

IMPACTS OF URBAN TRAFFIC INTERRUPTION AND CONGESTION ON VEHICULAR EXHAUST EMISSIONS

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DOCTOR OF PHILOSOPHY

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CERTIFICATE

This is to certify that **Arti Choudhary** has been working under my supervision since January, 2012 as a regular registered Ph.D. student. Her thesis entitled “**Impacts of Urban Traffic Interruption and Congestion on Vehicular Exhaust Emissions**” is an authentic record of the results obtained from the research work carried out under my supervision in Civil Engineering Department, Indian Institute of Technology Guwahati India. I certify that she has fulfilled all the requirements according to the rules of this institute regarding the investigations embodied in her thesis and this work has not been submitted elsewhere for a degree.

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DECLARATION

I declare that the work embodied in this thesis is the result of investigations carried out by me in the Department of Civil Engineering, Indian Institute of Technology Guwahati India. The sources referred in the creation of this work have been appropriately acknowledged by explicit references or footnotes. Other assistance received has been acknowledged. I have not knowingly copied or used the words or ideas of others without acknowledgement.

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ABSTRACT

The urbanization and economic development is strongly connected with demand for transportation. India currently has about 15 million cars, which is equivalent to 13 cars per 1000 populations. The share of passenger cars and auto-rickshaws on urban roads is high in developing countries; the numbers of trips in urban centers are also high in comparison to other personalized vehicles, which cause higher air pollution in urban city centre. A highly-trafficked stretch of an urban traffic corridor in Guwahati was selected for the study. The instantaneous measurements of emissions and speeds were carried out on the test route by integrating the auto-gas analyser and V-Box¹. The study measured tail-pipe emissions from passenger cars and auto-rickshaws during peak and off-peak hours and analysed according to different mileages with the instantaneous speed and acceleration for interrupted and congested traffic conditions.

The study characterized the instantaneous speed and different ranges of average speed linked with the exhaust emission for pollutants HC, CO, NO_x and CO₂. On-road emissions from interrupted and congested traffic-flow patterns was found to be too high as compared to the free-flow condition and was mainly influenced by the accelerating and decelerating speed due to frequent stop-and-go. It was found that several short-events lasting over fractions of a second, each lead to a sharp increase in pollutant emissions, indicate episodic conditions. The instantaneous speed and emission analysis also revealed that emission levels are sensitive to frequency and intensity of sharp acceleration and deceleration events.

¹ V-Box: has powerful GPS engine that can log speed and position of moving vehicle at 10Hz.

Further, the study found that magnitude of emission of pollutants CO and HC was the combine effect of higher frequency of travel time and low speed, whereas emissions of CO₂ and NO_x were increased with increasing speed. The emission modelling was carried out using Computer Programme to calculate Emission from Road Transport (COPERT–IV) and International Vehicle Emission (IVE) model, and compared with measured emission factors. The comparative analysis showed that measured emission is higher than the modelled emission during peak hours, especially for CO and HC. The EF of the COPERT–IV model which is based on average speed, were significantly deviated (under–prediction for CO, HC and over–prediction for NO_x) from the on–road EF. However, the EF of IVE model, which is based on instantaneous speed, was in good agreement with on–road EF during off–peak hours. Further, the study investigated possible mitigation options for emission reduction by upgrading to higher emission standards and shifting to cleaner fuel; and from regulation of the bus frequency on road. The regulation of the bus frequency means to impose restrictions on the number of the stoppages at a bus stop. The analysis found that, by upgradation to higher Euro–IV standards, the passenger car can reduce upto 57–60% of CO, 53–55% HC and 55% NO_x and 31–38% reduction in the CO₂ emissions. The shifting to cleaner fuel for auto–rickshaw can achieve upto 89% reduction in HC and CO, 23–56% in NO_x and 32–36% reduction in the CO₂ emissions. The regulation of the frequency of bus service at bus stop showed 40–66% emissions reduction in the CO and HC and 40% reduction in the emissions of CO₂ and NO_x. The mitigation strategies significantly reduced the tail–pipe emissions of CO, HC, CO₂ and NO_x. And the PH operating speed and sharp A/D events increased the CO and HC emissions significantly than the CO₂ and NO_x.

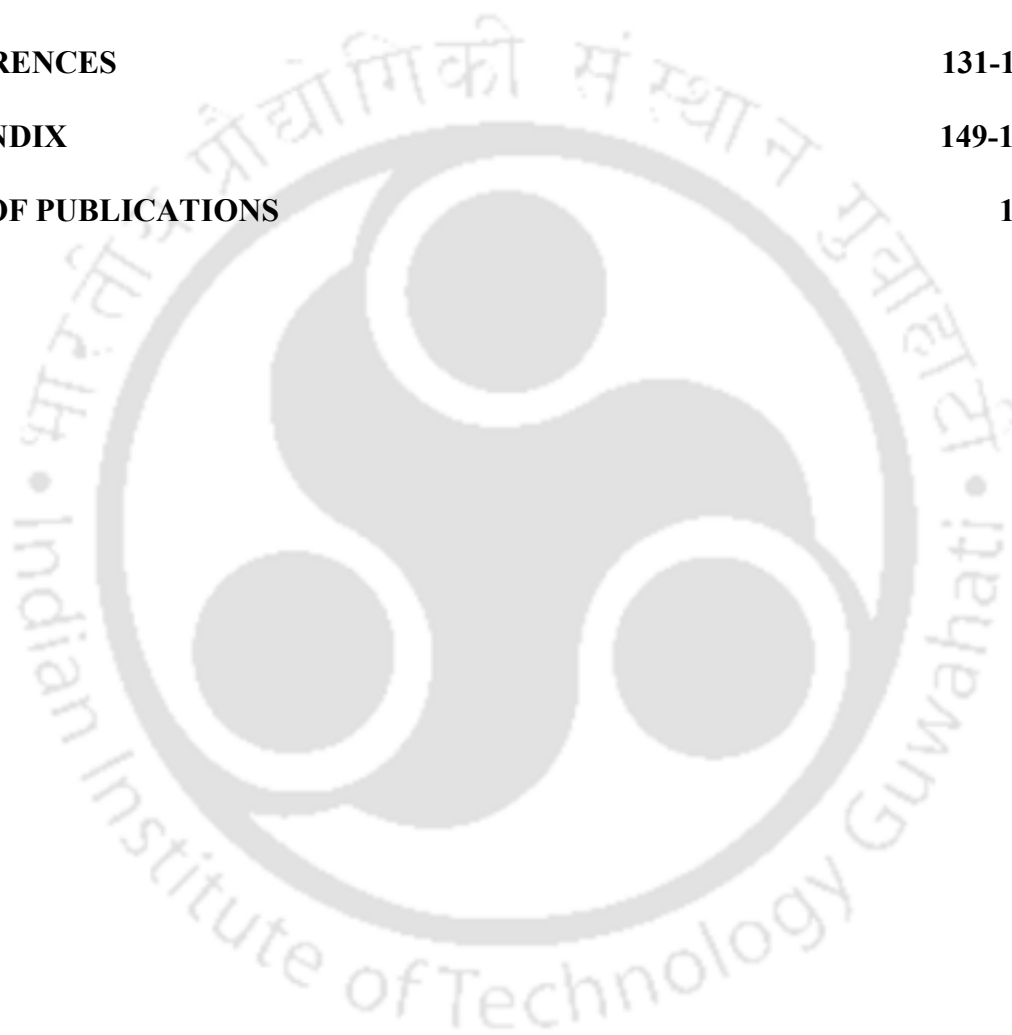
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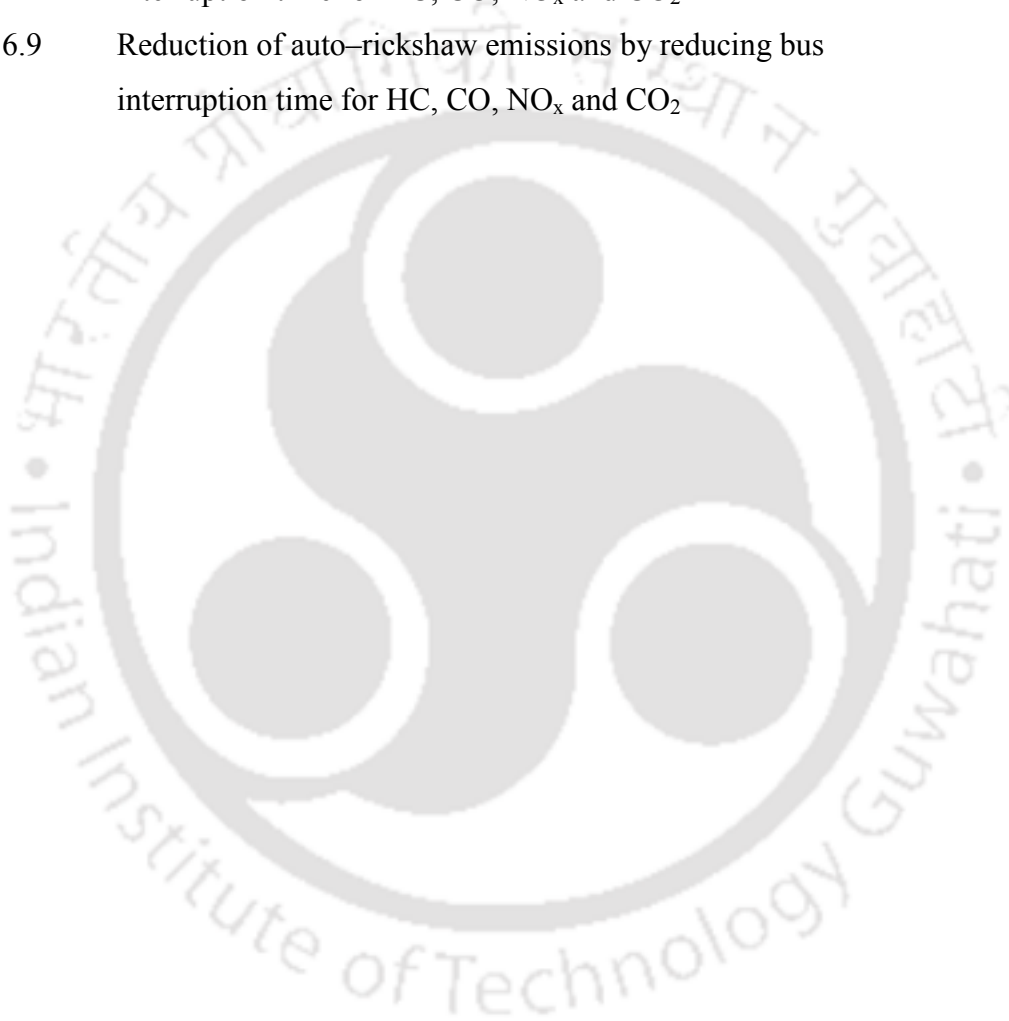


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LIST OF SYMBOLS

Syntax	Description
$E_{(g/s)}$	Emissions rate
M_{af}	Mass air flow
F_f	Instantaneous fuel flow rate
M_Q	Molecular weight of the exhaust gases
Q	Fraction of the exhaust gas
M_{exh}	Exhaust molar mass,
$EF_{i,m,n}$	Emission factor, for a given species i , of age m , and engine size n
$\alpha, \beta, \gamma, \delta, \epsilon, \zeta, \eta$ and θ	Coefficients of COPERT–IV equations
RF	Coefficient specific to a given engine size n , and technology level m .
V	Vehicle speed
g	Roadway gradient



LIST OF ABBREVIATIONS

Syntax	Description
MoSPI	Ministry of Statistics and Programme Implementation
CPCB	Central Pollution Control Board
GHG	Green House Gas
MoRTH	Ministry of Road Transport and Highway
LPG	Liquid Petroleum Gas
CNG	Compressed Natural Gas
HC	Hydrocarbon
CO	Carbon monoxide
CO ₂	Carbon dioxide
NO _x	Nitrogen oxides
PM	Particulate matters
OPH	Off-peak hour
PH	Peak hour
SGW	Stop-and-go wave
PLC	Pinned localized cluster
HCT	Homogeneous congested traffic
OCT	Oscillating congested traffic
MLC	Moving localized cluster
RC	Recurrent congestion
NRC	Non-recurrent congestion
LOS	Level of Service
HCM	Highway Capacity Manual
PCU	Passenger Car Unit
ICTs	Information and Communication Technologies
RFID	Radio Frequency Identification
ISA	Intelligent Speed Adaptation
CA	Congestion Assistant
SMART-SIGNAL	Systematic Monitoring of Arterial Road

	Traffic and Signals
LWR	Lighthill–Whitham–Richards
NJIT	New Jersey Institute of Technology
TRB	Transport Research Board
AADT	Annual Average Daily Traffic
LDV's	Light-duty vehicles
PC–MUV	Passenger car multi-utility vehicle
3W	Three-wheeler
2W	Two-wheeler
LHCV	Light heavy commercial vehicle
NDIR	Non-dispersive infrared
GPS	Global Positioning System
IVE	International Vehicle Emission
COPERT–IV	Computer Programme to Estimate Emissions from Road Transport
AS	Average speed
VN	Velocity noise
CV	Coefficient of variation of speed
FF	Free-flow
IF	Interrupted-flow
CF	Congested-flow
MPH	Morning peak hours
EPH	Evening peak hours
EF	Emission factor
VSP	Vehicle Specific Power
ANOVA	Analysis of Variance
BSFC	Brake Specific Fuel Consumptions
BMEP	Brake Mean Effective Pressure
ARAI	Automotive Research Association of India
EPA	Environmental Protection Agency

1.1 GENERAL

Unprecedented growth in vehicular population in Indian cities is mainly associated with the rapid growth in economy and rapid increase in urbanization (Singh, 2006). This has increased traffic demand in urban centres (Pucher et al., 2005). Urban population in India, in 1951, was about 17% which increased to 32% in 2011 and it is further expected to rise by another 35% by 2021 (Singh, 2012). As a result, the registered vehicle population in India has also increased from 55 million in 2001 to 142 million (61% growth) in 2011 (MoSPI, 2014). Of which 35% vehicles are in a few mega (i.e. those over 10 million population; Delhi, Mumbai, Kolkata) and metro (i.e. those over 1 million population; Chennai, Bangalore, Hyderabad) cities of India, which together share only about 11% of the human population of India (Kumar et al., 2011; Singh, 2012). This excessive growth has significantly increased air pollution and related health issues (Gurjar et al., 2010; Nagpure et al., 2011; Nagpure et al., 2014; Kumar et al., 2015). On-road traffic is the major contributor in the rise of air pollution in cities like Delhi as compared to other sources like industry, residential, and thermal power plants. (Bose and Srinivasachary, 1997; Goyal et al., 2013; Guttikunda and Calori, 2013; Jain et al., 2014; Kumar et al., 2015). The contribution of road vehicles to urban air pollution (carbon monoxide, CO; hydrocarbon, HC; nitrogen oxides, NO_x and particulate matter, PM) is 52% in Mumbai and close to one-third (33%) in Kolkata (CPCB, 2010).

The transport sector in India consumes about 17% of total energy and responsible for 60% production of the greenhouse gases (GHG) from various activities (Tedoy, 2008). The share of passenger cars and auto-rickshaws (three-wheelers) on urban roads is high in India. Auto-rickshaws are invariably used as low cost-taxis. The number of trips of these vehicles in urban centres is also more in comparison to other personalized vehicles (e.g. two-wheelers). For example, one auto-rickshaw in New Delhi travels on average 150 km daily (Reynolds et al., 2011b). Annual utilization of cars and taxis is more than two-wheelers, almost double, i.e. 12,600 km as compared with the 6,300 km of two-wheelers, in India (Singh, 2006; Ramachandra and Shwetmala, 2009). The share of vehicle population in India in 2011 is shown in Figure 1.1. The vehicles are two-wheelers (2W) including scooters, motorcycles, and mopeds; auto-rickshaw (3W); passenger car medium utility vehicle (PC-MUV) includes-cars, vans and jeeps; light heavy commercial vehicle (LHCV) includes-minibus, bus and truck; and others roadway vehicles including tractors and non-road vehicles (OTH).

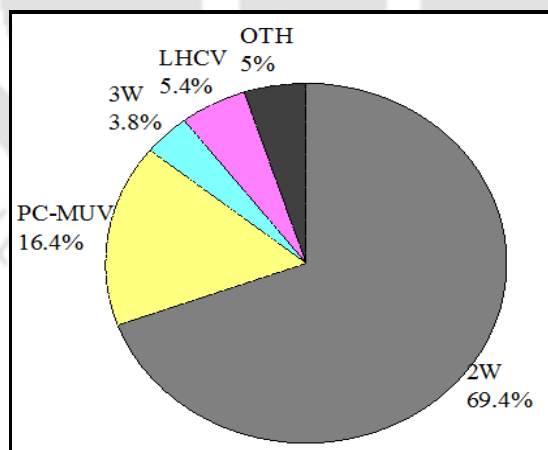


Figure 1.1 Passenger and commercial vehicle population in India and their shares in the total registered vehicles in 2011. (Source: Guttikunda and Mohan, 2014)

Auto-rickshaws are important in the Indian traffic as they are used as an intermediate public transport. They fill a vital niche in developing cities between private vehicle

ownership and fixed-route and large-capacity public transit systems (i.e. bus and metro) (Reynold et al., 2009). Figure 1.2 presents the share of auto-rickshaws in 20 fast growing cities of India on Y axis against the population of that city along X axis (in log scale), which shows the highest share in the megacities, with some exceptions in the tertiary cities (Reynold et al., 2009). Auto-rickshaws are the popular mode of private transportation because of the low initial and low running cost (Iyer, 2003). Because of its small size it negotiates the smaller streets and weaves through the mixed traffic (Iyer, 2003). Different types of auto-rickshaws are found on Indian roads but auto-rickshaws of capacity less than 4 persons including the driver occupy the roads are more and also have the largest market share, close to 80% (Iyer et al., 2013). Considerable share of auto-rickshaws in Indian traffic fleet and lack of adherence to lane marking (no-lane discipline) are unique and important features. Figure 1.3 shows the share of different types of three-wheelers in India based on the domestic sales for the fiscal year 2009–10.

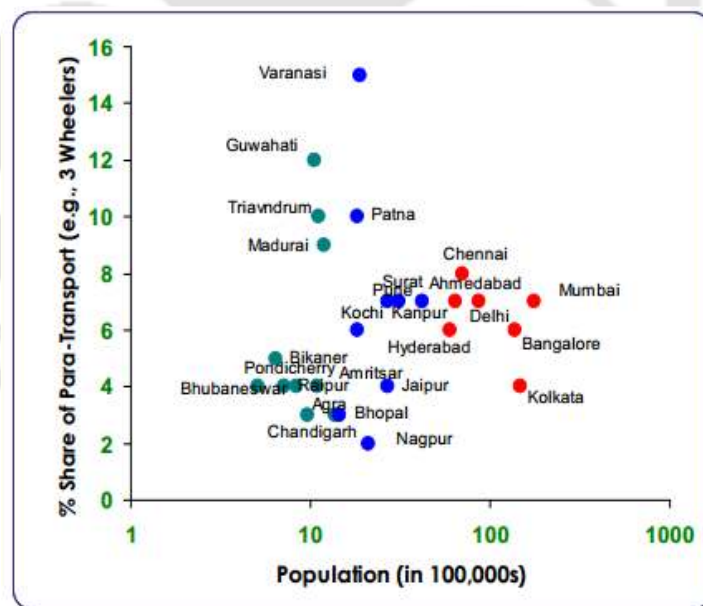


Figure 1.2 Percentage share of para-transport (auto-rickshaw) travel in different cities of India. Red dot-mega cities, blue dot-secondary cities and green dot-tertiary cities (Source: Ministry of Urban Development, Government of India, 2008)

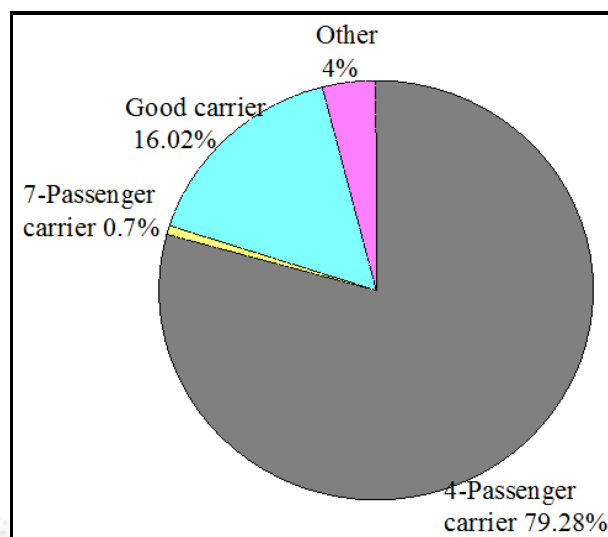


Figure 1.3 Share of different types three-wheelers in India based on the domestic sales for the fiscal year 2009–2010 (Source: Iyer et al., 2013)

1.2 URBAN TRAFFIC EMISSION AND AIR QUALITY

The increase in urban road transportation has significantly increased vehicular emissions. Several studies have shown that vehicular emissions are a major culprit for the air quality degradation in Indian cities (Gurjar et al., 2010; Kumar et al., 2011; Nagpure et al., 2011, 2014). Air quality is commonly assessed in terms of concentration of seven air pollutants such as CO, HC, lead (Pb), NO_x, ozone (O₃), particulates matter (PM₁₀, PM_{2.5}; particulate matter aerodynamic diameter less than 2.5 and 10 micron) and sulphur oxides (SO_x), and these are referred as criteria pollutants. The air pollutant concentrations in most of the mega and metro cities of India exceeds ambient air quality standards (Ghose et al., 2004). Megacity Delhi– the National Capital Region of India, is one of the most polluted city in the world having transport as the major source (Gurjar et al., 2004). The severity of air pollution in Indian cities can be realized from the fact that more than 2% of the people in the prime of their life (15 to 45 years) die prematurely in Delhi every year due to breathing and heart-related disorders caused by polluted air (Sengupta, 2001). As per the Supreme Court order the public transport vehicles in Delhi use

compressed natural gas (CNG), but the buses, presently operating in Delhi, constitute only 1% of vehicles and per passenger–km pollution generated by buses is much lower than the other personal and para–transit modes (Padam and Singh, 2001). Table 1.1 shows the emission factors (EF) of CO, HC, NO_x, SO₂, Pb and total suspended particulate (TSP) for different types of vehicles in Indian cities (Mumbai, Kolkata, Delhi, Chennai, Bangalore and Hyderabad). The emission of CO and HC is high for personalized modes (e.g., cars and 2W) and para–transit modes (e.g., 3W) in comparison with the buses and trucks. The shares of diesel vehicles on the Indian urban roads are also higher, for example, all the heavy duty vehicles (HDVs) and light commercial vehicles (LCVs) are diesel driven (Singh et al., 2014).

Table 1.1 Emission (g/km) of vehicles in Indian cities (Source: Sibal and Sachdeva, 2001)

Type of vehicle	CO	HC	NO _x	SO ₂	Pb	TSP
Two wheeler	8.30	5.18	-	0.01	0.004	-
Passenger car	24.03	3.57	1.57	0.05	0.01	-
Three wheeler	12.25	7.77	-	0.03	0.01	-
Bus	4.38	1.33	8.28	1.44	-	0.28
Truck	3.43	1.33	6.48	1.13	-	0.45
Light commercial vehicle	1.30	0.50	2.50	0.40	-	0.10

1.3 CRITICAL ISSUES OF URBAN TRAFFIC

Transport crisis in cities is characterized by congestion, degree of noise and air pollution, traffic fatalities and injuries (Pucher et al., 2007). In developing countries, for example, a mix of both motorized and non–motorized vehicles (heterogeneous traffic) traveling at different speeds are the causes of frequent interruption and congestion. The situation is exacerbated by the rapid growth of cities, urbanization, in adequate transport infrastructure, rampant suburban sprawl, rising motor vehicle ownership and use,

insufficient public transport, and inadequate as well as uncoordinated land use and transport planning (Pucher et al., 2005; 2007). Several policies have been initiated to improve urban mobility in Indian cities, primarily aiming to enhance and strengthen urban infrastructure and public transport (Gaur, 2002; Pucher and Dijkstra, 2003). Some of the conventional causes of traffic congestion are insufficient and inefficient public transportation, mixed use of dedicated roads, low-price parking policies, poor driving behaviour, lack of transport planning, and the absence of intelligent transport systems (Tiwari, 2002; Jain et al., 2012). Therefore, increasing vehicle numbers and vehicle activities makes traffic congestion and interruption most frequent phenomenon.

1.3.1 Traffic interruption and congestion

Transport related problems stemming from the rapid economic development, are affecting the environment at both local and global scale. Traffic congestion² is one of such critical outcomes. It is a regular phenomenon on urban roads and it becomes critical at traffic intersections and junctions. It increases commuting time, fuel consumption and cause higher pollutant emissions. It is defined in several ways, e.g. economist treat congestion as interactions between vehicles, and engineers link it with the levels of service and recognise congestion only when the road is either operating near or in excess of capacity. Travel time and delay³ (Turner et al., 1996; Schrank, 2002) and time index are also used to define congestion (Lomax et al., 2003; Medley and Demetsky, 2003). Each of these ways brings out different dimensions of traffic congestion. Largely, however, the definition of congestion on the basis of road capacity and traffic fleet speed is widely adopted in the literature.

² The deterioration of smooth free-flowing traffic conditions due to increased travel demand and/or reduced traffic movement capacity (Smit et al., 2008).

³ It is the travel time, during the congestion, in excess of that normally incurred under light or free-flow traffic condition (Schrank and Baker, 2002).

The congestion often results in longer queues and delay at signals, frequent stop-and-go, constant shifting of driving modes (i.e. from idle to acceleration to deceleration to cruise) and interruptions (Barth et al., 1996). Traffic congestion causing stopping delay and approach delay⁴ lengthens the total travel time and consequently increases the fuel consumption (Pandian et al., 2009). The cost and effect of congestion largely determined by the duration for which congestion lasts, the time lapsed in idle and acceleration modes, the speed of traffic fleet, and the effect of signal-timing and coordination (Ibrahim and Ramli, 2003; Kühlwein and Friedrich, 2005; Pandian et al., 2009). The pattern of traffic congestion varies daily, at different times of the day, with the change in traffic volume, with respect to the road capacity and with traffic-flow conditions determined by travel time, average speed, delay time and number of stops (Turner et al., 1996; Wen et al., 2014).

Urban traffic congestion is affecting urban agglomerations in developing countries and has multiple effects on urban economies (Alam and Rabbani, 2007). Traffic congestion is commonly perceived in terms of lower speed. However, the benchmark of low-level speed of vehicle varies from country to country. For example, in California where the speed falls to the level of 35 km/h continuously for 15 minutes, it is referred as congestion; whereas in Minnesota, average speed less than 45 km/h is considered as congestion during 6–9 am (Rao and Rao, 2012). In the Republic of Korea, traffic congestion is regarded when traffic-flow is below 30 km/h. The management of traffic demand and supply is responsible for traffic congestion (Arnott et al., 1991). Poor infrastructure and poor demand and supply management slow traffic-flow, which causes heavy congestion, for example, Varanasi city of India, has just 7% of total motorized

⁴ The stopping delay is the time for which a vehicle is stopped in queue while waiting to pass through the intersection (Pandian et al., 2009) and approach delay is the delay at upstream of the intersection consisting of deceleration and stopped delays in addition to the acceleration delay (Mousa, 2002).

vehicles of Delhi (MoRTH, 2011) but the poor traffic–flow attract congestion. Figure 1.4 shows average speed of vehicle during congestion in major urban cities of India in 2012.

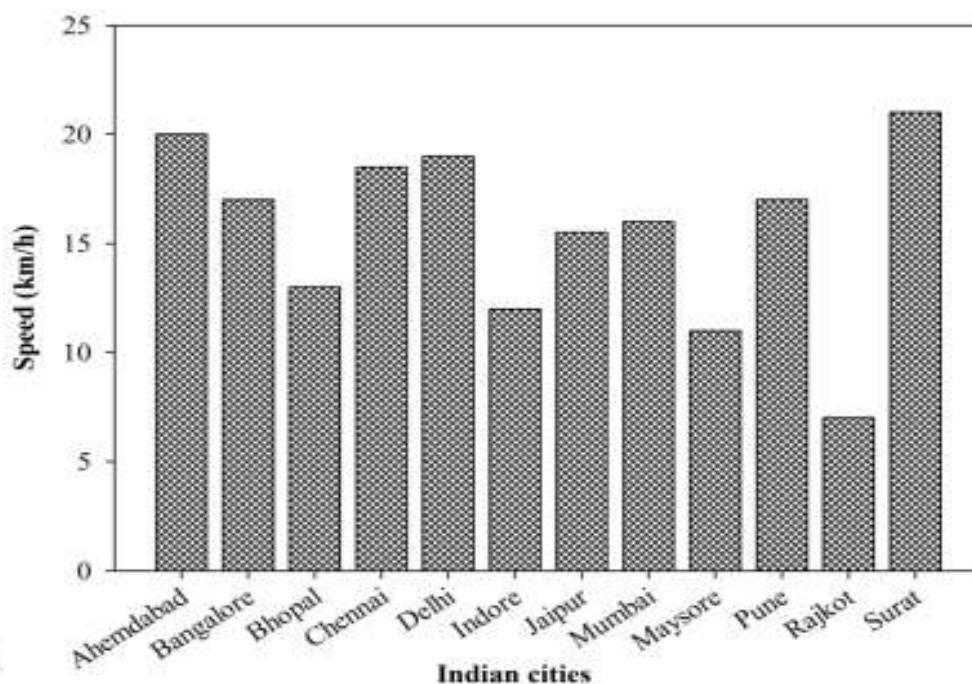


Figure 1.4 The average vehicular speed in major urban cities of India (Source: Report by EMBARQ, 2012)

1.3.2 Traffic emission due to interruption and congestion

Vehicular emissions depend on vehicle speed, vehicle–km, age of vehicle, and emission rate (Pandian et al., 2009). The quantity of major air pollutants, such as NO_x , HC, CO and CO_2 drastically increases with reduction in motor vehicle speeds. For example, at a speed of 75 km/h, emission of CO is 6.4 g/veh–km, which increases by five times to 33 g/veh–km at a speed of 10 Km/h (Singh, 2012). Problem is aggravated due to high average age and poor maintenance of vehicles. Replacement of old vehicles, introduction of liquid petroleum gas (LPG) and CNG, massive improvements in infrastructure and radical traffic management measures are required for the improvement of urban air quality (Ghose et al., 2004). Zhang et al. (2011) compared the work zone and rush–hour congestion with free–flow traffic and found high emissions during the transitional phase,

when traffic-flow changed from free to congested condition. According to Chen et al. (2007), low traffic speed with frequent acceleration and deceleration, particularly in congested conditions, are the main factors that aggravate vehicle emissions and cause higher emissions of CO and HC.

Amongst, the passenger cars share a major portion of traffic fleets on urban roads (Shukla and Alam, 2010). Vehicles in metropolises of India contribute about 70% of CO, 50% of HC and 30–40% of NO_x (CPCB, 2006) to the urban atmosphere. During rush hours, fuel consumption increases by 10% and emissions of CO, HC and NO_x emitted from passenger cars can increase upto 20% compared to non-rush hours (De Vlioger et al., 2000). Due to make and models and intensive drive-cycle auto-rickshaws are highly polluting (Ramachandra and Shwetmala, 2009). In recent years, alternative models of auto-rickshaws running on CNG and LPG are introduced to deal with the pollution problem (Lukic et al., 2007). The auto-rickshaw generally undergoes large wear and tear of the engines due to overloading, idling, and operating at less than ideal conditions, and lack of timely engine maintenance. In real-word, auto-rickshaws consume 15% more fuel and emit 49% more HC and 16% more PM_{2.5} (Grieshop et al., 2012). Reynolds et al. (2011a, b) also reported that auto-rickshaws with 2-stroke engines had about 20% higher fuel consumption and CO₂ emissions, and a much higher likelihood of being categorized as high-PM emitters, than those with 4-stroke engines. Within the group of 4-stroke vehicles, age is highly significant predictors with older models has a higher likelihood of being high-PM emitters. Reynolds et al. (2011a) stated that global warming commitment from 2-stroke CNG is more than twice that from 4-stroke CNG.

1.3.3 Greenhouse gases emission

Transport sector globally, contributes around 23% of CO₂, of which road traffic is responsible for almost three-quarters (Van der Hoeven, 2012). According to Unger et al. (2010) motor vehicles have emerged as the largest contributor to atmospheric warming. India is the fourth largest emitter of greenhouse gases globally, following China, the United States, and the European Union (Beermann et al., 2016). Although India still has a low per capita carbon level, due to its large population and growing economy, its share of global greenhouse gas emissions is rising, which is close to 6% of global CO₂ emissions, largely due to its population of about 1.28 billion in 2015 (Kern et al., 2008). The emission of CO₂ increasing in the developing countries due to its economic growth as well rising human population and vehicular population (CPCB, 2010). Roadway transport contributes major share of around 73% towards total CO₂ emissions and rest of 23% comes from aviation, international shipping and railways sector about 11%, 9% and 2%, respectively (CPCB, 2010). The Figure 1.5 shows the share of CO₂ emissions from different modes of transportation in India.

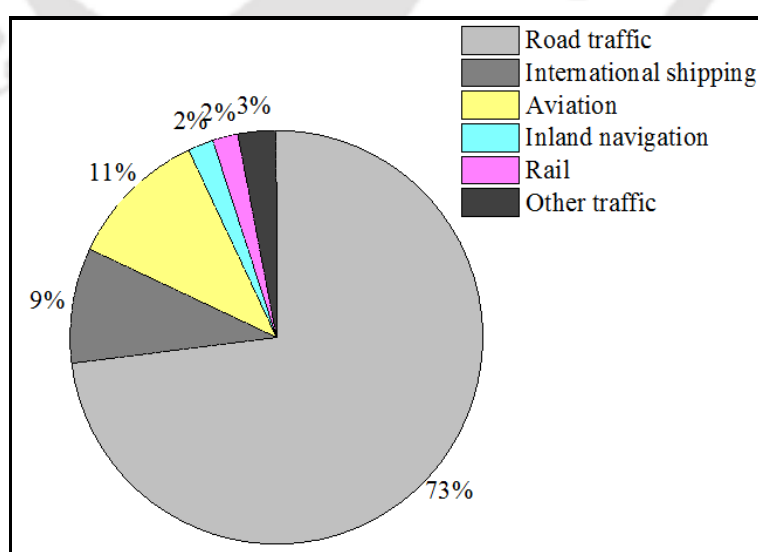


Figure 1.5 Share of CO₂ emission from different modes of transport sector
(Source: CPCB report 2010)

1.4 RESEARCH OBJECTIVE

The major objective of the research is to study the impacts on on-road instantaneous emissions of different traffic-flow patterns resulting from interruption and congestion in an urban traffic corridor. To accomplish this objective following tasks have been undertaken:

1. On-road measurements of instantaneous emissions of CO, HC, NO_x and CO₂ from the tail-pipe of auto-rickshaws and passenger cars of different mileages.
2. On-road characteristics of the traffic-flow during peak and off-peak hours.
3. On-road emission factors for different mileage passenger cars and auto-rickshaws during peak and off-peak hours.
4. Investigation of traffic-flow management and emission mitigation strategy.

1.4.1 Work plan

1. The selection of test route, test vehicles and traffic volume survey locations in an urban traffic corridor.
2. The source monitoring for instantaneous measurements of emission and speeds of the test vehicles.
3. The study of traffic-flow and composition, modal speed and the impact of average speed on exhaust emissions.
4. The study of the effect of speed and acceleration on exhaust emission of passenger cars and auto-rickshaws.
5. The study of the interrupted and congested-flow conditions and concomitant emissions.
6. The study of the effects of short-events on emissions.

7. The study of the effect of mileages on emissions.
8. The study of the correlation of share of travel time and speed vs concomitant emission.
9. The study of emission mitigation strategies by
 - i. regulating the operating speed and travel time
 - ii. upgradation of emission standards and switching to cleaner fuel
 - iii. implementing the traffic–flow management plan

1.5 NOVELTY OF THE RESEARCH

1. Emphasis on urban interruption, congestion and concomitant emissions of auto–rickshaws and passenger cars.
2. Real–world on–road measurements of instantaneous speed and tail–pipe emissions along with the regular traffic.
3. On–road emission factors of different mileage passenger cars and auto–rickshaws for different traffic–flow patterns.
4. Estimation of emission reduction by upgrading to emission standards, shifting to cleaner fuel, and by regulating city bus frequency.

1.6 ORGANIZATION OF THE THESIS

The thesis is organized in 7 Chapters. The Chapter 1 highlights the critical issues related to urban traffic–flow, causes of traffic congestion and interruption and includes discussion on the emission load due to interruption and congestion. Further, Chapter outlines the major research objectives, novelty statement and organization of the thesis. The Chapter 2 presents a comprehensive review including traffic congestion characteristics, patterns of traffic congestion and different methods of evaluating the

congestion, and effects of congestion on greenhouse gases. The Chapter 3 includes the experimental works on real-world measurements of instantaneous speed, acceleration and tail-pipe emissions of CO, CO₂, HC, O₂, and NO_x of passenger cars and auto-rickshaws of different mileages on a highly trafficked urban road in Guwahati. The Chapter 4 includes primary data analysis; it includes investigation of the urban traffic-flow characteristics such as traffic composition, traffic speed, frequency distribution of traffic speed during peak and off-peak hours and traffic-flow patterns. The Chapter 5 describes estimation of the emissions for the range of operating speed, instantaneous speed and analyse emission factors during peak and off-peak hour for different mileage test vehicles. Further, the Chapter describes emission modelling for developing emission factors of pollutants and greenhouse gas and concludes the comparative findings of results. The Chapter 6 describes the details on the impacts of urban traffic emissions for different driving behaviour, such as mileage; frequency of stop-and-go and impact of travel time and simultaneous speed. Further, Chapter describes the emission mitigation strategy, in which consequence of traffic-flow management strategy to reduce the traffic demand, emission mitigation strategy related to the vehicle technology, fuel type are discussed. Finally, the Chapter 7 provides a summary of the findings, the conclusions and discussion on its contribution to traffic related issues, research limitation and future scope.



2.1 INTRODUCTION

For mitigations, the knowledge on the relationship of traffic congestion with the pollutant emissions is essential. This review is focused on the potential causes of traffic congestion, its impacts on emissions of pollutants and greenhouse gases (GHGs) in urban environment. It is observed that an inadequate road capacity, a mixed traffic fleet, an aggressive driver behaviour, an increased vehicular population, a frequent stop-and-go condition and a delay event contribute most to congestion, which in term cause higher emissions. Therefore, to understand the link between exhaust emissions and various characteristics of congested traffic-flow, the important characteristics, responsible for congestion and higher emissions have been reviewed. This review also focused on the impacts of traffic congestion on the emissions of GHGs and discusses the technical and policy related mitigations. The Chapter begins with the patterns of traffic congestion, followed by traffic congestion characteristics including road characteristics, traffic composition and roadway capacity, traffic planning and management and driving behaviour. Subsequently, evaluation of traffic congestion, impact of traffic congestion and GHG emission followed by several mitigation policies are discussed.

2.2 PATTERN OF TRAFFIC CONGESTION

The traffic congestion which occurs in a specific pattern depends upon how the traffic is interrupted whether the junctions are signaled or unsignaled intersections or roundabouts, and also on the flow pattern of traffic (Helbing et al., 2009). It also depends

on the bottlenecks that occur incidentally at different times of the day and during peak hours (Bertini and Leal, 2005; Schonhof and Helbing, 2007). The congestion patterns are spatio-temporal, recurrent and non-recurrent in nature, which define different level of service for roadway traffic (Dowling et al., 2004; Helbing et al., 2009).

The spatio-temporal congestion pattern depends on the time it takes to occur and the space it occupies (Kerner, 2013). Schonhof and Helbing (2007) identified five different spatio-temporal traffic congestion patterns. For example, i) Stop-and-go wave (SGW) in which stop-and-go wave oscillations, depending upon the traffic-flow, propagate against the direction of the traffic-flow (Edie and Foote, 1958; Mika et al., 1969); ii) Pinned localized cluster (PLC), which is characterized by a local breakdown of the velocity and a higher density has a typical spatial extension that occurs at bottlenecks of the freeway during rush hours and does not move up or downstream (Helbing et al., 2009). It may form spontaneously or due to an upstream travelling perturbation, which ceases at the location of the bottleneck (Zielke et al., 2008); iii) Homogeneous congested traffic (HCT), which occurs for heavily congested roads, e.g. after serious accidents or during holiday traffic (Helbing et al., 2009); iv) Oscillating congested traffic (OCT), is another kind of extended congestion pattern having similar features as HCT about its development, growth and dissolution mechanism and the oscillations propagating upstream (Treiber et al., 2010); and v) Moving localized cluster (MLC), which propagates with the speed than staying at a particular place (Helbing et al., 2009). Treiber et al. (2010) simulated an open system with on-ramp as a function of the main flow and the ramp flow and described similar patterns of traffic congestion.

Traffic congestion patterns are also defined based on duration and time and named as recurrent and non-recurrent congestions (Dowling et al., 2004; Varaiya, 2007). The recurrent congestion (RC) is observed during morning or afternoon peaks (Chung et

al., 2012). Its location and duration is usually known to regular commuters and traffic operators (Han and May, 1989). The main cause of RC is excess travel demand, and inadequate traffic capacity or poor signal control (Han and May, 1989). It is a cyclic type of congestion occurring due to several factors such as excessive traffic-flow during peak hours (Kurzanskiy and Varaiya, 2010; Ishikawa et al., 2013), complex network-design structure and planning (Zhou et al., 2016), and frequent ramp-on and ramp-off (Spiliopoulou et al., 2014). Sun et al. (2015) found that recurrent bottlenecks at freeway/expressway cause traffic congestion in urban traffic system and on-ramp bottlenecks are the critical locations where it may result in congestion. The non-recurrent congestion (NRC), on the other hand, is unexpected and with unusual patterns may arise mainly from temporary conditions such as vehicle breakdown, accident or a temporary road work (Known et al., 2006; Hallenbeck et al., 2003; Skabardonis et al., 2003; Dowling et al., 2004).

