO₂, and NO_x) have been presented in this work. The PDS evaluated under controlled laboratory condition showed complete quenching of aerosol at near ambient condition for dilution ratios below 70:1 for light duty vehicle. Homogenous mixing and insignificant particle loss in the range of 5-19% were observed in the dilution system. On-road diesel passenger cars emitted high PM_{2.5} ranging from 56 to 356 mg km⁻¹ composed of large EC fraction (37-65%), while emissions from gasoline and CNG vehicles were observed as 46-78 mg km⁻¹ and 33-34 mg km⁻¹ respectively contained low EC (5-15%) and remarkably high OC (46-91%). The mass absorption cross sections (MAC) of aerosol at 880 nm were estimated in the range of 1.2 to 4.2 m²g⁻¹ of PM_{2.5} for diesel vehicles and were well explained by EC content of the aerosol samples. MAC for diesel vehicles showed similarity with values reported for wood fuel combustion in cooking stove indicating the two sources cannot be resolved on the basis of light absorption properties alone in source apportionment studies. The emissions from vehicles showed strong dependency on acceleration/deceleration, vehicle maintenance, engine type, and after-treatment technique. The national level emissions of aerosol and

gaseous pollutants (CO, CO₂, and NO_x) were estimated using new emission factors and fuel use data. The PM_{2.5}, EC, and OC emissions from the on-road transport sector for the base year 2013 contributed 7%, 17%, and 6% of total emissions from India. On-road transport is the second largest source of EC in the Indian region. The high emission fluxes of EC were observed over golden quadrilateral road network where heavy duty diesel vehicles dominate the on-road fleet. On the other hand OC emission fluxes shaded the regions with dense urban road network where relatively higher efficiency vehicles of gasoline and CNG rule the traffic density. The new emission estimates have implications in improving uncertainty bound in regional climate assessment through climate models.

सार

यह अध्ययन स्थिर और मोबाइल स्रोतों के उत्सर्जन माप के लिए पोर्टेबल डिल्यूशन सिस्टम (पीडीएस) के डिजाइन और मूल्यांकन की रिपोर्ट करता है। पीडीएस में पोर्टेबल डिल्यूशन टनेल, तप्त वाहिका और कण नमूनाकरण जांच, शून्य हवा असेंबली, मल्टी-स्ट्रीम कण सैंपलर, फ्ल्यू गैस विश्लेषक, सापेक्षिक आर्द्रता और तापमान सेंसर, वेग मीटर और बिजली आपूर्ति इकाई शामिल हैं। डीजल, गैसोलीन और कॉम्प्रेस्ड नैसर्गिक गैस (सीएनजी) द्वारा संचालित हल्की ड्यूटी वाहनों के ऑन-रोड ऑपरेशन के दौरान ट्रॉली पर लगाए गए सिस्टम को एरोसोल और गैसीय प्रदूषण के माप के लिए उपयोग किया गया था। वाहनों को भारत स्टेज श्रेणियों- II, III, और IV के आधार पर चुना गया था। इस काम में कार्बनिक और मौलिक कार्बन, पानी में घुलनशील आयनों, धातुओं, और गैसीय प्रदूषण (कार्बन मोनोऑक्साइड, कार्बन डाइऑक्साइड, और नाइट्रोजन आक्साइड) सहित जलवायु से संबंधित प्रदूषक की दूरी और ईंधन आधारित उत्सर्जन कारकों को प्रस्तुत किया गया है। नियंत्रित प्रयोगशाला की स्थिति के तहत मूल्यांकन किया गया पीडीएस ने प्रकाश ड्यूटी वाहन के लिए 70: 1 के नीचे डिल्यूशन अनुपात के लिए निकट परिवेश की स्थिति में एरोसोल की पूरी शमन को दिखाया। डिल्यूशन प्रणाली में घुलनशील मिश्रण और 5-19% की सीमा में कमजोर कण हानि देखी गई थी। ऑन-रोड डीजल यात्री कारों में बड़े मौलिक कार्बन अंश (37-65%) से बना 56-26 एमजी किमी⁻¹ से लेकर पीएम_{2.5} की उच्च मात्रा उत्सर्जित होती है, जबकि गैसोलीन और सीएनजी वाहनों के उत्सर्जन को 46-78 मिलीग्राम किमी⁻¹ के रूप में मनाया जाता था क्रमशः 33-34 मिलीग्राम किमी⁻¹ कम ईसी (5-15%) और उल्लेखनीय उच्च जैविक कार्बन (46-91%) 880 एनएम पर एरोसोल के बड़े पैमाने पर अवशोषण पार अनुभाग (एमएसी) डीजल वाहनों के लिए पीएम_{2.5} के 1.2 से 4.2 एम² जी⁻¹ की सीमा में अनुमानित थे और एरोसोल नमूनों की मौलिक कार्बन सामग्री द्वारा अच्छी तरह समझाया गया था। डीजल वाहनों के लिए एमएसी ने स्टूडिंग में लकड़ी ईंधन के दहन के लिए रिपोर्ट किए गए मूल्यों के साथ समानता दिखायी है, जो दर्शाता है कि दो स्रोतों को स्रोत विभाज्य अध्ययन में अकेले प्रकाश अवशोषण गुणों के आधार पर हल नहीं किया जा सकता है। वाहनों के उत्सर्जन में त्वरण / मंदी, वाहन रखरखाव, इंजन प्रकार, और उपचार के बाद तकनीक पर मजबूत निर्भरता दिखाई गई। एरोसोल और गैसीय प्रदूषण (कार्बन मोनोऑक्साइड, कार्बन डाइऑक्साइड, और नाइट्रोजन

