MODELING OF URBAN TRAFFIC EMISSIONS

A THESIS

Submitted in partial fulfilment of the
requirements for the award of the degree
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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this thesis entitled **Modeling of Urban Traffic Emissions** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Paper Technology, Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out at Centre for Transportation Systems (CTRANS) during the period from August 2007 to August 2011 under the supervision of Dr. B. R. Gurjar, Associate Professor, Department of Civil Engineering & Associated Faculty, CTRANS and Dr. Vivek Kumar, Assistant Professor, Department of Paper Technology & Associated Faculty, CTRANS, Indian Institute of Technology Roorkee, Roorkee, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

Date: 11/08/11 **(AJAY SINGH NAGPURE)**

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ABSTRACT

Urban road transport emissions are constantly increasing worldwide. In terms of pollution, Delhi had been ranked fourth among the 41 most polluted cities of the world (Goyal, 2007). It is observed from various studies that road transport is a major source of air pollution in megacity Delhi. In India, vehicular population and air pollution emissions are increasing in other rapidly growing cities also. To study urban road transport emissions, their health impacts, and future trends, the present thesis focus on development and application of VAPI model for this purpose. Considering CO and NO_x as indicator pollutants largely emitted from fossil fuel driven vehicles, the model results have been validated in Chapter 5 by comparing CO and NO_x emission estimates with their ambient air concentrations.

To understand the health status of megacity Delhi with respect to air pollution, this thesis evaluates the health risks in various districts of megacity Delhi in terms of mortality and morbidity (e.g., Total Mortality, Cardiovascular Mortality, Respiratory Mortality and Hospital Admission COPD) due to air pollution (Chapter 2). Risk of Mortality/Morbidity due to Air Pollution (Ri-MAP) model has been used to evaluate health risks. New Delhi district shows least number of mortality and morbidity cases among all districts while North-West Delhi district has highest number of cases from 2002 onwards. It is inferred from this study that there is urgent need to reduce urban air pollution in Delhi especially in the North-West Delhi district.

To appraise better measures to regulate the traffic emissions, proper quantification of vehicular emissions is a primary need. There are numerous models available to estimate vehicular emissions. But most of these models are based on the USA and European road transportation conditions. A new model, namely Vehicular Air Pollution Inventory (VAPI) model, has been developed and applied in this thesis that estimates road transportation emissions in Indian conditions (Chapter 3). The VAPI model can estimate emissions of 11 types of pollutants from 23 Indian vehicle categories.

Impact of altitude on emissions of various pollutants (e.g., CO, HC, 1-3 Butadiene, Formaldehyde, Acetaldehyde) from various vehicle categories have been assessed through VAPI model (Chapter 4). Delhi, Dehradun and Mussoorie have been taken as study areas because of their distinct geographical and climatic conditions. Findings reveal that ambient temperature, humidity and altitude influence vehicular emissions of CO, NO_x, 1-3 Butadiene, Formaldehyde

and Acetaldehyde. Altitude dominates over other climatic factors (temperature, humidity) for influencing emissions of most of the pollutants from different vehicle categories while ambient temperature is second to altitude. Thus, this study signifies that consideration of specific parameters of topography (altitude) and meteorology (ambient temperature) are necessary to avoid errors in vehicular emission estimations at a given location. It is inferred from the study that the government should apply proper measures to reduce emissions from vehicles (especially personal vehicles) in high altitudinal areas where the environmental conditions (e.g., less oxygen concentration) are not suitable for higher emissions.

Comprehensive exhaust emission inventories of eleven categories of pollutants from different vehicles for megacity Delhi for the period 1991 to 2010 have been developed by VAPI model (Chapter 5). Estimations show that emissions of most of the pollutants from private vehicles (e.g., two wheelers, cars) are increasing from 1991 to 2010 while moderate decline is observed in 2001. In case of commercial vehicles (e.g., three wheelers, taxis, buses, LCVs, HCVs) emission trends of most of the pollutants are not similar because of temporal changes in policies and technology. It is observed from the study that among all vehicle categories the two wheelers dominate in emissions of CO, HC, Acetaldehyde and Total PAHs, cars emit more CO_2, 1-3 Butadiene, Benzene, Formaldehyde, and Total Aldehyde and HCVs are responsible for higher emissions of NO_x and PM. These results can be used to design appropriate policy measures to reduce emissions of specific air pollutants.

Exhaust emission inventory of 11 pollutants is further extended for the year 2011 to 2020 in Chapter 6 based on two scenarios, (i) Business as Usual (BAU) and (ii) Best Estimates Scenario (BES). BAU scenario is the extension of previous exhaust emission inventory while BES scenario is developed according to future transportation policies (e.g., metro rail, shift of two wheeler two-stroke to four-stroke, etc). Significant differences have been observed between BAU and BES scenarios in terms of emissions. Delhi metro rail emerge as a significant measure to reduce emissions. Emission inventory of non-exhaust pollutants (e.g., VOCs, PM10, PM2.5) have also been developed for the period 1991 to 2010 (Chapter 7). Finally, uncertainty in model results and sensitivity to input parameters have been estimated by commercially available Oracle Crystal Ball 11.1.1.0.00 software in Chapter 8. It is observed that emissions of various pollutants from three wheelers, cars, buses and taxies have highest uncertainty. Furthermore, emission estimates are much sensitive to VKT and vehicle population in comparison to other input parameters. Thesis ends with conclusions and recommendations discussed in Chapter 9.

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ABBREVIATIONS

ADB	Asian Development Bank
AP	Attributable-Risk Proportion
ARAI	Automotive Research Association of India
ARB	Air Resources Board
BAU	Business as Usual
BES	Best Estimate Scenario
BES	Best Estimates Scenario
BRTS	Bus Rapid Transit System
BUS	Business as Usual Scenario
CALIMFAC	California Motor Vehicle Emissions Factor Model
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
COPERT	Computer Program to Calculate Emission from Road Traffic
CORINAIR	Core Inventory of Air Emissions
CPCB	Central Pollution Control Board
CRRI	Centre Road Research Institute
DSA	Delhi Statistical Abstract
DSS	Decision Support Systems
DUDGD	Department of Urban Development Government of Delhi
EMFAC	Emission Factor Model
GDP	Gross Domestic Product

Gg	Giga gram
GHG	Greenhouse Gas
GSSR	Global Sustainable Systems Research
HC	Hydro Carbon
HCV	Heavy Commercial Vehicles
IDC	Indian Driving Cycle
IGL	Indraprastha Gas Limited
IPCC	Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel on Climate Change
ISSRC	International Sustainable Systems Research Center
IVEM	International Vehicular Emission Model
Kg	Kilogram
Km	Kilometer
LCV	Light Commercial Vehicles
LDGV	Light Duty Gasoline Vehicle
LPG	Liquefied Petroleum Gas
Mg	Mega gram
MoEF	Ministry of Environment and Forest
MoST	Ministry of Surface Transport
MPI	Multi Pollutant Index
MVEI	Motor Vehicle Emission Inventory
NEERI	National Environmental Engineering Institute
NIUA	National Institute of Urban Affairs
NO_x	Oxides of Nitrogen
PAH	Polycyclic Aromatic Hydrocarbon

PCI	Per Capita Income
PDF	Probability Distribution Function
PM	Particulate Matter
QGEPA	Queensland Government Environmental Protection Agency
Ri-MAP	Risk of Mortality/Morbidity due to Air Pollution
RR	Relative Risk
RSPM	Respirable Suspended Particulate Matter
SO_2	Sulfur Dioxide
SPM	Suspended Particulate Matter
TERI	The Energy and Resources Institute
THC	Total Hydrocarbon
TII	Transparency International India
TSP	Total Suspended Particulate
UNEP	United Nations Environment Programme
UNO	United Nations Oragnization
US EPA	US Environmental Protection Agency
USA	United States of America
USDE	US Department of Energy
VAPIM	Vehicular Air Pollution Emission Inventory Model
VBA	Visual Basic Application
VKT	Vehicle Kilometer Travel
VOC	Volatile Organic Compound
VSP	Vehicle Specific Power
WHO	World Health Organization

CHAPTER 1

Introduction and Literature Review

1.1. GENERAL INTRODUCTION

Air pollution is commonly perceived as an urban problem associated with rapid industrial, vehicular and human population growth (Wakamatsu et al.,1996; Naser et al., 2009). It has been aggravated by developments that typically occur as country becomes industrialized, growing cities, increasing traffic, rapid economic development and higher levels of energy consumption. Fossils fuel combustion in different activities is major cause of air pollution in urban areas (Kumar et al., 2010, 2011). As a result of urban-centered economic growth in India, emissions of different pollutants are growing rapidly in industrial clusters and urban agglomerations including but not limited to megacities. Central Pollution Control Board, New Delhi (CPCB, 2000) has identified 23 Indian cities to be critically polluted due to large number of air pollution sources.

Currently, in India, the major source of urban air pollution is vehicular emissions followed by industries and thermal power plants (TERI, 2001b). The data shows that number of motor vehicles have increased from 0.3 million in 1951 to 72.7 million in 2004 in India (indiastate.com, 2010). Out of these, 32% are only concentrated in 23 metropolitan cities. Delhi itself accounts for about 8% of the total registered vehicles in India and has more registered vehicles than those in the other metro and megacities (e.g. Mumbai, Kolkata and Chennai) taken together (TERI, 2001b). The drastic increase in number of vehicles has significantly raised the emission loads of various pollutants. For example, Pachauri and Sridharan (1998) found that total pollution load from transportation sector in India has increased 68 times from 1947 (150 Tg) to 1997 (10300 Tg). During this period CO emission claimed the largest share (43%) of the total pollutants from transport sector, followed by NO_x (30%), HC (20%), SPM (5%), and SO_2 (2%). According to CPCB (2000), twelve major metropolitan cities in India produce 0.35 Gg of NO_x, 1.91 Gg of CO and 0.67 Gg of VOC annually from vehicular emissions alone. The quantum of vehicular pollutants emitted has been found highest in Delhi followed by Mumbai, Bangalore, Kolkata and Ahmadabad (TERI, 2001b).

Megacities have emerged as centers of high economic growth. A megacity is defined by the United Nations Oragnization (UNO) as a metropolitan area with a total population of more than or equal to ten million people (ADB, 2008). As a result of their constantly increasing population, megacities require more energy to support its infrastructure. The immense consumption of energy (fossil fuels, biomass, electric etc.) causes emissions of air pollutants that deteriorate the air quality at local level. Moreover, partly because the lifetimes of pollutants may be prolonged due to the high concentrations in megacity plumes, they can travel across and even between continents and causing air pollution problem at global level (Stohl et al., 2003). Megacity plumes contain large amounts of criteria pollutants, greenhouse gases, ozone precursors and aerosols; therefore, they potentially affect the atmosphere on a large scale (Molina and Molina, 2004.). Megacities, although generally confined on a relatively small area, are associated with such large emissions of pollutants that they can sometimes be larger than emissions from a whole country (Gurjar et al., 2005).

Delhi is one of the largest megacities in India as well as in south Asia. It is the most affluent city in India having highest per-capita income, highest number of cars per thousand population, highest number of cell phones, and also highest amount of personal income tax collected (IGES APN, 2001). Large number of small scale industries, increasing vehicle population and power plants are the major cause of air pollution in Delhi. From 1971 to 2001 the road length in Delhi increased from 8380 to 28,508 Km (i.e. 3.4 times) whereas the number of vehicles increased from 0.18 to 3.46 million (i.e. 20 times) leading to enhanced air pollution (Gurjar and Lelieveld, 2005). According to MoEF (1997) daily air pollution load from all sources in megacity Delhi increased from 1.45 Gg in 1991 to 3 Gg in 1997. A local survey has indicated that 30% of Delhi's population suffers from respiratory disorders due to air pollution, and that the incidence of respiratory diseases in Delhi is 12 times the national average (Kandlikar and Ramachandran, 2000).

Due to large amount of emission of various pollutants, ambient concentration levels of CO, SPM and NO_x and other such criteria air pollutants are exceeding the ambient air quality standards prescribed by CPCB and the WHO (Mukhopadhyay and Forssc, 2005, Gurjar et al., 2010) leading to various adverse effects on human health, vegetation, property and regional and global climate. According to the World Bank Report (1992) particulate matter (PM) on its own or in combination with SO_2 leads to an enormous burden of ill health, causing at least 500000 premature deaths and 4 - 5 million new cases of chronic bronchitis each year in India. The pattern of disease and death exhibited in Indian health data are highly suggestive of the possible importance of environmental factors in today's Indian health scene.

Given the fact that urban transport related emissions are increasing rapidly, especially in Indian megacities, it is necessary to design and implement suitable policy measures and technological interventions to reduce vehicular emissions for improving urban ambient air quality. The Indian government has formulated number of legislations, policies, and programs for protecting the environment. Air (Prevention and control of pollution) Act-1981 and the Environment (Protection) Act-1986 are some of the legislations passed by Indian government for maintaining and improving environment quality in India (TERI, 2001a). Government has launched various controlling measures like technology to meet cleaner emission standard (e.g. EURO I, EURO II) clean fuel (e.g. CNG, LPG), and improved engine technology for reducing emission from transportation sector. During the last few years, the awareness of people for protection of the environment in society has been gradually increasing. Various types of pressure groups are acting in defense of the environment. The government is also promoting more and more regulations to protect the environment and the community in general. One of such successful initiatives to improve urban air quality is the introduction of clean fuel, i.e. CNG, in public transport fleet of megacity Delhi. Modeling of vehicular emissions is a necessary tool to design and study the effectiveness of such policy measures. The present thesis deals with the modeling of emissions from exhaust and non-exhaust vehicles and assesses the impact of policy and technological interventions using scenario based analysis.

1.2. LITERATURE REVIEW

1.2.1. Background of Traffic Emission

Degrading urban air quality has emerged as a significant worldwide problem with most of the cities attaining pollution levels above the World Health Organization (WHO) guidelines (Faiz, 1993; Lyons et al.,, 2003; Lim et al., 2006, 2007). Ambient air quality in Indian megacities often reach levels high enough to cause substantial impacts on human health and urban environmental quality (Singh et al., 1997; Sharma and Khare, 2001; Kumar, et al., 2004; Shandilya et al., 2007; Tandon et al., 2008) which is similar for most of the world cities (Molina et al., 2007). Over the past decades, the urban road transportation has increased, which in turn has significantly increased vehicular emissions (Anderson et al., 1996; Lyons et al., 2003; Gurjar et al., 2004; Suppan and Schadler, 2004; Namdeo et al., 2010). Presently this is of prime significance for developing countries like India, where the rapid rate of urbanization leads to increased number of vehicles and emissions (White and Whitney, 1992; WHO/UNEP, 1992; Lyons et al., 2003; Gurjar et al., 2004; Namdeo, 2008). Several studies (Fenger, 1999; Colvile et al., 2001; Vardoulakis et al., 2003; Gurjar et al., 2004) indicate that contribution of road transportation for worsening urban air quality is increasing day by day, which is directly attributing various human-health and environmental problems (Saija and Romano, 2002). As a result, in recent decades urban traffic emissions and their impacts on air quality at the local, regional and even worldwide level has received great attention from researchers, policy makers and the general public.

Road transportation plays important economic and social roles in cities. Nevertheless, it is also the origin of various externalities such as mentioned in above paragraphs. To control transport induced problems it is necessary to accurately estimate the magnitude and contribution of the road transportation towards degrading air quality in order to implement appropriate policies. Researchers have developed various direct and indirect measurement methods to quantify emissions from transportation sector. However, due to the quantity of information required to determine the different parameters related to traffic emissions, direct measurement becomes impractical and expensive. Thus indirect measurement through emission models represents a cost effective alternative to direct measurements (Booth, et al., 2002; Namdeo et al., 2002; Nesamani et al., 2006; Gokhale and Khare, 2004, 2005). Emissions from vehicles can be calculated by using appropriate emission inventory models following general principle of the summation of the product of an emission factor and the amount of traffic for each type of vehicle and their operation. The elaboration of emission inventories through manual method or emission models on a regional or local basis is a necessary step when setting up plans to control the levels of pollutants. Thus, the emission inventory is a key component of any air pollution control program (Costa, and Baldasano, 1996; Yamaji et al., 2004; Zavala et al., 2006). Traffic emission models, which are computer programs with built-in methodologies to compute the emissions from vehicles, can be used as the best possible and/or reliable tool for developing emission inventories. Each of these methodologies requires the input of specific parameters and data, e.g. the emission factor (exhaust, evaporative), vehicle types, vehicle operation etc. (Costa, and Baldasano, 1996). This section will highlight vehicle emissions sources, types and their measurements. A detailed review of available vehicular emission inventory models that have been developed and used by several researchers with the view to serving as a guide regarding traffic emission assessment is given in Chapter 3.

1.2.1.1.Emission Inventory

A fundamental requirement in the effort to control pollution in any form is to quantify the emissions being released. An emission inventory is the quantity of pollutants released from any source (e.g. industry, power plant, and vehicle) into the atmosphere during any time or activity (Mensink, et al., 2000). Compilation of emission inventory for scientific use started in the 1970s for oxides of sulfur and nitrogen (Benkovitz, 2001). It identifies the type of pollutants released and their rate from various sources in a certain geographical area during particular time span (Creelman, 1997). Emission source category, type of pollutants, geographical area, and time period of emissions estimation and methodology use for emission estimation are main characteristics of it (Creelman, 1997; Costa, and Baldasano, 1996).

As stated above, emission inventory forms the foundation of an air quality management program (Creelman 1997, Benkovitz, 2001). For development of any strategy to reduce the most important causes of air pollution reliable emission data are essential. It plays very important role for implementing policies and norms for reducing emissions and their effects at local and regional level. It is the major data input for air pollution transformation and dispersion model, which when coupled with exposure assessment models also help in assessment of health risks. It is also important for various other management options (e.g., fuel pricing regulation, demand management, transport planning and technological controls) to reduce the most contributing causes of air pollution (e.g. industrialization, use of highly polluting fuels, increasing reliance on motor vehicles and energy pricing policies) within given geographic location (Loibl et al., 1993; Creelman, 1997). The following are some important uses of emission inventories (Creelman, 1997):

- It helps to identifying major emission sources
- It serves a decision maker factor for determining air quality regulations
- It is very useful for estimating air quality impacts
- It is used for determining efficiency of specific emission control equipment.
- It is helpful for determining emission credits for banking or trading (e.g. Clean Development mechanism)
- It is used to determine the expected or actual effectiveness of pollution prevention programs.

Traffic emission inventory is an essential tool for assessing and predicting air quality and for evaluating policy choices to control vehicular emissions. Because of numerous input variables (e.g. vehicle type, fuels, road grade, climate etc.) with higher uncertainty, it is very tedious amd irrelevant to develop traffic emission inventory manually. To overcome these difficulties numerous emission models are developed by different countries and organizations for estimating vehicular emissions for clearer perspective on effective future scenarios regarding air quality and transportation management (Afotey, 2008, Davis et al., 2005*)*

1.2.1.2. Traffic Emission Modeling

Traffic emission models are the computer programs, which estimate emissions released by the vehicles during their operation and other activities during particular time span and region (Cappiello, 2002). An emission model estimates and projects the emissions at regional or national level, permitting to obtain the emission inventories at these levels. They also simulate and evaluate the efficiency of emission control measures (e.g. policy, technology change, etc.) in transport sector at local and regional level (Pronello and André, 2000; Barratt, 2001; Cappiello, 2002; Afotey, 2008). For environmental problems, the decision processes are illustrated by a high amount of complexity, uncertainty, and subjectivity (Colorni et al., 1999). For such situations emission models can be used in the context of Decision Support Systems (DSS) to provide the analyst and the decision maker with quantitative estimates, trends, and insight on the policies simulated (Guariso and Werthner, 1989; Cappiello, 2002). Fig. 1.1 shows a DSS framework that can be designed to develop policy in context to the traffic emissions. The framework includes a model-based traffic emission inventory development and policy generation and their impact evaluation module. In DSS the model-based emission inventory receives data and actions from on-road vehicles, which are directly affected by current policies (Fig 1.1). The policy generation module evaluate the policy and sends back to the emission inventory module for the development of new policy (Fig 1.1). In general approach emission model estimating emissions from road traffic is the summation of the product of emissions from all vehicular emissions source (running exhaust starts hot soaks, diurnals resting loss, running loss etc.), vehicular activities and other climatic and topographic variables (Cloke et. al., 1998; Hung and Tong, 2002; Benkovitz, 2001). Possibly earliest emission model was published by Rose et al. (1965) who found an empirical relationship between HC, CO and CO_2 emission per unit distance and journey travel speed (Smit, 2006). There are various approaches adapted by different countries for vehicle emission modeling each with its own strengths, weaknesses and limitations. At present several models are available in various countries for preparation of emission inventories from transport sectors.

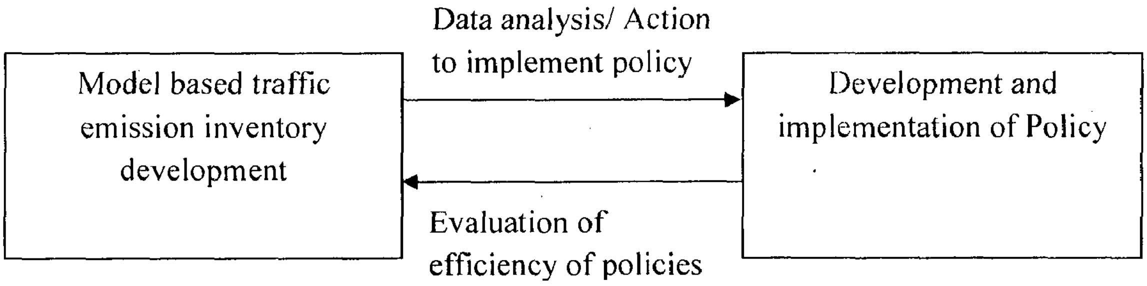


Fig. 1.1 : DSS framework for policy development and emission control

Emission inventory models have adopted various emission calculation methodologies and are categorized accordingly. Some models estimate only vehicular emission rates, whereas others calculate total emissions for mobile sources (Afotey, 2008). The level of complexity of emission calculation methodology depends basically on the availability of input data. Generally, three types of input data are needed: vehicle activities (e.g. vehicle-kilometers, speed), an emission factor (e.g. g/veh-km), and external climatic and geographic factors (e.g. altitude, temperature, humidity) for emission calculations. Fig. 1.2 lists the input variables and the model output.

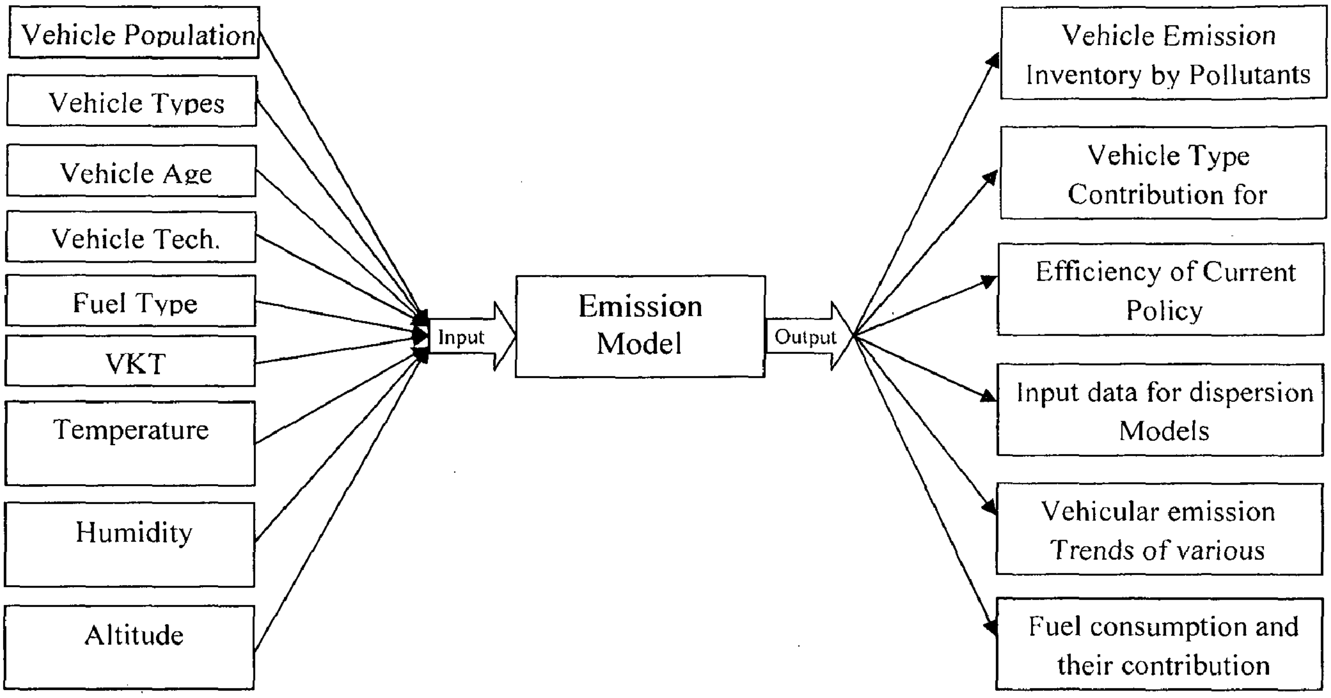


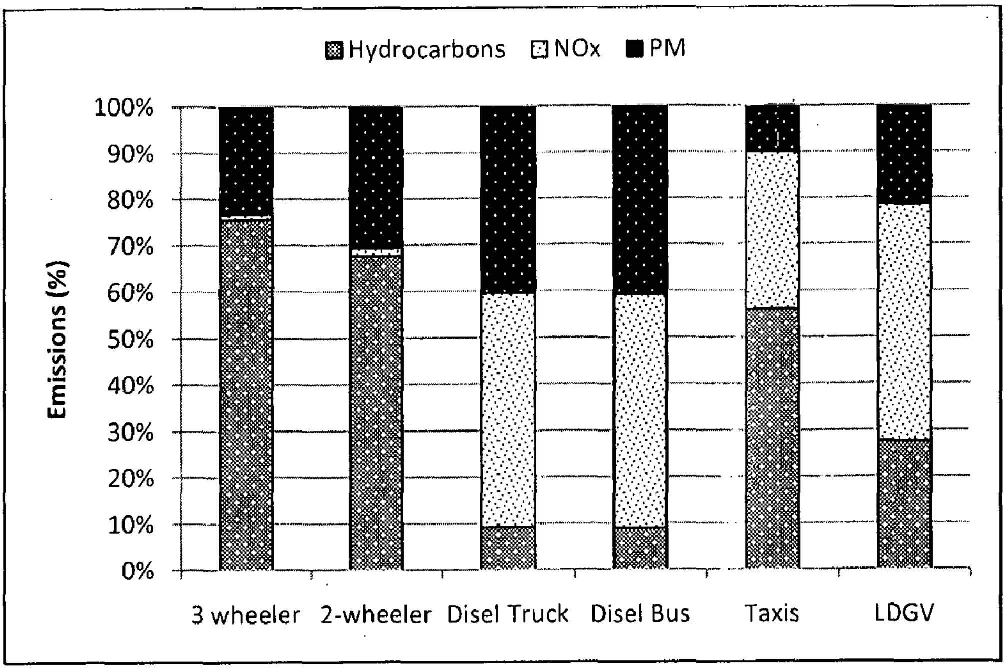
Fig.1.2: The input and output of emission models

Numerous emission models have been developed worldwide (discussed in Chapter 3) to assess emissions from transport sector (Hung and Tong, 2002). The COST 319 working group reviewed about 39 emission models, which are used in Europe and in USA (Negrenti, 1995; Pronello, and André, 2000). Shearn et al. (1996) mentioned 22 pollution-modeling tools while Algers et al. (1998) discussed about 58 micro-simulation models developed in Europe, USA, Canada, Australia and Japan. They found that 52% of them predicted exhaust emissions while 16% estimated roadside pollution levels (Reynolds and Broderick, 2000). These models employ variety of approaches and have number of different applications (Negrenti, 1998). Each model has its own significant characteristics: some are as macroscopic (city or country related models), whilst others have a more local (street level) character. Some models only calculate emission from individual vehicle or emission of individual pollutants from various vehicles, whilst others take into account only specific aspects (e.g., the cold start effect) of the pollutant emission process. In theoretical aspects it is possible to classify system for the models based on such features. Practically the sectors of application of different types of models do not have closed boundaries, but often show a remarkable degree of overlap. To account these limitations only a rough classifications of models based on the most relevant characteristics is possible (André, et al., 1999).

1.2.2. Emission and Health Risk Scenario in Delhi

Delhi is one of the Indian megacities, having highest pollution in its atmosphere. Major causes of air pollution in Delhi are large number of small scale industries, increasing vehicular population and power plants. Delhi was among the top five SO_2 emitter megacities of the world in early nineties and transport sector was the prime culprit for it (Garg et al., 2001). Gurjar et al., (2004) have demarcated an inter-annual variability in the emission trend ranging between 90 and 113 Gg during 1991 to 2000. But Garg et al (2001) estimated that emissions of SO_2 (in terms of per km^2) decreased from 48 to 47 Mg between 1990 to 1995.

CPCB (1995) data show that almost 50% of the total emission is released from vehicular activities, followed by domestic, industrial, and power plants. It was found that from 1990-91 to 1995-96, annual NO_X emission from gasoline consumption increased from 3.5 Gg to 4.5 Gg respectively, whereas it was 8 Gg in 1990-91 and 12.8 Gg in 1995-96 from diesel (Sharma et al., 2002). According to Xie and Shah (2002), diesel driven vehicles were the major source of NO_X emission in Delhi (Fig. 1.3), whereas least contribution was from two and three wheelers.



LDGV- Light Duty Gasoline Vehicle, Source: Xie, and Shah , (2002)

Fig. 1.3. Contribution of vehicle category in NO_x, PM and HC emissions in Delhi in1996

In terms of suspended particulate matter (SPM), Delhi is the fourth most polluted city in the world (Gadhok, 2000). Gurjar et al. (2004) and Reddy and Venkataraman (2002), estimated that 15% of Delhi's respirable suspended particulate matter (RSPM) emission results from automotive traffic. Transport contributed about 19% to TSP emission in the year 2000 and almost doubled from 15 Gg in 1990 to 28 Gg in 2000 (Gurjar et al., 2004). According to ADB (2005), diesel driven vehicles are the major contributor of PM emission among all vehicle categories in megacity.

Incidence of respiratory diseases in Delhi is 12 times the national average, and 30% of Delhi's population suffers from respiratory disorders (Kandlikar and Ramachandran, 2000). Its poor air quality is held responsible for about 18600 premature deaths per year (TERI, 2001a). The largest impact of pollutant (e.g., particulate, SO_2) on daily deaths in Delhi occurs in the age group of 15–44 years (Cropper et al., 1997), an age group that may spend most time outdoors. Other study suggests that about 40,000 Indians are dying early every year because of air pollution: 7500 in Delhi, 5700 in Mumbai and 4500 in Kolkata, and it has been estimated that in Delhi these deaths can be avoided by a 142 μgm^{-3} reduction in RSPM (Brandon and Homman, 1995). A recent World Bank study shows that a 10% reduction in RSPM in Delhi might result in 1000 fewer deaths each year (World Bank, 2003). One out of every ten school children in Delhi suffers from asthma that is worsening due to air pollution (Aggarwal, 1999).

Above discussion suggests that emission inventory is the essential tool for air quality management program and emission models are the computer programs, which are helpful for developing emission inventory with more accuracy. There are several vehicular emission models available in the world; which have their own limitations in Indian context (as discussed in Chapter 3). On the basis of literature review discussed in present chapter and Chapter 3, following gaps were found, which have been addressed in this study:

1. There is no health risk study available for megacity Delhi with decadal (1991 to 2010) heath risk estimates at districts level.
2. There is no vehicular emission inventory model available which supports emission estimation according to availability of data in Indian conditions.

3. Thorough emission inventory of megacity Delhi does not exist for exhaust and non----exhaust emission for 11 types of pollutants and 27 categories of vehicle type for the period of 1991 to 2010 and future up to 2020.

1.3. OBJECTIVES OF THE THESIS

While the main objective of the thesis is to develop a comprehensive and simple vehicular air pollution emission inventory (VAPI) model for estimating emission of various pollutants (e.g. CO, HC, NO_x, CO_2, PM, Benzene, 1-3 Butadiene, Formaldehyde, Acetaldehyde, Total PAH, Total Aldehyde) from on-road vehicles in Indian cities. The main reason of developing the model is to determine the contribution of urban transportation sector in emissions of various pollutants and provide user friendly tool for estimating vehicular emissions in the Indian context. In addition, the present study includes the following:

1. Assessment of the air pollution related health risk in megacity Delhi by using Risk of Mortality/Morbidity due to Air Pollution (Ri-MAP) model for the year 1991 to 2010.
2. Development of Vehicular Air Pollution Inventory (VAPI) model for exhaust and non-exhaust emission inventory preparation.
3. Understanding the impact of various climatic (e.g. temperature, humidity) and geographical (e.g., altitude) correction factors on emission of various pollutants. Emission estimations have been made using Vehicular Air Pollution Inventory (VAPI) model for three cities (Delhi, Dehradun and Mussoorie) having different geographical and climatic conditions.
4. Development of exhaust emission scenarios for various pollutants (e.g., CO, HC, NO_x, CO_2, PM, Benzene, 1-3 Butadiene, Formaldehyde, Acetaldehyde, Total PAH, Total Aldehyde) to estimate emissions from the on-road vehicles in megacity Delhi and trend analysis from 1991 to 2010 using VAPI model.
5. Scenario based projection of future emissions of above mentioned pollutants from the on-road vehicles in megacity Delhi using VAPI model. Two scenarios; Business as Usual Scenario (BUS) and Best Estimate Scenario (BES) have been used for this purpose.

6. Determination of the contribution of non-exhaust (e.g., PM10, PM2.5) and evaporative (e.g., VOC) emissions from the on-road vehicles in megacity Delhi using VAPI model.
7. Uncertainty and sensitivity analysis of emission estimates obtained from VAPI model.

1.4. THESIS ORGANIZATION

Thesis has been organized in following manner:

1. Introduction and Literature Review
2. Human Health Risk in megacity Delhi due to Air Pollution
3. Development of vehicular air pollution inventory (VAPI) model
4. Impact of Altitude on Emissions of Criteria (CO, NO_x) and Hazardous (1-3 Butadiene, Formaldehyde, Acetaldehyde) Pollutants from Vehicles
5. Exhaust Emissions from On-Road Vehicles in Megacity Delhi (1991-2010)
6. Future Vehicular Emission Scenario for Megacity Delhi (2011-2020)
7. Non Exhaust Emissions from Vehicles in Megacity Delhi (1991-2010)
8. Uncertainty and Sensitivity Analysis of Exhaust and Non Exhaust Emissions from Vehicles
9. Conclusions and Recommendations

1.4.1 Brief Outline of the Thesis

A brief outline of the detailed study carried out in this thesis can be summarized as follows:

Continuous exposure to air pollutants may lead to effects like cardiovascular mortality, respiratory mortality and hospital admission COPD (Chronic Obstructive Pulmonary Disease). Quantitative health risk assessments are used to support environmental policy decisions. Keeping this in mind, health risk assessment is carried out for megacity Delhi in Chapter 2 using the Risk of Mortality/Morbidity due to Air Pollution (Ri-MAP) model.

The worsening air quality in Indian urban agglomerations is primarily attributed to the rise in motor vehicle population and resulting exhaust emissions. Vehicles are significant source of air pollutants that can impair human health and the environment as discussed in Chapter 2. To understand the contribution from this source, it is essential to estimate the fuel-specific and vehicle-category specific emissions. Hence, an emission inventory model is developed in Chapter 3, which includes study of available models (e.g., IVE, COPERT, etc.), and development of an appropriate model for estimating traffic emissions in Indian context. The aspiration to work in this area is drawn from the severe impact of mobile source emissions on human health and the environment in Indian cities particularly megacities, which are experiencing rapid economic growth and degrading air quality. Despite their importance as a major source, emission scenario from mobile sources have been inadequately illustrated to date in India and as such there is an opportunity to make a significant contribution in this field.

Emissions from the vehicles depend on various factors such of fuel type, engine technology as well as on topographical and climatic conditions (e.g. altitude, humidity, temperature). Altitudes affects the driving pattern and impinge on the load and pressure conditions inside internal combustion engines that in turn result in altitude–induced changes in vehicular emission characteristics. In Chapter 4, therefore, impact of topographical (e.g. altitude) and meteorological (e.g. temperature, humidity) parameters has been studied by using VAPI model . Three cities – Delhi, Dehradun and Mussoorie were selected for this study as these have distinct geographical and meteorological features. While Delhi is a low altitude megacity with a plain topography, both Dehradun and Mussoorie are high altitude cities and prominent tourist destinations in Uttrakhand, India.

It is observed in Chapter 2 that SPM and NO_x are having significant impact on human health. Various studies suggested that on road vehicles contribute major part of NO_x and SPM in megacity Delhi. Looking these aspects, comprehensive emission inventory of megacity Delhi for various air pollutants has been developed from 1991 to 2010 in Chapter 5. Study suggests that emission of CO, HC, 1-3 butadiene from vehicles in megacity Delhi is increasing from 1991 to 1999 while after 1999 it is going with quite similar trend with some fluctuation. The emission trend of CO_2 and total PAH is increasing from 1991 to 2010. Initially from 1991 to 2001 emissions of NO_x, PM, formaldehyde and total aldehyde increased, while sudden fall is observed in NO_x, PM, formaldehyde and total aldehyde emissions during 2002 followed by increasing trend after 2002.

The VAPI model has also been applied to project the emissions from on-road vehicles until 2030. Emissions of pollutants have been estimated by using VAPI model from 2011 to 2020 considering Business As Usual (BAU) and Best Estimate Scenario (BES). Comparisons of both scenarios have been made in Chapter 6. It is observed that BES scenario gives low emission trend than BAU scenario.

Non-Exhaust emissions (e.g. Evaporative, Tyre wear, Brake wear, Road Dust Suspension) from various vehicle categories have been estimated through VAPI model in Chapter 7. In this chapter, emission quantities of VOC, PM10 and PM2.5 from vehicles, vehicle share of pollutants, and their emission trends have been discussed for the period 1991 to 2010.

In Chapter 8, uncertainty assessment has been done for exhaust and non-exhaust emissions from vehicles in megacity Delhi. To assess uncertainties of variables in the vehicular emissions Tier 2 methodology, which employs Monte Carlo Stochastic Simulation technique (also referred as Monte Carlo method) suggested by IPCC (2001), have been used. The core of Monte Carlo analysis is to vary the input parameters (i.e. population, per capita consumption and emission factors) in accordance with Probability Distribution Function (PDF). In the present chapter propagation of errors through complex calculations have been done. The crisp estimates of every parameter in the calculation are replaced by a probability distribution which describes the range of values that the parameter can take as well as the probability that a certain value will actually occur. This procedure is then repeated a large number of times (e.g., 20000 trials) so that a large number of combinations of different input parameters occur. All calculations for this study were performed with the commercially available Oracle Crystal Ball (11.1.1.0.00) software on a desktop computer.

Finally, Chapter 9 deals with the conclusions drawn from air pollution induced health risk estimates to vehicular emission estimations and uncertainty analysis of exhaust and non-exhaust emissions in megacity Delhi. Furthermore, the recommendations for the future work are also presented here.

CHAPTER 2

Human Health Risks in Megacity Delhi due to Air Pollution

2.1. INTRODUCTION

Megacities are very large urban sprawls confronted with a multitude of environmental challenges including soaring air pollution emissions. Thus megacities tend to be global risk areas making their inhabitants vulnerable to air pollution induced adverse health impacts. It is required to estimate such risks and help initiate national and international efforts to improve the sustainability of megacity life worldwide. Several studies, e.g., Mage et al. (1996), Gurjar et al. (2004), Madronich (2006), Gurjar et al. (2008), Butler et al. (2008), have been conducted on air pollution emissions and their implications in megacities. For example, Gurjar et al. (2008) have evaluated and ranked megacities in terms of their trace gas and particle emissions and ambient air quality, and highlighted the air pollution impacts by calculating the Multi-Pollutant Index (MPI) in the 18 largest megacities of the world. That work basically ranks these cities on the basis of overall effects of air pollutants integrated within MPI. It was found that the megacities in several developing countries of Asia, including Dhaka (Bangladesh) and Karachi (Pakistan), were among the ones with poorest air quality. The limitation of the study carried out by Gurjar et al. (2008), however, was that it did not address the direct health impacts of air pollutants in terms of the estimation of number of mortality or morbidity cases occurring annually due to a particular pollutant. The estimation of the direct impacts of air pollutants in terms of the number of excess deaths or the number of various diseases is required in defining specific and effective control measures to tackle the urban air pollution problem.

Modeling of human exposures to environmental pollutants is of crucial importance for the evaluation of public health risks (Vostal, 1994). Here, spreadsheet Risk of Mortality/Morbidity due to Air Pollution (Ri-MAP) model (using the Microsoft Office Excel 2003-2007 platform) has been proposed to evaluate the direct health impacts of various criteria air pollutants present in urban air sheds. Ri-MAP is applied in a case study to assess health impacts of air pollution in various districts of megacity Delhi during the period 1991 to 2010. It is to note that present study takes into account the effects of each pollutant individually and does not consider the synergistic effects of two or more pollutants. This is an important limitation of the study as some pollutants can be more harmful in the presence of other pollutants, and the sensitivity to poor air quality also depends on other environmental and nutritional factors.

2.2. MATERIAL AND METHODS

2.2.1. Background of relative risk

In epidemiology, the relative risk (RR) is the probability of developing an illness caused by the exposure to various pollutants (Rothman et al., 2008; WHO, 2003). The values of relative risks and baseline incidence related to different air pollutants, e.g., sulphur dioxide (SO_2), total suspended particles (TSP), nitrogen dioxide (NO_2), and various types of diseases have been used as default values as specified by the World Health Organization (WHO) and are shown in Table 2.1. These values of relative risks and corresponding baseline incidences have been adopted from the relevant input data files of WHO's air quality health impact assessment software AirQ2.2 (URL: http://www.euro.who.int/air/activities/20050223_5), which are based on various studies, e.g., Atkinson and Anderson (1997), Burret and Doles (1997), Spix (1997), Sunyer (1997), Touloumi (1997), and WHO (2000).

Table 2.1: WHO default values of relative risk (per 10 μg/m^3 increase of daily averages for SO_2, TSP and NO_2) corresponding to mortality

Pollutant	Mortality	Relative Risk (RR)	Baseline Incidence Per 100000 (I)[b]
SO_2	Total	1.004 (1.003-1.0048)[c]	1013
	Cardiovascular	1.008 (1.002-1.012)	497
	Respiratory	1.010 (1.006 -1.014)	66
	Hospital Admission COPD*	1.0044 (1-1.011)	1014
TSP	Total	1.003 (1.002-1.007)	1013
	Cardiovascular	1.002 (1-1.006)	497
	Respiratory	1.008 (1.004 -1.018)	66
	Hospital Admissions COPD[a]	1.0044 (1-1.0094)	1014
NO_2	Total		-
	Cardiovascular	1.002 (1-1.004)	497
	Respiratory		-

[a] COPD: Chronic Obstructive Pulmonary Disease
[b] Baseline Incidence per 100000 is based on threshold limit given in WHO guideline
[c] Lower and upper limits (range) of the 95% confidence interval of RR values

2.2.2. Concentration response equations

Quantification of the health impact due to exposure to a particular air pollutant is based on the population attributable-risk proportion (AP) concept (Rothman et al. 2008; Douwes et al. 2002). The attributable-risk proportion (AP), i.e. the fraction of health outcome, which can be attributed to the exposure in a given population (assuming there is a causal association between exposure and the health outcome and there are no major confounding effects on this association) for a certain time period can be calculated using Eq. (2.1) (WHO, 1999).

$$AP = \frac{\sum\{[RR(c)-1]\times p(c)\}}{\sum[RR(c)\times p(c)]} \qquad (2.1)$$

Where, RR(c) = Changed relative risk for the health outcome in category c of exposure can be calculated by Eq. (2.2) , and p(c) = proportion of the population in category c of exposure which could vary according to the degree of exposure in different area. For instance, residential and industrial zones have different degrees of exposure so that populations in these regions are affected in different ways. However, due to the lack of availability of required data, we have taken the uniform exposure in all districts throughout the entire city.

$$\mathrm{RR(c)} = \frac{(\mathrm{C-T})}{10} \times (\mathrm{RR} - 1) + 1 \qquad (2.2)$$

Where, C = Ambient air concentration of a pollutant, T = Threshold level of the pollutant as recommended by the WHO, and RR = Relative risk (RR) for the selected health outcome, which can be derived from the exposure-response function obtained from local epidemiological studies. Since no such local studies were available for all the districts considered, we have used the WHO default values as presented in Table 2.1.

The population exposure distribution is determined at the exposure assessment stage. The simple way to assess population exposure from monitoring data is to use some selected or all monitoring stations in the respective districts and to take arithmetic mean of selected concentrations for each time unit. This average (daily or yearly) value is then used as indicator of the exposure of the whole population of districts: hence, one population - one value for a specified time period. For this purpose, we have used daily data of 9 monitoring stations spread throughout all districts of megacity Delhi and taken selected concentrations for each year.

Knowing (or often assuming) a certain baseline frequency (at threshold concentration value given by WHO guideline) of selected health outcome in the population (i.e., I), the rate (or number of cases per unit population) attributed to the exposure in population (i.e., IE) can be calculated as (WHO, 1999):

$$IE = I \times AP \qquad (2.4)$$

For a population of given size N, the IE can be converted to the estimated number of cases attributed to exposure (i.e., NE) using Eq. (2.5):

$$NE = IE \times N \qquad (2.5)$$

Consequently, the frequency of outcome in the population free from exposure (i.e., INE) can be estimated as under:

$$INE = I - IE = I \times (1 - AP) \qquad (2.6)$$

Knowing the relative risk at a certain level of pollution and the estimated incidence in non-exposed population, the excess incidence [i.e., ΔI(c)] and excess number of cases [i.e., ΔN(c)], respectively, at a certain category of exposure (c) can be calculated using following equations:

$$\Delta I(c) = (RR(c) - 1) \times p(c) \times INE \qquad (2.7)$$

$$\Delta N(c) = \Delta I(c) \times N \qquad (2.8)$$

All the above formulas are based on the assumption that RR estimate is used in this analysis adjusted for any possible confounding. When the limits of confidence interval for the RR estimate are used in Eq. (2.1), we obtain the corresponding upper and lower limits of AP estimate, and the respective range for number of cases in the population, attributed to the exposure. Eq. (2.8) is used to calculate excess number of cases of death in model denotes the number of mortalities in the exposed population. In practice, however, the uncertainty of the impact (and the range of the estimated effect) is greater due to errors in exposure assessment and non-statistical uncertainty of exposure-response function.

2.3. RESULTS

2.3.1. Case Study: Megacity Delhi

To test and apply the above methodology, a case study has been performed to determine the inter-annual variation of the excess number of cases in various districts of the megacity Delhi. The WHO default values of RR are given for TSP. However, due to the lack of TSP data for various districts of Delhi, suspended particulate matter (SPM) concentration have been used as a surrogate for TSP.

The methodology described in Section 2.2 depends mainly upon population and ambient air pollution concentration. Since population for only the census of 1991 and 2001 are available, population forecasts carried out by the Delhi Planning Commission are considered for other years (Table 2.2). The ambient atmospheric concentrations of criteria pollutants, namely; SO_2, NO_2 and SPM, are the annual average concentration data (Tables 2.3, 2.4, 2.5) monitored and estimated by the Central Pollution Control Board (CPCB), Delhi, which has been taken from CPCB. In previous study Gurjar et al. (2010) estimated health risk for entire megacity Delhi. In this chapter health risks have been calculated for various districts of the megacity Delhi. There are 9 districts in megacity Delhi (Table 2.2). Concentration data of respective monitoring station in each district is used for calculating district-wise health risk estimates. In absence of monitoring station data for any district, air quality data of nearest monitoring station has been used for calculating health risk of that district.