The level of service (LOS) is another scale used to define level of traffic-flow (Mannering et al., 2007). It is a qualitative measure of speed and the travel time, traffic interruption, freedom to manoeuvre, safety, driving comfort and operating cost (TRB, 2000). The LOS was first introduced in the highway capacity manual (HCM) (TRB, 2000). According to a range of operating conditions and the drivers perceptions, the LOS is categorized in six different classes (A to F), which define the degree of traffic-flow (TRB, 2000; Fang et al., 2003). The LOS categories are further extended from A to J by Cameron (1996) and A to I by Baumgaertner (1996). According to Cameron (1996), three minutes of wait at a congested urban intersection is common with an average delay of more than two minutes. The majority of delays fall in the C to D range, about 10% in the E range, and only 5% in the F range (Pécheux et al., 2000) whereas class A and B are known as free-flow condition (TRB, 2000).

Traffic congestion is a dynamic phenomenon which occurs in specific patterns (Schonhof and Helbing, 2007). From the foregoing discussion it can be concluded that in the real-world, RC, MLC, PLC and SGW are all similar but different in the source of origin and qualitatively may be defined by level of service D and E (Pécheux et al., 2000; Dowling et al., 2004; Helbing et al., 2009). Whereas, NRC, HCT and OCT are originated from the same source but have different scale of measurements (Helbing et al., 2009; Anbaroglu et al., 2014). The NRC, HCT and OCT can be defined as E and F (Pécheux et al., 2000; Dowling et al., 2004; Helbing et al., 2009). Figure 2.1 shows traffic congestion patterns and their correlations with LOS.

2.3 CHARACTERISTICS OF TRAFFIC CONGESTION

An urban traffic system is the combination of different elements like road traffic-flow and traffic-flow management elements and their interactions (Golob and Recker., 2003). The traffic congestion is a consequence of poor road condition (Tang et al. 2014a). The inadequate-road infrastructure, a poor-traffic planning, and an aggressive driving contribute to congestion up to 70% (Remi et al., 2009). Traffic-flow in urban areas exhibits different but systematic characteristics on working days, non-working days, and national holidays and also on different weather period (Wen et al., 2014). It is defined by LOS by using variables such as, average traffic speed, delay time and the travel time (Litman, 2004). Recently, different measures are also adopted to characterize the traffic congestion. For example, Sun et al. (2014) used a traffic performance index to determine the causes of traffic congestion. Similarly, Younes and Boukerche (2014) presented an efficient congestion detection protocol to evaluate the traffic characteristics of each road segments (the road section connecting between any two successive intersections). The important characteristics are described in the subsequent sections.

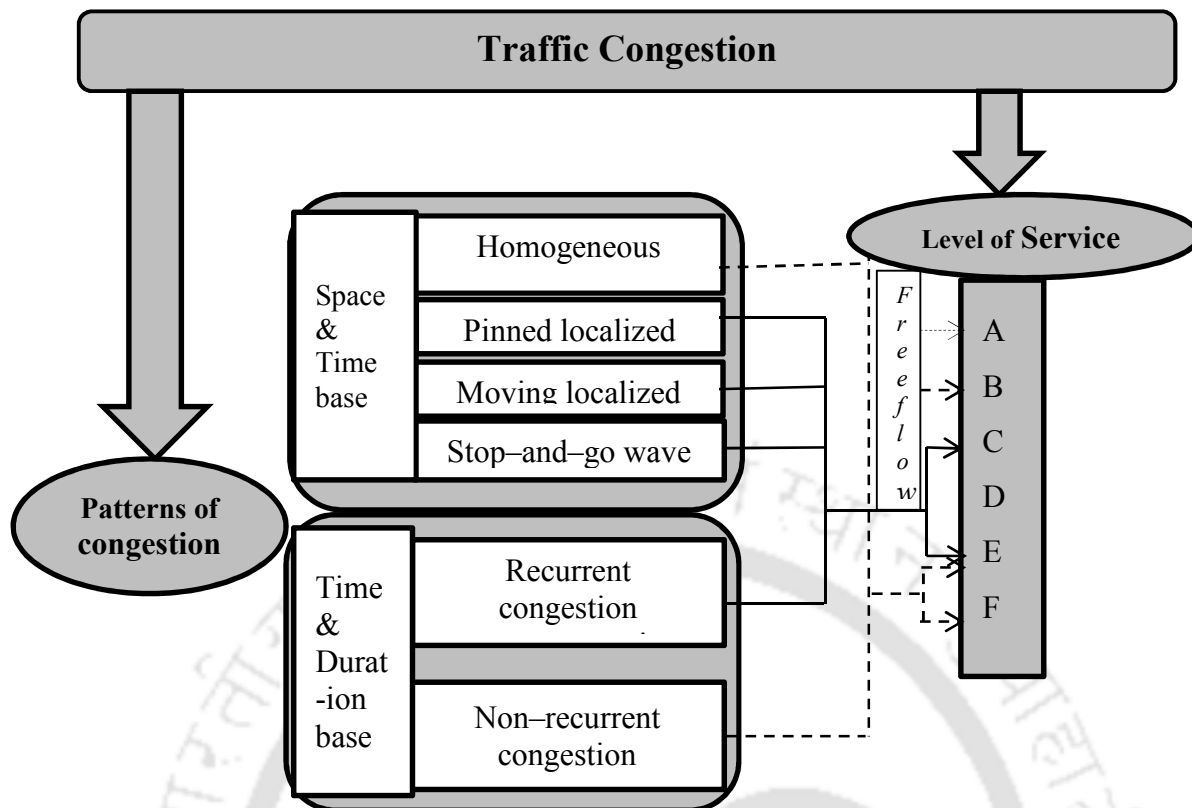


Figure 2.1 Traffic congestion patterns and their correlations with LOS (A– free–flow, B and C–stable vehicle flow, D–less stable vehicle flow, E–unstable vehicle flow, and F–traffic congestion (TRB, 2000))

2.3.1 Road characteristics

The road characteristics are described by the geometry of roads or intersections, the quality of the pavement and any prevailing control conditions (Karlaftis and Golias, 2000). The geometric factor deals with vertical and horizontal profiles, lane or road width and configuration whether it is a signalised intersection, a simple un–signalised junction, or a roundabout (Hassan and Easa, 2003). Table 2.1 lists the effect of different roadway characteristics on traffic–flow.

2.3.2 Traffic composition and roadway capacity

The capacity analysis provides a quantitative measure of the roadway facility (Harwood et al., 1999). It depends largely on the traffic–flow pattern and the geometric design of

the road (Hashim and Abdel-Wahed, 2012). For example, a curved road has lesser capacity compared to a straight road (Polus and Shmueli, 1997). The traffic composition affects the speed to volume relationship (Kockelman and Shabih, 2000; Chandra et al., 2015). Vlahogianni (2007) in an empirical study on the relationship of travel speeds and

Table 2.1 Effects of roadway characteristics on traffic-flow

Road characteristics	Effects of roadway characteristics on traffic-flow	References
Road width and configuration	<ul style="list-style-type: none"> • Widening of the road width can increase the equilibrium speed and traffic-flow. • At narrow road, disturbance in traffic-flow makes stop-and-go more severe at moderate density. 	Tang et al. (2011)
		Zhou and Shi (2016)
Road conditions	<ul style="list-style-type: none"> • Road condition affects the uniform flow and also starting and braking processes. • Good road condition can enhance the speed and traffic-flow. • Poor road condition and unregulated parking along streets often create bottlenecks. • Roadway speed can be augmented by 10–15% by providing a good riding surface. 	Tang et al. (2012)
		Tang et al. (2014a)
		Remi et al. (2009)
		Chandra (2004)
Road gradients	<ul style="list-style-type: none"> • More than 5% road gradient increases the load on vehicular operation. 	Jackson and Aultman-Hall (2010)
Roadway lane	<ul style="list-style-type: none"> • Multilane traffic-flow is more complex which is affected by each lane's width, number of lanes and lane-changing. • The stop-and-go in two-lane system is more severe than that is in three-lane system. • The lane-changing phenomenon becomes severe with increasing number of lanes. 	Tang et al. (2014b)

traffic volume with the traffic composition in an urban signalized arterial and concludes that taxis and motorcycles primarily affect the speed-volume relationship on urban arterials. The traffic composition is uncertain particularly in case of heterogeneous traffic-flow (Dey et al., 2008). This is significant in Indian context as the traffic is heterogeneous wherein all vehicles of different types move together without following a

lane discipline. It is often expressed in passenger car unit (PCU)⁵ to study road capacities (Chandra and Kumar, 2003; Yang and Zang, 2005; Chandra et al., 2015). The PCU is influenced by the number of lanes, lane width, modal size and share of individual vehicle type in the fleet (Khanokar et al., 2014). The different size vehicles and undivided roads have a reasonable effect on the fleet speed, which mostly decreases (Minh et al., 2005). The PCU value of the vehicle increases with the increase in lane width (Chandra and Kumar, 2003). The effect of the lane width on the PCU values is apparently linear but the slope of the linearity depends on the type of vehicle (Chandra and Kumar, 2003). Narrow roads in case of a mixed traffic produce a more negative effect on road capacity. According to Dey et al. (2008) the capacity of a two-lane road decrease as the proportion of three-wheeler, tractor, or heavy vehicle increases in a mixed traffic stream. In a modelling study of heterogeneous traffic-flow using HETEROSIM model Arkatkar and Arasan (2010) examined the trend of PCU over the traffic volume and found that change in PCU values of the different categories of vehicles directly influences vehicle speed.

2.3.3 Traffic planning and management

Effective planning and management of traffic is essential to ease congestion and to reduce emissions (Gärling and Schuitema, 2007). That is because the traffic related problems in several countries have worsened due to rapidly expanding and urbanising cities, giving rise to a mixed traffic fleet of motorized and non-motorized modes sharing same roadways, inadequate and uncoordinated land use and poor transport planning (Tiwari, 2002). A study by Pucher et al. (2005) reported that in the transport systems, particularly in developing countries, traffic injuries and fatalities, environmental

⁵ Useful in the evaluations of road capacities

pollution, roadway congestion and inadequate public transport are the most severe problems.

Table 2.2 Effects of policies and ICTs on traffic–flow management

Transport management	Role of roadway policies and advance techniques in transport management	References
Roadway infrastructure	<ul style="list-style-type: none"> • Poorly planned road–networks are the main cause of hotspots for congestion. • Ill–planned flyover only shifts the location of the problem without bringing any benefit. • Smart decentralized traffic–based navigation system can be powerful and cost–efficient tool. 	Jain et al. (2012) Maitra et al. (2004) Leontiadis et al. (2011)
Traffic control scheme	<ul style="list-style-type: none"> • Stopped delay is a function of the signal timing, traffic volume and traffic composition. • Signal control schemes result in stopping a larger fraction of speed violators and yield higher emissions. 	Mousa (2002) Coelho et al. (2005a, b)
Advance traffic management technology	<ul style="list-style-type: none"> • ICT and RFID are the suitable traffic control technologies. • Real time delays are quantified efficiently with the adaptive signal control system. 	Al-Khateeb and Johari (2008); Yokota (2004) Liu et al. (2002)

In several developing countries, non–motorized transport is an integral element of urban transport (Tiwari, 1999; 2002). In a study on Indian cities observed that bicycle and human–pulled rickshaw (non–motorized) are observed to be sharing the same road and make the overall traffic–flow sub–optimal (Tiwari, 2002). The roadway traffic has severe health effect on pedestrians, bicyclists, commuters and rickshaw pullers health since they have higher exposure to the pollutants released by vehicles. For example, Panis et al (2010) demonstrated that bicyclists are exposed longer and have 4.3 times higher deposition of pollutants in lungs as compared to passengers in cars. The information and communication technologies (ICTs) also have important application in traffic–flow managements (Giannopoulos, 2004). Table 2.2 lists the effect of roadway infrastructure, traffic control and advance technology on traffic–flow management.

2.3.4 Driving behaviour

The aggressive-driving behaviour has increasingly become common (Lajunen et al., 1998) due to rising traffic congestion events on urban roads (Shinar, 1998). The urban driving increases fuel consumption of petrol-driven cars (i.e. 20–45%) and emissions by several times during rush hours (De Vlieger et al., 2000). This effect may be attributed to the driving behaviour and traffic conditions (Khorashadi et al., 2005). A study of comparison of real-world and modelled emissions under variable driving conditions concludes that aggressive driving causes more emissions (Ericsson, 2001; Nam et al., 2003; Brundell-Freij and Ericsson, 2005). According to Hallmark et al. (2002), driving patterns at different intersections are influenced by queue position, downstream and upstream lane volume, share of heavy vehicles and the link speed. According to the Sierra research results, driver spending about 2% of total driving time in aggressive condition that contributes about 40% of the total emissions (Samuel et al., 2002). The driving behaviour also varies with the driver's age (Simons-Morton et al., 2005). Recently a study by Constantinos and Konstantino (2011) showed that generally drivers of the age 65 and above tend to reduce vehicle speed more than the drivers of the age group 25–65 years, irrespective of driving condition. The driving profile is also linked with the streets and traffic environments besides drivers behaviour (such as occurrence and density of junctions controlled by traffic lights speed limits and street functions) (Guerrieri et al., 2015; Tollazzi et al., 2015).

During peak hours, traffic speed drops and traffic-flow is interrupted. This phenomenon is associated with different aspects of power (kinetic energy for vehicle motion), acceleration and gear-changing behaviour of vehicle having potential impacts on emission and fuel consumption (Ericsson, 2001). Some studies on the impact of

congestion assistant (CA)⁶ on driving behaviour, acceptance and work load in a driving simulator (Van Driel et al., 2007; Brookhuis et al., 2009; Young et al., 2011) reveal that it improves the safety of the system, enhances traffic efficiency (due to reduced headway times), and reduces emissions (through lower accelerations). Lee and Abdel-Aty (2008) study the effect of warning messages and variable speed limits on driver speed and found that these means can be beneficial in reducing speed variation and congestion.

Thus, it is clear that congestion events on roads are largely led by the interruptions of traffic-flow and traffic-flow is interrupted often due to poor road infrastructure, ineffectiveness of traffic management, and aggressive driving behaviour.

2.4 EVALUATION OF TRAFFIC CONGESTION

Traffic congestion may be quantified by various methods depending upon the objectives, e.g. by determining congestion index, time and density bound methods (Lomex et al., 2003). The time-based method measures variations in travel time, travel speed or travel rate (the inverse of speed) (Schrank, 2002). The density-based method measures traffic volume, density of vehicles per mile, or volume-to-capacity ratio to define congestion (J. d'Abadie and Ehrlich, 2002). The freeway congestion index simultaneously captures the extent and duration of congestion on freeways (Thurgood, 1995) and the buffer time index to shows the effect of congestion on the reliability of travel rates along the roadway (Medley and Demetsky, 2003; Lomex et al., 2003). The buffer index addresses travel time of an individual vehicle trip (Lyman et al., 2007; Czuch and McDaniel,

⁶ It includes information on congestion, an active gas pedal (a counter force applied to the pedal when a jam approaches), and stop-and-go (Van Driel et al., 2007).

2011). The traffic congestion is also defined based on travel time and delay⁷ (Turner et al., 1996; Schrank, 2002). J. d'Abadie and Ehrlich (2002) used distance-based and time-based measures to describe severity of congestion. The distance-based measures define vehicle-kilometers of travel in congestion and time-based measures define vehicle hours of travel in congestion.

Several studies have reported the quantification of the level of congestion using various values of vehicle delay and queue length to determine the congestion levels on roads and at intersections. For example, Sharma et al. (2007) in a study carried out in Lincoln city of Nebraska, quantified vehicle delay and queue length as a measure of traffic congestion at a signalized intersection, based on the arrival and departure profiles generated from the loop detector using various methodologies. Similarly, Liu and Ma (2008) proposed the SMART-SIGNAL (Systematic Monitoring of Arterial Road Traffic and Signals) system to calculate traffic volume and queue length. Liu et al. (2009a) carried out a study in Minneapolis, USA, used the high-resolution event data with the Lighthill-Whitham-Richards (LWR)⁸ shockwave theory to estimate a time-dependent queue length. Cheng et al. (2012) also adopted shockwave approach to estimate the queue length using probe trajectories in a signalized intersection, for city Madison, USA. Viti and Zuylen (2009) studied the dynamic and stochastic behaviour of traffic in Netherland, at controlled junctions using probabilistic modelling to explain the dynamic and stochastic properties of queues. Zhenga et al. (2013) carried out a study in Ann Arbor, Michigan and developed an algorithm for estimating average control delay and

⁷ It is the travel time, during the congestion, in excess of that normally incurred under light or free-flow traffic condition (Schrank and Baker, 2002).

⁸ The Lighthill-Whitham-Richards (LWR) traffic-flow model hypothesizes that flow is a function of density at any point of the road. Traffic shockwave theory is derived from this model to analytically solve the partial differential equation (PDE) of the model (Lighthill and Whitham, 1955; Richards, 1956).

queue length at signalized intersections using traffic counts collected from properly configured traffic sensors, such as inductance loop or video image.

Besides, several other aspects are also developed and used invariably to measure the traffic congestion (Ko and Guensler 2005; Zhang et al., 2012). The boundary between the C and D LOS is used as the baseline for indicating possible congestion by the New Jersey Institute of Technology (NJIT) (Spasovic, 2001) and HCM (TRB, 2011). Stathopoulos and Karlaftis (2002) used log logistic function for estimating the duration of congestion in Athens. Cottrell (1998) also used a statistical logistic function to predict the probability of congestion recurrence on freeways with an important explanatory variable that is the ratio of annual average daily traffic volume (AADT) to hourly capacity. Yunteng et al. (2007) combined traffic demand and supply to describe congestion at a signalized intersection in Shanghai, based on loop detector⁹. Ko and Guensler (2005) presented a Gaussian mixture model to identify the congestion characteristics for Georgia, based on speed distribution, which used Kernel density technique to investigate the form of speed distributions. Zhang et al. (2012) introduced the congestion factor to evaluate the real-time status of the traffic congestion along a roadway segment, in China and to predict the sub-critical state of traffic jams. The level of traffic congestion is significantly affected by local environment such as weather condition, roadway infrastructure and traffic management (Golob and Recker, 2003; Cool et al., 2010; Guerrieri et al., 2015).

Thus, various methods are used to measure traffic congestion but the most measures are based on travel-time and speed, which are easy to comprehend and satisfy the widest range of requirements for decreasing congestion (Chang, 2010). The time-

⁹ It is the in-pavement device that uses magnetic fields to detect the presence and/or passage of vehicles in a roadway traffic lane.

based measures accurately reflect the way travelling public perceive congestion than other methods (Bhat and Sardesai, 2006).

2.5 IMPACTS OF TRAFFIC CONGESTION

Traffic congestion impacts economy and environment due to its multiple interactions with economic, social and environmental aspects (Bagazzi, 2012). The congestion events cost economy due to loss of fuels and wastage of time and thus pollutant emissions are linked with economic, environmental and social issues (Weisbrod et al., 2003). Schrank and Lomax (2007) carried out a study in Texas and reported total annual average travel delay in 2005 of about 38h. The congestions, due to low speeds, do not produce sufficient mechanical turbulence (Benson, 1989) to dilute and disperse the pollutants, which as a result, increase due to accumulation with time within the traffic corridor particularly during low winds (Kumar et al., 2008). Thus, vehicles with low speed emit more and contribute to higher pollutant concentration in urban areas producing local hotspots of poor air quality (Jain et al., 2012).

Traffic junctions help the smooth operation of road-networks. But due to unprecedented increase in vehicular population, traffic junctions, particularly in urban centres are contributing to additional congestions by increasing queuing length and queuing time and hence become pockets of higher emissions and poor air quality (Coelho et al., 2006). According to Gokhale (2011), traffic-flow with different modal events and meteorology at traffic intersections contribute to higher pollutant concentrations and even affect the locations of critical pollutant levels due to constantly changing traffic-flow conditions within the influence of traffic intersections. Thaker and Gokhale (2016) recently carried out a study in Guwahati city and investigated the effect of different traffic-flow patterns on the pollutant dispersion in a real asymmetric urban

street canyon, which shows that congested-flow condition can increase the concentrations on the leeward side up to about 47% for perpendicular winds.

Vehicular emission is influenced by several vehicle and traffic characteristics such as vehicle weight, engine load, level of inspection and maintenance, traffic composition on the road, fleet speed (Faiz et al., 1996; Vlahogianni; 2007) similarly, by operating modes such as idle, cruise, acceleration and deceleration, and by road characteristics such as longitudinal grade, curves and pavement quality (Guensler, 1993; Barth et al., 1996). Most of these characteristics during congestions or congested-flow conditions cause higher emissions (Bachman, 1998; De Haan and Keller, 2000). It contributes to constant change in the driving pattern, increase in number of speedups, slowdowns, and stops and starts, all of which lead to higher emissions, particularly, with frequent high power acceleration and deceleration (Sjodin et al., 1998). Recently, Adak et al. (2016) carried out a study in Dhanbad, India and concluded that traffic congestion causing stopping delay and approach delay¹⁰ lengthens the total travel time and consequently increases the total emission. Shukla and Alam (2010) also estimated the effect of delay and non-delay events in Delhi and found that the difference between non-delay and delay events is from 60–150% for NO_x, 30–200% for HC, 60–400% for CO and 15–110% for CO₂. Zhang et al. (2011) conducted a study in Ann Arbor, Michigan and studied the effect of the time for which congestion lasts (congested period) on emissions and concluded that as compared to free-flow traffic the work zone and rush-hour congestion accounts for higher emission. Several studies carried out in the recent last decade reported the increase in vehicular exhaust emissions during congestion

¹⁰ The stopping delay is the time for which a vehicle is stopped in queue while waiting to pass through the intersection (Pandian et al., 2009) and approach delay is the delay upstream of the intersection consisting of deceleration and stopped delays in addition to the acceleration delay (Mousa, 2002).

is affected by the duration of congestion and the traffic speed during the congestion (Kuhlwein and Friedrich, 2000; Kuhlwein and Friedrich, 2005; Singh et al., 2007; Pandian et al., 2009).

Traffic congestion also impacts public health (Levy et al., 2010). Tonne et al. (2008) studied the effect of congestion charging on health in London and found that congestion charging zone, can gain 183 years of life per 100,000 populations. According to Eliasson et al. (2009), enforcing congestion charging zone in Stockholm can avoid 20–25 deaths annually due to traffic-related air pollution in the inner city, and 25–30 in the metropolitan area, having 1.4 million inhabitants. Zhang and Batterman (2009) studied that a 30 min per day travel delay can account for about $21 \pm 12\%$ of the exposure to benzene and $14 \pm 8\%$ to $PM_{2.5}$ to a typical working adult on weekdays and, therefore, health risk from congestion is potentially significant and in 2013 reported that it increases with travel time and the duration of rush-hour (Zhang and Batterman, 2013).

For the estimation of vehicular emissions different emission models are reported in literature, such as COPERT-IV (Computer Programme to estimate Emissions from Road Transport) using average vehicle speeds to estimate the emission (Smit et al., 2008). Several European countries used COPERT-IV model for emission estimation of roadway traffic (Kioutsioukis et al., 2004; Kassomenos et al., 2006; Achour et al., 2011; Kousoulidou et al., 2013). Another commonly used model is an instantaneous emission models, such as Instantaneous Vehicle Emission model (IVE) and Motor Vehicle Emission Simulators model (MOVES) based on actual driving patterns, i.e. instantaneous speed and acceleration/deceleration profiles, and also account congestion and local conditions more appropriately to estimate the emission. The IVE model used by several Asian countries (China and India) for estimating the impacts of fleet technology improvements, traffic-flow improvements, and fuel modifications on criteria

pollutants, toxics, and global warming gases from on-road vehicles (Wang et al., 2006; Hui et al., 2007; Oanh et al., 2012; Shrestha et al., 2013; Shah and Zeeshan, 2016).

Traffic congestions have undesirable impacts on city centres and urban dwellers (Levy et al., 2010). Several policies exist in different countries to reduce traffic congestion and its menace (Lawphongpanich et al., 2006; Lindsey, 2006 and 2010). But the increasing numbers of vehicles, especially on urban centre do not provide optimal benefits of a policy. Therefore, better approach is still needed to balance supply and demand with growing urbanization.

2.6 IMPACT ON GHG EMISSIONS

Globally, the transport sector's contribution to total CO₂ emitted from fuel combustion is around 23%, of which road traffic is responsible for almost three-quarters (Van der Hoeven, 2012). The urban road networks, in Texas, carrying increasingly large numbers of vehicles are adding large amounts of tail-pipe emissions, including both greenhouse gases (GHGs) and pollutants detrimental to air quality (Schrank and Lomax, 2007). This problem is exacerbated by the stop-and-go nature of congestion (Grote et al., 2016). According to Unger et al. (2010) in New York motor vehicles have emerged as the greatest contributors to atmospheric warming. Teddy (2006) reported that in New Delhi, India road, rail and air are responsible for CO₂ emissions of 80%, 13% and 6%, respectively. Ramachandra and Shwetmala (2009) described that in India the contribution of CO₂ to road transport about 94.5% (258.10 Tg) during the year 2003–04. Edward Sullivan (2009), underlined that an understanding of the relationship between the road LOS policies and GHG emissions could help reduce the emissions related to global climate change in California. Public transport can save considerable CO₂ emissions for the same travel distance as compared to private travel modes (Sperling and

Salon, 2002). Barth and Boriboonsomsin (2008) carried out a study in California and found that the combination of different strategies such as congestion mitigation, speed management and shock-wave-suppression technique can reduce CO₂ emissions up to about 20%. ECMT (2007) stated that carbon and fuel taxes are the ideal measures for addressing CO₂ emissions. California Energy Commission (2005) emphasised on the vehicle technologies lighter and smaller vehicles to reduce CO₂ emissions from the transport sector. Further, improvements in terms of power train efficiency and alternative technologies like hybrid and fuel-cell vehicles can reduce emissions CO₂ (Emadi et al., 2008; Ong et al., 2011).

O’Ryan et al. (2002) studied the GHG scenarios for Chile and found that passenger travel consumes twice the energy of freight travel and urban travel consumes about 42% of the national transport energy. Under almost any scenario, vehicle use, energy use and GHG emissions would increase greatly during the coming decades (Kumar Bose and Sperling, 2002). Stone et al. (2009) analysed the effectiveness of smart growth development patterns and vehicle fleet hybridization to reduce the emission from mobile source and observed that compared to aggressive-smart-growth scenario, the growth in emissions under a business-as-usual scenario reduced by 34%. Whereas, the complete conversion of light vehicles fleet to hybrid-electric vehicles can offset the expected growth in emissions by 97% (Stone et al., 2009). Barth and Boriboonsomsin (2009) studied eco-driving strategies to reduce emissions including changing of driving behaviour by providing general static advice to the driver (e.g. do not accelerate too quickly, reduce speed, etc.). According to this study, providing dynamic advice to the drivers, it is possible to save 10–20% fuel and lower of CO₂ emissions without a significant increase in the travel time (Barth and Boriboonsomsin, 2009). Henser (2008) evaluated a number of policies potential for reducing CO₂ emission, which revealed that

traffic volume, speed, truck share, road grade and temperature influence CO₂ emission. Gruden (2006) suggested that CO₂ problem will be alleviated by the use of biomass as a raw material for biofuels and as a carbon dioxide sink. Leighty et al. (2012) developed several transition scenarios for meeting California target of GHG emission reduction below 80% of 1990 by 2050 from transportation sector of California by focussing more on light-duty vehicles (LDVs).

Transport related CO₂ can be reduced by strategies such as vehicle-fuel economy, fuel carbon-content and a vehicle mile travelled (Cervero and Murakami, 2010). Schipper (2001), who studied the interaction between transport policy and CO₂ emissions in the world, reported that practices like car-free Sundays are useful measures. According to Ramachandra and Shwetmala (2009) the consumption of energy in the transport sector of India during 2005–06 was about 17% (36.5 mtoe, million tons of oil equivalents) of the country's total energy (217 mtoe) that included coal, diesel, gasoline and electricity. According to Li (2011) over the period of 1991–2005, energy consumption from urban transport by 23 major urban cities in India was more than doubled, growing from 103–209 pJ (petajoule), and carbon emissions increased from 7.9–15.3 mt. In a study of Azomahou et al. (2006), per capita CO₂ emissions in India followed upward trend with respect to economic development.

Therefore, transport infrastructure provisions in cities which reduce congestions, fuel consumption, improve traffic-flow and so on play an increasingly important role in GHG mitigation.

2.7 CONGESTION MITIGATION POLICIES

A number of policies is developed and implemented to manage the traffic demand in many countries (Seik, 2000; Lee et al., 2003; Eliasson and Mattsson, 2006; Hensher and

Puckett, 2007; Odeck and Brathen., 2008; Guo et al., 2008; Eliasson et al., 2009) to reduce traffic congestion events. There are two common ways to alleviate traffic congestions, i.e. increase road capacity (i.e. supply) or reduce traffic (i.e. demand), of which increasing capacity does not fetch the desired results because of the limitation on capacity which may be engrossed by induced travel demand (Goodwin, 1996; Hansen and Huang, 1997). For example, Gokhale (2012) studied the comparison of emissions and air quality at an intersection and a roundabout and found that pollutant emissions are several times higher at intersections as compared with the roundabouts because at roundabout traffic-flow is continuous although speed is bit reduced. Thus, structural changes in the existing infrastructure may also reduce congestion and associated problems, which however may not be practical always (Maitra et al., 2004).

Therefore, several studies have addressed demand management as a tool to resolve congestion events (Meyer, 1999; Gärling et al., 2002; Eriksson et al., 2010). Beevers and Carslaw (2005) studied the congestion charging scheme adopted in London and analysed the impacts on air quality. They observed the reduction in emissions by about 12% in the charging zone. Similar scheme when tried in Stockholm in 2006, demonstrated that urban road toll scheme improves travel time and traffic-flow resulting into positive economic and environmental impacts (Eliasson et al., 2009). Creutzig and He (2009) reported that joint demand and supply policies are substantial in reducing the damaging impacts of transportation. Many cities during the same time era adopted congestion charging or low emission zones to reduce both traffic congestion and health impacts of traffic emissions (Yang and Huang, 2005; Lawphongpanich et al., 2006; Lindsey, 2006; Tsekeris and Voss, 2009; Lindsey, 2010). Singapore introduced road pricing scheme for demand management long back for example, manual area licensing

scheme started in 1975 and subsequently an Electronic road pricing system in 1998 found efficient and effective in curbing traffic congestion (Seik, 2000).

A simple quantity control method, such as plate–number–based road space rationing method is adopted by many Latin American cities like Mexico and Sao Paulo (Barter et al., 2003). These schemes fetched observable reduction in congestion and improvement in air quality under short–term rationing (Han et al., 2010). Cai and Xie (2011) also reported the impacts of using an "odd and even number" and concluded that such traffic restriction policy may be effective as a short–term measure in dealing with a sudden increased transportation demand and congestion during major events. The driving restrictions often promote increase in the number of vehicles in circulation as well as a change toward old, cheap and polluting vehicles, which is demonstrated in Mexico (Davis, 2008; Mahendra, 2008). Viegas (2001) suggested that quality of the mobility system quite similar to the LOS scheme, in which, the prices across space, time and transport modes are managed to provide good quality service.

Chin and Smith (1997) and Seik (1998) studied the vehicle ownership quota system in Singapore in 1995 to control and limit the growth in supply of private vehicles. Goddard (1997) proposed a scheme of tradable vehicle use permits as a cost–effective complement for more effectively dealing with air quality and congestion. A few studies besides traffic congestion policies studied the wealth redistribution between motorists and the community. For example, Kockelman and Kalmanje (2005) proposed a credit–based congestion pricing, a revenue–neutral policy, wherein road tolls are based on the negative externalities associated with driving under congested conditions. Raux (2007) suggested a tradable driving rights scheme in urban areas with its potential for tackling

congestion and traffic-related pollution and found that allocating quotas of driving rights for free to urban inhabitants could be an alternative.

The pareto-improving scheme¹¹, equitable and acceptable pricing, was proposed by a few researchers (Song et al., 2009; Lawphongpanich and Yin, 2010) in which the problem of finding pareto-improving tolls was formulated as a mathematical program with complementary constraints, and proposed a solution algorithm via manifold sub-optimization. Liu et al. (2009b) and then Nie and Liu (2010) studied the static congestion pricing model and revealed that self-financing and pareto-improving scheme is a feasible road price-refunding system. Guo and Yang (2010) investigated pareto-improving congestion pricing cum revenue refunding schemes in general networks and established a sufficient condition for the existence of origin-destination specific.

There are three key traffic congestion management schemes, demand management, congestion charging and quantity control reported in the literatures. These have potential to reduce consequences of traffic congestion and also are practically adoptable. The successful implementations of which, however, depend on the coordinated efforts of proper regulation, management, public and political contribution (Viegas, 2001).

2.8 SUMMARY AND DISCUSSION

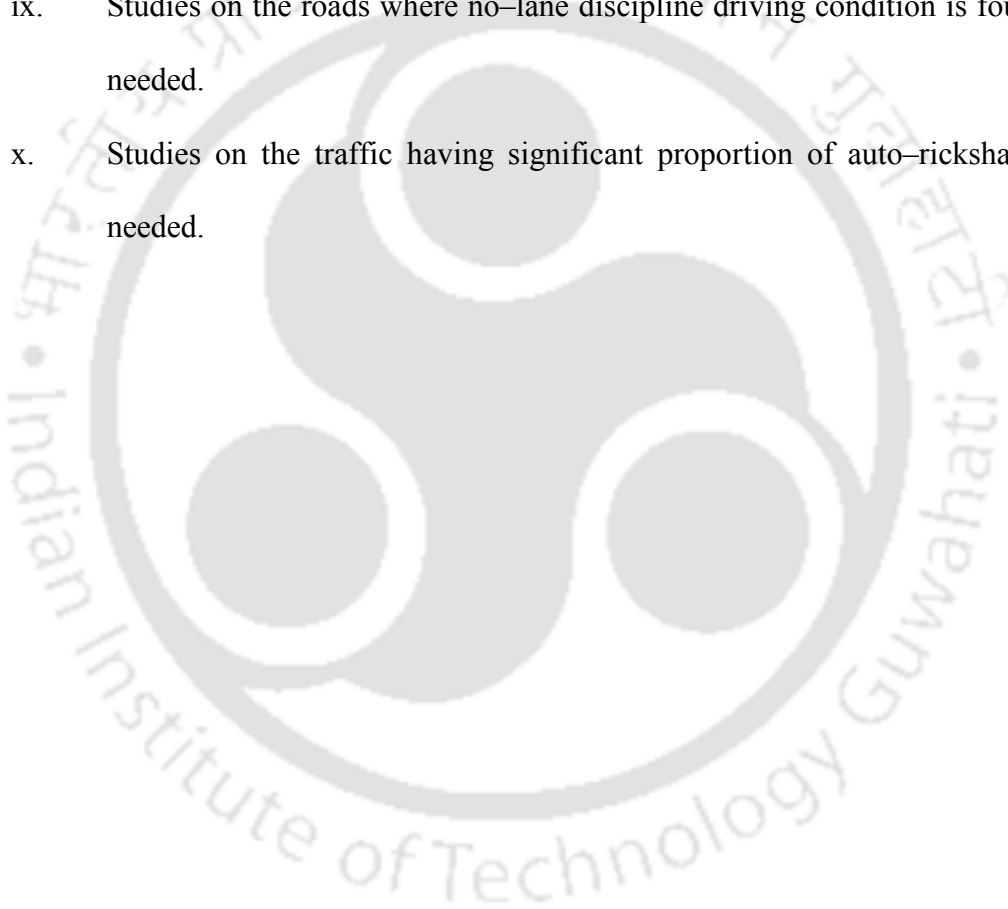
The foregoing discussion deduce that it is challenging to tackle traffic congestion in urban centres because of the involvement of several factors related to vehicles, traffic, infrastructure and even the way the traffic-flow management is done. There are several

¹¹ It is the phenomenon in which at least one individual becomes better off without anyone becoming worse off. Congestion tolls are considered if they reduce travel delay or improve social benefit and no user is worse off in terms of travel cost measured, e.g., in units of time (Lawphongpanich and Yin, 2010).

ways by which traffic congestion and concomitant emissions can be reduced. However, it has been perceived that there is no any single measure which can do so, instead, there is a necessity of combining the most possible measures depending upon the local conditions to deal with the traffic congestion and to reduce the related higher emissions. The following observations need attention of the researchers to arrive at a suitable understanding of the traffic congestions and impacts on emissions and air quality in urban areas:

- i. A thorough field measurement study of traffic–flow during congestion events including the share of each vehicle type different times of the day and simultaneous measurements of emissions and air quality is essential to determine the interrelationships.
- ii. More detailed studies relevant to impacts of traffic congestion events on emissions and air quality under different traffic–flow conditions e.g. free, interrupted, congested, are necessary to ascertain the principal component of the urban road network to reduce congestion.
- iii. The influencing factors need to be identified and quantified for accurate assessment of congestion events and emissions to model the resulting air quality during such events.
- iv. The potential changes in travel behaviour and vehicle technology are two major factors that complicate the evaluation of congestion mitigation effects on emissions.
- v. More research is needed to investigate under what conditions traffic–flow improvements contribute to an overall net increase or decrease in emissions.

- vi. Future research should be targeted on the evaluation of factors that are most critical and require urgent intervention from exhaust emissions viewpoint during congestions.
- vii. Researches to describe the impact and behaviour of different vehicle make and model on traffic congestion and emission are needed.
- viii. There is a need to investigate a traffic management framework that can suitably deal with frequent traffic congestion events in typical urban areas.
- ix. Studies on the roads where no-lane discipline driving condition is found are needed.
- x. Studies on the traffic having significant proportion of auto-rickshaws are needed.





Chapter 3

EXPERIMENTAL METHODS AND DATA COLLECTION

The Chapter describes the collection procedures, instrumentation and synchronization of data. For investigating the proposed research problems, a highly-trafficked stretch of an urban traffic corridor in Guwahati was selected. The field work includes the selection of a test-run route, test vehicles— passenger cars and auto-rickshaws, collection of traffic volume data, and on-road instantaneous speed and emission measurements. The scientific and standard methods have been followed for carrying out the field work and data collection.

3.1 SELECTION OF A STUDY REGION

A highly-trafficked stretch of an urban traffic corridor in Guwahati was selected for the study. This road segment represents typical urban traffic-flow with high traffic volume, mix vehicles, no-lane discipline, frequent interruption and congestion due to interaction with pedestrians and vehicles. Further given the characteristics of the road segment, it may be possible with the proposed research objectives to develop traffic management plan to reduce emissions and thereby air pollution exposure. Such a nature of traffic corridor and traffic-flow is observed in other urbanised Indian cities. Figure 3.1a shows a map of the study region with a test-run route and Figure 3.1b shows the traffic-flow on the test-run route taken at camera point 1. The test-run was of 3.8 ± 0.2 km long, double lane, of 16 m wide each. The study was conducted in the month of March 2014. The traffic corridor houses a

number of offices, commercial shops and, therefore, attracts a large volume of traffic and people. Due to frequent interactions of vehicle to vehicle and of vehicles to people, traffic-flow is interrupted most of the times, while during peak hours, longer stoppages at signals lead to severe congestion. The test-run route has intense development around and experiences frequent pedestrian interruptions. The traffic signals, bus stoppages and roadside parking are not regulated, which significantly impact the traffic-flow patterns on the route, affecting the level of service. There is no parking on the road however, and roadside parking is observed all times of the day and due to mix traffic-flow several lanes are formed in each direction particularly during peak hours. As seen from the Figure 3.1b, the traffic on the test-run route is mixed with a larger share of passenger cars, auto-rickshaws and two-wheelers. The road segment does not have traffic lights and both the lanes are heavily trafficked by cars, particularly, during peak hours.

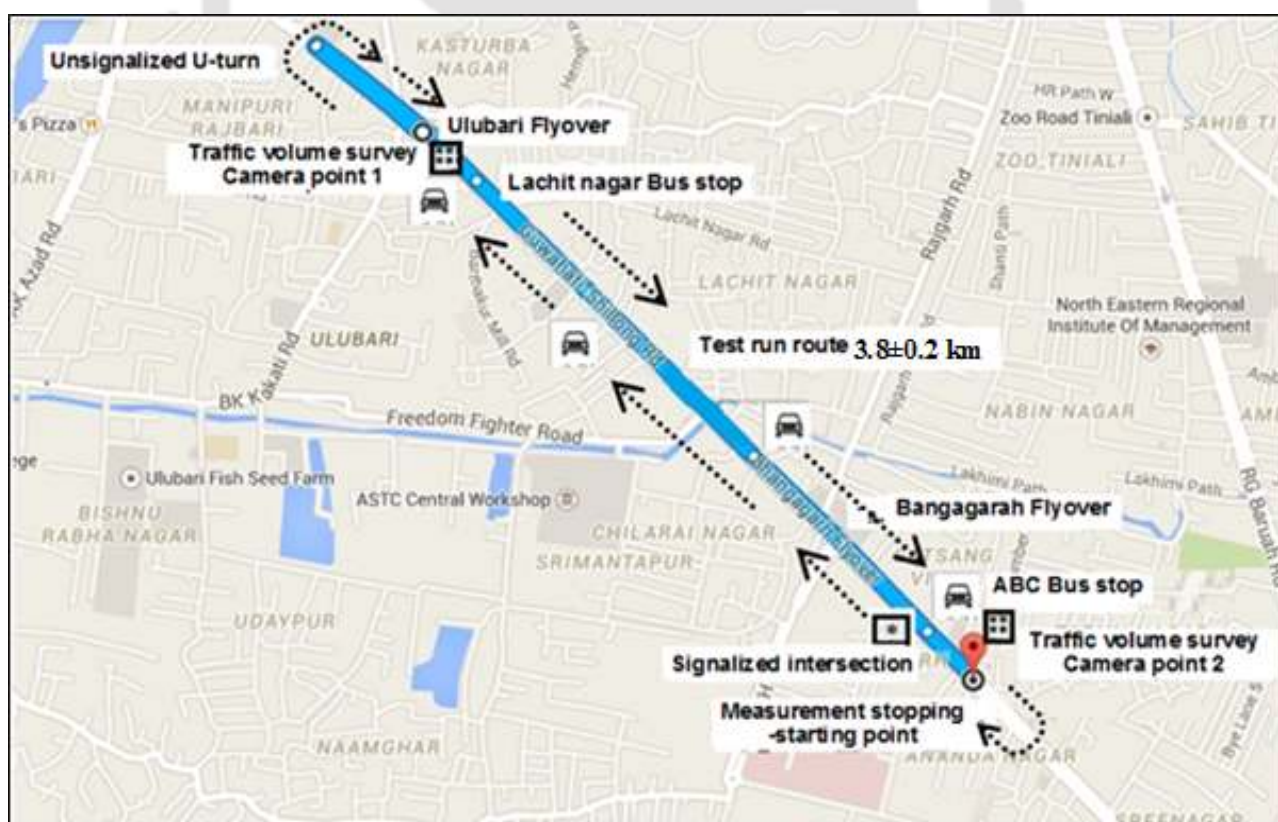


Figure 3.1a Test-run route in the urban centre of Guwahati (Source: Google map, accessed on 25 January 2015)

3.2 FIELD MONITORING

Field work was carried out to collect traffic volume data, tail-pipe instantaneous emission data of the test vehicles (passenger cars and auto-rickshaws) along with the vehicle speeds.