आक्साइड) का राष्ट्रीय स्तर का उत्सर्जन नए उत्सर्जन कारकों और ईंधन के उपयोग के डेटा का उपयोग कर अनुमान लगाया गया था। आधार वर्ष 2013 के लिए ऑन-रोड परिवहन से पीएम2.5, मौलिक कार्बन और जैविक कार्बन उत्सर्जन, भारत से कुल उत्सर्जन में 7%, 17%, और 6% योगदान दिया। भारतीय क्षेत्र में ऑन-रोड परिवहन मौलिक कार्बन का दूसरा सबसे बड़ा स्रोत है। मौलिक कार्बन के उच्च उत्सर्जन फ्लक्स सुनहरा चतुर्भुज सड़क नेटवर्क पर निरीक्षण किया जहां भारी शुल्क वाले डीजल वाहनों पर सड़क के बेड़े पर हावी है। दूसरी ओर, जैविक कार्बन उत्सर्जन फ्लक्स ने घने शहरी सड़क नेटवर्क वाले क्षेत्रों को छायांकित किया, जहां गैसोलीन की अपेक्षाकृत उच्च दक्षता वाले वाहन और सीएनजी नियम यातायात घनत्व पर शासन करते हैं। जलवायु उत्सर्जन के माध्यम से क्षेत्रीय जलवायु मूल्यांकन में बाध्य अनिश्चितताओं को सुधारने में नए उत्सर्जन के अनुमानों का असर है।

TABLE OF CONTENTS

CERTIFICATE.....	i
ACKNOWLEDGEMENTS.....	ii
ABSTRACT.....	iii
LIST OF FIGURES	ix
LIST OF TABLES.....	xiii
LIST OF ABBREVIATIONS.....	xv
Chapter 1 Introduction.....	1
1.1 Background and Motivation.....	1
1.2 Objectives.....	4
1.3 Thesis Organization.....	5
Chapter 2 Aerosol Emissions from Vehicles and Climate Effects.....	7
2.1 Introduction.....	7
2.2 Climate Impact of Aerosol.....	8
2.3 Aerosol and Gaseous Emission Estimates from On-road Vehicles in India.....	11
2.4 Dilution Sampling Methods: Aerosol Measurement Technique.....	15
2.5 Summary.....	17
Chapter 3 Development and Evaluation of Portable Dilution System.....	18
3.1 Introduction.....	18
3.2 Methodology.....	20
3.2.1 Details of Portable Dilution System.....	20
3.3 Experiment Procedure.....	23
3.3.1 Determination of Particle loss.....	23
3.3.2 Gasifier Exhaust Measurement.....	24
3.3.3 Diesel Vehicle Emission Measurement.....	28