Table 2.2: Districts-wise population of megacity Delhi (1991-2010)

	North-West	South	West	North-East	South-West	East	North	Central	New Delhi	Total
1991	1777968	1501881	1433038	1085250	1087573	1023078	686654	656533	168669	9420644
1992	1864581	1565012	1490897	1139532	1140884	1060375	695598	655511	169685	9790821
1993	1955414	1630796	1551092	1196529	1196807	1099032	704659	654491	170708	10175543
1994	2050672	1699345	1613717	1256377	1255472	1139099	713838	653472	171736	10575383
1995	2150570	1770776	1678871	1319219	1317013	1180626	723136	652455	172771	10990935
1996	2255334	1845210	1746656	1385203	1381570	1223666	732555	651439	173812	11422815
1997	2365203	1922772	1817177	1454488	1449291	1268276	742097	650425	174859	11871665
1998	2480423	2003594	1890546	1527239	1520333	1314513	751764	649413	175913	12338153
1999	2601256	2087814	1966876	1603628	1594856	1362435	761556	648402	176973	12822971
2000	2727976	2175574	2046289	1683839	1673033	1412103	771476	647393	178039	13326839
2001	2860869	2267023	2128908	1768061	1755041	1463583	781525	646385	179112	13850507
2002	3000236	2362316	2214863	1856496	1841069	1516939	791705	645379	180191	14394752
2003	3146392	2461614	2304288	1949354	1931315	1572241	802018	644374	181277	14960382
2004	3299668	2565087	2397324	2046857	2025984	1629558	812464	643371	182369	15548239
2005	3460410	2672908	2494116	2149237	2125293	1688966	823047	642370	183468	16159194
2006	3628983	2785262	2594816	2256737	2229470	1750538	833768	641370	184574	16794157
2007	3805769	2902339	2699581	2369615	2338754	1814356	844629	640372	185686	17454070
2008	3991166	3024337	2808577	2488138	2453395	1880500	855631	639375	186804	18139914
2009	4185595	3151463	2921973	2612590	2573655	1949056	866776	638380	187930	18852708
2010	4389495	3283933	3039948	2743266	2699810	2020110	878066	637386	189062	19593510

Table 2.3: Ambient air concentrations of SO_2 observed at different monitoring stations of megacity Delhi from 1991 to 2010

	Shahzada Bagh (Industrial)	Shahadra (Industrial)	E.S.I. Disp., Najafgarh Road (Industrial)	Nizamuddin (Resi.)	Ashok Vihar (Resi.)	Janakpuri (Resi.)	Siri Fort (Resi.)	Netaji Nagar, Post Office (Resi.)	Town Hall (Resi.)
1991	12.8	17.3	25.5	12.9	16.5	11.8	8.4	52.3	106.1
1992	29.6	16.6	20.6	16.9	17.6	16.4	13.4	12.7	24.4
1993	25.4	22.4	21.5	13.7	17.7	15.1	16.5	16.3	30.7
1994	30.1	21.3	34.4	16.1	21.1	16.1	12.5	23.5	52.8
1995	26	22.2	30.5	15.9	17.7	17.9	14.5	23.4	43.1
1996	22.5	19.9	17.4	17.5	16.2	17	15	11.5	22.7
1997	24.2	16	18.7	17.7	14.2	15.7	12.9	10.2	17.5
1998	22.3	17.8	14.8	15.6	15.3	17.1	15.7	7.8	12.2
1999	20.6	20.2	19.6	17.1	11.5	17.4	19.6	13.7	17.4
2000	17	17.7	14.8	18.2	11.6	18.6	15.9	8.3	14.3
2001	13.6	13	13.9	16.9	8.2	16.4	13.8	7.6	13.3
2002	9.7	16.7	16.7	13.1	6.4	13.7	11.8	7.3	11.5
2003	6.9	11.4	13.4	12.2	6.1	11.7	9	7.2	11.5
2004	12	10	10	7	11	11	10	8	10
2005	13.8	8	8.9	6.6	8.3	9.2	7.8	8.3	10.1
2006	15.5	8.9	10.1	10.1	11.4	9.7	7.5	6.4	9.5
2007	14.6	4.4	4.6	4.6	13.6	4.2	4.2	4.3	4.4
2008	13	5	6	5	5	5	5	5	10
2009	13	5	7	4	8	4	5	5	6
2010	13.0	4.7	3.9	3.6	8.2	2.5	3.0	5.0	5.7

Threshold values for SO_2 considered in calculation is 50 $\mu g m^{-3}$ (WHO 1987; 2000)

Table 2.4: Ambient air concentrations of NO_x observed at different monitoring stations of megacity Delhi from 1991 to 2010

	Shahzada Bagh (Industrial)	Shahadra (Industrial)	E.S.I. Disp., Najafgarh Road (Industrial)	Nizamuddin (Resi.)	Ashok Vihar (Resi.)	Janakpuri (Resi.)	Siri Fort (Resi.)	Netaji Nagar, Post Office (Resi.)	Town Hall (Resi.)
1991	25.2	24.6	61.2	25.2	31.3	32.7	24.2	66.9	108.4
1992	29.2	34.9	24.7	30.1	32.8	31	24.1	24.1	41
1993	33.4	35.1	25.7	30.1	31	37.8	31.8	31.7	51.7
1994	37.6	29	60	37.2	30	36	28.3	55.8	77.7
1995	45.3	27.6	52	37	28.5	37.2	28.9	57.2	110.8
1996	41.8	28.4	40.4	36.4	25.6	36.9	31.5	45.9	75.3
1997	44.8	29.3	38	37.4	22.9	34.8	29.3	32.2	37.7
1998	40	28.7	38.9	35.1	21.4	32.1	28	36.5	44
1999	44	25	47.3	31.7	19.9	30	24.8	45.7	54.5
2000	41.4	26	57	33.6	27	32.5	24.6	52.6	64
2001	35.4	22.5	65.4	35.7	19.5	37.3	22.5	52.5	70.1
2002	33.9	36.3	36.3	39.3	26	39.5	27.3	42.6	53.3
2003	39.3	32.6	45.2	43.3	32.2	44.2	31.8	46.4	58.9
2004	56	47	39	53	60	45	39	35	41
2005	48.9	45.5	33.8	22.6	64.7	43.7	48.9	32.2	47.3
2006	44.1	48	42.9	42.9	58	49.1	50.6	37.9	50.8
2007	76.7	35.9	46.9	46.9	96.4	31.6	31.6	37.1	42.3
2008	75	58	49	53	69	42	38	49	77
2009	74	47	42	47	94	37	38	42	55
2010	74	47	42	48	98	37	38	42	55

A threshold value for NO_2considered in calculation is 40 μgm^{-3} (WHO 1997; 2000; 2006).

Table 2.5: Ambient air concentrations of SPM in different monitoring stations of megacity Delhi from 1991 to 2010

	Shahzada Bagh (Industrial)	Shahadra (Industrial)	E.S.I. Disp., Najafgarh Road (Industrial)	Nizamuddin (Resi.)	Ashok Vihar (Resi.)	Janakpuri (Resi.)	Siri Fort (Resi.)	Netaji Nagar, Post Office (Resi.)	Town Hall (Resi.)
1991	373	325	544	296	259	391	255	336	728
1992	498	364	191	358	321	372	351	344	480
1993	421	383	622	362	322	393	353	377	588
1994	373	350	719	443	340	426	331	499	537
1995	369	437	475	398	406	422	408	308	472
1996	393	446	527	413	361	352	348	303	479
1997	282	313	425	362	307	343	367	288	401
1998	354	371	498	342	313	340	384	342	465
1999	316	345	535	283	317	312	337	339	505
2000	342	282	671	279	306	242	225	491	590
2001	378	291	625	261	273	278	324	398	561
2002	468	415	415	329	425	442	378	421	534
2003	354	343	425	315	356	291	281	352	478
2004	484	338	357	356	508	345	315	334	328
2005	523	280	275	275	517	248	278	298	278
2006	637	406	398	398	581	350	190	336	380
2007	495	357	430	430	555	334	334	344	335
2008	529	459	460	408	355	406	371	398	508
2009	512	364	394	410	401	346	295	360	478
2010	521	420	398	465	400	373	324	391	480

A threshold value for TSP considered in calculation is 90 μgm^{-3} (WHO 1987).

The results obtained from the above case study, using the proposed spreadsheet model (Ri-MAP) incorporating concentration response Eqs. (2.1) to (2.7), have been illustrated in Fig. 2.1 to 2.9.

2.3.1.1. New Delhi

Fig. 2.1(a)-2.1(d) illustrate the trend of excess number of cases of total mortality, cardiovascular mortality, respiratory mortality and hospital admission due to Chronic Obstructive Pulmonary Disease (COPD) in New Delhi district of megacity Delhi. No definite trend has been identified in Fig. 2.1 (a)-2.1(d) due to irregular variation in concentrations of pollutants in New Delhi area. In 1991 excess number of cases of total mortality was 81 followed by 152 in 1995, and 70 in 2000. In 2005 excess number of cases of total mortality was 101 while 126 in 2010 (Fig.2.1a). In case of cardiovascular mortality excess number of cases in 1991 was 27 followed by 51 in 1995, 23 in 2000, 35 in 2005 and 42 in 2010 (Fig. 2.1b). Excess number of cases of respiratory mortality was 13 in 1991, 23 in 1995, 11 in 2000, 16 in 2005 and 20 in 2010 in New Delhi (Fig. 2.1c). Excess number of cases of hospital admission COPD in 1991 was 116 and 215 in 1995 followed by 101 in 2000, 148 in 2005 and 179 in 2010 (Fig. 2.1d). Implementations of various policies like EURO I, II & III norms, CNG conversion program in 2002, and phasing out of old vehicles during the study period might be responsible for the variations in excess number of cases for different mortality and morbidity.

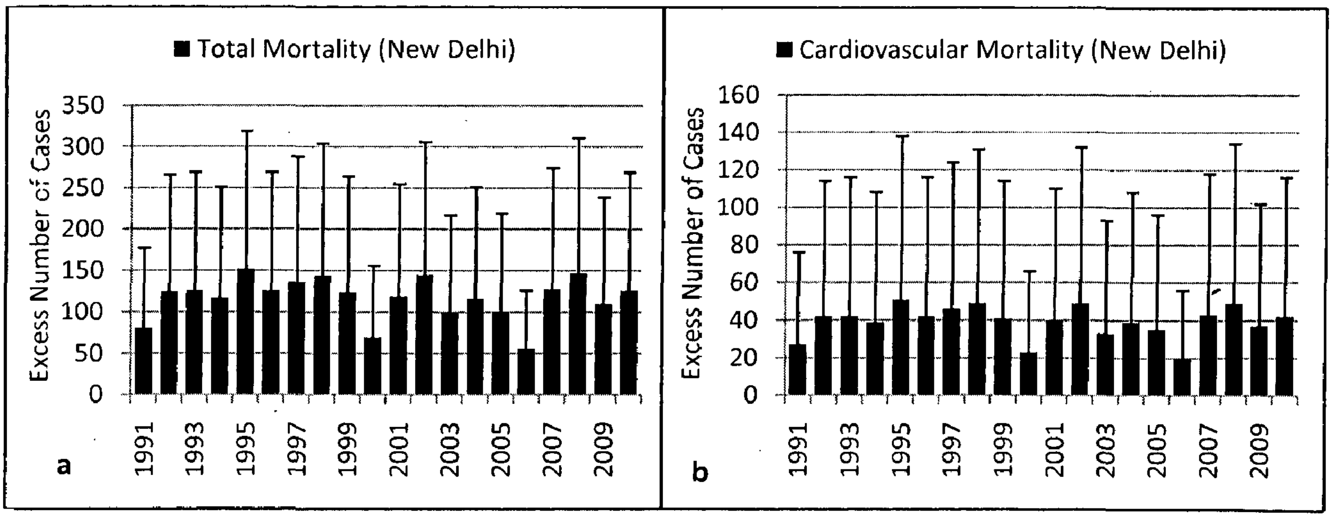


Fig. 2.1: Excess number of cases of (a) Total mortality (b) Cardiovascular Mortality COPD in New Delhi

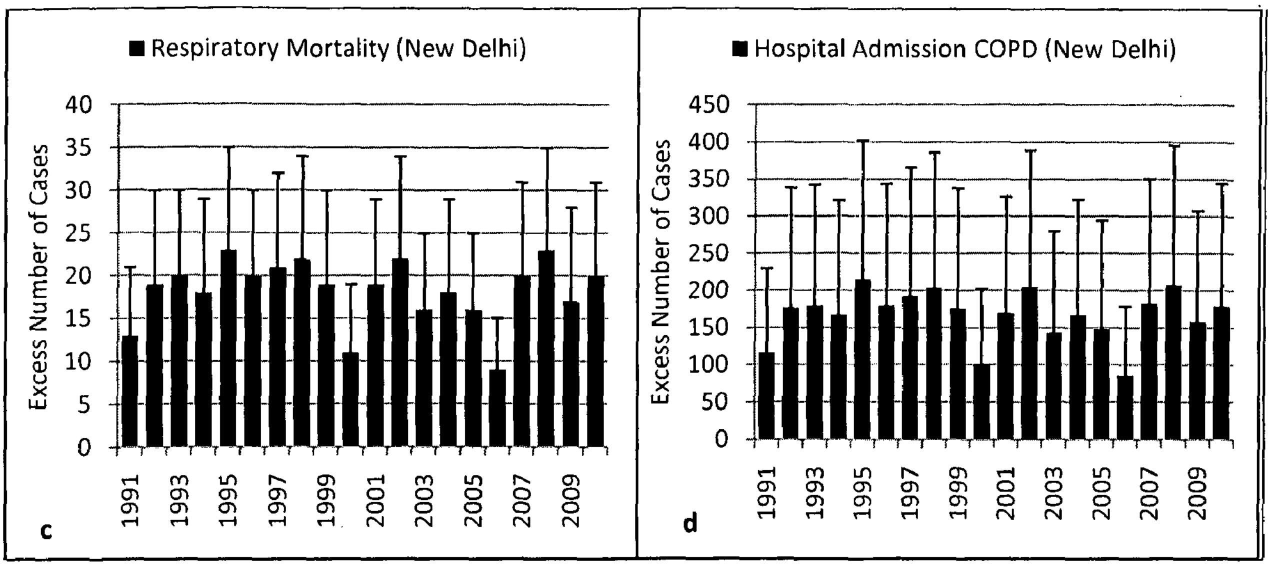


Fig. 2.1: Excess number of cases of (c) Respiratory Mortality (d) Hospital Admission COPD in New Delhi

2.3.1.2. Central Delhi

Fig. 2.2 (a) to 2.2(d) shows the excess number of cases of total, cardiovascular, respiratory mortality and hospital admission COPD cases in Central Delhi district of megacity Delhi. No specific trend is observed in excess number of cases for total, cardiovascular, respiratory mortality and hospital admission COPD. Highest excess number of cases is observed in year 1991 for all mortality and morbidity because of higher concentration of pollutants in year 1991. In 1991 excess number of cases of total mortality in Central Delhi district is 1258, while in 1995 it is 725 followed by 871 in 2000, 352 in 2005 and 685 in 2010 (Fig. 2.2a). Excess number of cases of cardiovascular mortality in 1991 was 553 followed by 275 in 1995, 120 in 2005 and 238 in 2010 (Fig. 2.2b). In case of respiratory mortality, excess number of cases in 1991 was 169, 101 in 1995 and 122 in year 2000 (Fig. 2.2c). In 2005 excess number of cases of respiratory mortality was 55 and 100 in 2010 in Central Delhi district. Excess number of cases of hospital admission COPD in 1991 was 1788 in Central Delhi followed by 1125 in 1995, 1273 in 2000 and 982 in 2010 (Fig. 2.2d). As discussed in previous paragraph, change in policies and timely phasing out of vehicles might be responsible for fluctuation in excess number of cases.

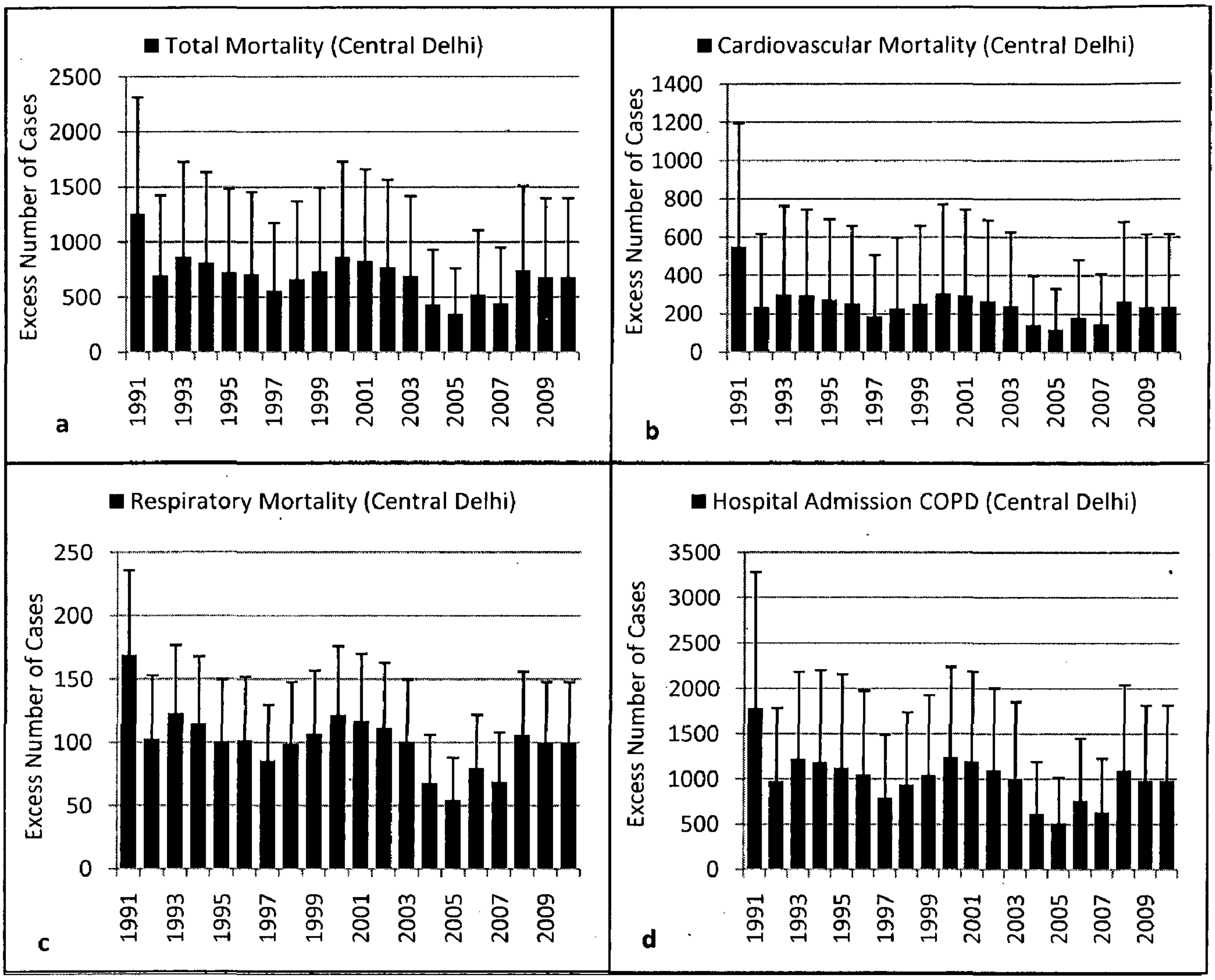


Fig. 2.2: Excess number of cases of (a) Total mortality in (b) Cardiovascular Mortality (c) Respiratory Mortality (d) Hospital Admission COPD in Delhi Central

2.3.1.3. North Delhi

Excess number of cases of mortalities and morbidity in North Delhi district is given in Fig. 2.3(a) to 2.3(d). Distinct types of trends are observed in mortalities and morbidity in North Delhi region. From 1991 to 1997 excess number of cases of mortalities and morbidity are going with negative slope. After that from 1997 to 2002 increasing trend is observed. While in 2003 sudden dip in excess number of mortalities and morbidity is observed and from 2003 to 2005 trend is going on similar way. In 2006 increased excess number of cases is observed and after that trend is going on similar way till 2010 with fewer cases in 2007. In 1991 excess number of cases of total mortality was 889, followed by 688 in 1995, 802 in 2000, and 717 in 2005 and 996 in 2010 (Fig. 2.3a). In case of cardiovascular mortality in 1991 excess number of cases were 332 while in 1995 it is 250, followed by 278 in 2000, 246 in 2005 and 352 in

2010 (Fig. 2.3b). In 1991 excess number of cases of respiratory mortality were 126 in North Delhi districts followed by 100 in 1995, 118 in 2000, and 108 in 2005 and 143 in 2010 (Fig. 2.3c). Excess numbers of cases of hospital admission of COPD in 1991 were 1272; in 1995 it is 1035, followed by 1148 in 2000, 1029 in 2005 and 1444 in 2010 (Fig. 2.3d).

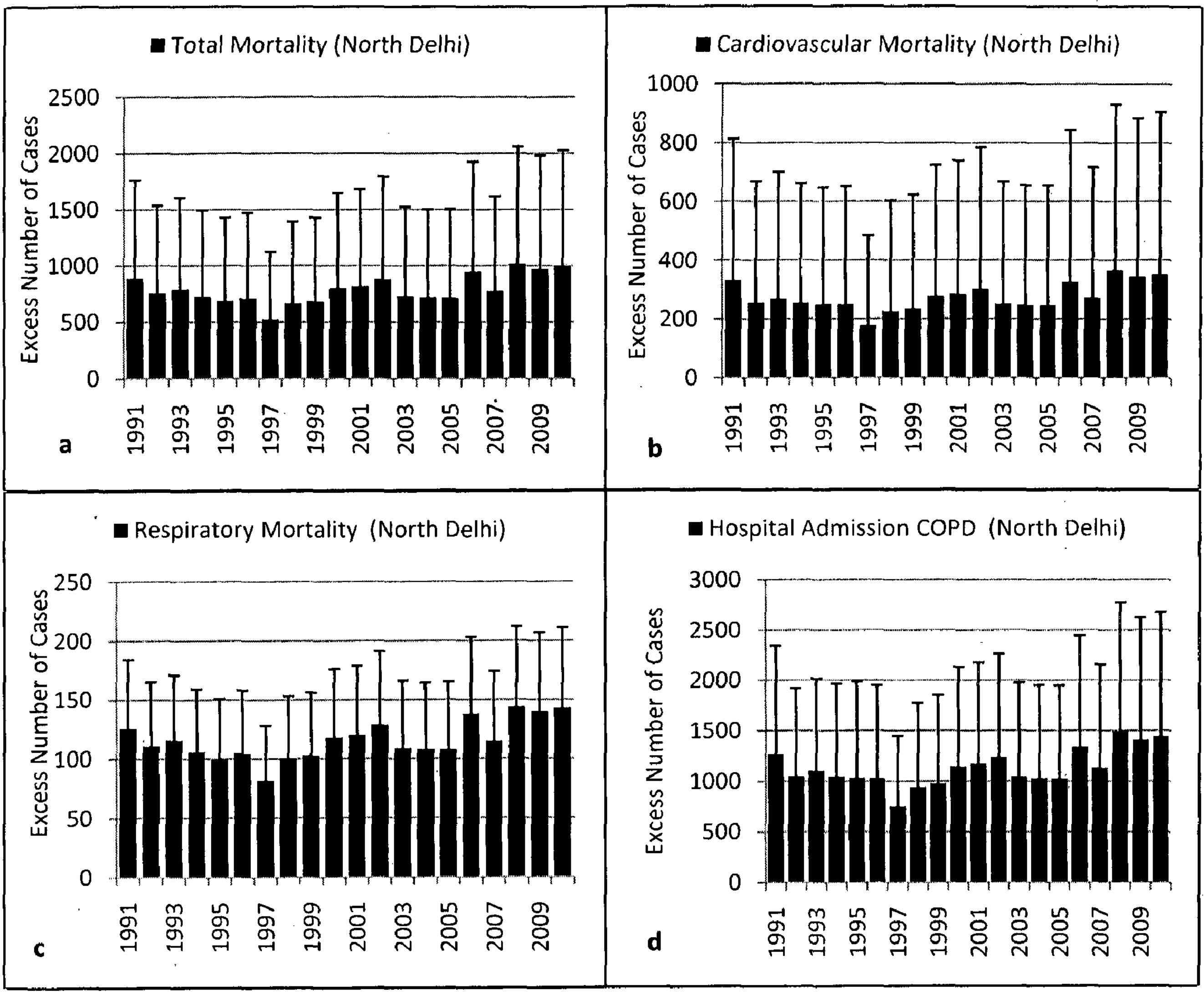


Fig. 2.3: Excess number of cases of (a) Total mortality (b) Cardiovascular Mortality (c) Respiratory Mortality (d) Hospital Admission COPD in North Delhi

2.3.1.4. East Delhi

Excess number of cases of mortalities and morbidities for East Delhi district of megacity Delhi are given in Fig. 2.4(a) to (d). From 1991 to 1996 excess number of cases of moralities and morbidities going on quite increasing way while in 1997 decrease in mortalities and morbidities is found. In 1991 excess number of cases of total mortality was 683 followed by 1128 in 1995, 779 in 2000, 932 in 2005 and 1859 in 2010 (Fig. 2.4a). In case of cardiovascular mortality excess number of cases in 1991 was 228 and in 1995 it was 381 followed by 260 in 2000, 317 in 2005 and 636 in 2010 (Fig. 2.4b). About 107 numbers of cases of respiratory mortality was found in 1991 while in 1995 it was 169. In 2000 excess number of cases of respiratory mortality was 124 followed by 147 in 2005 and 279 in 2010 (Fig. 2.4c). In 1991 excess number of hospital admission COPD was 972 followed by 1586 in 1995, 1115 in 2000, 1357 in 2005 and 2653 in 2010 (Fig. 2.4d).

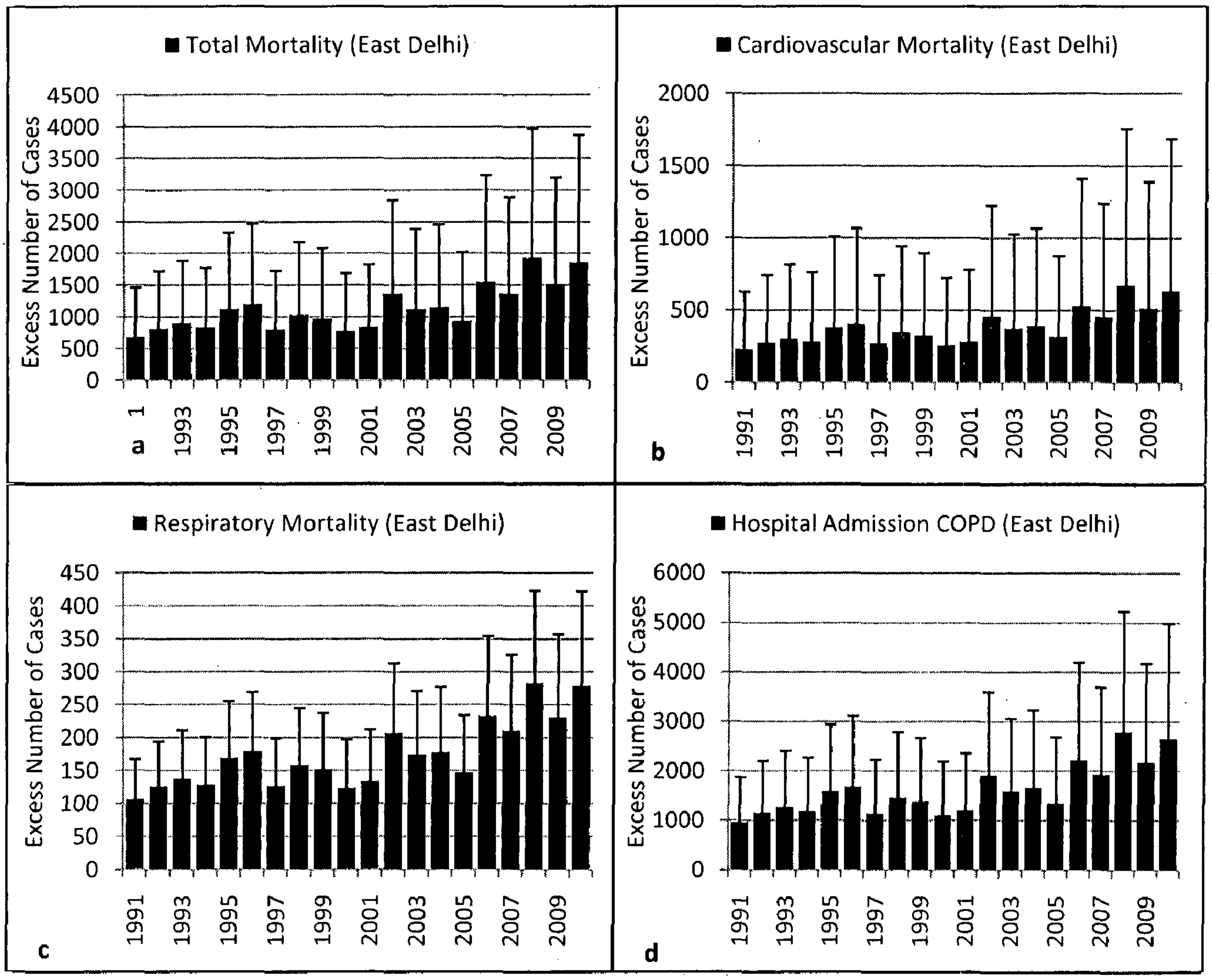


Fig. 2.4: Excess number of cases of (a) Total mortality (b) Cardiovascular Mortality (c) Respiratory Mortality (d) Hospital Admission COPD in East Delhi

2.3.1.5. South West Delhi

Initially from 1991 to 1994 excess number of cases of mortalities and morbidities in South West districts of Delhi show increasing trend while sudden decrease in excess number of cases is observed in 1995. From 1995 excess number of cases started increasing till 2000. While from 2001 to 2005 excess number of cases shows a decreasing trend and after that it is going on increasing way. In 1991 excess number of cases of total mortalities is 796 followed by 841 in 1995, 1841 in 2000, 1265 in 2005 and 2270 in 2010 (Fig. 2.5a). About 292 number of cardiovascular mortality was found in the year 1991 while in 1995 it was 296. In 2000 excess number of cases of cardiovascular mortality was 638 followed by 422 in 2005 and 767 in 2010 (Fig. 2.5b). Excess number of cases of respiratory mortality in 1991 was 120 in south west district of Delhi while in 1995 it was 129. In 2000 excess number of cases of respiratory mortality was 268 followed by 200 in 2005 and 346 in 2010 (Fig. 2.5c). In case of hospital admission COPD excess number of cases in 1991 was 1200 followed by 2625 in 2000, 1807 in 2005 and 3220 in 2010 (Fig. 2.5d).

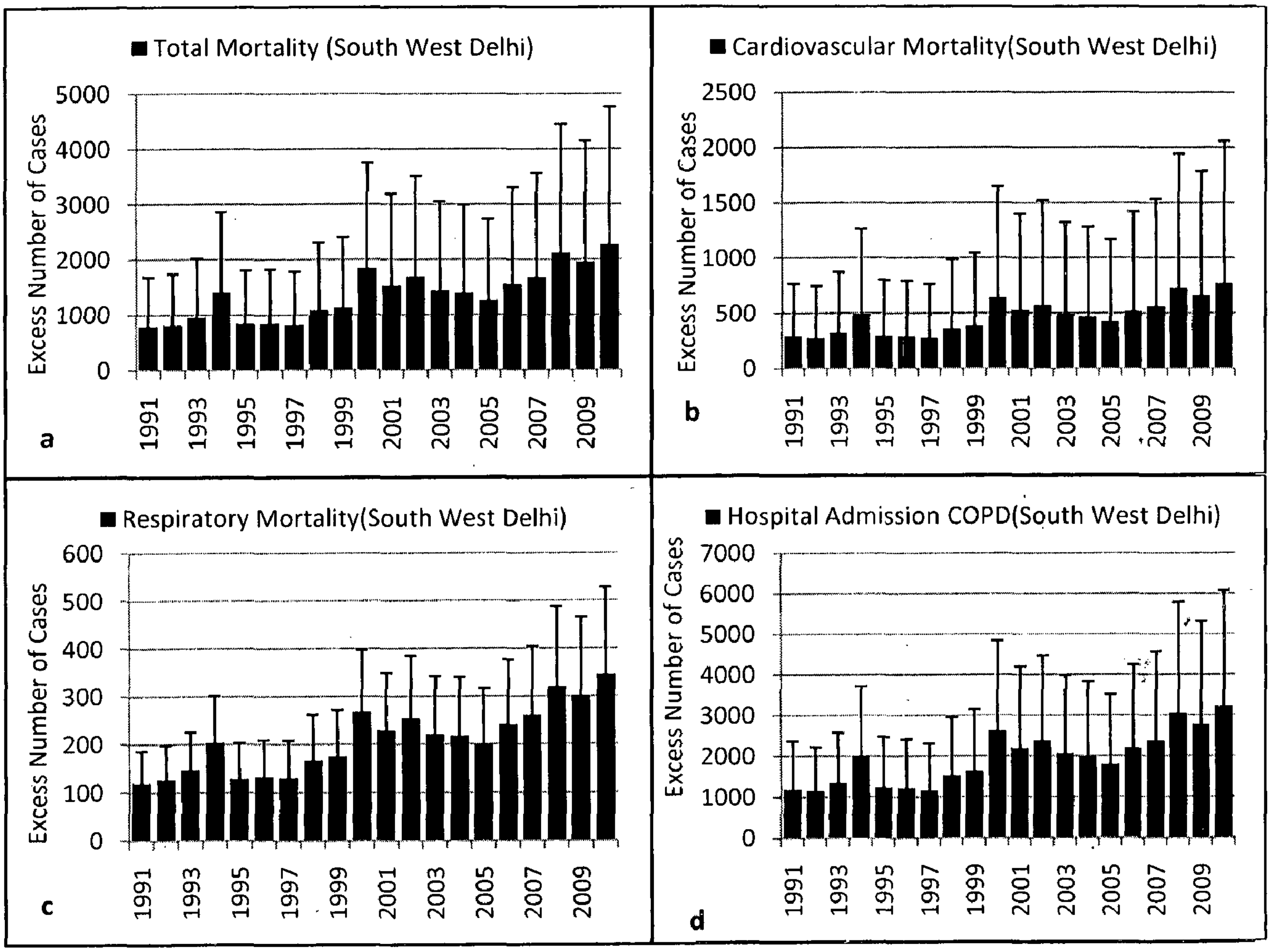


Fig. 2.5: Excess number of cases of (a) Total mortality (b) Cardiovascular Mortality (c) Respiratory Mortality (d) Hospital Admission COPD in South West Delhi

2.3.1.6. North East Delhi

No definite trend is observed in excess number cases of mortalities and morbidity in North East district of Delhi. Minimum excess number of cases of mortalities and morbidity is observed in the year 2005 while maximum number is observed in 2010. In 1991 excess number of cases of total mortality was 2080 followed by 1466 in 1995, 2265 in 2000, 1178 in 2005 and 2949 in 2010 (Fig. 2.6a). In case of cardiovascular mortality in 1991 excess number of cases was 915 while in 1995 it was 557 followed by 801 in 2000, 403 in 2005, and 1026 in 2010 (Fig. 2.6b). In 1991 excess number of cases of respiratory mortality was 280 and in 1995 it was 204 followed by 318 in 2000, 185 in 2005 and 430 in 2010 (Fig. 2.6c). About 2956 excess number of hospital admission of COPD cases was found in 1991 followed by 2275 in 1995, 3233 in 2000, 1725 in 2005 and 4228 in 2010 (Fig. 2.6d). The reason is already discussed in earlier paragraph of section 2.3.1.1, which states that high population of old age vehicles in certain year and their phasing out in another year might be responsible for the fluctuation in excess number of cases.

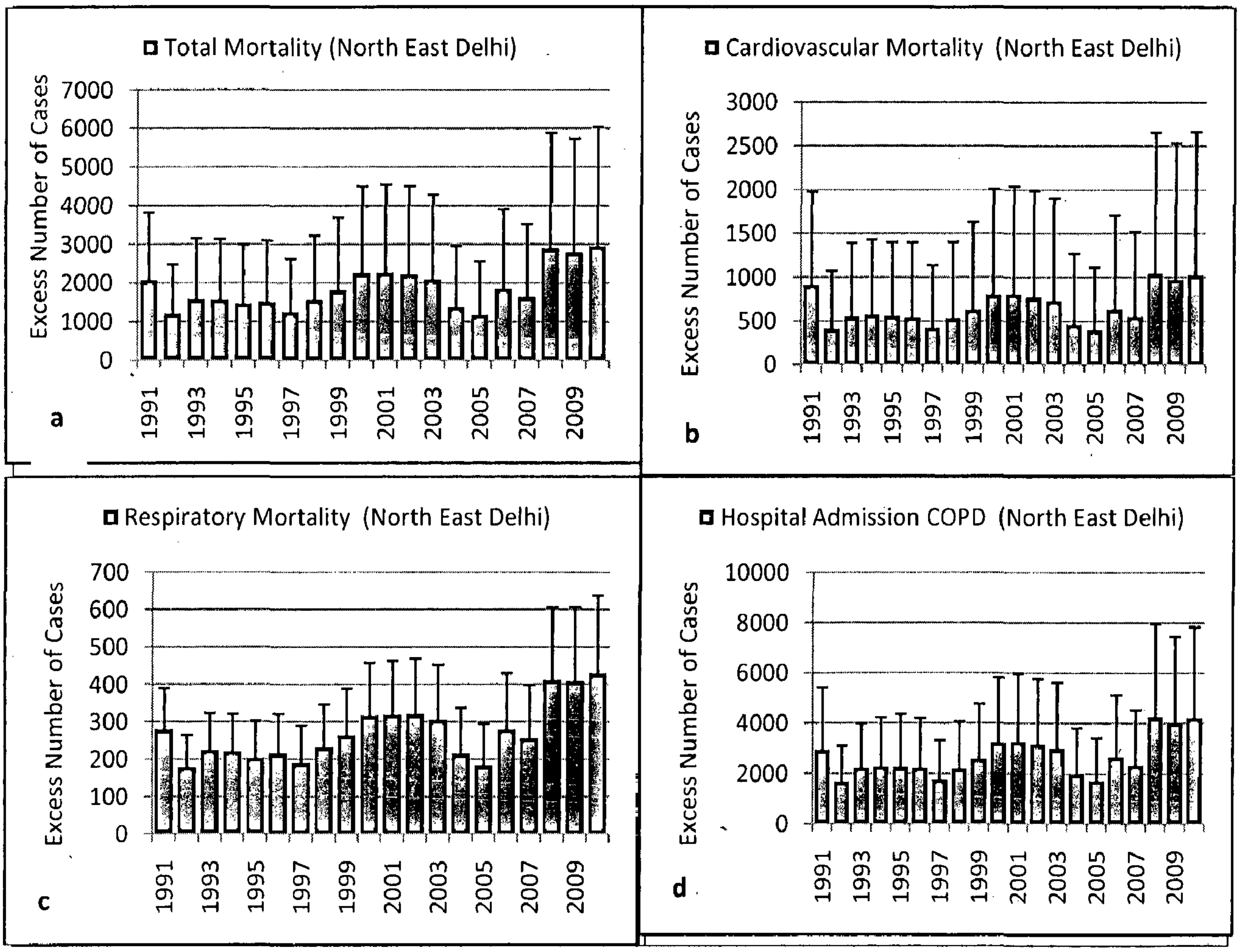


Fig. 2.6: Excess number of cases of (a) Total mortality (b) Cardiovascular Mortality (c) Respiratory Mortality (d) Hospital Admission COPD in North East Delhi

2.3.1.7. West Delhi

Excess number of cases of mortality and morbidity for West Delhi region are given in Fig. 2.7(a-d), which shows that trend of excess number of cases of mortality and morbidity, is going on very irregular manner. In 1991 excess number of cases of total mortality was 1487 while in 1995 it was 1659 followed by 2063 in 2000, 1236 in 2005 and 2505 in 2010 (Fig. 2.7a). In case of cardiovascular excess number of cases in 1991 was 510 followed by 566 in 1995, 704 in 2000, and 411 in 2005 and 842 in 2010 (Fig. 2.7b). About 219 numbers of cases of respiratory mortality is found in 1991 which became 247 in 1995 followed by 306 in 2000, 1999 in 2005 and 383 in 2010 (Fig. 2.7c). In case of hospital admission COPD in 1991 excess number of cases was 2108 and in 1995 it was 2349 followed by 2919 in 2000, 1775 in 2005 and 3542 in 2010 (Fig. 2.7d). Large population of old age vehicles might be responsible for high excess number of cases, while their phasing out for less excess number of cases.

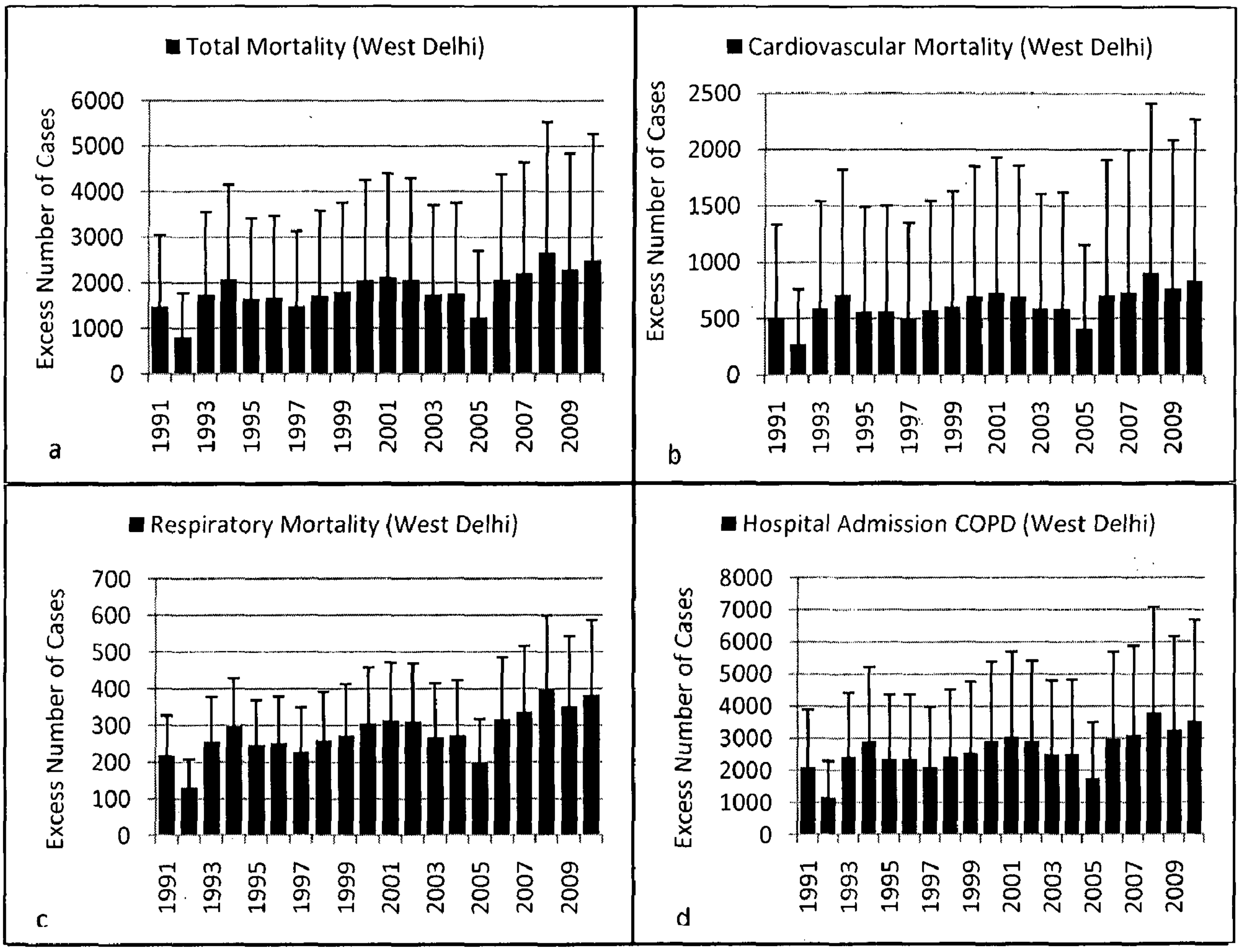


Fig. 2.7: Excess number of cases of (a) Total mortality (b) Cardiovascular Mortality (c) Respiratory Mortality (d) Hospital Admission COPD in West Delhi

2.3.1.8. South Delhi

Trend of excess number of cases of mortality and morbidity in South Delhi is going in increasing way from 1991 to 2010 [Fig. 2.8 (a-b)]. In 1991 excess number of cases of total mortality was 802 followed by 1540 in 1995, 1021 in 2000, 1435 in 2005 and 2794 in 2010 (Fig. 2.8a). In case of cardiovascular mortality in 1991 excess number of cases was 267 followed by 518 in 1995, 339 in 2000, 478 in 2005 and 947 in 2010 (Fig. 2.8b). In respiratory mortality excess number of cases in 1991 was 128 while in 1995 it was 234, followed by 165 in 2000, 229 in 2005 and 424 in 2010 (Fig. 2.8c). Excess number of cases of hospital admission COPD in 1991 was 1149; in 1995 it was 2174 followed by 1468 in 2000, 2055 in 2005 and 3972 in 2010 (Fig. 2.8d). In this district there is an overall increasing trend except a few dips, which might be due to the high density of vehicle population.

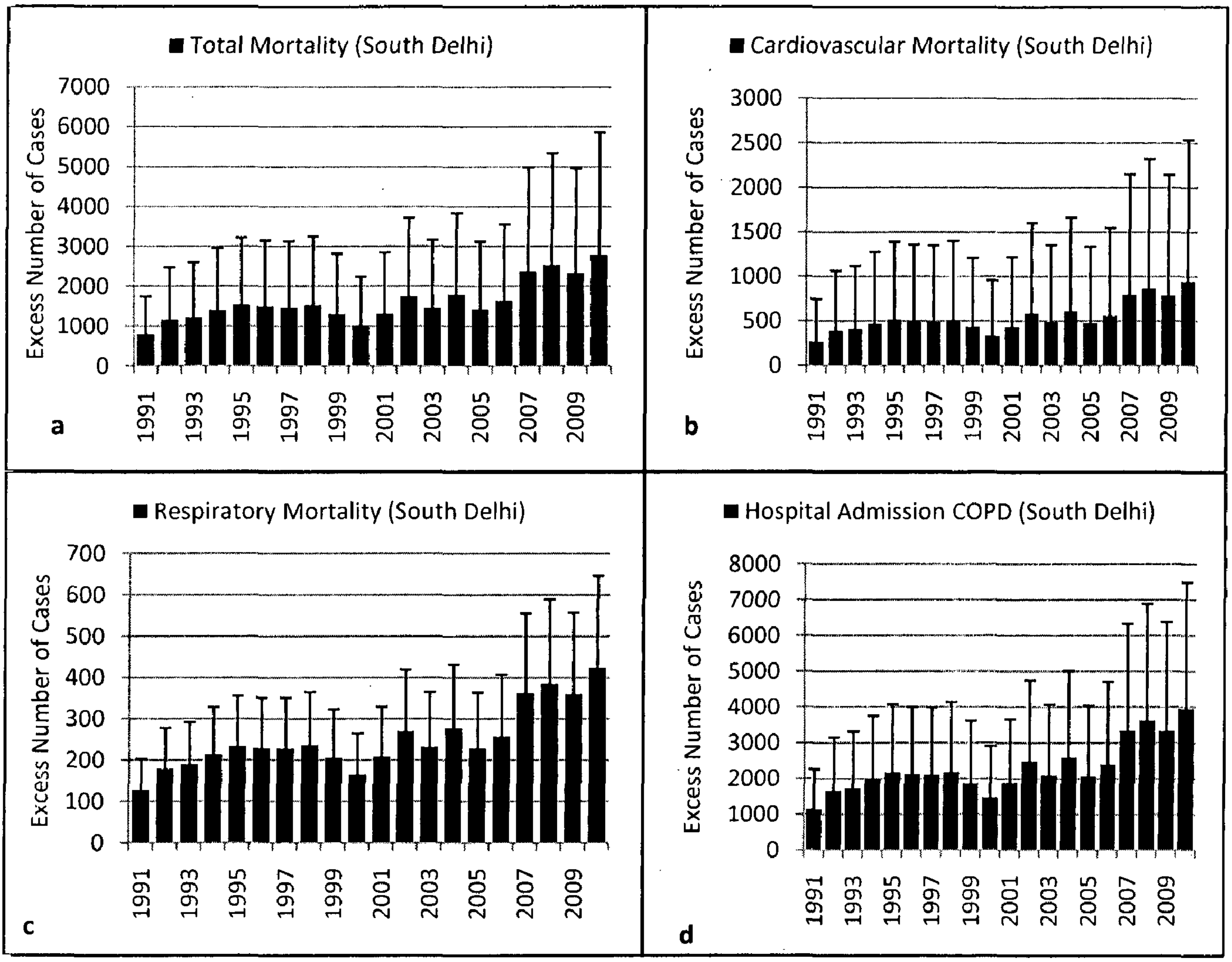


Fig. 2.8: Excess number of cases of (a) Total mortality (b) Cardiovascular Mortality (c) Respiratory Mortality (d) Hospital Admission COPD in South Delhi

2.3.1.9. North West Delhi

Fig. 2.9(a) to 2.9 (d) shows the excess number of cases of various mortality and morbidity in North West Delhi district of megacity Delhi. Fig. 2.9(a-d) shows that excess number of cases of mortality and morbidity are going on increasing way from 1991 to 2010. In case of total mortality excess number of cases of total mortality in 1991 was 869 followed by 1886 in 1995, 1682 in 2000, 4065 in 2005 and 4035 in 2010 (Fig. 2.9a). About 289 number of cases of cardiovascular mortality is found in year 1991 followed by 635 in 1995, 561 in 2000, 1438 in 2005 and 1524 in 2010 (Fig. 2.9b). In case of respiratory mortality excess number of case in 1991 was 140 while in 1995 it was 286 followed by 265 in 2000, 582 in 2005 and 576 in 2010 (Fig. 2.9c). Approximate 1248 number of cases of hospital admission COPD is found in 1991 followed by 2662 in 1995, 2401 in 2000, 5876 in 2005 and 6305 in 2010 (Fig. 2.9d).