Figure 3.1b Section of the test-run route taken at camera point 1

3.2.1 Traffic volume

The traffic volume count was done with a video camera placed near the turning point at Ulubari flyover at camera point 1 (Figure 3.1a). It was done for a full week, each day twelve hours from 7 am to 7 pm (March 1–8, 2014). Another video was placed near the Bhangagarh flyover at camera point 2 (Figure 3.1a) during the test vehicle runs. The videotapes were analysed manually for a 100 m stretch on the road from the camera point 1. Such method has also been followed by Robertson (1994). The data were also analysed to determine traffic-flow patterns and traffic composition. The videotapes analysis revealed that traffic volume, commercial activity, and roadside parking on the both lanes were similar.

The traffic composition was classified into four categories– two-wheelers (scooters, motorbikes and moped; 2W), three-wheelers (auto-rickshaws; 3W), four-wheelers (cars, jeeps and medium-utility vehicles; PC-MUV), and light-heavy commercial vehicles (bus, minibus and small trucks; LHCV). The speeds were estimated for each category vehicle for 5 min travel time. Similarly, the videotapes of camera point 2 were analysed for speeds and traffic count to calculate traffic density (veh/km), which describes the traffic-flow condition on the road.

3.2.2 Test vehicles

The results of the social survey and the analysis of the videotapes revealed that a large proportion of cars comprising of brands Eon, Omni and Wagon-R and 2-stroke auto-rickshaws ply in the traffic corridor. In order to bring representativeness of the traffic fleet in the corridor these cars were selected arbitrarily of three different mileages and similarly auto-rickshaws of two different mileages. The test vehicles specifications are tabulated in Table 3.1.

3.2.3 Instrumentations

The real-world measurements of instantaneous speed, acceleration, deceleration and tail-pipe emissions of passenger cars and auto-rickshaws were measured for both the directions of road segment with an auto-gas analyser and a V-Box.

Table 3.1 Test vehicle specifications

SN.	Specification	Passenger cars			Auto-rickshaw	
		Eon	Omni	Wagon-R		
1	Mileage	9,200 km	52,000 km	142,000 km	45,000 km	100,000 km
2	Manufacturer	Hyundai	Maruti suzuki	Maruti suzuki	Bajaj	Bajaj
3	Weight (kg)	725	785	885	335	335
4	Max power (bhp)	55@ 5500 rpm	35@ 5000 rpm	67@ 6200 rpm	7@ 500 rpm	7@ 500 rpm
5	Engine displacement (cc)	814	796	998	145.45	145.45
6	Bore×stroke (mm ²)	67x77	68x72	68x60	57x57	57x57
7	Cylinder no.	3	3	3	1	1
8	Euro standards	III	III	III	none	none

3.2.3.1 Auto-gas analyzer

The auto-gas analyzer (make: INDUS Scientific Pvt. Ltd., model: PEA205) is used for testing emissions at ambient temperature and pressure from automotive engines, driven on petrol, CNG and LPG (INDUS Scientific Pvt. Ltd). It is designed and manufactured as per the international standards (ISO 3430) and national standards as per specifications issued by the Indian Ministry of Transport and Highways (MoRTH/CMVR/TPA-115/116). The analyser logs the data with RS323 interface into the computer. It uses non-dispersive infrared (NDIR) method to detect CO, CO₂, and HC emissions and electrochemical cell for O₂ and NO_x emissions. The auto-gas analyser measures nitric oxide (NO) as NO_x. The installation of the analyzer to light duty vehicle takes about 15 min and additional 20 min for the initial calibration, which involves device zeroing and heating of the sample line. The zeroing is done to prevent the drift of the analyser. The range of pollutants and the other specification of the analyser given by the manufacturer are tabulated in Table 3.2. Figure 3.2 shows the auto-gas analyser. It has two external connections, a power cable connected to an independent battery, and the emission sampling probe to be inserted into the tail-pipe.

Table 3.2 Specifications of auto–gas analyser

Pollutant	Range	Data resolution	Accuracy
CO	0-15 %	0.01 %	± 0.06 % vol.
CO ₂	0-20 %	0.01 %	± 0.50 % vol.
HC	0-30000 ppm	1 ppm	± 12 ppm vol.
NO _x	0-5000 ppm	1 ppm	Not available



Figure 3.2 The auto–gas analyser

3.2.3.2 V–Box

The V–Box measures instantaneous speed, position of the vehicle and record data with 10 Hz data–logging frequency (Figure 3.3). It is used for the measurement of speed and the position of a moving vehicle, based on a range of high performance GPS receiver (3 to 1.8 m). It also has two video cameras as its important components for recording of the front and rear view of the test vehicles. The data are recorded onto a compact flash or SD (secure digital) card by the V–Box.

3.2.4 Instantaneous tail–pipe emission and speed

The instantaneous measurements of emissions and speeds were carried out on both the directions of the test–route by integrating the auto–gas analyzer and V–Box with a computer and camera. Each test vehicle was run at three different times of the day to capture the real characteristics of the range of speed and acceleration, deceleration of urban traffic. During each time, test–run was repeated to produce at least two sets of data

and each run lasting for 25 to 45 min depending upon the traffic on the road. Tests were carried out during 7:00–8:30 am, which is an off-peak time, during 10:30–11:30 am, which covers the morning peak time and 4:30–5:30 pm, which covers the evening peak time. These time periods are described as off-peak hours (OPH), morning peak hours (MPH) and evening peak hours (EPH) respectively.



Figure 3.3 The V-Box with its accessories

The Figure 3.4 shows the probe connection of auto-gas analyser to the tail-pipe of the test vehicle, passenger car. Figure 3.5 shows the data logging system kept inside the test vehicle and Figure 3.6 shows the V-Box video screen during the test run. The emissions of CO, CO₂, HC, O₂ and NO_x were recorded every second and the speed every one tenth of a second. Since two separate instruments were used, four stopping points on the test-route were selected to enable manual synchronization. Two at the starting point, near camera point 2, and two at the turning point, near camera point 1. At these four stopping points, the test vehicles were stopped until the auto-gas analyser shows the pollutants reading zero, and at this time the V-Box shows the speed zero, and then further run was completed.



Figure 3.4 Auto-gas analyser probe connection to tail-pipe of a test vehicle

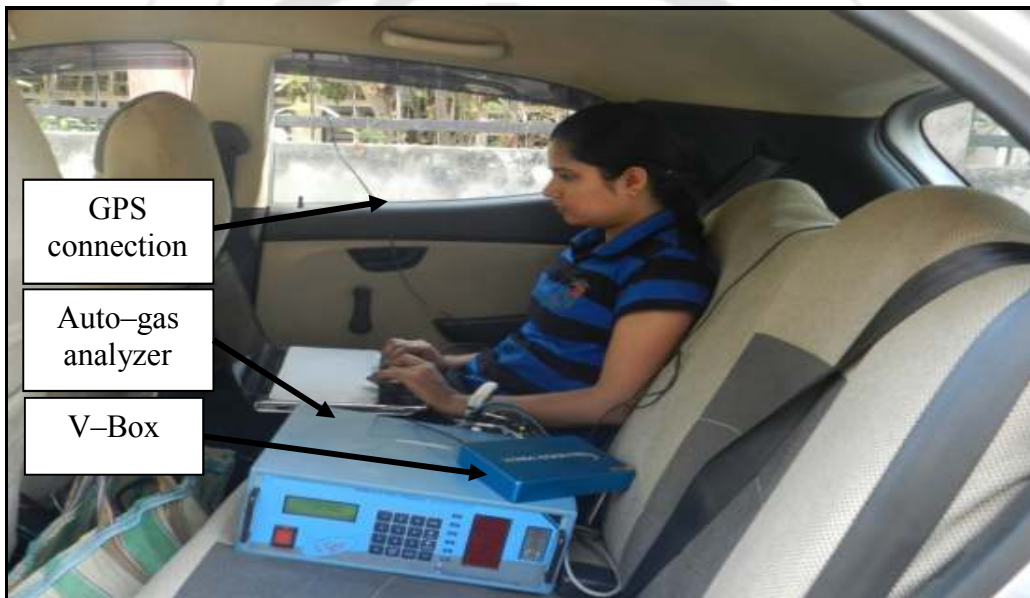


Figure 3.5 Data logging from auto-gas analyser and V-Box



Figure 3.6 V-Box video screens during a test vehicle run

3.3 SYNCHRONIZATION OF DATA

Since two different instruments were used for instantaneous emission and speed measurements, data synchronization was an important step. For proper synchronization of data files, four stoppage points were marked at the roadway stretch. Test vehicles were made to stop at these marked points. As the engine stopped, the V-Box recorded zero speed and auto-gas analyzer recorded the pollutants concentration zero. This was the first step of data synchronization, which was done during the test-run itself. These four marked points show zero readings in data files, which were used to combine two files into a single file. The V-Box videos were helpful in visual synchronization of speeds and emissions data. The recorded video of V-Box, shows the speed of vehicle with time and traffic-flow conditions at the same time (of the front and rear view), as shown in Figure 3.6. The steps of data synchronization are shown in Figure 3.7. The Appendix-I presents a raw data file of auto-gas analyzer and Appendix-II shows synchronized data file.

The instantaneous mass emission rates of CO, CO₂, HC, and NO_x of the passenger car and auto-rickshaw, in g/s, were calculated by method described by Saini et al. (2013) as given by equation 1. This was done to relate instantaneous emission with the accelerating /decelerating events and instantaneous speed.

$$E_{(g/s)} = \left((M_{af} + F_f) \cdot M_Q \cdot Q \right) / M_{exh} \quad (1)$$

where, M_{exh} is the exhaust molar mass, F_f the instantaneous fuel flow rate, M_{af} the mass air flow, $E_{(g/s)}$ the emissions rate, Q the fraction of exhaust gases, and M_Q is the molecular weight of the exhaust gases.

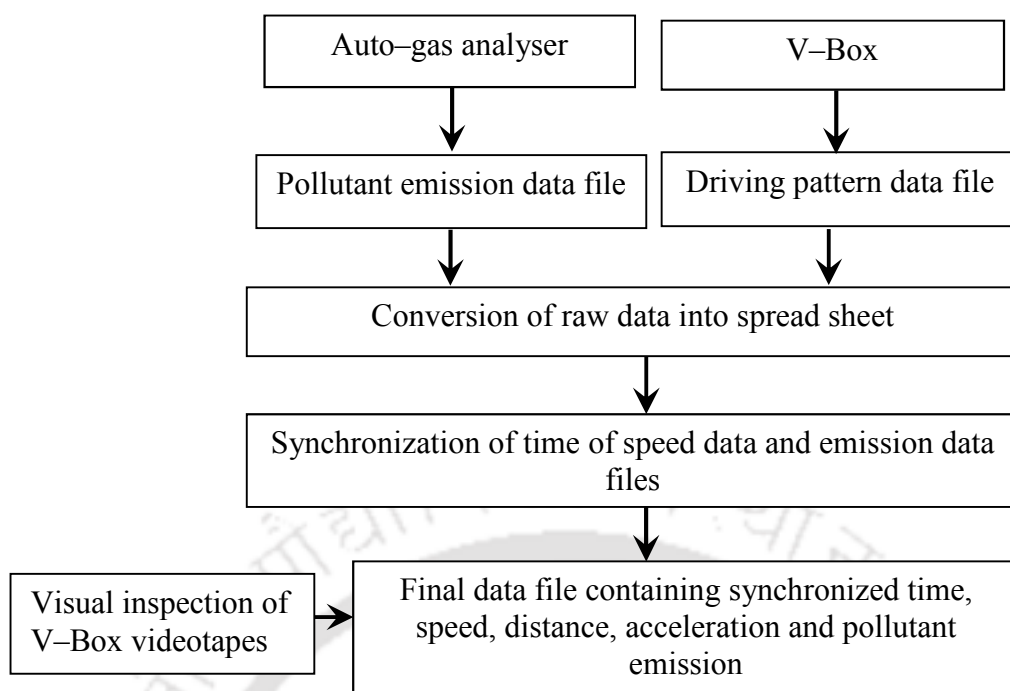


Figure 3.7 Data synchronization

3.4 DATA INPUTS FOR ANALYSIS

The vehicle emission rates are largely related to vehicle characteristics, including vehicle classification, vehicle specification, operating conditions and environmental condition (Ntziachristos et al., 2009). The vehicle characteristics includes vehicle category, fuel type and vehicle emission control level; vehicle specification involves vehicle age, accumulated mileage, inspection and maintenance; the operating conditions includes cold or hot starts, average and instantaneous vehicle speed; the environmental condition includes ambient temperature, humidity and altitude. This study used two models to estimate the emission factors, an average speed based COPERT-IV model and an instantaneous speed based international vehicle emission (IVE) model, both require different input information.

In COPERT-IV model, emission factors are a function of average travel speed, fuel quality, ambient temperature and ageing (Ntziachristos et al., 2009). The emission

factors were calculated by using the unique equation, which was selected based on the vehicle classification (Chapter 5, Table 5.5), fuel type, average speed and mileage. The details of test vehicle speed (Chapter 4, Table 4.1), fuel type and other vehicle specification (Table 3.1) collected to run the model. The IVE model needs instantaneous speed, vehicle start-up and stop numbers, vehicle specification (Table 3.1), and share of different vehicle types on fleet and composition (Chapter 4, Figure 4.1 and 4.2) and the environmental conditions including ambient temperature, humidity and altitude. For IVE, road side parking and personal users of vehicle were surveyed for identifying the average age of vehicles plying in the selected study region and found that the fleet comprises mostly 5–7 year old cars and three-wheelers. The instantaneous speeds of test vehicles (passenger cars and auto-rickshaws) were recorded by using the V-Box. Meteorological parameters such as ambient temperature and relative humidity were recorded simultaneously by a weather monitoring instrument (make: Envirotech Instruments Pvt. Ltd., model no. WM251).



The strength of a study lies in the quality and resolution of the data. The data on traffic and instantaneous speed related emissions were primarily collected, processed and analysed to obtain meaningful description for studying the impacts of traffic and its various characteristics on the emission.

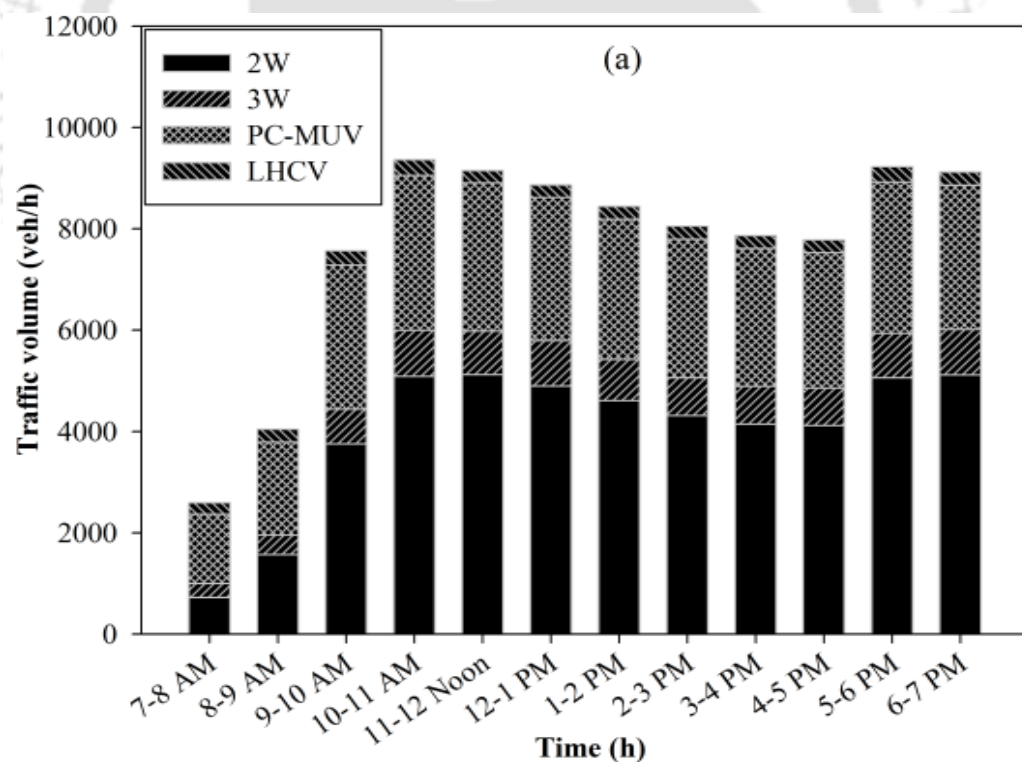
4.1 TRAFFIC-FLOW CHARACTERISTICS

The videotaped real-time traffic at camera point 1 (Chapter 3, Figure 3.1a) was studied in lab for determining various characteristics such as the composition, speed and various traffic-flow patterns for both lanes of the road segments.

4.1.1 Traffic-flow rate

Figure 4.1 and 4.2 shows the hourly variation of traffic-flow of different category vehicles on working days, averaged from Monday to Friday and non-working days, averaged from Saturday to Sunday, combined from both directions. The error bars in Figure 4.2 show hourly standard deviations. The traffic-flow on both working and non-working days exhibits a typical trend with two peaks, around noon-time and in the evening. The lowest traffic was observed during 7–8 am in both cases and higher traffic during 10 am–12 noon and 4–7 pm, on working days, whereas, on non-working days, it was observed during 11 am to 1 pm and 6–7 pm. However, the traffic composition changed every hour, especially the proportion of two-wheelers and three-wheelers but

only 5 to 7% change were found between working days and non-working days traffic composition. The traffic-flow condition was assumed to be similar in both the directions on the road segment. However, heavy traffic was observed in both the directions throughout the day. Table 4.1 shows the descriptive statistics of hourly traffic volume and traffic speed for working and non-working days. The analysis shows that there is a slight difference in the mean value of traffic volume for working and non-working days whereas, mean value of the hourly traffic speed was found to be about same. The positive value of kurtosis coefficient of hourly traffic volume indicates that data distribution has heavier tails and a sharper peak than the normal distribution and the negative value of skewness of traffic volume suggest that distribution is toward left, whereas traffic speed data is slightly skewed toward right.



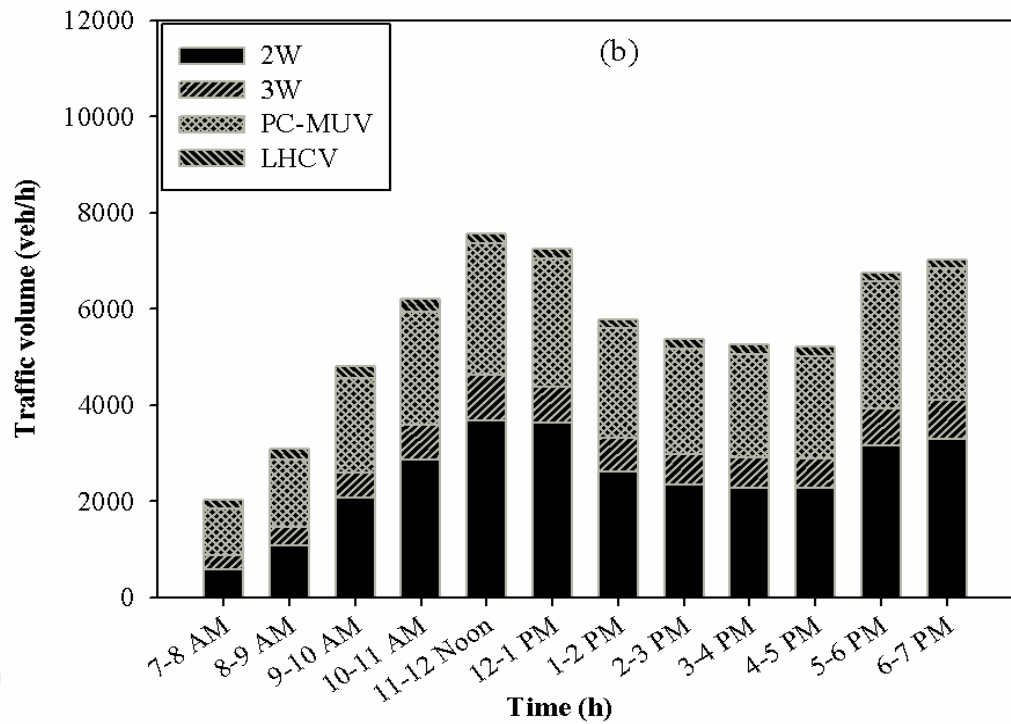
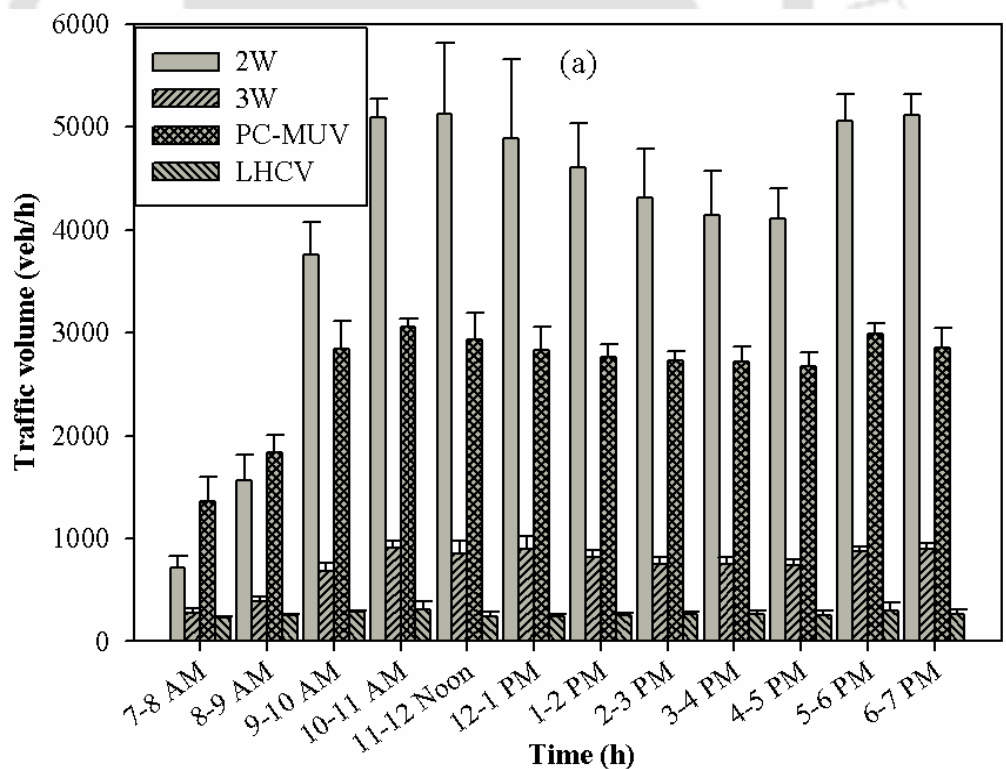


Figure 4.1 The hourly variation of the proportion of traffic composition for (a) working days (average of Monday to Friday), and (b) non-working days (average of Saturday to Sunday)



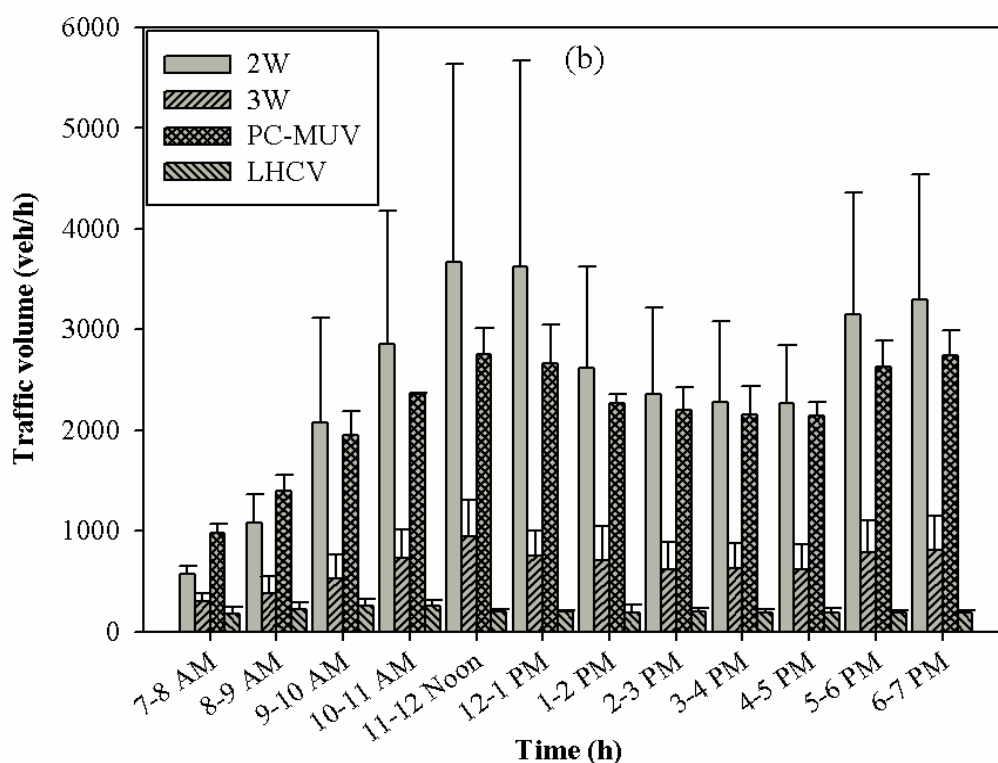


Figure 4.2 The hourly traffic composition for (a) working days, (average of Monday to Friday) and (b) non-working days (average of Saturday to Sunday), each with standard deviation as error bars

Table: 4.1 Descriptive statistics for hourly traffic composition and traffic fleet speed for working and non-working days

Descriptive Parameters	Working days		Non-working days	
	Hourly traffic volume (veh./h)	Hourly traffic speeds (km/h)	Hourly traffic volume (veh./h)	Hourly traffic speeds (km/h)
Mean	7676.0	33.5	5529.0	32.5
Std. error	621.4	3.2	479.8	3.2
Median	8245.0	32.2	5575.0	29.5
Std. deviation	2152.4	11.1	1661.9	11.1
Sample variance	4632925.8	123.9	2761911.6	122.0
kurtosis	2.4	0.4	0.5	1.1
skewness	-1.8	0.9	-0.9	1.3
Minimum	2591.0	19.7	2023	21.7
Maximum	9368.0	57.5	7576	57.5
Count	12	12	12	12

4.1.2 Traffic composition

The total traffic composition combined from both directions was observed to be around same (within 3%) from day to day, while that varied about 5 to 7% between working and non-working days as shown in Figure 4.3. It has been observed that about 87% of the total traffic was comprised of two and four-wheelers (2W+PC-MUV) followed by 9 to 10% of three-wheelers (3W) and mere 3 to 4% of buses (LHCV). During the OPH, PC-MUV and 2W shared each 52% and 28%, respectively, while during the PH, it was observed to be 34%, and 53%, respectively (Figure 4.3d, e and f).

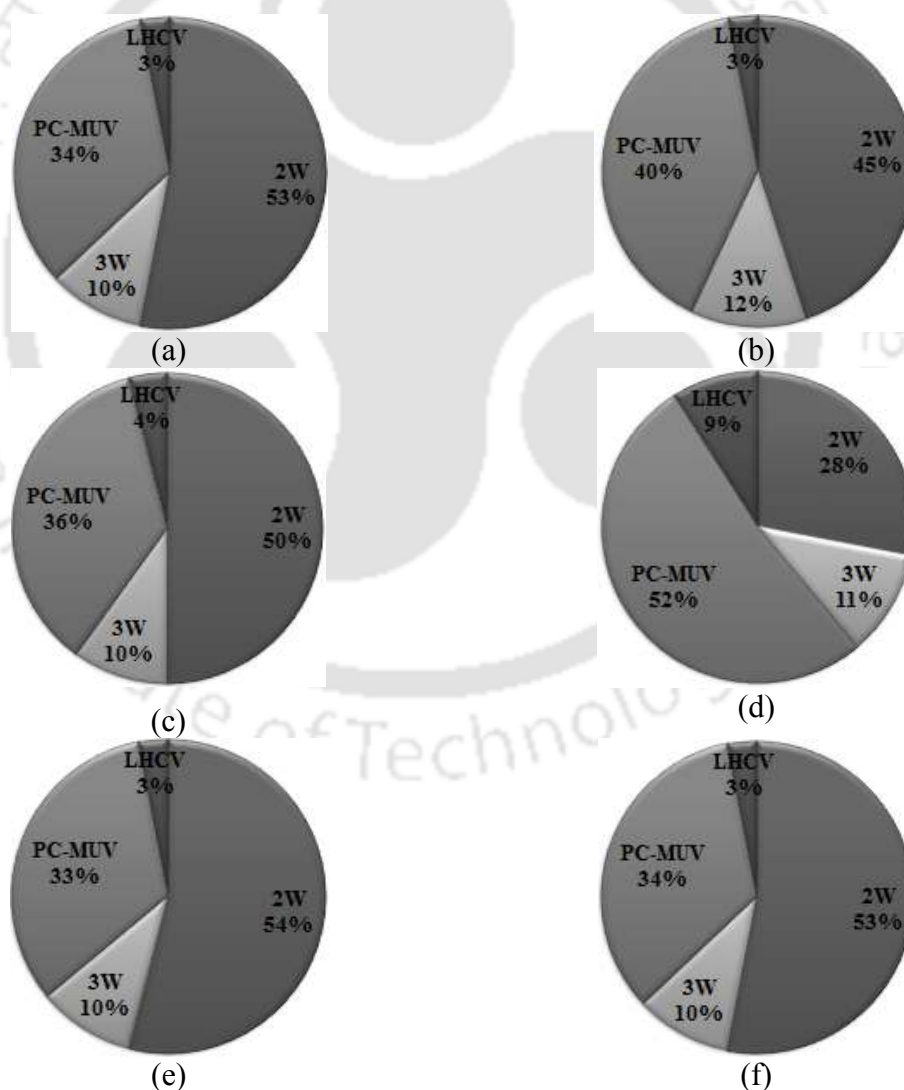


Figure 4.3 The vehicle composition for (a) working days (b) non-working days (c) a whole week, (d) morning off-peak 7–8 am, (e) morning peak, 10 am to 12 noon, and (f) evening peak, 4–6 pm

4.1.3 Traffic–flow vs speed

Traffic speed and volume are two important characteristics, which directly affect the traffic–flow on roads (Anjaneyulu and Nagaraj, 2009). Therefore, the time variation of speed due to traffic volume has been used to describe and define the traffic–flow patterns. The videotapes at camera point 2 (Chapter 3, Figure 3.1a) was analysed for traffic volume (veh/5 min) and traffic speed (km/h) for defining the various traffic–flow patterns. Three descriptive statistics were used to represent the relationship, viz.–average speed (AS) in km/h; velocity noise (VN) a standard deviation of speed in km/h and the coefficient of variation of speed (CV), the ratio of VN and AS. Figure 4.4 (a, b, c) shows the relationships of– AS, VN and CV with traffic volume (veh/5 min) in which the minimum volume suggests the free–flow condition and higher volume suggests the density near roadway capacity. As the traffic volume increased, the AS decreased and VN and CV increased, which after reaching the volume of about 400, dropped continuously indicating the higher level of vehicle to vehicle interactions, which further increases.

As traffic volume increases, the interaction between the vehicles increases, i.e. the speed of a vehicle is affected by the vehicles plying together with it, which results in the increase of variation in the speed, as has been observed from the sharp rise in CV and VN. Further, increase in volume forces a vehicle to reduce its speed. In this condition, fluctuation in average speed is less, which decreases the standard deviation and also decreases the ratio of VN/AS. Thus, these three characteristics (AS, VN and CV) together with traffic volume describe the three different traffic–flow conditions–

- I. Traffic–flow condition 1: shows slow increase in CV and VN at lower traffic volume and higher traffic speed.

- II. Traffic–flow condition 2: shows sharp increase in CV and VN with increasing traffic volume and decreasing traffic speed.
- III. Traffic–flow condition 3: as traffic volume approaches to near roadway capacity CV and VN decrease sharply that forces vehicles to crawl.

4.1.4 Traffic–flow patterns

The Figure 4.5 shows the best polynomial fits to the AS, VN and CV, which distinguish the traffic–flow patterns. The R^2 values were 0.95, 0.96, and 0.97 for AS vs traffic volume, AN vs traffic volume and CV vs traffic volume, respectively. The adjusted R^2 values were 0.94, 0.95 and 0.96 for AS vs traffic volume, AN vs traffic volume and CV vs traffic volume, respectively. The equations of fits and relevant statistics have been presented in the Appendix V. The three distinct zones have been identified from the CV and traffic volume relationship by taking tangents at the points of inflection, which resulted into two break points classifying in to three distinct levels of traffic–flow (Anjaneyulu, and Nagaraj, 2009). It has been observed that the speed characteristics show distinct zones with the increasing traffic volume. The best polynomial fits of AS, VN and CV with traffic volume show three distinct zones marked as Level 1, 2 and 3 based on speed gradient. The Level–1 represents the free–flow condition in which initially the traffic volume is less, the vehicular speed is more and the variation of speed (CV) is low indicating the least vehicle to vehicle interaction. As the traffic volume increases the CV sharply increases. This represents Level–2 in which a higher fluctuation in speed occurs due to phase transition from free–flow to random stop–and–go. The frequent stop–and–go causes higher deviation from mean speed and, therefore, a higher CV is observed. The Level–2 represents the interrupted traffic–flow condition. After this, vehicle to vehicle interaction increases and also traffic volume approaches to roadway

capacity, which forces the vehicles to crawl, leading to the decrease of CV. This represented the congested-flow condition, Level-3.

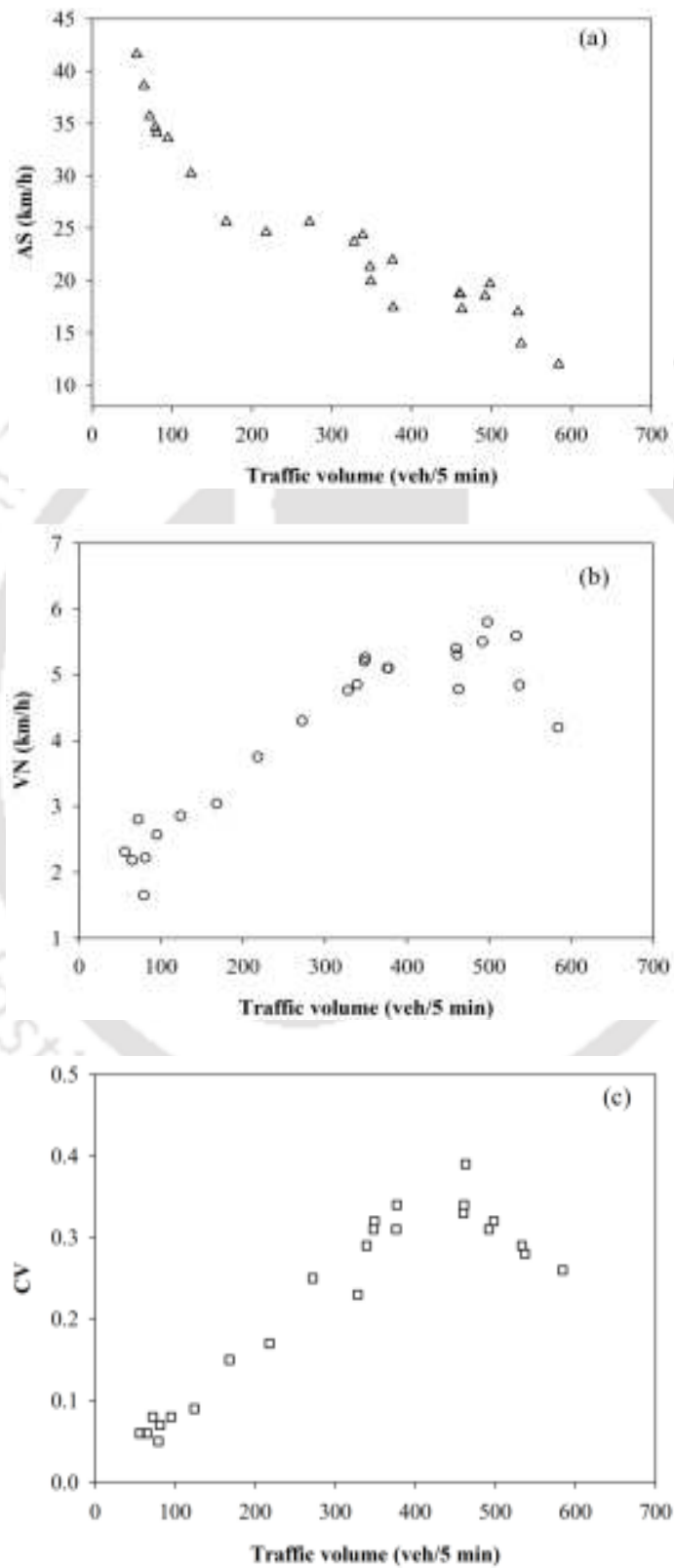


Figure 4.4 Relationship of traffic volume and speed for the test runs

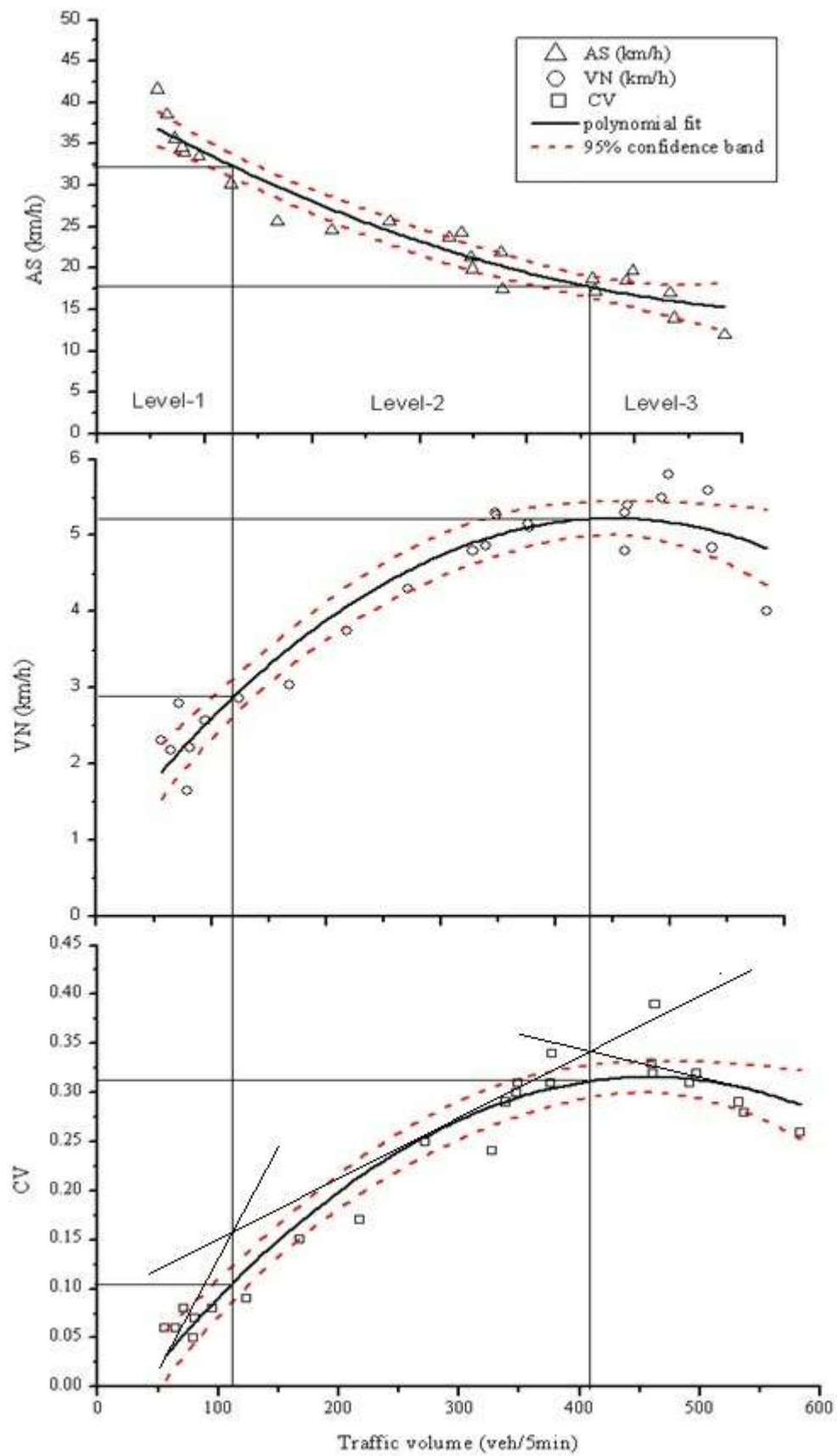


Figure 4.5 Different levels of traffic-flow patterns observed in the test runs

4.1.5 Instantaneous traffic speed

The emission is sensitive to speed (Andre and Pronello, 1997). As three traffic-flow conditions are observed at different speed characteristics, the emissions would also vary with the traffic-flow patterns observed. These three traffic-flow patterns during the test runs are free-flow (FF), interrupted-flow (IF) and congested-flow (CF). The corresponding vehicle speeds have been estimated from the instantaneous speeds. The V-Box files and videotapes were analysed for all test vehicles. Table 4.2 shows the average speed for different traffic-flow patterns. During the morning peak hours (MPH) and evening peak hours (EPH), about 50% of the total travel time, the test vehicles had a low speed of about 8 km/h \pm 4.0. The average vehicle speeds for FF was found to be 34 km/h \pm 3.7, for IF, it was 20.7 km/h \pm 3.9, and for CF it was 8.4 km/h \pm 4.2.