3.4	Chemical Characterization of Aerosol	30
3.4.1	Organic and Elemental Carbon Analysis	30
3.4.2	Water Soluble Ions Analysis	31
3.4.3	Trace Elements Analysis	31
3.5	Effect of Dilution on Aerosol Number and Volume Concentration.....	32
3.6	Mixing Performance of Dilution Tunnel	33
3.7	Effect of Dilution Ratio on Aerosol Mass and Chemical Species.....	38
3.7.1	PM _{2.5} Emission Factors	38
3.7.2	Effect of Dilution on Elemental and Organic Carbon.....	42
3.7.3	Water Soluble Ions and Trace Metals	45
3.8	Summary.....	48
Chapter 4 Emissions of Aerosol and Gaseous Pollutants from Light Duty Vehicles		50
4.1	Introduction.	50
4.2	Material and Methods.....	51
4.2.1	On-road Experimental Set-up	51
4.2.2	PM _{2.5} and its Gravimetric, Chemical and Optical characterization	60
4.3	Vehicle Driving Profile	63
4.4	Chemical and Optical Properties of Aerosol	65
4.4.1	Emission Factor of PM _{2.5} and its Chemical Constituents	65
4.4.1.1	Emission Factors of Elemental Carbon	72
4.4.1.2	Emission Factors of Organic Carbon	78
4.4.1.3	EC/OC Ratio.....	81
4.4.1.4	Emission Factors of Water Soluble Ions	82
4.4.1.5	Emission Factors of Trace Elements	86
4.4.1.6	Correlation among Chemical Species of PM _{2.5}	91
4.4.1.7	Mass Closure Assessment	97
4.4.2	Optical Properties of PM _{2.5}	98

4.5	Emissions of Gaseous Pollutants.....	100
4.5.1	Variation of Emission Rate with Speed	100
4.5.2	Emission Factors of CO	104
4.5.3	Emission Factors of CO ₂	106
4.5.4	Emission Factors of NO _x	111
4.6	Summary.....	112
Chapter 5 Emission Estimate for On-road Transport Sector of India		114
5.1	Introduction	114
5.2	Methodology.....	115
5.2.1	Emission Estimate.....	115
5.2.2	Fuel Use Estimates.....	116
5.2.2.1	Estimation of On-road Vehicles	116
5.2.3	Estimation of On-road Superemitters	119
5.2.4	Fuel Based Emission Factors of Aerosol and Gases.....	120
5.2.5	Emission Factors of Superemitters	121
5.2.6	Propagation of Uncertainties.....	122
5.3	On-road Vehicle Stock and Fuel Consumption.....	126
5.3.1	On-road Vehicle Stock and Traffic Volume	126
5.3.2	Estimates of Fuel Consumption	129
5.4	Emissions of Aerosol and Gases	130
5.4.1	Emissions of PM _{2.5} and Carbonaceous Aerosols	132
5.4.2	Comparison of Emission Estimate.....	138
5.4.3	Spatial Distribution of Aerosol Emissions using Activity-level Proxies.....	141
5.4.4	Emissions of Gaseous Pollutants	143
5.4.5	Comparison of Emission Estimates of Gases	150
5.4.6	Spatial Distribution of Gaseous Emissions.....	153

5.5 Summary.....	156
Chapter 6 Conclusions	157
6.1 Conclusions	157
6.2 Novelty of the Research	158
6.3 Scope of Future Work.....	159
References	161
Appendix A1	180
Appendix A2	183
Publications	190
Bio-Data	191