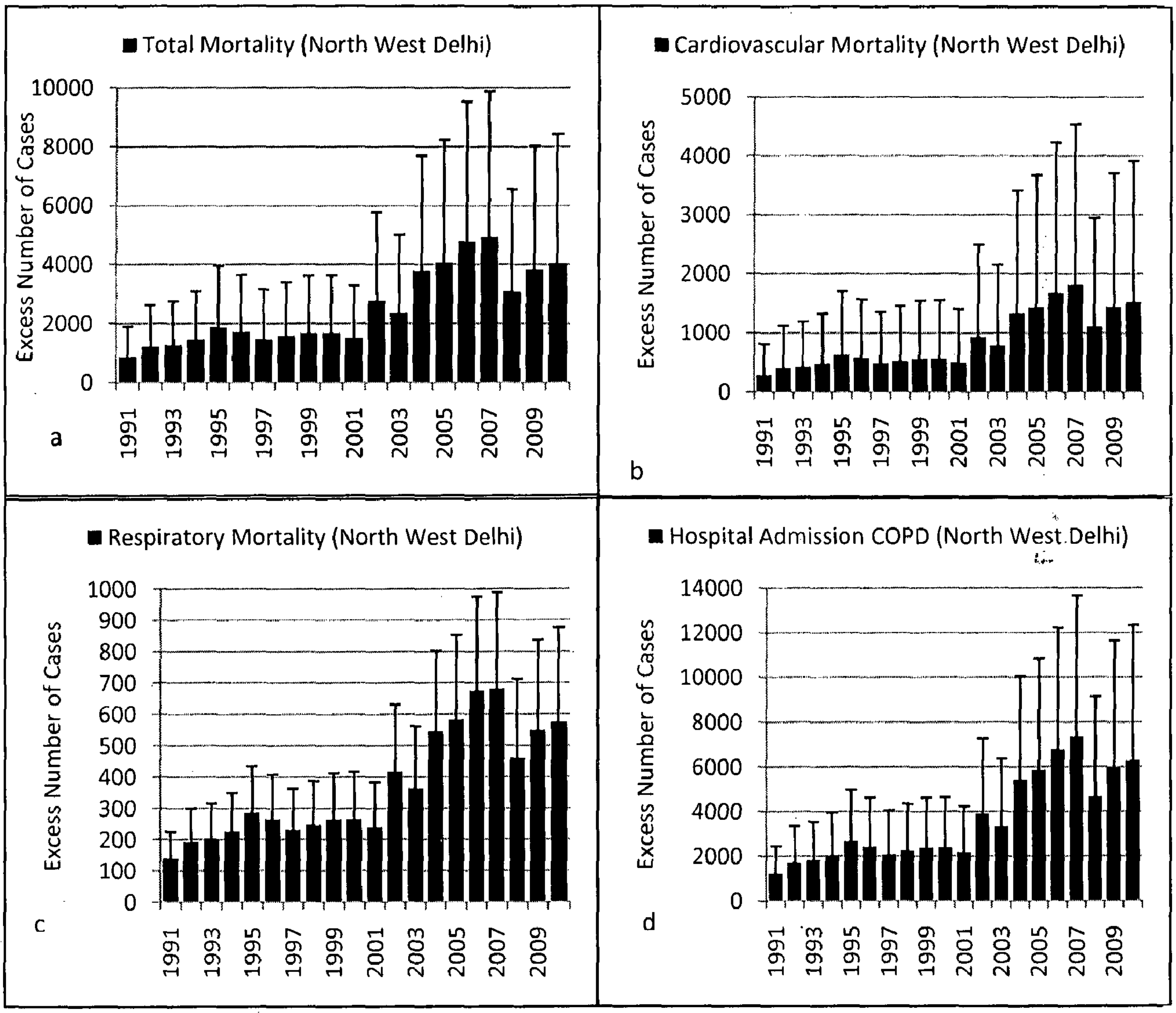


Fig. 2.9: Excess number of cases of (a) Total mortality (b) Cardiovascular Mortality (c) Respiratory Mortality (d) Hospital Admission COPD in North West Delhi

2.4. DISCUSSION

2.4.1. Total Mortality

Dissimilar trends are observed in excess number of mortality cases for various districts of Delhi. In 1991 excess number of mortality in New Delhi district of Delhi was 81 which is least excess number of cases of mortality among all districts of Delhi. Highest excess number of cases is observed in North-East Delhi (2080) districts in 1991 followed by West (1487) and Central (1258) districts of Delhi. In 1995 highest excess number of cases of total mortality was found in North West (1886) Delhi district followed by West (1659) and South (1540) district. Total mortality is fluctuating with respect to concentration and increasing population. In 2000 North East districts having highest number (2265) of total mortality cases while second largest number of mortality rate is found in West (2063) district followed by South West (1841) districts. New Delhi district is having least number of total mortality rates among all districts. In 2005 highest number of total mortality cases found in North West districts followed by South and South West districts. From 2002 onwards excess number of mortality rate is continually higher in North West district because of higher concentration of pollutants and higher population. In 2010 excess number of total mortality in North West district is 4035 which is highest among all districts. In 2010 North East district is in second position with respect to total mortality rate followed by South Delhi district.

2.4.2. Respiratory Mortality

In case of respiratory mortality highest excess number of cases is found in North East district (280) of Delhi in 1991 followed by West district (219) and Central district (169) respectively. In 1995 highest excess number of cases of respiratory mortality is found in North West district (286) followed by West Delhi (247) and South Delhi (234) while New Delhi having least excess number of cases. In 2000 North-East district having highest number of respiratory cases followed by West and South West districts. After 2002 North West Delhi is in top position till 2010 because of higher concentration of pollutants.

2.4.3. Cardiovascular Mortality

In case of cardiovascular mortality, North East district is in first position in 1991, followed by West and Central districts. With 635 excess numbers of cases position of North West district is first for cardiovascular mortality during 1995 while West district is in second position followed by North East district. Among all districts New Delhi having least number of respiratory mortality cases throughout the study period. In 2000 excess number of cases of respiratory mortality was highest in North East district followed by West and South West district of Delhi. From 2002 to 2010 position of North West district is in top for the excess number of cases of respiratory mortality.

2.4.4. Hospital Admissions due to Chronic Obstructive Pulmonary Disease

Hospital admission COPD cases are highest in North East district of Delhi in 1991 followed by West and Central district of Delhi. In 1995 highest number of hospital admission COPD cases is observe in North West district while West and North East district is in second and third position respectively. In Year 2000 excess number of cases of hospital admission of COPD is observed highest in North East district followed by West and South West district of megacity Delhi. From 2002 North West district is in top position till 2010 for highest number of excess number of cases of hospital admission of COPD.

2.5. SCOPE OF THE MODEL

Average annual concentrations of SO_2, NO_2 and TSP are used for the present calculations and comparisons of relative risks. The conventional indices being developed until now are based on the pollutant's mean concentration and thus are limited in scope in identifying the health risk in quantitative terms. For example, high peak levels are considered to be particularly harmful but the relevant observational database (e.g., Breitner et al., 2009) is still lacking. On the other hand, emerging research suggests that exposure to lower concentrations of pollutants over longer periods also results in adverse health effects (Kyle et al., 2002). Investigators have found increased mortality from several specific causes to be associated with long-term exposure to particulate matter, which may include cardiopulmonary mortality (Dockery et al., 1993), respiratory mortality (Abbey et al., 1999) and mortality in infants up to 1 year of age (Woodruff et al., 1997). Kyle et al. (2002) observes that methods to represent long-term exposures to multiple pollutants are needed. The proposed spreadsheet model "Ri-MAP" thus provides a viable option in view of the limited available information. The results from this study could be useful for the national governments of developing countries and organizations like WHO to help formulate air quality guidelines and to provide incentives for dealing with the health risks and hazards related to ambient air pollution.

2.6. METHODOLOGICAL LIMITATIONS AND FUTURE SCOPE

There are several methodological limitations which restricts the scope of the proposed approach. For example;

i) The risk estimates (related to both mortality and morbidity associated with exposure to air pollution) are based on results of cohort studies primarily conducted in the United States. Thus, there is inherent uncertainty in such results when we use them to assess health risks in cities of other countries.

ii) In reality, a population is exposed to a mixture of air pollutants present in the ambient air which may cause synergistic effects that we have not considered. Moreover, we have simply added pollutant-specific impacts to assess the overall health risk induced by criteria air pollutants. Such a simplistic assumption may lead to erroneous results when the (under) estimated values are considered in absolute terms.

iii) Since daily average data were not available for all the districts, we have used annual average air quality concentrations of different districts whereas relative risk (RR) values pertain to increase in daily average concentrations. This may be a source of error in risk estimates. However, since our aim was to inter-compare the RR values in different cities instead of absolute risk values, we expect this error may not change relative positions of cities in terms of RR values.

iv) We are uncertain of the quality and accuracy of air quality data available through secondary literature, which we have used for health risk estimations. This could be a substantial source of uncertainty in case of certain cities which are from less developing countries having less resources, expertise and air quality monitoring infrastructure.

v) We have considered only TSP, SO_2 and NO_2 with threshold limits, whereas recent studies show serious health impacts of fine and ultrafine particles (e.g., PM_{10}, $PM_{2.5}$, $PM_{0.1}$) and ozone (Brunekreef and Holgate, 2002; Pope and Dockery, 2006, Ostro et al., 2009). Moreover, effects have been seen at very low levels of exposure, and it is unclear whether a threshold concentration exists for particulate matter and ozone below which no effects on health are likely (Brunekreef and Holgate, 2002). Such literature call for upgradation of the proposed approach in the light of new evidences (e.g., Jerrett et al., 2009).

vi) At present, globally and particularly in developing countries, research to quantify chronic effects of air pollution, to identify the determinants of variation in health response to an exposure between various populations, as well as quantifying the impacts of air pollution based on disease burden are much needed to improve the scope and reliability of health impact analysis. Given the huge gap on this front, our results require adequate caution when they are applied in for the formulation of policy instruments and action programs, and we recommend that our method is repeated based on the best available and most recent air quality data for the location under study.

vii) Since air quality monitoring stations are always limited in number in a given city, the modeled ambient air quality concentrations are generally used in Ri-MAP kind of models for health risk estimates. However, modeled air quality concentrations are as much uncertain as the emission data used in the model. To address this issue, the subsequent chapters in present thesis primarily deal with the development of a comprehensive emission inventory model for urban transport sector.

2.7. CONCLUSION

Health risks (e.g. mortality/ morbidity) have been estimated for various districts of megacity Delhi using Risk of Mortality/Morbidity due to Air Pollution (Ri-MAP) model. It is observed that New Delhi district has least amount of access number of cases of mortality /morbidity – less population of New Delhi area might be responsible for that.

It is found that higher ambient concentration of SPM and NO_x is responsible for access number of mortality and morbidity in various districts of megacity Delhi. According to Gurjar et al. (2004) vehicles are largest contributor of the NO_x and second largest contributor of the SPM in megacity Delhi. At present there is no indigenous tool available for calculating emissions of various pollutants from vehicles in Indian cities. To fill this gap, a MS Excel 2003-2007 and Visual Basic Application (VBA) based emission inventory model has been developed (as explained in Chapter 3) for estimating emissions from urban transport sector in Indian cities.

CHAPTER 3

Development of Vehicular Air Pollution Inventory Model

3.1. INTRODUCTION

An emission inventory is an important tool for assessing and simulating air quality and for evaluating policy choices (Davis et al., 2005) for air quality management (NARSTO, 2010). Typically, the road transport emission inventory is developed through manual method or using computer based vehicular emission models. A number of sophisticated vehicle emission models are available in developed countries that can predict emissions based on available vehicle types, fuel category, vehicle kilometers traveled, emission standards and various correction factors. All these models are highly complicated because of huge input data requirement according to region. Application of these models in developing countries like India is difficult due to requirement of extensive data in absence of which they use default values of different input parameters and give erroneous results. Most of the available models are based on the US and European emission factors and conditions, which are not straight way applicable in the existing conditions of a developing country like India. Chapter 2 concludes that SPM and NO_x may have significant impact on human health, with vehicles as major contributors of SPM and NO_x. Thus the vehicular emission modeling is an essential requirement for the assessment of air quality and health risk. To fill the gap in Indian context, Vehicular Air Pollution Inventory (VAPI) model has been developed in this chapter.

3.2. AVAILABLE MODELING APPROACHES

Various emission models are used worldwide to estimate emissions from mobile sources. Generally these models are termed as travel speed emission models and also referred to as average speed emission models. These models simulate average speed adjusted emission factors for a particular vehicle class. Earliest emission model was published by Rose et al. (1965) who found an empirical relationship between HC, CO and CO_2 emissions per unit distance and journey travel speed (Smit, 2006). Various approaches are adapted by different countries and regions for vehicle emission modeling, each with its strength, weakness and limitations. Some of the models available in various countries and regions for emission estimation from transport sector are described below.

3.2.1. MOBILE

The Environmental Protection Agency (EPA) developed MOBILE model for calculating emissions from highway vehicles in all the US States except California (Cappiello, 2002). MOBILE 6 (USEPA, 2002) is the latest series of MOBILE models, the first version of which dates back to 1978 (Cappiello, 2002). It calculates emissions of HC, NO_x and CO from passenger cars, motorcycles, light and heavy-duty trucks for calendar years between 1970 and 2050. It estimates emission by considering external geographical and climatic parameters (e.g., ambient temperature, humidity, altitude) (Brzezinski and Newell, 1998).

The model is based on large number of experimental data involving thousands of emission tests on large number of vehicles in the USA. It calculates basic emission rates for a travel speed of 31.5 km/h for light duty petrol (gasoline) vehicles which are classified in terms of model year and vehicle technology. MOBILE 6 uses Equation (3.1) for computing hot running emissions of per unit distance (e_x) in freeway and arterials as a function of travel speed for 5 mile per hour speed increments.

$$e_x = SCF\ (BER\ + EO) \tag{3.1}$$

Where,

e_x = emission in per unit distance,

SCF = Speed Correction factor,

BER = Basic emission rate, and

EO = emission offset, which is a correction factor to account for BER " off-cycle" emissions, i.e. additional emissions due to high power operation which are not included in the BER. EO is a model variable that is calculated as a second order function of BER. (Smit, 2006)

3.2.2. EMFAC

California Air Resources Board (ARB) has developed Emission Factor Model (EMFAC) for estimating emissions from motor vehicles operating on highways, freeways and local roads in California (EMFAC, 2007). This model is one of the four Motor Vehicle Emission Inventory (MVEI) models that are used together to develop emission inventories in California. EMFAC accepts input from CALIMFAC (California Motor Vehicle Emissions Factor Model), which provides basic emission rates and WEIGHT to estimate vehicle activity by model year. That leads to produce emission factors which are then corrected in EMFAC for several correction factors. The last model BURDEN combines vehicle travel data (VKT, number of starts, number of vehicles) with EMFAC's emission factors to produce the emission inventory (Smit, 2006)

EMFAC has been periodically updated and has been around since 1988 when the first major improvements were reported (Smit, 2006). EMFAC 2001 version 2.08 is the latest one in this series (EMFAC, 2007). In EMFAC model, the emission rates are multiplied with vehicle activity data provided by regional transportation agencies to calculate statewide or regional emission inventories. The model calculates emission factors and emission inventories for HC, CO, NO_x, CO_2 and PM. Based on emissions of CO, CO_2 and Total Hydrocarbon (THC), it also calculates fuel consumption. Based on the fuel consumption data, model calculates emissions of SO_x and Pb. For calculating hot running emissions of vehicles in per unit distance (e_x), EMFAC uses Equation (3.2):

$$e_x = BER \times SCF = BER \times EXP[b_1(v - 27.4) + b_2(v - 27.4)^2 \qquad (3.2)$$

Where,

BER= It is the mean emission factor value of the individual vehicle, which is calculated as the total emissions (g) generated during the laboratory test procedure using the unified cycle length (mile),

SCF= Speed Correction factors, developed from 12 driving cycles, which are referred to as the Unified Correction Cycles or UCCs (Gammariello and Long, 1996),

b_1 and b_2= are model parameters, and

v= is speed expressed as mile per hour (Smit, 2006).

3.2.3. COPERT

The Computer Program to Calculate Emission from Road Traffic (COPERT) is the most commonly used model in Europe, for official national emissions inventories from road traffic (Bellasioa et al., 2007). The first real European initiative for developing emission inventory was the Core Inventory of Air Emissions (CORINAIR) working group on emission factors for calculating emissions from road traffic. The working group began in 1987 with the aim of emission inventory methodology development for estimation of vehicle emissions for the reference year of 1985. This methodology was transformed into the computer program "COPERT" (Computer Program to Calculate Emission from Road Traffic), which was released in 1989 (Eggleston et al., 1993). Newer versions of COPERT were released in 1991 (COPERT 90), 1997 (COPERT II), 2000 (COPERT III) and the most recent in-use version was made available in public domain in 2007 (COPERT IV).

COPERT computes hot running, evaporative and other activities (including vehicle tyre and brake wear) emission factors. It covers exhaust emissions of CO, NO_x, VOC, CH_4, CO_2, N_2O, NH_3, SO_x, diesel exhaust particulate matter (PM), PAHs and POPs, Dioxins and Furans and heavy metals contained in the fuel (e.g., Lead, Cadmium, Copper, Chromium, Nickel, Selenium and Zinc). A detailed NMVOC split is also included to distinguish hydrocarbon emissions as alkenes, alkynes, aldehydes, ketones and aromatics. It also computes hot running fuel consumption and on the basis of this fuel consumption it calculates emissions of some other pollutants produced as a fraction of fuel consumption (Ntziachristos et al., 2000).

The methodology allows the estimation of emissions for 105 vehicle categories belonging to following five main classes: passenger cars, light duty vehicles, heavy duty vehicles, urban buses and coaches, and two wheelers. Vehicles belonging to such main classes are then distributed according to the fuel type (Ntziachristos et al., 2000). In principle, total emissions are calculated by summing emissions up from three different sources, namely, the thermally stabilized engine operation (hot), the warming-up phase (cold start) and due to evaporation. In that respect, total emissions can be calculated by Equation (3.3):

$$E_{TOTAL} = E_{HOT} + E_{COLD} + E_{EVAP} \qquad (3.3)$$

Where,

E_{TOTAL}: Total emissions (g) of any pollutant for the spatial and temporal resolution of the application

E_{HOT} : Emissions (g) during stabilized (hot) engine operation

E_{COLD} : Emissions (g) during transient thermal engine operation (cold start)

E_{EVAP} : Emissions (g) from fuel evaporation. Emissions from evaporation are only relevant for NMVOC species from gasoline powered vehicles.

For volatile organic compounds (VOCs), expressions for the determination of the evaporative emissions are also given. A methodology has been recently introduced for calculating the emissions of PM from brakes, tyres and pavement wear. Since vehicle emissions depend on the engine operation (i.e. driving situation), exhaust emissions are calculated as function of average speed for three driving conditions: urban, rural and highway (Ntziachristos, 2000). Therefore, as far as driving conditions are concerned (spatial desegregation), total emissions can be calculated by using Equation (3.4):

$$E_{TOTAL} = E_{URBAN} + E_{RURAL} + E_{HIGHWAY} \qquad (3.4)$$

Where, E_{URBAN}, E_{RURAL}, $E_{HIGHWAY}$: Total emissions (g) of any pollutant for the respective driving situation (COPERT, 2007).

3.2.4. QGEPA

The Queensland Government Environmental Protection Agency (QGEPA) has developed the QGEPA model, which is an Australian travel speed emission model, for its use in the air emission inventory for South-East Queensland (QGEPA, 2002).

The QGEPA model (QGEPA, 2002) consists of a hot running emission factor database (CO, HC, PM and NO_x) expressed as g/km, where emission factor is a function of travel speed (i.e. eleven travel speed points). Emission factors are available for several technology classes of light duty vehicles (e.g., petrol, diesel and LPG), heavy duty vehicles (diesel, CNG, LPG) and motorcycles.

This model uses separate emission factors for estimating cold start and evaporative emissions. It also provides emission factors (unit mass/km) for a range of non-regulated pollutants such as hydrocarbons, N_2O, NH_3 and PAH. Speed correction factors for travel speed are used for evaporative running loss emissions but not for start emissions. Emission factors are directly taken from other published models such as COPERT III in cases where no Australian emission test data were available (e.g., motorcycles, CNG and LPG heavy duty vehicles, specific pollutants) (Smit, 2006).

3.2.5. IVEM

The International Vehicle Emissions (IVE) model is a computer model formulated to estimate emissions from motor vehicles. It is specifically designed to have the flexibility needed by developing countries in their efforts to address mobile source air emissions and it has been applied in several cities worldwide including Pune in India. The model predicts local air pollutants, GHG emissions and toxic pollutants. The IVE model has been developed as a joint effort of the University of California at Riverside, College of Engineering – Center for Environmental Research and Technology (CE-CERT), Global Sustainable Systems Research (GSSR), and the International Sustainable Systems Research Center (ISSRC). Funding for model development was provided by the U.S. Environmental Protection Agency (IVEM, 2004). The latest version is IVE 1.2.2, published in January 2008 (Guo et al., 2008). The basic advantage of IVE model is that it takes into account various technologies and conditions that exist in most of the developing countries. This also includes vehicle driving patterns, vehicle specific power (VSP) and engine stress distributions, which have a profound effect on the tailpipe emissions of vehicles (Hui et al., 2007).

The model requires some user information such as the types and ages of the vehicle fleet and local conditions such as ambient temperature and fuel specifications. The model uses this input to estimate emissions during each type of driving. The IVE Model estimates criteria and toxic pollutants, and also GHGs. The pollutants include: CO, VOC, NO_x, $PM_{2.5}$, PM_{10}, CO_2, N_2O, CH_4, NH_3, Benzene, lead, 1, 3 Butadiene, and aldehydes. The software contains separate emission rates for each pollutant and each operational condition, including temperature, driving speed, and mix of cold and warm-up operation. The model also adjusts emission rates to reflect changes in fuel characteristics and the type of vehicle inspection and maintenance program, if any, in operation.

The model uses a database made up of two sections:

- Basic emission rates as a function of technology type; and
- Real-world adjustment factors to account for the effects of different operating conditions.

The model is designed with the capability of estimating emissions from a single roadway, activities, or an entire region for a wide range of time periods (Hui, et al., 2007). The basic of emission calculation process in IVE model is to apply a base emission rate with a series of correction factors to estimate the amount of emissions from variety of vehicle types (Equation 3.5-3.6). Equation 3.5 estimates the adjusted emission rate by multiplying the basic emission rate by various correction factors. Equation 3.6 weights the adjusted emission rate by the travel fraction for each technology and amount of each driving type for each technology. Final step in Equation 3.6 is to multiply these results by the ratio of average velocity of LA4 driving cycle and average velocity of the modeled cycle and multiply by the distance traveled (for running emissions only). The result is the overall fleet running emissions for allocated distance or time (in grams).

$$\boldsymbol{Q}_{[t]} = \boldsymbol{B}_t \times \boldsymbol{K}_{(base)[t]} \times \boldsymbol{K}_{(temp)[t]} \times \boldsymbol{K}_{(Hmd)[t]} \times \boldsymbol{K}_{(IM)[t]} \times \boldsymbol{K}_{(fuel)[t]} \times \boldsymbol{K}_{(Alt)[t]} \times \boldsymbol{K}_{(Cntry)[t]} \tag{3.5}$$

$$\boldsymbol{Q}_{running} = \boldsymbol{U}_{[FTP]} \times \boldsymbol{D}/\boldsymbol{U}_c \times \Sigma_t\{\boldsymbol{f}_{[t]} \times \boldsymbol{Q}_{[t]} \times \Sigma_d[\boldsymbol{f}_{[dt]} \times \boldsymbol{K}_{[dt]}]\} \tag{3.6}$$

Where,

$B_{[t]}$: Base emission rate in for each technology (start (g) or running (g/km)

$Q_{[t]}$: Adjusted emission rate for LDCVs running (g)

Q : Average emission rate for entire fleet (running (g))

$f_{[t]}$: Fraction of travel by specific technology

$f_{[dt]}$:Fraction of each type of driving or soak by specific technology

$U_{[FTP]}$:Average velocity from the specific driving cycle, as input by user in Location File (kph)

$K_{(base)[t]}$:Adjustment to the base emission rate

$K_{(Tmp)[t]}$: Temperature Correction Factor

$K_{(Hmd)[t]}$: Humidity Correction Factor

$K_{(Alt)[t]}$: Altitude Correction Factor

$K_{(Fuel)[t]}$: Fuel quality Correction factors

$K_{(IM)[t]}$: Inspection/Maintenance Correction Factor

$K_{(cntry)[t]}$: Country Correction Factor

B[t] : Base emission rate in for LDCVs running (g/km)

D : Distance traveled by LDCV in one day (km)

Ei : Emission of compound i (CO, NO_x, VOC)

K(Fuel)[t] : Fuel Quality Correction Factor

K[dt] : Driving Correction Factor

3.3. PRIMARY LIMITATIONS OF AVAILABLE MODELS

The major primary limitations of available models can be listed as below:

- All the models described above have been developed in developed countries, for instance, the US, Japan, Australia, etc., where exhaustive dataset are available. Due to much difference in technology, infrastructure, driving cycles etc. in the developed countries and that of a developing country like India, application of these models in Indian context may give erroneous results.
- Although IVE model is specially designed for developing countries like India, but again it is similar to the U.S. and European models in complexity and input data requirements. It is very difficult to compile such dataset in India.
- Emission factor or basic rate of emissions of all models is the US and Europe based, which enhance the error in models emissions for India.
- Most of the models are not able to give output for more than one year.
- Most of the models require experimental data, which are often not available for Indian conditions.
- Most of the models are region specific.

Due to above-mentioned reasons, available models are not capable to simulate traffic conditions and emissions in Indian cities and thus cannot realistically evaluate the impact of different policies and norms to reduce emissions from transportation sector in India. Neither it is possible with these models to carry out predictions based on pragmatic future scenarios in Indian context.

3.4. POLLUTANTS CONSIDERED IN VAPI MODEL

Due to significance of the pollutants and availability of country specific emission factors, following pollutants are selected for exhaust emission estimation in the proposed VAPI Model.

3.4.1. Criteria Pollutants

CO, NO_x, PM are the three important pollutants which are emitted from vehicular exhaust. According to EPA, motor vehicle exhaust contributes about 60 percent of all CO emissions in the USA. Higher levels of CO generally occur in areas with heavy traffic congestion, like in cities, and 95 percent of all CO emissions may come from motor vehicle exhaust (US EPA, 2010). Similarly as per the study by Gurjar et al. (2004) vehicles contribute about 80% of CO and NO_x and 20% of PM in the atmosphere of Indian city like Delhi. After observing significance of criteria pollutants (CO, NO_x, PM) emissions from transport sector these pollutants are considered in model.

3.4.2. Hazardous Pollutants

These pollutants may also be referred to as toxic air pollutants. These pollutants are responsible for the increased chances of developing critical health issues upon exposure such as cancer, damage to the immune system and reproductive birth defects. Benzene, 1-3 Butadiene, Formaldehyde, Acetaldehyde, Total Aldehyde and Total PAH are important hazardous pollutants and vehicle contribute significant amount of these pollutants to the atmosphere.

3.4.3. Carbon Dioxide

One of the primary determinants of CO_2 emissions from mobile sources is the amount of carbon in the fuel (US EPA, 2005). Apart from industrial CO_2 production through various industrial combustion processes, CO_2 production in ambient air is largely contributed by the fuel combustion of vehicles.

3.4.4. Hydrocarbon

Hydrocarbon emissions result when fuel molecules in the engine do not burn or burn only partially. Hydrocarbons react in the presence of NO_x and sunlight to form ground-level ozone, a major component of smog. Ozone can irritate the eyes, damage lungs, and aggravate respiratory problems. It is most widespread urban air pollution problem. Some kinds of exhaust hydrocarbons are also toxic, with the potential to cause cancer (XRT, 2010).

3.5. MODEL DESIGN

For improving the current state of mobile emissions modeling in country like India, a versatile and easy-to-use modeling tool called VAPI (Vehicular Air Pollution Inventory) model was developed for calendar years between 1991 and 2030. VAPI is an excel spreadsheet and VBA (Visual Basic for Applications) based model, which estimates on-road vehicle emissions for Indian cities. It calculates running exhaust, evaporative and non exhaust emissions from vehicles. Fig. 3.1 describes the basic diagram of core architecture of the model. This model is designed for estimating emissions of pollutants like CO_2, PM, NO_x, CO, Benzene, 1-3 Butadiene, Formaldehyde, Acetaldehyde, Total Aldehyde, and Total PAH from running exhaust, VOC from evaporations, and PM_{10}, $PM_{2.5}$ from tyre and break wear. Vehicular emissions depend on several factors such as type of fuel, driving cycle, engine technologies as well as on topography and climatic conditions (e.g. altitude, humidity, temperature). In VAPI model only three correction factors were used for running emissions estimation, which are altitude, temperature, and humidity.

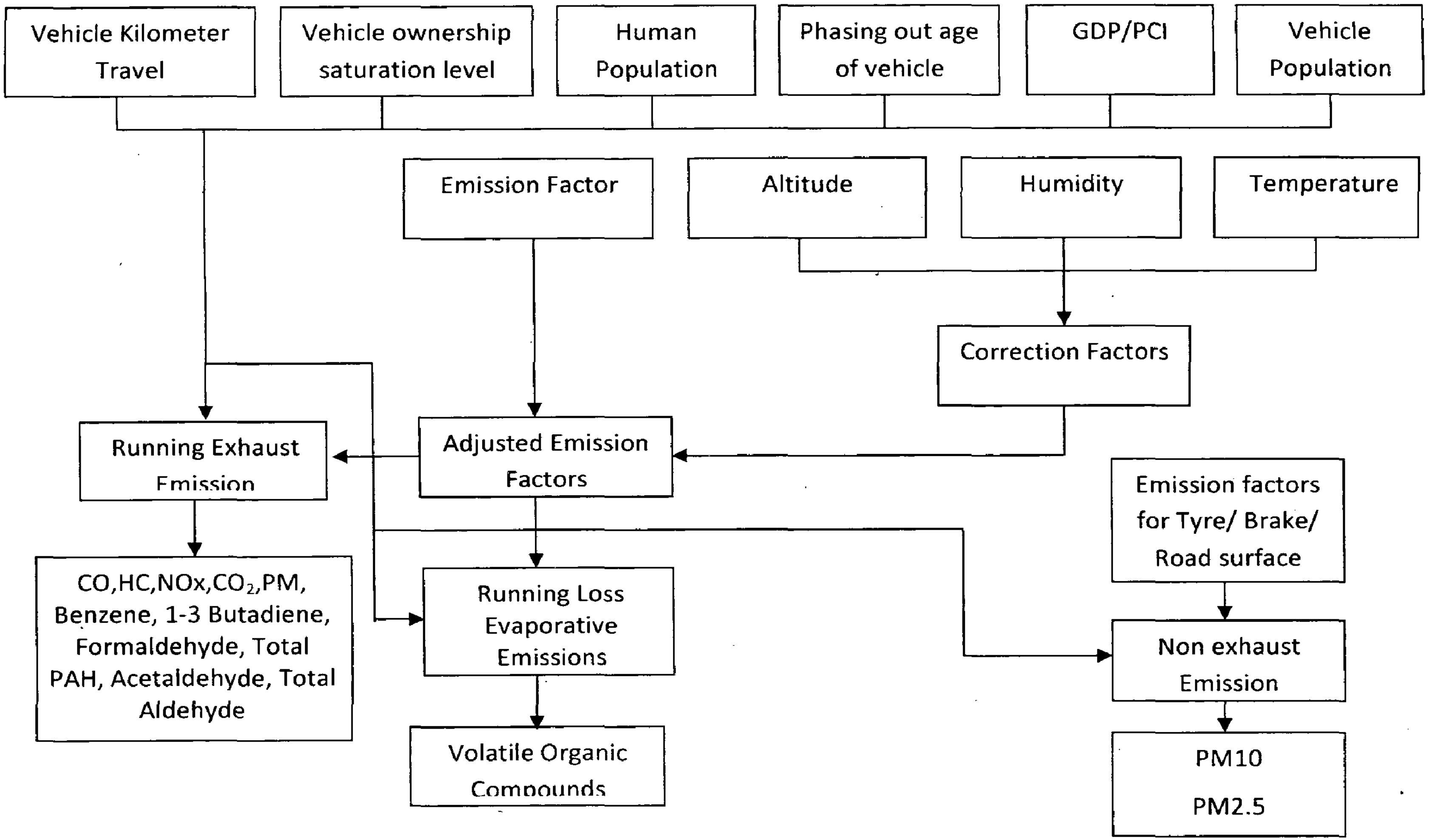


Fig. 3.1. Schematic diagram of core architecture of VAPI model

3.6. RUNNING EXHAUST EMISSIONS

The basis of running exhaust emission calculation process in VAPI model is to apply a base emission rate (emission factor) with climatic (e.g., temperature, humidity) and geographical (e.g., altitude) correction factors. Equation 3.7 estimates the adjusted emission rate of pollutants for various vehicle categories by multiplying the basic emission rate with the correction factors such as Altitude, Temperature and Humidity. Equation 3.8 estimates the emissions of various pollutants from different vehicle categories by adjusted emission rate, vehicle population and distance travel.

$$E_{api} = EF_{pi} \times C_{tpi} \times C_{hpi} \times C_{api} \qquad (3.7)$$

$$E_{tpi} = P_i \times E_{api} \times V_i \times D_{ti} \qquad (3.8)$$

D_{ti} = Annual traveling days of i vehicle category

E_{api} = Adjusted emissions rate of pollutant p from i vehicle category

EF_{pi} = Emissions factor of pollutant p from i vehicle category

EF_{tpi} = Total emissions of pollutant p from i vehicle category

C_{Tpi} = Temperature correction factor of pollutant p of i vehicle category

C_{hpi} = Humidity correction factor of pollutant p of i vehicle category

C_{api} = Altitude correction factor of pollutant p of i vehicle category

P_i = Population of i vehicle category

V_i = Per day distance travel by i vehicle category

3.6.1. Emission Factors

As it is commonly professed, an appropriately compiled emission inventory is the basic building block of any air quality management system in a country and two necessary building blocks required for compiling it are the emission factors and activity data. An emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. For transport sector, emission factors are usually expressed as the mass of pollutant divided by unit distance travelled by the vehicle (g/km). For VAPI model, country based emission factors developed by ARAI (Automotive Research Association of India, Pune) have been used. Emission factors were developed using the existing condition of Indian vehicles. Following are specifications given by ARAI (2007) for developing the emission factors:

- In-use vehicles of different vintages (viz, 1991-1996, 1996-2000, Post-2000 and Post-2005) were included in the emission factor estimating test to understand the effect of technology on emission factors and give appropriate representation to all kinds of vehicles plying on Indian roads.
- Emission factors are based on exhaust emission testing of in-use 2 Wheelers, 3 Wheelers, Passenger Cars, LCVs and HCVs on Chassis dynamometer.
- All emission factors based on Indian Driving cycle for 2-W, 3-W and Pre-2000 4W, while Modified Indian Driving cycle (IDC) was used for testing for post-2000 4W. For comparative purpose, post-2000 4W were also tested on IDC.
- Different inertia settings were used depending on the vehicle category as follows:
    - 2-wheelers: ULW (Unladen Weight) + 75 kg
    - 3-wheelers gasoline: 225 kg (3 passengers × 75)
    - 3-wheeler diesel: Gross Vehicle Weight (GVW)
    - Passenger cars: ULW+225 kg (3 passengers × 75 kg)
    - Multi Utility Vehicles: ULW+450 kg (6 passengers × 75kg)
    - LCV
        - Bus: ULW + 1500 kg (equivalent to 20 passengers of 75 kg weight each)
        - Trucks: GVW (As specified by the vehicle manufacturer)
    - HCV:
        - Bus – ULW + 4500 kg (Equivalent to 60 passengers of 75 kg each)
        - Trucks – GVW (To be limited to 20 ton max. for GVW > 20tons. If GVW is less than 20 tons, Inertia will be set to the maximum specified GVW)

According to ARAI (2007), suggested emission factors were analyzed with regard to vintage effect, fuel effect, and maintenance effect after the test.

ARAI (2007) has given emission factors for 40 vehicles category and subcategory according to their vintage. Because it is difficult to get vehicle population data according to ARAI (2007) emissions factors, vehicle categories have been categorized according to possible data availability. As per data availability, vehicle types are available in two categories; Broad and Fine. In broad category, there are seven types of vehicle data, while in fine category 23 types of vehicle data are available. For getting emission factors according to the broad and fine categories, ARAI emission factor data are averaged according to vehicle types (Table 3.1 and 3.2).

Table 3.1: Emission Factors used for broad category of vehicle data (ARAI, 2007)

		g/km					mg/km					
		CO	**HC**	**NO$_x$**	**CO$_2$**	**PM**	**Benzene**	**1-3 Butadiene**	**Formaldehyde**	**Acetaldehyde**	**Total Aldehyde**	**Total PAH**
Two Wheeler	1991-1996	6.543	3.763	0.078	21.505	0.042	0.006	0.004	0.001	0.005	0.012	0.794
	1997-2000	3.560	2.184	0.086	23.568	0.038	0.001	0.005	0.005	0.006	0.015	0.150
	2001-2005	2.325	1.552	0.220	25.856	0.041	0.005	0.006	0.005	0.001	0.010	0.386
	Post 2005	1.650	0.918	0.195	31.820	0.029	0.005	0.006	0.025	0.016	0.048	0.866
Car/Taxis	1991-1996	4.750	0.840	0.950	95.650	0.008	0.213	0.132	0.018	0.011	0.045	0.158
	1997-2000	2.797	0.538	0.547	134.811	0.069	0.401	0.084	0.020	0.003	0.060	0.119
	2001-2005	1.431	0.259	0.351	140.229	0.035	0.005	0.008	0.007	0.001	0.012	0.126
	Post 2005	0.967	0.216	0.325	144.944	0.030	0.005	0.007	0.023	0.002	0.028	0.102
Three Wheelers	1991-1996	10.233	3.747	0.617	79.750	0.677	0.021	0.006	0.024	0.007	0.040	1.596
	1997-2000	10.233	3.747	0.617	79.750	0.677	0.021	0.006	0.024	0.007	0.040	1.596
	2001-2005	1.470	1.147	0.337	83.752	0.114	0.012	0.006	0.010	0.006	0.020	0.723
	Post 2005	1.283	0.847	0.400	92.303	0.050	0.006	0.007	0.042	0.072	0.158	1.243
Buses	1991-1996	13.060	2.400	11.240	817.520	2.013	0.153	0.031	0.101	0.015	0.126	1.012
	1997-2000	4.480	1.460	15.250	920.770	1.213	0.101	0.009	0.102	0.003	0.119	3.652
	2001-2005	7.930	2.070	8.855	737.250	0.795	0.013	0.002	0.010	0.014	0.046	0.283
	Post 2005	3.920	0.160	6.530	602.010	0.300	0.010	0.010	0.052	0.008	0.146	1.372
Goods	1991-1996	8.287	2.100	6.190	442.783	1.178	0.192	0.011	0.101	0.011	0.149	4.838
	1997-2000	7.893	1.767	5.657	453.430	1.060	0.076	0.097	0.070	0.009	0.128	4.470

		g/km					mg/km					
		CO	**HC**	**NO_x**	**CO_2**	**PM**	**Benzene**	**1-3 Butadiene**	**Formaldehyde**	**Acetaldehyde**	**Total Aldehyde**	**Total PAH**
Vehicle	2001-2005	2.998	0.678	3.625	405.600	0.574	0.055	0.107	0.017	0.003	0.031	3.789
	Post 2005	0.250	0.190	0.670	255.980	0.096	0.268	0.040	0.014	0.008	0.037	0.125
LCV	1991-1996	2.780	1.835	2.365	245.425	0.784	0.278	0.008	0.106	0.006	0.156	4.959
	1997-2000	2.190	1.335	1.565	261.395	0.608	0.104	0.137	0.059	0.004	0.123	4.407
	2001-2005	1.997	0.780	1.733	286.670	0.352	0.071	0.141	0.002	0.004	0.013	3.729
	Post 2005	0.250	0.190	0.670	255.980	0.096	0.268	0.040	0.014	0.008	0.037	0.125
HCV	1991-1996	19.300	2.630	13.840	837.500	1.965	0.020	0.018	0.093	0.020	0.137	4.598
	1997-2000	19.300	2.630	13.840	837.500	1.965	0.020	0.018	0.093	0.020	0.137	4.598
	2001-2005	6.000	0.370	9.300	762.390	1.240	0.005	0.007	0.061	0.020	0.084	3.971
	Post 2005	6.000	0.370	9.300	762.390	1.240	0.005	0.007	0.061	0.020	0.084	3.971

LCV: Light Commercial Vehicle, HCV: Heavy Commercial Vehicle

Table 3.2: Emission Factors used for fine category of vehicle data (ARAI, 2007)

		g/km					mg/km					
		CO	HC	NO_x	CO_2	PM	Benzen	1-3 Butadiene	Formaldehyde	Acetaldehyde	Total Aldehyde	Total PAH
Two Wheeler Scooters 4-S	1991-1996	0.93	0.65	0.35	33.83	0.015	0.0051	0.01680	0.0062	0.0009	0.0087	0.0062
	1997-2000	0.93	0.65	0.35	33.83	0.015	0.0051	0.01680	0.0062	0.0009	0.0087	0.0062
	2001-2005	0.93	0.65	0.35	33.83	0.015	0.0051	0.01680	0.0062	0.0009	0.0087	0.0062
	Post 2005	0.40	0.15	0.25	42.06	0.015	0.0015	0.01280	0.1048	0.0576	0.1716	1.5200
Two Wheeler Scooters 2-S	1991-1996	6.00	3.68	0.02	24.75	0.073	0.0062	0.00420	0.0003	0.0165	0.0309	2.2482
	1997-2000	5.15	2.49	0.03	24.65	0.073	0.0013	0.00445	0.0033	0.0024	0.0092	0.0067
	2001-2005	5.48	2.75	0.03	23.80	0.060	0.0042	0.00308	0.0096	0.0024	0.0162	0.3892
	Post 2005	3.84	2.23	0.02	30.11	0.056	0.0065	0.00763	0.0256	0.0287	0.0693	0.6439
Two Wheeler Motor-cycles 4-S	1991-1996	3.12	0.78	0.23	22.42	0.010	0.0043	0.00210	0.0010	0.0015	0.0053	0.9233
	1997-2000	1.58	0.74	0.30	23.25	0.015	0.0012	0.00300	0.0103	0.0016	0.0173	0.5124
	2001-2005	1.57	0.56	0.41	24.90	0.035	0.0095	0.00600	0.0022	0.0016	0.0061	0.7878
	Post 2005	1.28	0.54	0.32	31.80	0.024	0.0070	0.00453	0.0034	0.0018	0.0077	0.6785
Two Wheeler Motor-cycles 2-S	1991-1996	5.64	2.89	0.04	23.48	0.010	0.0088	0.00820	0.0023	0.0003	0.0081	0.0035
	1997-2000	2.96	2.44	0.05	24.17	0.015	0.0003	0.00780	0.0002	0.0007	0.0010	0.0008
	2001-2005	2.96	2.44	0.05	24.17	0.035	0.0003	0.00780	0.0002	0.0007	0.0010	0.0008
	Post 2005	2.96	2.44	0.05	24.17	0.024	0.0003	0.00780	0.0002	0.0007	0.0010	0.0008
Two Wheeler	1991-1996	0.81	0.50	0.29	20.09	0.010	0.0032	0.00610	0.0000	0.0037	0.0089	0.3373
	1997-2000	0.81	0.50	0.29	20.09	0.010	0.0032	0.00610	0.0000	0.0037	0.0089	0.3373

		g/km					mg/km					
		CO	**HC**	**NO$_x$**	**CO$_2$**	**PM**	**Benzen**	**1-3 Butadiene**	**Formaldehyde**	**Acetaldehyde**	**Total Aldehyde**	**Total PAH**
Mopeds 4-S	2001-2005	0.81	0.50	0.29	20.09	0.010	0.0032	0.00610	0.0000	0.0037	0.0089	0.3373
	Post 2005	0.81	0.50	0.29	20.09	0.010	0.0032	0.00610	0.0000	0.0037	0.0089	0.3373
Two Wheeler	1991-1996	11.41	7.70	0.02	15.37	0.060	0.0035	0.00160	0.0004	0.0000	0.0036	0.0014
Mopeds 2-S	1997-2000	2.96	2.77	0.03	21.13	0.060	0.0020	0.00390	0.0059	0.0231	0.0395	0.2249
	2001-2005	0.45	3.10	0.04	29.69	0.060	0.0008	0.00320	0.0024	0.0010	0.0053	0.0017
	Post 2005	0.46	0.60	0.02	36.81	0.018	0.0008	0.00040	0.0371	0.0071	0.0441	1.7500
Car/Taxi Petrol	1991-1996	4.75	0.84	0.95	95.65	0.008	0.2126	0.13220	0.0181	0.0109	0.0453	0.1577
	1997-2000	4.83	0.58	0.65	98.62	0.020	0.0010	0.00670	0.0013	0.0001	0.0084	0.1862
	2001-2005	2.35	0.21	0.18	131.91	0.005	0.0006	0.00220	0.0051	0.0012	0.0089	0.2305
	Post 2005	1.72	0.18	0.14	141.94	0.004	0.0004	0.00227	0.0024	0.0008	0.0088	0.0926
Car/Taxi CNG	1991-1996	0.85	0.79	0.53	149.36	0.001	0.0005	0.00025	0.0058	0.0017	0.0074	0.0159
	1997-2000	0.85	0.79	0.53	149.36	0.001	0.0005	0.00025	0.0058	0.0017	0.0074	0.0159
	2001-2005	0.33	0.41	0.38	137.37	0.004	0.0005	0.00025	0.0058	0.0017	0.0074	0.0159
	Post 2005	0.33	0.41	0.38	137.37	0.004	0.0005	0.00025	0.0058	0.0017	0.0074	0.0159
Car/Taxi LPG	1991-1996	6.78	0.85	0.50	130.85	0.001	0.0040	0.00620	0.0145	0.0101	0.0245	0.0600
	1997-2000	6.78	0.85	0.50	130.85	0.001	0.0040	0.00620	0.0145	0.0101	0.0245	0.0600
	2001-2005	2.72	0.23	0.20	140.05	0.002	0.0006	0.00160	0.0005	0.0011	0.0021	0.0247
	Post 2005	2.72	0.23	0.20	140.05	0.002	0.0006	0.00160	0.0005	0.0011	0.0021	0.0247
Car/Taxi	1991-1996	0.77	0.24	0.53	147.62	0.163	0.7997	0.16250	0.0331	0.0004	0.1029	0.1157

		g/km					mg/km					
		CO	HC	NO_x	CO_2	PM	Benzen	1-3 Butadiene	Formaldehyde	Acetaldehyde	Total Aldehyde	Total PAH
Diesel	1997-2000	0.77	0.24	0.53	147.62	0.163	0.7997	0.16250	0.0331	0.0004	0.1029	0.1157
	2001-2005	0.51	0.20	0.67	155.66	0.125	0.0198	0.02765	0.0157	0.0018	0.0277	0.1301
	Post 2005	0.29	0.14	0.47	152.21	0.070	0.0108	0.01418	0.0523	0.0026	0.0599	0.1705
Three Wheeler Petrol 4-S	1991-1996	1.97	0.84	0.40	62.69	0.030	0.0036	0.00320	0.0062	0.0012	0.0224	0.5140
	1997-2000	1.97	0.84	0.40	62.69	0.030	0.0036	0.00320	0.0062	0.0012	0.0224	0.5140
	2001-2005	1.97	0.84	0.40	62.69	0.030	0.0036	0.00320	0.0062	0.0012	0.0224	0.5140
	Post 2005	2.29	0.77	0.53	73.80	0.015	0.0006	0.00040	0.0132	0.0125	0.0609	0.4954
Three Wheeler Petrol 2-S	1991-1996	3.15	6.04	0.30	54.50	0.110	0.0062	0.00480	0.0426	0.0110	0.0623	2.9760
	1997-2000	3.15	6.04	0.30	54.50	0.110	0.0062	0.00480	0.0426	0.0110	0.0623	2.9760
	2001-2005	1.37	2.53	0.20	62.41	0.045	0.0026	0.00380	0.0162	0.0175	0.0362	1.9610
	Post 2005	1.15	1.63	0.16	71.50	0.043	0.0053	0.00800	0.1054	0.1979	0.3954	2.0500
Three Wheeler CNG 4-S	1991-1996	1.00	0.26	0.50	77.70	0.015	0.0359	0.00420	0.0072	0.0012	0.0085	0.4035
	1997-2000	1.00	0.26	0.50	77.70	0.015	0.0359	0.00420	0.0072	0.0012	0.0085	0.4035
	2001-2005	1.00	0.26	0.50	77.70	0.015	0.0359	0.00420	0.0072	0.0012	0.0085	0.4035
	Post 2005	1.00	0.26	0.50	77.70	0.015	0.0359	0.00420	0.0072	0.0012	0.0085	0.4035
Three Wheeler CNG 2-S	1991-1996	0.69	2.06	0.19	57.71	0.118	0.0049	0.00610	0.0051	0.0071	0.0149	0.3237
	1997-2000	0.69	2.06	0.19	57.71	0.118	0.0049	0.00610	0.0051	0.0071	0.0149	0.3237
	2001-2005	0.69	2.06	0.19	57.71	0.118	0.0049	0.00610	0.0051	0.0071	0.0149	0.3237
	Post 2005	0.69	2.06	0.19	57.71	0.118	0.0049	0.00610	0.0051	0.0071	0.0149	0.3237

		g/km					mg/km					
		CO	HC	NO_x	CO_2	PM	Benzen	1-3 Butadiene	Formaldehyde	Acetaldehyde	Total Aldehyde	Total PAH
Three Wheeler LPG 4-S	1991-1996	4.39	3.60	0.08	54.57	0.721	0.0269	0.01130	0.0022	0.0072	0.0097	0.6315
	1997-2000	4.39	3.60	0.08	54.57	0.721	0.0269	0.01130	0.0022	0.0072	0.0097	0.6315
	2001-2005	1.70	1.03	0.04	68.15	0.130	0.0057	0.01690	0.0075	0.0040	0.0142	0.3358
	Post 2005	1.70	1.03	0.04	68.15	0.130	0.0057	0.01690	0.0075	0.0040	0.0142	0.3358
Three Wheeler LPG 2-S	1991-1996	4.39	3.60	0.08	54.57	0.721	0.0269	0.01130	0.0022	0.0072	0.0097	0.6315
	1997-2000	4.39	3.60	0.08	54.57	0.721	0.0269	0.01130	0.0022	0.0072	0.0097	0.6315
	2001-2005	1.70	1.03	0.04	68.15	0.130	0.0057	0.01690	0.0075	0.0040	0.0142	0.3358
	Post 2005	1.70	1.03	0.04	68.15	0.130	0.0057	0.01690	0.0075	0.0040	0.0142	0.3358
Three Wheeler Diesel	1991-1996	23.16	1.60	1.47	130.18	1.199	0.0293	0.00130	0.0261	0.0025	0.0481	1.1796
	1997-2000	23.16	1.60	1.47	130.18	1.199	0.0293	0.00130	0.0261	0.0025	0.0481	1.1796
	2001-2005	2.09	0.16	0.69	173.85	0.347	0.0175	0.00140	0.0155	0.0048	0.0233	0.7989
	Post 2005	0.41	0.14	0.51	131.61	0.091	0.0123	0.01120	0.0072	0.0057	0.0169	1.1847
Bus Diesel	1991-1996	13.06	2.40	11.24	817.52	2.013	0.1529	0.03130	0.1007	0.0148	0.1259	1.0123
	1997-2000	4.48	1.46	15.25	920.77	1.213	0.1008	0.00930	0.1015	0.0029	0.1191	3.6515
	2001-2005	12.14	0.39	11.50	668.00	0.795	0.0126	0.00170	0.0104	0.0136	0.0458	0.2833
	Post 2005	3.92	0.16	6.53	602.01	0.300	0.0101	0.00960	0.0523	0.0082	0.1458	1.3715
Bus CNG	1991-1996	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
	1997-2000	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
	2001-2005	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA

		g/km					mg/km					
		CO	HC	NO$_x$	CO$_2$	PM	Benzen	1-3 Butadiene	Formaldehyde	Acetaldehyde	Total Aldehyde	Total PAH
	Post 2005	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
LCV Diesel	1991-1996	3.07	2.28	3.03	327.29	0.998	0.5427	0.00940	0.1975	0.0117	0.2957	8.1284
	1997-2000	3.00	1.28	2.48	333.31	0.655	0.2015	0.21470	0.1176	0.0059	0.2169	3.7742
	2001-2005	3.66	1.35	2.12	401.25	0.475	0.1959	0.41540	0.0028	0.0083	0.0222	8.2679
	Post 2005	3.66	1.35	2.12	401.25	0.475	0.1959	0.41540	0.0028	0.0083	0.0222	8.2679
LCV CNG	1991-1996	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
	1997-2000	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
	2001-2005	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
	Post 2005	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
HCV Diesel	1991-1996	19.30	2.63	13.84	837.50	1.965	0.0199	0.01750	0.0925	0.0197	0.1374	4.5975
	1997-2000	19.30	2.63	13.84	837.50	1.965	0.0199	0.01750	0.0925	0.0197	0.1374	4.5975
	2001-2005	6.00	0.37	9.30	762.39	1.240	0.0049	0.00740	0.0610	0.0000	0.0837	3.9707
	Post 2005	6.00	0.37	9.30	762.39	1.240	0.0049	0.00740	0.0610	0.0000	0.0837	3.9707
HCV CNG	1991-1996	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
	1997-2000	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
	2001-2005	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA
	Post 2005	3.72	3.75	6.21	806.50	0.002	0.0006	0.00001	0.0069	0.0007	NA	NA

LCV: Light Commercial Vehicle, HCV: Heavy Commercial Vehicle

3.7. CORRECTION FACTORS

The emission estimation process of VAPI model is based on applying emission factors with two correction factors; namely, climatic (Temperature, Humidity) and one geographical (Altitude). Correction factors data are derived from International Vehicular Emission Model (IVEM, 2008). Correction factors are selected according to the vehicle types and their vintage. IVE model has given correction factor data according to three vehicle kilometer travel (VKT) categories, which are <25000 km, 26000 to 50000 km, and >50000 km for two wheelers and three wheeler, and <79000 km, 800000 to 161000 km and >1610000 km for other vehicles. It is observed from IVE model correction factors data that all three VKT category wise correction factors are similar. We have, therefore, taken data of correction factors according to vehicle types given in broad and fine categories.