Table 4.2 Test vehicle speeds in different traffic-flow conditions

Test vehicle	Mileage in km	Vehicle speed during OPH (7–8 am) in km/h			Vehicle speed during MPH (10.30–11.30 am) in km/h			Vehicle speed during EPH (4.30–5.30 pm) in km/h		
		FF	IF	CF	FF	IF	CF	FF	IF	CF
Passenger cars	9,400	36.0±4.6	23.4±4.5	8.0±4.6	35.9±3.4	22.6±4.0	8.0±4.1	36.4±4.5	21.5±4.2	9.2±3.9
	52,000	37.1±4.6	23.7±4.2	8.4±4.9	33.7±3.3	21.5±4.2	7.4±4.1	NA	NA	NA
	142,000	33.2±4.0	23.3±4.1	7.7±4.6	35.9±4.5	21.4±4.3	9.7±4.0	34.0±2.4	20.9±4.0	8.2±4.3
Auto-rickshaws	45,000	35.6±3.6	24.0±4.4	6.5±4.4	32.9±2.2	22.3±4.3	7.8±4.5	32.4±0.9	14.0±4.1	9.6±3.8
	100,000	35.2±2.8	23.9±4.2	7.7±4.8	32.7±2.1	22.0±4.4	9.5±3.5	32.5±1.7	22.7±3.4	9.4±3.8
Average speed (km/h)		35.4±3.9	23.6±4.3	7.6±4.7	34.2±3.1	21.9±3.4	8.5±4.0	33.8±2.4	19.8±4.0	9.1±4.0

NA- due to technical problem occurred in auto-gas analyzer.

4.1.6 Frequency distribution of travel time and speed

The travel time of a vehicle to reach particular destination depends upon traffic density, which affects its speed (Akcelik, 1996). The Figure 4.6a and 4.6b shows the frequency distribution of vehicle travel time and speeds for passenger car and auto-rickshaw, respectively during OPH, MPH and EPH. It has been observed that during both MPH and EPH, the passenger cars and auto-rickshaws were travelled more at 10–30 km/h while during OPH it was 30–40 km/h. The speed limit on the road is 50 km/h but due to high traffic volume and mixed flow conditions travel speed rarely exceeds the limit.

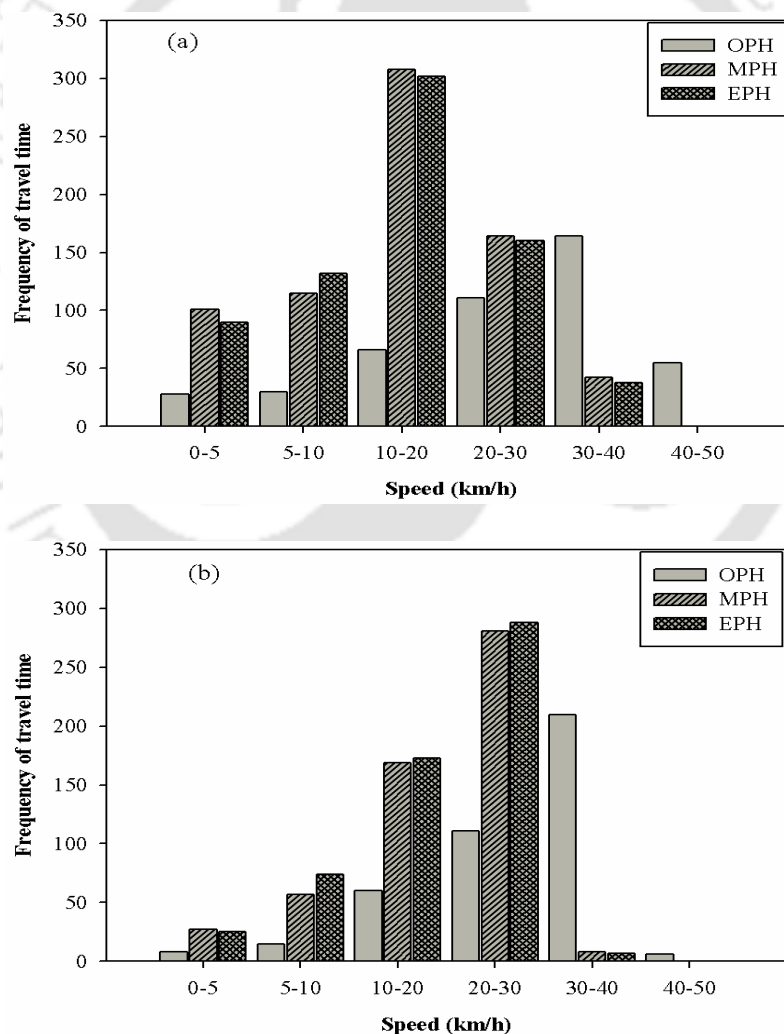


Figure 4.6 Frequency distribution of vehicle travel time and speed (a) passenger car, (b) auto-rickshaw during OPH and MPH and EPH

4.2 INSTANTANEOUS EMISSION ANALYSIS

The instantaneous emissions of CO, HC, CO₂ and NO_x were recorded for both the directions of test route with the help of auto-gas analyzer and compiled as per the synchronization procedure (Chapter 3, Figure 3.7). The V-Box data on acceleration and deceleration for every second were analysed separately for each test vehicle of different test runs (a typical synchronized data set is shown in Appendix II). The synchronized data was found to be logically in order and detailed analysis has been presented in subsequent Chapters.

4.3 SUMMARY AND DISCUSSION

The videotape analysis at the camera point 1 and 2 reveals the different composition of vehicles during different hours of the day. The descriptive statistics of traffic volume and traffic speed helped to classify the three different traffic-flow conditions. It has been found that during PH, passenger cars and auto-rickshaws mostly traveled in the speed range of 10–20 km/h and 20–30 km/h, respectively. Since, the emission is sensitive to speed and traffic-flow patterns and the share of particular speed range, this analysis is important to examine the relationship between emission rate and operating speed of the test vehicles for different traffic-flow conditions.



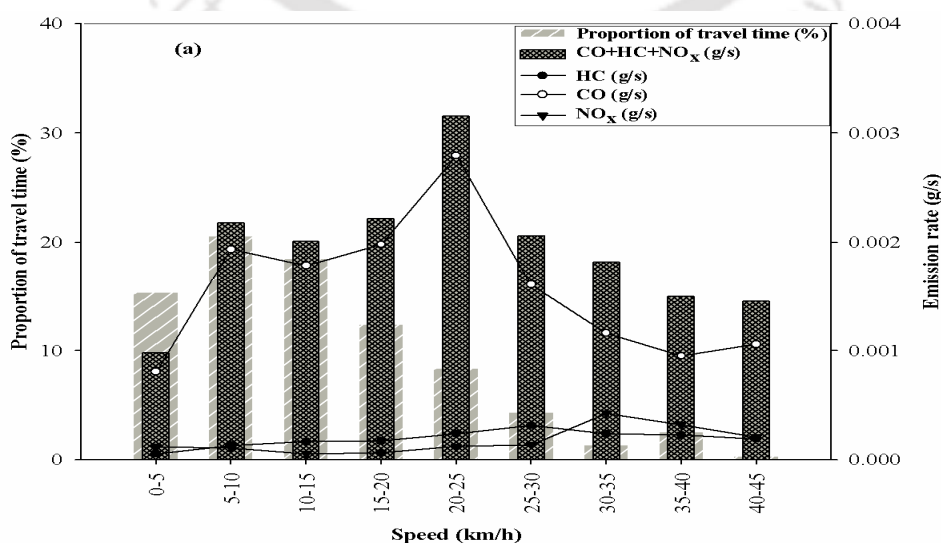
The exhaust emission is the result of a vehicle type and its operating condition on the road. The emission, therefore, directly depends upon the vehicle operating speed and its mileage.

5.1 TRAVEL TIME VS EMISSION IN DIFFERENT SPEEDS

The maximum vehicle speed was observed to be about 45 km/h against the speed limit of 50 km/h. The test vehicles during OPH had an average speed of 34 ± 3.7 km/h. The fleet had a large percentage of passenger cars and auto-rickshaws, as shown in Figures 5.1 and 5.2. During critical hours, i.e. PH, the average speed was reduced to 14.6 ± 1.5 km/h. The amount of time passenger cars and auto-rickshaws spent during PH and OPH in different speed intervals along with the total and pollutant wise emissions have been shown in Figure 5.1 (a, b and c). The bars indicate the proportions of time the vehicle spent in the corresponding speed range with the overlaid bars showing the total emission rate of CO, HC, and NO_x. The lines indicate the emission rate of CO, HC and NO_x. For over 70% of the time, the passenger car was in the speed lower than 30 km/h, out of which maximum time it was in 10–25 km/h, and, therefore, the emission rates during this speed range was also relatively higher, indicating that on urban roads during PH, traffic experiences constant change between interrupted and congested-flow conditions. The higher emission rate observed in the speed range of 35–45 km/h might be attributed to a sharp acceleration caused by some events. The emission rate for all the pollutants further

increased with increasing mileage as observed in Figure 5.1 (b) and (c) compared to Figure 5.1 (a). The speed distributions observed for different mileages of cars and auto-rickshaws were different, which could be attributed to the day to day variability. This might be because the test run for all different mileages were conducted on different days.

Similarly, the auto-rickshaw for about 80% of the time had speed less than 35 km/h in which for most time it was in the range of 10–35 km/h. The emission rate was also high for the speed range of 10–35 km/h. This indicates that on urban roads during PH, traffic experiences constant fluctuation between IF and FF conditions (i.e. 20–35 km/h). It has been observed that for similar mileage travel, auto-rickshaws emitted higher emissions as compared to the passenger cars (Figure 5.2a and 5.2b). During PH, several parameters such as travel time, traffic density, time in idle mode and congestion period increased. Table 5.1 shows the time spent by the test vehicles in different flow patterns during both PH and OPH. It was found that during PH, the test vehicles spent 12%, 48%, 32% and 8% of the total time in idle, congested, interrupted and FF conditions, respectively, which was observed to be exactly opposite during the OPH. Similarly, traffic density during PH was also much higher than that during the OPH. These characteristics correspond to both the direction of the test run during OPH and PH.



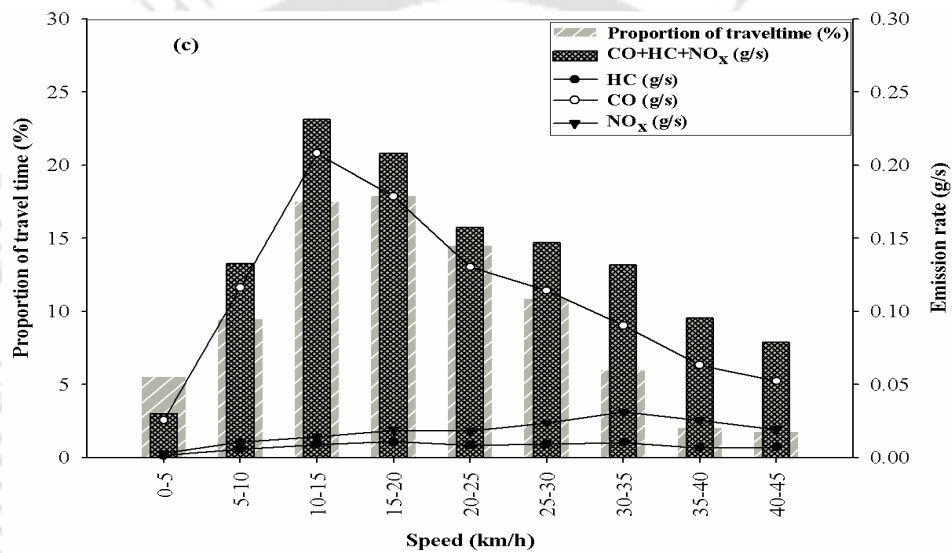
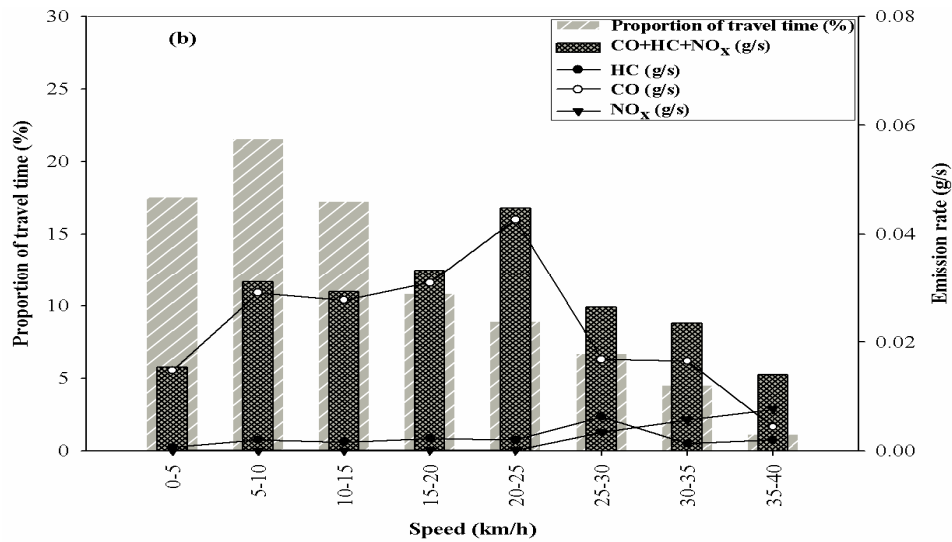
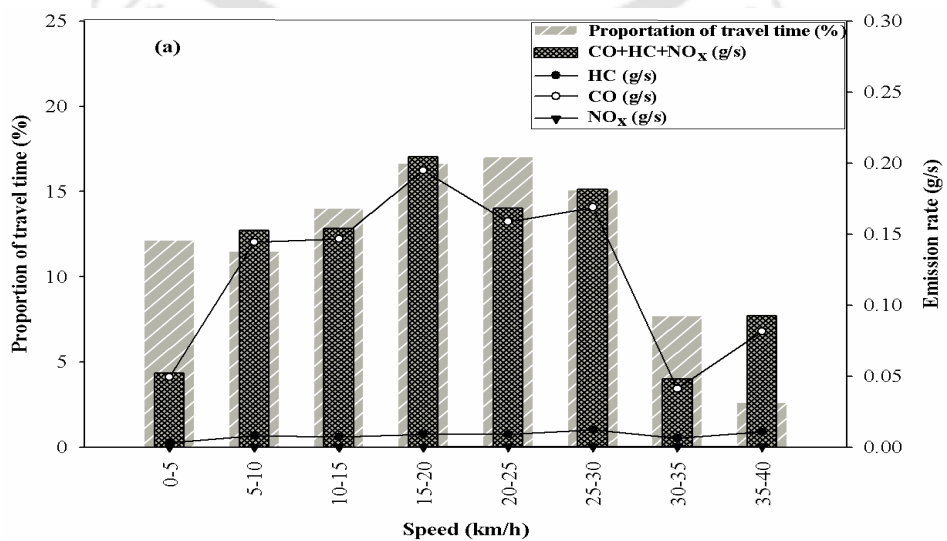


Figure 5.1 The emission rate and proportion of travel time distributions for different speeds and different mileages of passenger cars; (a) 9,200 km, (b) 52,000 km, and (c) 142,000 km



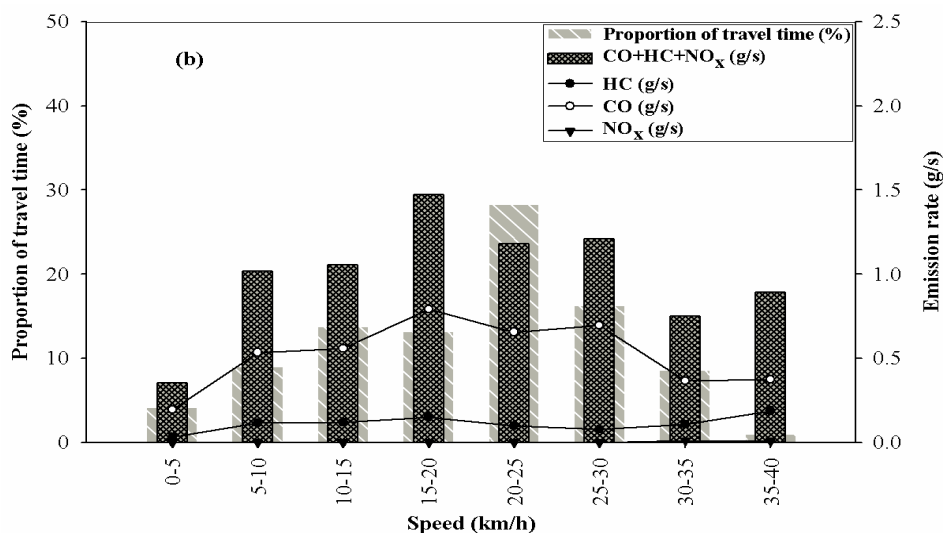


Figure 5.2 The emission rate and proportion of travel time distributions for different speeds and different mileages of auto-rickshaw; (a) 45,000 km, and (b) 100,000 km

Table 5.1 Traffic-flow characteristics during OPH and PH

S.No	Characteristics	OPH	PH
1	Distance (km)	3.8±0.2	3.8±0.2
2	Time (s)	477.0±43.0	904.0±93.3
3	Average speed (km/h)	34.0±3.7	14.6±1.5
4	Congestion period (%)	12.5±4.4	47.8±4.4
5	Interruption period (%)	16.7±2.0	31.6±3.7
6	Free-flow period (%)	64.9±1.5	8.3±2.0
7	Idle period (%)	5.9±1.0	12.3±2.8
8	Density ¹² (veh/km/lane)	31.0±4.0	373.0±7.0

5.2 INSTANTANEOUS EMISSION

The instantaneous emissions and speeds were analysed in real-world driving conditions for both the direction of test route and representative 300s were used to analyse the behaviour of instantaneous emissions and speeds. In the real-world driving, up to 50–60% of the emissions were emitted during sharp peaks lasting for short-times. Similar

¹² Travel time of each vehicle category was determined for 5 min difference during PH and OPH from the video tapes over 100 m stretch, which gives the speed of vehicle. Further speeds and traffic count (veh/h) data were used to calculate roadway density (traffic count divided by traffic speed gives traffic density).

findings have been reported in some studies (Frey et al., 2001; De Haan and Keller, 2000). It was found that the frequency of occurrence of short-lasting peaks depends upon the fluctuation in speed and driving pattern. For this, short-time traces of the test-runs of auto-rickshaw and passenger car during PH were analysed in detailed for examining the effect of sharp accelerating speed on emission levels. Figure 5.3 and 5.4 show passenger car and auto-rickshaw instantaneous emissions of CO, HC, NO_x and CO₂ for accelerating and decelerating speeds during PH. It was found that 70% of the time test vehicle had a speed of about 30 km/h with several stop-and-goes. It was observed that the frequent stop-and-go produced higher peaks in the emissions of CO, HC and NO_x. The stop-and-go pattern involves frequent gearshift and high-power interval (Elmi and Al Rifai, 2012) and the main causes of higher emission and, thus, increases the amount of emissions during PH. A sharp rise in emission rates was observed when the test vehicles encountered a sharp acceleration as well as deceleration lasting for 5 to 7 s. The highest peak in the pollutant emissions was observed during deceleration at around 121s (Figure 5.4). Similar observations are made by Zhang et al. (2011). These pollutants are emitted at higher rates during sharp peaks. These peaks occur for a small amount of time during the trip. Emission rates start increasing the same time when acceleration and deceleration starts increasing and reach highest levels and stay at that level as long as vehicle stays in that driving mode. During sharp decelerations fuel injection cuts off, which leads to the cylinder misfire producing higher emission puffs (Figure 5.4) (Goodwin and Ross, 1996; An et al., 1997). It has been further observed that CO₂ emissions follow the speed profile and sharp and continuous drops in speed also reduced the emissions. The results of this analysis for both passenger car and auto-rickshaw were indicative of the high emissions during sharp and continuous acceleration, irrespective of the low or high vehicle speed.

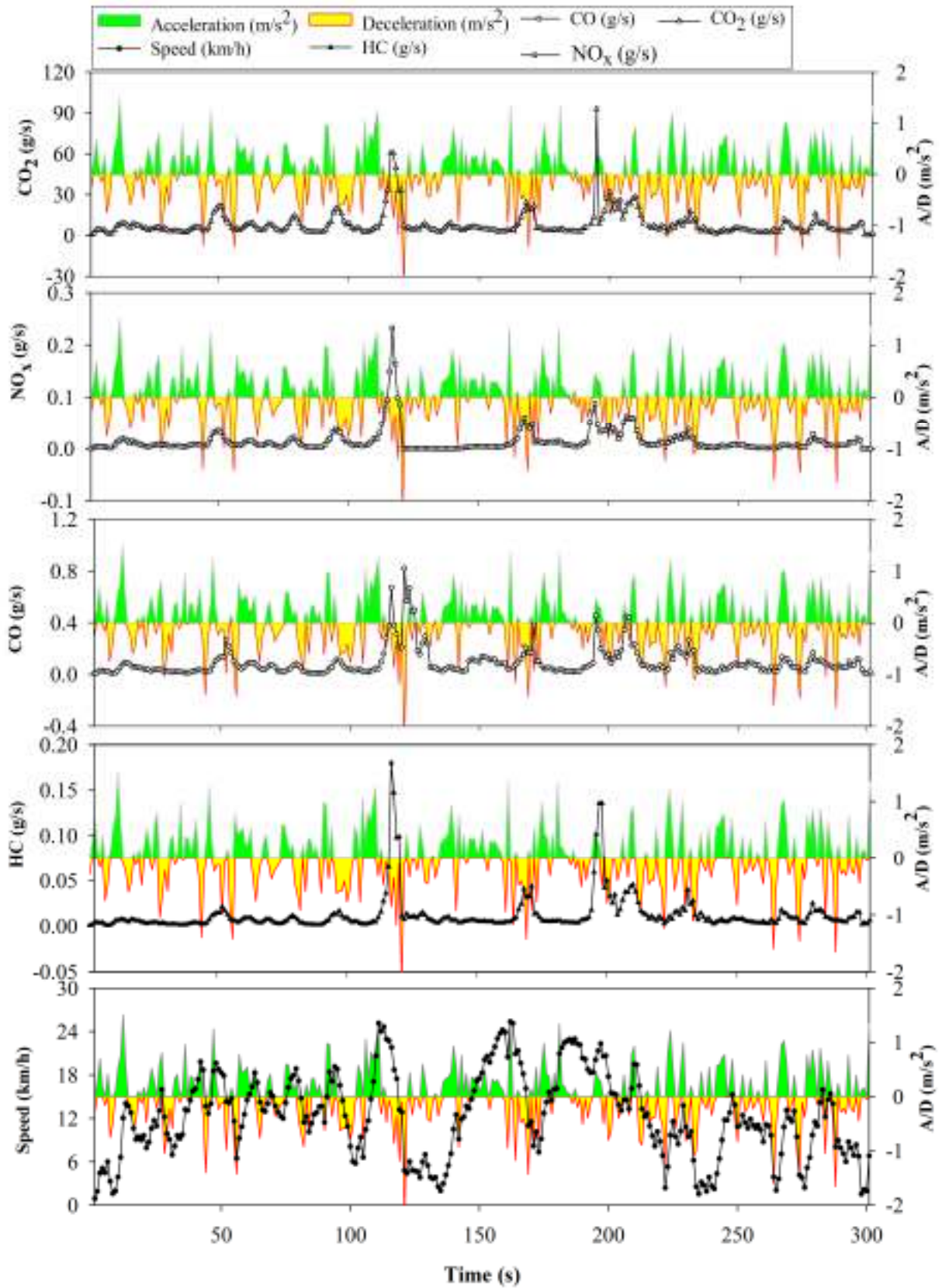


Figure 5.3 The instantaneous emissions of CO₂, NO_x, HC, CO and accelerating/decelerating (A/D) events with instantaneous speed for passenger car

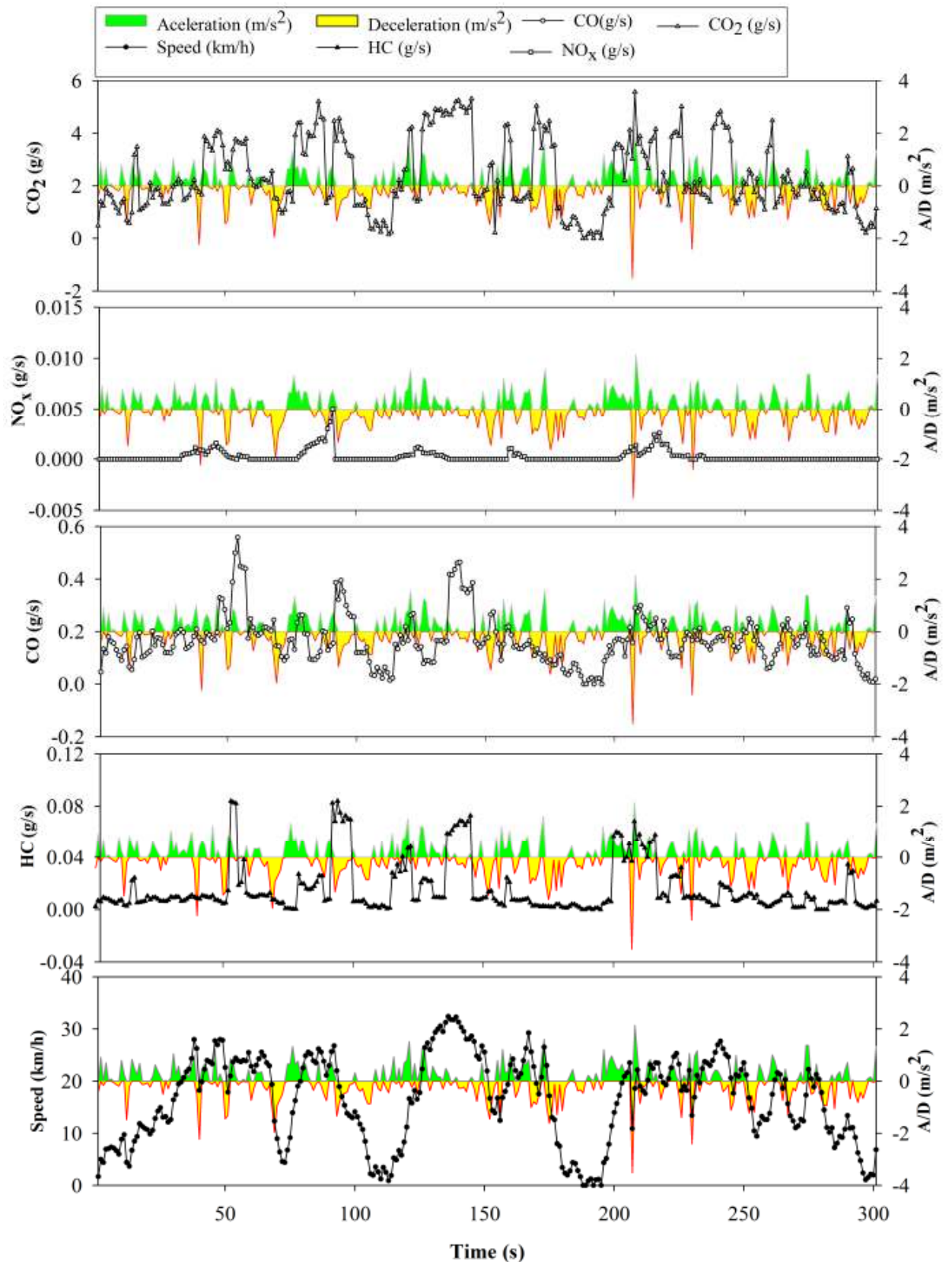


Figure 5.4 The instantaneous emissions of CO₂, NO_x, HC, CO and accelerating/decelerating (A/D) events with instantaneous speed for auto-rickshaw

5.3 EMISSION FACTORS BY TAIL-PIPE MEASUREMENTS

Emission factors (EF) vary with operation characteristics, vehicle age, vehicle category and model and with different control measures. Several studies reported the EF for passenger cars of different mileages, models and different roadway conditions as reported in Table 5.2. The literature reported the emission ranges of pollutants CO, HC and NO_x, 0.23 to 43.2 g/km, 0.02 to 4.3 g/km and 0.08 to 2.57 g/km, respectively (Fu et al., 2001; Yao et al., 2007; Wang et al., 2014 and Sahu et al., 2014). The measured EF of CO, HC and NO_x for passenger cars of different mileages and for different flow patterns also lie in between the already reported emission ranges, such as from 0.18 to 50.62 g/km, from 0.02 to 2.72 g/km and from 0.02 to 2.62 g/km, respectively. Similarly, a few studies carried out on Indian auto-rickshaw for pollutants CO and NO_x, reported the range from 1.37 to 4.30 g/km and from 0.11 to 0.20 g/km, respectively (Mashelkar et al., 2002; Sahu et al., 2014) and EF of HC as 2.05 g/km (Mashelkar et al., 2002). The measured EF for CO, HC and NO_x ranges from 6.81 to 76.94 g/km, from 1.02 to 17.67 g/km and from 0.02 to 0.76 g/km, respectively. This comparative analysis shows that the EF of pollutants depends upon several factors such as mileage, traffic-flow patterns, roadway conditions and vehicle type. The Table 5.2 shows the variation of EF according to different variables reported in the literature and Table 5.3 shows the variation of measured EF for different mileages and different flow patterns for passenger cars and auto-rickshaws.

For passenger car, measured EF of CO and HC were found to be about 3–4 times higher during CF (at average speed 8.5±4 km/h) and 1.5–2.5 times higher during IF condition (at average speed 21±4 km/h) as compared to the FF condition (at average speed 33±4 km/h). However, the measured EF of NO_x was about 1.5–2.5 times higher

during FF condition as compared to the CF. For auto-rickshaw, the measured EF of CO and HC were found to be about 2–8 times higher during CF and 2–5 times during IF as compared to FF condition and NO_x was 2–5 times higher during FF as compared to the CF. The Table 5.4 shows the EF for different mileage passenger cars and auto-rickshaws. For passenger car, for example, as mileage increased from 9,200 to 52,000 km and to 142,000 km the EF of CO and HC also increased considerably, e.g. for mileages from 9,200–52,000 km led to 6–12 times increase in the EF of CO, HC and NO_x and with the further increase in mileage to 142,000 km, the EF increased about 40–52 times from the EF observed for the vehicles with mileage of 9,200 km. During PH, the EF of CO and HC were 2–4 times higher as compared to OPH and of NO_x was about 2 times higher during OPH. For auto-rickshaw as mileage increased from 45,000–100,000 km, the EF of CO, HC increased about 3–8 times and of NO_x increased about 18 times. During PH, EF of CO and HC was found to be about 4–7 times higher from OPH and of NO_x was about 2 times higher in OPH.

Table 5.2 Emission factors from recent studies

Type of vehicle		Pollutants	EF (g/km)		Reference
			Freeway	Arterial	
Passenger car	14,800 mileage	CO	2.39	3.88	Yao et al., 2007
		HC	0.15	0.25	
		NO _x	0.08	0.11	
	>81,000 mileage	CO	3.66	5.92	
		HC	0.11	0.18	
		NO _x	0.40	0.58	
Passenger car			Model ≤ 2000	Model >2000	Wang et al., 2014
	CO	14.60±22.90	0.23±0.29		
	HC	3.19±5.04	0.02±0.02		
Passenger car, and three-wheeler	CO		2001-2005	2006-2010	Sahu et al., 2014
			1.37 (3W)	1.37 (3W)	
		1.30 (PC)	0.84 (PC)		
	NO _x	0.20 (3W)	0.20 (3W)		
			0.20 (PC)	0.09 (PC)	
Passenger car		CO	43.20		Fu et al., 2001
	HC	4.30			
	NO _x	1.60			
Auto-rickshaw		CO	4.30		Mashelkar et al., 2002
	HC	2.05			
	NO _x	0.11			
Light duty vehicle		CO	1.90–4.40		Steinemann and Zumsteg, 2003
	NO _x	0.60–1.80			
All type vehicles, tunnel study		CO	6.20±0.20		Kristensson et al., 2004
	NO _x	1.30±0.12			
All type vehicles, tunnel study		CO	2.62±0.13		Kohler et al., 2005
	NO _x	0.68±0.12			
All type vehicles, tunnel study		CO	3.46±0.26		Hwa et al., 2002
	NO _x	0.90±0.18			

Note: Freeway—a road that has no intersection and can be used without paying toll (Homburger and Kell, 1988).

Arterial—a high-capacity of urban road, which deliver traffic from collector roads to freeways (Homburger and Kell, 1988).

Table 5.3 Emissions factor during different traffic–flow patterns and traffic speed for both direction of test route

Test vehicle and mileage in km		Traffic condition	No. of trips	Speed (km/h)	CO (g/km)	HC (g/km)	NO _x (g/km)
Passenger cars	9,200	FF	4	36.39±4.5	0.18±0.2	0.02±0.02	0.05±0.04
		IF	4	21.71±4.3	0.34±0.3	0.04±0.01	0.04±0.1
		CF	4	9.36±3.8	0.78±0.7	0.07±0.1	0.07±0.1
	52,000	FF	4	33.79±3.4	1.18±0.1	0.24±0.2	0.05±0.03
		IF	4	21.65±4.2	6.26±5.1	0.37±0.2	0.02±0.02
		CF	4	7.38±4.0	11.91±8.2	0.69±0.4	0.02±0.03
	142,000	FF	4	32.30±1.7	7.61±5.4	0.82±0.6	2.62±1.6
		IF	4	20.90±3.5	17.25±11.0	1.89±1.4	1.47±1.3
		CF	4	8.50±3.9	50.62±32.9	2.72±1.8	0.02±0.03
Auto–rickshaws	45,000	FF	4	34.13±4.5	6.81±5.2	1.02±0.8	0.05±0.03
		IF	4	21.20±4.3	29.64±10.8	1.65±0.6	0.04±0.02
		CF	4	8.50±3.9	50.62±32.9	2.72±1.8	0.02±0.03
	100,000	FF	4	33.90±4.0	23.07±18.5	8.03±2.5	0.76±0.5
		IF	4	20.50±3.5	43.17±34.2	7.85±5.2	0.16±0.1
		CF	4	9.60±3.9	76.94±65.7	17.67±13.4	0.17±0.1

Table 5.4 Emissions factor during OPH and PH speed for both direction of test route

Test vehicle and mileage in km		Traffic-flow condition	Travel time (s)	Distance (km)	CO (g/km)	HC (g/km)	NO _x (g/km)
Passenger cars	9,200	OPH	450.0	3.8	0.18±0.2	0.02±0.02	0.05±0.1
		MPH	1124.5	3.8	0.59±0.4	0.05±0.04	0.03±0.01
		EPH	737.0	3.8	0.50±0.4	0.05±0.04	0.05±0.04
	52,000	OPH	425.6	3.9	1.02±0.1	0.24±0.2	0.11±0.03
		MPH	1154.0	3.9	8.79±6.7	0.52±0.4	0.05±0.02
		EPH	NA	NA	NA	NA	NA
	142,000	OPH	503.0	3.7	7.61±5.4	0.82±0.6	2.62±1.6
		MPH	815.0	3.8	34.13±26.1	1.91±1.5	1.41±1.6
		EPH	939.0	3.8	20.82±16.2	2.32±1.8	1.55±1.1
Auto–rickshaws	45,000	OPH	510.0	3.9	6.81±5.2	1.02±0.1	0.05±0.03
		MPH	720.0	3.7	35.39±14.8	1.94±1.4	0.04±0.03
		EPH	787.0	3.8	57.59±22.1	2.84±1.3	0.03±0.02
	100,000	OPH	504.0	3.7	23.07±18.5	8.03±2.5	0.88±0.4
		MPH	798.0	3.8	55.26±22.3	11.37±5.8	0.51±0.5
		EPH	693.0	3.8	120.70±47.2	19.82±11.8	0.54±0.5

Note: NA– technical problem occurred in the auto–gas analyzer

5.4 EMISSION FACTORS BY MODELS

5.4.1 COPERT-IV

The COPERT-IV uses average speed-dependent emission equations, which are characteristic of a given vehicle type to estimate emissions (Ntziachristos et al., 2009). Average speed (ranging from 10 to 100 km/h) based emission algorithms are commonly used around the world to estimate emissions from road traffic at a national or regional level (Achour et al., 2011; Kousoulidou et al., 2013). The model utilizes an empirical speed-dependent emission factor equation developed from multiple real-world tests on many urban drives (Ntziachristos et al., 2000). The emission factor functions are specific for different vehicle classes, fuel types, Euro norms and engine capacities, but it does not consider driving condition. The equation 1 and 2 were used to estimate emission factors for auto-rickshaws and passenger cars (Edward and Bright, 2008). The test vehicle (passenger cars and auto-rickshaws) specifications are listed in Table 3.1 (Chapter 3) and different vehicle classes of COPERT-IV are listed in Table 5.5. The selected passenger cars as per the COPERT-IV were classified as class M1 and the auto-rickshaw class L3 ($>50\text{cm}^3$ and 2-stroke) (Ntziachristos et al., 2009).

Table 5.5 Vehicle classification defined in COPERT–IV model
(Sources: INE–SERMARNAT, Ntziachristos, et al., 2009)

Vehicle Type	The vehicle classification and description
Passenger cars	M1: vehicles used to transport passengers that have 8 or fewer seats in addition to that of the driver
Light-duty vehicles	N1: vehicles used to transport goods that have a weight not exceeding 3.5 tons
Heavy-duty vehicles	N2, N3: vehicles used to transport of goods that have a weight exceeding 3.5 tons
Buses	M2, M3: vehicles used to transport passengers
Mopeds	L1, L2: vehicles with an engine cylinder capacity not exceeding 50 cm ³ and designed to not exceed a speed of 40 km/h
Motorcycles	L3: vehicles with an engine cylinder capacity exceeding 50 cm ³ and/or designed to run at speeds exceeding 40 km/h

The emission factor for passenger cars and auto-rickshaws were calculated by using equations 2 and 3 (Edward and Bright, 2008).

$$EF_{i,m,n} = \left(\frac{(\alpha + \gamma \cdot V + \varepsilon \cdot V^2 + \zeta / V)}{(1 + \beta \cdot V + \delta \cdot V^2)} \right) \cdot (1 - RF) \quad (2)$$

$$EF_{i,m,n} = \alpha + \beta \cdot V + \gamma \cdot V^2 + \delta \cdot V^3 + \varepsilon \cdot V^4 + \zeta \cdot V^5 \quad (3)$$

$EF_{i,m,n}$ is the emission factor, in g/km for a given species i , of age m , and engine size n ; V the average vehicle speed (km/h), and α , β , γ , δ , ε , ζ , η and θ are coefficients related to emission factors for specific vehicle, i.e. Euro 1, 2, 3 . . . ; and RF are the coefficient specific to a given engine size n , and technology level m . The details of coefficients are presented in Appendix–III.

5.4.1.1 Emission factor estimation

It was found that for lower mileage (9,200 km) passenger car, the deviation between the measured and modelled EF was less. For HC at congested speed (<15 km/h), the modelled EF deviated by about 55–85% from the measured EF whereas, for speed >15 km/h, the deviation decreased progressively up to 20%. For CO, for <15 km/h the

modelled EF deviated by 25–55% from the measured EF and for >15 km/h speed, the modelled EF deviated by 3–12 %. For NO_x, the model over predicted the EF for the entire range of speeds. As an example, the measured and modelled EF of 9,200 km mileage have been shown in Figure 5.5 (a, b and c). It was, however, observed that the deviation further increased with the increasing mileage of the passenger cars and auto-rickshaws. Therefore, a correction factor for all the test vehicles were estimated by taking ratio of the measured and modelled EF and the average correction factor was used to standardize the modelled EF of other higher mileages of passenger cars and auto-rickshaws. Appendix VI describes the deviation of measured and modelled EF for other mileages test vehicles without correction factors. Table 5.6 shows the correction factor of pollutants CO, HC and NO_x for passenger cars and auto-rickshaws. These factors are multiplicative and observed to be higher for higher mileage vehicles (142,000 km for car and 100,000 for auto-rickshaw). Similar findings are reported by Kousoulidou et al. (2010) in which deviation is in the range from 30 to 225 for the estimates by COPERT-IV. The deviations in estimated EF compared to measure EF occurred largely during low traffic speed when the traffic-flow pattern is usually nearing congestion. Similar conclusion is being made in a study of Borge et al. (2012).