LIST OF FIGURES

Figure 2.1 Radiative forcing ($W m^{-2}$) due to pollutants for the period from pre-industrial (1750) to present (2011).	9
Figure 2.2 Mean radiative forcing ($mW m^{-2}$) due to aerosols and ozone from different sectors for India and China.	10
Figure 3.1 Schematic of dilution sampling system including dilution tunnel, duct, particle sampling probe, multi-stream particle sampler, zero air assembly, power supply unit.	22
Figure 3.2 Schematic diagram of experimental setup used for measuring number based particle loss in portable dilution system.	24
Figure 3.3 Experimental set-up for evaluation of dilution system in laboratory with emission from downdraft gasifier cookstove.	26
Figure 3.4 Points of measurement for evaluation of mixing performance of dilution tunnel in longitudinal and radial cross-sectional direction. All dimensions are in 'mm'.	27
Figure 3.5 Schematic diagram of multi-stream $PM_{2.5}$ sampler.	28
Figure 3.6 Experimental set-up for evaluation of a dilution system on chassis dynamometer for light duty diesel vehicle.	30
Figure 3.7 Total number and volume concentration of NaCl particles and change in concentration at different dilution ratios. The bars in plot 'a' and 'c' are showing total number and volume concentrations averaged from three experiments without dilution tunnel (WODT) and with dilution tunnel operated at different dilution ratios (30:1 to 90:1). The triangular legends indicate the change in number and volume concentrations due to the presence of dilution tunnel operated at different dilution ratios. The plot b and d show the normalized number and volume concentrations distribution without and with dilution tunnel operated at different dilution ratios.	34

Figure 3.8 Comparison of flow based and CO ₂ based dilution ratios in the dilution tunnel.	35
Figure 3.9 Variation of CO ₂ concentration measured in longitudinal direction at different points from the end of dilution tunnel in (a) gasifier cookstove and (b) diesel vehicle experiments.	36
Figure 3.10 Variation of CO ₂ concentration at different points in the radial direction measured in gasifier cookstove experiments conducted at different dilution ratios.	36
Figure 3.11 Variation of temperature, relative humidity and pressure drop in the longitudinal direction at different dilution ratios for (a) gasifier cook stove and (b) diesel vehicle. Error bars represent one standard deviation around mean of 4 measurements at each point.	37
Figure 3.12 Average PM _{2.5} emission factors and residence time for fuelwood combustion in gasifier cookstove.	39
Figure 3.13 PM _{2.5} emission factors and residence time for diesel vehicle experiments.	40
Figure 3.14 Variation in emission factors of elemental carbon, organic carbon and total carbon measured on quartz filters for gasifier cook stove experiments conducted at different dilution ratios. Q is the sum of front quartz (FQ) and backup quartz (QBQ), particulate OC is estimated as Q-QBT (quartz behind Teflon).	43
Figure 3.15 The variation of elemental carbon, organic carbon and total carbon with dilution ratios for light duty diesel vehicle. The error bars are estimated using maximum (25%) variation observed from repeated OC, EC measurements on quartz filter.	45
Figure 4.1 Schematic of aerosol emission measurement system (AEMS) for mobile sources.	52
Figure 4.2 Selected route for on-road operation of vehicle during emission measurement.	57

Figure 4.3 Comparison of on-road driving pattern from the present work and modified Indian Driving Cycle (MIDC).	64
Figure 4.4 Scatter plot of speed versus acceleration/deceleration of vehicle from on-road operation and comparison with MIDC.	65
Figure 4.5 Age-wise emission factors of PM _{2.5} , EC, and OC from on-road operation of light duty vehicles.	68
Figure 4.6 Box plot of emission factors of PM _{2.5} , EC, OC and EC to OC ratio from present work and comparison with literature.	75
Figure 4.7 Average emission factors of water soluble ions measured during on-road operation of light duty vehicles.	84
Figure 4.8 Average emission factors of trace elements measured during on-road operation of light duty vehicles.	87
Figure 4.9 Mass closure of PM _{2.5} for light duty vehicles.	97
Figure 4.10 Linear regression plot between estimated BC and the measured EC for diesel vehicles.	99
Figure 4.11 (a) Variation in mass absorption cross-sections (MAC) with (a) EC/PM _{2.5} , (b) OC/PM _{2.5} for diesel vehicle, (c and d) for gasoline vehicles. The error bars are one standard deviation around mean from the set of the experiments of diesel and gasoline vehicles.	99
Figure 4.12 Emission rates for CO, CO ₂ , and NO _x as a function of vehicle speed and acceleration/deceleration for diesel (top panel), gasoline (middle panel) and CNG (bottom panel) passenger cars.	102
Figure 5.1 On-road vehicle populations and their age-distribution in India for the year 2013 for various categories.	128