3.7.1. Temperature

IVE model has given temperature correction factor for CO, NO_x, 1-3 Butadiene, Formaldehyde and Acetaldehyde at low temperature (4°C) and high temperature (40°C). Temperature correction factor data is selected according to vehicle types. Some correction factor data are similar for two or three vehicle types, hence similar correction factor data is used according to IVE model. For calculation of correction factor for ambient temperature, simple linear growth has been calculated between low and high temperature (Equation 3.9) and correction factors are calculated according to that growth rate (Equation 3.10).

$$C_{TG} = \left[\left(\frac{C_{tHigh}}{C_{tLow}}\right)^{\frac{1}{(tHigh-tLow)}} - 1\right] \times 100 \qquad (3.9)$$

$$C_T = C_{tLow} \times (1 + C_{TG})^{(tT-tLow)} \qquad (3.10)$$

C_{TG} =Growth rate of correction factor according to low and high temperature

C_{tHigh} = Correction factor in high temperature (40 °C)

C_{tLow} = Correction factor at low temperature (4°C)

tHigh = High Temperature (40 °C)

tLow = Low temperature (4°C)

C_T = Correction factor at ambient temperature

tT = Ambient temperature

3.7.2. Humidity

Humidity correction factor data are also available for pollutants like CO, NO_x, 1-3 Butadiene, Formaldehyde and Acetaldehyde at 20% and 80% humidity. For getting the correction factors according to ambient humidity, growth rate has been obtained between 20% and 80% humidity by Equation 3.11. Based on obtained growth rate correction factor has been calculated for ambient humidity using Equation 3.12.

$$C_{hG} = \left[\left(\frac{C_{h80\%}}{C_{h20\%}}\right)^{\frac{1}{(80-20)}} - 1\right] \times 100 \qquad (3.11)$$

$$C_h = C_{h20\%} \times (1 + C_{hG})^{(h-20)} \qquad (3.12)$$

C_{hG} =Growth rate of correction factor according to 20% and 80% humidity

$C_{h80\%}$= Correction factor at 80% humidity

$C_{h20\%}$ = Correction factor at 20% humidity

C_h = Correction factor at ambient humidity

h = Ambient humidity

3.7.3. Altitude

Altitude correction factor data are also available for CO, NO_x, 1-3 Butadiene, Formaldehyde and Acetaldehyde at 950 m and 1700 m (as given by IVE model). For getting impact of altitude on vehicular emissions, growth rate of correction factor have been calculated between 950 m and 1700 m (Equation 3.13). After obtaining growth rate, correction factor have been calculated for altitude of the area (Equation 3.14).

$$C_{AG} = \left[\left(\frac{C_{a1700m}}{C_{a950m}} \right)^{\frac{1}{(1700-950)}} - 1 \right] \times 100 \quad (3.13)$$

$$C_a = C_{a950m} \times (1 + C_{AG})^{(a-950)} \quad (3.14)$$

C_{aG} =Growth rate of correction factor according to 950 m and 1700m

C_{a1700m} = Correction factor at 1700 m altitude

C_{a950} = Correction factor at 950 m altitude

C_a = Correction factor at a altitude

a = altitude

3.8. BASE LINE METHODOLOGY

3.8.1. Vehicle Population

India has one time vehicular registration system; hence it is very hard to find out actual on-road vehicle population. Keeping this point in mind, VAPI model has been designed to calculate on-road vehicular population based on the phasing out age and annual registration of vehicles. In VAPI model, on-road vehicular population and projection have been calculated based on the steps described below:

3.8.1.1. Present and Past Registered Vehicles

For getting on-road vehicle population from registered vehicle, registered vehicle population have been projected for past year by using Equation (3.15, 3.16). After getting past year registered vehicle population on-road vehicle population have been calculated by using Equation (3.17).

$$x_{Pi} = \left[\left(\frac{RPi_{Final}}{RPi_{Initial\,Pi}} \right)^{\frac{1}{t}} - 1 \right] \times 100 \qquad (3.15)$$

x_{pi} : Average geometric rate of annual growth of population of i vehicle category

$RPi_{\text{Initial pi}}$: Registered population of i vehicle category at the initial year of the period

$RPi_{\text{Final pi}}$: Registered population of i vehicle category at the final year of the period

t : Length of time (years) between the initial year and final

$$RPi_{Final} = RPi_{Initial\,Pi} \times \left(1 + x_{pi}\right)^{t} \qquad (3.16)$$

$$O_{Rpi} = RP_{Ci} - RP_{(C-Z)i} \qquad (3.17)$$

O_{Rpi} = On-road of population of i vehicle category

RP_{Ci} = Registered population of i vehicle category at current year c

$RP_{(C-Z)i}$ = Registered population of i vehicle category, in current year minus phasing out age of vehicle where Z is the phasing out age of vehicle.

3.8.1.2. Vehicle Population Projection

The demand of vehicle ownership largely depends on gross domestic product (GDP) and per capita income (PCI) of the area (Singh, 2006a). Schafer (1998), Dargay and Gately (1999), Schafer and Victor (2000), Preston (2001) and many other researchers have shown that there is a close relationship between GDP/PCI and demand for vehicles (Singh, 2006b). The relationship between the growth of vehicle ownership and GDP/PCI is highly non-linear (Dargay et al., 2007). If we plot level of vehicle population per capita against GDP/PCI, the graph is expected to look like an *S*-shaped curve. Vehicle population is expected to increase slowly at the lowest income levels, and then more rapidly as income rises, finally slows down as saturation level approaches (Dargay et al. ,2007; Singh, 2006a). There are many functional forms that can describe such a process, for example, the logistic, logarithmic logistic, cumulative normal, and Gompertz functions (Dargay et al., 2007). Among various functional forms, logistic and

Gompertz functions are the two most widely used ones to describe a process represented by an *S*-shaped curve. It was observed from various studies (Dargay and Gately, 1999; Singh, 2006; Dargay et al., 2007) that Gompertz model is more suitable for projecting future vehicle population, because it is relatively easy to estimate and is more flexible than the logistic model.

Letting V_{pt} denote the long-run equilibrium level of vehicle ownership (vehicles per 1000 people) and letting G denote GDP or PCI. The Gompertz model can be written as:

$$V_{pt} = \lambda e^{\alpha e^{\beta G}} \tag{3.18}$$

where λ is the saturation level (measured in vehicles per 1000 people), G is GDP or per capita income and α (slope) and β (Intercept) are parameters, which define the shape or curvature of the function. The parameter values α and β are calculated by Equation 3.19 and 3.20 (Brown, 2001).

$$\alpha = \frac{n(\sum GP_{it})-(\sum G)(\sum P_{it})}{n(\sum(G^2)-(\sum G)^2} \tag{3.19}$$

$$\beta = \frac{(\sum P_{it})(\sum(G^2))-(\sum x)(\sum GP_{it})}{n(\sum(G^2)-(\sum G)^2} \tag{3.20}$$

Where

G = GDP for commercial and public transport and PCI for private vehicle
Pit = Per thousand vehicle population of i category of vehicle in particular year (t)
n = years for calculating

After this, for analyzing data using a curve fitting protocol it is necessary to determine the goodness of fit. Essentially this means estimating how well the curve describes the data. The most commonly used measure of the goodness of fit is least squares. Basic principal behind it is the magnitude of difference between data points and the curve is a good measure of how well the curve fits data (Brown, 2001). The least squares fitting method squares the residual value to eliminate the effects of positive or negative deviation from the fit (Equation 3.21) (Brown, 2001).

$$SS = \sum_{i=1}^{n}(Pit - Pitfit)^2 \qquad (3.21)$$

Where, *Pit* is per thousand vehicle of i category's data point, *Pit*fit is the value of the curve at point *Pit*, and SS is the sum of squares. The best fit of the data is the linear function that has smallest value for the squared sum (SS) of all differences.

3.8.2. Vehicle Vintage wise Calculation

Because emission factors and correction factors are based on vehicle vintage or model year (like 1991-1996, 1997-2000, 2001-2005 and post-2005) hence it is necessary to calculate vehicle vintage wise population. It is very difficult to estimate vintage wise vehicle population in particular year from calculated on-road vehicle population due to phasing out of vehicle population. To resolve these problems, percentage of vintage wise vehicles has been obtained from registered vehicle population data and applied it to on-road vehicle population. Following steps have been carried out to calculate model wise vehicle population in VAPI model:

In the first step, vehicle population is projected for past and future vehicles by simple growth rate formula (Equation 3.15, 3.16). After getting registered vehicles for all year, each year registered vehicle population are calculated by Equations (3.22)

$$P_{myi} = P_{fi} - P_{pi} \qquad (3.22)$$

Where

Pmyi = Each year newly registered (model wise) population of i category vehicle

Pfi = Population of i category vehicle in current year

Ppi = Population of i category vehicle in previous (current year-1) years

After getting each year newly registered vehicle population, population of vehicle with respect to their vintage and their phasing out age have been distributed to each year (like in 2005 vehicle population, number of 2004, 2003, 2002 vintage vehicle population). After getting vehicle population according to their models or vintage in each year, percentage of various models present in each year vehicle population have been calculated by Equation (3.23)

$$\%RP_{yi} = \frac{RP_{yi} \times 100}{RP_{Ci}} \qquad (3.23)$$

% Rpyi = Vintage/Model year wise percentage of population of i category vehicle in each year
Rpyi = Registered model year wise population of i category vehicle in each year

After getting percentage of vintage wise vehicle population for registered vehicle population in each year this percentage is applied for on-road vehicles by using Equation (3.24).

$$O_{Ryi} = \frac{O_{Rpi} * \%RP_{iy}}{100} \qquad (3.24)$$

Oryi = On-road model year wise population of i category vehicle in each year

3.8.3. Evaporative Emissions

The vehicular evaporative emissions are found to be the largest contributor to total evaporative emissions of VOCs. Running losses from petrol driven vehicles dominate the evaporative emissions with respect to other sources (e.g. hot soak emission, diurnal emissions, and resting losses) (Srivastava and Majumdar, 2010). Running losses are the result of vapor generated in gasoline tanks during vehicle operation, which are most significant during periods of high ambient temperatures. The combined effect of high ambient temperature and exhaust system heat can generate a significant amount of vapor in the gasoline tank (Ahlvik et al., 1997). VAPI model can give running losses evaporative emissions. VAPI model calculate evaporative adjusted emission factor by using Equation 3.25 while total emissions are estimated by Equation 3.8 (discussed in section 3.6).

$$E_{api} = EF_{pi} \times C_{tpi} \times C_{api} \qquad (3.25)$$

3.8.3.1. Emission Factor

Due to scarcity of country specific data, emission factors of IVE model have been incorporated in VAPI model for estimating evaporative emissions.

Table 3.3: Evaporative emission factor (g/km)

Two Wheeler	Car (Petrol/CNG)	Three Wheeler (Petrol/CNG)	Bus/LCV/HCV (CNG)
0.029753486	0.029939445	0.029753486	0.263286699

Source: IVEM 2004

3.8.3.2. Correction Factors

For calculating evaporative emissions from petrol and CNG driven vehicles, correction factors are taken from IVE model. IVE model has given only two local correction factors (altitude, humidity) for evaporative emissions. Equations (3.9, 3.10, 3.13 and 3.14) have been used to calculate correction factors according to local conditions (e.g. altitude, temperature).

3.8.4. Non Exhaust Emissions

Non-exhaust PM from road traffic is generated mechanically by abrasion (wear) of tyre, brake, and road pavement and by the re-suspension process of road dust (Baidya, 2008). Various researchers have suggested that non-exhaust emissions are dominant contributor to total PM_{10} and $PM_{2.5}$ emissions from road transportation (Abu-Allaban et al., 2003; Gaffney et al., 1995; Zimmer et al., 1992; CEPMEIP, 2003; Lenschow et al., 2001). Country specific emission factors are not available for estimating non-exhaust emissions. Also, very less number of non-exhaust factors are available for the USA and European countries. Due to scarcity of country specific emission factors, the USA based emission factors (Table 2.4) are used for calculating non-exhaust emissions in VAPI model. There is very less impact of external factors on non-exhaust emissions. Because of unavailability of correction factors for non-exhaust emissions, VAPI model uses following simple formula for calculating emissions (Equation 3.26).

$$E_{tpi} = P_i \times E_{pi} \times V_i \times D_{ti} \qquad (3.26)$$

D_{ti} = Annual traveling days of i vehicle category in year t
EF_{pi} = Emissions factor of pollutant p from i vehicle category
EF_{tpi} = Total emissions of pollutant p from i vehicle category in year t
P_i = Population of i vehicle category
V_i = Per day distance travel by i vehicle category

Table 3.4: Emission factors (mg/km) for non-exhaust emissions from vehicles

	2W	Car	3W	LCV	HCV	Source
			Road dust suspension			
PM_{10}	67	168	100	168	1263	Abu-Allaban et al., 2003
$PM_{2.5}$	2.7	6.8	4.1	6.8	46.1	Abu-Allaban et al., 2003
			Tyre wear			
PM_{10}	2.4	5.9	3.5	5.9	5.9	Granell et al., 2005
$PM_{2.5}$	0.6	1.5	0.9	1.5	1.5	Granell et al., 2005
			Brake wear			
PM_{10}	4.8	12	7.2	12	93	Abu-Allaban et al., 2003
$PM_{2.5}$	0.4	1	0.6	1	1.5	Abu-Allaban et al., 2003

Secondary Sources: Baidya, 2008

3.9. INPUT VARIABLES FOR MODEL

3.9.1. Vehicle Types

For calculation of vehicular emissions, most of the emission models require vehicle and/or vehicular population information in detail (e.g. vehicle vintage, vehicle technology, emission control, model, fuel used etc.). In a developing country like India it is very difficult to obtain simple vehicle population data for any city because of existing vehicle registration system and poor data management. Considering above points, VAPI model estimates emissions based on two types of vehicle population categories (i.e., broad and fine) according to available data in India.

3.9.1.1. *Broad Categories*

This is the simplest category of vehicle population input data. In India vehicle population data for most of the cities are available in this format only. Vehicle population is divided in seven categories of vehicle types (Table 3.5). VAPI model can estimate emissions from vehicles if user provides simplest broad category of vehicle population data.

Table 3.5: Vehicle types in broad input category

1	2	3	4	5	6	7
Two Wheeler	Car/Taxis	Three Wheelers	Buses	Goods Vehicle	LCV	HCV

3.9.1.2. *Fine Categories*

A fine category of vehicle population includes vehicles type and their subtypes. In India, data according to this category is very hard to find in most of the cities. In this category, 23 types of vehicles are available, which are sub categorized to eight main types of vehicles (Table 2.6).

Table 3.6: Vehicle types in fine vehicle category

Two Wheeler	Car/Taxi	Three Wheelers	Bus	LCV	HCV
Scooters	7. Petrol	Petrol	18.Diesel	20.Diesel	22.Diesel
1.4-S	8. CNG	11.4-S	19.CNG	21.CNG	23.CNG
2. 2-S	9. LPG	12.2-S			
Motor-cycles	10.Diesel	CNG			
3.4-S		13.4-S			
4.2-S		14.2-S			
Mopeds		LPG			
5.4-S		15.4-S			
6.2-S		16.2-S			
		17.Diesel			

3.9.2. GDP/PCI

This is the second input variable for the model, because model estimates future vehicle population based on GDP and PCI. Commercial and public transport vehicle population is calculated according to GDP; while private vehicle population is calculated based on PCI. VAPI model required present and future GDP and PCI data for estimating future vehicle population.

3.9.3. Phasing-Out Age of Vehicle

In India, vehicle population data is available in cumulative registration form but not in on-road form. For getting on-road vehicle population, VAPI needs phasing out age of vehicles. Based on the phasing out age of vehicle, VAPI model automatically calculates on-road vehicle population and model year of the vehicles. There are eight types of vehicles for which user has to provide the phasing-out age of vehicle (Table 3.7).

Table 3.7: Vehicle types for giving phasing out of vehicle age

Two Wheeler	Car	Taxis	Three Wheelers	Buses	Goods Vehicle	LCV	HCV

3.9.4. Population

For estimating future vehicle population, VAPI model needs population of the city for all the study years. Based on given population, VAPI model calculates per 1000 vehicles population and according to per 1000 vehicle population it also calculates future vehicle population.

3.9.5. Saturation Level

This is the maximum vehicle ownership level. Model calculates future vehicle population based on Gompertz function. Gompertz function requires per thousand saturation level of various vehicle types.

3.9.6. Vehicle Kilometer Travel (VKT)

For estimating emissions, VAPI model requires per day vehicle kilometer travel data.

3.9.7. Temperature/Humidity/Altitude

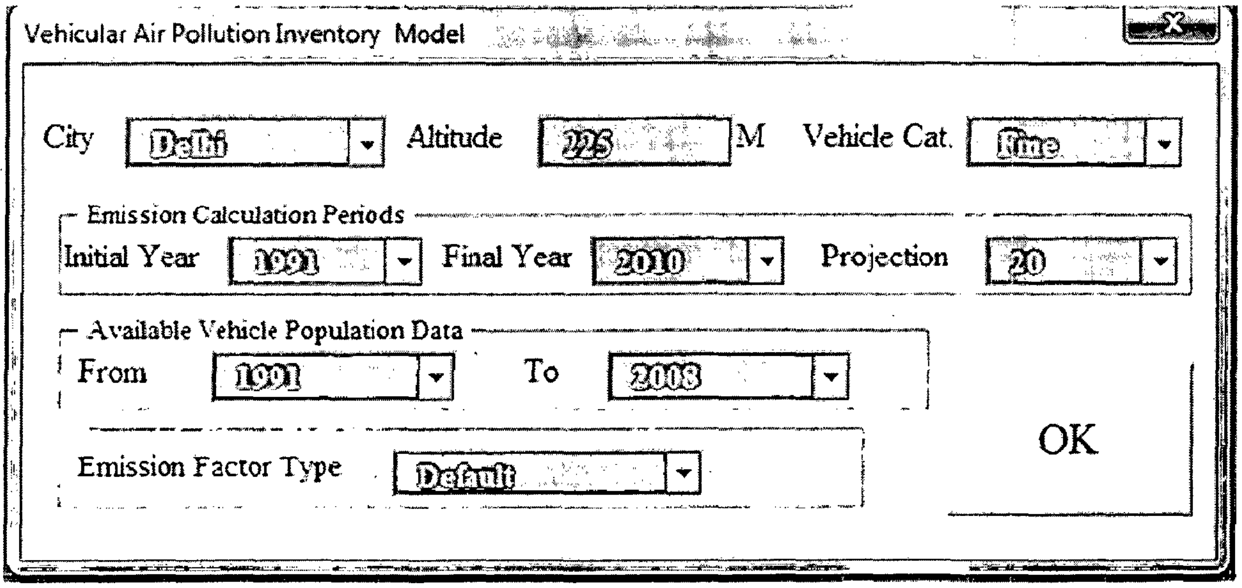
Because VAPI model estimates emissions on the bases of correction factors of temperature, humidity and altitude, hence it is required to give the value of these parameters for all the study years.

3.10. LIMITATIONS OF VAPI MODEL

1. Speed related correction factor is not used in the model.
2. Model needs cumulative registered vehicle population for calculation.
3. Model estimates emission from 1991 to 2030 only.
4. User should not give 0 values in the first three and last three input rows because it gives wrong results.
5. Only two climatic and one geographical correction factor is considered in the model.
6. Less categories of vehicle population are available in the model which restricts its use at the international level.

Initial Input Form:

For calculating emissions VAPI model requires the basic data in one form (Fig. 3.1)



City: Delhi
Altitude: 225 M
Vehicle Cat.: Time

Emission Calculation Periods
Initial Year: 1991
Final Year: 2010
Projection: 20

Available Vehicle Population Data
From: 1991
To: 2008

Emission Factor Type: Default

Fig. 3.2: Initial input form of VAPI model.

3.11. CONCLUSION

A straightforward spreadsheet method, the Vehicular Air Pollution Inventory (VAPI) Model has been proposed in this chapter and applied in Chapters 4, 5 and 6. It aims to calculate emissions of various pollutants from road transport in the urban areas of India. Three correction factors, two climatic (humidity, temperature) and one geographic (altitude) have been used in VAPI model to make emission estimations more realistic. Importance of these correction factors is illustrated in Chapter 4. In present study past, present and future emission inventory of on-road vehicles of megacity Delhi have also been developed in Chapter 5 and 6.

CHAPTER 4

Impact of Altitude on Emissions of Criteria (CO, NO_x) and Hazardous (1-3 Butadiene, Formaldehyde, Acetaldehyde) Pollutants from Vehicles

4.1. INTRODUCTION

Transport sector is one of the major anthropogenic sources of criteria (e.g., CO, HC) and hazardous (e.g., 1-3 Butadiene, Formaldehyde, Acetaldehyde) air pollutants (Gao, 2007; Matthes et al., 2005; Jiang and Fast, 2004). Vehicular emissions depend on several factors such as type of fuel, driving cycle, engine technologies as well as on topography and climatic conditions (e.g., altitude, humidity, temperature). Altitude influences the driving pattern and affect the load and pressure conditions inside internal combustion engines that in turn result in altitude–induced changes in vehicular emission characteristics (Nagpure et al., 2011).

To understand the impact of altitude on vehicular emissions in Indian cities, Delhi, Dehradun and Mussoorie were selected for this study as these cities have distinct geographical and meteorological characteristics (see Section 4.2). Delhi is a low altitude megacity with plain topography, while both Dehradun and Mussoorie are high altitude cities and prominent tourist destinations in Uttrakhand, India. A large number of tourists travel to these cities, which generally peaks during weekends. Since traffic emissions are a large source of ozone precursor gases (like CO, HC, 1-3 Butadiene, Formaldehyde and Acetaldehyde) (Jiang and Fast, 2004) and the photochemical production of surface or tropospheric ozone is also dependent on topographical, meteorological and climatological conditions, it is important to examine the impact of altitude on vehicular emissions. Few groups have studied the effects of altitude on tailpipe emissions from heavy–duty road vehicles (Bishop et al., 2001) or fuel cell buses (Spiegel et al., 1999). However, there is rarely a study available in the literature, which considers influence of altitude on emissions from Indian vehicles.

The first aim of this study is to estimate the emission rates of CO, HC, 1-3 Butadiene, Formaldehyde and Acetaldehyde from various vehicle categories using Vehicular Air Pollution Inventory (VAPI) model, which is briefly described in Chapter 3. The other aim of the study is to investigate the influence of altitude and meteorology on pollutants emitted from vehicles.

Findings of this study would help air quality control authorities to design future mitigation strategies for vehicle-emitted pollutants. It also presents an approach to assess and evaluate the emission rates in different geographical and climatic conditions. It may also serve as a tool to estimate vehicular emissions with respect to local topography and meteorological conditions.

4.2. STUDY AREAS

The present study focuses on Delhi, Dehradun and Mussoorie. Monthly variation of temperature and humidity in Delhi, Dehradun and Mussoorie are illustrated in Fig. 4.1 (a and b). Delhi is located between 28° 24' 17" to 28° 53' 00" North and 76 ° 50' 24" to 77 ° 20' 37" East in northern part of India at an elevation of 225 m above the mean sea level (MSL). The population of Delhi in 2009 was 19 million (projected based on data taken from Census of India, 2001). As seen in Fig. 4.1a, it has a semi-arid climate with high variation between summer and winter temperatures.

Dehradun (30° 19' 0" latitude and 78° 2' 0" longitude) is situated on the south of Shiwalik range of Himalayas at an elevation of 682 m above MSL. Population of Dehradun in 2009 was about 1.5 million (projected based on Census of India, 2001). Besides, Dehradun also experiences a floating tourist population of about 12 million per year (NIUA, 2007). The average monthly maximum and minimum temperature ranges between 27 °C and 11 °C (Fig. 4.1a).

Mussoorie (30° 27' 43" latitude and 78° 04' 15" longitude) is a highly crowded hill station in Uttarakhand, located on the lower Himalayan ranges with a mean altitude of 1826 m. Population of Mussoorie in 2009 was about 27 thousand (projected based on Census of India 2001). It experiences a floating tourist population of about 3.8 million per year. Mussoorie has a cool climate from April to October (temperature ranging between 6.5 °C and 21.6 °C), with monsoon showering between June and August. Temperature is generally moderate from September to November and snowfall is usually observed in January. The average monthly maximum and minimum temperature ranges between 22 °C and 6 °C (Fig. 4.1a, 4.1b).

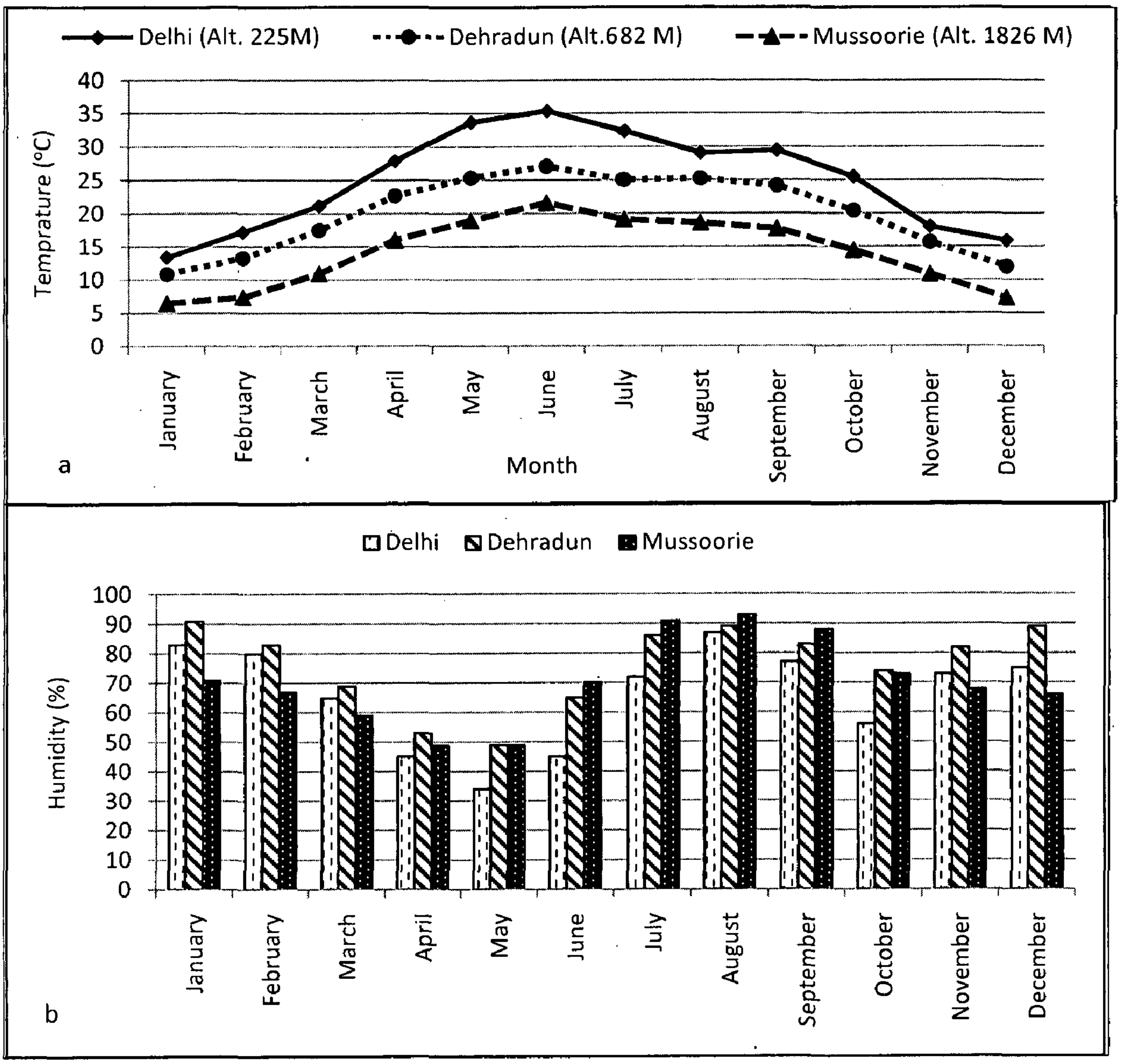


Fig. 4.1: Monthly average (a) temperature and (b) humidity trends in Delhi, Dehradun and Mussoorie over the year (Data for Delhi, Dehradun and Mussoorie is taken from: DSA (2006), NIC (2009) and Singh (1995)

4.3. ESTIMATION OF EMISSION RATES FROM VEHICLES

Emission rates of CO, HC, 1-3 Butadiene, Formaldehyde, and Acetaldehyde from various vehicle categories in all selected cities were estimated using Vehicular Air Pollution Inventory (VAPI) model using country based emission factors (ARAI, 2007). Post-2005 emission factors have been used for estimating emissions of above mentioned pollutants for all three cities. For getting emissions from various vehicles, per day average vehicle kilometer travels (VKT) in each city have been used in VAPI model (Table 4.1).

Table 4.1: Per day mileage (km) for different categories of Vehicles

Vehicle type	VKT (km/day)
2-wheelers	27
3-wheelers	110
Passenger cars	41
Taxis	82
Multi utility vehicles	101
Buses	164
LCVs*	110
HCVs**	82

*Light Commercial Vehicles, **Heavy Commercial Vehicles

4.4. RESULTS AND DISCUSSION

4.4.1. CO emissions

4.4.1.1. Two Wheelers

Fig. 4.2a illustrates monthly variation in emission rates of CO in Delhi, Dehradun and Mussoorie from two wheelers; whereas, Fig. 4.1a shows monthly variation in temperature. Both figures show similar trend i.e. increased emission rates of CO with increasing monthly average temperature. High emission rates of CO were observed in June, while the lowest emission rate was observed in January which is the coldest month at all three locations (Fig. 4.1a and 4.2a). One possible reason for high CO emission rates in two wheelers during summer months could be higher vaporization of fuel due to the use of carburetor air/fuel control.

Fig. 4.2b shows annual CO emissions from two wheelers to be 2035, 2181 and 3805 kg/yr respectively in Delhi, Dehradun and Mussoorie. This also illustrates gradual increase in CO emissions along with rising altitude. Possible reason could be the gradual decrease in oxygen concentrations with increasing altitude that may lead to incomplete combustion of fuel (USDE, 2006) and consequently higher release of CO emissions. It should be noted that emission calculation is based on the assumption of having the same distance travelled per day (27 km/day) by all two wheelers in each of the city. Fig. 4.2c shows the estimated emission rates (g/km) in Delhi, Dehradun and Mussoorie. Two-stroke scooters emits higher CO in all three cities, followed by two- and four-stroke motorcycles, while four-stroke scooters and two-stroke mopeds are least CO emitters among all two wheelers category. In case of two wheelers VAPI model suggests that if people prefer four-stroke scooters and two-stroke mopeds for traveling rather than other types of two wheelers, the resulting emissions will be lower.

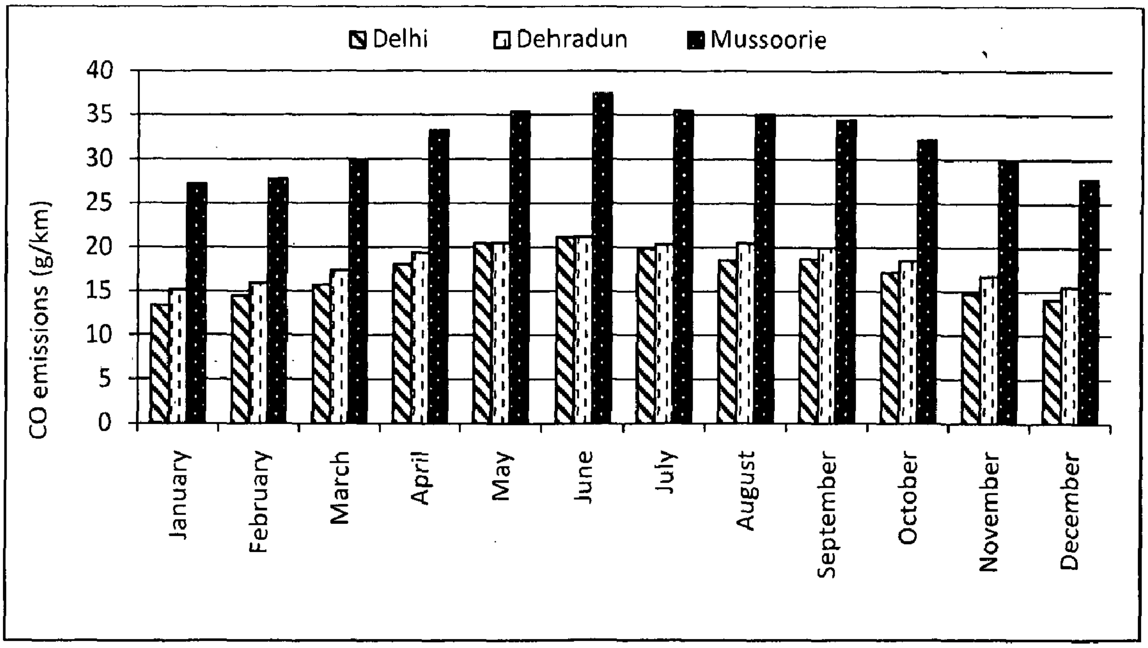


Fig. 4.2 (a): Monthly CO emissions rate from two wheelers in Delhi, Dehradun and Mussoorie

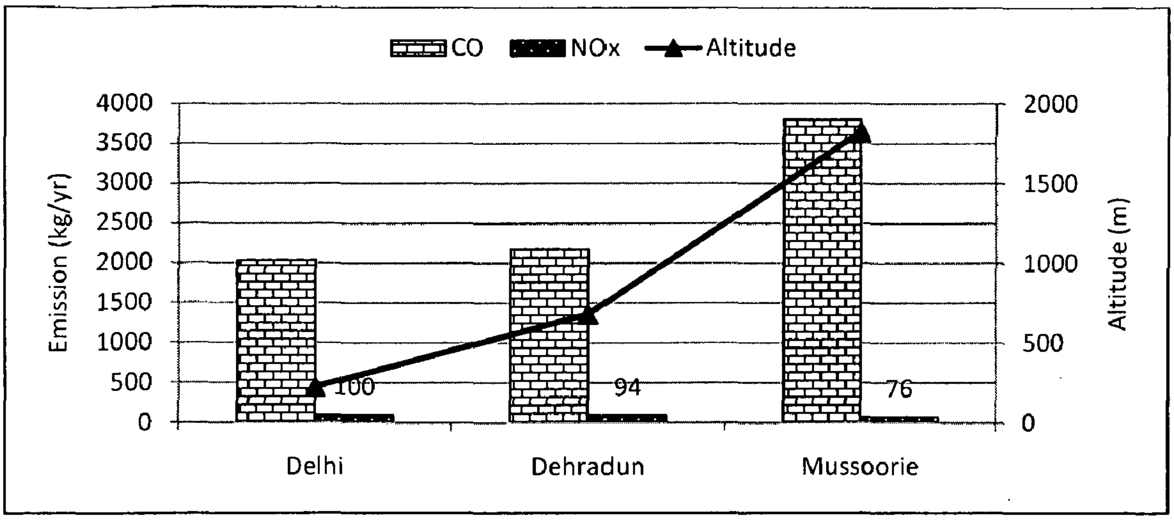


Fig. 4.2 (b): Annual emissions (kg/yr) of CO, NO_x per two wheeler in Delhi, Dehradun and Mussoorie

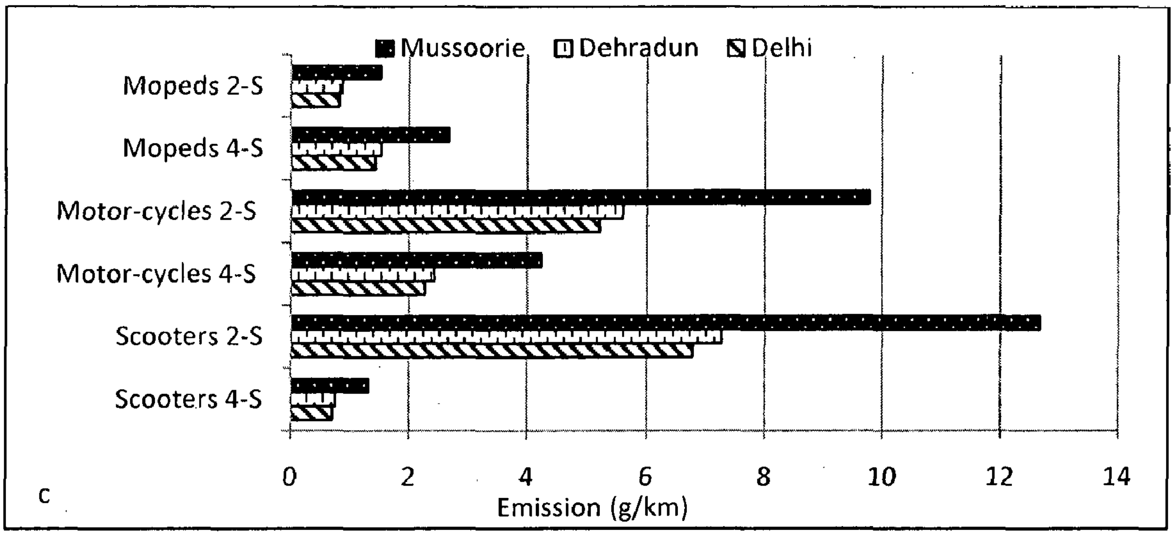


Fig. 4.2 (c): Estimated CO emission rates from various two wheelers in Delhi, Dehradun and Mussoorie

4.4.4.2. Cars

Fig. 4.3 (a-c) depicts monthly variation of CO emission rate from various categories of cars in Delhi, Dehradun and Mussoorie. Emission rate of petrol driven cars is increasing with monthly average temperature. Among all cities emission rates of petrol cars are the highest in Delhi, while the least in Mussoorie (Fig.4.3a). Emission rates of CNG and LPG driven cars are decreasing with increase in ambient temperature in all three cities (Fig.4.3 b and c) while with concern to altitude emission rates are higher in Delhi, followed by Dehradun and Mussoorie. In the month of June (high temperature) emission rate of CNG and LPG driven car is the least, while in January and December emission rate is more compared to other months. There is no impact of altitude, temperature and humidity on diesel driven cars. Fig. 4.3d suggests that diesel driven cars are more environment friendly than other cars in case of CO emissions.

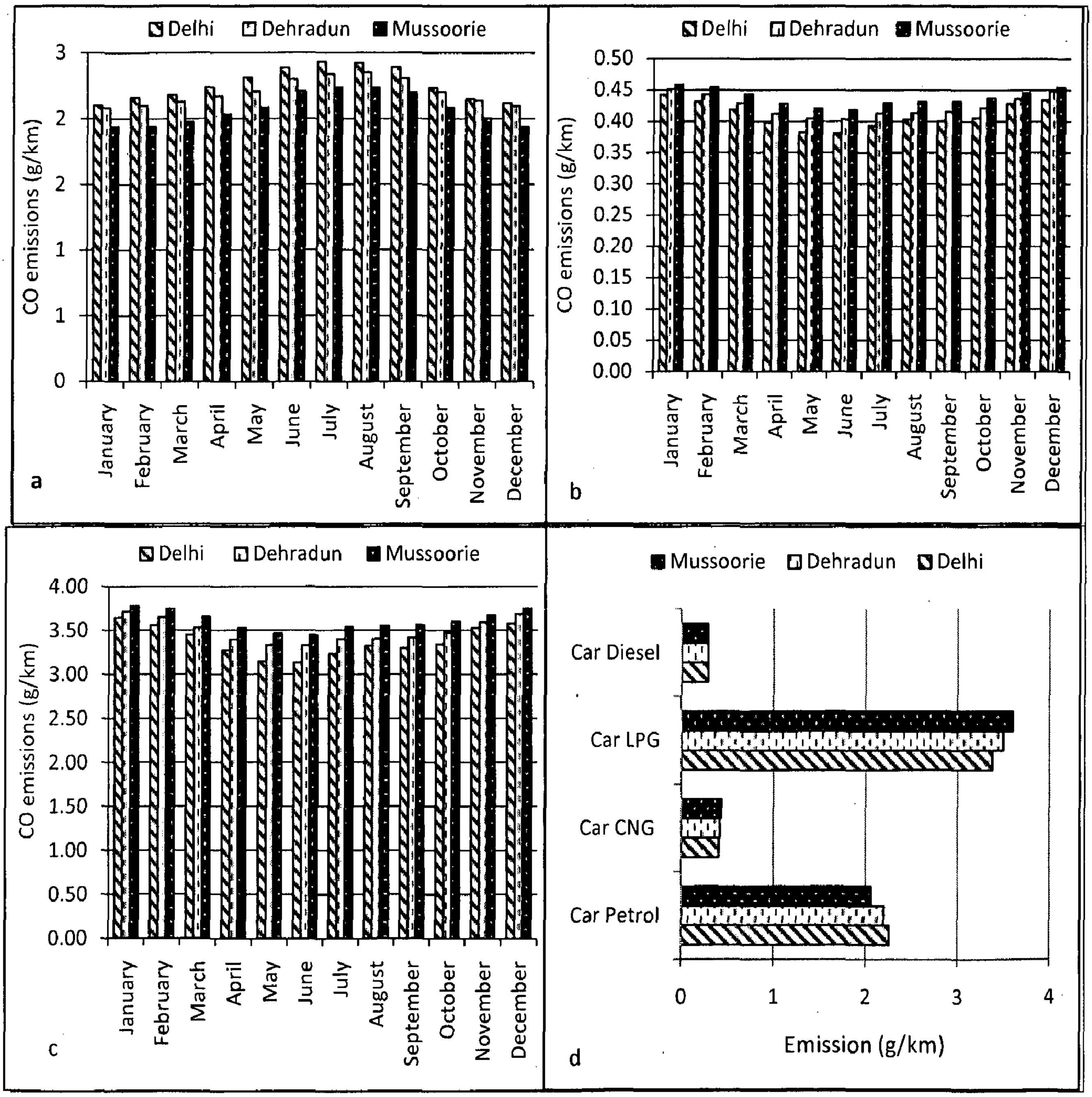


Fig. 4.3: Monthly CO emission rate from (a) Car Petrol (b) Car CNG (c) Car LPG and (d) Estimated CO emission rates according to fuel from cars in Delhi, Dehradun, and Mussoorie

Fig. 4.4 (a-d) illustrates the annual emissions of CO from various cars and impact of altitude on CO emissions from various car categories. Fig 4.4a depicts that CO emissions decrease with increasing altitude from petrol driven cars. It is observed that annual emission of CO per vehicle from petrol driven cars in Delhi, Dehradun and Mussoorie is 406, 395 and 372 kg respectively. Emissions from CNG and LPG driven car show similar trends (CO increasing with altitude) while in case of diesel driven car, no difference is observed in CO emissions.

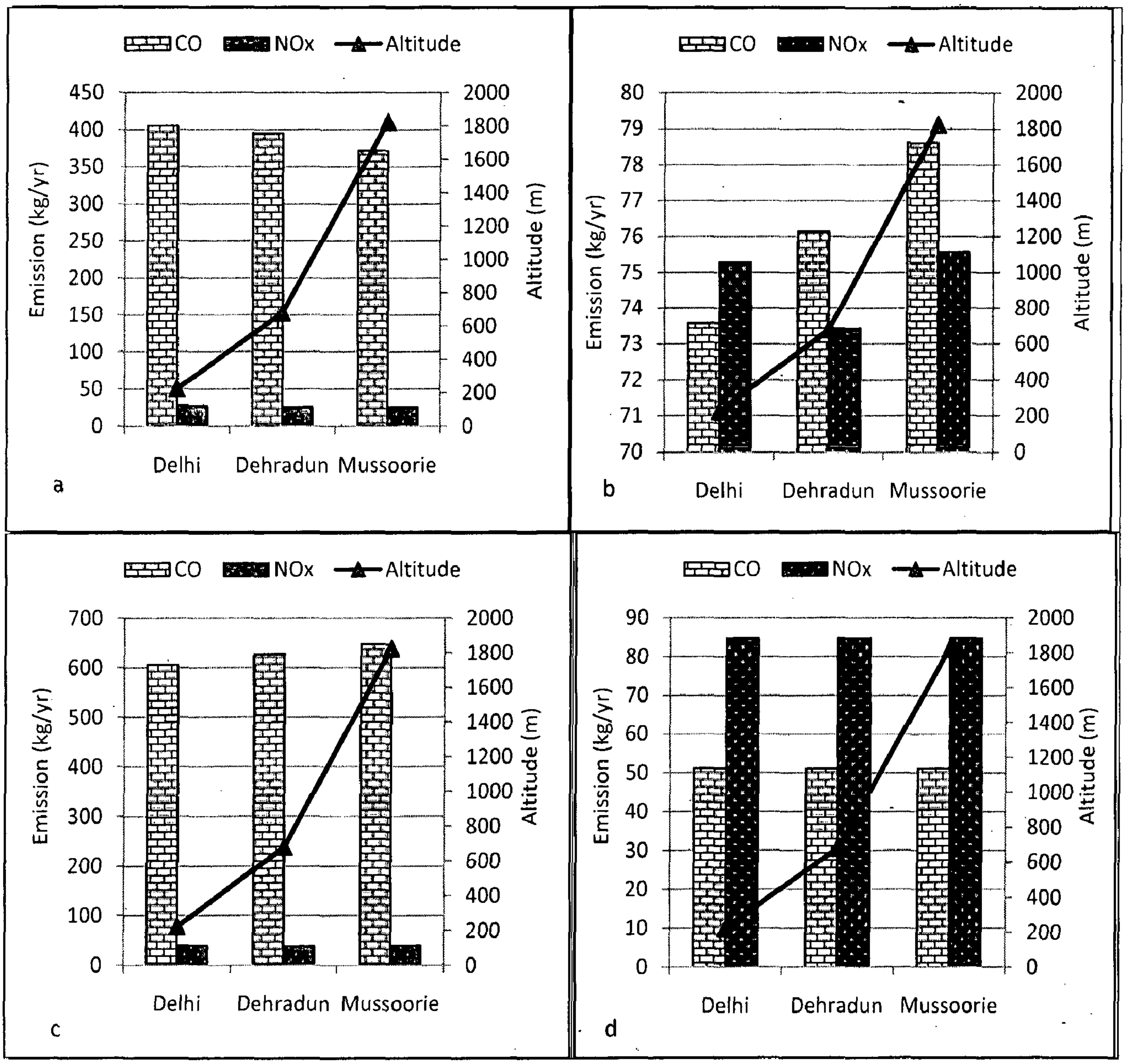


Fig. 4.4: Annual emission (kg/yr) of CO, NO_X from per car using (a) Petrol, (b) CNG (c) LPG and (d) Diesel as a fuel in Delhi, Dehradun, and Mussoories

4.4.4.3. Three wheelers

There are seven categories of three wheelers in terms of fuel use. Among all climatic and topographic factors, altitude and temperature are the dominating factors in case of exhaust CO emissions from three wheelers. In case of petrol driven three wheelers from both two- and four-stroke category, estimated emission rates are the highest in Mussoorie, showing the dominance of altitude (Fig. 4.4a-b). Monthly emission rates of both two- and four-stroke category show similar trends. In case of petrol driven three wheelers, emission rates are less in winter, and the highest in summer. Emission trend of CO from CNG and LPG is presented in the Fig. 4.5 (c-d) and 4.6 (a-b). Emissions of CO are high in July, August and September; this might be because of higher humidity and temperature during these months. No impact of temperature and humidity is observed on diesel driven three wheelers.