Table 5.6 Correction factors for test vehicles mileages for pollutants CO, HC and NO_x

Test vehicles and mileage in km		Correction factor		
		CO	HC	NO _x
Passenger cars	9,200	1.21	1.45	0.58
	52,000	8.26	14.54	0.74
	142,000	32.89	70.62	0.79
Auto-rickshaws	45,000	5.86	1.17	0.45
	100,000	17.22	9.55	0.54

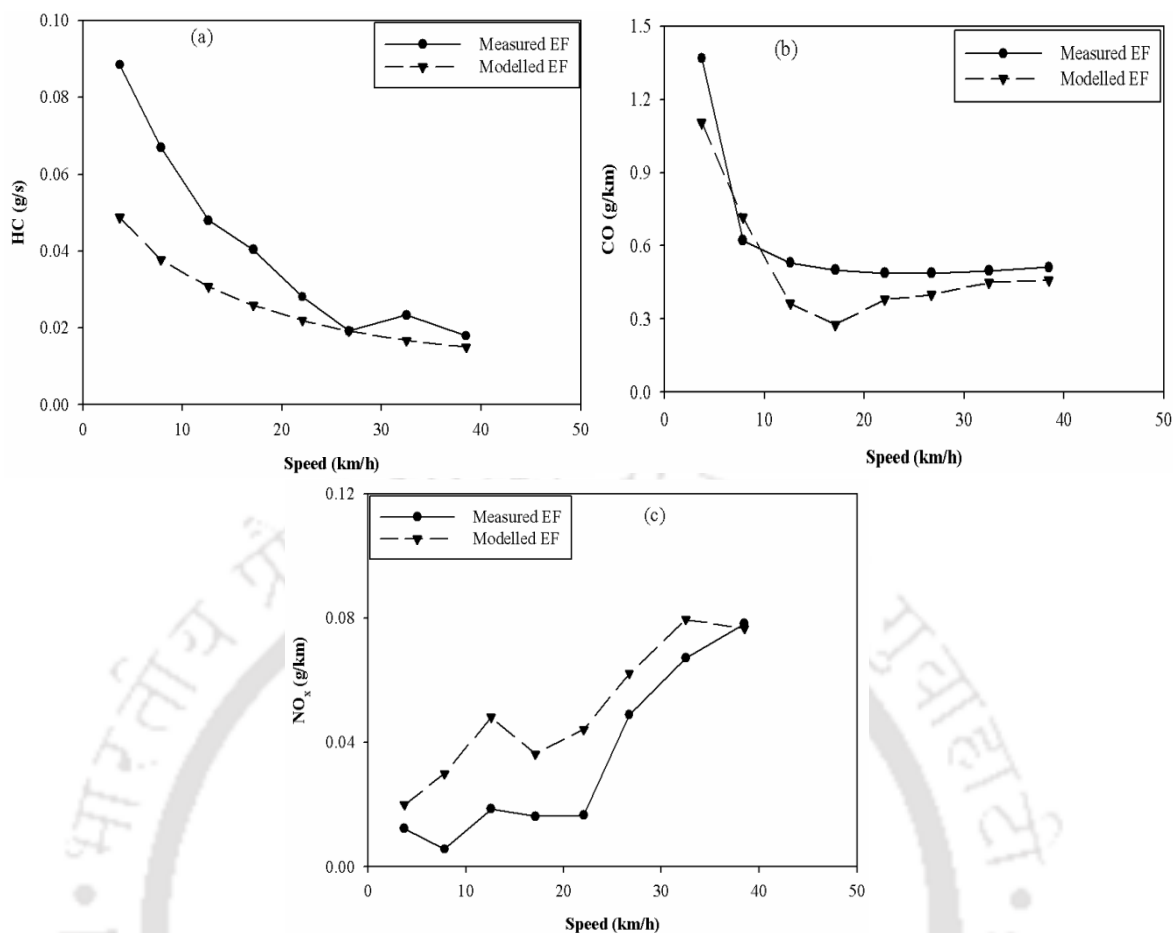


Figure 5.5 The comparison of measured and modelled EF of passenger car of mileage 9,200 km for (a) HC, (b) CO and (c) NO_x

Table 5.7 shows the summary of root mean square error (RMSE) deviation in EF with and without mileage correction factors. After mileage correction factor the deviation between measured and modelled EF is significantly reduced. The Figure 5.6 (a, b and c) and 5.7 (a and b) shows the comparison of measured and modelled EF after mileage correction factors. It has been found that at lower speed, modelled EF under predicted measured EF for CO and HC. Since, in real-world during PH, especially at interrupted speed, vehicle undergoes frequent stop-and-go condition, which causes higher emission, is not considered in COPERT-IV model. Therefore, at lower speeds, the measured EF was found higher as compared to modelled EF. For NO_x, the model over predicted the EF in the lower range (up to 25 km/h) and under predicted the EF for the range of speed beyond 25 km/h for the 9,200 km and 142,000 km mileages after the application of

correction factors. Whereas, for the mileage 52,000 km better agreement was observed for the lower speeds up to 25 km/h, with slight overprediction beyond 20 km/h for passenger car. Whereas, the model EF of NO_x for auto-rickshaw of mileage 45,000 km show better agreement with measured EF but for mileage of 100,000 km modelled EF were under predict for lower speed range (up to 20 km/h) and over predicted for higher speed range (beyond 20 km/h). The deviation in modelled EF from measured indicates that COPERT-IV model not suitable for lower speed range emission characterization.

Table 5.7 Summary of RMSE with and without mileage correction factors of test vehicles for pollutants CO, HC and NO_x

Test vehicle mileage in km		HC		CO		NO _x	
		RMSE without mileage correction	RMSE with mileage correction	RMSE without mileage correction	RMSE with mileage correction	RMSE without mileage correction	RMSE with mileage correction
Passenger cars	9,200	0.02	0.01	0.2	0.1	0.1	0.1
	52,000	0.5	0.1	4.3	1.1	0.1	0.1
	142,000	2.1	0.2	16.7	1.9	2.7	0.4
Auto- rickshaws	45,000	2.3	0.7	32.8	14.4	0.5	0.01
	100,000	17.6	4.3	80.6	20.6	0.5	0.04

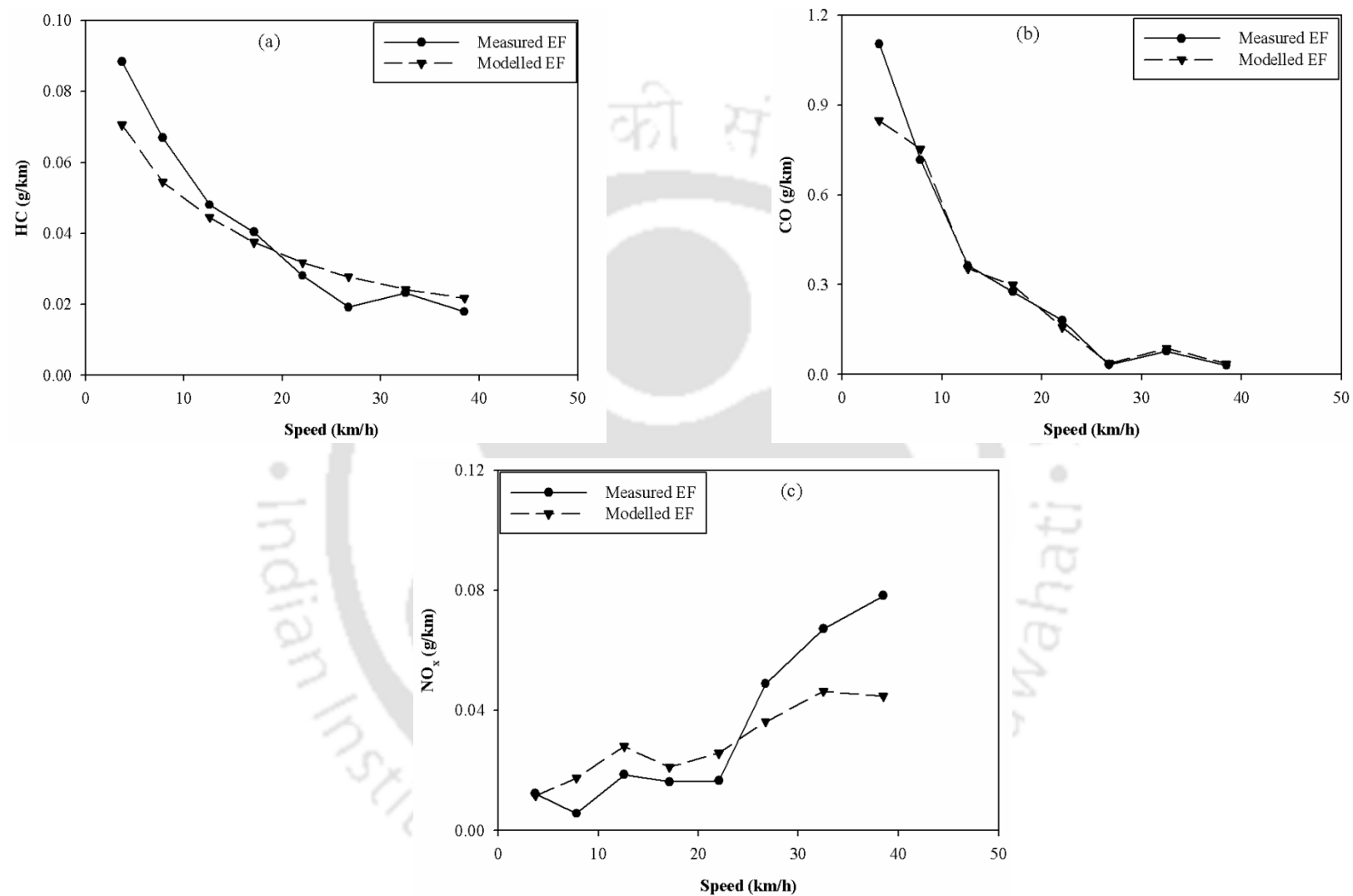


Figure 5.6a The comparison of measured and modelled EF of 9,200 km mileage passenger car after mileage correction factor for pollutants (a) HC, (b) CO and (c) NO_x

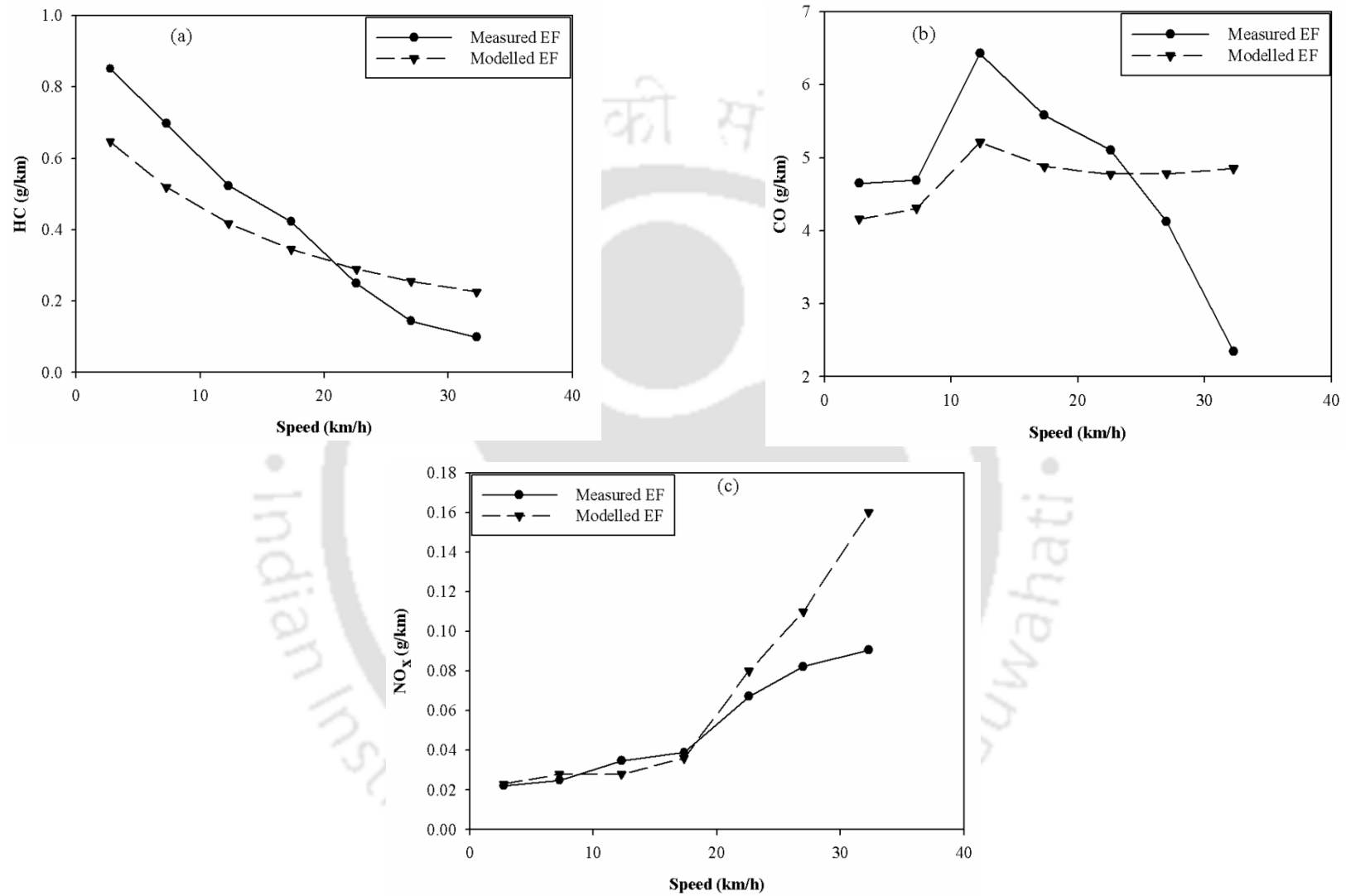


Figure 5.6b The comparison of measured and modelled EF of 52,000 km mileage passenger car after mileage correction factor for pollutants (a) HC, (b) CO and (c) NO_x

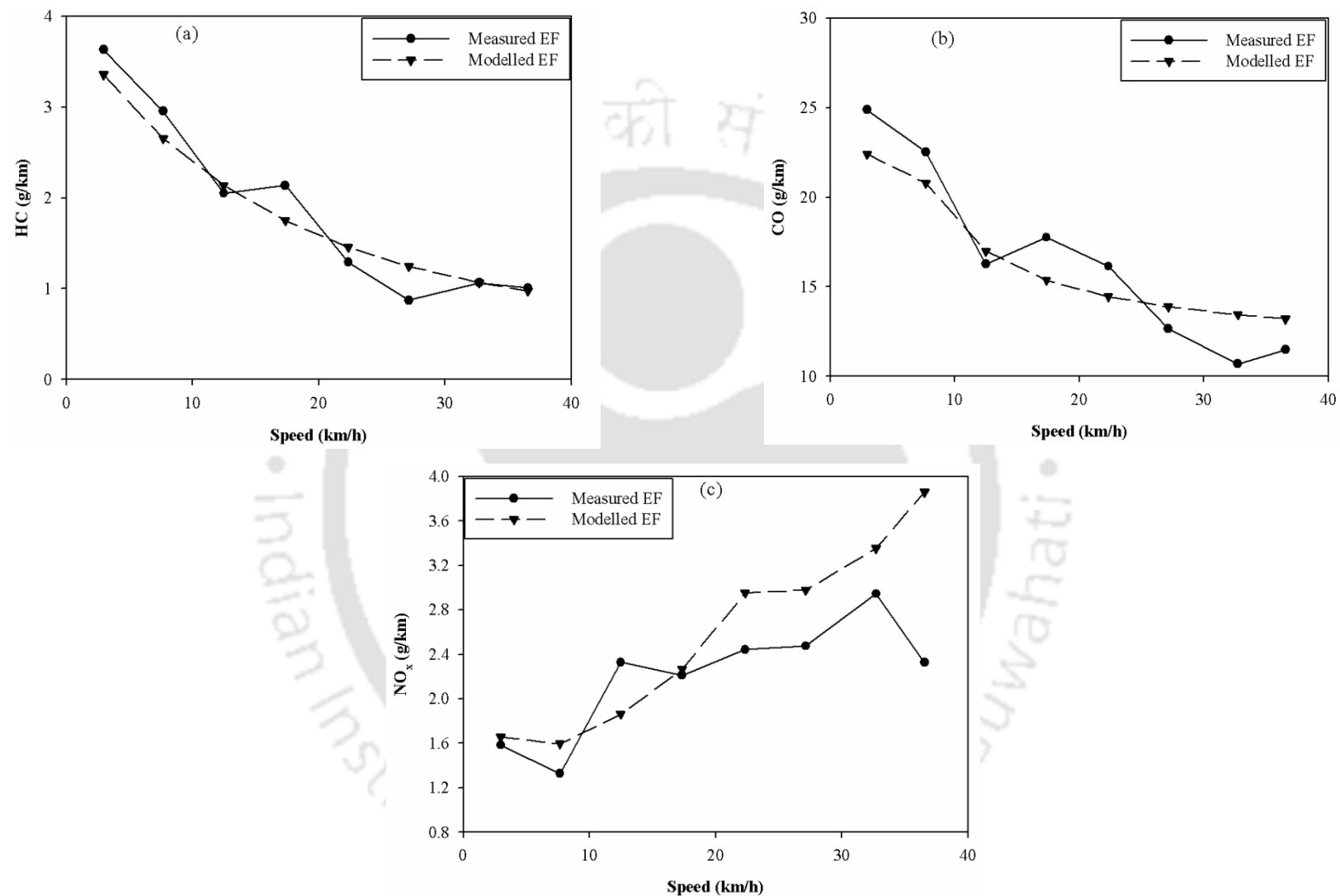


Figure 5.6c The comparison of measured and modelled EF of 142,000 km mileage passenger car after mileage correction factor for pollutants (a) HC, (b) CO and (c) NO_x

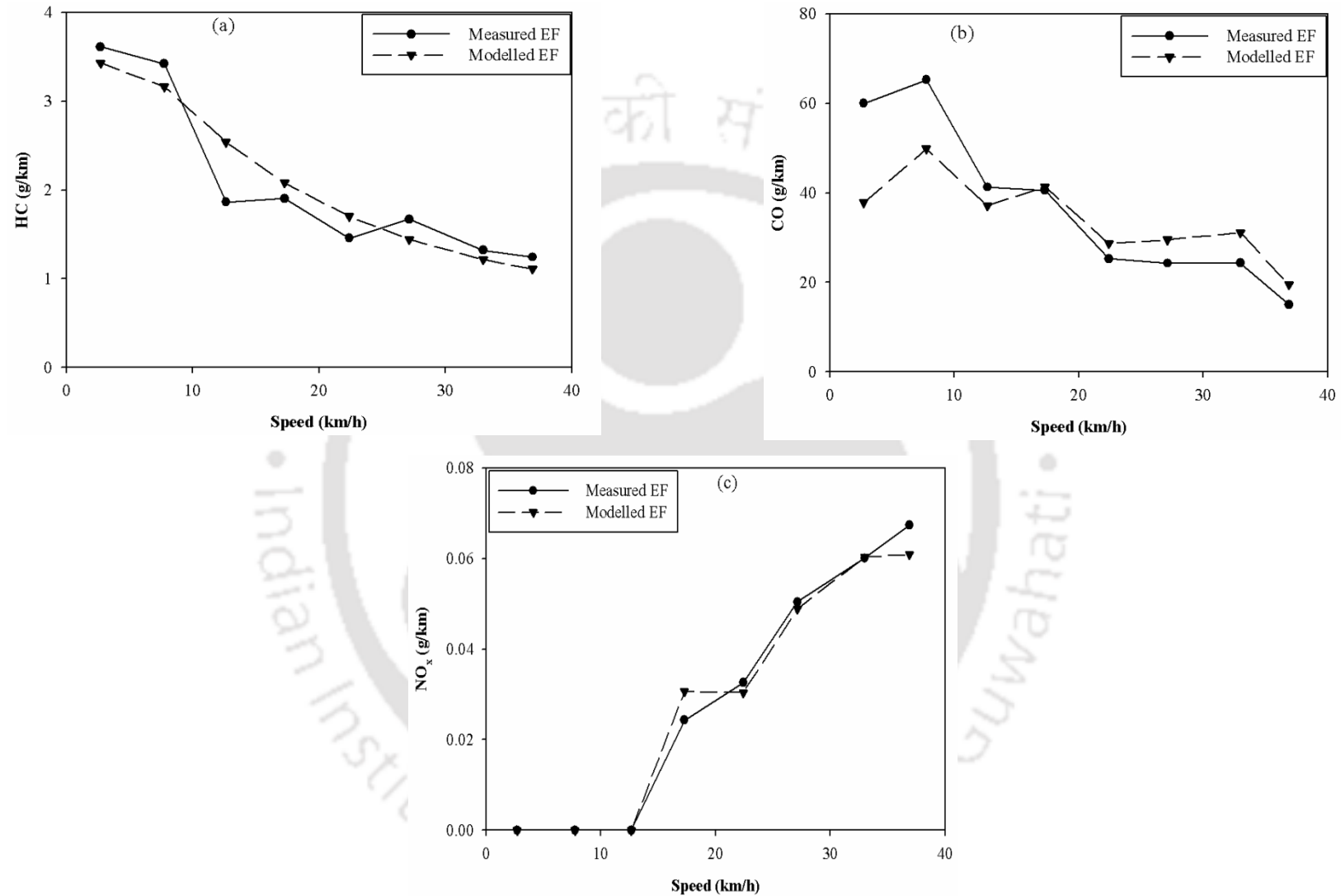


Figure 5.7a The comparison of measured and modelled EF of 45,000 km mileage auto-rickshaw after mileage correction factor for pollutants (a) HC, (b) CO and (c) NO_x

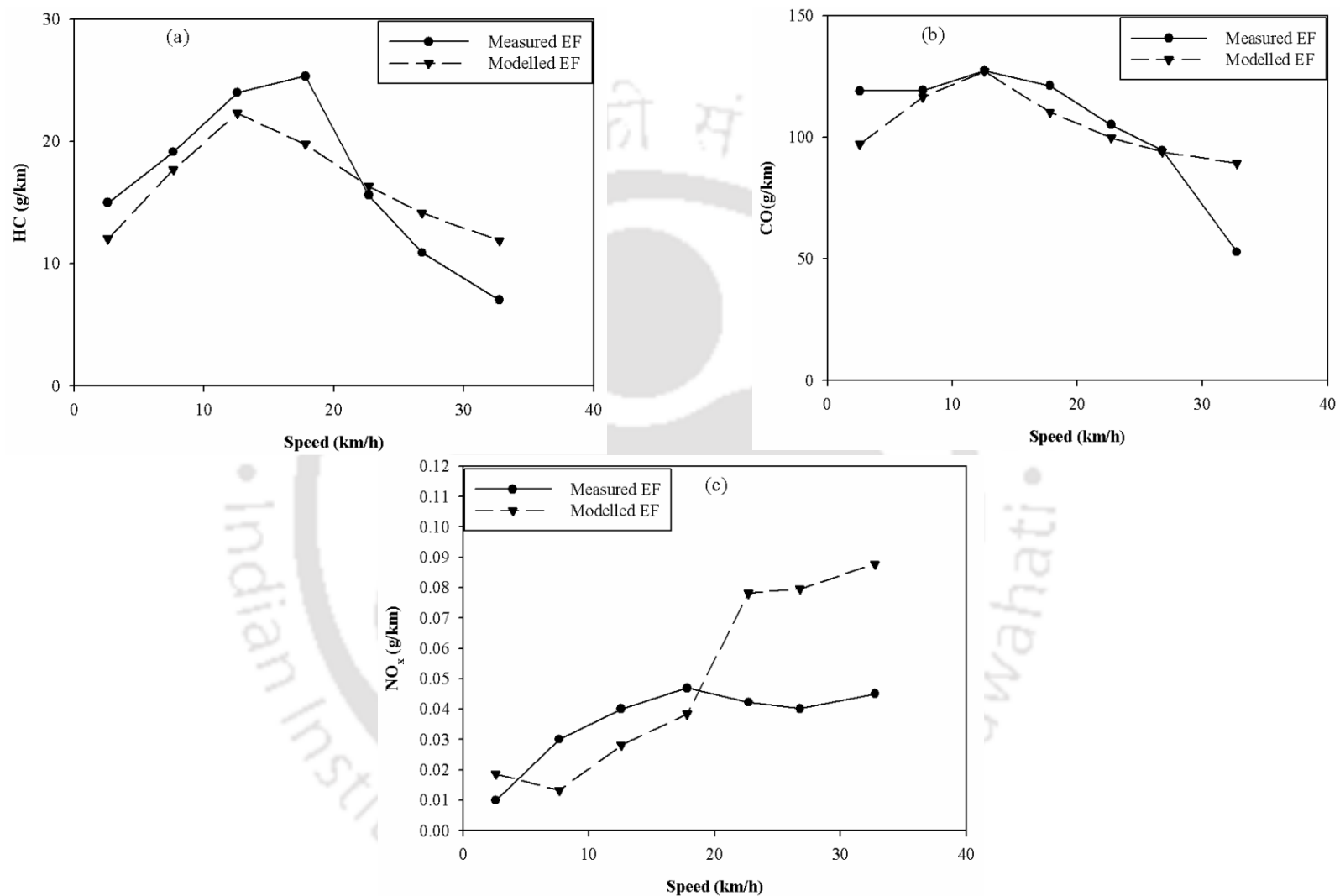


Figure 5.7b The comparison of measured and modelled EF of 100,000 km mileage auto-rickshaw after mileage correction factor for pollutants (a) HC, (b) CO and (c) NO_x

5.4.2 IVE

The IVE (International Vehicle Emission) model incorporates various vehicle technologies and on-road real driving operations (ISSRC, 2013) and has been applied in several cities in developing countries, e.g. Mexico City (Mexico), Pune (India), Beijing and Shanghai (China) (ISSRC, 2013), and Hanoi (Vietnam) (Oanh et al., 2012). The IVE model needs several variables, including instantaneous speed, technical characteristics of vehicles, fuel characteristics, and meteorological parameters for the estimation of EF (ISSRC, 2014). It uses location and fleet files. The instantaneous speed, start and stop duration and number of test vehicle are two main variables of the location file, used for estimation of emission factor by using vehicle specific power (VSP) (Pua et al., 2015). Along with the primary important data (instantaneous speed, start and stop duration and number of test vehicles), it requires some secondary input information that includes meteorological parameters (temperature, humidity), altitude of the city and fuel characteristics (ISSRC, 2014). The gasoline fuel characteristic includes contents of sulphur (300 ppm), lead (0%), benzene (1.5%), and oxygen (0%) (Kamyotra et al., 2010). The fleet file requires vehicle technology index and vehicle composition as input information. The vehicle technology indexes of test vehicles are listed in Table 5.8.

5.4.2.1 Vehicle specific power

Driving condition and engine load affects the emission (Zhang and Frey, 2006). The instantaneous pollutant emissions vary with vehicle weight, engine load and emissions control technology, road conditions and gradient (Wyatta et al., 2014), speed, acceleration and environmental conditions, for example, temperature and atmospheric pressure (Yaoa et al., 2013).

Table 5.8 A summary of primary and secondary data

Parameter	The IVE input file
Primary data:	
The instantaneous speed profile: 3 passenger cars and 2 auto-rickshaws	For vehicle specific power (VSP) estimation of location file
The number of start per day: 6 in passenger car and 10 in auto-rickshaw	For soak bin estimation of location file
The vehicle technology index: 3 passenger cars of technology index 189, 190, 191 and auto-rickshaw of index 1171, 1172 (Appendix IV A)	For fleet file compilation
Secondary data:	
Fuel specification, temperature (21°C–28°C) and humidity (40%–65%)	For location file

Therefore, real-time emissions obtained from the on-board measurements are useful when combined with the VSP to establish a link between emission and driving behaviour for different vehicle categories. The VSP represents the energy used by an internal combustion engine to move a vehicle (Boroujeni and Frey, 2014). It is equal to the product of a vehicle's speed and equivalent acceleration, which includes the effect of the aerodynamic drag (Hucho, 1998), and the road's gradient and friction (Frey et al., 2008; Prati et al., 2014). The equation 4 is used for estimating the VSP (Jimenez-Palacios, 1998). The VSP can be positive or negative depending upon the acceleration and the roadway gradient (Zhang and Frey, 2006).

$$VSP = 1.1 \cdot a \cdot V + 0.132 \cdot V + 0.000302 \cdot V^3 + g \cdot V \cdot a \cdot \tan(\sin(\theta)) \quad (4)$$

where, VSP is the vehicle specific power (kw/ton), V the vehicle speed (m/s), a vehicle acceleration (m/s^2), θ the road grade in meters elevation change per meter of road distance (radians), g is the acceleration due to gravity, the term $(1.1 \cdot a \cdot V)$ represents the kinetic power demand on the vehicle as it accelerates or decelerates, the term

$(0.132 \cdot V)$ represents the engine friction and wheel friction power demand, the term $(0.000302 \cdot V^3)$ represents the power demand due to air friction and the term $g \cdot V \cdot a \cdot \tan(\sin(g))$ represents the power demand due to the road slope (Zhang and Frey, 2006; Frey et al., 2006).

5.4.2.2 Estimation of emission factor

The IVE model incorporates data related to vehicle operations and does not rely on a set of group of cycles to estimate emissions (ISSRC, 2014). The IVE model estimates emissions by taking the fraction of time that a vehicle spends in individual VSP bins (Davis et al., 2005). The IVE model categorised VSP into 60 bins. It considers instantaneous speed from the on-road mobile sources and allows input driving information into the model for the estimation of emission (Davis et al., 2005; Liu et al., 2007). Driving parameters are entered on a day or on an hour-by-hour basis, allowing specific calculation of emissions by the hour or for a specific roadway (ISSRC, 2014).

5.4.2.3 Operating kinetics and VSP

Table 5.9 shows the PH and OPH VSP bins with corresponding operating characteristics. The four mode of VSP bins were observed, which are categorised as bin ≤ 10 , 11, 12 and ≥ 13 . The Appendix IV B and C show the VSP distribution in 60 bins. During PH the share of bin 11 and 12 was about 51–53% and 36%, respectively and the rest 15% was shared by ≤ 10 and ≥ 13 bins. The bin ≤ 10 shows deceleration and have average speed 19.8 ± 6.7 km/h. The bin 11 shows transition phase or combination of acceleration and deceleration (A/D) having minimum speed of 11 ± 7 km/h, and 16.6 ± 8 km/h for passenger car and auto-rickshaw, respectively. The bin 12 shows positive energy of higher power with high share for both test vehicles. The bin ≥ 13 shares only 5–6% but need higher

power through average speed for both types of vehicles, which leads to higher exhaust emission. Whereas, during OPH the share of ≥ 13 bin was higher (45–48%) and the share of ≤ 10 bin was lower (8–10%). It has been observed that all four bins, speed range is more or less same but ≤ 10 bin and bin 11 define decelerating speed profile whereas bin 12 and ≥ 13 bin define accelerating speed profile, similar to PH.

The share of VSP bins and emission rate of CO, HC, CO₂ and NO_x for passenger car and auto-rickshaw were shown in Figure 5.8a and 5.8b. It has been observed that VSP bin 11 and 12 have the highest percentage of share during PH. The passenger car and auto-rickshaw both have similar percentage of share of VSP bins during PH but emission rates were found to be higher in auto-rickshaws as compared to passenger cars. It has been observed that the emissions of CO and HC significantly increases for bin 11, which continues to increase for PH whereas, for CO₂ and NO_x, it was found to be higher for OPH. Shrestha et al. (2013) reported the similar trends.

Table 5.9 VSP bin distribution for passenger car and auto-rickshaw during PH and OPH

VSP bin		Passenger car				Auto-rickshaw			
		% share	Average speed (km/h)	Acceleration (m/s ²)	VSP (kw/ton)	% share	Average speed (km/h)	Acceleration (m/s ²)	VSP (kw/ton)
PH	≤ 10	6.8	19.8 ± 6.7	-2.0 to -0.1	-14 to -3	4.6	19.9 ± 4.7	-0.5 to -0.1	-8 to -3
	11	51.3	11.4 ± 7.7	-0.1 to 0.8	-0.2 to 1.2	53.4	16.6 ± 8.1	-0.1 to 1.0	-0.1 to 1.5
	12	36.0	16.94 ± 7.0	0 to 1.2	1.2 to 5	35.8	21.1 ± 5.7	0 to 1.4	1.5 to 5.5
	≥ 13	5.7	24.92 ± 6.3	0.5 to 2.0	5 to 15	6.2	32.0 ± 3.8	0 to 0.6	1 to 7
OPH	≤ 10	10.0	30-40	-1.5 to -0.2	-15 to -2	9.6	28-40	-1.0 to -0.3	-5 to -7
	11	16.9	28-45	-0.1 to 0.9	-1 to 1.5	13.4	25-42	-0.2 to 0.8	-0.2 to 5
	12	25.6	28-45	0 to 0.5	0.5 to 6	21.5	25-40	0.5 to 1.2	5 to 8
	≥ 13	47.5	28-45	0.2 to 2.5	6 to 20	55.5	25-40	1 to 1.8	3 to 12

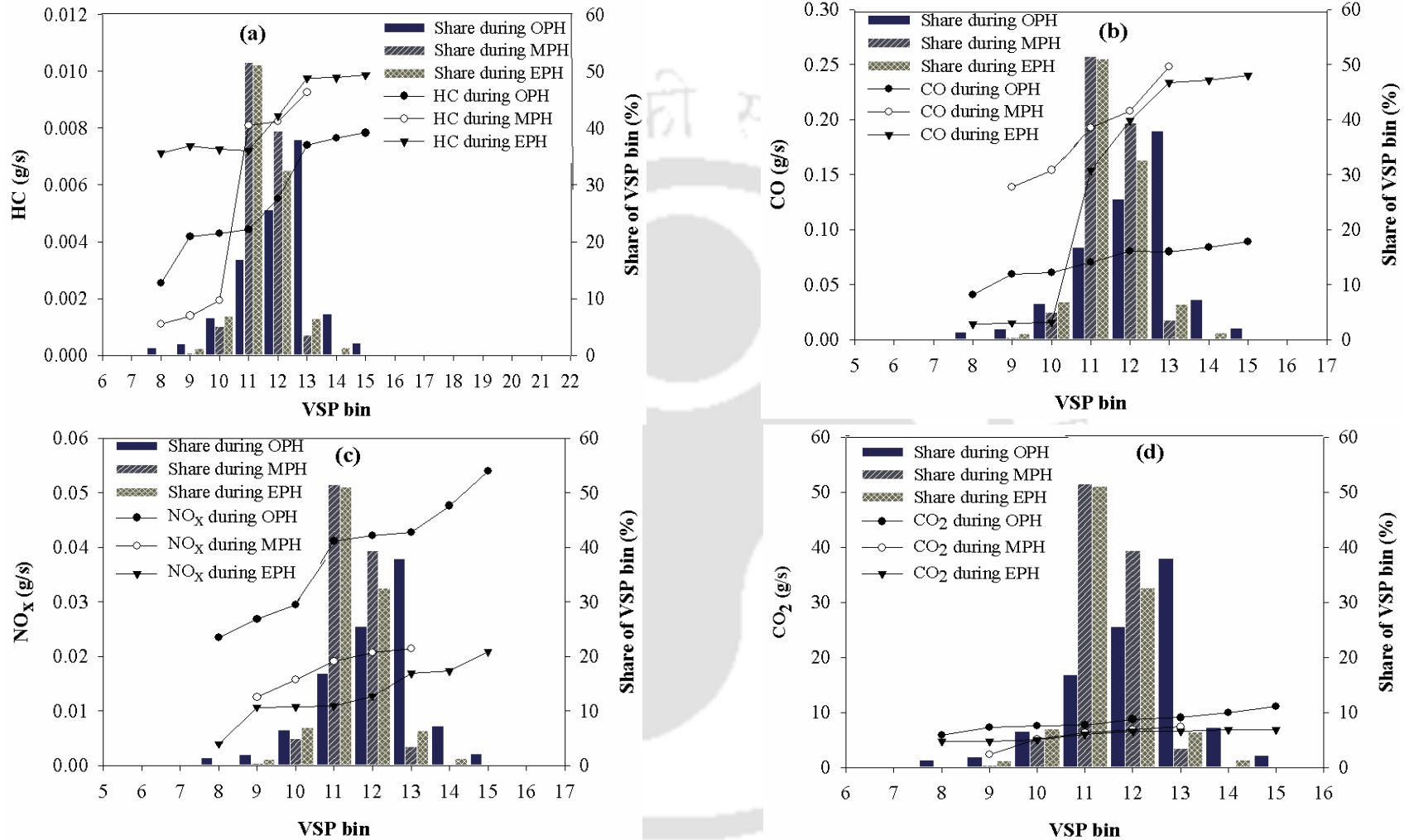


Figure 5.8a The share of different VSP bins during PH and OPH for passenger car for pollutant (a) HC, (b) CO, (c) NO_x and (d) CO₂

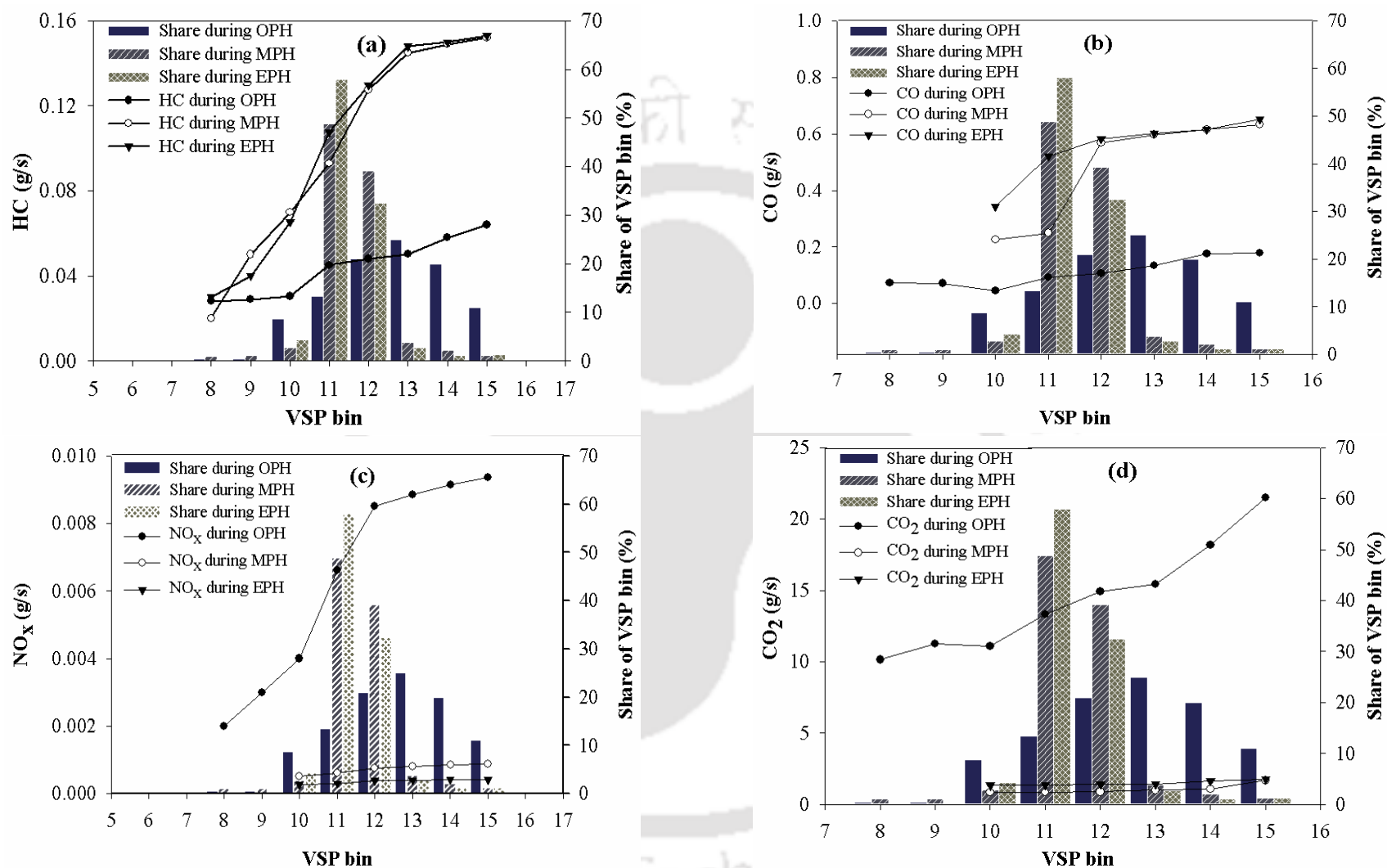


Figure 5.8b The share of different VSP bins during PH and OPH for auto-rickshaw for pollutant (a) HC, (b) CO (c) NO_x and (d) CO₂

5.5 COMPARISON OF MEASURED AND MODELLED EF

The measured emission of CO, HC, CO₂ and NO_x were compared with the modelled EFs for the passenger car and auto-rickshaw. For passenger car, it was found that measured EF during PH (MPH and EPH) was higher than the modelled EF of pollutants. The measured CO of passenger car was 6–35% higher than the modelled EF, similarly for HC, the measured EF were 18–29% higher during PH especially during EPH. For CO₂, the measured EF was 14–17% higher during PH. But the measured and modelled EF during OPH matched well for HC, CO and CO₂. This higher on-road EF during PH is due to stop-and-go type traffic-flow pattern. The IVE model overpredicts NO_x (12–35% higher) both PH and OPH, attributed to lean air to fuel ratio (Dowling, 2005). The Figure 5.9a shows measured and modelled EF of passenger cars for HC, CO, CO₂ and NO_x.

Similar, to the passenger cars, in auto-rickshaws during OPH the modelled EF closely matched with the measured EF. The EF of CO measured were 29–57% higher than the modelled EF during PH especially in the EPH. The EF of measured HC 9–12% higher than modelled EF and the EF of measured CO₂ was 5% higher than modelled. The NO_x emission was overpredicted by about 48–57%. Similar finding for NO_x is reported in the literature (Shrestha, 2013). These results made it clear that operating conditions like duration and number of sharp A/D have direct effect on emission rates, especially at low speed and sharp A/D when the traffic-flow is interrupted. Figure 5.9b showed the measured and modelled EF for auto-rickshaw.