Figure 5.2 Fuel consumption of diesel, gasoline, and CNG for road transport sector of India. Triangular legends indicate scaled fuel consumption of MOPNG and Pandey and Venkataraman (2014) for the year 2013.	131
Figure 5.3 PM _{2.5} , EC, and OC emissions by fuel type from road transport of India.	136
Figure 5.4 Age-wise emissions of PM _{2.5} , EC, and OC from Indian transport sector for the year 2013, SE= denotes superemitter.	137
Figure 5.5 Aerosol emissions from road transport in India from present work and comparison with literature.	140
Figure 5.6 Spatial distribution of aerosol emissions (tons/grid/year) for Indian road transport for the base year 2013 (Top panel) and compared with emission inventory (bottom panel) reported by Sadavarte and Venkataraman (2014) scaled for year 2013.	144
Figure 5.7 CO, CO ₂ , and NO _x emissions for road transport of India for the base year 2013.	148
Figure 5.8 Age-wise emissions of CO, CO ₂ , and NO _x from Indian road transport sector for the base year 2013.	149
Figure 5.9 Emissions CO, CO ₂ , and NO _x from road transport sector in India from present work and comparison with literature	152
Figure 5.10 Spatial distribution of CO, CO ₂ , and NO _x for road transport sector of India for the base year 2013. CO and NO _x reported in tons grid ⁻¹ year ⁻¹ and CO ₂ in kilotons grid ⁻¹ year ⁻¹ .	155

LIST OF TABLES

Table 2.1 Previous aerosol emission estimates for road transport in India.	13
Table 2.2 Previous emission estimates of gaseous pollutants for road transport in India.	14
Table 2.3 Salient features of previous dilution sampling systems design.	16
Table 3.1 Description of instruments used in present study.	26
Table 3.2 Emission factors of PM _{2.5} and relative contribution of chemical species for wood combustion in gasifier cookstove.	38
Table 3.3 Emission factors of PM _{2.5} and relative contribution of chemical constituents for light duty diesel vehicle.	41
Table 4.1 Characteristics of selected vehicles for on-road emission measurement.	53
Table 4.2 Quality assurance and quality control (QA/QC) parameters of aerosol species.	61
Table 4.3 Main characteristics of on-road driving pattern and MIDC.	65
Table 4.4 Comparison of vintage, odometer reading and PM _{2.5} emission factors for vehicle used in present work and reported by ARAI.	69
Table 4.5 Distance based emission factors of PM _{2.5} , EC and OC for light duty vehicles of various age group and comparison with literature.	76
Table 4.6 Average relative contribution (in %) of chemical species to total PM _{2.5} for 4-wheeler diesel vehicles and in comparison with the literature.	89
Table 4.7 Average relative contribution (in %) of chemical species to total PM _{2.5} for 4-wheeler gasoline vehicles and in comparison with the literature.	90
Table 4.8 Sources of chemical species of PM _{2.5} emitted from tail pipe exhaust.	92
Table 4.9 Correlation matrix of chemical species of PM _{2.5} for 4-wheeler diesel vehicles.	94
Table 4.10 Correlation matrix of chemical species of PM _{2.5} for 4-wheeler and 2-wheeler gasoline vehicles	95