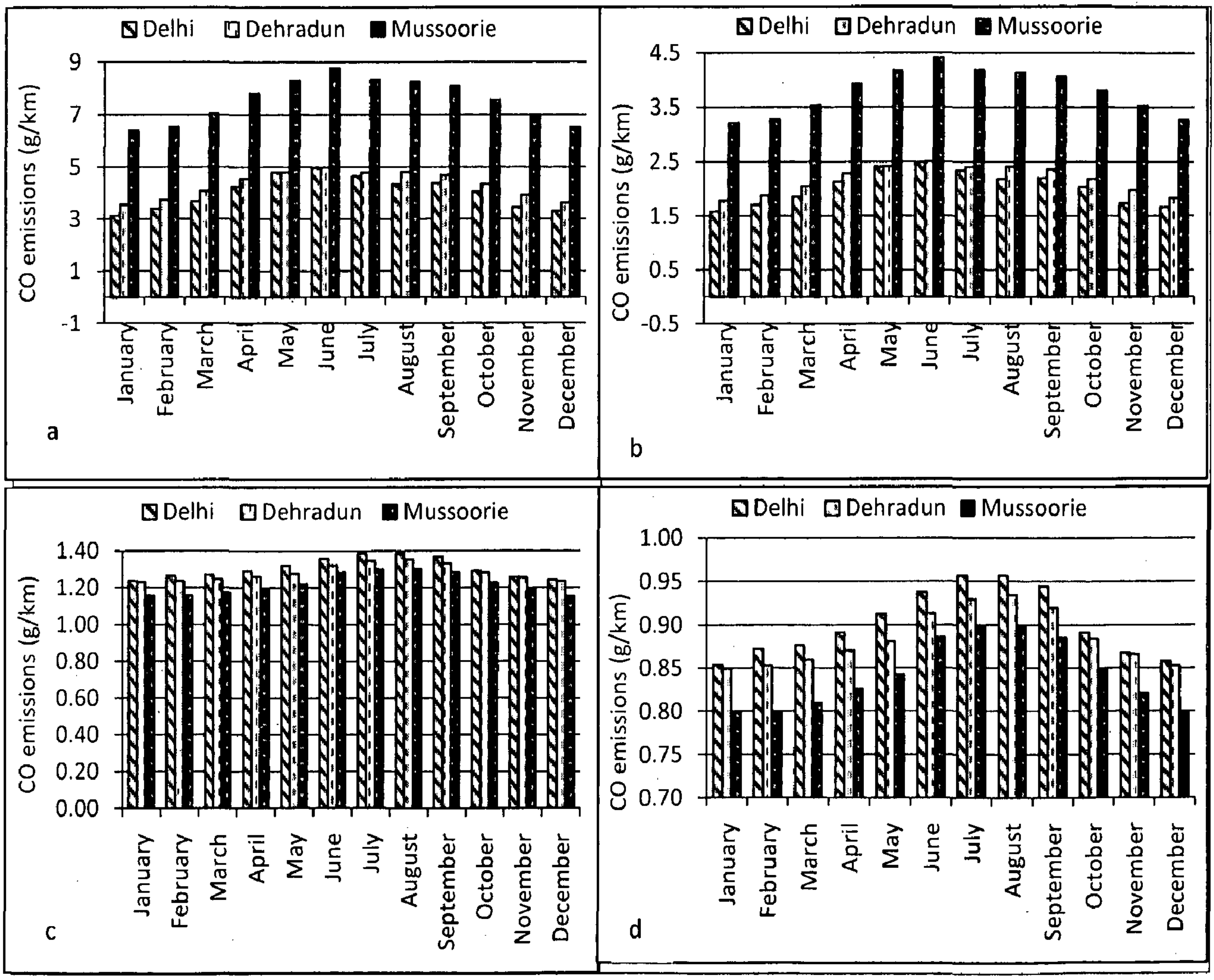


Fig. 4.5 : CO emission rate from three wheeler (a) Petrol 4-S (b) Petrol 2-S (c) CNG 4-S (d) CNG 2-S in Delhi, Dehradun and Mussoorie

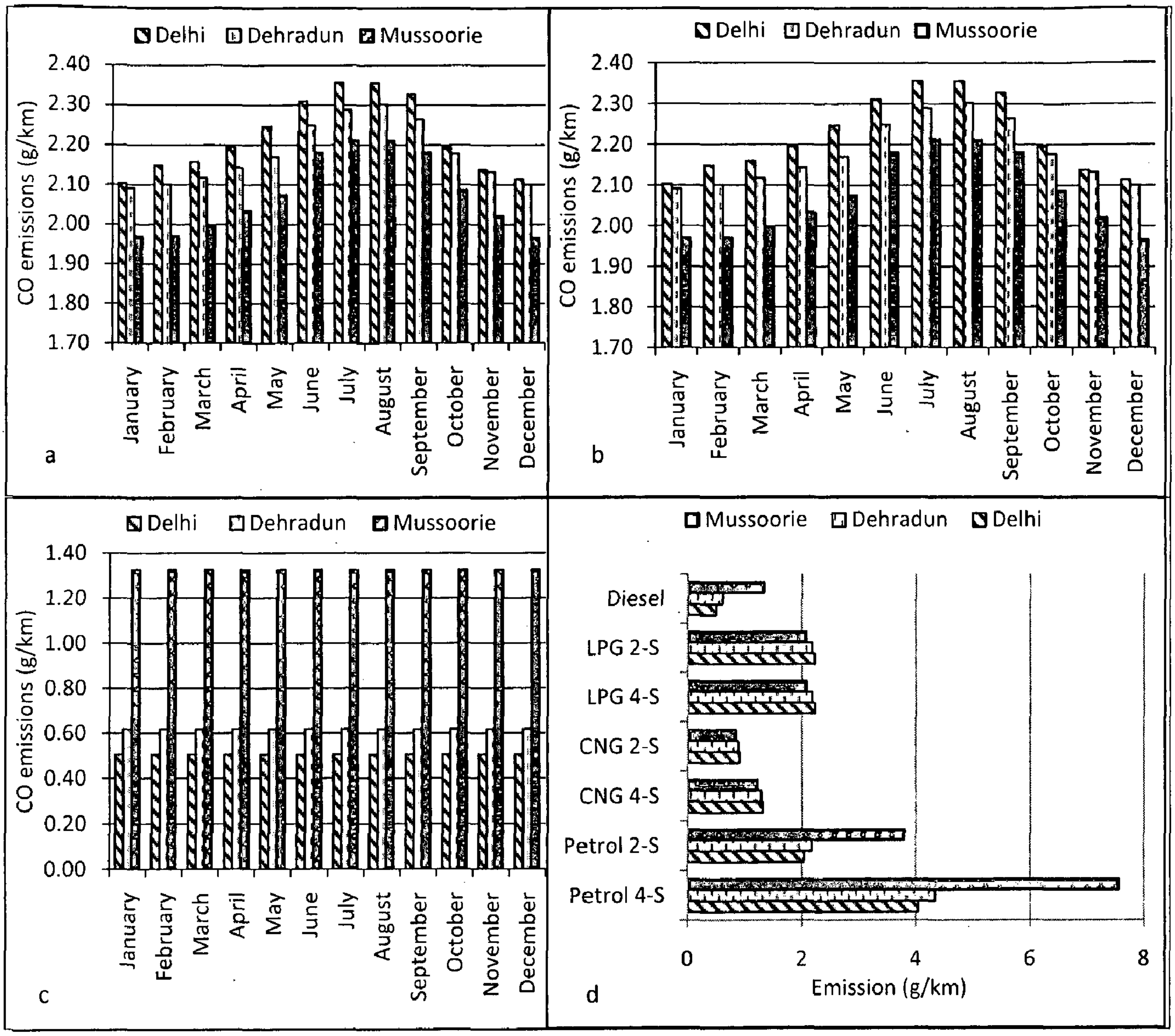


Fig. 4.6: CO emission rate from three wheeler (a) LPG 4-S (b) LPG 2-S (c) Diesel and (d) Estimated CO emission rates as per fuel used in three wheelers in Delhi, Dehradun and Mussoorie

Fig. 4.7 (a-d) and 4.8 (a-c) indicate that CO emission rates of three wheelers are affected by altitude. For petrol driven three wheelers, CO emission rates are increasing with altitude (Fig.4.7 a-b); whereas, for CNG and LPG driven three wheelers, emission rate decreases with increasing altitude (Fig.4.8 a-b). Comparisons among all kind of three wheelers with respect to their emission rate are presented in Fig 4.6d. It is observed that diesel and CNG 2-stroke three wheelers are more environment friendly among all three wheelers in case of CO emission.

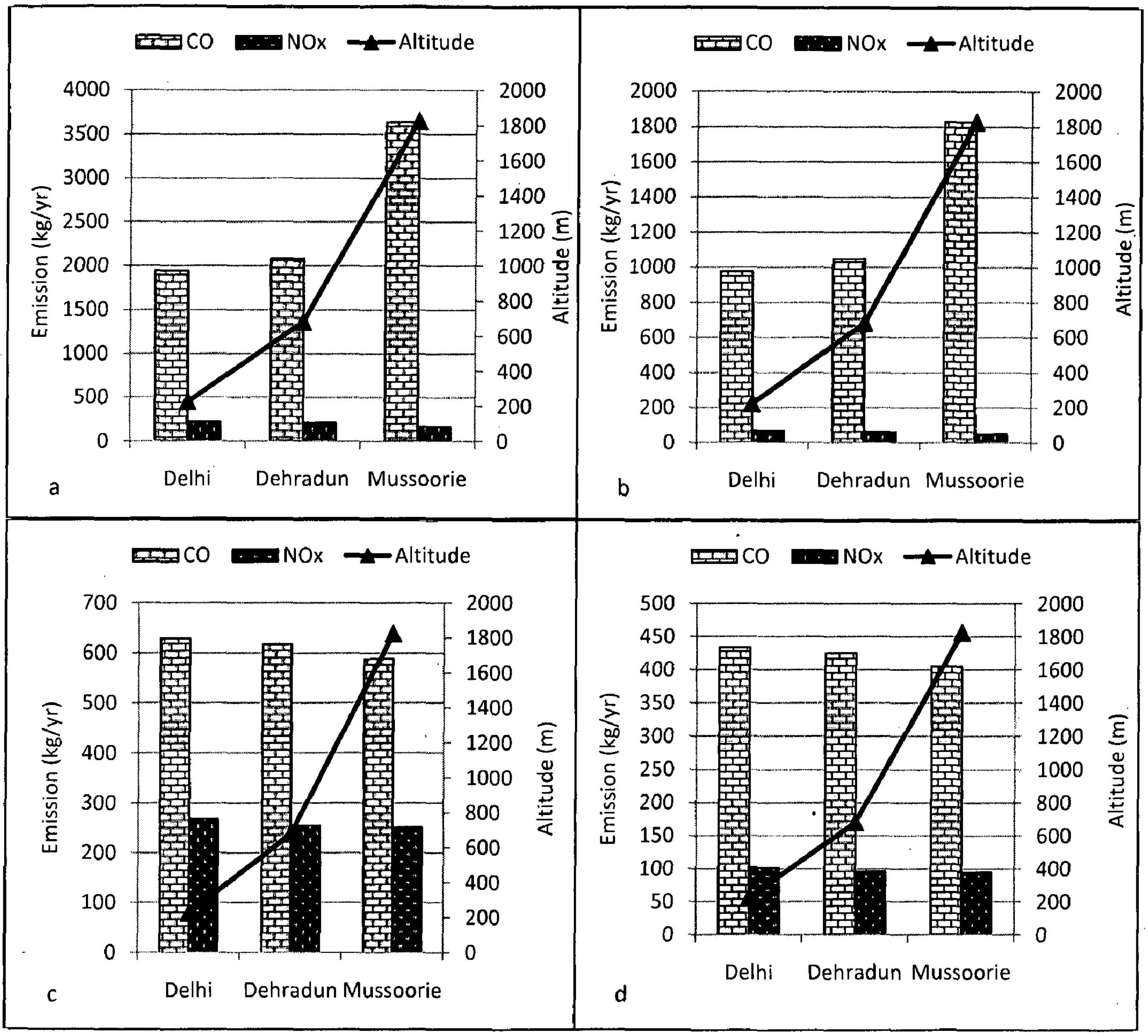


Fig. 4.7: Annual emission (kg/yr) of CO, NO_x from (a) Petrol 4-S (b) Petrol 2-S (c) CNG 4-S (d) CNG 2-S per three wheeler in Delhi, Dehradun, and Mussoorie

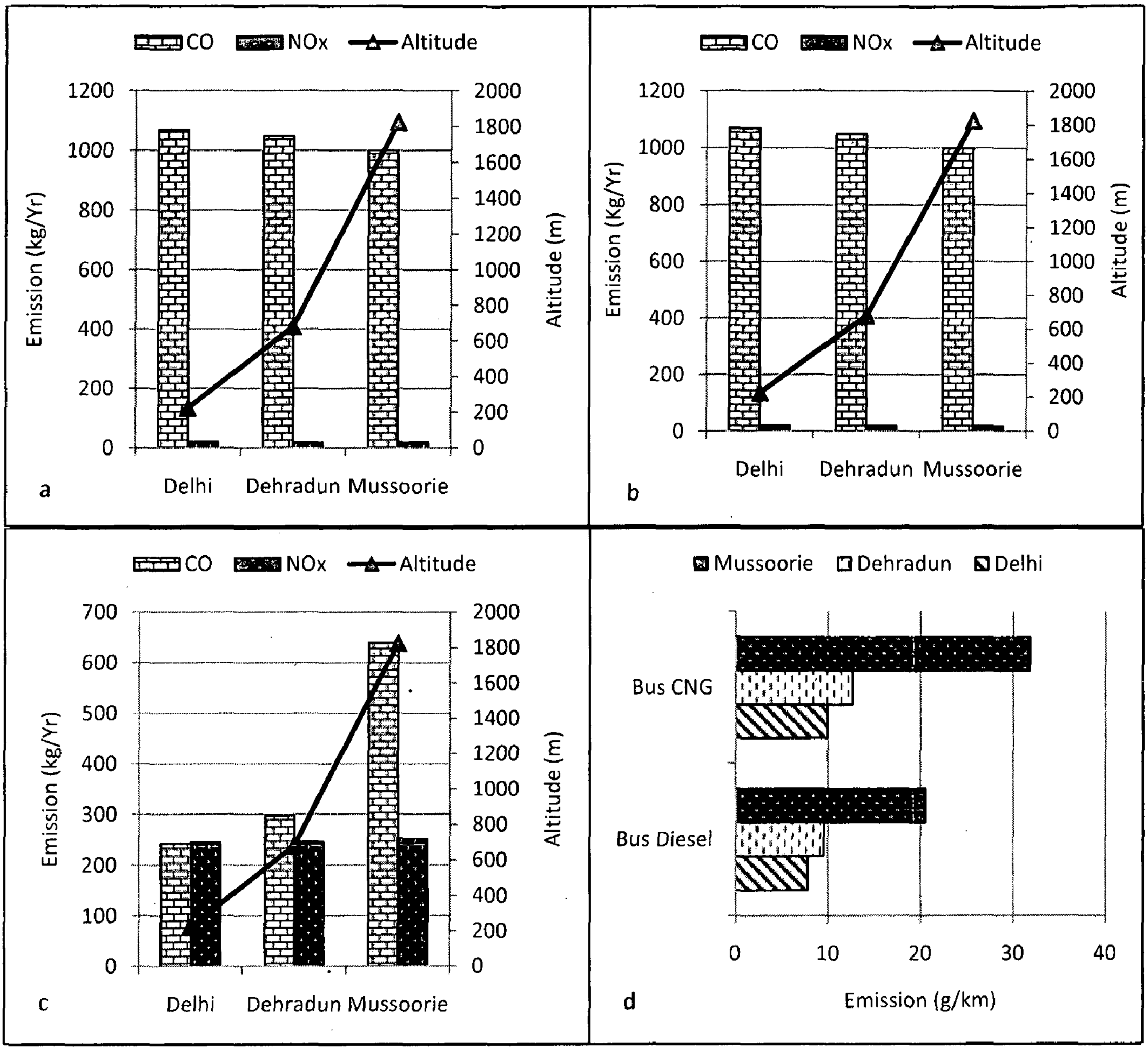


Fig. 4.8: Annual emission (kg/yr) of CO, NO_x from (a) LPG 4-S (b) LPG 2-S (c) Diesel per three wheeler in Delhi, Dehradun and Mussoorie (d) Esstimated CO emission rates according to fuel from bus in Delhi, Dehradun, and Mussoorie

4.4.4.4. Buses

No monthly variations have been observed in CO emissions from diesel buses, while CNG buses show minute difference. Emission rates of CO from CNG buses are less in summer, while higher in winter. It is clear from the results that CO emissions from CNG buses increase with decreasing ambient monthly average temperature and vice versa. The highest emission rate is observed in January and December, while the least is observed in in June and July. It seems that among all three parameters altitude is dominating for the buses, followed by ambient temperature and humidity. Annual emission rates of CO from both CNG and diesel buses are the highest in Mussoorie and the least in Delhi (Fig. 4.9 c-d). Also, it is observed that diesel buses emit less CO than CNG buses in all the three cities (Fig 4.8d).

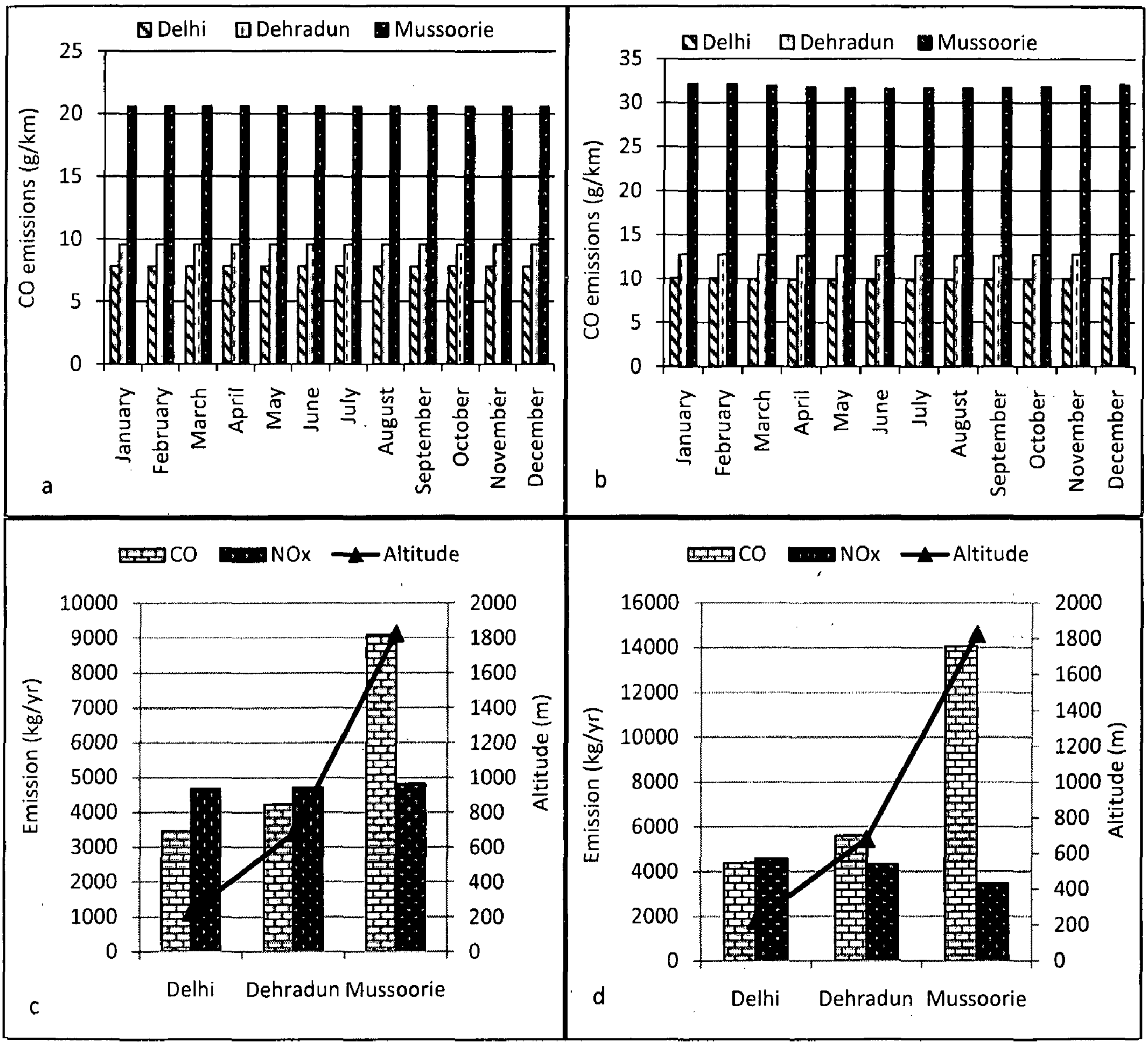


Fig. 4.9: CO emission rate from buses (a) diesel (b) CNG; and annual emissions (kg/yr) of CO, NO_x from (c) diesel (d) CNG buses in Delhi, Dehradun and Mussoorie

4.4.4.5. Light Commercial Vehicles (LCVs)

For diesel driven LCVs, trends of CO emission rate are same for all months in all cities while in case of CNG driven LCVs minute differences have been observed (Fig. 4.10a). It seems that emissions are affected by temperature in case of CNG driven LCVs (Fig. 4.10d). There is no effect of altitude on diesel driven LCVs, while noticeable effects are observed on CNG driven LCVs (Fig. 4.10c-d). The observations indicate that diesel driven LCVs emit less CO than CNG driven LCVs in all the three cities (Fig. 4.11a).

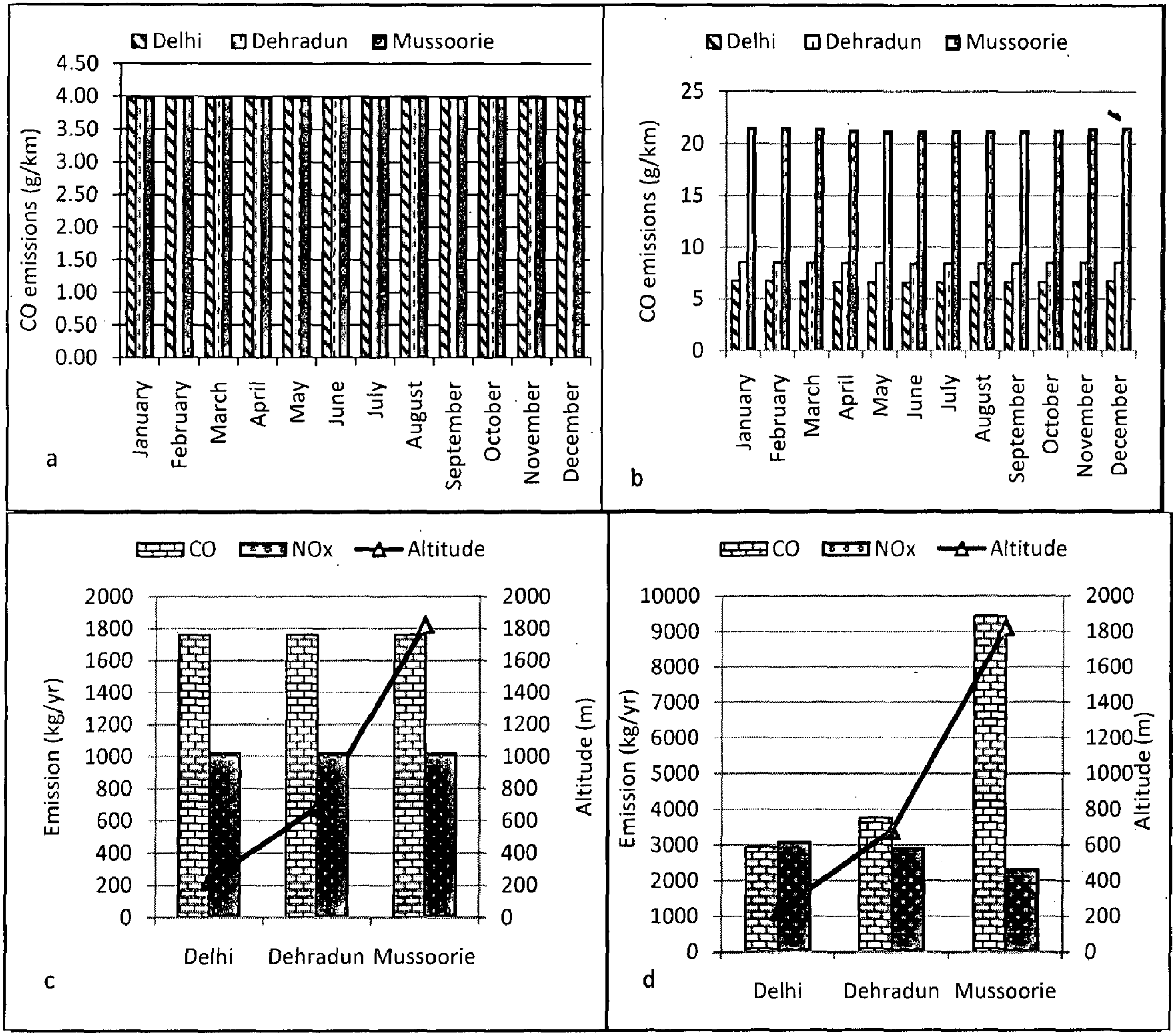


Fig. 4.10 : CO emission rate from LCVs (a) diesel (b) CNG and Annual emission (kg/yr) of CO, NO_x from (c) diesel (d) CNG LCVs in Delhi, Dehradun and Mussoorie

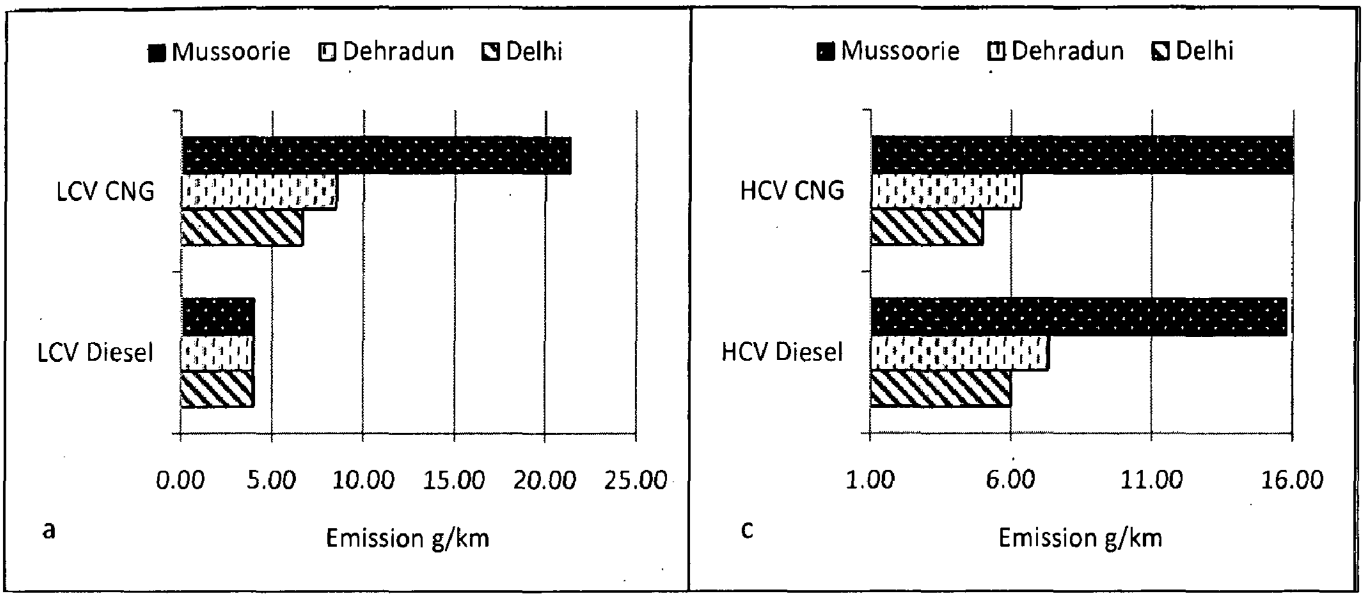


Fig. 4.11: Estimated CO emission rates as fuel used in per (a) LCVs and (b) HCVs in Delhi, Dehradun and Mussoorie

4.4.4.6. Heavy Commercial Vehicles (HCVs)

No significant changes have been observed in the emission rates of CO from diesel driven HCVs in all the three cities. In case of CNG driven vehicles, CO emissions increase with decreasing ambient temperature. Fig. 4.12 (c-d) illustrates the impact of altitude on HCVs and indicates that there is increase in CO emissions with altitude. Minute differences have been observed between diesel and CNG driven HCVs with respect to CO emissions (Fig 4.11b).

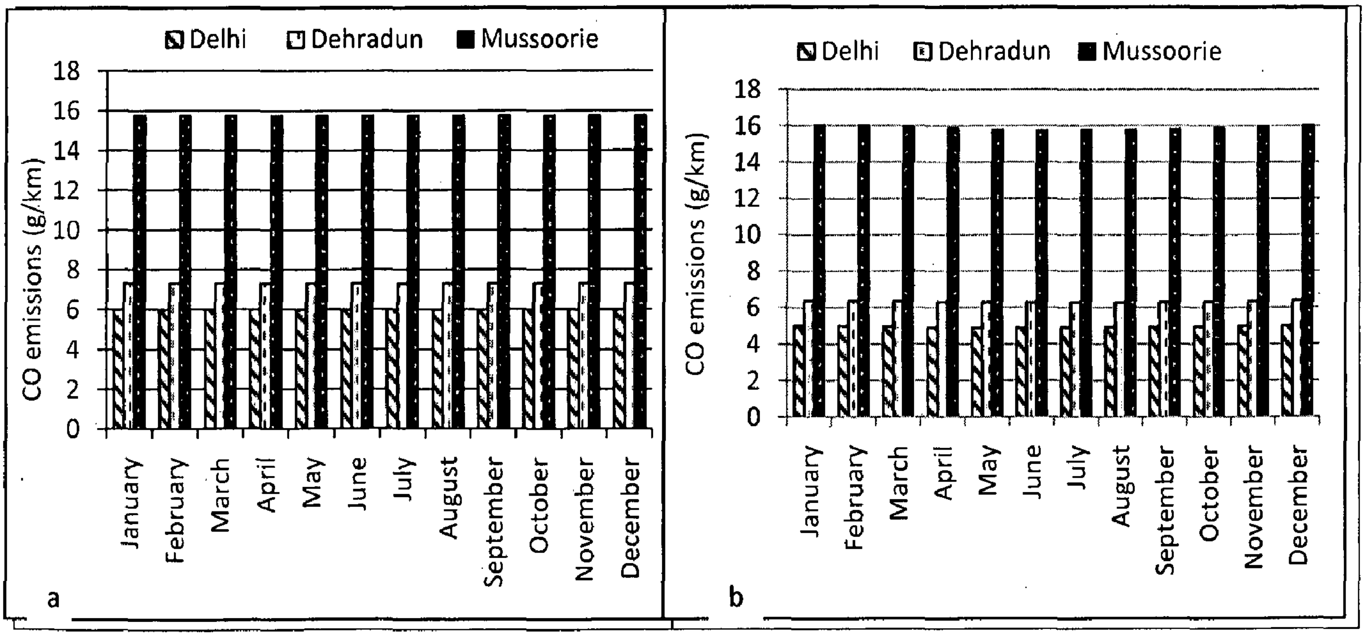


Fig.4.12. CO emission rate from HCVs (a) diesel (b) CNG in Delhi, Dehradun and Mussoorie

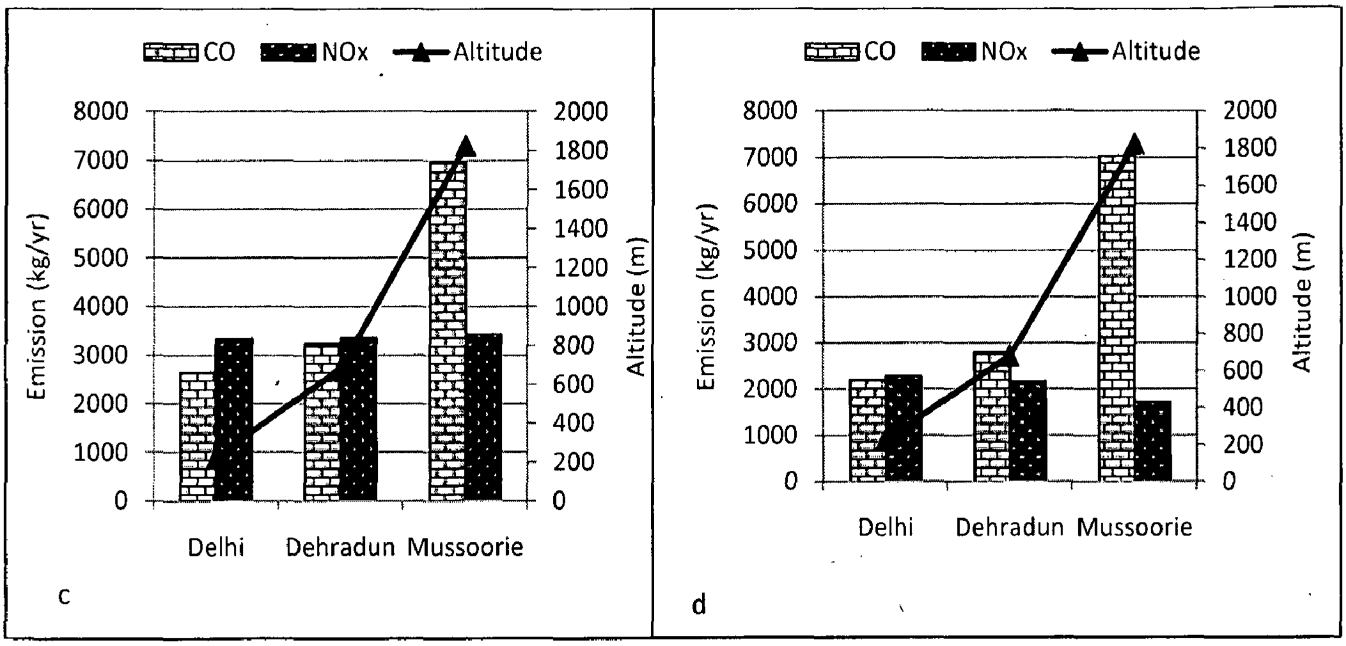


Fig.4.12: Annual emission (kg/yr) of CO, NO_x from (c) diesel (d) CNG HCVs in Delhi, Dehradun and Mussoorie

4.4.5. NO_x emissions

4.4.5.1. Two Wheelers

Fig. 4.13a shows monthly variation in emission rates of NO_x from two wheelers in selected cities. Two wheelers emit minimum NO_x in August (most humid month of the year) with 0.72 g/km, 0.69 g/km and 0.54 g/km in Delhi, Dehradun and Mussoorie, respectively. Maximum emission rates have been found in the month of January (coldest month of the year), with 0.92 g/km, 0.84 g/km, 0.70 g/km in Delhi, Dehradun and Mussoorie, respectively (Fig. 4.13a). After observing Fig.4.1 (a - b) and 4.13a, it seems that emission rate is affected by both humidity and temperature in case of individual city. Emission rate increases with decreasing humidity and ambient temperature and vice–versa. Results suggest that humidity and ambient temperature have combined effects and hence, the model estimated minimum NO_x emission rate in August and maximum in January.

Fig.4.2b shows annual NO_x emissions which are highest for Delhi (~100 kg/yr) and lowest for Mussoorie (~76 kg/yr). Unlike CO, opposite trend is observed in case of NO_x i.e. decrease in emissions with increase in altitude (Fig 4.2b). It also means that NO_x emissions decrease in conjunction with decreasing ambient temperature and increasing altitude. The possible reason for such decrease could be the use of rich fuel/air mixture during combustion at high altitude, resulting in relatively less emissions of NO_x. Fig. 4.13b shows adjusted emission rate of NO_x from various two wheelers. The results suggest that four-stroke motorcycles emit highest NO_x among all two wheelers, followed by four-stroke moped and scooter, while two-stroke moped emit least NO_x followed by two-stroke scooter and motorcycle.

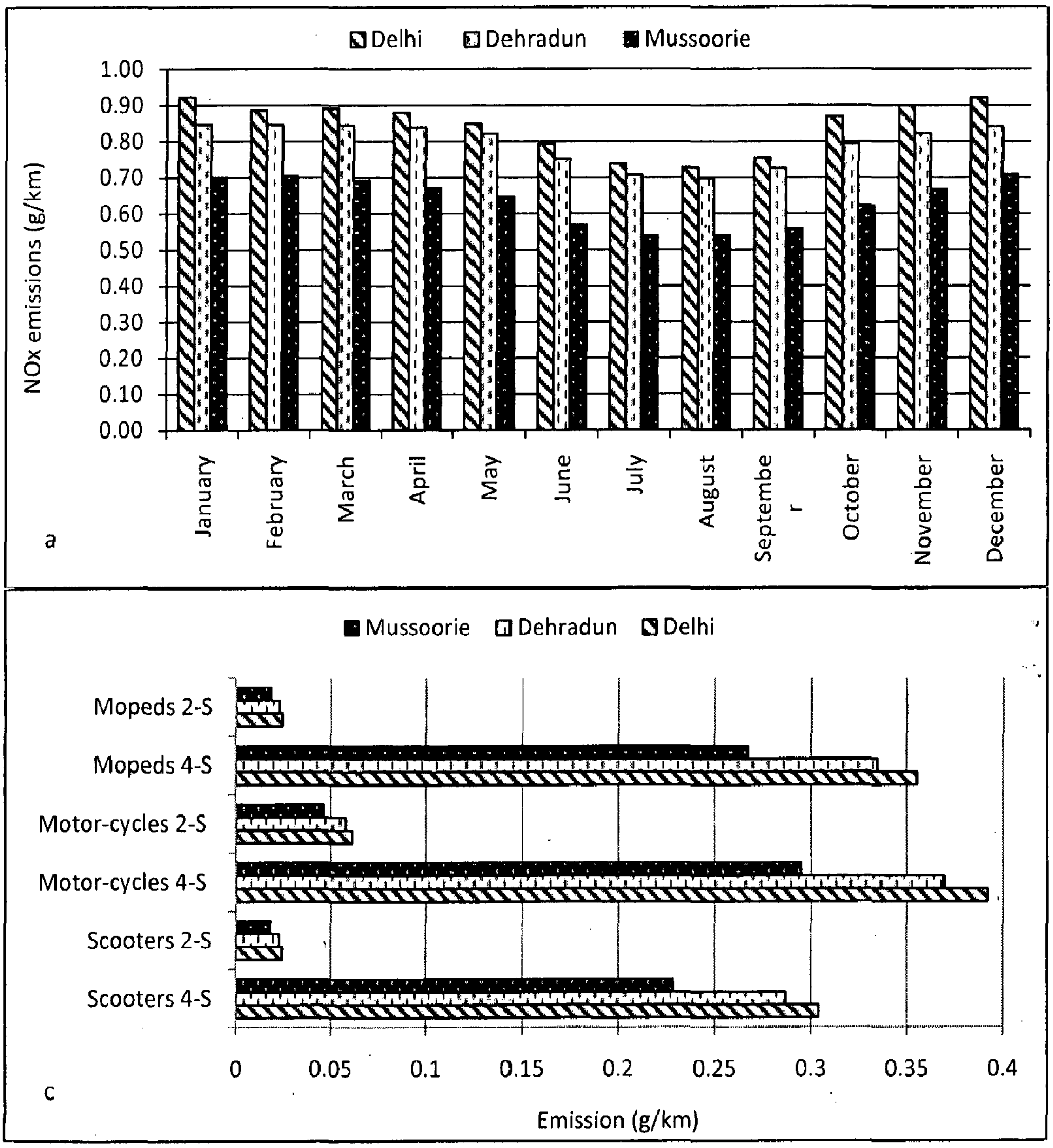


Fig. 4.13: (a) Monthly NO_x emissions from two wheelers (b) Estimated NO_x emission rates from various two wheelers in Delhi, Dehradun and Mussoorie

4.4.5.2. Cars

Fig. 4.14 (a-c) shows the emission rate of NO_x from cars according to their fuel use in Delhi, Dehradun and Mussoorie. Highest emission rate of NO_x from petrol driven car (Fig. 4.14a) is observed in the month of May in Delhi (0.176 g/km), Dehradun (0.161 g/km) and Mussoorie (0.155 g/km). May is the least humid and among top three hottest month of the year in all three cities and according to IVEM correction factor database NO_x emission increases with decreasing humidity and increasing temperature. Least emission rates have been observed in the month of January in Delhi (0.137 g/km), Dehradun (0.132 g/km) and Mussoorie (0.136 g/km). January is the coldest and among most humid month of the year, and as per IVEM correction factor NO_x emission decreases with decreasing temperature and increasing humidity. Fig.4.14 (b-c) shows the emission rate of NO_x from CNG and LPG driven cars in all three cities. Emission trend of NO_x from CNG and LPG is similar to trend of humidity in all three cities. The highest emission rate of NO_x from CNG and LPG driven cars is observed in the month of May, while the least in August. It seems that humidity is dominating over temperature in all the three cities. According to IVE model there is no direct effect of altitude on the petrol, LPG and CNG driven cars (IVEM, 2008). From altitude perspective, petrol driven car emits highest emission of NO_x in Delhi (27.49 kg/yr), followed by Dehradun (25.97 kg/yr) and Mussoorie (25.92kg/yr). CNG driven car emits higher NO_x emissions in Mussoorie (75.58 kg/yr), followed by Delhi (75.29 kg/yr) and Dehradun (73.45 kg/yr). LPG driven car emits higher emissions of NO_x in Mussoorie, followed by Delhi and Dehradun, while no effects are observed on diesel driven cars. Fig. 4.14d shows the emission contribution of various cars using different fuels in all three cities. It suggests that emission rate of petrol driven cars is least among all categories in all the three cities, followed by LPG and CNG cars. Among all the cars, diesels driven cars are the most dominating emitter of NO_x.

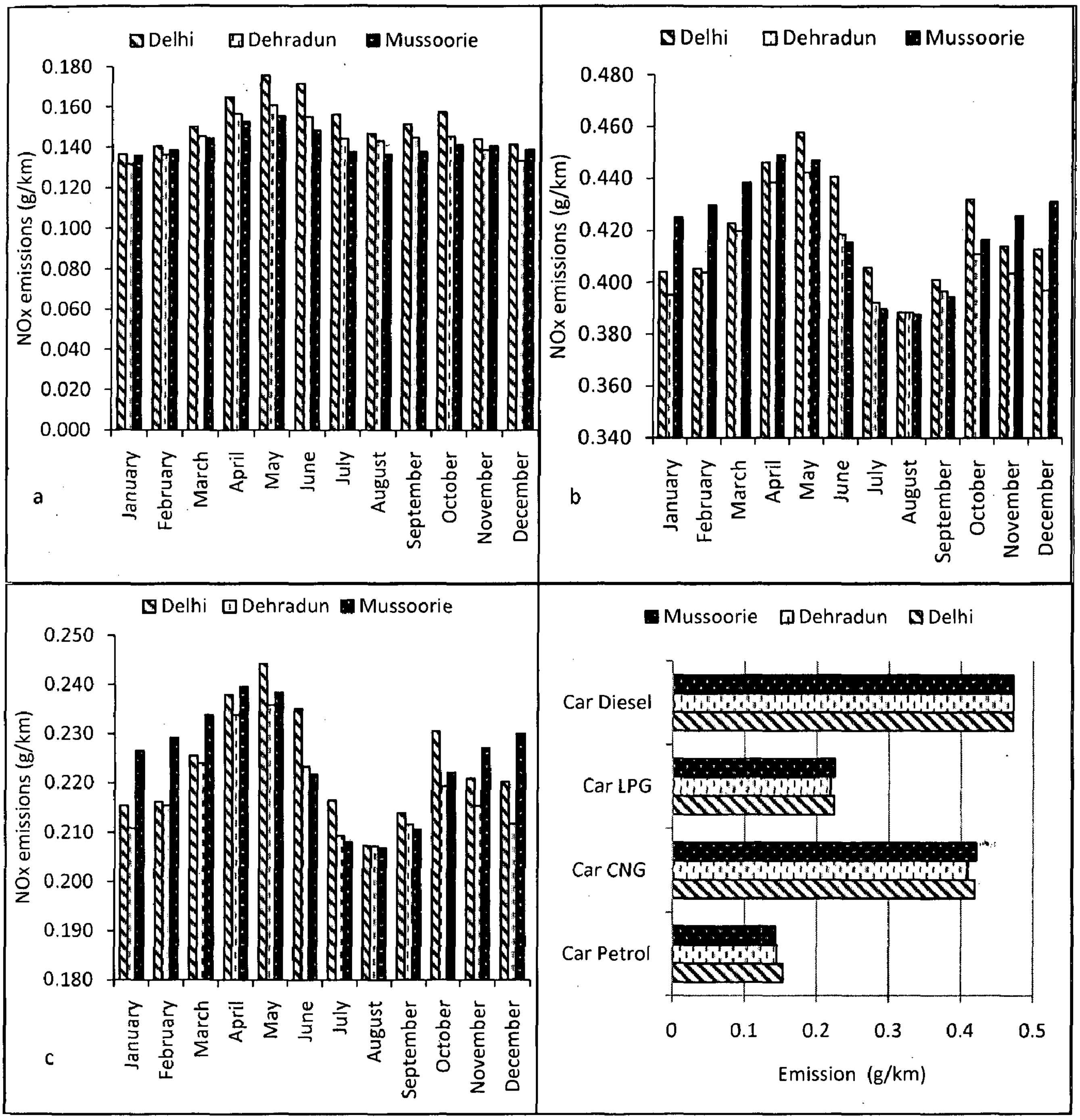


Fig. 4.14: NO_X emission rate from (a) Car Petrol (b) Car CNG (c) Car LPG and (d) Estimated NO_X emission rates according to fuel from car in Delhi, Dehradun, and Mussoorie

4.4.5.3. Three wheelers

Fig. 4.15a shows the emission rate of four-stroke petrol driven three wheelers in Delhi, Dehradun and Mussoorie. Highest emission rate of NO_x from petrol driven four-stroke three wheelers is observed in the month of January in Delhi (0.515 g/km), Dehradun (0.473 g/km) and in the month of December in Mussoorie (0.395 g/km). Least NO_x emissions are observed in the month of August in all the cities. Minimum emission of NO_x from petrol driven two-stroke- three wheelers is observed in the month of August in Delhi, Dehradun and Mussoorie (Fig.15b). While maximum emissions are observed in the month of January in Delhi, Dehradun and in the month of February in Mussoorie. The observations suggest that NO_x emission from three wheelers is a combined effect of both ambient temperature and humidity. Minimum emission in the month of August is because of higher humidity and temperature and maximum emission in the month of December- February is because of less ambient temperature and humidity.

Emission rate of NO_x from four-stroke CNG three wheelers is highest in the month of May in Delhi (0.639 g/km), Dehradun (0.587 g/km) and Mussoorie (0.568 g/km) (Fig. 15c). Minimum emission rate is observed in the month of January in Delhi (0.501 g/km) and Dehradun (0.483 g/km) and August in Mussoorie (0.499 g/km). Similar to four-stroke CNG three wheelers, NO_x emission from two-stroke three wheelers using CNG is highest in the month of May and least in the month of January in all the three cities (Fig. 15d). With concerned to ambient temperature and humidity, NO_x emission from CNG three wheelers is effected by both factors simultaneously.

NO_x emission rate from petrol driven two- and four-stroke three wheelers is highest in Delhi (lower altitude), while least in Mussoorie (higher altitude area) (Fig.4.7a-b). Just opposite to petrol driven three wheelers, emission rate of CNG driven three wheelers is highest in Mussoorie and least in Delhi (Fig. 4.7c-d).