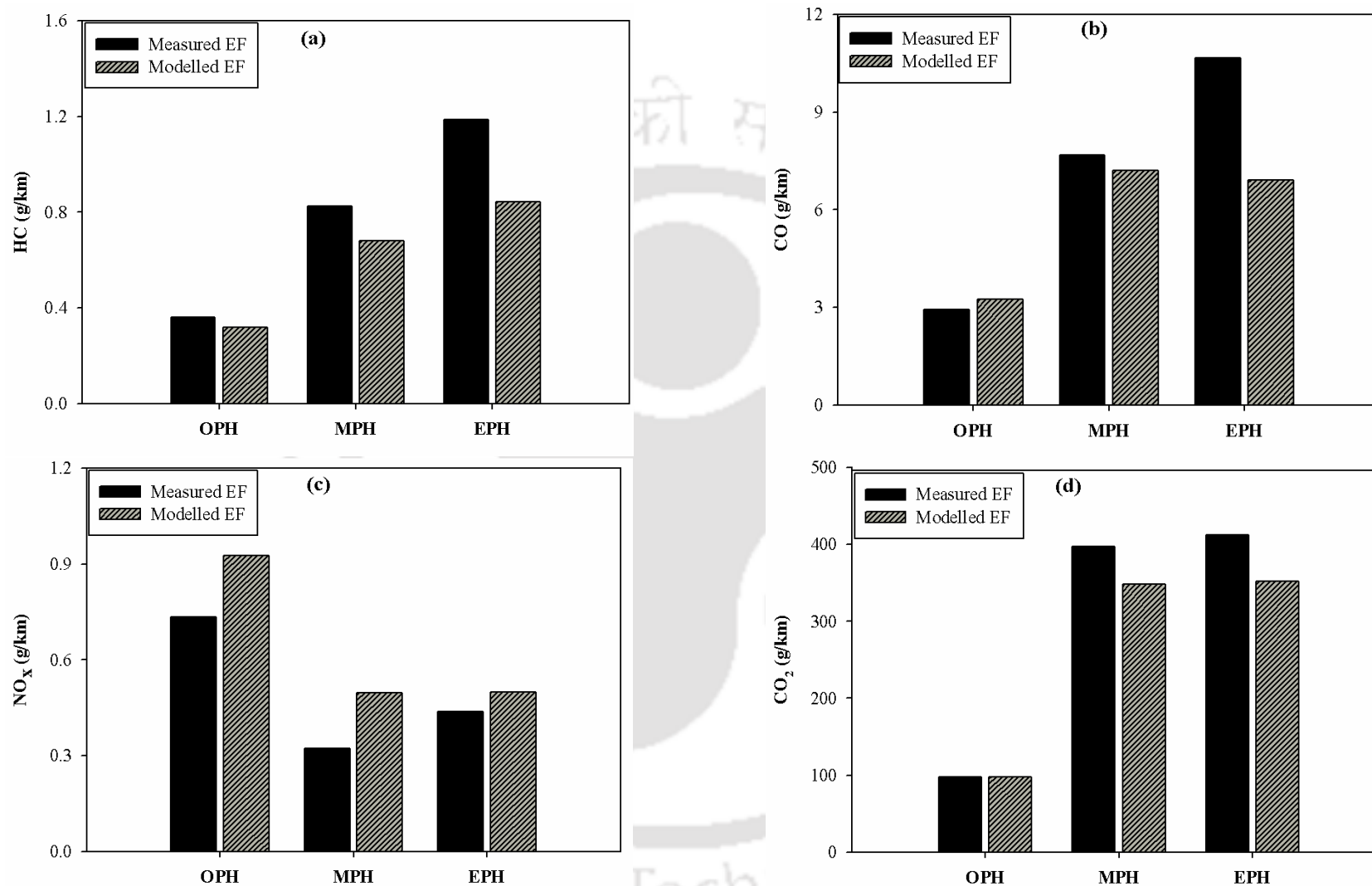


Figure 5.9a The comparison of measured and modelled EF of passenger car for pollutants (a) HC, (b) CO (c) NO_x and (d) CO₂

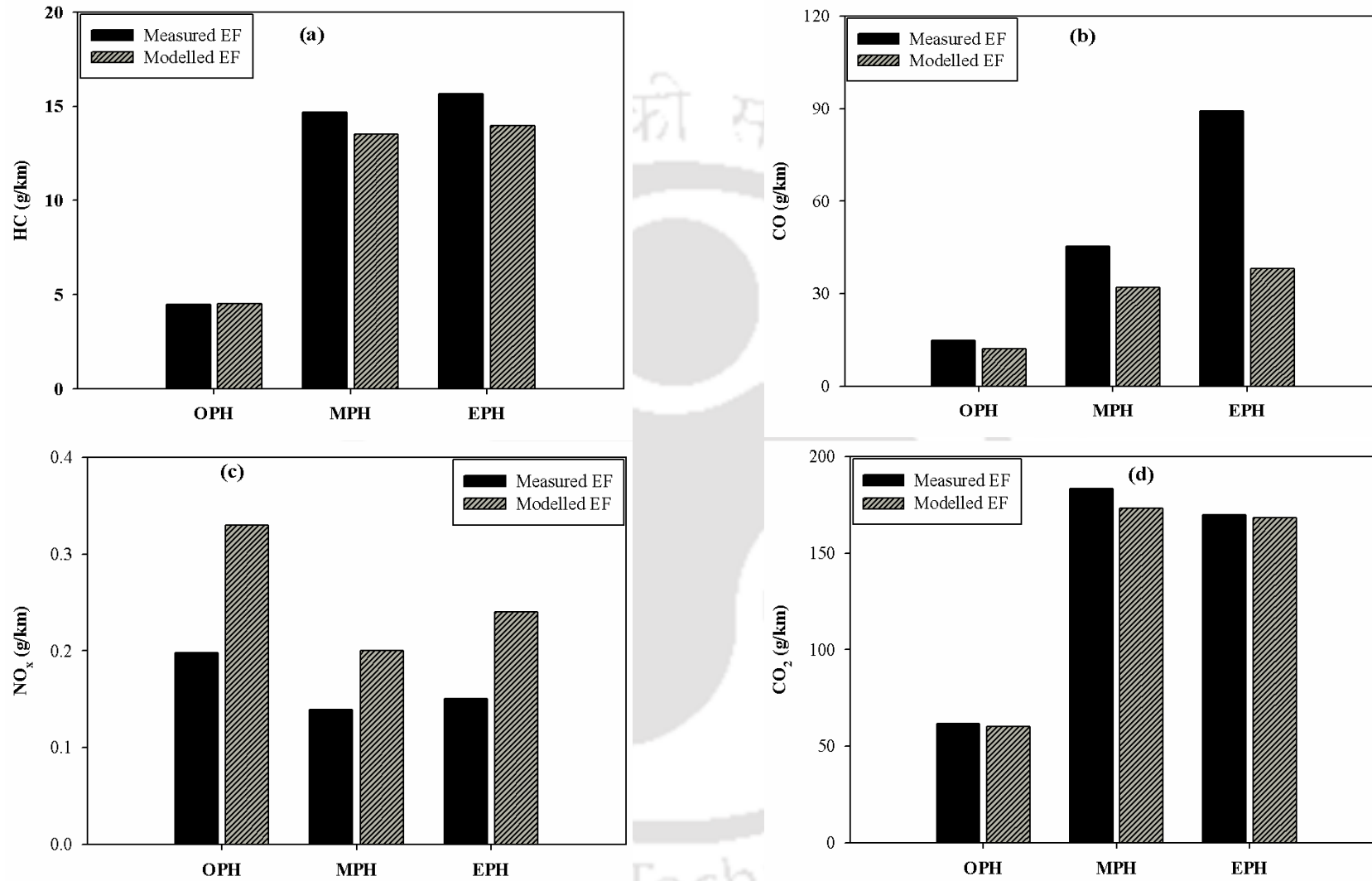


Figure 5.9b The comparison of measured and modelled EF of auto-rickshaw for pollutants (a) HC, (b) CO (c) NO_x and (d) CO₂

5.6 COMPARISON OF COPERT-IV AND IVE MODEL

The results indicate that the on-road real-world EF is higher than the modelled (by both COPERT-IV and IVE) EF for pollutants CO and HC. This is attributed to the on-road operating conditions such as sharp acceleration/deceleration and stop-and-go events, which cause higher engine load, engine misfire and sometimes fuel injection cut off especially during deceleration events (Goodwin and Ross, 1996; An et al., 1997). No-lane discipline and lack of adherence also worsens the traffic-flow, which results in to higher emissions. The COPERT-IV and IVE models used as tools to calculate road transport emissions, comparative studies, emission inventory development and evaluation of emissions for several what-if-scenarios. The difference in the results between two may be attributed to lack of adherence to lanes. Both models have different principles of analysis for example COPERT-IV is average speed based emission model, does not account for instantaneous events, and therefore the results are highly deviated (under-prediction for CO, HC and over-prediction for NO_x) from the on-road EF. The instantaneous emission model, IVE accounts for very fine scale input information to estimate the EF therefore, during OPH the IVE modelled EF show good agreement with on-road EF. For PH also, the results are found close to the on-road EF. Since on-road operating condition is very unpredictable, the estimation of EF especially for PH is not adequate for instantaneous emission models. However, the IVE model results were found to be closer to the real-world on-road EF.

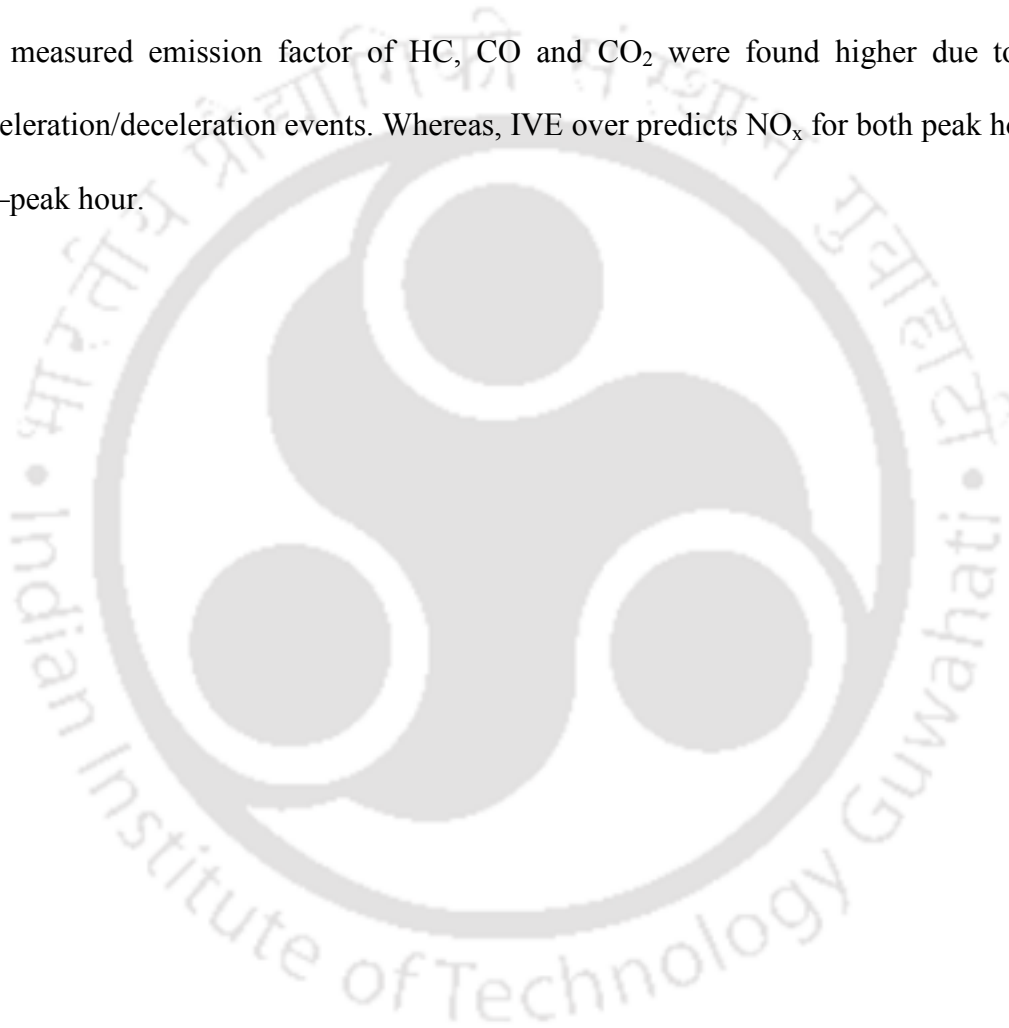
5.7 SUMMARY AND DISCUSSION

The analysis of the speed and instantaneous emission concluded that traffic congestion occurs during both peak and off-peak hours but spends more time in congestion during peak hours than it spends during off-peak hours and hence emissions rise nearly double

during peak hours. Passenger cars and auto-rickshaws both have different flow characteristics; at the same speed the emissions of CO and HC are high but emission of NO_x is low in auto-rickshaws and passenger cars. Short-events like frequent gearshift and frequent stop-and-go occurring during interruptions and congestion are the main causes of higher emissions on urban roads since they lead to sharp increase or decrease in acceleration and deceleration. Unlike to speed, acceleration and deceleration are not well correlated to emission rate as observed in short-event analysis though, acceleration seems to have significant impacts on the total emission of a trip. Therefore, the number of the occurrences of sharp acceleration and deceleration and the time spent in each mode determines the amount of emission significantly. Traffic-flow patterns when change from free to interrupted to congested, emission load of CO and HC emissions also increases in that order.

The measured emission factors have been further compared with an average speed model COPERT-IV and instantaneous speed model IVE. Several studies have demonstrated effective applications of the IVE model to estimate the vehicle emissions (Oanh et al., 2012; Shrestha et al., 2013; Shorshani et al., 2015). The IVE model is used for estimating emissions due to dynamic behaviour of traffic, rather than static. It accounts for instantaneous driving patterns and different technology vehicles with feasible and low-cost data. It has been mostly used for national and regional emission inventories (Shorshani et al., 2015). The COPERT-IV model, which is based on average speed, does not represent real world driving conditions. Therefore, it results in to higher deviation in the measured and modelled values as compared to IVE. It has been found that at lower speed the measured EFs deviated from those modelled by COPERT-IV EF for HC and CO. Since, in real-world during PH vehicle undergoes frequent stop-and-go condition, which causes higher emission that is not considered in COPERT-IV model.

Therefore, at lower speeds, deviation in the emission was found higher as compared to the higher speed range. This deviation further increased with the increasing mileage of the passenger cars and auto-rickshaws. Therefore, a correction factor for other mileages was estimated. It over predicts NO_x emission factor for entire range of speed this due to poor air to fuel ratio (Dowling, 2005). The IVE model results indicate that during off-peak hour measured and modelled emission factor matched well but during peak hour, the measured emission factor of HC, CO and CO_2 were found higher due to sharp acceleration/deceleration events. Whereas, IVE over predicts NO_x for both peak hour and off-peak hour.



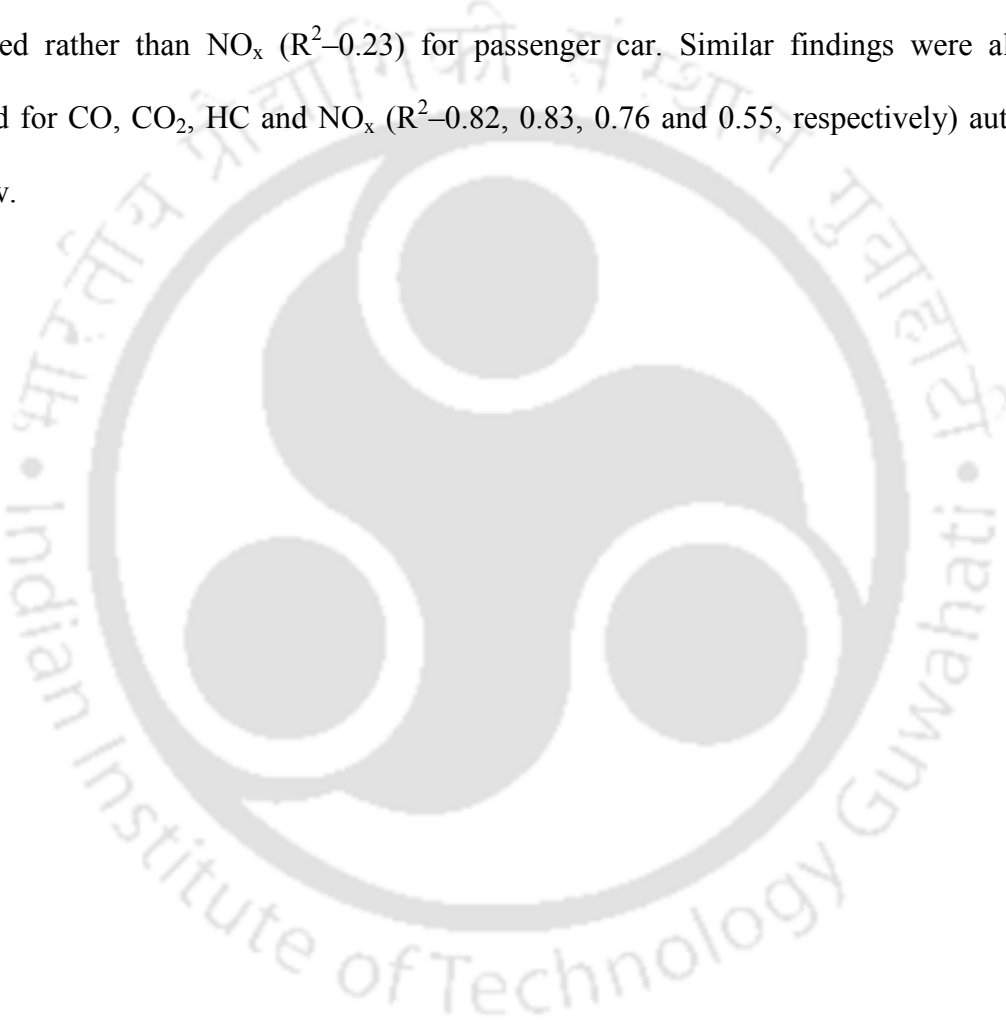


In this Chapter, impacts of various traffic–flow characteristics on emissions and possible mitigation options have been examined. Several policies are studied and analysed in the literature for reduction of traffic congestion events and its consequences. For example, Beevers and Carslaw (2005) studied the congestion charging scheme in London, implemented in 2003. The road pricing scheme for demand management in Singapore is implemented in 1975 and subsequently an electronic road pricing system in 1998 for curbing traffic congestion (Seik, 2000). Similarly, traffic restriction policies, such as odd and even number scheme reported by Cai and Xie (2011) in Beijing during 2008 Olympic Games was implemented. This study analysed the local traffic–flow condition and vehicle technology to mitigate the urban emissions. In the present study, the emission mitigation analysis has been carried out using the field data and the emission models for three different schemes, e.g. up–gradation to higher emission standards, switching to cleaner fuel and by restricting a certain type of vehicle that causes congestion on urban roads.

6.1 SPEED VS EMISSION

During PH, traffic undergoes frequent changes between IF and CF, which is one of the important sources of higher emission (Chapter 5). The emission rates found out for instantaneous speeds (Chapter 5) were averaged for 5s. Figure 6.1 shows the emission rate of passenger car and Figure 6.2 of auto–rickshaw for pollutants of CO, HC, NO_x and

CO₂. Passenger car and auto-rickshaw both shows maximum emission rate for speed range 5 to 30 km/h for CO, CO₂ and HC whereas, for NO_x it increased with the increase in speed. The regression analysis also indicates that the driving patterns in the range of speed from 0 to 30 km/h are highly emission intensive for CO, CO₂ and HC for passenger car as well as for auto-rickshaw. For example, the R² values for CO, CO₂ and HC (R²-0.64, 0.84 and 0.83, respectively) indicate better correlation and good fit for EF and speed rather than NO_x (R²-0.23) for passenger car. Similar findings were also observed for CO, CO₂, HC and NO_x (R²-0.82, 0.83, 0.76 and 0.55, respectively) auto-rickshaw.



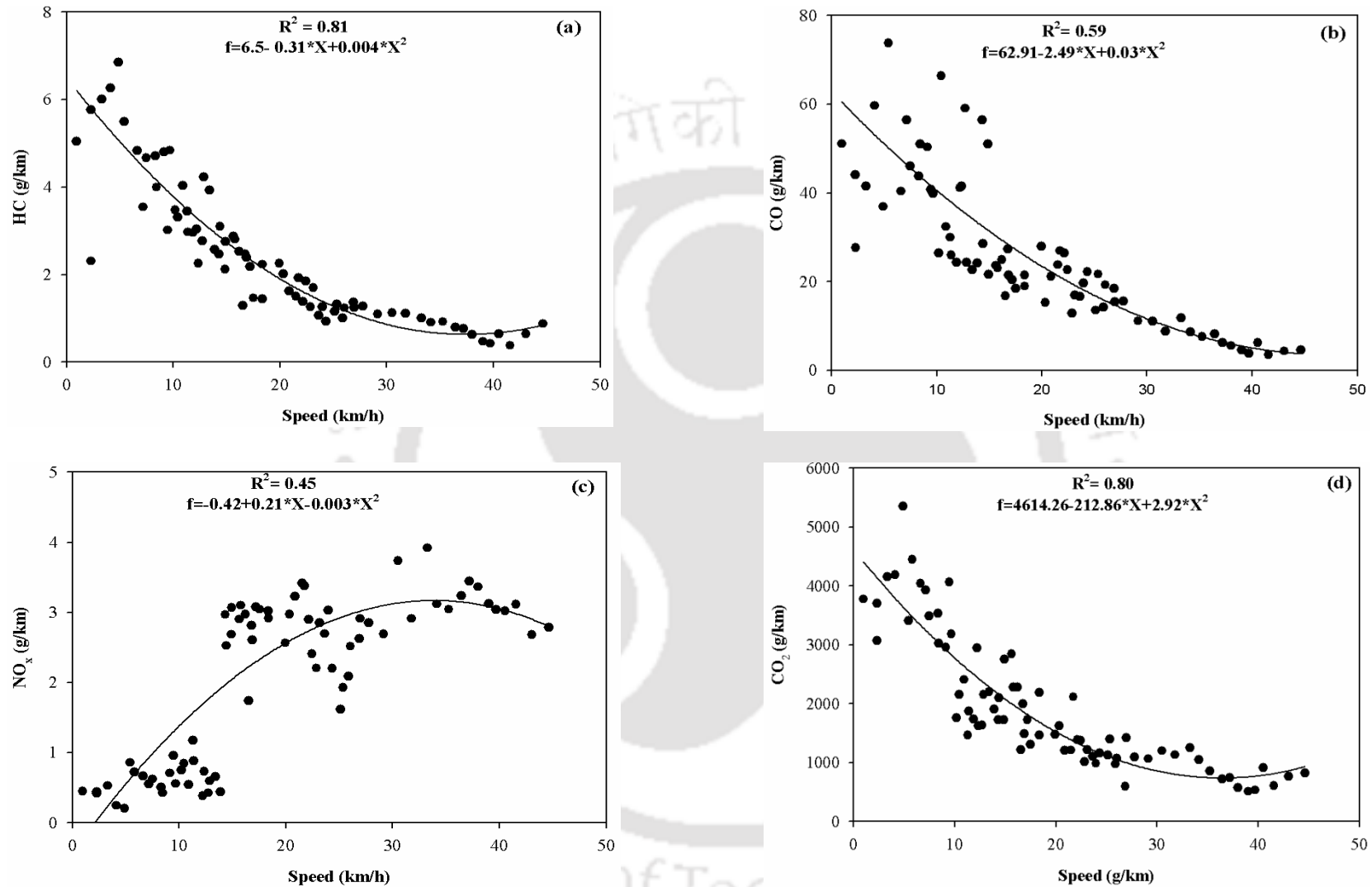


Figure 6.1 The speed dependent emission rates of passenger car of mileage 142,000 km for (a) HC, (b) CO, (c) NO_x (d) CO₂

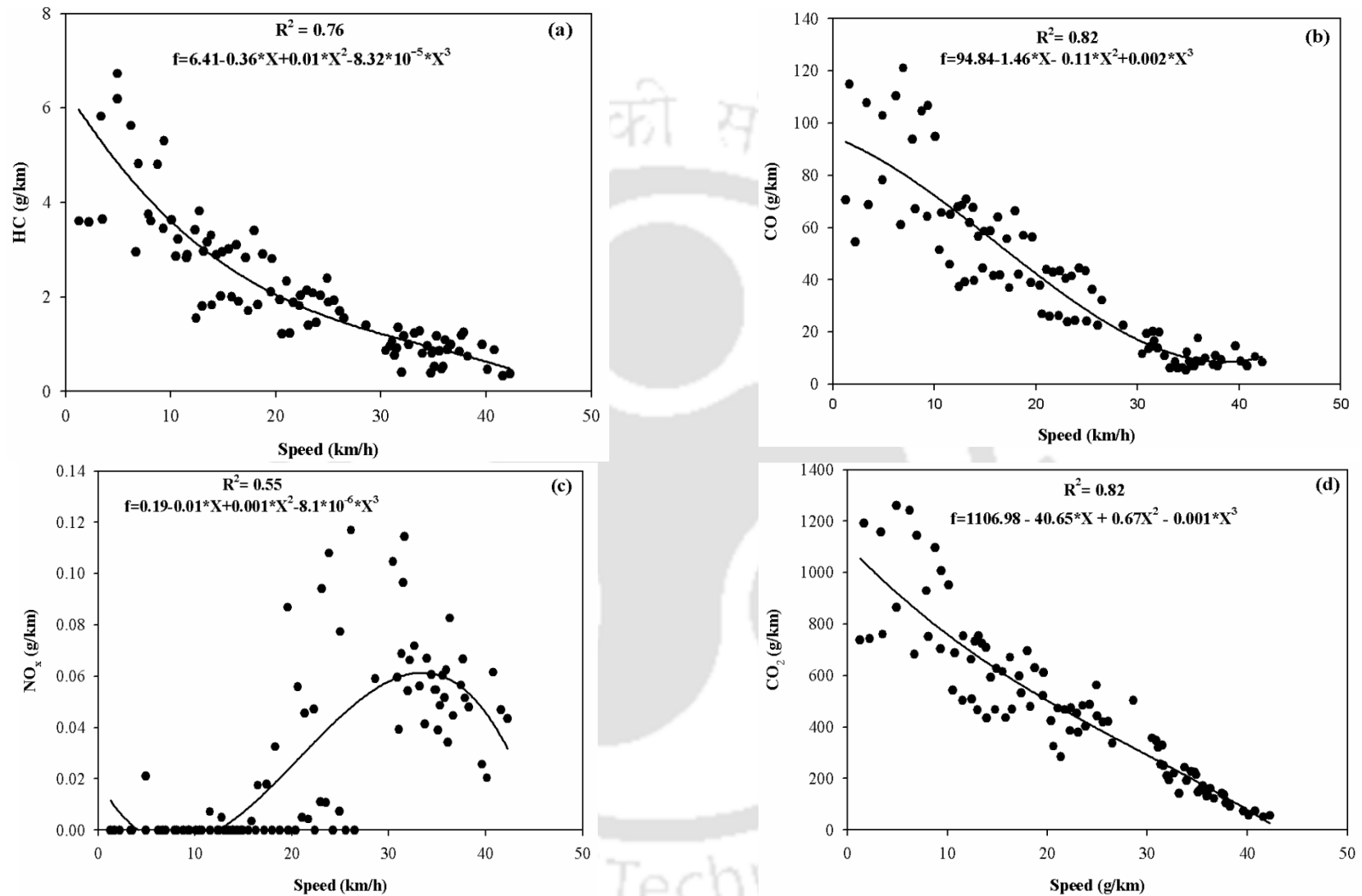


Figure 6.2 The speed dependent emission rates of auto-rickshaw of mileage 45,000 km for (a) HC, (b) CO, (c) NO_x (d) CO₂

6.2 TRAVEL TIME AND SPEED VS EMISSION

Several factors effecting the congestion are related to the overall demand for road use (Jain, 1996). Congestion on the road is triggered when many people want to move at the same time and too many vehicles are on the limited road space (Down, 2000). The vehicular exhaust is influenced by many operating variables of which particularly important in urban driving are, speed, period and number of sharp acceleration and deceleration, number and time of the stop-and-go pattern (Faiz et al., 1996). The air to fuel ratio also changes with mode of operation, for example, whether it is cruising, accelerating, decelerating or idling (Joumard, 1999; Marsden, 2001). In this study, travel time during PH was increased more than twice the travel time of OPH due to reduction in operating speed. The operating speed directly affects the vehicular exhaust emissions. Therefore, the relationship of exhaust emissions in different traffic-flow conditions corresponding to the travel time spent in those conditions for 60s has been analysed for a period of 10 minutes of the test-runs. Figure 6.3a and 6.3b shows the correlation of travel time and corresponding emission for 10 consecutive minutes of test-run for passenger car and auto-rickshaw in different traffic-flow patterns respectively. To study the effect of operating speed and corresponding travel time, the vehicle speed categorized into 0–5, 5–15, 15–30 and above 30 km/h corresponding to idle-flow, CF, IF and FF, respectively. It was found that during the test-run, the passenger cars and auto-rickshaws travelled for over 80% of the time in the speed range 10–30 km/h.

Figure 6.4a and 6.4b shows the emission rate of CO, HC, NO_x and CO₂ for passenger car and auto-rickshaw corresponding to different traffic-flow patterns. It has been observed that the magnitude of emission rate in both passenger car and auto-rickshaw is due to higher time of travel and lower operating speed for the pollutants CO

and HC. The emission rate of NO_x significantly increased for speed of >30 km/h but did not show any effect for time of travel. The magnitude of CO₂ emission rate was found higher for IF condition as compared to the combination of higher travel time and lower speed.

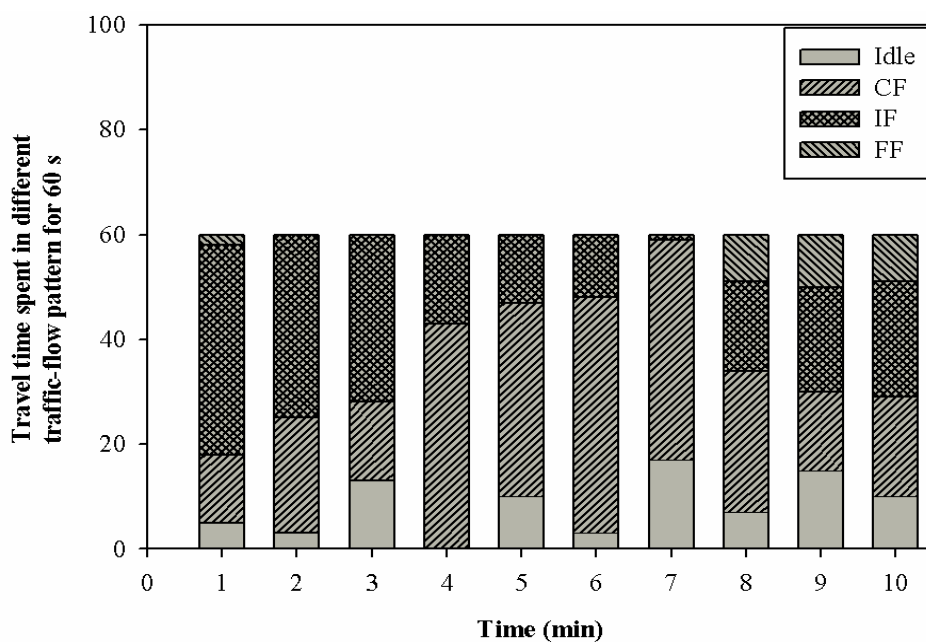


Figure 6.3a Travel time spent in different traffic-flow patterns by passenger car during PH

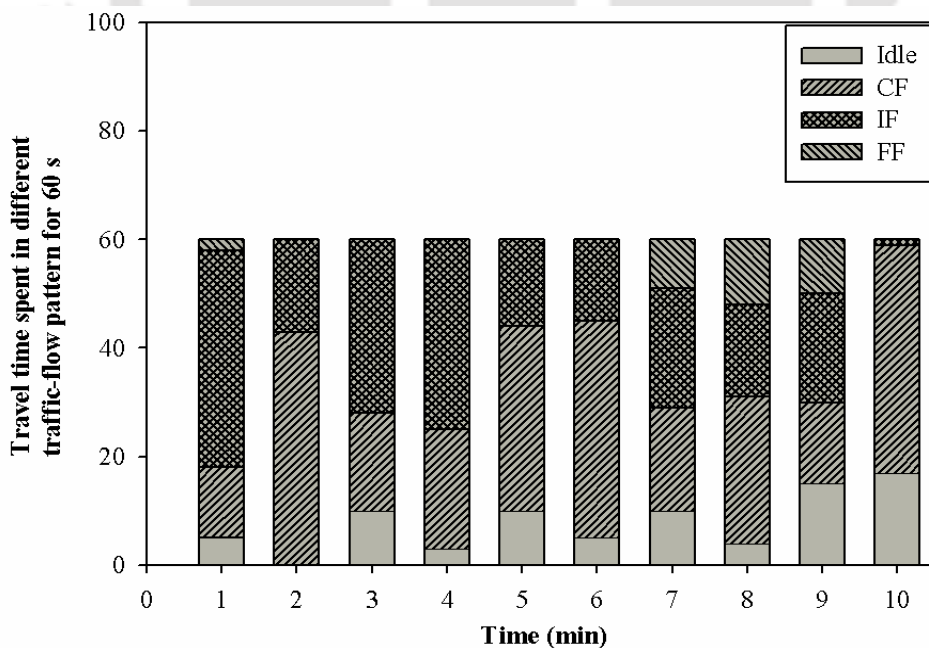
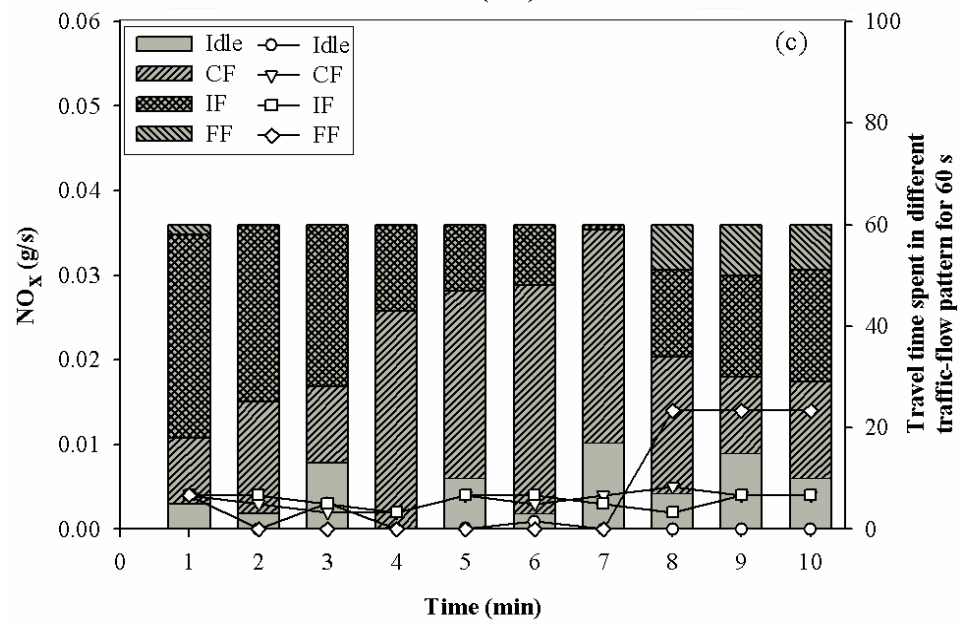
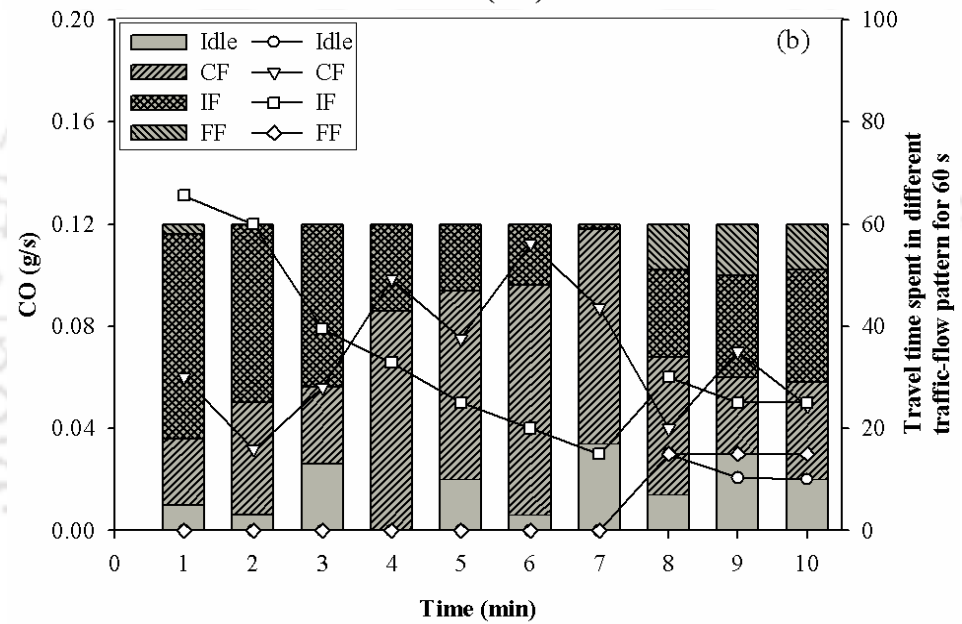
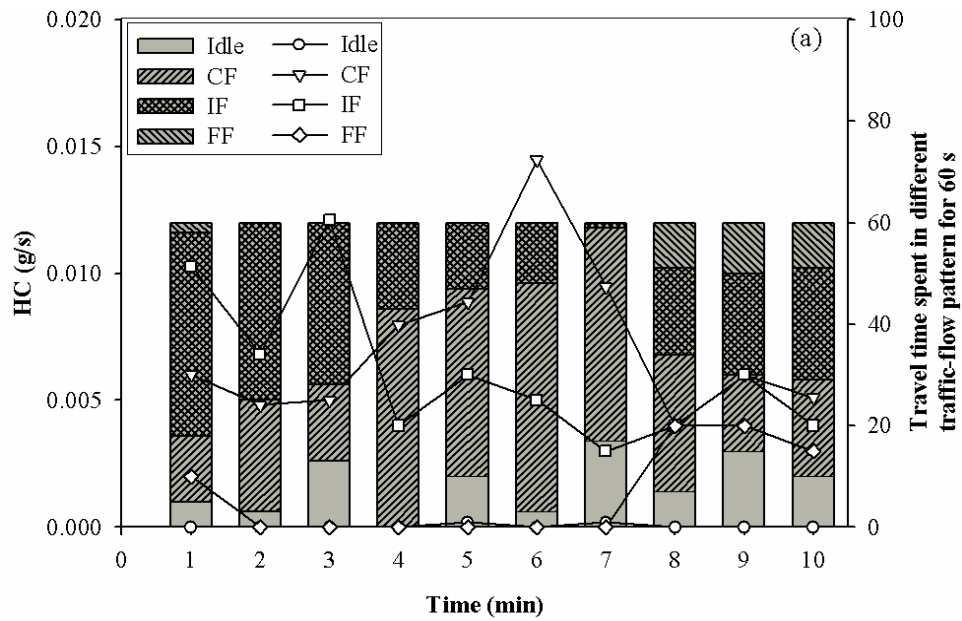


Figure 6.3b Travel time spent in different traffic-flow patterns by auto-rickshaw during PH



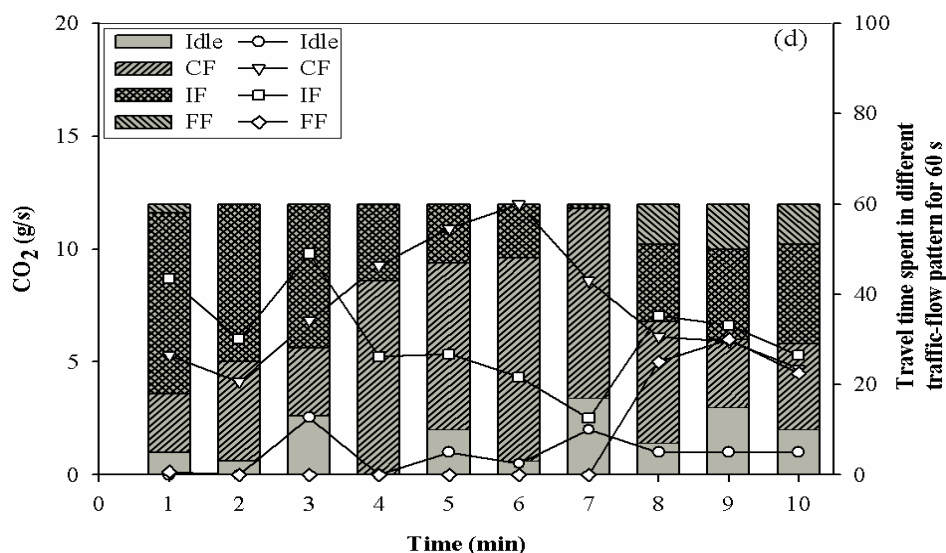
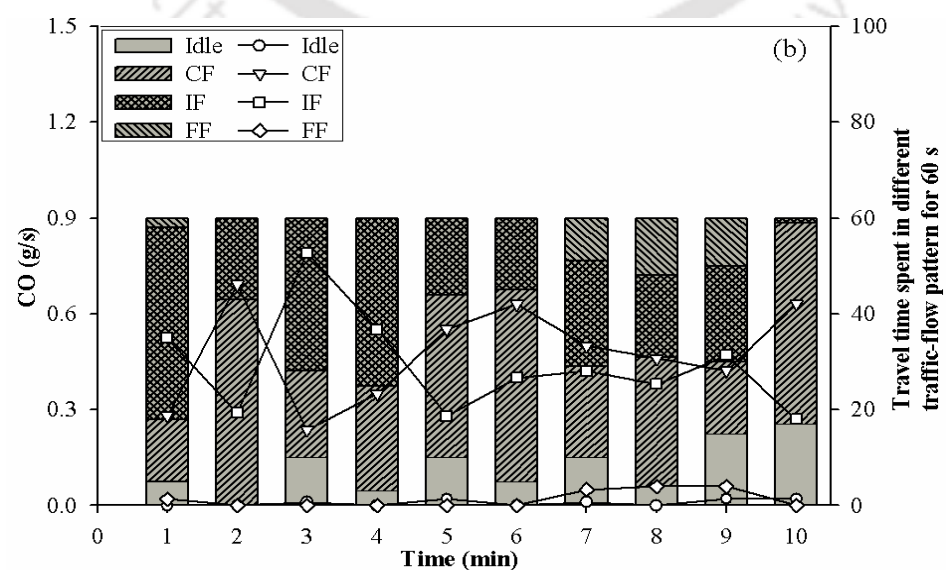
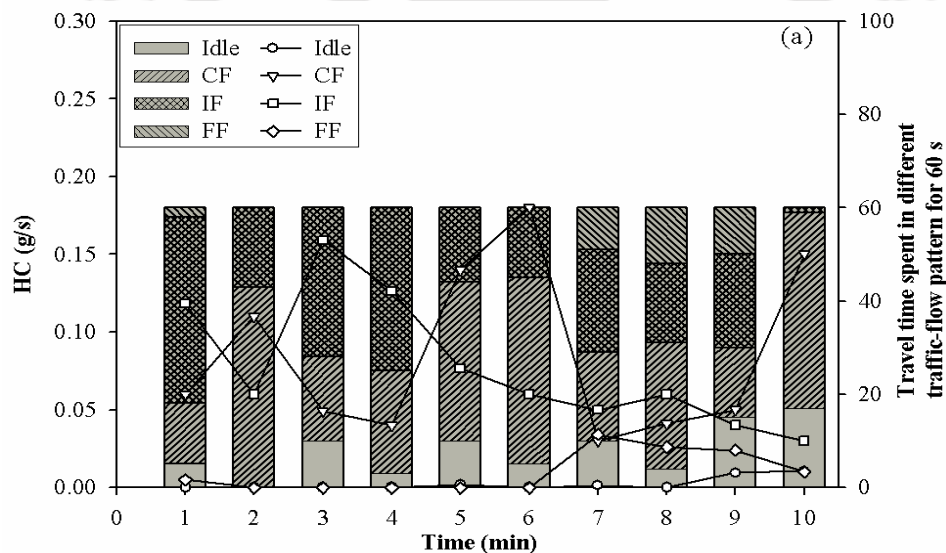


Figure 6.4a The variation of pollutants emission in different traffic-flow pattern corresponding to time spent in each traffic-flow patterns during PH in passenger car



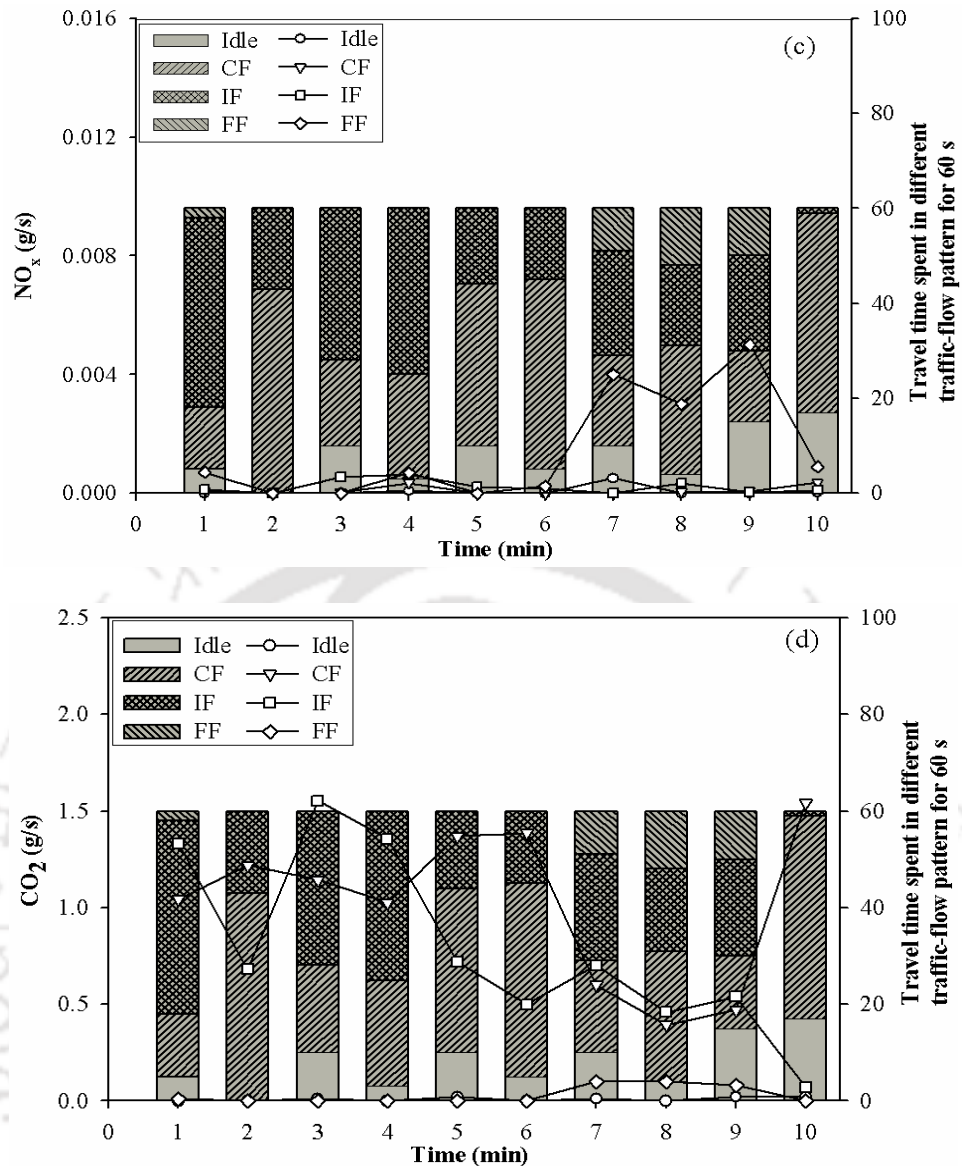


Figure 6.4b The variation of pollutants emission in different traffic–flow pattern corresponding to time spent in each traffic–flow patterns during PH in car auto–rickshaw

To determine the combine effect of travel time and associated speed on exhaust emission, a speed–time spent factor, which is a multiplication of average speed of particular flow class and the time spent of that class, was used. Details of speed–time spent factor are tabulated in appendix VII. The Figure 6.5a and 6.5b shows the relationship of pollutants emission rate with the speed–time spent factor for passenger car and auto–rickshaw, respectively. It was observed that CO, HC and CO₂ emission increases as the factor increases for both passenger car and auto–rickshaw. Therefore, the

speed at which vehicles run and the time they spend directly affect the emission, which has been shown in the Figure 6.5a and 6.5b. However, the emission of NO_x show opposite trends, has higher emission for combination of higher speed and lesser time spent and similarly very low emission was observed for combination of lower speed and higher time spent.