Table 4.11 Correlation matrix of chemical species of PM _{2.5} for 4-wheeler and 3-wheeler CNG vehicles.	96
Table 4.12 Emission factors of CO, CO ₂ , and NO _x from present work and in comparison with the literature.	110
Table 5.1 Annual distance travelled by vehicles in different categories.	119
Table 5.2 Vehicle mileage of different vehicle categories.	120
Table 5.3 Fuel based average emission factors of PM _{2.5} , EC, and OC used in the present study for emission estimate.	123
Table 5.4 Fuel based average emission factors of CO, CO ₂ , and NO _x used in the present study for emission estimate.	124
Table 5.5 Emission factors of PM _{2.5} , EC, OC, CO, CO ₂ , and NO _x for superemitter vehicles	125
Table 5.6 On-road population and traffic volume of vehicles of different categories.	129
Table 5.7 State-wise traffic volume and fuel consumption from road transport sector of India for the base year 2013.	132

LIST OF ABBREVIATIONS

Acronyms	Expanded form
AAOD	Absorption Aerosol Optical Depth
AEMS	Aerosol emission measurement system
ARAI	Automotive Research Association of India
ATN	Attenuation
BC	Black Carbon
BS	Bharat Stage
CFCs	Chlorofluorocarbons
CH ₄	Methane
CI	Compressed Ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO ₂	Carbon di-oxide
COPERT	Computer Programme to Calculate Emissions from Road Transport
CPCB	Central Pollution Control Board
CRDI	Common Rail Direct Ignition
CVS	Constant Volume Sampler
DI	Direct Ignition
DOC	Diesel Oxidation catalyst
DPF	Diesel Particulate Filter
DR	Dilution ratio
EC	Elemental Carbon
EGR	Exhaust Gas Recirculation
ED-XRF	Energy Dispersive X-Ray fluorescence
FTP	Federal Test Procedure
GHGs	Greenhouse gases
GISS	Goddard Institute for Space Studies
GPS	Global positioning System
HBEFA	Handbook of Emission Factors for Road Transport
HC	Hydrocarbon
HDV	Heavy duty vehicle
ICP-MS	Inductively Coupled Plasma–Mass Spectrometer
IEA	International Energy Agency
IEO	International Energy Outlook
IISER	Indian Institute of Science Education and Research
IPCC	Intergovernmental Panel on Climate Change

IR	Infrared
LDV	Light duty vehicle
LDDV	Light duty diesel vehicle
LDGV	Light duty gasoline vehicle
LMV	Light motor vehicle
LPM	Liter per minute
MIDC	Modified Indian driving cycle
MORTH	Ministry of Road Transport and Highway
MOEF	Ministry of Environment and Forests
MOPNG	Ministry of Petroleum and Natural Gas
MPFI	Multi point fuel ignition
MPS	Micro-Proportional Sampling System
MOBILE	Mobile vehicle emission model
MSA	Methane Sulphonic Acid
NASA	National Aeronautics and Space Administration
NEDC	New European driving cycle
NMVOC	Non-methane volatile organic carbon
NO _x	Oxides of nitrogen
N ₂ O	Nitrous oxides
OC	Organic Carbon
PM _{2.5}	Particulate Matter (diameter < 2.5 µm)
PDS	Portable Dilution System
PFD	Partial flow dilution
PEMS	Portable Emission Measurement Systems
PSAP	Particle soot/absorption photometer
QA	Quality assurance
QC	Quality control
QBQ	Quartz behind Quartz
QBT	Quartz behind Teflon
RF	Radiative Forcing
RH	Relative humidity
SI	Spark ignition
SIAM	Society of Indian Automobile Manufacturers
SOF	Soluble organic fraction
SRI	Southern Research Institute
TC	Turbocharger
TWC	Three way catalytic converter
TOA	Top of the Atmosphere
TOR	Thermal Optical Reflectance
TWC	Two-way catalyst

UDC	Unified driving cycle
USEPA	United States Environment Protection Agency
UV	Ultra-Violet
VKT	Vehicle kilometer travel