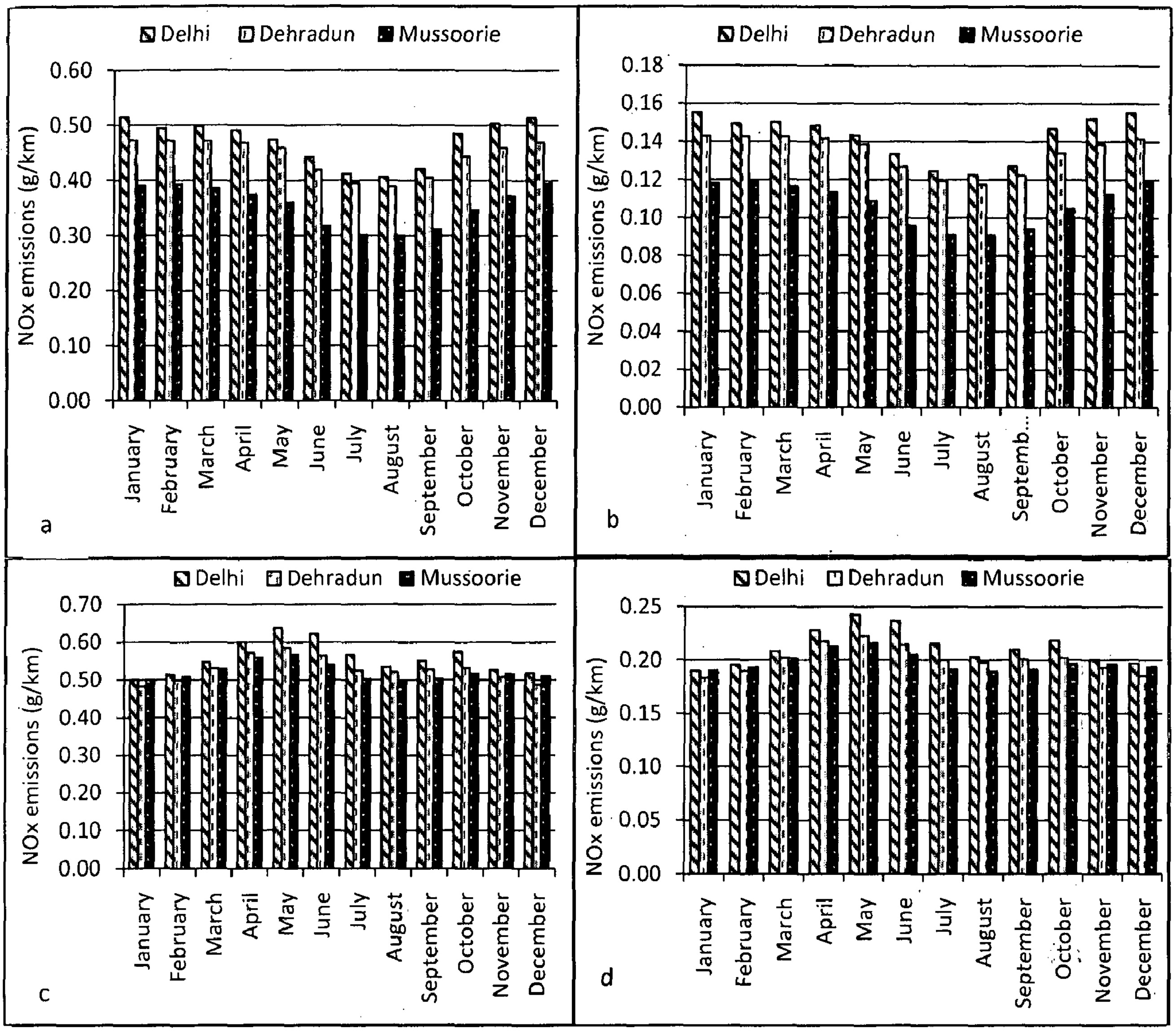


Fig. 4.15: NO_x emission rate from three wheeler (a) Petrol 4-S (b) Petrol 2-S (c) CNG 4-S (d) CNG 2-S in Delhi, Dehradun and Mussoorie

Emission of NO_x from LPG three wheelers is highest in the month of May in Delhi (0.051g/km), followed by Dehradun (0.047 g/km) and Mussoorie (0.045 g/km) (Fig. 4.16a), while least emissions are observed in December and January (Fig. 4.8a-b). There is no impact of ambient temperature and humidity on the diesel driven three wheelers (Fig. 4.16b). With concern to altitude, NO_x emissions are higher in Delhi (21.54 kg/yr), followed by Dehradun (20.39 kg/yr) and Mussoorie (20.12 kg) (Fig. 4.8c). It was observed that among all types of three wheelers, LPG driven three wheelers emit the least NO$_X$, while contribution of CNG driven two-stroke three wheelers is the highest (Fig. 4.16c).

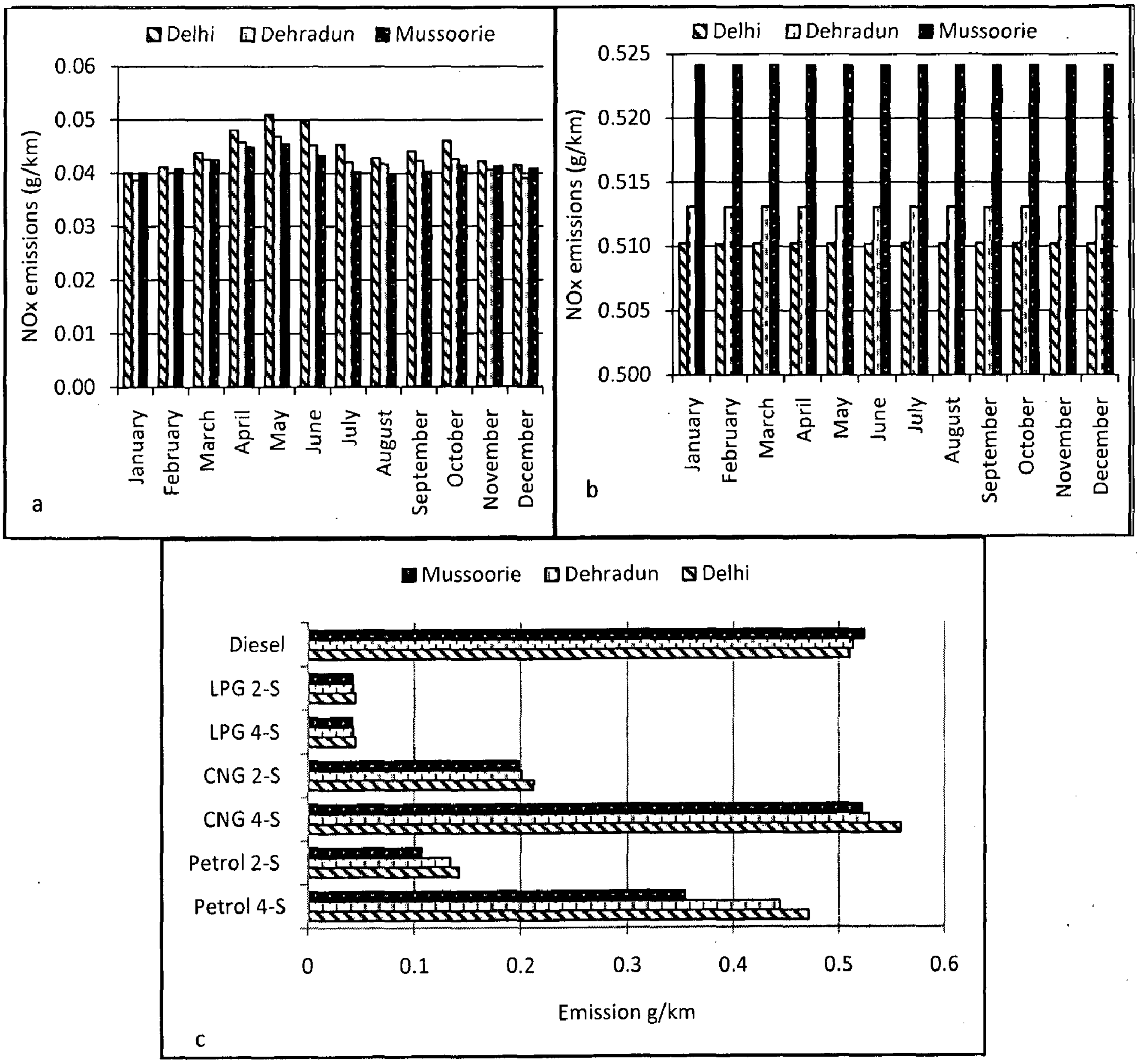


Fig. 4.16: NO$_X$ emission rate from three wheelers (a) LPG 4-S and 2-S (b) Diesel and (c) Estimated NO$_X$ emission rates according to fuel used inthree wheelers in Delhi, Dehradun and Mussoorie

4.4.5.4. Buses

Fig. 4.17 (a-b) shows NO_x emissions from diesel and CNG driven buses respectively. No significant impact of ambient temperature and humidity on diesel driven buses has been observed. CNG bus shows very minute deviation in emission rates, due to monthly variation in ambient temperature and humidity (Fig.4.17b). Fig 4.9c shows the NO_x emissions from diesel buses. It suggests that NO_x emission increases with altitude. The highest annual emissions are observed in Mussoorie (4820 kg/yr), followed by Dehradun (4719 kg/yr) and Delhi (4693 kg/yr). For CNG driven buses, highest emission is estimated in less altitudinal area, with Delhi (4587 kg/yr), followed by Dehradun (4335 kg/yr) and Mussoorie (3459 kg/yr). Fig. 4.18a illustrates the emission contribution of buses according to fuel use, indicating that CNG driven buses emit less NO_x rather than diesel driven buses.

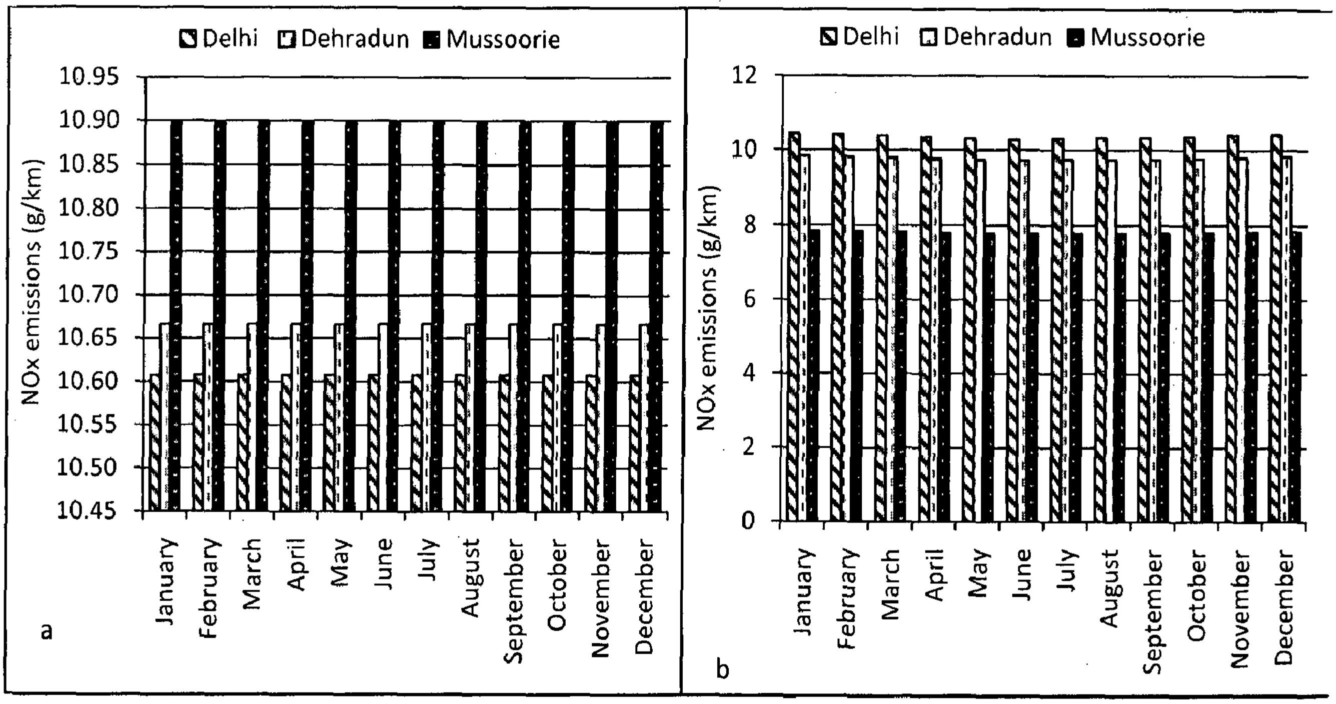


Fig. 4.17: NO_x emission rate from buses (a) diesel and (b) CNG in Delhi, Dehradun and Mussoorie

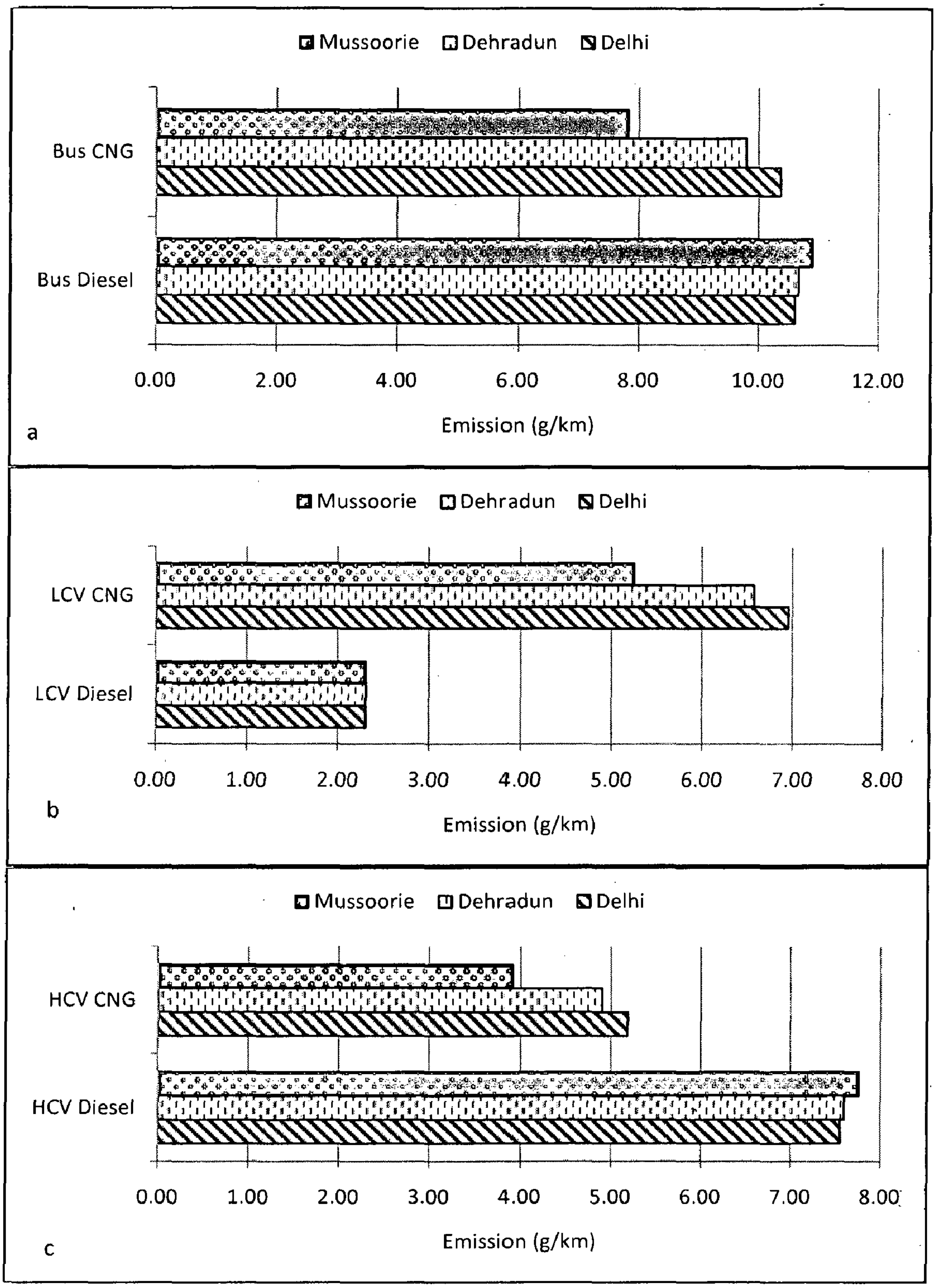


Fig. 4.18: Estimated NO_x emission rates according to fuel from (a) Bus, (b) LCVs and (c) HCVs in Delhi, Dehradun and Mussoorie

4.4.5.5. Light Commercial Vehicles (LCVs)

No impact of altitude, humidity and temperature is observed on diesel driven LCVs (Fig. 4.19a), while minute effects are observed on CNG driven LCVs. The highest emission of NO_x is observed in the month of January in Delhi, Dehradun and Mussoorie, while the least during June (Fig 4.19 b). Considering the impact of altitude, maximum emission is observed in Delhi (3077 kg/yr), followed by Dehradun (2908 kg/yr) and Mussoorie (2320 kg/yr) (Fig.4.10b). As per fuel used (i.e. Diesel, CNG) contribution of diesel driven LCVs for NO_x emission is lesser than CNG driven LCVs (Fig. 4.18b).

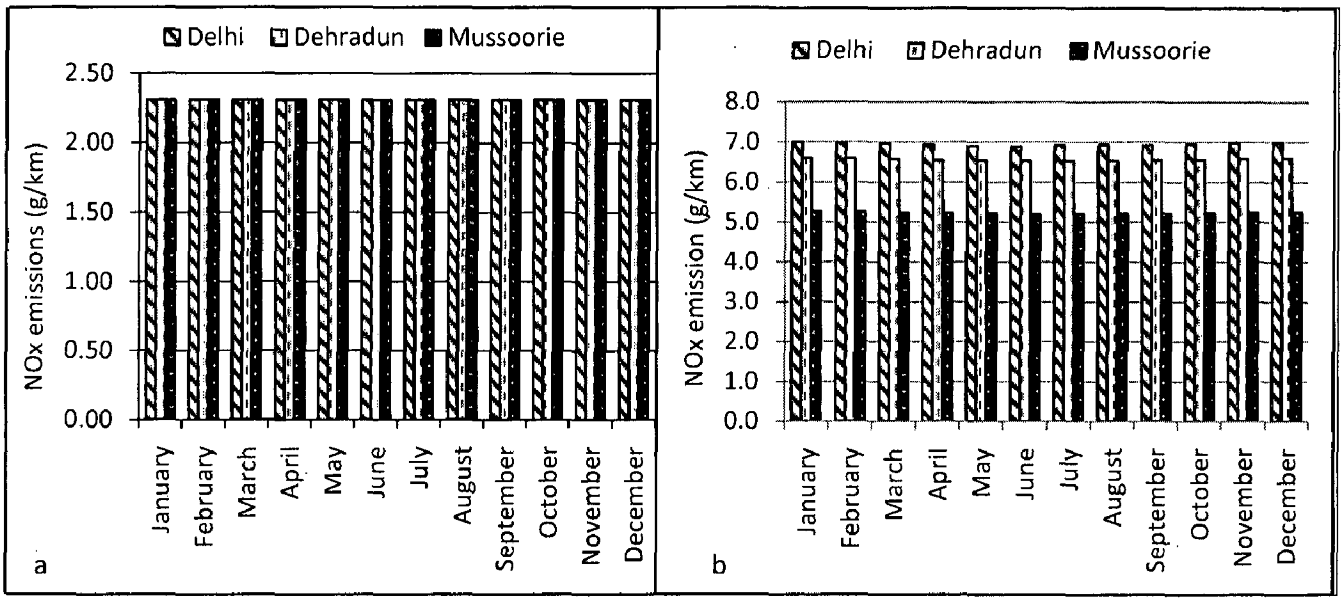


Fig. 4.19: NO_x emission rate from LCVs (a) diesel and (b) CNG in Delhi, Dehradun and Mussoorie

4.4.5.6. Heavy Commercial Vehicles (HCVs)

Fig. 4.20 (a-b) illustrates the emissions of NO_x from HCVs in Delhi, Dehradun and Mussoorie. No effect of humidity and ambient temperature is observed on emission of NO_x from diesel driven HCVs (Fig. 4.20a), while infinitesimal effect is observed from CNG driven HCVs (Fig.20b). Highest emission of NO_x from CNG driven HCVs is observed in the month of January in Delhi (5.22 g/km), followed by Dehradun (4.92 g/km) and Mussoorie (3.92 g/km); while least emission is observed in the month of June in all the three cities. Considering the impact of altitude on diesel driven HCVs, highest emission is observed in Mussoorie (3432 kg/yr), followed by Dehradun (3360 kg/yr) and Delhi (3341 kg/yr) (Fig. 4.12c). While CNG driven HCVs show quite opposite trend, with NO_x emissions higher in less altitude area- Delhi (2294 kg/yr), followed by Dehradun (2167 kg/yr) and Mussoorie (1729 kg/yr) (Fig 4.12d). As per contribution of NO_x, CNG driven HCVs emits less emission than diesel driven HCVs (Fig. 4.18c)

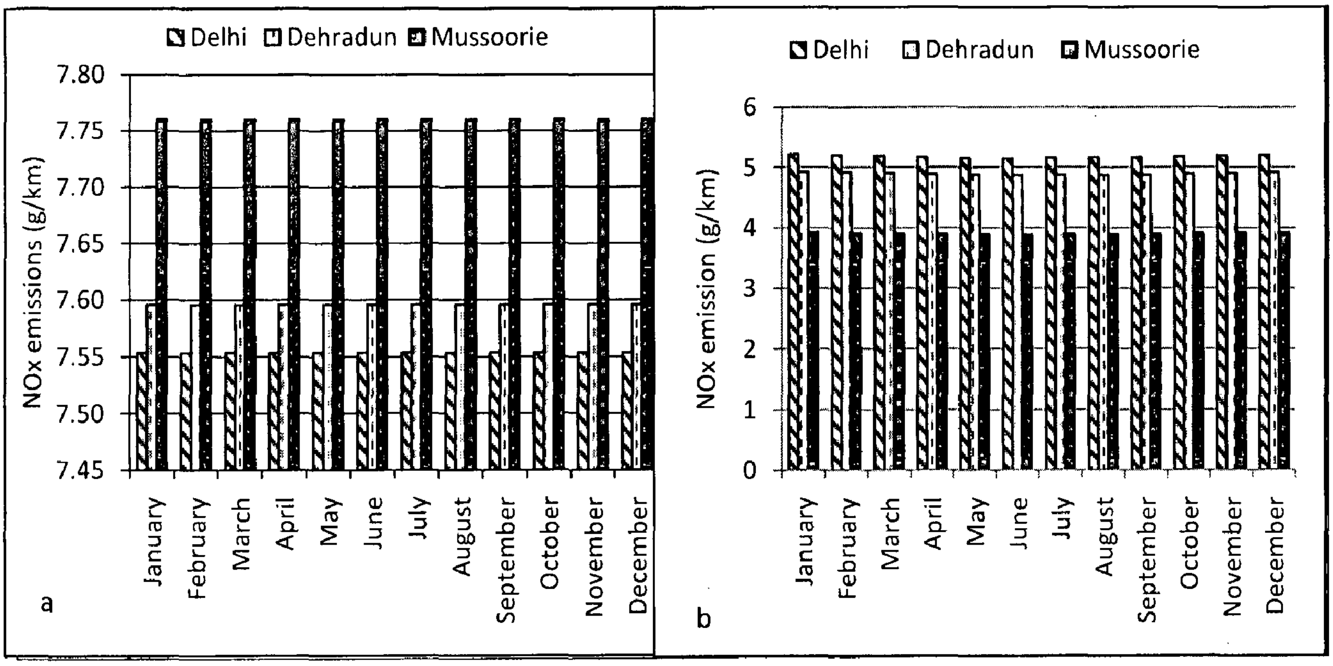


Fig. 4.20: NO_x emission rate from HCVs (a) diesel and (b) CNG in Delhi, Dehradun and Mussoorie

4.4.6. 1-3 Butadiene emissions

4.4.6.1. Two Wheelers

As visible from Fig. 4.21a emission rate of 1-3 Butadiene from two wheelers is highest in the month of June in Delhi (45 µg/km), Dehradun (49 µg /km) and Mussoorie (75 µg/km), while minimum in January in all the three cities. June is the hottest and January is the coldest month of the year in all three cities.

Fig. 4.21b shows the annual emission in all three cities. Highest emissions are observed in the highest altitude area i.e. Mussoorie (8691 mg/yr), while least in Delhi (5181 mg/yr) which has the least altitude among all three cities. As visible from Fig. 4.21c emission rate of two-stroke moped is least among all two wheelers, followed by four-stroke motorcycle and moped.

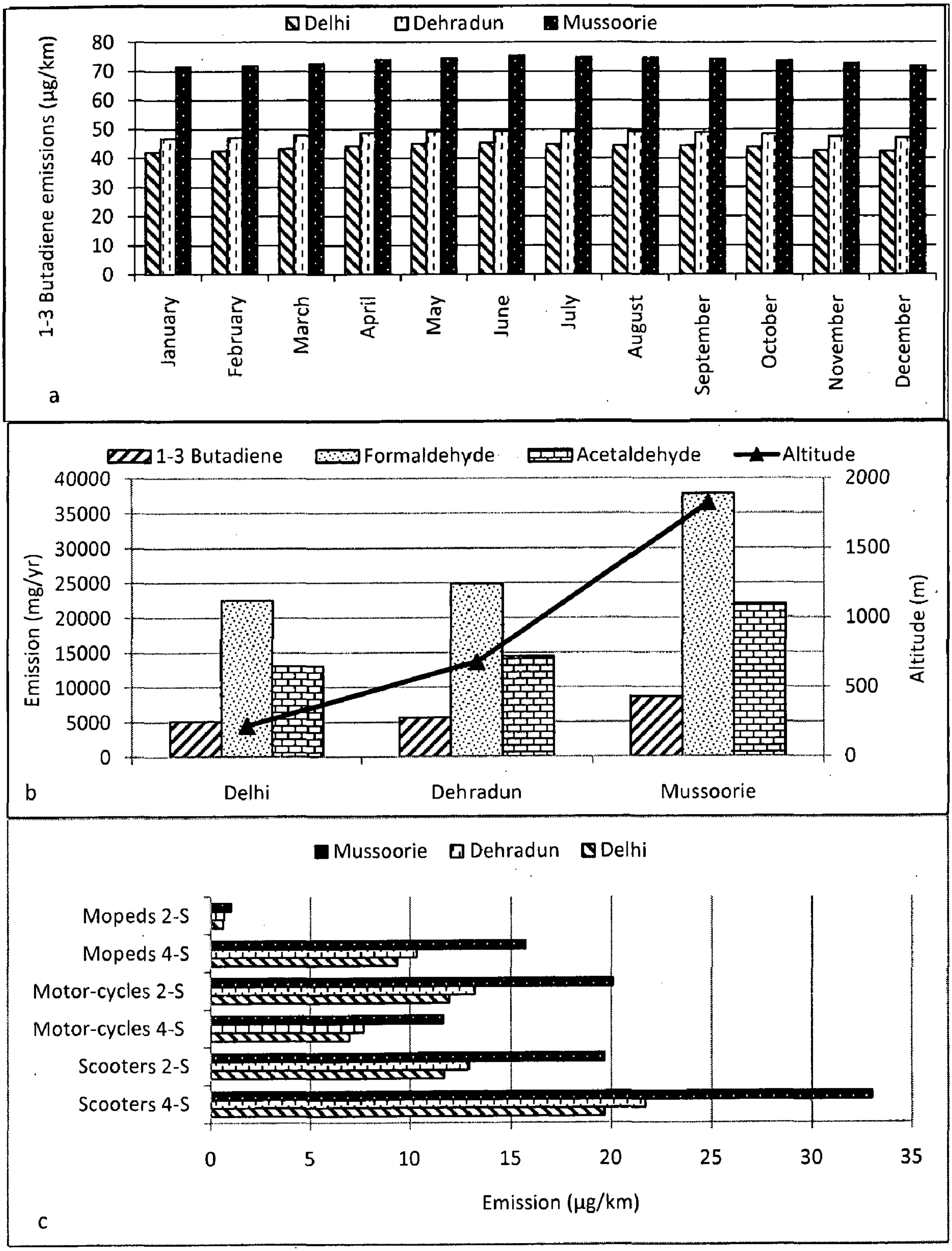


Fig. 4.21: (a)Monthly 1-3 Butadiene emissions rate from two wheelers (b) Annual emission (mg/yr) of 1-3 Butadiene, Formaldehyde and Acetaldehyde from two wheeler and (c) Estimated 1-3 Butadiene emission rates from various two wheelers in Delhi Dehradun, and Mussoorie

4.4.6.2. Cars

Emission of 1-3 Butadienes from petrol driven car is shown in Fig. 4.22a. Highest emission rate of 1-3 Butadiene is observed in the month of August in Delhi (2.699 μg/km), Dehradun (2.685 μg/km) and Mussoorie (2.66 μg/km), while least during January in Delhi (2.622 μg/km), Dehradun (2.62 mg/km) and Mussoorie (2.57 μg/km). Fig. 4.22a indicates that 1-3 Butadiene emissions have combined effect of ambient temperature and humidity.

Highest emission rate of 1-3 Butadienes from CNG driven car is observed in the month of January (Fig. 4.22b) in Delhi (0.302 μg/km), Dehradun (0.307 μg/km) and Mussoorie (0.316 μg/km). Least emissions are observed in June in Delhi (0.258 μg/km), Dehradun (0.274 μg/km) and Mussoorie (0.285 μg/km). January is the coldest month of the year with high humidity, while June is the hottest month of the year with less humidity. Fig. 4.22b suggests that 1-3 Butadiene emission from CNG driven car increase with decreasing temperature and humidity.

Similar to CNG driven cars, emission of LPG driven car is highest in the month of January in Delhi (1.931 μg/km), Dehradun (1.966 μg/km) and Mussoorie (2.025 μg/km), while in June emission rate of 1-3 Butadiene is least in all the three cities (Fig. 4.22c). The above findings suggest that 1-3 Butadiene emission from LPG driven car increases with decreasing temperature and vice versa. There is no significant effect of temperature and humidity on diesel driven car. CNG driven cars emit least 1-3 Butadiene emission among all types of car, followed by LPG and petrol driven cars, while emission rate of diesel driven cars is highest among all cars (Fig. 4.22d).

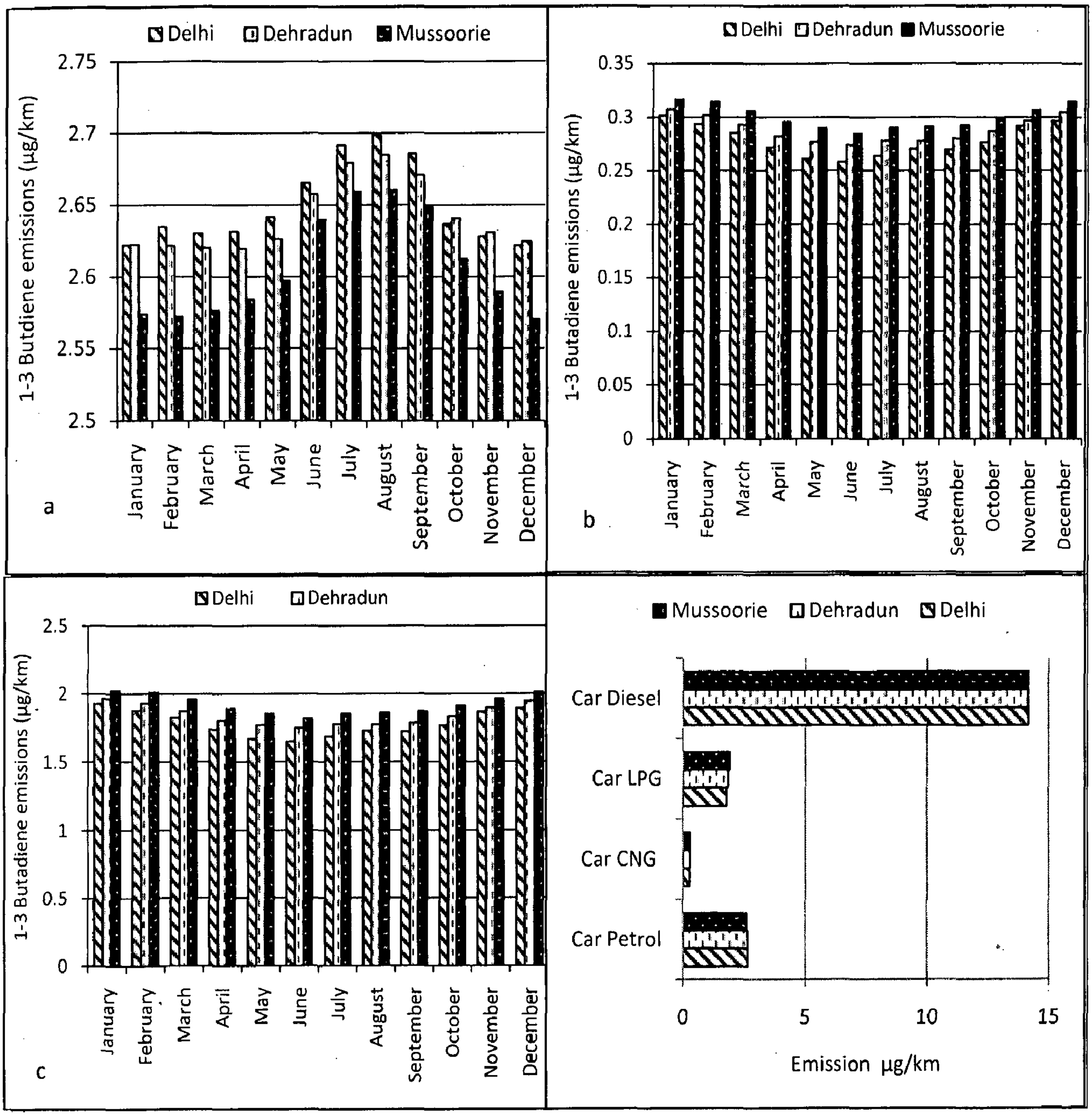


Fig. 4.22: 1-3 Butadiene emission rate from (a) Car Petrol (b) Car CNG (c) Car LPG and (d) Estimated 1-3 Butadiene emission rates of 1-3 Butadiene according to fuel from car in Delhi, Dehradun and Mussoorie

Emission of 1-3 Butadiene from petrol driven car is highest in Delhi (476 mg/yr), followed by Dehradun (474 mg/yr) and Mussoorie (468 mg/yr) (Fig. 4.23a). It means 1-3 Butadiene emissions from petrol driven car is decreasing with increasing altitude. For CNG driven cars, 1-3

Butadiene emissions are highest in Mussoorie (54 mg/yr), followed by Dehradun (52 mg/yr) and Delhi (50 mg/yr) (Fig. 4.23b). It means emission of 1-3 Butadiene increase with altitude. As visible from Fig. 4.23c, 1-3 Butadiene emission is highest in Mussoorie (345 mg/yr), followed by Dehradun (331 mg/yr) and Delhi (320 mg/yr). For LPG driven car, emission of 1-3 Butadiene increases with altitude, while no effect of altitude is observed on diesel driven car.

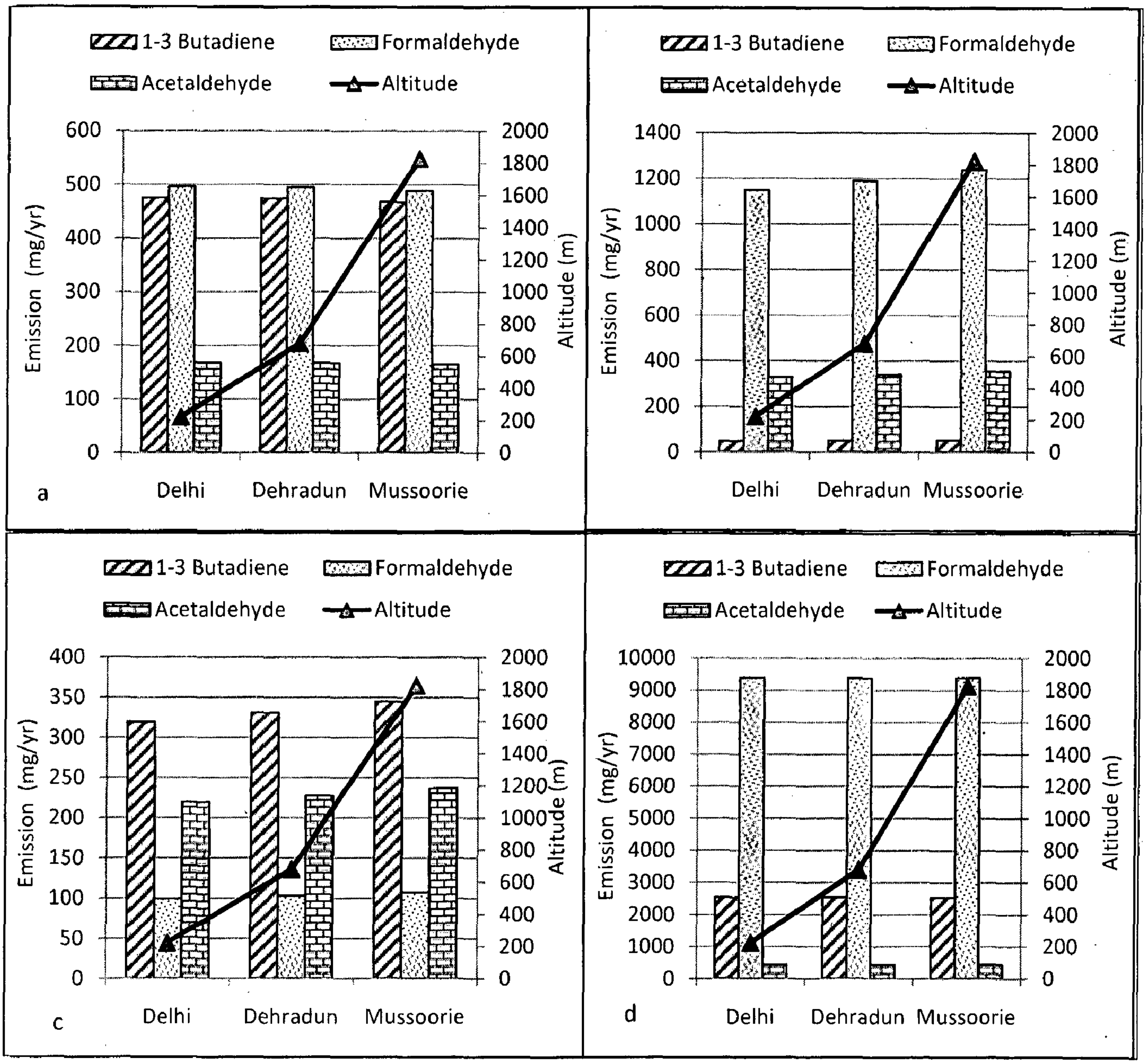


Fig. 4.23: Annual emission of 1-3 Butadiene, Formaldehyde, and Acetaldehyde from per car using (a) Petrol, (b) CNG (c) LPG and (d) Diesel as a fuel in Delhi, Dehradun, and Mussoorie

4.4.6.3. Three wheelers

Emissions of 1-3 Butadiene from four-stroke petrol driven three wheelers are given in Fig. 4.24a. As seen, emissions of 1-3 Butadiene is highest in month of June in Delhi (0.462 µg/km), Dehradun (0.504 µg/km), and Mussoorie (0.767956 µg/km), while least during January. Since, June and January are the hottest and coldest months of the year respectively, it can be said that emissions of 1-3 Butadiene increase with temperature and vice versa. With concern to humidity, January is among the most humid months of the year, whereas June among the least humid.

Fig. 4.24b shows the emissions of 1-3butadiene from two-stroke petrol driven three wheelers in Delhi, Dehradun and Mussoorie. Highest emission rate has been observed in June in Delhi (9.246 µg/km), Dehradun (10.083 µg/km) and Mussoorie (15.359 µg/km), while least during the month of January in all three cities (Fig. 4.24 b). It suggests that emission of petrol driven two-stroke three wheelers rise with temperature. Fig. 4.24c shows the emission of 1-3 Butadiene from four-stroke CNG driven three wheelers. In Fig. 4.24c emissions of 1-3 Butadiene are highest in the month of August in Delhi (4.924 µg/km), Dehradun (4.918 µg/km) and Mussoorie (4.909 µg/km), while least in the month of May in Delhi (4.819 µg/km) and Dehradun (4.829 µg/km) and during April (4.803 µg/km) in Mussoorie. August is among the most humid month of the year, while May and April among least humid. Hence, on the basis of above statement it can be concluded that 1-3 Butadiene emission from four-stroke CNG driven three wheeler is mostly affected by humidity. With increment in humidity emission rate increases and vice versa. Fig. 4.24d shows the emission of 1-3 Butadiene from CNG driven two-stroke three wheelers. As observed in Fig. 4.24d it is found that emission of 1-3 Butadiene is highest in the month of August in Delhi (7.152 µg/km), Dehradun (7.143 µg/km) and Mussoorie (7.129 µg/km), while least during May in Delhi (6.999 µg/km) and Dehradun (7.013 µg/km) and in April in Mussoorie (6.976 µg/km). Similar to CNG driven four-stroke three wheelers, humidity is the dominating factor for 1-3 Butadiene emissions from two-stroke petrol driven three wheelers.

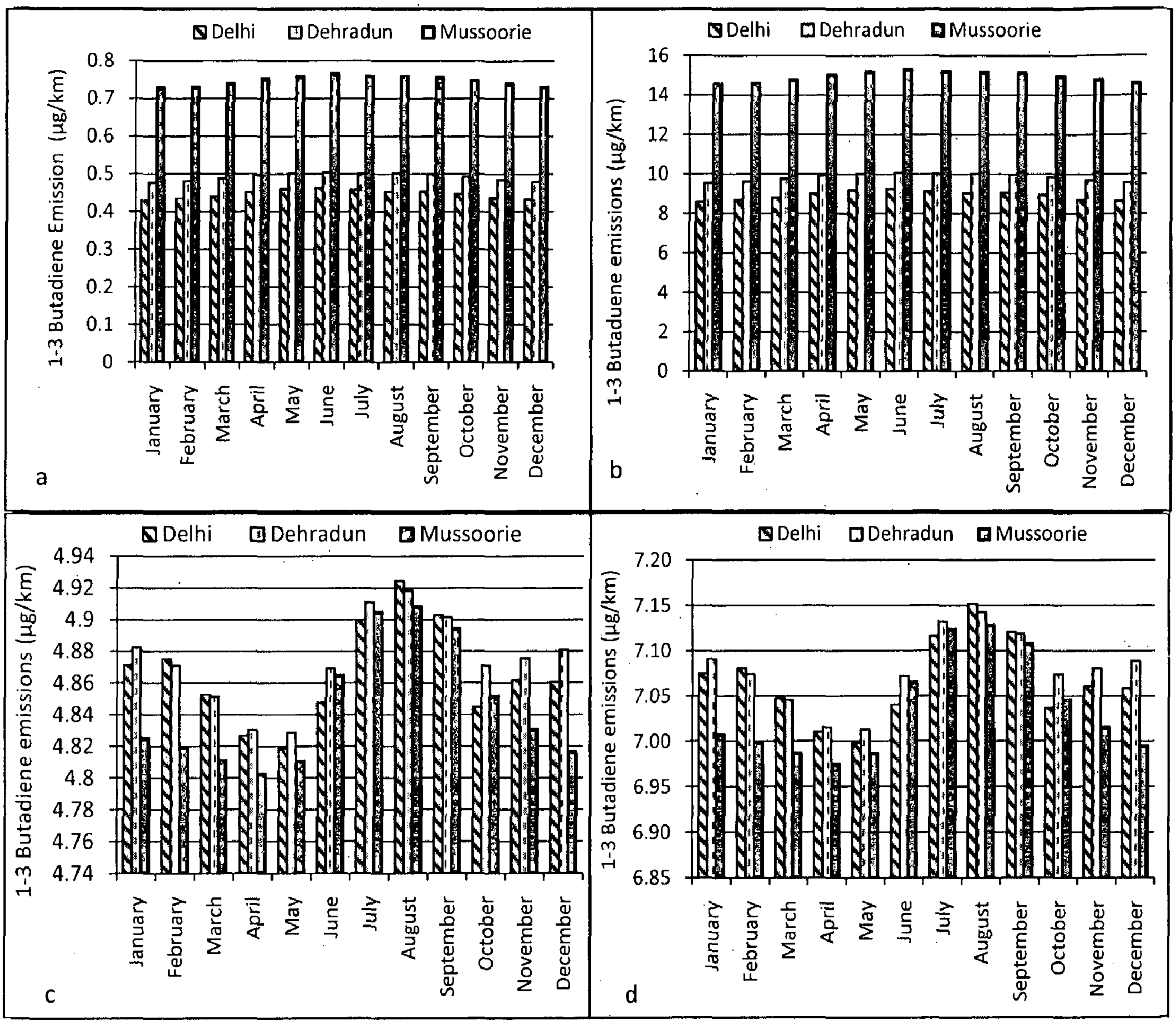


Fig. 4.24: 1-3 Butadiene emission rate from three wheeler (a) Petrol 4-S (b) Petrol 2-S (c) CNG 4-S (d) CNG 2-S in Delhi, Dehradun and Mussoorie

Fig. 4.25a shows the emission rate of 1-3 Butadiene from two- and four-stroke LPG driven three wheelers. It is found that emission rate of 1-3 Butadiene is highest in the month of August in Delhi (19.815 μg/km), Dehradun (19.791 μg/km) and Mussoorie (19.751 μg/km), while least during May in Delhi (19.389 μg/km) and Dehradun (19.431 μg/km) and in April in Mussoorie (19.326 μg/km). As per previous discussion for CNG driven three wheelers, humidity again plays a dominating role for 1-3 Butadiene emissions from LPG driven three wheelers. No effect of humidity and temperature is observed on diesel driven three wheelers (Fig. 4.25b), while impact of altitude on diesel driven three wheelers is visible from Fig. 4.25d. It suggests that 1-3

Butadiene emissions rate of diesel driven three wheelers is higher in Mussoorie (high altitude city) while least in Delhi (less altitude city). Fig. 4.25c shows that emission rates of petrol driven four-stroke three wheelers are least among all three wheelers, followed by CNG driven four and two-stroke three wheelers.

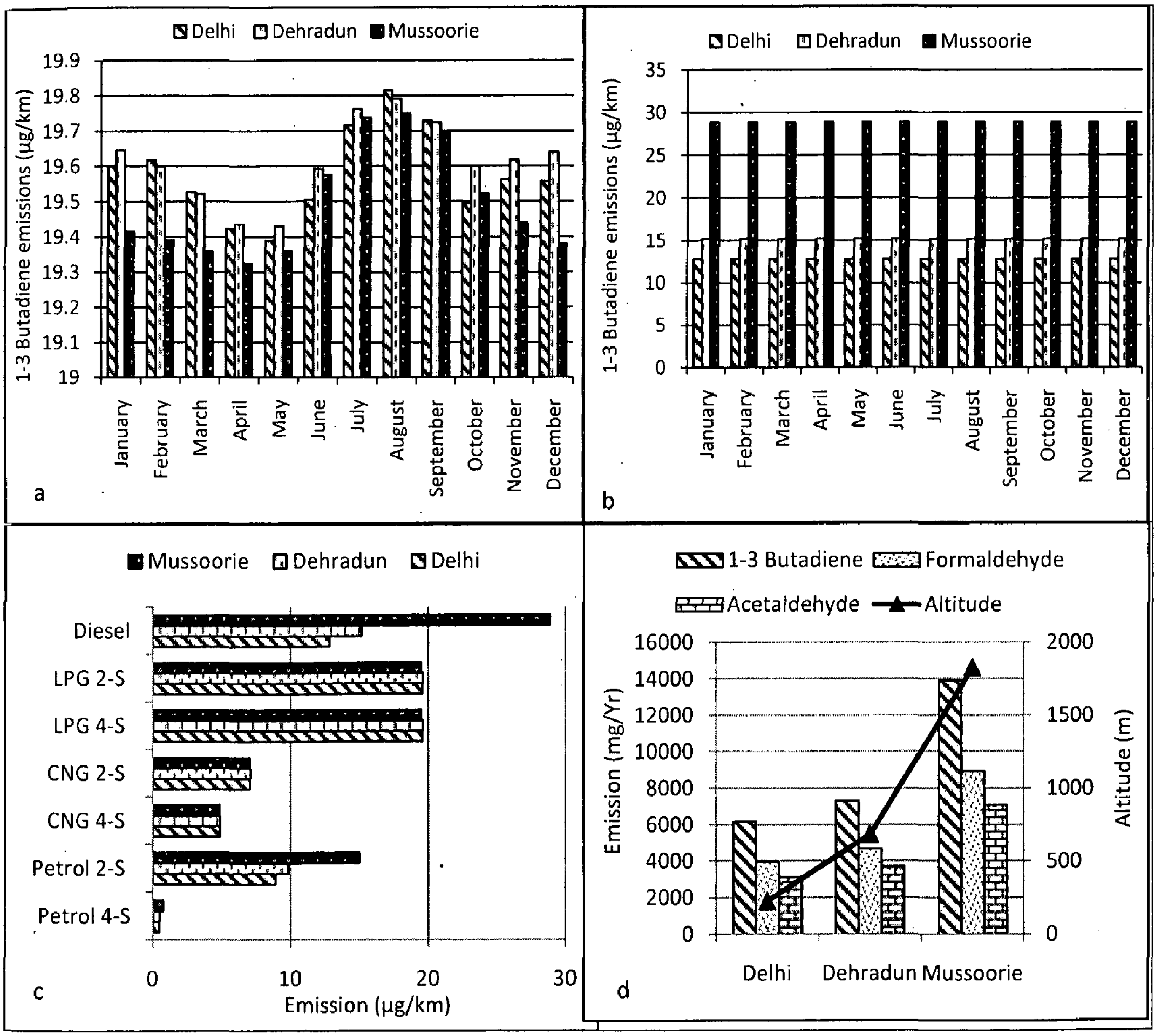


Fig. 4.25: 1-3 Butadiene emission rate from three wheelers (a) LPG 4-S and 2-S (b) Diesel (c) Estimated 1-3 Butadiene emission rates according to fuel from three wheeler in Delhi, Dehradun, and Mussoorie and (d) Annual emission (mg/yr) of 1-3 Butadiene, Formaldehyde, and Acetaldehyde from Diesel driven three wheelers in Delhi, Dehradun and Mussoorie

Fig. 4.26a shows the emissions of 1-3 Butadiene from four-stroke petrol driven three wheelers. It shows that emissions are higher in Mussoorie (361 mg/yr), followed by Dehradun (237 mg/yr) and Delhi (215 mg/yr) (Fig. 4.26a). For petrol driven two-stroke three wheelers higher emission is observed in Mussoorie (7215 mg/yr), followed by Dehradun (4742 mg/yr) and Delhi (4301 mg/yr). On the basis of above discussion, it can be concluded that for two and four-stroke petrol driven three wheelers emission of 1-3 Butadiene is higher in high altitudinal area and least in less altitude area. No effects of altitude on CNG and LPG driven three wheelers are found.