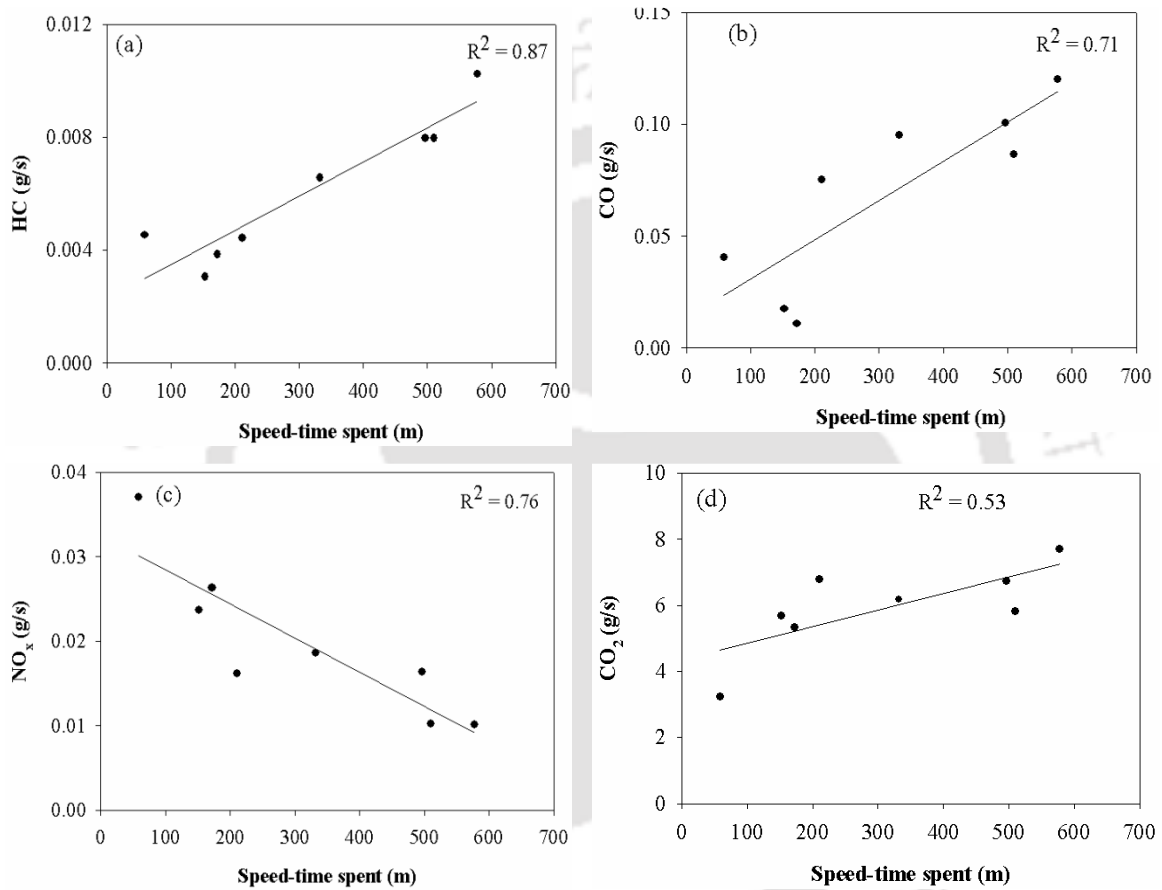
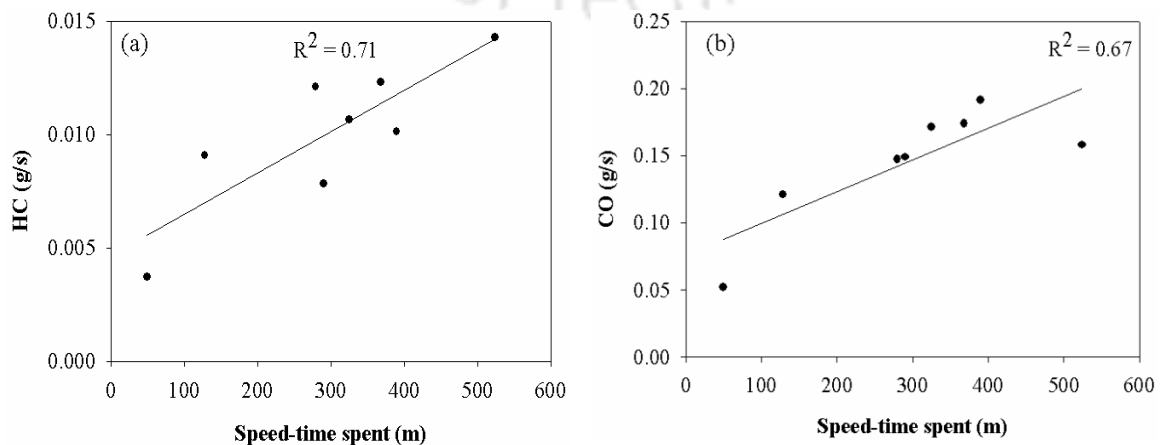


Figure 6.5a The relationship of speed–time spent with the emission of pollutants (a) HC, (b) CO, (c) NO_x and (d) CO_2 for passenger car of mileage 142,000 km



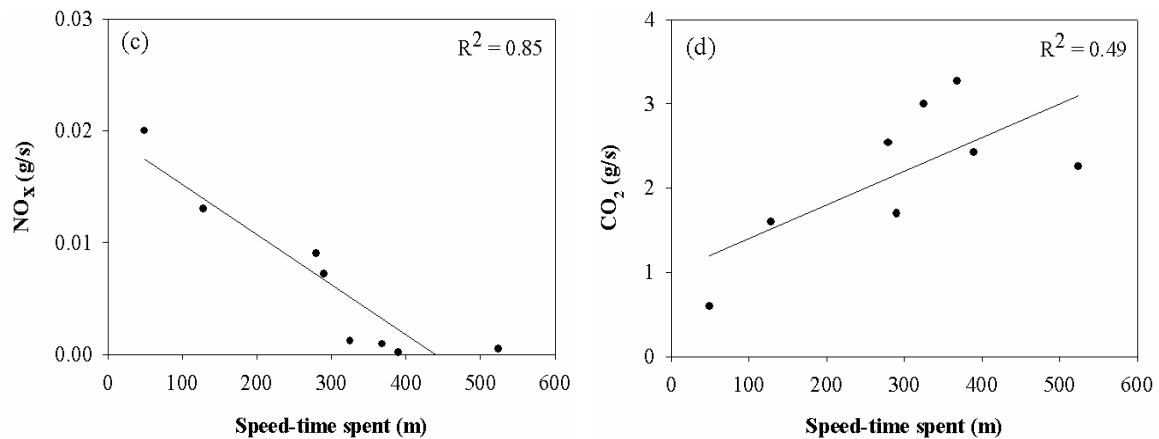


Figure 6.5b The relationship of speed–time spent with the emission of pollutants (a) HC, (b) CO, (c) NO_x and (d) CO₂ for auto–rickshaw of mileage 45,000 km

6.3 MILEAGE VS EMISSION

The vehicle mileage is another factor that determines the amount of emissions from a vehicle (Ntziachristos et al., 2000). The one–way ANOVA analysis was used to analyse the effect of mileage on exhaust emission. The completely randomised single–factor analysis of variance test (ANOVA) was applied to identify the statistically significant effects of vehicle mileage on emissions (Ntziachristos and Samaras, 2000). Using this test, the average emission values of different mileage classes of test vehicles were compared in an attempt to find any statistically significant differences between them (rejection of the null hypothesis of equal means). With the Tukey–Kramer emission mileage matrix¹³ (Barnes, 1994), correlation of mileages with different mean values can be revealed. The double input matrix in Table 6.1 presents the results of this procedure. The cells of the matrix correspond to pair–wise comparison of different mileage classes of passenger cars and auto–rickshaws found in the same row and column of the cell. This matrix has been built with 150 observations for passenger cars and 189 for auto–rickshaws. According to these results, it has been observed that for 52,000 km and

¹³ **Tukey–Kramer method** is a single–step multiple comparison procedure and statistical test. It can be used in conjunction with an ANOVA (Post–hoc analysis) to find means that are significantly different from each other (Barnes, 1994).

above, mileage has significant impact on emission from passenger car for pollutants CO, HC and NO_x. Similarly, for auto-rickshaw also, increasing mileage has significant impact on emission of CO and HC. Summary of the mean emission values obtained from ANOVA for each mileage class is given in Table 6.2, which leads to the conclusion that there is a statistically significant correlation of CO, CO₂ and HC emissions with mileage.

Table 6.1 The Tukey–Kramer emission–mileage matrix

Test Vehicles		Passenger cars			Auto-rickshaws	
		9,200 km	52,000 km	142,000 km	45,000 km	100,000 km
Passenger cars	9,200 km	-	CO, HC	CO, HC, NO _x	CO, HC, CO ₂	CO, HC, CO ₂
	52,000 km		-	CO, HC, CO ₂ , NO _x	CO, HC, CO ₂	CO, HC, CO ₂
	142,000 km			-	CO, CO ₂ , HC, NO _x	CO, HC, CO ₂ , NO _x
Auto-rickshaws	45,000 km				-	CO, HC
	100,000 km					-

Table 6.2 Summary of mean emission values ANOVA analysis

Test vehicles	Mileage in km	CO (g/s)	HC (g/s)	NO _x (g/s)	CO ₂ (g/s)
Passenger cars	9,200	0.12	0.0002	0.0006	9.50
	52,000	0.17	0.002	0.0005	5.18
	142,000	0.22	0.012	0.018	8.40
Auto-rickshaws	45,000	0.07	0.08	0.002	1.95
	100,000	0.13	0.10	0.004	1.38

6.4 UPGRADATION OF EMISSION STANDARDS AND SWITCHING TO CLEANER FUEL

The upgradation of technology and switching over cleaner fuels significantly reduce the emissions (Oanh et al., 2012). These two scenarios in which the conversion of petrol

driven auto-rickshaws and passenger cars with the alternative fuel CNG and upgrading to Euro-IV technology, respectively have been studied. The scenario of Euro-III to Euro-IV conversion for passenger cars reduced the significant emissions of CO, HC, CO₂ and NO_x. It has been observed that when Euro-III cars were replaced with Euro-IV, the reduction of 57–60% CO, 53–55% HC and about 24% CO₂ during peak hours was achieved and 55% of NO_x and 28% of CO₂ was achieved during OPH. Ong et al. (2011) also reported that replacement of the ancient passenger cars with Euro-IV has positive results in terms of fuel consumption and reduction of pollutant emissions. Figure 6.6 shows the comparison of the IVE modelled EF for Euro-III and Euro-IV passenger cars.

The CNG has become a promising alternative fuel for road transport as Reynold et al. (2011b) reported that phase-out of conventional two-stroke engine technology appears to be a desirable policy for CNG auto-rickshaws in Delhi. It is mostly methane and cleaner than gasoline or diesel (Demirbas, 2002). It is observed that CNG has lower brake mean effective pressure¹⁴ (BMEP), brake specific fuel consumptions¹⁵ (BSFC), higher efficiency and lower emissions of CO, CO₂ and HC (Aslam et al., 2006). It has been found that with the CNG conversion of auto-rickshaw, the reduction of 87–89% CO, 88–89% HC, and about 32% CO₂ during PH and of 23–56% NO_x, 36% CO₂ during OPH as compared to the gasoline auto-rickshaw were achieved. In addition, the use of CNG improves fuel economy on average mileage travelled by a vehicle per liter of fuel (Ong et al., 2011). Figure 6.7 shows the comparison of the IVE modelled EF for gasoline and CNG auto-rickshaws.

¹⁴ BMEP: a quantity that relating to the operation of a reciprocating engine is a valuable measure of an engine's capacity to do work that is independent of engine displacement (Gupta, 2012).

¹⁵ BSFC: is the ratio of the engine fuel consumption to the engine power output. BSFC has units of grams of fuel per kilowatt-hour (g/kWh) or pounds mass of fuel per brake horsepower-hour (lb/bhp-hr) (Gupta, 2012).

Guwahati has a higher percentage share of travel of auto-rickshaw per day, of which 70% are two-stroke, highly polluting. Therefore, there is an ample scope for reducing emission by switching over to CNG by phasing out two-stroke engine auto-rickshaws.



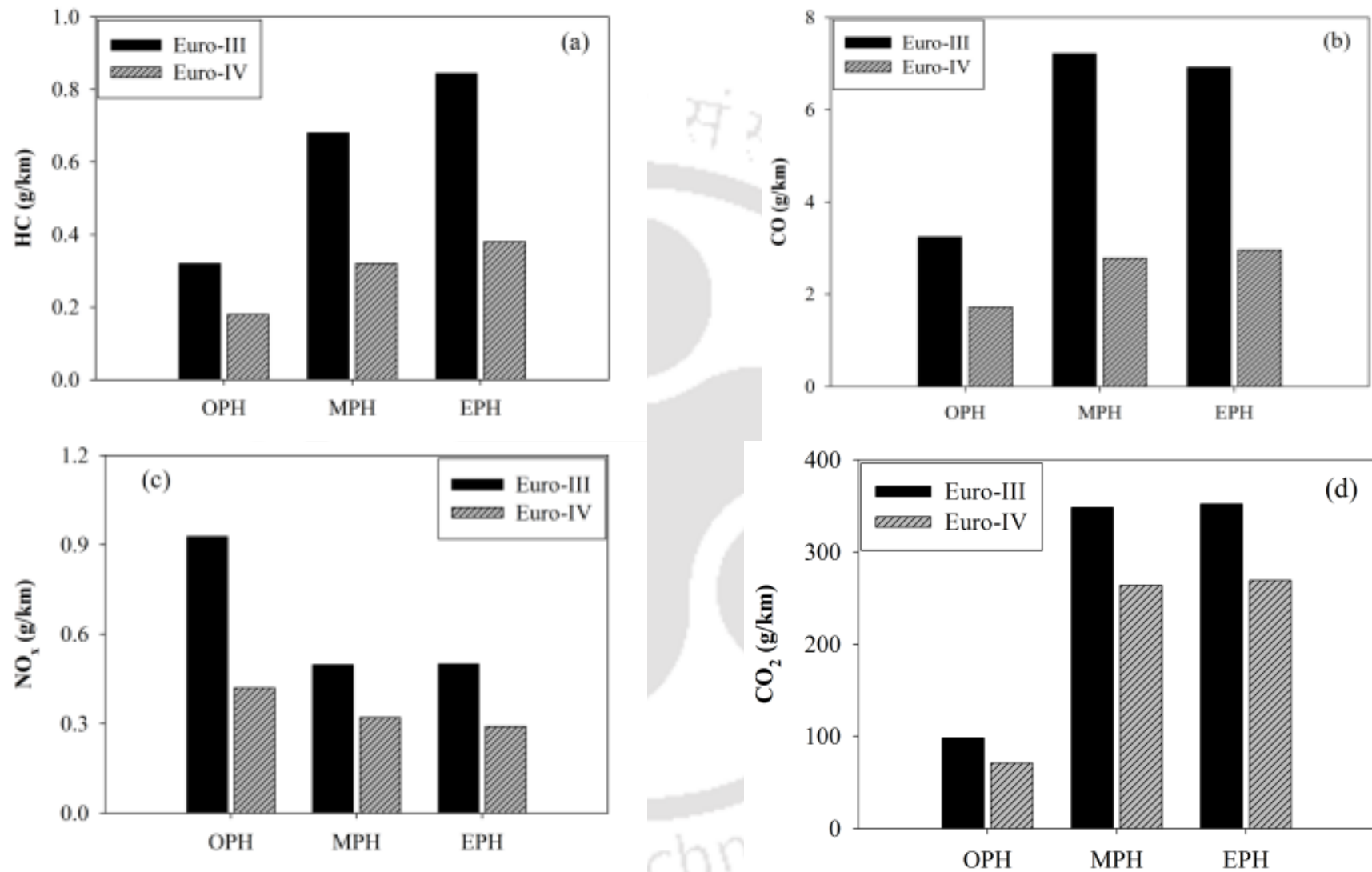


Figure 6.6 The comparison of the IVE modelled EF for Euro-III and Euro-IV passenger car for (a) HC, (b) CO (c) NO_x and (d) CO₂

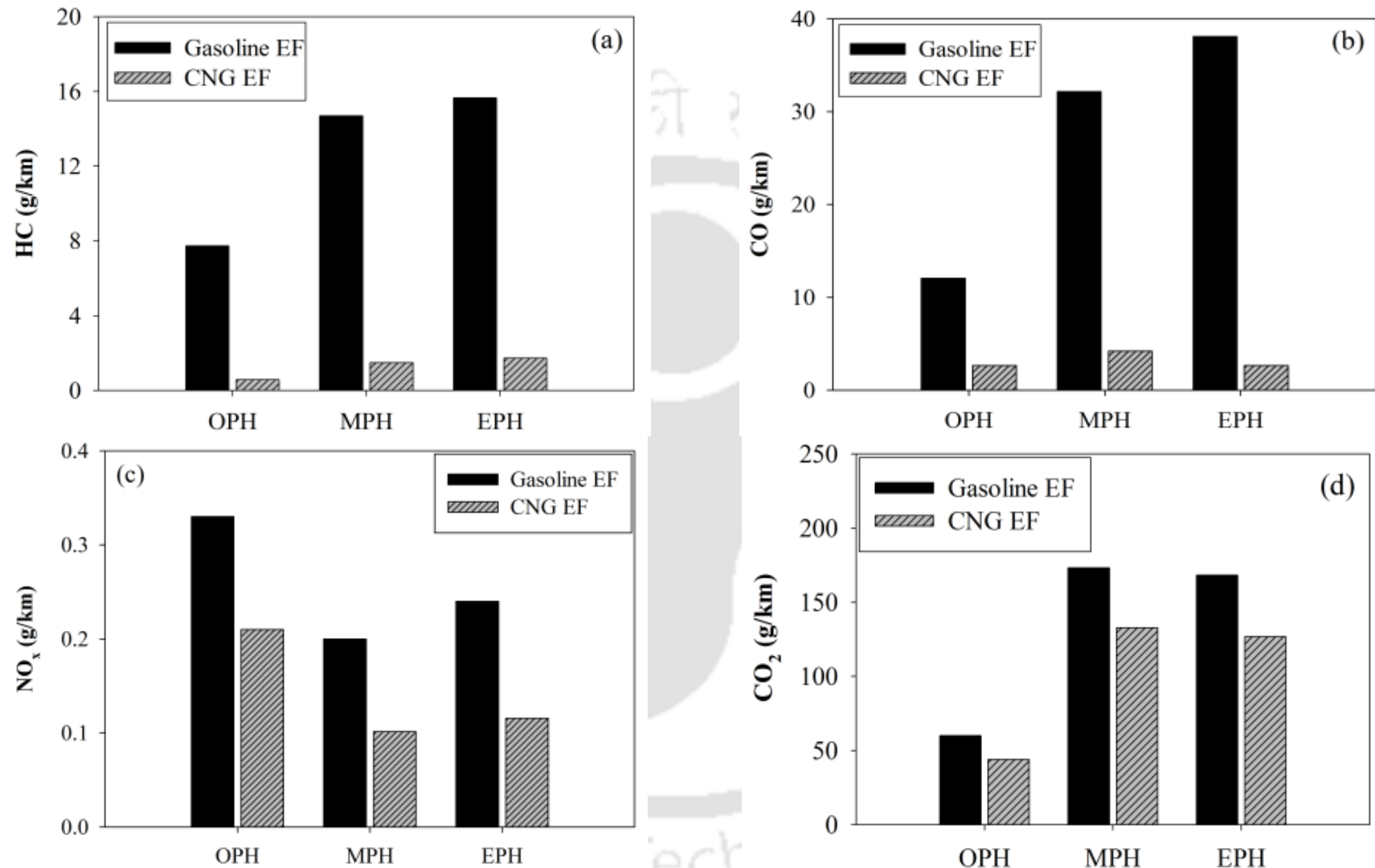


Figure 6.7 The comparison of the IVE modelled EF for gasoline and CNG driven auto-rickshaw for (a) HC, (b) CO (c) NO_x and (d) CO₂

6.5 TRAFFIC–FLOW MANAGEMENT

6.5.1 Management of public transport

Traffic–flow management is needed in Indian cities to reduce congestion and concomitant emissions (Singh, 2006). Some metropolitan cities of India have modest traffic–flow management and enforcement of traffic regulations (e.g. Delhi and Bangalore). But several big cities and towns lack even the basic infrastructure such as stop signs, traffic signals, lane striping, and other regulatory and directional signage. Along with these basic infrastructures, strict enforcement of traffic regulations can ease congestion and reduces fuel consumption and emission loads (Pucher et al., 2005; Jaiswal and Sharma, 2005). It has been perceived that public transport mainly buses in urban areas interrupts the traffic–flow, which often leads to congestion (Pucher et al., 2004). Besides, unregulated stoppages cause frequent congestion and higher emission (Sriraman, 2015).

The operational behaviour of the buses on the test route was studied from videotapes. It was observed from the videotape analysis that roadside parking, unregulated stopping of buses and lack of zebra crossings for pedestrian are the major causes of interruption in regular traffic–flow (Chapter 3, Figure 3.1b). Besides, the random stoppages of buses in between the bus stops make traffic interruption more frequent. It was also observed that frequency of the buses, passenger demands and pedestrian interruption affects the traffic–flow, travel time and emission rate. The analysis of bus stoppages causing interruption is given in Table 6.3. It has been observed that 30 ± 5 buses halt in one hour (during 10–11 am and 4–6 pm), which means 1 bus per 2 min interval indicating a constant bottleneck near the bus stop. The average halt time of each bus was 43 ± 23 s. At the same time passenger activity was found to be 2 persons

(1.8 people) in one bus. This indicated that demand was less than the supply and further pedestrian interruption was counted as 85 passengers per hours. These results indicate that buses and pedestrian crossing the road are the main causes of interruption of traffic-flow. If the frequency of buses is decreased from 1 bus per 2 min to 1 bus per 5 min the time of interruption during peak hour can be reduced by 40%.

Table 6.3 Bus stoppage and interruption over 100 m stretch of the test route

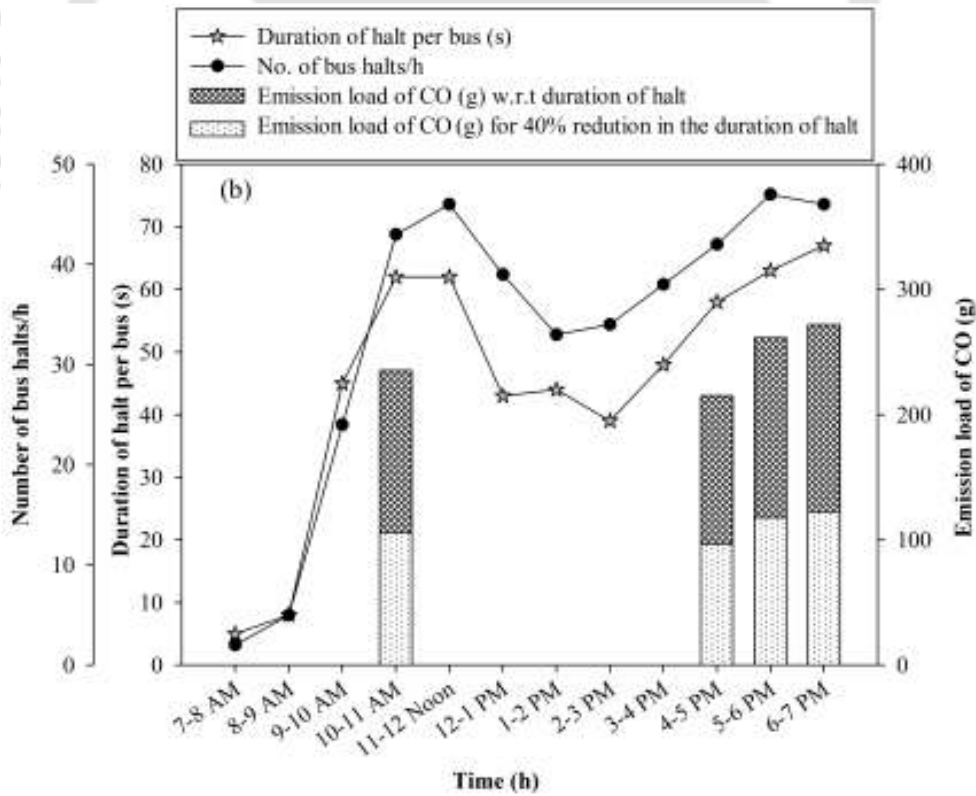
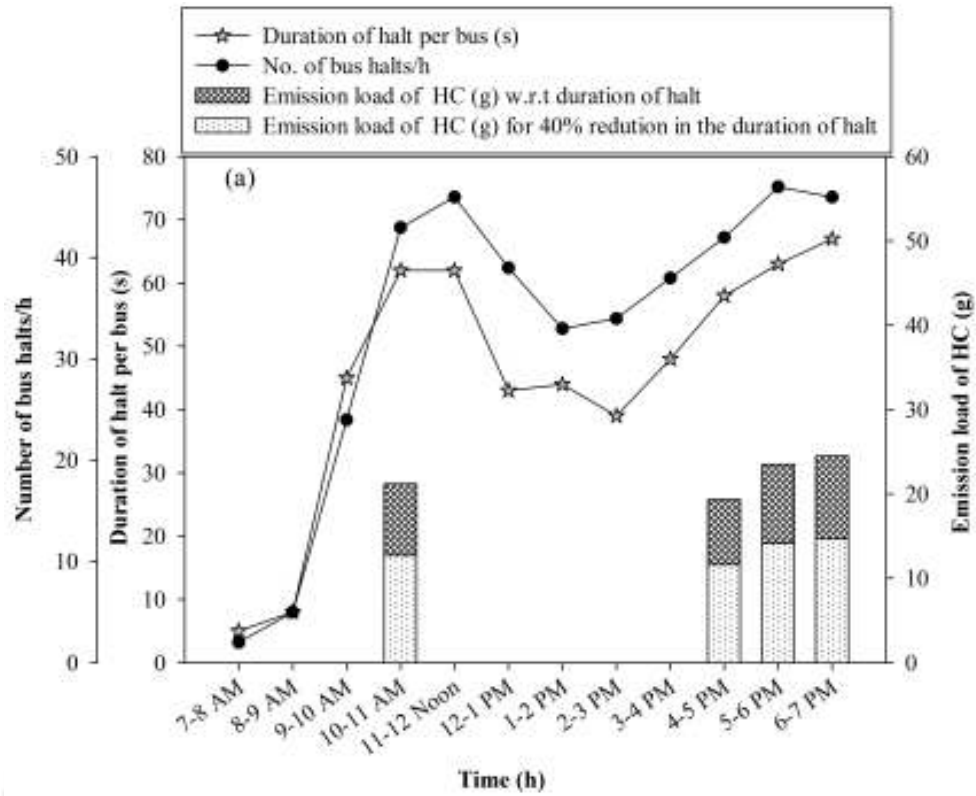
Bus activity	No./duration of activity	Activity of one bus during PH	No/duration of activity for one bus
Bus halts in one hour	30±5 No.	Frequency	1 bus per 2 min
Average duration of halts per bus (s) during PH per bus	43±23 s	Passenger activity	2 No. per bus
Total time of interruption (s)	30·43=1290 s	Ratio of Time:Bus:Passenger	60:30:54 (60min:30bus:54person) or 2:1:2
Passenger demands in PH	54 No.	What if scenario for Time:Bus:Passenger	60:12:54 or 5:1:5
Pedestrian activity	85 No.	Total time of interruption for what if scenario	516 s
Per km bus stops	3 No.	Reduction in interruption time	40%

6.5.2 Regulation of buses and passengers

The reduction in frequency of buses reduces interruption with a minimal extra load of passengers on the bus, which can reduce emissions drastically. As was found in travel time frequency analysis during PH, there is 80% probability that passenger cars run at a speed of 12±5 km/h and auto-rickshaws at a speed of 22±3.5 km/h (Appendix VII). The instantaneous emissions for these speeds of passenger car (mileage 142,000 km/h) and auto-rickshaw (100,000 km/h) were used for analysis. Due to 40% reduction in time of interruption, about 66% reduction in the emissions of CO and HC was achieved during

PHs. The Figure 6.8 (a, b, c and d) shows the emission reduction of passenger car due to 40% reduction in bus interruption time during PHs for pollutants HC, CO, NO_x and CO₂, respectively. Similarly, the Figure 6.9 (a, b, c and d) shows the emission reduction of auto-rickshaw due to 40% reduction in bus interruption time during PHs for pollutants HC, CO, NO_x and CO₂ respectively. It was found that due to PH operating conditions, such as stop-and-go traffic-flow patterns, emission load of HC and CO was higher. Therefore, reduction of bus interruption time can improve the traffic-flow and also significant reduction (about 66%) in emission load of HC and CO can be achieved. The emission rates of NO_x and CO₂ at low speed (12±5 km/h and 22±3.5 km/h for passenger car and auto-rickshaw, respectively) were less. Therefore, the reduction was also less for NO_x and CO₂ as compared to CO and HC.

This analysis demonstrated that city buses though less in number as compared to the cars, their operations involving frequent stoppages interrupt the traffic causing it to contribute to more emissions. This is particularly a problem in India where there are no dedicated bus lanes and the roads are narrow and is difficult to predict the growth in traffic.



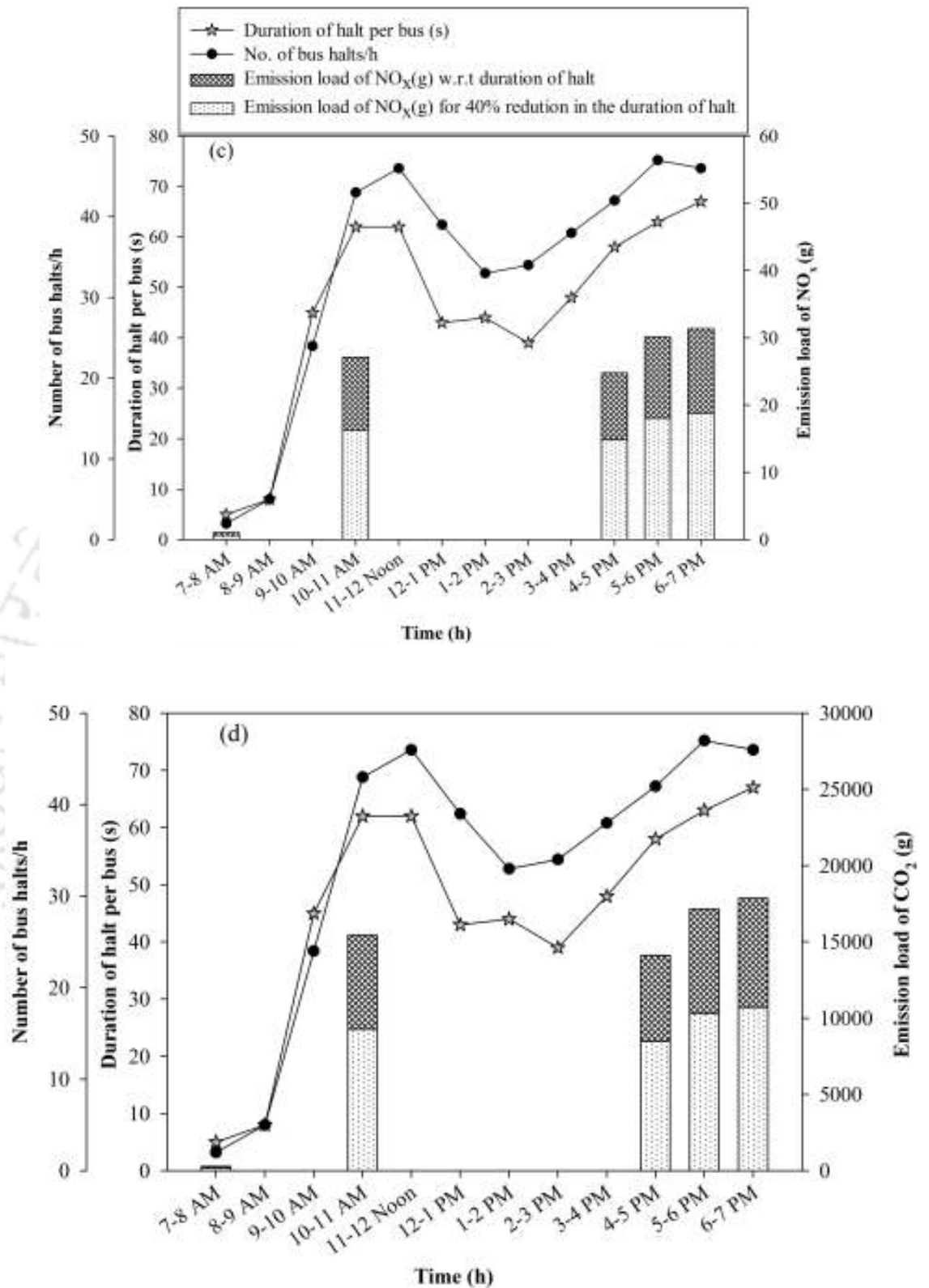
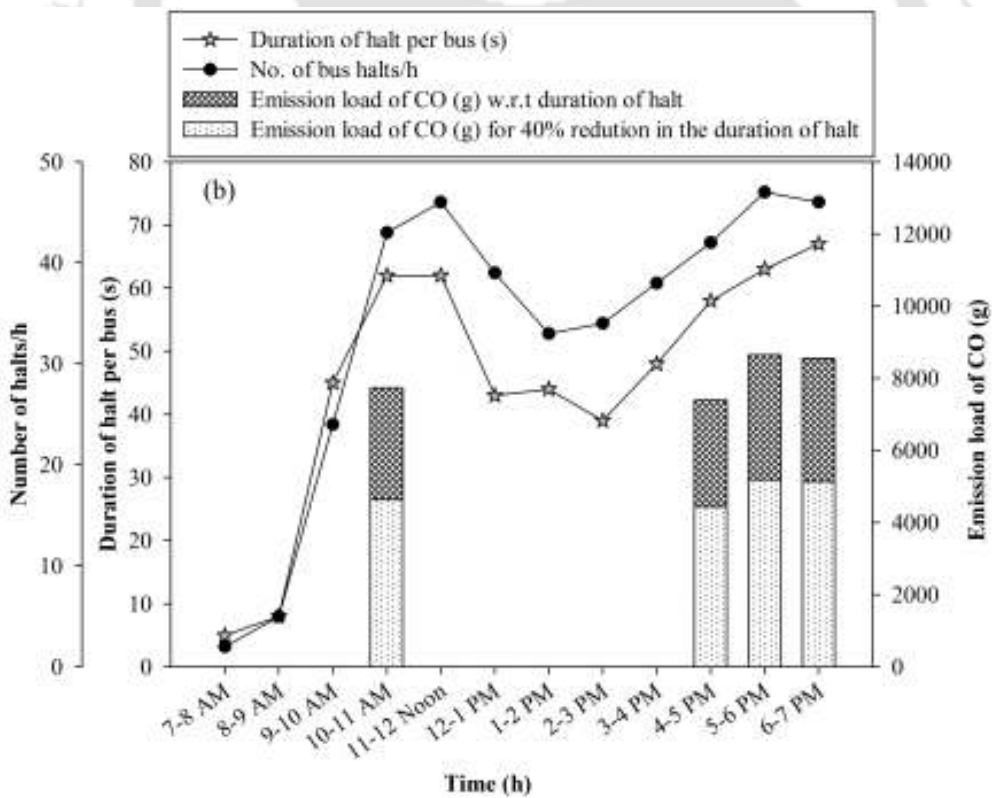
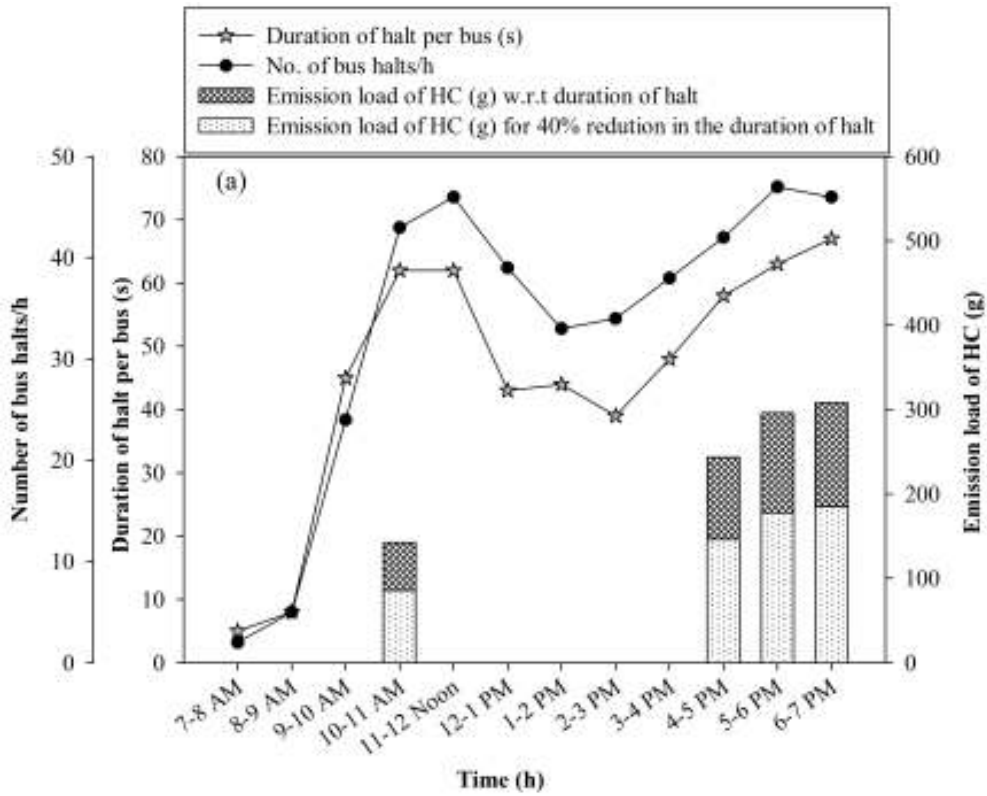


Figure 6.8 The reduction of passenger car emissions by reducing bus interruption time for (a) HC, (b) CO, (c) NO_x and (d) CO₂



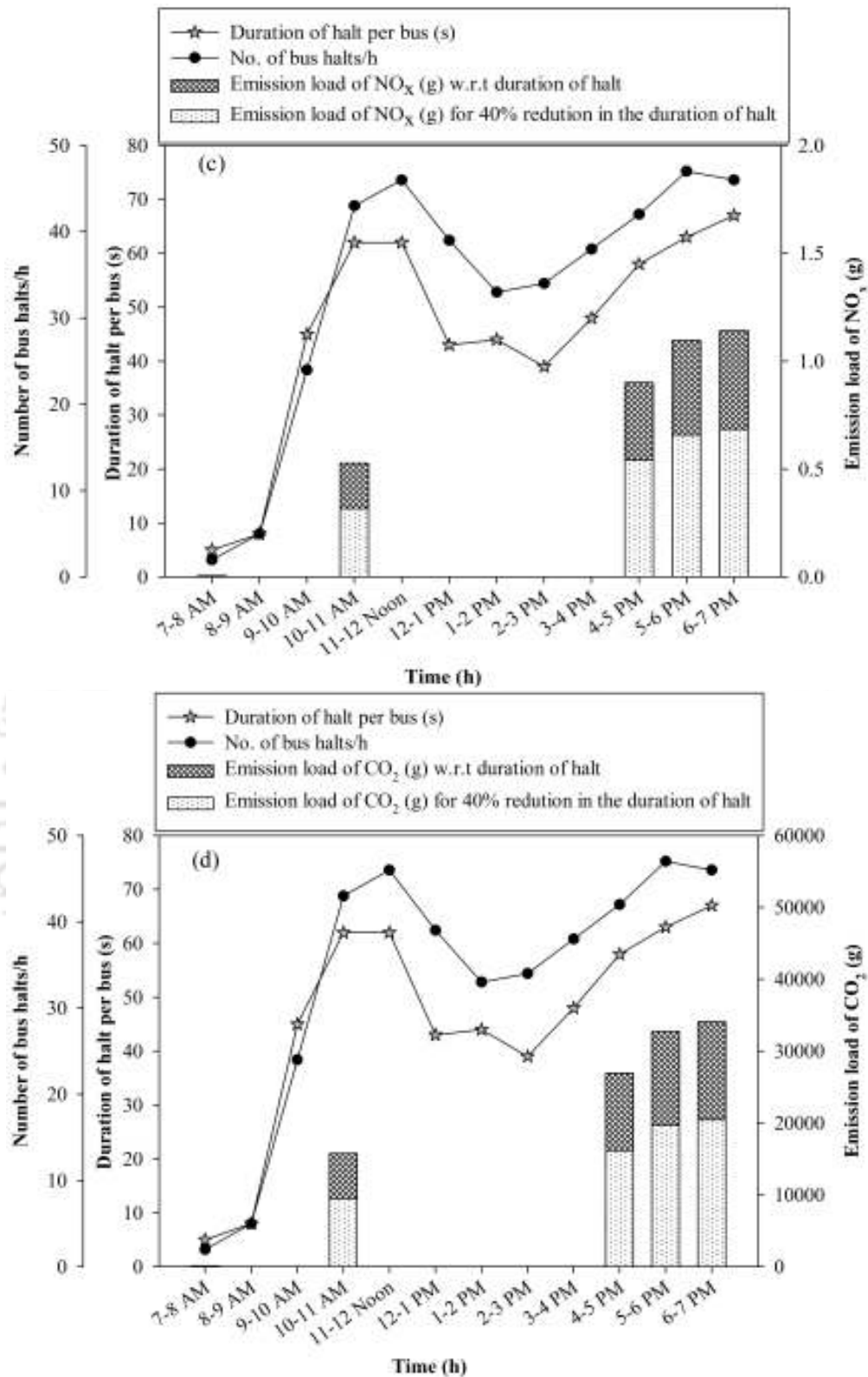


Figure 6.9 The reduction of auto-rickshaw emissions by reducing bus interruption time for (a) HC, (b) CO, (c) NO_x and (d) CO₂

6.5.3 Comparison of emission reduction strategies

The results are summarized in Table 6.4. It can be concluded that during PH all three mitigation strategies significantly reduces the tail-pipe emissions of CO, HC, CO₂ and NO_x. Since, the PH operating speed and sharp A/D events significantly increase the magnitude of CO and HC emission as compared to other (CO₂ and NO_x) pollutants. Therefore, the suggested mitigation strategies are efficient in reduction of CO and HC.