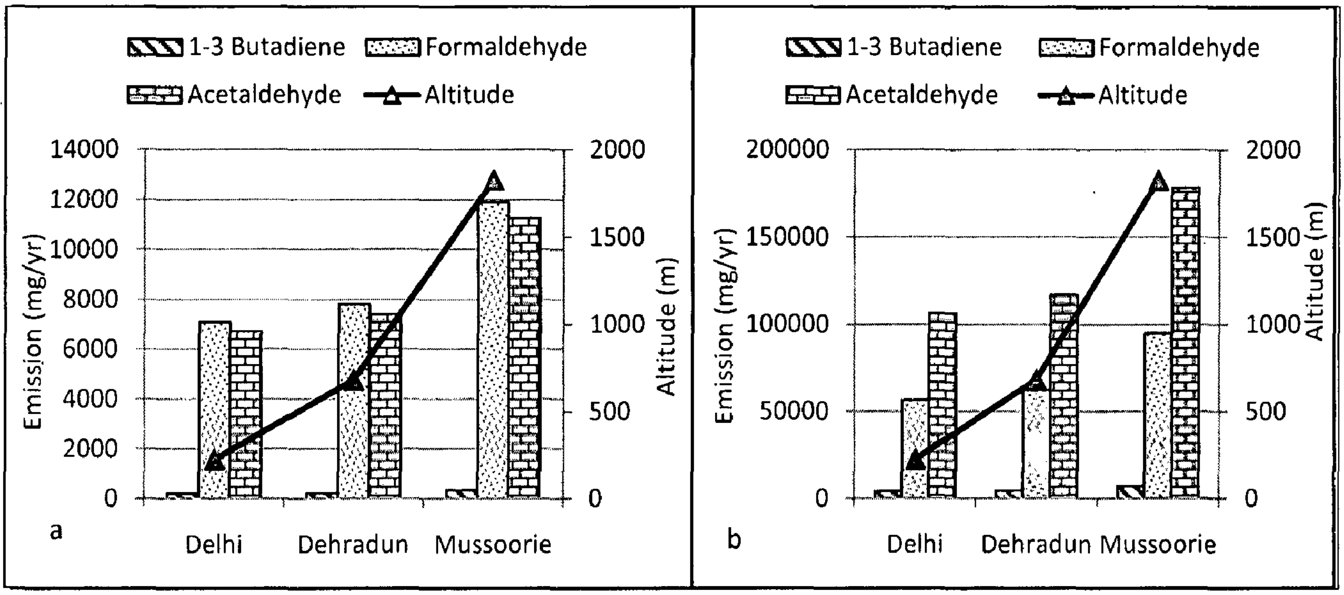


Fig. 4.26: Annual emission of 1-3 Butadiene, Formaldehyde, and Acetaildehyde from (a) Petrol 4-S (b) Petrol 2-S three wheeler in in Delhi, Dehradun, and Mussoorie

4.4.6.4. Buses

There is no effect of temperature and humidity on emission of 1-3 Butadiene diesel driven buses, while emissions of CNG driven buses show significant influence of temperature and humidity (Fig. 4.27a, b). Fig. 4.27b shows that emission of 1-3 Butadiene from CNG driven bus is highest in the month of January, while least during June. Fig. 4.27b indicates that emission of 1-3 Butadiene decreases with increasing temperature in CNG buses. Fig. 4.27 (c and d) shows the emission of 1-3 Butadiene from diesel and CNG driven buses in Delhi, Dehradun and Mussoorie. It indicates the impact of altitude on emission of 1-3 Butadiene from diesel and CNG driven buses. For both diesel and CNG driven buses, 1-3 Butadiene emissions increase with altitude. In comparison to diesel driven buses, 1-3 Butadiene emissions are very less in CNG driven buses.

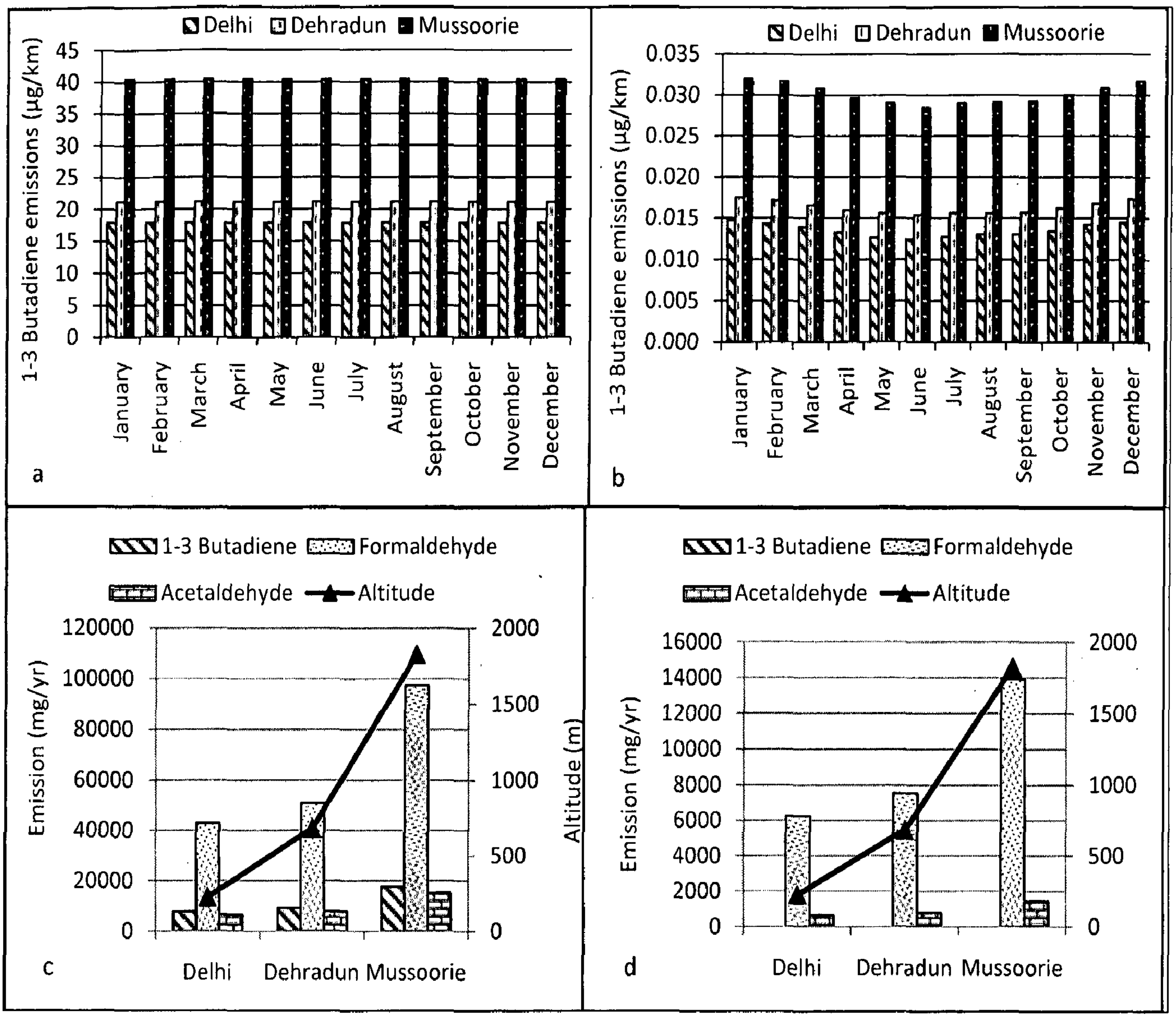


Fig. 4.27: 1-3 Butadiene emission rate from bus (a) diesel (b) CNG and Annual emission (kg/yr) of 1-3 Butadiene, Formaldehyde, and Acetaldehyde from (c) diesel (d) CNG bus in Delhi, Dehradun and Mussoorie

4.4.6.5. Light Commercial Vehicles (LCVs)

No effect of temperature, humidity and altitude is observed on emissions of 1-3 Butadiene from diesel driven LCVs (Fig. 4.28 a, c), while the impact of above factors is noticeable on CNG driven LCVs. Fig. 4.28b shows the impact of ambient temperature and humidity on 1-3 Butadiene emissions. It indicates that emissions are higher in winter (i.e. January, December), while less in the hot season (i.e. May, June). Lesser humidity is observed in the month of May and June, while higher in winter season. It means that emission of 1-3 Butadiene increases when ambient temperature decreases and humidity increases and vice versa. With concern to altitude, emissions of 1-3 Butadiene increase from CNG driven LCVs with increase in altitude. Estimations suggest that CNG driven LCVs emits less emission of 1-3 Butadiene than diesel driven LCVs.

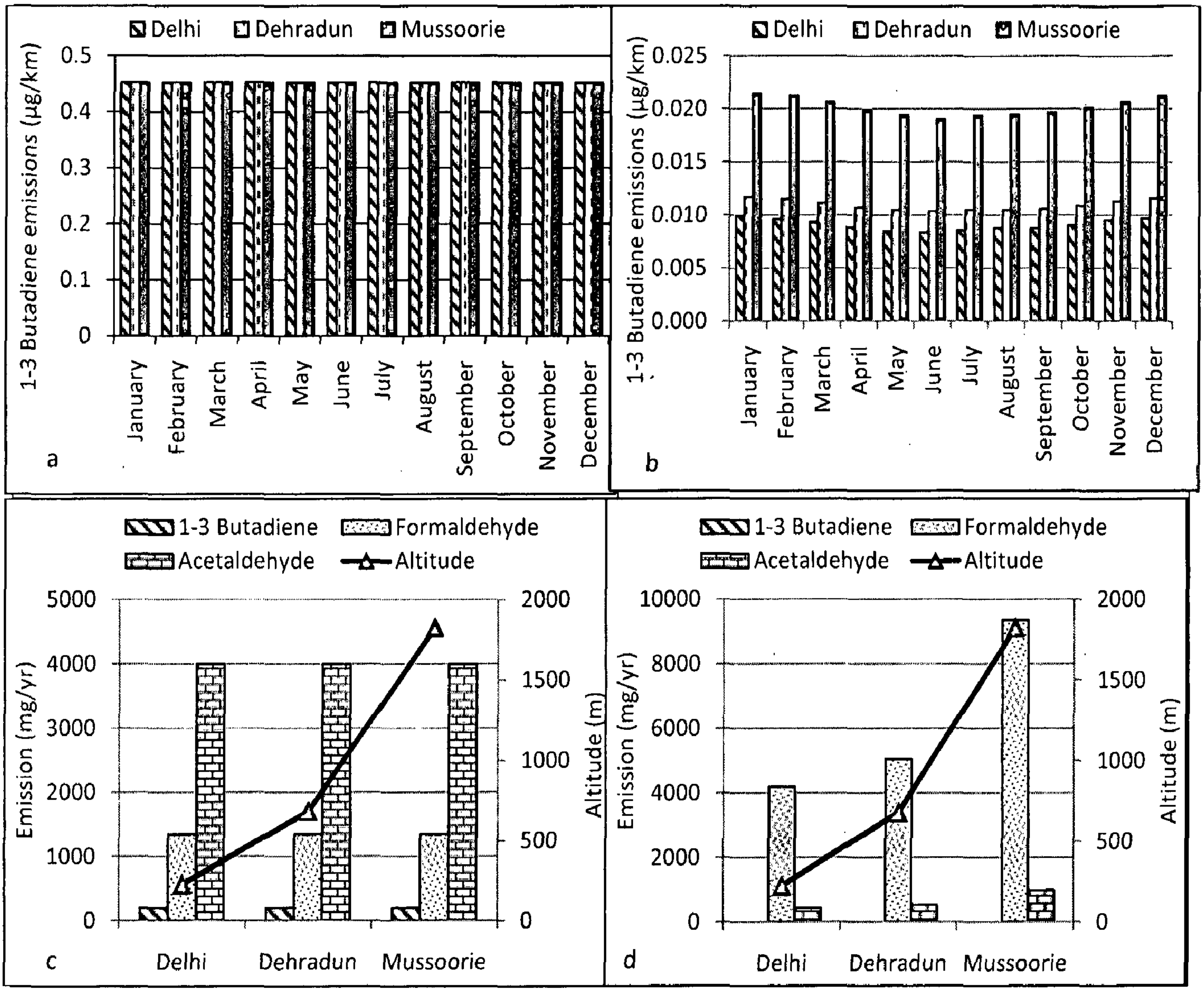


Fig. 4.28: 1-3 Butadiene emission rate from LCVs (a) diesel (b) CNG and Annual emission (mg/yr) of 1-3 Butadiene, Formaldehyde, and Acetaldehyde from (c) diesel (d) CNG LCVs in Delhi, Dehradun and Mussoorie

4.4.6.6. Heavy Commercial Vehicles (HCVs)

No effects of temperature and humidity are observed on the emissions of 1-3 Butadiene from diesel driven HCVs (Fig. 4.29a). While CNG driven HCVs show the effects of humidity and temperature on it. Highest emission is observed in January, while least is observed during June

(Fig. 4.29b). June is among the months having less humidity while January has the highest humidity of the year in Delhi, Dehradun and Mussoorie. Above discussion suggests that emission of 1-3 Butadiene increases with decreasing ambient temperature and rising humidity and vice-versa (Fig. 4.29b). Fig. 4.29c shows the impact of altitude on 1-3 Butadiene emissions from diesel driven HCVs. It indicates that emissions are increasing with altitude and CNG driven HCVs also show similar trend. (Fig. 4.29d). It was observed that emission of 1-3 Butadiene from diesel driven HCVs is about 100 times higher than CNG driven HCVs.

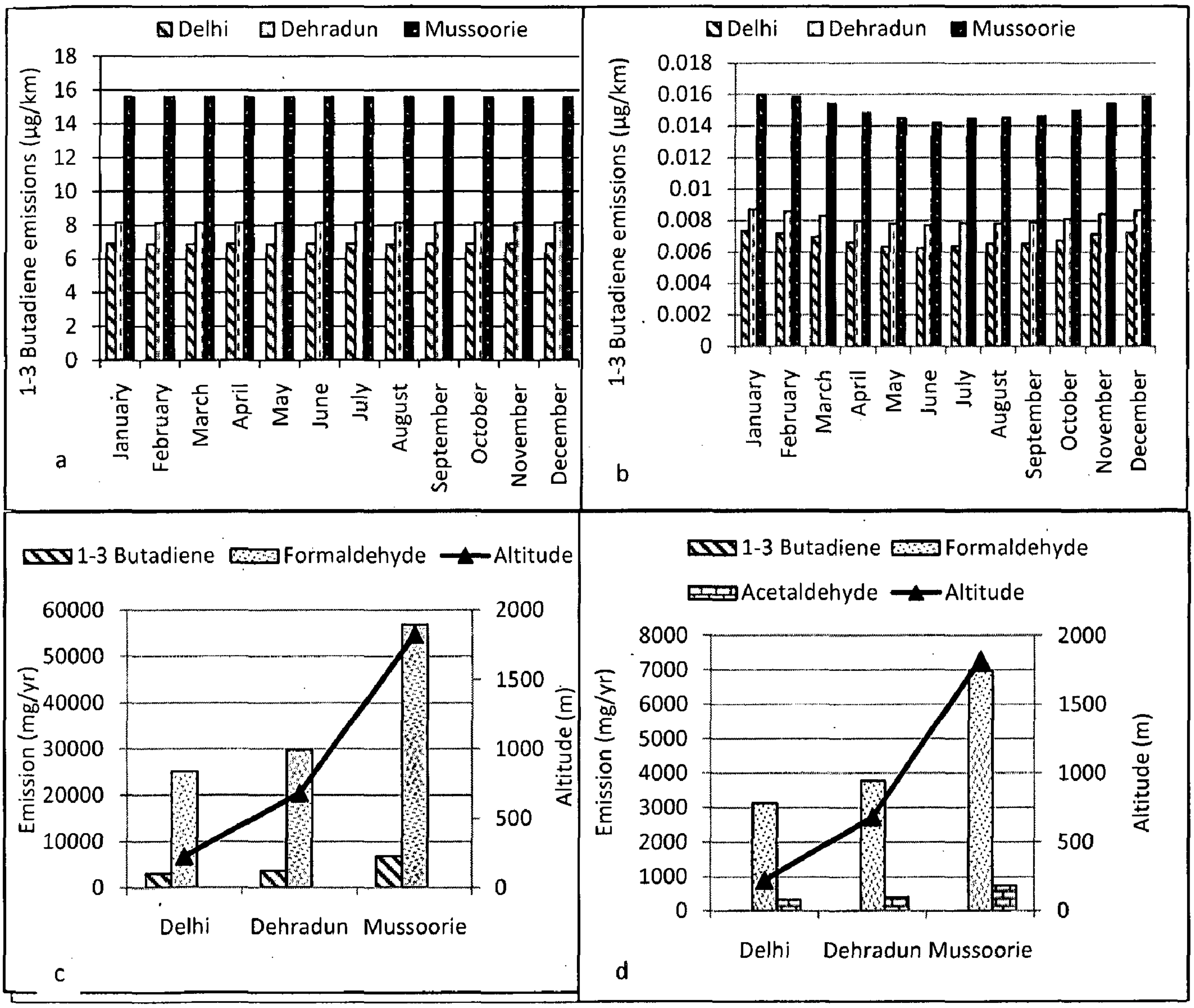


Fig. 4.29: 1-3 Butadiene emission rate from HCVs (a) diesel (b) CNG and Annual emission (kg/yr) of 1-3 b , Formaldehyde, and Acetaildehyde from (c) diesel (d) CNG HCVs in Delhi, Dehradun and Mussoorie

4.4.7. Formaldehyde emissions

4.4.7.1. Two Wheelers

Fig. 4.30a shows the emission rate of Formaldehyde from two wheelers in Delhi, Dehradun and Mussoorie. It is observed that emission rate of Formaldehyde from two wheelers is highest in the month of June in Delhi (197.748 μg/km), Dehradun (215.63 μg/km) and Mussoorie (328.477 μg/km). On the other hand, least emission rates are observed during January in Delhi (183.528 μg/km), Dehradun (204.075 μg/km) and Mussoorie (312.038 μg/km). It indicates that emissions of Formaldehyde increase with temperature and vice versa. Similarly, with increase in humidity it increases and vice versa. Fig. 4.21b shows the relationship between altitude and Formaldehyde emissions. It shows that emissions increase with altitude. Highest annual emissions have been estimated in Mussoorie (37876 mg/yr), followed by Dehradun (24894 mg/yr) and Delhi (37876 mg/yr). Fig. 4.30b shows the estimated emission rate of various two wheelers in all three cities. The figure reveals that two-stroke motorcycles have least emission rate in all three cities, followed by four-stroke motorcycles, while four-stroke scooters emit highest Formaldehyde among all the two wheelers.

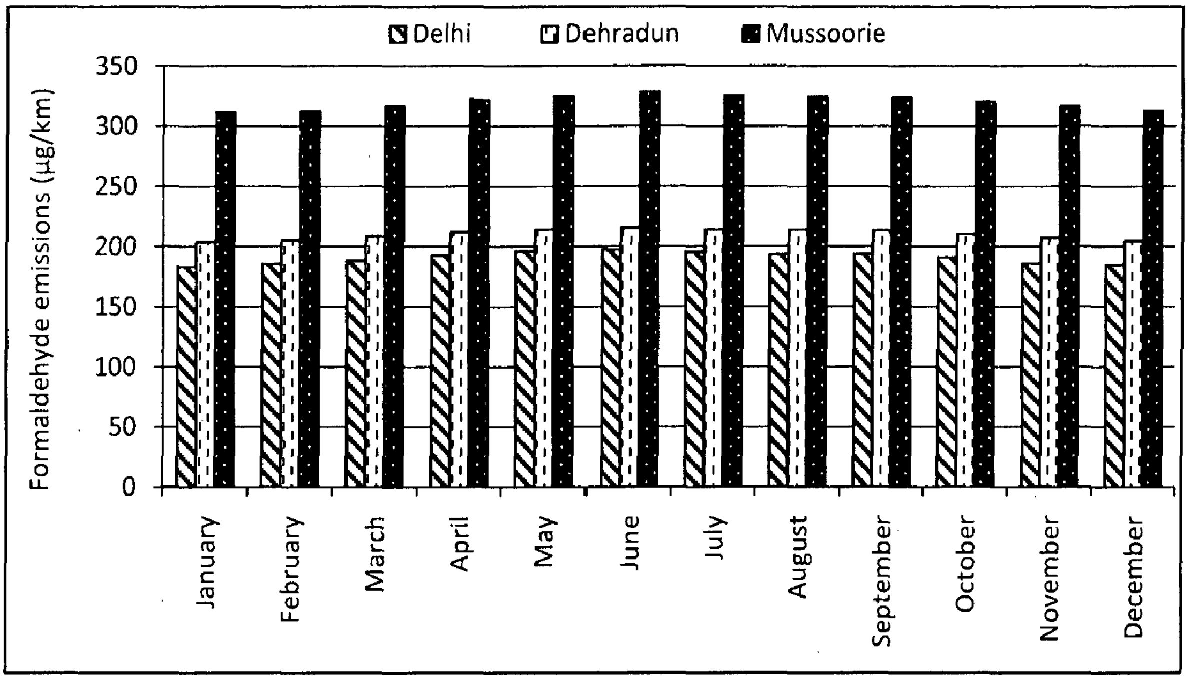


Fig. 4.30: (a) Monthly Formaldehyde emissions from two wheelers in Delhi, Dehradun, and Mussoorie

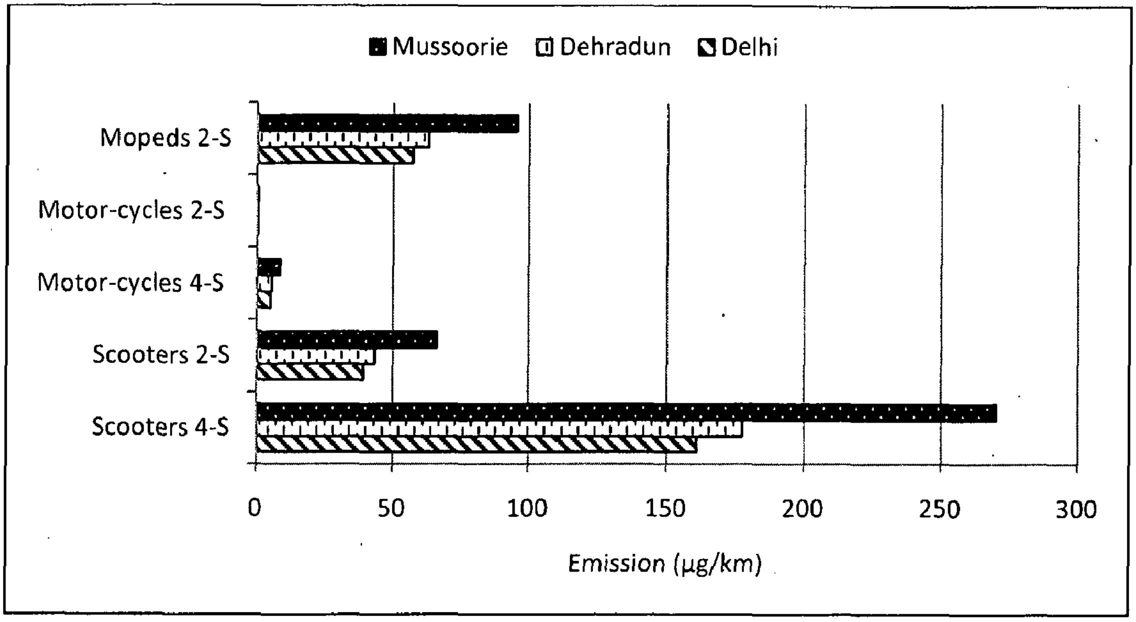


Fig. 4.30: (b) Estimated Formaldehyde emission rates from various two wheelers in Delhi, Dehradun, and Mussoorie

4.4.7.2. Cars

Fig. 4.31a shows the emission rate of petrol driven cars in Delhi, Dehradun and Mussoorie. It shows that Formaldehyde emission is highest in the month of August in Delhi (2.818 µg/km), Dehradun (2.803 µg/km) and Mussoorie (2.778 µg/km). While least emission rate have been observed in the month of December in Delhi (2.737 µg/km) and Mussoorie (2.684 µg/km) and during April in Dehradun (2.736 µg/km). Fig.4.31b shows the emission rate of Formaldehyde from CNG driven cars. It indicates that emission of Formaldehyde is higher in the month of January in Delhi (6.938 µg/km), Dehradun (7.064 µg/km) and Mussoorie (7.277 µg/km), while least emissions are observed in the month of June in respective cities. Similar to CNG driven cars, highest emission of LPG driven car is observed in the month of January and least during June (Fig. 4.31c). On the above basis, it can be concluded that emissions of Formaldehyde decreases with increase in ambient temperature and vice versa in CNG and LPG driven cars; while humidity shows a direct relation with Formaldehyde emissions from petrol driven cars. No effect of temperature and humidity is observed on diesel driven cars.

Fig. 4.23a shows the relationship between altitude and Formaldehyde emission from petrol driven cars. The figure reveals that annual emission of Formaldehyde from petrol driven cars is higher in low altitudinal area like Delhi, while less emission is observed in the high altitudinal area like Mussoorie. In case of CNG and LPG driven cars, Formaldehyde emissions increase with altitude (Fig. 4.23 b, c). There is no effect of altitude on diesel driven cars (Fig. 4.23d). Fig. 4.31d shows the emission rate of different car types in Delhi, Dehradun and Mussoorie. It shows that LPG driven cars emit less Formaldehyde in comparison to other car types, followed by petrol driven cars.

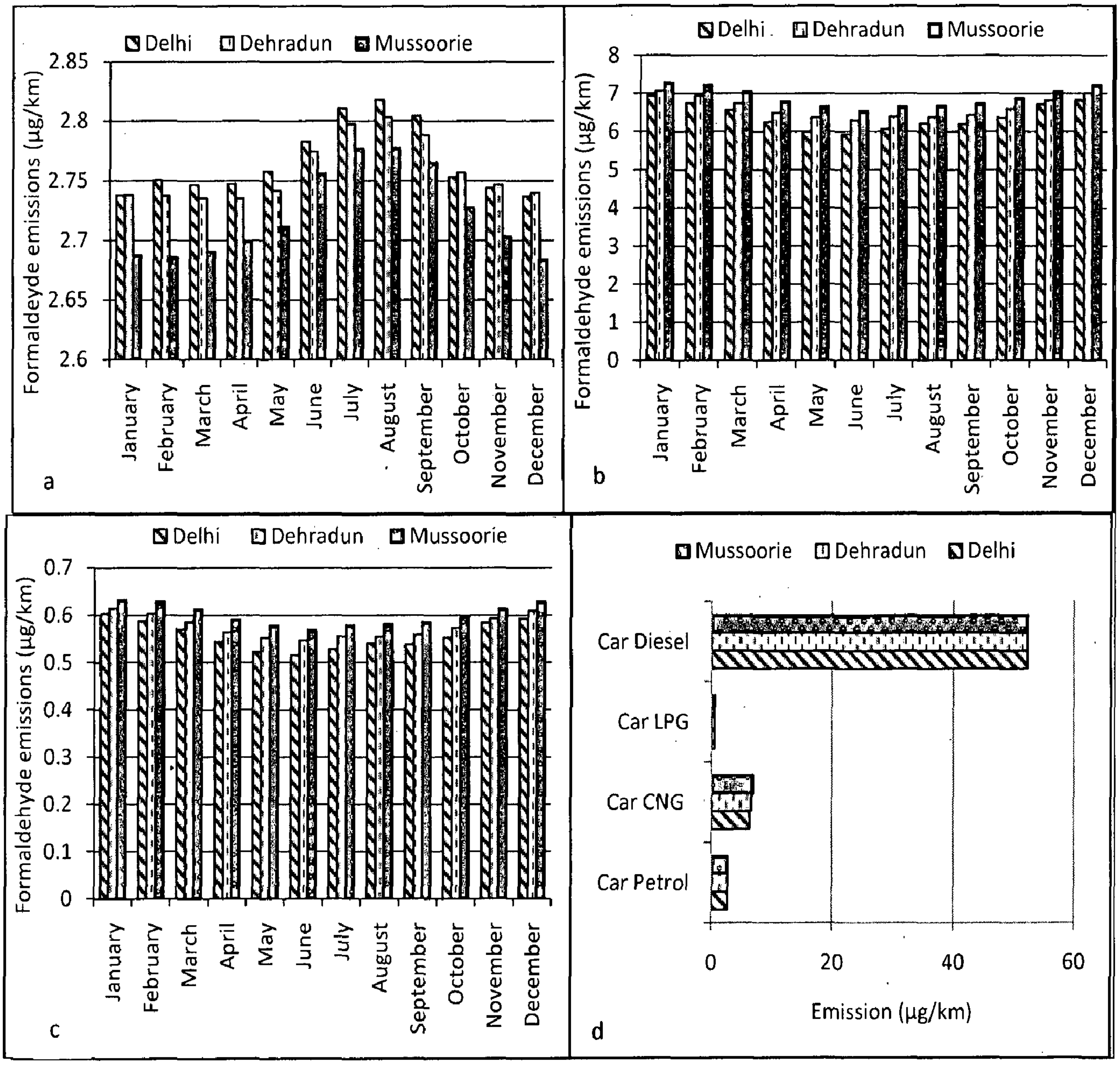


Fig. 4.31: Formaldehyde emission rate from (a) Car Petrol (b) Car CNG (c) Car LPG and (d) Estimated Formaldehyde emission rates according to car type in Delhi, Dehradun, and Mussoorie

4.4.7.3. Three wheelers

Fig. 4.32a shows the emission rates of Formaldehyde from petrol driven four-stroke three wheelers. It is observed that emission of Formaldehyde is highest in the month of June (hottest month) in Delhi (15.257 µg/km), Dehradun (16.636 µg/km) and Mussoorie (25.342 µg/km); while least during January in all three cities (Fig. 4.32a). It can be concluded on the above basis, that emission of Formaldehyde from four-stroke petrol driven three wheelers increases with increasing ambient temperature and vice versa. Similar to petrol driven four-stroke three wheelers, emission rate of Formaldehyde from petrol driven two-stroke three wheelers increases with temperature (Fig. 4.32b). Fig. 4.32 (c and d) indicates that Formaldehyde emissions from two-strokes and four-strokes CNG driven three wheelers is higher in August, the most humid month in all three cities. Least emission rate of Formaldehyde is observed in the month of May in Delhi, Dehradun; while in the month of April in Mussoorie. May and April are among the least humid months of the year. Fig. 4.32c and 4.32d suggest that humidity is dominating over temperature and with increase in humidity, emissions of Formaldehyde increases from four-strokes and two-strokes CNG driven three wheelers and vice versa (Fig. 4.32c, d).

Fig. 4.26a shows the annual emission of Formaldehyde from petrol driven four-stroke three wheelers in Delhi, Dehradun and Mussoorie. It shows that emission of Formaldehyde increase with altitude. Estimations suggest that emission of Formaldehyde in Delhi is 7097 mg/yr, Dehradun- 7825 mg/yr and 11905 mg/yr in Mussoorie. Similar to four-stroke petrol driven three wheelers, two-stroke petrol driven three wheelers show same trend. Formaldehyde emissions from two-stroke petrol driven three wheelers are 56665 mg/yr in Delhi followed by 62481 mg/yr in Dehradun and 95063 mg/yr in Mussoorie. There is no effect of altitude on CNG and LPG driven three wheelers as per the findings of the study.

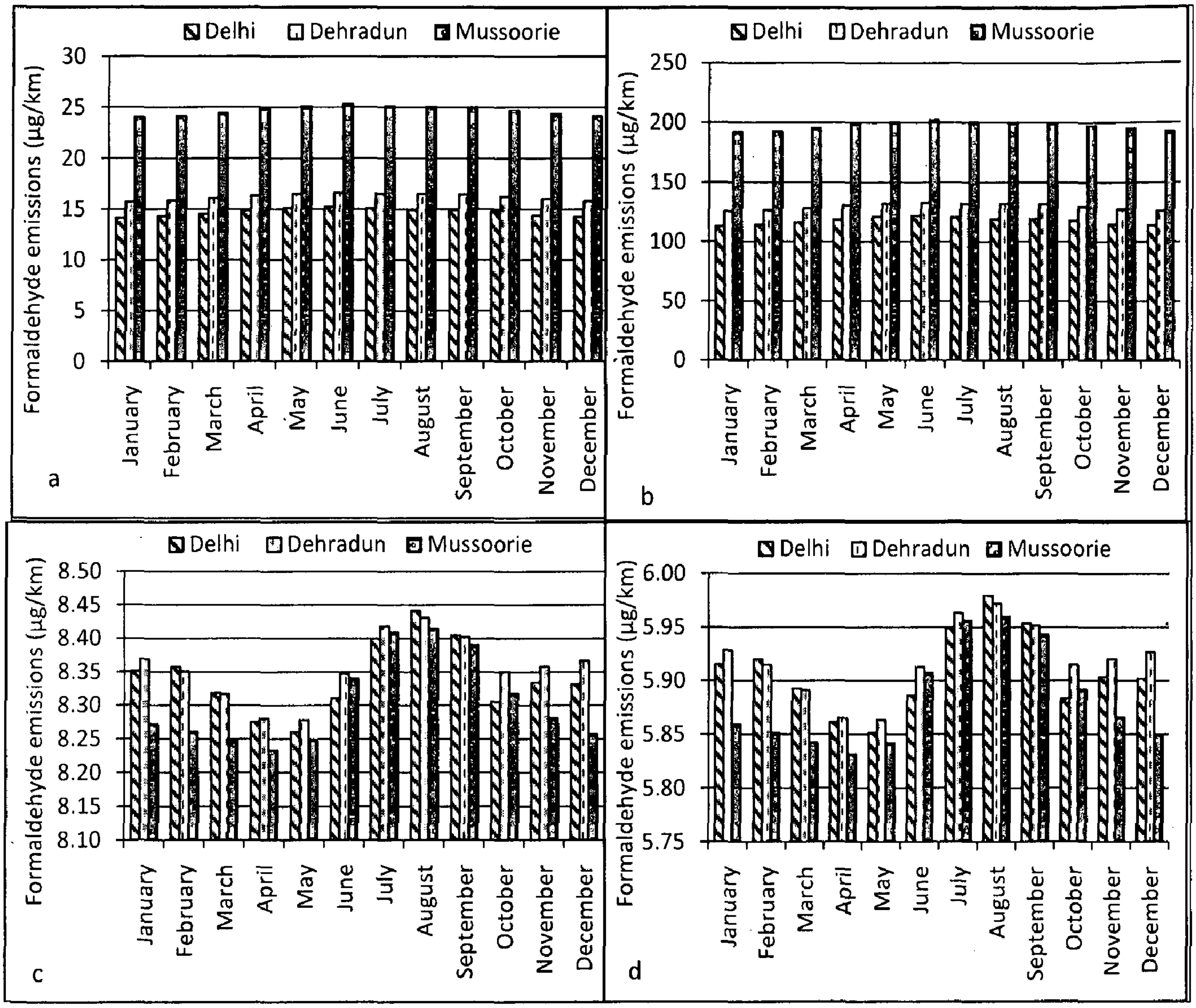


Fig. 4.32: Formaldehyde emission rate from three wheeler (A) Petrol 4-S (B) Petrol 2-S (C) CNG 4-S (D) CNG 2-S in Delhi, Dehradun and Mussoorie

Fig. 4.33 (a and b) shows the emission rates of Formaldehyde from LPG driven four-stroke and two-stroke three wheelers in all the three cities. Estimation suggest that highest emission of Formaldehyde from LPG driven two- and four-stroke three wheelers is in the month of August (most humid month) in all the three cities. Least emission is observed in the month of May in Delhi and Dehradun and during April in Mussoorie. Both April and May are among the least humid months. On the above discussion it can be concluded that Formaldehyde emission from two- and four-stroke LPG driven three wheelers increases and decreases with humidity. The results suggest that there is no effect of ambient temperature and humidity on emission of

Formaldehyde from diesel driven three wheelers (Fig. 4.33c). Fig. 4.25d shows that emission of Formaldehyde from diesel driven three wheelers is affected by altitude. It indicates that emission of Formaldehyde increases with altitude. Fig. 4.33d shows that two-stroke CNG driven three wheelers are the best three wheelers which emit least amount of Formaldehyde emission. While two-stroke petrol driven three wheelers emit highest Formaldehyde in all three cities.

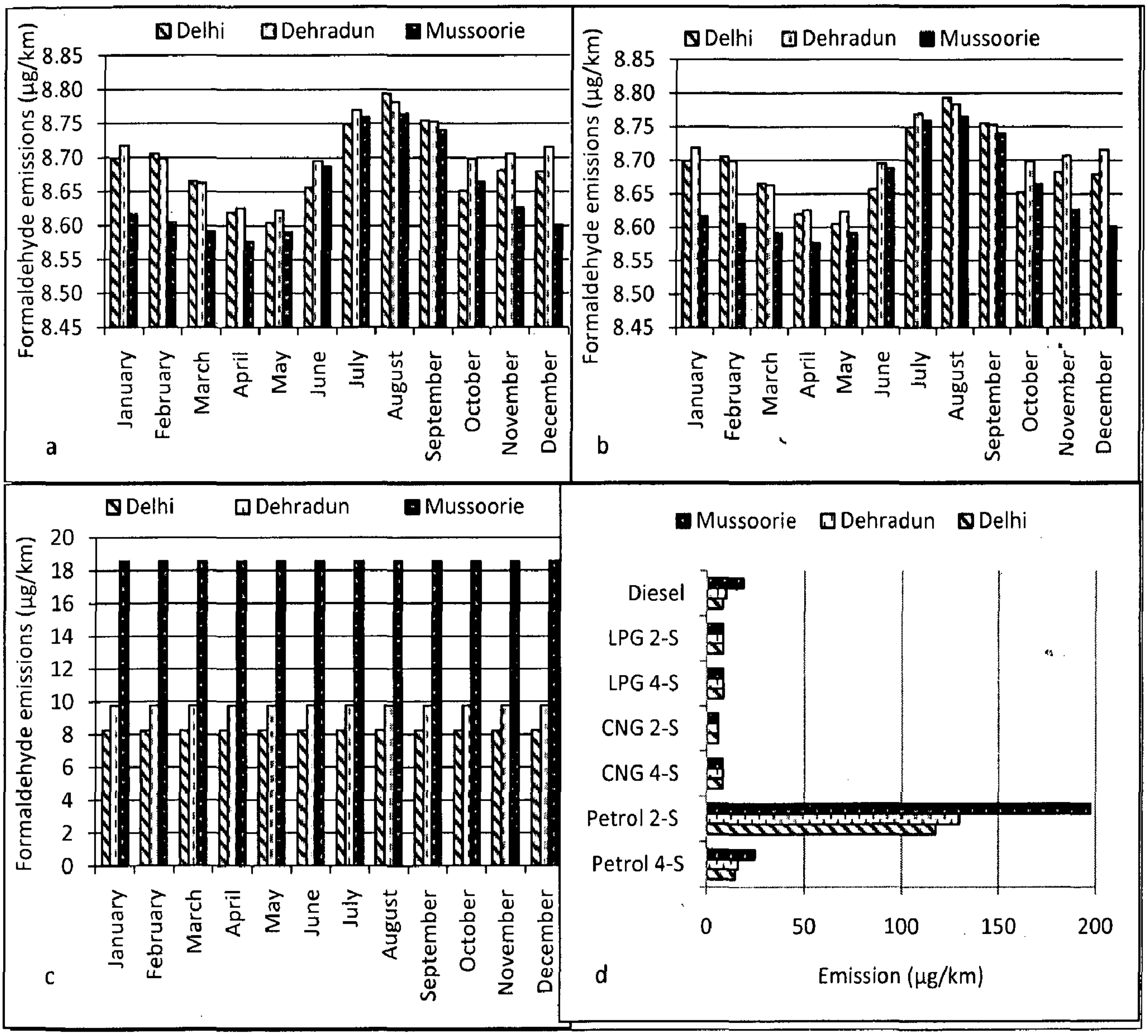


Fig. 4.33: Formaldehyde emission rate from three wheeler (a) LPG 4-S (b) LPG 2-S (c) Diesel and (d) Estimated Formaldehyde emission rates according to fuel from three wheeler in Delhi, Dehradun, and Mussoorie

4.4.7.4. Buses

No effects of humidity and temperature is observed on diesel driven buses (Fig. 4.34 a) while the impact is significant as shown in Fig.4.34b on CNG driven buses. Fig. 4.34b shows the emission of Formaldehyde from CNG driven buses during various months of the year. It shows that emission of Formaldehyde is highest in the month of January (coldest month of year) in Delhi, Dehradun and Mussoorie, while least in the month of June (among most hot months of the year). Fig. 4.34b suggests that when ambient temperature increases, emissions of Formaldehyde from CNG buses decrease and vice-versa. Here ambient temperature is dominating factor than humidity. Fig. 4.27c shows that Formaldehyde emissions from diesel driven buses are highest in Mussoorie (97475 mg/yr), followed by Dehradun (51048 mg/yr) and Delhi (43125 mg/yr). Similar to diesel driven buses, emission from CNG driven buses are highest in Mussoorie (13958 mg/yr), followed by Dehradun (7553 mg/yr) and Delhi (6272 mg/yr). Accordingly, it can be concluded that emission of Formaldehyde from both diesel and CNG driven buses are increasing with altitude. Emission rate of Formaldehyde from CNG driven buses is lesser than diesel driven buses.

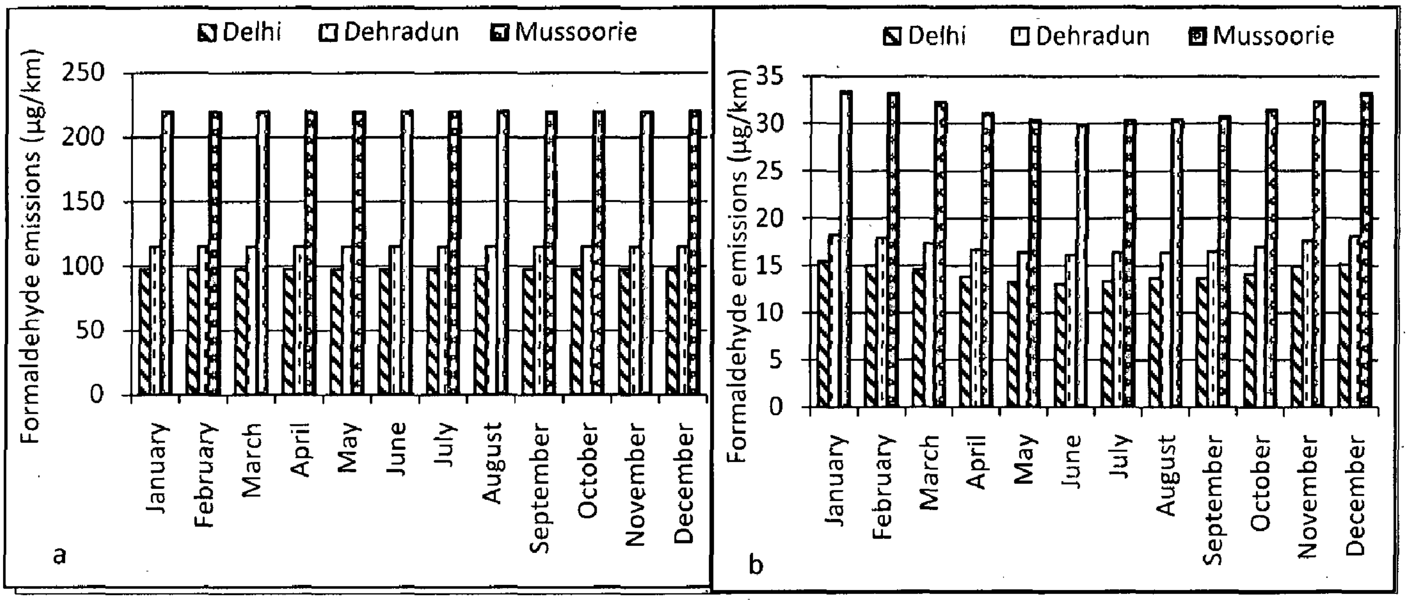


Fig. 4.34 : Formaldehyde emission rate from bus (a) diesel and (b) CNG in Delhi, Dehradun and Mussoorie

4.4.7.5. Light Commercial Vehicles (LCVs)

There are no effects of temperature, humidity and altitude on emission of Formaldehyde from diesel driven LCVs (Fig. 4.28c, 4.35a). While CNG driven LCVs are affected by change in ambient temperature, humidity and altitude (Fig. 4.28 d, 4.35b). Fig. 4.35b shows that emission of Formaldehyde increases with decrease in ambient temperature. Highest emission is observed in the month of January in Delhi (10.37 μg/km), Dehradun (12.27 μg/km) and Mussoorie (22.42 μg/km); while least during June in Delhi (8.76 μg/km), Dehradun (10.83 μg/km) and Mussoorie (19.96 μg/km). Estimates indicate that emission of Formaldehyde from diesel driven LCVs is lesser than CNG driven LCVs.

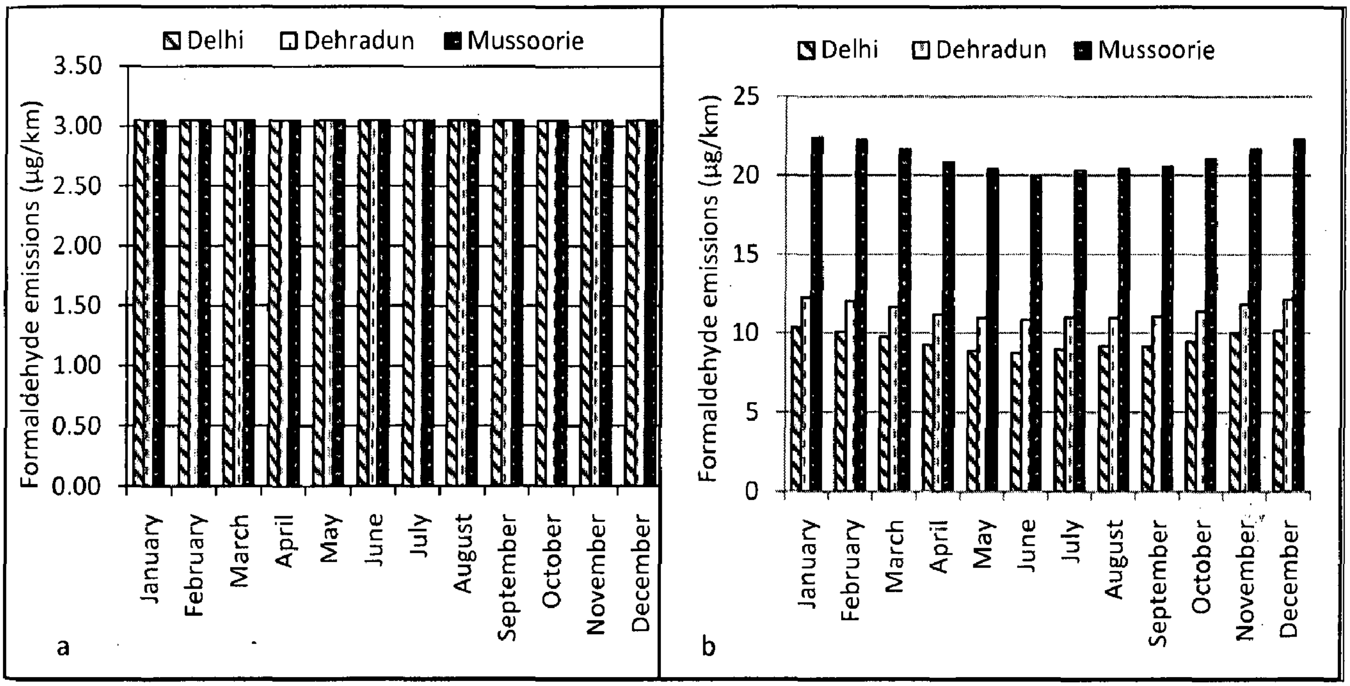


Fig. 4.35: Formaldehyde emission rate from LCVs (a) diesel and (b) CNG in Delhi, Dehradun and Mussoorie

4.4.7.6. Heavy Commercial Vehicles (HCVs)

No effects of ambient temperature and humidity are observed on the emission of Formaldehyde from diesel driven HCVs (Fig. 4.36a). However, there is a significant impact of altitude, humidity and temperature on CNG driven HCVs. The highest emission of Formaldehyde from CNG driven HCVs is observed in the month of January in Delhi (6.53 μg/km), Dehradun (8.07

μg/km) and Mussoorie (14.88 μg/km), whereas least during June in Delhi (7.73 μg/km), Dehradun (9.14 μg/km) and Mussoorie (16.71 μg/km). With respect to altitude, emission of Formaldehyde from diesel driven HCVs is highest in Mussoorie (56845 mg/yr), followed by Dehradun (29770 mg/yr) and Delhi (25149 mg/yr) (Fig. 4.29c). Similar to diesel driven HCVs, emission of Formaldehyde from CNG driven HCVs is highest in Mussoorie (6979 mg/yr), followed by Deharadun (3777 mg/yr) and Delhi (3136 mg/yr) (Fig. 4.30 d). Emission rate of Formaldehyde from CNG driven HCVs is quite less than diesel driven HCVs.