Table 6.4 Summary of emission mitigation strategies

SN.	Emission mitigation methods	HC	CO	NO _x	CO ₂
1	Upgradation from Euro-III to IV	53–55%	57–60%	55%	31–38%
2	Shifting of Gasoline fuel to CNG	89%	89%	23–56%	32–36%
3	Regulating the bus frequency	40–66%	40–66%	40%	40%

6.5.4 Improvement of traffic-flow

The multivariate regression has been carried out with the number of bus halts per hour and duration of each bus halts (s) as predictor variables and CO, HC, CO₂ and NO_x emission factor as the outcome variables. The regression coefficients and R² values for passenger car and auto-rickshaw are tabulated in Table 6.5 and 6.6, respectively.

The numbers of bus halts were found to be in positive correlation with the HC and CO emissions for both passenger car and auto-rickshaw. Whereas, CO₂ and NO_x, shows negative correlation with the predictor variables, for example, increasing the number of bus halts decreased the speed of passenger cars and auto-rickshaw which reduced the emissions of CO₂ and NO_x.

Table 6.5 Summary of regression statistics of traffic–flow management for passenger car

Variables	Symbol	HC (mg/s)		CO (mg/s)		CO ₂ (mg/s)		NO _x (mg/s)	
		Value	Sig.	Value	Sig.	Value	Sig.	Value	Sig.
No of bus halts per h	β_1	0.027	0.004	-0.620	0.002	-212.64	0.001	-3.50	0.003
Duration of each bus halts (s)	β_2	0.028	0.040	3.48	0.03	-226.71	0.04	5.46	0.03
Constant	β_0	2.76	0.02	18.26	0.02	1173	0.03	99.44	0.02
R ²		0.97		0.98		0.96		0.95	
Adjusted R ²		0.95		0.97		0.93		0.92	
Standard error		0.33		5.3		119		14.59	

Table 6.6 Summary of regression statistics of traffic–flow management for auto–rickshaw

Variables	Symbol	HC (mg/s)		CO (mg/s)		CO ₂ (mg/s)		NO _x (mg/s)	
		Value	Sig.	Value	Sig.	Value	Sig.	Value	Sig.
No of bus halts per h	β_1	0.036	0.006	1.17	0.003	-12.67	0.001	0.0001	0.004
Duration of each bus halts (s)	β_2	0.033	0.01	5.00	0.02	24.67	0.04	-0.0007	0.03
Constant	β_0	4.66	0.03	78.19	0.02	119	0.04	0.059	0.04
R ²		0.89		0.94		0.95		0.89	
Adjusted R ²		0.82		0.91		0.92		0.81	
Standard error		0.81		9.88		33.60		0.003	

6.6 SUMMARY AND DISCUSSION

The exhaust emission is influenced by many operating variables of which particularly important in urban driving are, speed, duration and number of sharp acceleration and deceleration, number and time of the stop–and–go pattern. The analysis concluded that the emission rates of CO, HC and CO₂ are higher for the speed range of 10–30 km/h whereas, emission rate of NO_x was maximum for >30 km/h speed. The study also reveals that the travel time of the test vehicles during peak hour is more than twice the travel time during off–peak hour due to reduction in operating speed. The operating speed directly affects the vehicular exhaust. Therefore, it can be said that the magnitude of

emission is the combine effect of higher frequency and lower speed for the pollutants CO and HC. Another important variable of emission is the mileage of vehicle, has significant effect on emission of pollutants CO, CO₂ and HC.

Further, the mitigation options related to technology, fuel and traffic-flow management were investigated in order to reduce interruption and concomitant emission. The analysis was done with the observed data as well as the IVE modelled data. The comparison for Euro-III and Euro-IV EF showed that passenger cars can reduce upto 57-60% of CO, 53-55% HC, 55% reduction in the NO_x and 31-38% reduction in the CO₂ emissions can be achieved by upgrading to high emission standards. The results for auto-rickshaw revealed that upto 89% reduction in HC and CO, 23-56% in NO_x and 32-36% reduction in the CO₂ emissions can be achieved. And the local traffic-flow management can reduce about 40-66% emissions of CO and HC and about 40% of the CO₂ and NO_x emissions.

Although, an effective public transport system comprised of buses is a good solution and has been used many places around the world (Koshy and Arasan, 2005; Tang et al., 2009), in Indian traffic-flow condition lack of adherence to lanes, chaotic stoppages of buses on urban roads often cause interruptions and congestions. Therefore, traffic management strategy, as studied in this research, can reduce the interruptions and congestions and associated higher emissions.

7.1 GENERAL CONCLUSION

Urban traffic-flow exhibits different patterns mainly resulted from the poor traffic management, which is resulted from the inadequate infrastructure, an unregulated roadside parking and a frequent pedestrian to vehicle interaction frequently observed on the road segment which may be, due to inadequate infrastructure for pedestrians. These factors together with the variable composition of vehicles in the traffic govern the rate of exhaust emissions. This study demonstrated that the traffic-flow patterns such as free-flow, interrupted-flow and congested-flow cause different level of emissions, generally, increases in that order. The impacts of instantaneous speed, travel time, average speed and mileage on exhaust emission of pollutants HC, CO, CO₂ and NO_x have been investigated for both the directions of test route. The emission modelling has been carried out using COPERT-IV and IVE models. The comparison with the measured emission has been done and the emission mitigation strategy related to the vehicle technology, fuel type and traffic-flow management has been investigated.

7.2 SPECIFIC CONCLUSION

- As the traffic-flow pattern changes from free to interrupted to congested-flow, the emissions of CO and HC increase, whereas the emissions of NO_x decrease in that order. The emission of CO₂ found higher in interrupted-flow pattern.

- The operating speed, duration and number of sharp acceleration and deceleration, number and time of the stop-and-go events, played key roles and influenced the emissions significantly.
- The magnitude of emission is the combine effect of higher frequency of travel time and low speed, particularly, for the pollutants CO and HC, whereas emissions of NO_x increase with the increasing speed. The emission rate of CO₂ found higher for IF condition as compared to the combination of higher frequency of travel time and lower speed.
- The IVE model performed better than COPERT-IV model. The results are indicative for change in COPERT-IV for more accurate emission estimation of real-world driving.
- The peak hour emissions are reduced drastically for the technology switch over and the use of cleaner fuel type (CNG), i.e. upgradation to higher Euro-IV standards, the passenger car, about 57–60% reduction of CO and 53–55% HC, 55% of NO_x and 31–38% of CO₂ can achieved. The shifting to cleaner fuel for auto-rickshaw achieved upto 89% reduction in HC and CO, 23–56% in NO_x and 32–36% reduction in the CO₂ emissions. This concludes that faster technology intrusion and cleaner fuel can bring significant emission reduction.
- The substantial emission reduction can also be achieved by the local traffic-flow management e.g. by limiting the frequency of bus stoppages. The 40% reduction in interruption time reduced up to 40–66% emissions of CO and HC and 40% of CO₂ and NO_x.
- Even on flat terrain higher emissions are observed during both accelerating as well as decelerating irrespective of speeds.

7.3 SPECIFIC FINDINGS OF THE RESEARCH

- Three traffic-flow patterns have been identified and classified as free-flow, interrupted-flow and congested-flow from the on-road traffic volume and traffic speed of both the directions of the road.
- The average speed at which traffic undergoes free-flow, interrupted-flow and congested-flow has been found to be 34 ± 3.7 km/h, 20.7 ± 3.9 km/h and 8.4 ± 4.2 km/h, respectively.
- The local traffic-flow management can reduce the significant level of emissions from gasoline passenger cars and auto-rickshaws.

7.4 CONTRIBUTION OF THE RESEARCH

The insufficient and inefficient public transportation, mixed use of roads, low-price parking policies, poor driving behaviour and lack of transport planning makes traffic congestion and interruption the most frequent phenomenon on urban roads. The most severe outcomes of this are the restricted urban mobility and higher pollutant emissions. The effective transport planning and environmental policies depends on the accurate assessment of vehicle exhaust emissions during different traffic-flow conditions. Therefore, this study attempts to evaluate the effect of different traffic-flow patterns on speed, acceleration, travel time and associated pollutant emissions. The major contributions of the study are:

- The real-world on-road emissions of CO, CO₂, HC and NO_x for the highly used modes of urban transportation- passenger cars and auto-rickshaws on Indian urban roads have been measured.

- The classification of different traffic-flow patterns (free-flow, interrupted-flow and congested-flow) based on the operating speeds has been done.
- The real-world on-road emission factors of different mileage test vehicles for different traffic-flow patterns have been found out. This is a significant contribution as earlier studies carried out in India (Ramachandra and Shwetmala, 2009), used driving cycle and chassis dynamometer based emission factors (ARAI¹⁶).
- The causes of frequent interruption and congestion on an urban trafficked road have been identified as unregulated bus stops and poor infrastructure for pedestrians.
- The findings of this research have been used to demonstrate how emissions from the urban transportation can be reduced by implementing various measures (up-gradation to higher emission standards, shifting to cleaner fuel and regulating city bus frequency).

7.5 LIMITATION OF THE RESEARCH

This research has been carried out on petrol driven passenger cars and auto-rickshaw. However, inclusion of two-wheelers may influence the result. Diesel driven vehicles were not included due to lack of instrumentation. The traffic-flow condition was assumed to be similar in both the directions of the road segment.

7.6 FUTURE SCOPE

- Two-wheelers may be included to improve the on-road emission factors.

¹⁶ ARAI: Automotive Research Association of India

- More number of vehicles having different mileages may be studied to build the relationship of mileage and emissions of pollutants.
- The on-road measurements of different fuelled auto-rickshaws may provide better emission scenario on the roads.
- The roadway gradient (complex terrain) to estimate the effect on emission rate of different vehicle types may be studied.





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APPENDIX

APPENDIX I

RAW EMISSION DATA FILE

*A200CD-172AS*G0010\$*M2+ 00.000\$*N2+ 00000\$*O2+ 00.00\$*P2+ 25.00\$*Q2+ 0000\$*R200000\$*S2:0.18\$*T24.126\$*U2----\$*V2036.3\$*W2+ 0.000\$*X2----\$*Y2----\$
*A300CD-172AS*G0010\$*M3+ 00.000\$*N3+ 00000\$*O3+ 00.00\$*P3+ 25.00\$*Q3+ 0000\$*R300000\$*S3:0.18\$*T34.126\$*U3----\$*V3036.3\$*W3+ 0.000\$*X3----\$*Y3----\$
*A400CD-172AS*G0010\$*M4+ 00.000\$*N4+ 00000\$*O4+ 00.00\$*P4+ 25.00\$*Q4+ 0000\$*R400000\$*S4:0.18\$*T44.126\$*U4----\$*V4036.3\$*W4+ 0.000\$*X4----\$*Y4----\$
*A500CD-172AS*G0010\$*M5+ 00.000\$*N5+ 00000\$*O5+ 00.00\$*P5+ 25.00\$*Q5+ 0000\$*R500000\$*S5:0.19\$*T54.126\$*U5----\$*V5036.3\$*W5+ 0.000\$*X5----\$*Y5----\$
*A600CD-172AS*G0010\$*M6+ 00.000\$*N6+ 00000\$*O6+ 00.00\$*P6+ 25.00\$*Q6+ 0000\$*R600000\$*S6:0.18\$*T64.126\$*U6----\$*V6036.3\$*W6+ 0.000\$*X6----\$*Y6----\$
*A700CD-172AS*G0010\$*M7+ 00.000\$*N7+ 00000\$*O7+ 00.00\$*P7+ 25.00\$*Q7+ 0000\$*R700000\$*S7:0.19\$*T74.126\$*U7----\$*V7036.3\$*W7+ 0.000\$*X7----\$*Y7----\$
*A800CD-172AS*G0010\$*M8+ 00.000\$*N8+ 00000\$*O8+ 00.00\$*P8+ 25.00\$*Q8+ 0000\$*R800000\$*S8:0.18\$*T84.126\$*U8----\$*V8036.3\$*W8+ 0.000\$*X8----\$*Y8----\$
*A900CD-172AS*G0010\$*M9+ 00.000\$*N9+ 00000\$*O9+ 00.00\$*P9+ 25.00\$*Q9+ 0000\$*R900000\$*S9:0.20\$*T94.126\$*U9----\$*V9036.3\$*W9+ 0.000\$*X9----\$*Y9----\$
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Appendix

*A400CD-172AS*G0010\$*M4+ 00.000\$*N4+ 00000\$*O4+ 00.00\$*P4+ 20.91\$*Q4+ 0000\$*R400000\$*S4:0.19\$*T44.126\$*U4----\$*V4036.3\$*W4+ 0.000\$*X4----\$*Y4----\$
*A500CD-172AS*G0010\$*M5+ 00.000\$*N5+ 00000\$*O5+ 00.00\$*P5+ 20.92\$*Q5+ 0000\$*R500000\$*S5:0.20\$*T54.126\$*U5----\$*V5036.3\$*W5+ 0.000\$*X5----\$*Y5----\$
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*A700CD-172AS*G0010\$*M7+ 00.000\$*N7+ 00000\$*O7+ 00.00\$*P7+ 20.91\$*Q7+ 0000\$*R700000\$*S7:0.20\$*T74.126\$*U7----\$*V7036.3\$*W7+ 0.000\$*X7----\$*Y7----\$
*A800CD-172AS*G0010\$*M8+ 00.000\$*N8+ 00000\$*O8+ 00.00\$*P8+ 20.91\$*Q8+ 0000\$*R800000\$*S8:0.18\$*T84.126\$*U8----\$*V8036.3\$*W8+ 0.000\$*X8----\$*Y8----\$
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*A800CD-172AS*G0010\$*M8+ 00.000\$*N8+ 00000\$*O8+ 05.85\$*P8+ 05.73\$*Q8+ 0011\$*R800000\$*S8:0.20\$*T84.126\$*U8----\$*V8036.3\$*W8+ 0.000\$*X8----\$*Y8----\$

APPENDIX II

SYNCHRONIZED DATA FILE FOR A TEST VEHICLE

Auto gas analyzer data (Instantaneous emission)					V-Box data (Instantaneous speed)						
CO %	HC ppm	CO ₂ %	O ₂ %	NO _x ppm	Run number	Speed (km/h)	Time	Distance (m)	Longi- tude	Lati- tude	Acceleration (m/s ²)
0.011	0	0.4	20.78	0	1	2.841	267.1	208.28	-5506.32	1569.706	0.86
0.011	0	0.4	19.81	0	1	6.303	268.1	209.55	-5506.32	1569.706	1.43
0.011	0	3.35	16.89	0	1	9.844	269.1	211.84	-5506.32	1569.707	0.85
0.011	0	3.35	14.53	9	1	11.834	270.1	214.86	-5506.32	1569.708	0.48
0.011	0	3.35	11.14	28	1	11.622	271.1	218.2	-5506.31	1569.709	0.34
2.665	108	3.35	9.2	42	1	11.29	272.1	221.34	-5506.31	1569.711	0.17
2.665	108	3.35	6.85	63	1	12.372	273.1	224.57	-5506.31	1569.712	0.19
2.665	108	8.6	5.67	87	1	14.938	274.1	228.34	-5506.31	1569.714	1.55
2.665	108	8.6	4.39	147	1	14.977	275.1	232.52	-5506.31	1569.715	-0.4
2.665	108	8.6	3.8	203	1	15.381	276.1	236.63	-5506.31	1569.717	0.82
2.243	134	8.6	3.18	294	1	17.905	277.1	241.25	-5506.3	1569.719	0.61
2.243	134	8.6	2.92	352	1	20.131	278.1	246.57	-5506.3	1569.721	0.41
2.243	134	10.83	2.87	433	1	21.589	279.1	252.38	-5506.3	1569.723	-0.06
2.243	134	10.83	2.96	490	1	22.656	280.1	258.54	-5506.3	1569.725	0.17
2.243	134	10.83	3.01	580	1	23.142	281.1	264.92	-5506.3	1569.728	-0.19
1.422	134	10.83	2.92	643	1	23.326	282.1	271.38	-5506.29	1569.731	0.84
1.422	134	10.83	2.7	740	1	23.059	283.1	277.82	-5506.29	1569.734	-0.37
1.422	134	11.58	2.53	807	1	23.459	284.1	284.27	-5506.29	1569.736	0.53
1.422	134	11.58	2.31	909	1	23.823	285.1	290.81	-5506.29	1569.739	0.01
1.422	134	11.58	2.19	969	1	24.423	286.1	297.52	-5506.28	1569.742	-0.13
1.117	134	11.58	2.04	1034	1	25.374	287.1	304.46	-5506.28	1569.745	-0.51

Appendix

1.117	134	11.58	1.96	1056	1	26.614	288.1	311.73	-5506.28	1569.748	0
1.117	134	12.09	1.88	1070	1	27.332	289.1	319.25	-5506.27	1569.751	-0.24
1.117	134	12.09	1.85	1077	1	28.315	290.1	327	-5506.27	1569.754	0.24
1.117	134	12.09	1.85	1099	1	27.9	291.1	334.84	-5506.27	1569.757	-0.22
1.166	135	12.09	1.97	1120	1	27.547	292.1	342.52	-5506.27	1569.76	0.78
1.166	135	12.09	2.21	1151	1	27.903	293.1	350.19	-5506.26	1569.763	0.28
1.166	135	11.86	2.33	1162	1	28.461	294.1	358.04	-5506.26	1569.767	0.41
1.166	135	11.86	2.38	1160	1	28.572	295.1	366	-5506.26	1569.77	-0.74
1.166	135	11.86	2.33	1150	1	29.247	296.1	374.02	-5506.25	1569.773	0.28
1.144	139	11.86	2.21	1137	1	29.774	297.1	382.25	-5506.25	1569.777	-0.34
1.144	139	11.86	2.13	1133	1	29.94	298.1	390.56	-5506.25	1569.78	0.03
1.144	139	12.16	2.03	1137	1	30.218	299.1	398.89	-5506.24	1569.783	-0.13
1.144	139	12.16	1.98	1142	1	30.684	300.1	407.34	-5506.24	1569.786	0.24
1.144	139	12.16	1.93	1161	1	31.739	301.1	416.01	-5506.24	1569.79	0.2
0.619	139	12.16	1.89	1189	1	32.958	302.1	425	-5506.23	1569.793	0.21
0.619	139	12.16	1.84	1260	1	33.695	303.1	434.23	-5506.23	1569.797	0.58
0.619	139	12.49	1.81	1323	1	34.245	304.1	443.66	-5506.23	1569.801	-0.15
0.619	139	12.49	1.78	1423	1	34.277	305.1	453.17	-5506.22	1569.805	0.18
0.619	139	12.49	1.77	1483	1	33.681	306.1	462.62	-5506.22	1569.808	-0.28
0.491	131	12.49	1.76	1556	1	32.952	307.1	471.86	-5506.21	1569.812	0.22
0.491	131	12.49	1.76	1596	1	32.011	308.1	480.87	-5506.21	1569.815	-0.24
0.491	131	12.67	1.74	1655	1	31.632	309.1	489.69	-5506.21	1569.818	-0.44
0.491	131	12.67	1.72	1700	1	31.887	310.1	498.5	-5506.2	1569.822	0.26
0.491	131	12.67	1.7	1777	1	32.348	311.1	507.41	-5506.2	1569.825	0.75
0.459	124	12.67	1.68	1828	1	32.809	312.1	516.45	-5506.2	1569.829	-0.07
0.459	124	12.67	1.67	1899	1	33.41	313.1	525.64	-5506.19	1569.833	0.53

APPENDIX III

COPERT–IV Empirical equations for EF estimation of passenger car

Pollutants	Coefficient of gasoline passenger car for Euro 1 and post-Euro 1						
	$EF_{i,m,n} = \left(\frac{(\alpha + \gamma \cdot V + \varepsilon \cdot V^2 + \zeta / V)}{(1 + \beta \cdot V + \delta \cdot V^2)} \right) \cdot (1 - RF)$						
	α	β	γ	δ	ε	ζ	RF
CO	7.17E+01	3.54E+01	1.14E+01	-2.48E-01	0	0	1
HC	5.57E-02	3.65E-02	-1.10E-03	-1.88E-04	1.25E-05	0	1
NO_x	9.29E-02	-1.22E-02	-1.49E-03	3.97E-05	6.53E-06	0	1

COPERT–IV Empirical equations for EF estimation of auto-rickshaw

Pollutants	Coefficient of gasoline auto-rickshaw for Euro 1 and post-Euro 1					
	$EF_{i,m,n} = \alpha + \beta \cdot V + \gamma \cdot V^2 + \delta \cdot V^3 + \varepsilon \cdot V^4 + \zeta \cdot V^5$					
	ζ	ε	γ	δ	β	α
CO	-4.82E-09	1.52E-06	-1.90E-04	1.29E-02	-4.43E-01	1.04E+01
HC	-1.10E-09	3.84E-07	-5.45E-05	4.23E-03	-1.75E-01	3.72E+00
NO_x	-1.74E-11	1.09E-08	-1.87E-06	1.30E-04	-3.54E-03	4.97E-02

APPENDIX IV–A

Vehicle technology index for fleet file input information

Description	Fuel	Weight	Air/Fuel Control	Exhaust Control	Evaporative Control	Age in km (K=1000)	Technology Index	Fraction vehicles
Auto/Sml Truck	Petrol	Lt	Multi-Pt FI	Euro-III	PCV/Tank	<79K	189	0.25
Auto/Sml Truck	Petrol	Lt	Multi-Pt FI	Euro-III	PCV/Tank	80-161K	190	0.52
Auto/Sml Truck	Petrol	Lt	Multi-Pt FI	Euro-III	PCV/Tank	>161K	191	0.23
Sml Engine	Petrol	Lt	2-Cycle	None	None	26-50K	1171	0.35
Sml Engine	Petrol	Lt	2-Cycle	None	None	>50K	1172	0.65



APPENDIX IV-B

VSP power groups distribution for passenger car

Stress mode	VSP power groups																			
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
8 AM, Average speed 36 km/h																				
Low	0	0	0	0	0	0	0	0	1.40	2.00	6.60	16.90	25.60	38.0	7.30	2.20	0	0	0	0
Medium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 AM, Average speed 20 km/h																				
Low	0	0	0	0	0	0	0	0	0	0.42	5.01	51.57	39.46	3.55	0	0	0	0	0	0
Medium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 AM, Average speed 20 km/h																				
Low	0	0	0	0	0	0	0	0	0.17	1.19	6.96	51.10	32.60	6.45	1.36	0.17	0	0	0	0
Medium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX IV–C

VSP power groups distribution for auto-rickshaw

Stress mode	VSP power groups																			
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
8 AM, Average speed 36 km/h																				
Low	0	0	0	0	0	0	0	0	0.45	0.45	8.70	13.40	21.00	25.00	20.00	11.00	0	0	0	0
Medium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 AM, Average speed 20 km/h																				
Low	0	0	0	0	0	0	0	0	1.02	1.02	2.77	48.88	39.21	3.77	2.11	1.20	0	0	0	0
Medium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5 PM, Average speed 18 km/h																				
Low	0	0	0	0	0	0	0	0	0.10	0.10	4.26	58.00	32.43	2.75	1.12	1.21	0	0	0	0
Medium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Nonlinear Regression - Dynamic Fitting for Velocity noise Vs traffic volume

Equation: Polynomial, Cubic

$$f=y_0+a*x+b*x^2+c*x^3$$

Dynamic Fit Options:

Total Number of Fits	200
Maximum Number of Iterations	200

Parameter Ranges for Initial Estimates:

	Minimum	Maximum
y0	-48.6847	146.0540
a	-0.6107	0.2036
b	-0.0005	0.0016
c	-1.5322E-006	5.1074E-007

Results for the Overall Best-Fit Solution:

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9793	0.9589	0.9528	1.7640

	Coefficient	Std. Error	t	P	VIF
y0	48.6847	2.2632	21.5111	<0.0001	39.5082<
a	-0.2036	0.0336	-6.0505	<0.0001	1087.8083<
b	0.0005	0.0001	4.3855	0.0003	3098.0868<
c	-5.1074E-007	1.2815E-007	-3.9855	0.0007	831.3714<

Analysis of Variance:

Uncorrected for the mean of the observations:

	DF	SS	MS
Regression	4	15892.5700	3973.1425
Residual	20	62.2319	3.1116
Total	24	15954.8019	664.7834

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	3	1453.7213	484.5738	155.7317	<0.0001
Residual	20	62.2319	3.1116		
Total	23	1515.9532	65.9110		

Statistical Tests:

PRESS 87.4436

Durbin-Watson Statistic 0.9879 Failed

Normality Test Passed (P = 0.9871)

K-S Statistic = 0.0894 Significance Level = 0.9871

Constant Variance Test Passed (P = 0.8468)

Power of performed test with alpha = 0.0500: 1.0000

Nonlinear Regression - Dynamic Fitting for Coefficient of variation of speed Vs Traffic volume

Equation: Polynomial, Cubic

$$f=y_0+a*x+b*x^2+c*x^3$$

Dynamic Fit Options:

Total Number of Fits	200
Maximum Number of Iterations	200

Parameter Ranges for Initial Estimates:

	Minimum	Maximum
y0	-0.0502	0.1507
a	-0.0003	0.0001
b	-4.7540E-006	1.4262E-005
c	-2.0640E-008	6.8799E-009

Results for the Overall Best-Fit Solution:

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9839	0.9680	0.9632	0.0218

	Coefficient	Std. Error	t	P	VIF
y0	0.0502	0.0279	1.7994	0.0871	39.5082<
a	-0.0001	0.0004	-0.2507	0.8046	1087.8072<
b	4.7540E-006	1.5140E-006	3.1400	0.0052	3098.0830<
c	-6.8799E-009	1.5804E-009	-4.3532	0.0003	831.3703<

Analysis of Variance:

Uncorrected for the mean of the observations:

	DF	SS	MS
Regression	4	1.4923	0.3731
Residual	20	0.0095	0.0005
Total	24	1.5018	0.0626

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	3	0.2863	0.0954	201.6684	<0.0001
Residual	20	0.0095	0.0005		
Total	23	0.2958	0.0129		

Statistical Tests:

PRESS 0.0147

Durbin-Watson Statistic 2.2482 Passed

Normality Test Passed (P = 0.8889)

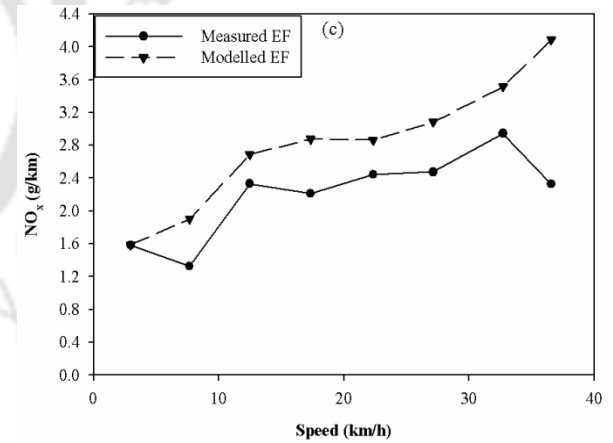
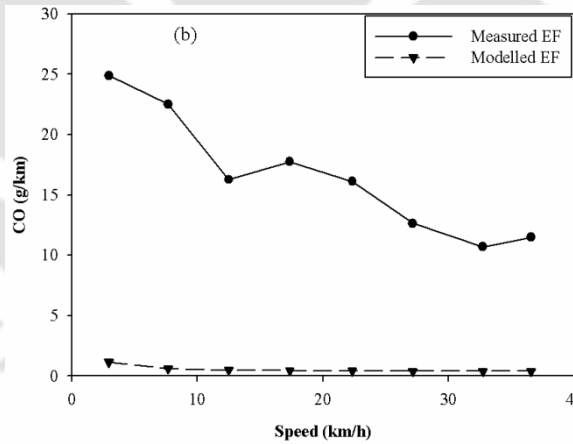
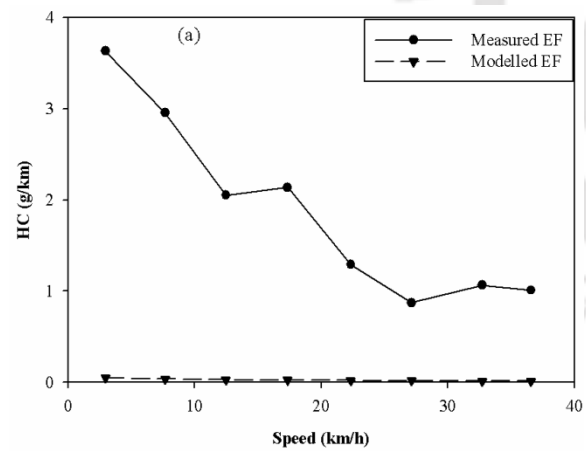
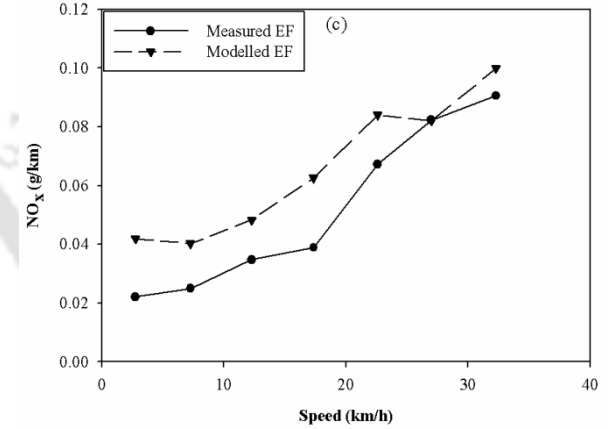
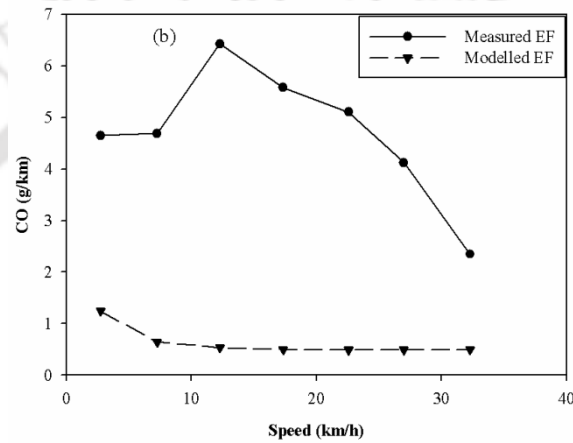
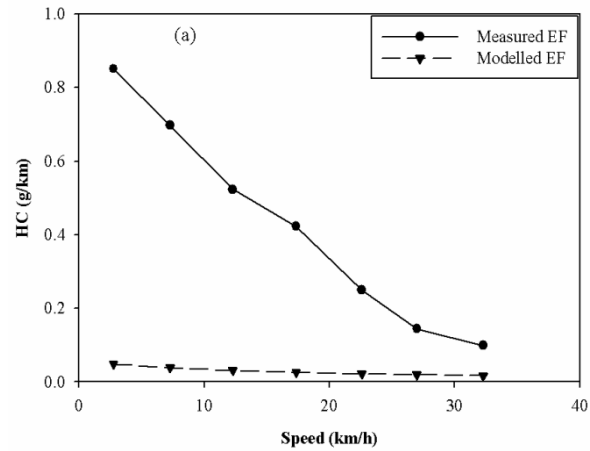
K-S Statistic = 0.1152 Significance Level = 0.8889

Constant Variance Test Passed (P = 0.1448)

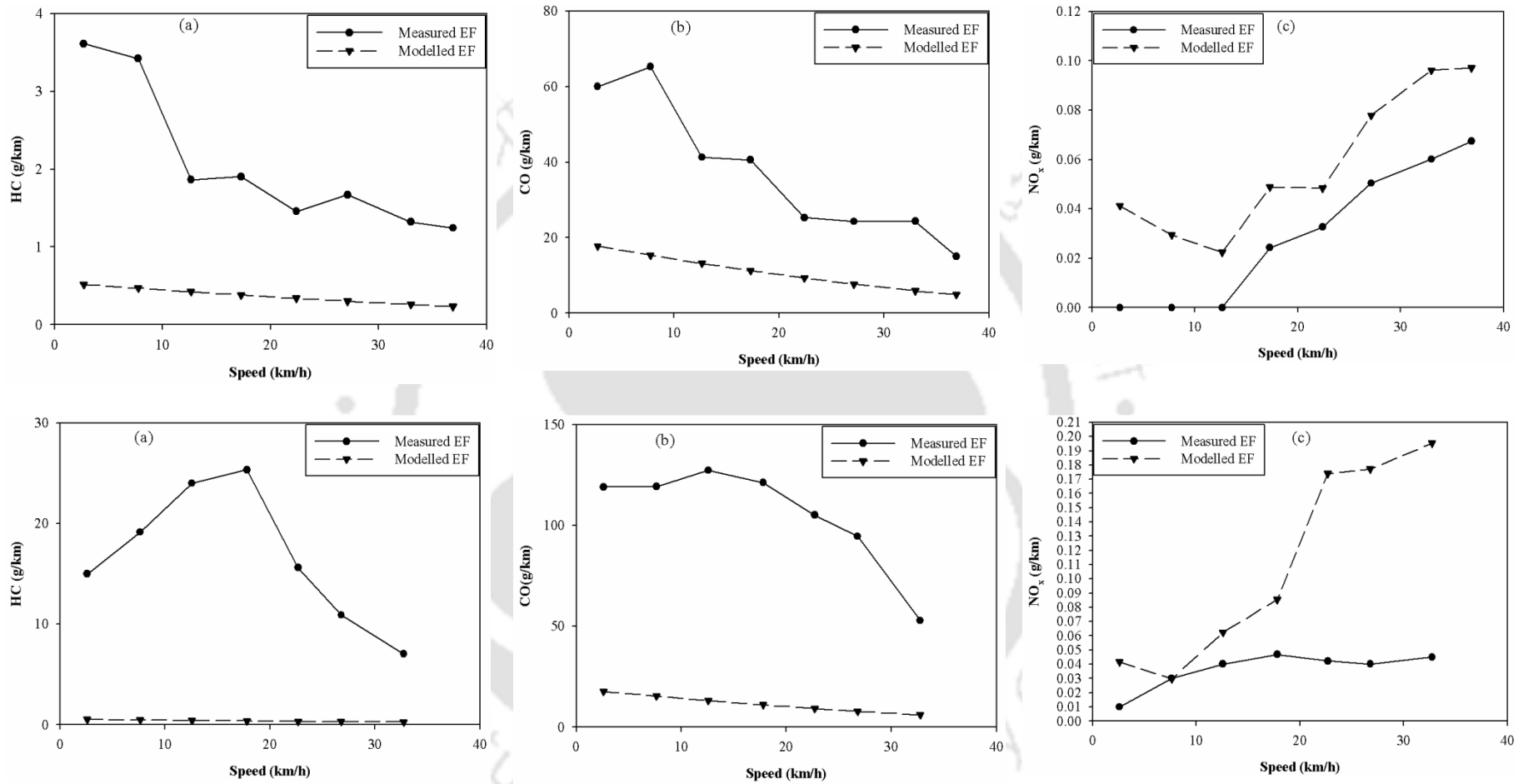
Power of performed test with alpha = 0.0500: 1.0000

APPENDIX VI

Comparative Analysis of Measure and COPERT-IV modelled emissions of passenger car of mileage 52,000 km and 142,000 km



Comparative Analysis of Measure and COPERT-IV modelled emissions of auto-rickshaw for mileage 45,000 km and 100,000 km



APPENDIX VII

Speed-frequency factor analysis data set for passenger car (mileage 142,000 km)

Speed range (km/h)	Speed (m/s)	Frequency	Factor (V*frequency)	HC (g/s)	CO (g/s)	NO _x (g/s)	CO ₂ (g/s)
0-5	0.79	74	58.46	0.005	0.041	0.001	3.239
5-10	2.13	99	210.87	0.004	0.075	0.016	6.783
10-15	3.47	147	510.09	0.008	0.086	0.010	5.814
15-20	4.82	120	578.40	0.010	0.125	0.010	7.700
20-25	6.21	80	496.80	0.008	0.101	0.016	6.738
25-30	7.54	44	331.76	0.007	0.095	0.019	6.174
30-35	9.06	19	172.14	0.004	0.011	0.026	5.328
35-40	10.16	15	152.40	0.003	0.017	0.024	5.687

Speed-frequency factor analysis data set for auto-rickshaw (mileage 45,000 km)

Speed range (km/h)	Speed (m/s)	Frequency	Factor (V*frequency)	HC (g/s)	CO (g/s)	NO _x (g/s)	CO ₂ (g/s)
0-5	0.72	69	49.68	0.004	0.052	0.020	0.599
5-10	2.14	60	128.40	0.009	0.121	0.013	1.601
10-15	3.50	83	290.50	0.008	0.149	9.00e-3	1.698
15-20	4.82	81	390.42	0.010	0.192	7.20e-3	2.422
20-25	6.24	84	524.16	0.014	0.158	1.21e-3	2.256
25-30	7.51	49	367.99	0.012	0.174	9.21e-4	3.273
30-35	9.03	36	325.08	0.010	0.171	1.92e-4	3.000
35-40	10.35	27	279.45	0.012	0.147	5.00e-4	2.536



LIST OF PUBLICATIONS

Journals

I. Published

Choudhary, A., and Gokhale, S. (2016). Urban real-world driving traffic emissions during interruption and congestion. *Transportation Research Part D: Transport and Environment*, 43, 59–70.

II. Submitted

Choudhary, A., and Gokhale, S. Urban traffic congestion with its impacts on vehicular exhaust emissions and mitigations. *Environmental Monitoring and Assessment* (under review).

Choudhary, A., and Gokhale, S. Environmental benefits of urban traffic-flow management. *Science of Total Environment* (under review).

Conferences

Choudhary, A., and Gokhale, S. (2016). Using traffic-flow and speed to quantify urban traffic congestion. *European Geosciences Union General Assembly 2016*, April 17–22, Austria, Vienna.

Choudhary, A., and Gokhale, S. (2015). Using traffic-flow and speed to quantify urban traffic congestion. *3rd Conference of Transportation Research Group of India (CTRG)*, December 17–20, Kolkata.

Choudhary, A., and Gokhale, S. (2015). Investigation of CO₂ emission reduction strategy from in-use gasoline vehicle. *National Conference on Challenges in Environmental Research*, June 4–6, IIT Guwahati.

Choudhary, A., and Gokhale, S. (2015). The impacts of speed and acceleration on auto-rickshaw exhaust emissions during peak times on urban roads. *International Conference on Sustainable Energy and Built Environment*, March 12–13, VIT University, Vellore.