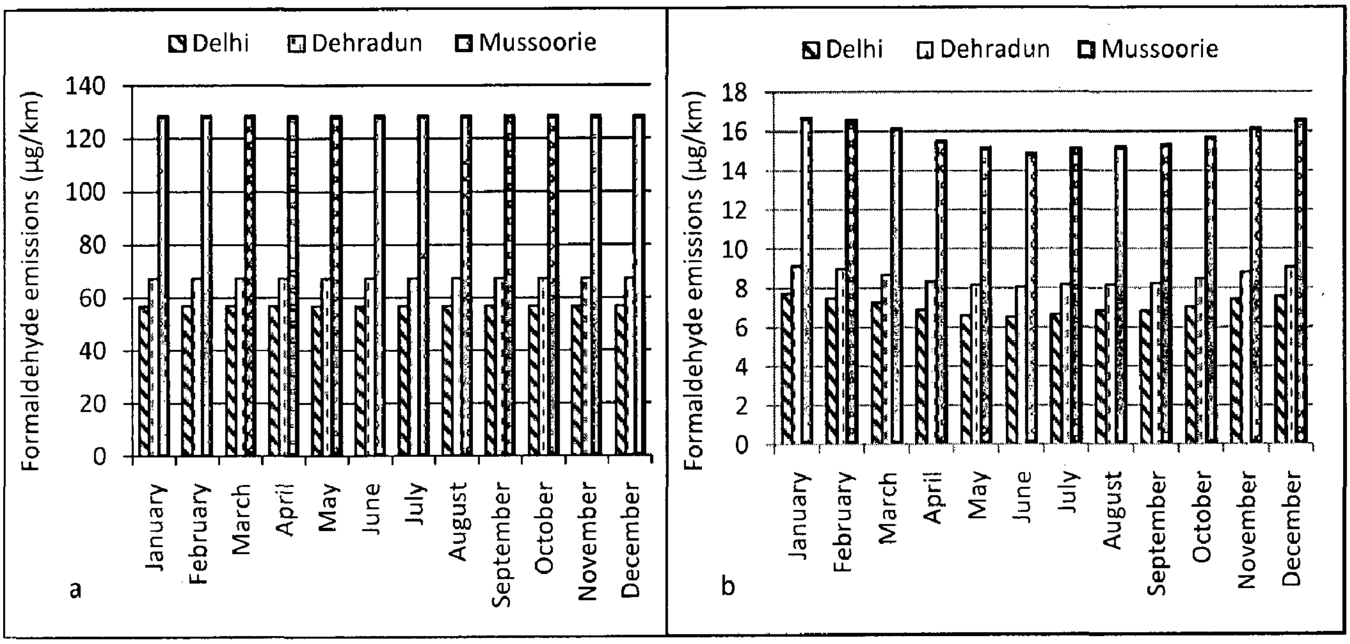


Fig. 4.36: Formaldehyde emission rate from HCVs (a) diesel and (b) CNG in Delhi, Dehradun and Mussoorie

4.4.8. Acetaldehyde emissions

4.4.8.1. Two Wheelers

Fig. 4.37a shows monthly Acetaldehyde emissions from two wheelers in Delhi, Dehradun and Mussoorie. It indicates that Acetaldehyde emissions are highest in the month of June in Delhi (115.022 μg/km), Dehradun (125.423 μg/km) and Mussoorie (191.061 μg/km). Least emission is observed in the month of January in Delhi (106.75 μg/km), Dehradun (118.701 μg/km) and Mussoorie (181.499 μg/km). Above observations suggest that temperature is a dominating factor compared to humidity for Acetaldehyde emissions from two wheelers. Acetaldehyde emissions increase with temperature. Fig. 4.21b shows the emission of Acetaldehyde from two wheelers increase with altitude. Fig. 4.37b shows the Acetaldehyde emission rate with respect to various two wheelers type. It reveals that among all two wheelers, Acetaldehyde emission rate of two-stroke motorcycles is minimum, followed by four-stroke motorcycles and mopeds, while four-stroke scooters have maximum emission rate.

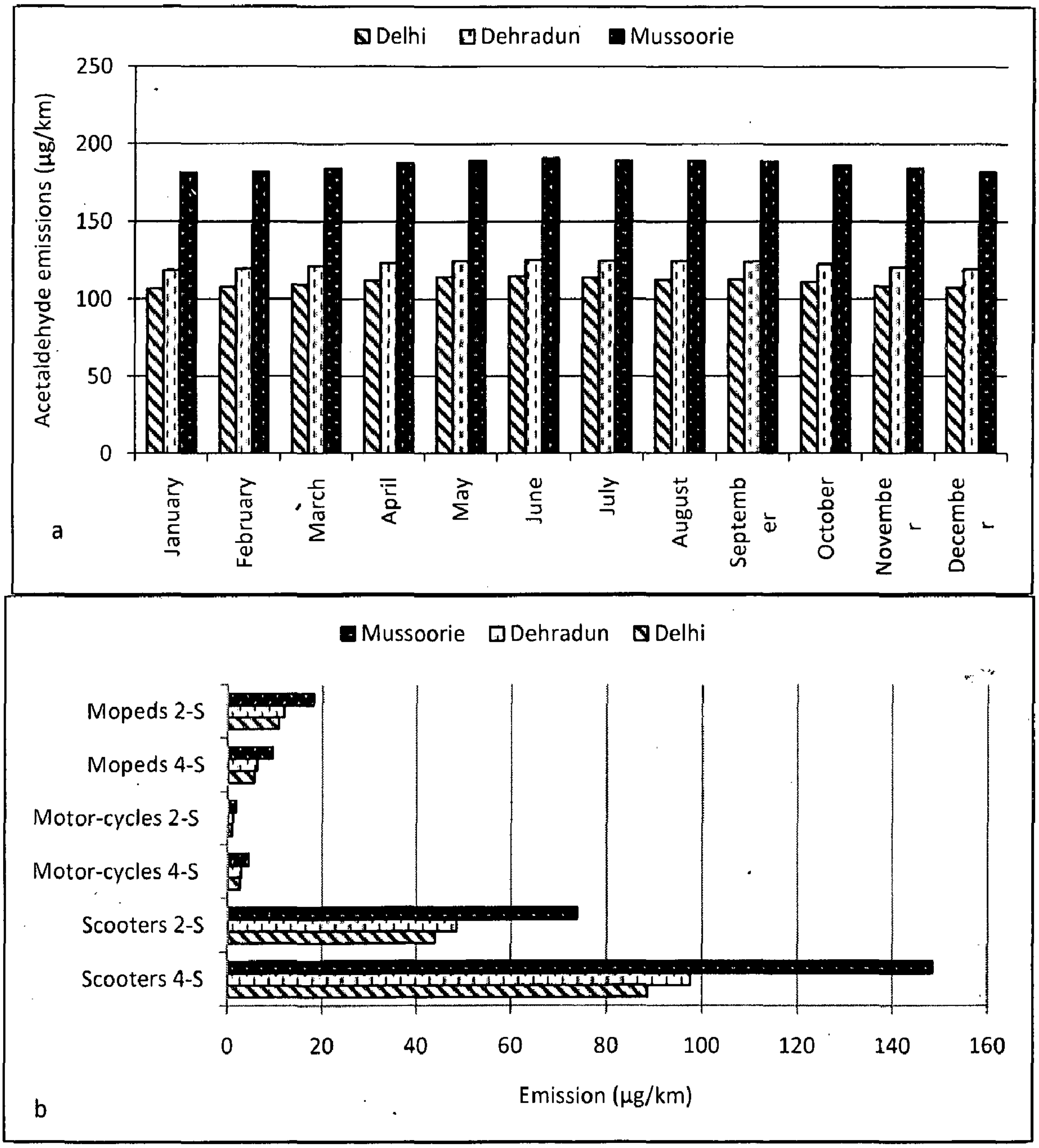


Fig. 4.37: (a) Monthly Acetaldehyde emissions from two wheelers (b). Estimated Acetaldehyde emission rates from various two wheelers in Delhi, Dehradun and Mussoorie

4.4.8.2. Cars

Fig. 4.38a shows the emission of Acetaldehyde from petrol driven cars indicating highest emission of Acetaldehyde is in the month of August in Delhi (0.952 µg/km), Dehradun (0.947 µg/km) and Mussoorie (0.938 µg/km). Least emission is observed in the month of December in Delhi and Mussoorie, and April in Dehradun (Fig.4.38a). August is among the most humid month of the year, while December and April are among the least humid months of the year. Fig. 4.38b shows the emission of Acetaldehyde from CNG driven cars in all three cities. It indicates that CNG driven cars emit highest emission of Acetaldehyde in the month of January in Delhi (1.991µg/km), Dehradun (2.027 µg/km) and Mussoorie (2.088 µg/km). Least emission of Acetaldehyde is observed during June in Delhi (1.704 µg/km), Dehradun (1.807 µg/km) and Mussoorie (1.879 µg/km). Thus it can be concluded that Acetaldehyde emissions from CNG and LPG driven cars increase when temperature decreases and vice versa. Highest emission rate of Acetaldehyde from LPG driven cars is observed in the month of January in all three cities, while least in January. There are no effects of altitude, humidity and temperature on the diesel driven cars (Fig. 4.23d). Fig. 4.23a shows the annual emission of Acetaldehyde from petrol driven cars. It shows that emission of Acetaldehyde increase with decrease in altitude, whereas emission from CNG and LPG driven cars increase with altitude. As per Acetaldehyde emission rate, petrol driven cars emit the least emission in comparison to other fuel driven cars (Fig.4.38 d).

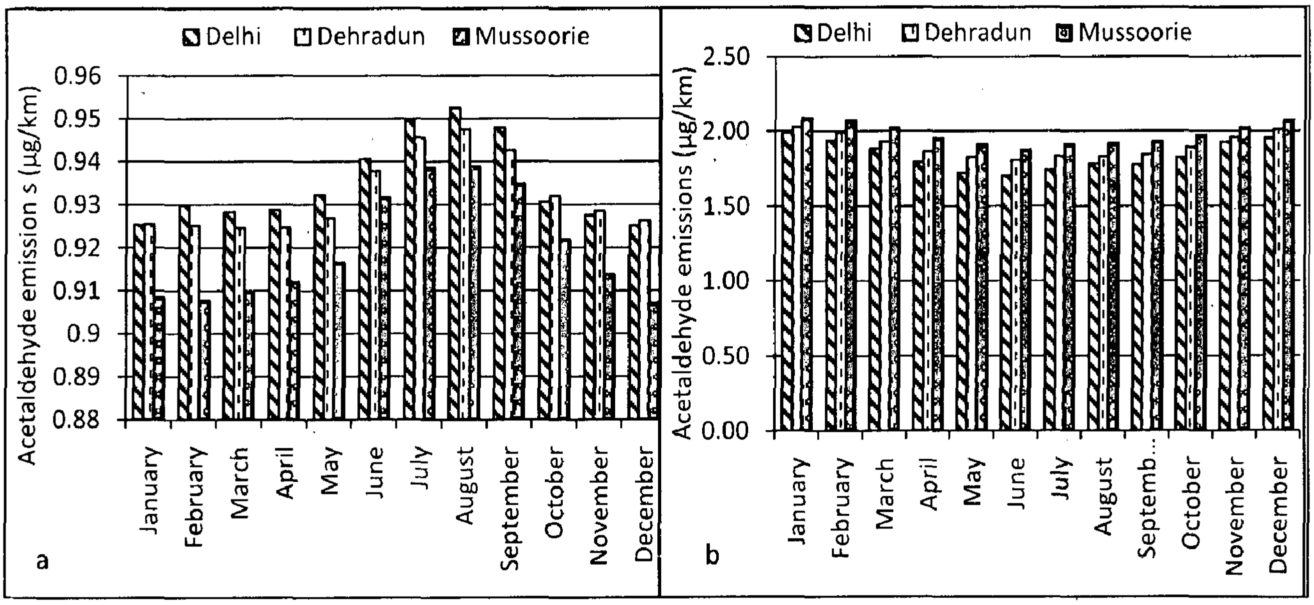


Fig. 4.38: Acetaldehyde emission rate from (a) Car Petrol (b) Car CNG in Delhi, Dehradun, and Mussoorie

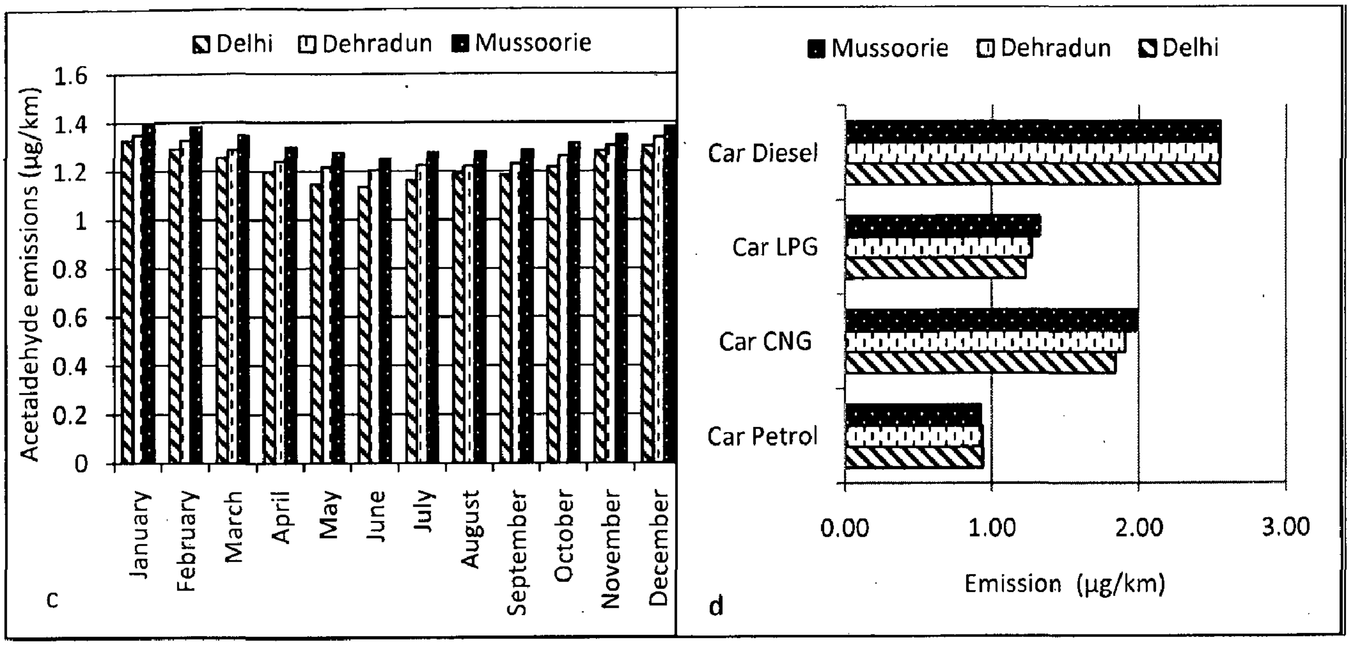


Fig. 4.38: Acetaldehyde emission rate from (c) Car LPG and (d) Estimated Acetaldehyde emission rates according to fuel from car in Delhi, Dehradun, and Mussoorie

4.4.8.3. Three wheelers

Fig. 4.39 (a- b) shows the emission rate of Acetaldehyde from petrol driven four- and two-stroke three wheelers. Highest emission rate is observed in the month of June in Delhi, Dehradun and Mussoorie, while least in January. Fig. 4.39c shows that emission rate of Acetaldehyde from CNG driven two-stroke three wheelers is highest during January in Delhi (8.235 µg/km), while in the month of August in Dehradun (8.314 µg/km) and Mussoorie (8.298 µg/km). Least emission rate has been observed in the month of May in Delhi and Dehradun, and April in Mussoorie. January and August are among the highest humid months of the year, while April and May are least humid months. Similar to CNG driven two-stroke three wheelers, emission rate of Acetaldehyde from four-stroke CNG driven three wheelers is highest in the month of August in Delhi (1.407 µg/km), Dehradun (1.405 µg/km) and Mussoorie (1.402 µg/km), while least during May in Delhi (1.377 µg/km), Dehradun (1.38 µg/km) and April in Mussoorie (1.372 µg/km). There is no effect of altitude on Acetaldehyde emissions from CNG driven two-stroke and four-stroke three wheelers.

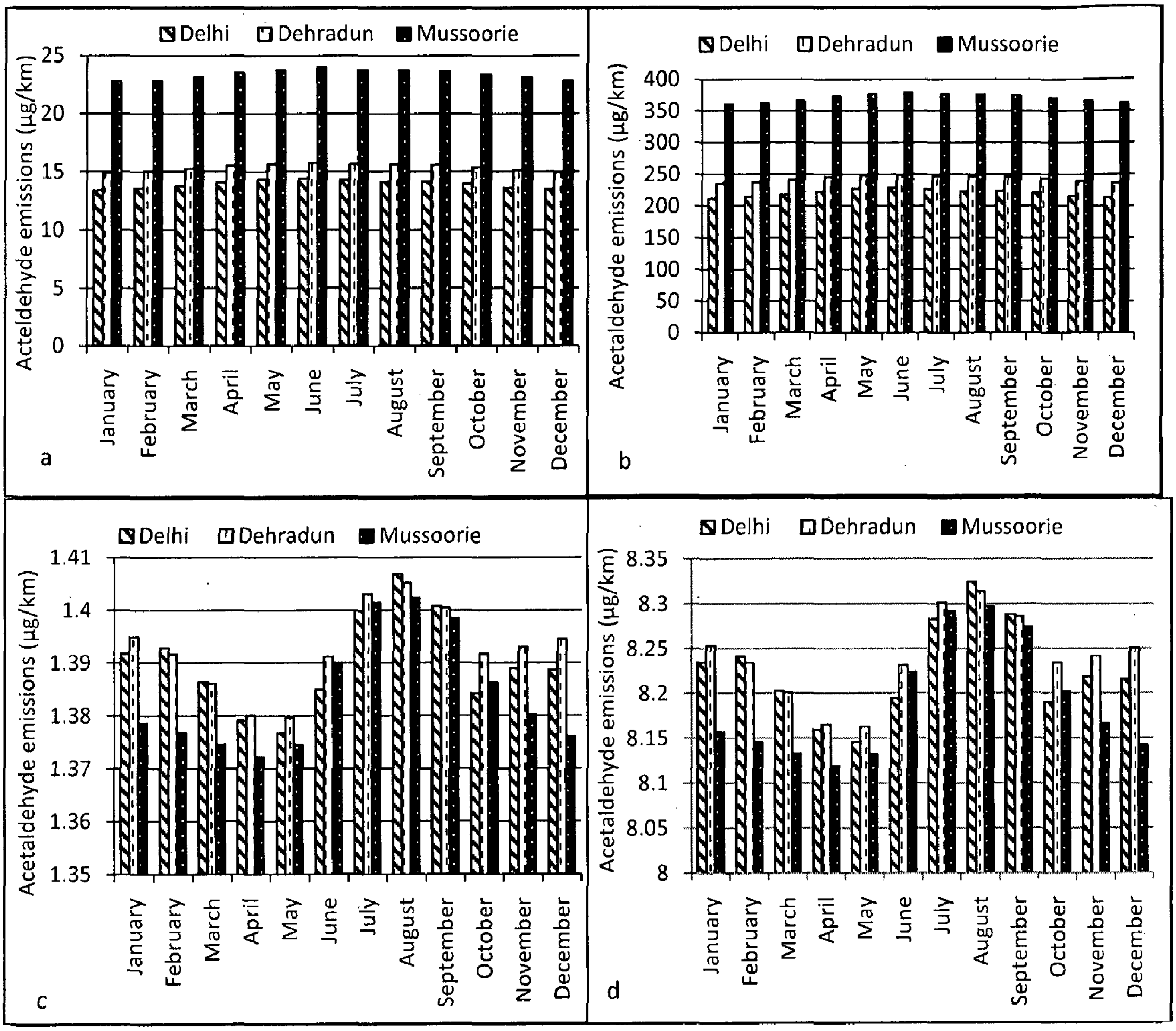


Fig. 4.39: Acetaldehyde emission rate from three wheeler (a) Petrol 4-S (b) Petrol 2-S (c) CNG 4-S (d) CNG 2-S in Delhi, Dehradun and Mussoorie

Fig. 4.40a shows the emission rate of Acetaldehyde from LPG driven two- and four-strokes three wheelers. It is found that, emission rate of Acetaldehyde from LPG driven three wheelers is highest in the month of August in Delhi (4.69 µg/km), Dehradun (4.684 µg/km) and Mussoorie (4.675 µg/km). Least emission rate has been found in the month of May in Delhi (4.589 µg/km), Dehradun (4.599 µg/km) and during April (4.574 µg/km) in Mussoorie. August is the most humid month of the year, while April is the least. No effects of temperature and humidity are observed on diesel driven three wheelers (Fig. 4.40b). Fig.4.40c shows the fuel wise emission rate from three wheelers. It indicates that CNG driven four-stroke three wheelers emit least amount of Acetaldehyde from its tail pipe. There is no effect of altitude on LPG driven two-stroke and four-stroke three wheelers. While effects of altitude is observed on emission of Acetaldehyde from diesel driven three wheelers. Fig. 4.25d shows that emission of Acetaldehyde from diesel driven three wheelers increase with altitude. The results suggest that Mussoorie has the highest emission rates, while Delhi has less emission rates because of lower altitude.

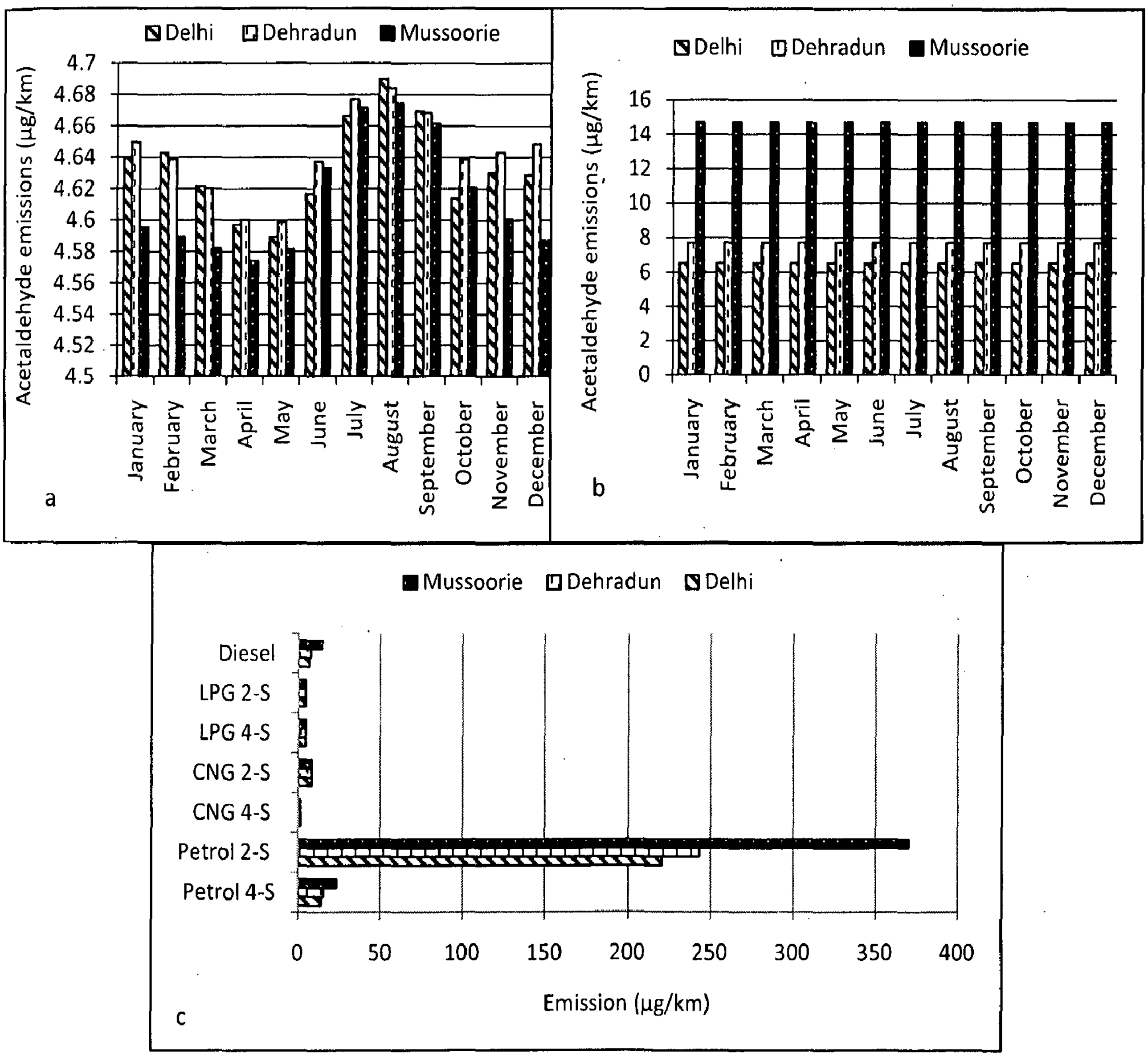


Fig. 4.40: Acetaldehyde emission rate from three wheeler (a) LPG 4-S & LPG 2-S (b) Diesel and (c) Estimated Acetaldehyde emission rates according to fuel from three-wheeler in Delhi, Dehradun and Mussoorie

4.4.8.4. *Buses*

No effect of temperature and humidity is observed on diesel driven buses (Fig. 4.41a). Fig. 4.41b shows the emission rate of Acetaldehyde from CNG driven buses. It indicates that highest emission occurs during January in Delhi (1.635 µg/km), Dehradun (1.934 µg/km) and Mussoorie (3.535 µg/km), while least in June in all three cities. It shows that emission of Acetaldehyde decreases with increasing ambient temperature and vice versa. Fig. 4.27 (c and d) shows that emissions of Acetaldehyde from both CNG and diesel driven buses increase with altitude. Compared to diesel driven buses, emission of Acetaldehyde from CNG driven buses is very less.

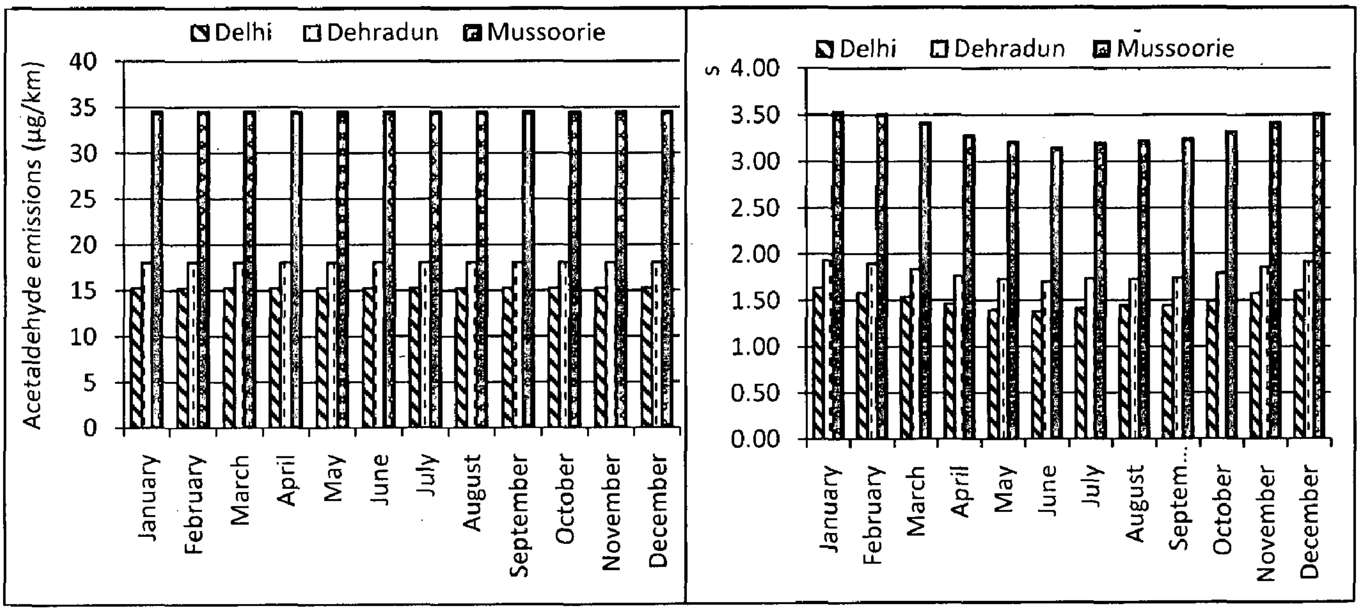


Fig. 4.41: Acetaldehyde emission rate from buses (a) diesel and (b) CNG in Delhi, Dehradun and Mussoorie

4.4.8.5. *Light Commercial Vehicles (LCVs)*

There are no effects of ambient temperature, humidity and altitude on diesel driven LCVs (Fig. 4.28c, 4.42a). Fig.4.42b shows the emission rate of Acetaldehyde from CNG driven LCVs. Highest emission rate of Acetaldehyde is observed in the month of January in Delhi (1.097 µg/km), Dehradun (1.297 µg/km) and Mussoorie (2.371 µg/km) while least during June. With concern to altitude, emission of Acetaldehyde increases with increasing altitude and vice versa (Fig. 4.28d). Similar to buses, emission rate of CNG driven LCVs is less in comparison to diesel driven LCVs.

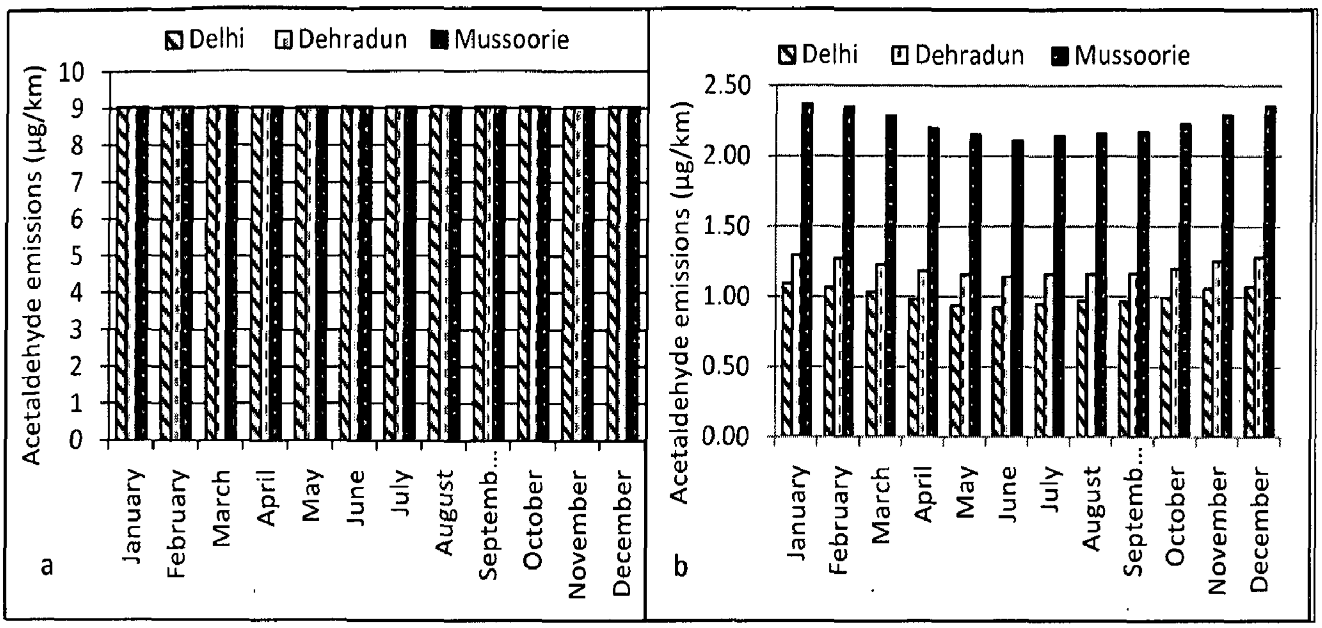


Fig. 4.42: Acetaldehyde emission rate from LCVs (a) diesel and (b) CNG in Delhi, Dehradun and Mussoorie

4.4.8.6. Heavy Commercial Vehicles (HCVs)

Fig. 4.43 shows the monthly emission rate of Acetaldehyde from HCVs in Delhi, Dehradun and Mussoorie. It is observed that HCVs emits highest emission in the month of January in Delhi (0.817 µg/km), Dehradun (0.967 µg/km) and Mussoorie (1.767 µg/km) while least emission is observed in June. It shows that Acetaldehyde emissions are decreasing with increasing temperature and vice versa. As per altitude effects Fig. 4.29d suggest that with increasing altitude, Acetaldehyde emission rate from HCVs is also increasing.

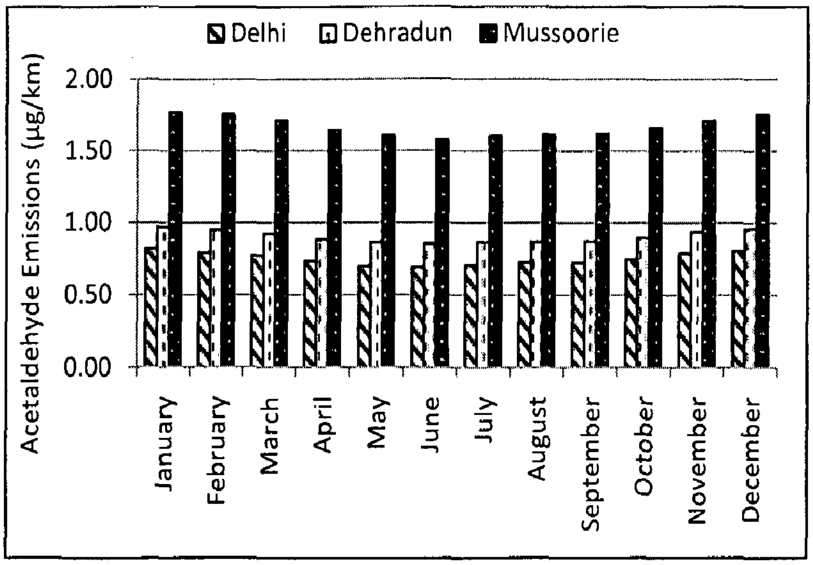


Fig. 4.43: Acetaldehyde emission rate from HCVs CNG in Delhi, Dehradun and Mussoorie

4.5. CONCLUSION

Emission rates of CO, NO_x, 1-3 Butadiene, Formaldehyde and Acetaldehyde from various vehicle categories were estimated for three Indian cities and influences of altitude, humidity and ambient temperature were investigated. Results indicate that ambient temperature, humidity and altitude influence vehicular emissions of CO, NO_x, 1-3 Butadiene, Formaldehyde and Acetaldehyde. Altitude is dominating over other climatic factors (temperature, humidity) for influencing emissions of most of the pollutants from different vehicle categories while ambient temperature is second to altitude.. Thus, this study signifies that consideration of specific parameters of topography (altitude) and meteorology (ambient temperature) is necessary to avoid errors in vehicular emission estimations at a given location.

The results presented in this study can have policy implications related to sustainability issues of transportation systems, public health and environmental protection. For example, higher traffic emissions of CO and HC, together with favorable atmospheric conditions, in high altitudinal areas can affect the atmospheric chemistry of tropospheric ozone leading to human health problems and vegetation impairment. A combination of lower level of oxygen and higher concentration of CO in high attitudes can adversely affect the public health by enhancing formation of carboxyhemoglobin in human blood.

Since this study presents preliminary results and we have analyzed the limited data sets, a further study will be useful to strengthen the findings of this work. Furthermore, a detailed study of the influence of vehicular emissions (including all types of road vehicles) on atmospheric ozone chemistry would be useful to address this issue in a comprehensive manner in high altitude regions.

CHAPTER 5

Exhaust Emissions from On-road vehicles in megacity Delhi (1991-2010)

5.1. INTRODUCTION

On-road vehicles are major sources of air pollutants in urban areas. Their impact on air quality is even larger in rapidly growing megacities of developing countries (e.g., Delhi in India) (Gurjar et al., 2010; Assamoi and Liousse, 2010). Present chapter constructs and describes vehicular emission inventory for megacity Delhi for the years 1991 to 2010 by using Vehicular Air Pollution Inventory (VAPI) Model (already described in Chapter 3). Future scenarios of vehicular emissions from 2011 to 2020 for megacity Delhi are presented in Chapter 6.

5.2. METHODOLOGY

5.2.1. Input parameters for VAPI Model

5.2.1.1. Vehicle Population

Registered vehicle population data have been obtained from Economic Survey of Delhi (ESD 2001, 02) and Delhi Statistical Abstract (DSA, 2008) for the years 1991 to 2008. VAPI model requires registered vehicle population data according to Indian vehicle registration systems (cumulative form). In case of Delhi population data of certain vehicle categories (e.g., commercial vehicles) are not available in cumulative form for all the years due to phasing out program in 2002. Private registered vehicles population data are available in the form of cumulative numbers from 1991 to 2008; while commercial vehicle population data are available in cumulative form from 1991 to 2001 and 2002 to 2008 only. Hence, emissions from commercial vehicles (e.g., three wheelers, buses and taxis) have been calculated in two parts; first before phasing out (i.e. before 2002) and second after phasing out (i.e. after 2002). To understand emission contributions of various vehicles in total road traffic emissions, fine types of vehicle category (e.g., two and four stroke scooter, motorcycle and moped, petrol car, diesel car, CNG car etc.) have been chosen from the VAPI model; while in case of Delhi vehicle population data are available in the form of broad category (e.g., two wheelers, cars, buses etc.) without their sub categorization (e.g., two-stroke two wheelers, four-stroke two wheelers, CNG cars, LPG cars etc.). In absence of vehicle subcategories, vehicle populations have been classified according to field survey data available in various studies. For example, in case of two wheelers, ratio of their subtypes (e.g., scooter, motorcycle and moped) is taken from India Infoline (2009) and Singh and Awasthi (2008) for the years 1992-2008. For engine types of two wheelers (such as two-strokes, four-strokes) data is adopted from Iyer and Badami (2007). It is hard to find population data of cars according to fine categories (e.g., Car CNG, Car LPG, Car Petrol, Car Diesel) given in VAPI model. With an aim to obtain more precise calculations, CNG car population data is taken from Purwaha (2006) and Ravindra et al. (2006); while petrol and diesel cars data are adopted from EPCA (2007). Prior to 2000-02, majority of commercial vehicles were operating on diesel and gasoline (Goyal and Jaiswal, 2006; Goyal and Sidhartha, 2003). In 2001, the Delhi government strictly implemented clean fuel (CNG) for operation of commercial vehicles (e.g., buses, three wheelers, taxis), which was also made applicable for LCVs from 2006. After phasing out old age (8 years for buses, 10 for three wheelers and 20 years for taxis) commercial vehicles (three wheelers, buses and taxis) in 2002 government of Delhi converted remaining commercial vehicles from other fuel to CNG. For CNG equipped three-wheeler data is derived from various studies (e.g., Ravindra et al., 2006; Parivesh, 2009; ENVIS, 2009; CPCB, 2009; IGL, 2009a). Due to unavailability of fuel and technology wise three wheelers population data ,it is assumed that before CNG implementation 90% of the three wheelers were petrol driven and with two-stroke engines, while about 10% were petrol driven and with four-stroke engines. Because of the government of Delhi banned registration of two-stroke three-wheelers with effect from May 1st, 2002 and converted all on-road two-stroke three-wheelers to four-stroke engines. It is assumed that after 2002 most of the three wheelers are equipped with four-stroke engines (EPCA, 2004). Data according to fuel types for taxi population is obtained from various studies (Ravindra et al., 2006; ENVIS, 2009; Narain and Krupnick, 2007). Bus population data is obtained from De (2009), Purwaha (2006) and Ravindra et al. (2006). It is assumed that after 2002 all internal registered buses were CNG equipped due to CNG norms implementation. Because of scarcity of LCVs and HCVs data, ratio of LCVs and HCVs is taken from Das and Parikh (2004), while CNG fueled LCVs population is taken from Indiastate.com (2010), ENVIS (2009), Ravindra et al. (2006), Narain and Krupnick (2007) and CPCB (2009). Furthermore, taking into account the external vehicles entering into or leaving

Delhi, ratios of internal to external populations specified by Mashelkar (2002) and DUD (2007) for the years 2001 and 2005 are used to include such population in estimates (Fig. 5.1).

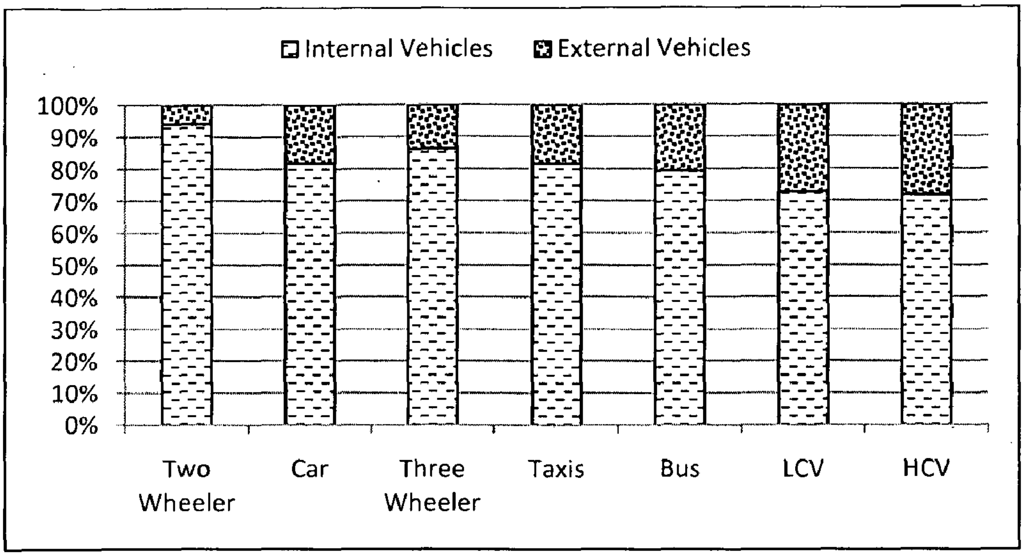
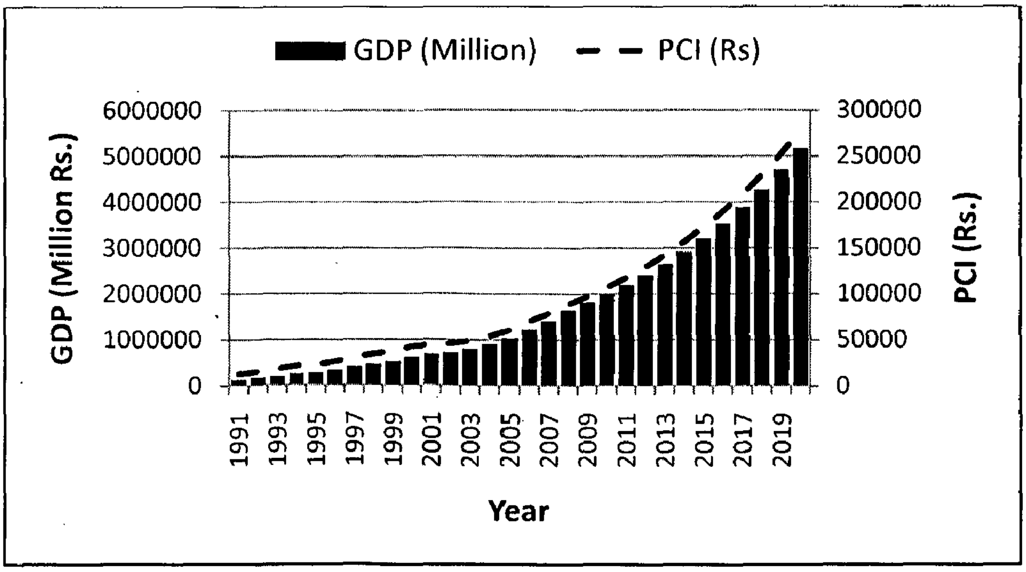


Fig. 5.1: Ratio of internal and external vehicle in Delhi (2005)

5.2.1.2. GDP/Per Capita Income

Gross domestic product (GDP) and per capita income (PCI) data for the years 1991-2010 were taken from various sources (e.g., Govt. of Delhi, 2003, 2009; ESD, 2008-09) while future trend was extrapolated for years 2010-2020, assuming a 10% annual growth in GDP, as suggested by Planning Commission and Economic survey of Delhi (ESD, 2008-09) (Fig. 5.2).



Source: Govt. of Delhi, 2003, 2009, ESD, 2008-09

Fig.5.2: Present and forecasted GDP and Per Capita Income (PCI) for Delhi

5.2.1.3. Vehicle Age

In India, vehicle population data is available in cumulative registered form and they are not actual on-road vehicle population. It is observed that after certain age vehicles are scraped or because of government norms old age vehicles get phased out from Delhi. For calculating the on-road vehicle population, VAPI model requires the phasing out or scraping age of vehicles. For getting on-road vehicle population of Delhi, the vehicle age data is taken from CRRI (2000) and Kokaz et al. (2001) from 1991 to 2000 (Table 5.1). However, after 2000 vehicle age data is taken from Mittal and Sharma (2003). In 2002, government of Delhi phased out all old age (15 year old two wheelers, 20 old year car, 10 year old three wheelers,8 year old buses and 15 year old HCVs and LCVs) three wheelers, taxis and buses from Delhi, and also canceled their registration. Hence, in case of three wheelers, it is assumed that all three wheelers from 2002 are CNG equipped and all the three wheelers registered in 2002 will be phased out after 2012.

Table 5.1: Average Service Life of vehicles in Delhi

	2-Ws	**3-Ws**	**Car**	**Taxis**	**MUV**	**Trucks**	**Buses**
Mittal and Sharma, 2003	15	10	20	10	15	15	8
CRRI, 2002	17	12	17	17	17	17	17
TII, 2006	-	-	-	-	-	10	-
Bose, 2006	15	-	15	-	-	-	-
Roychowdhury, 2001	-	15	-	-	-	-	-
Kokaz et Al., 2001	15	10	25	15	-	12	8
Vehicle Age Considered in the present study							
1991-2000	17	12	25	25		17	8
2001-2020	15	10	20	15		15	8

5.2.1.4. Vehicle Kilometers Travel

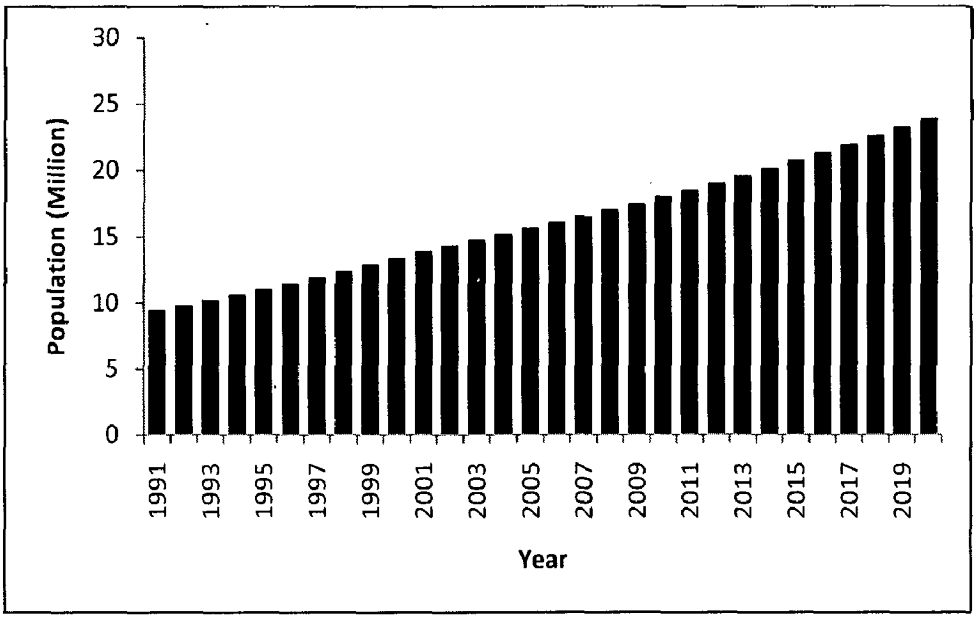
Less data is available for Vehicle Kilometer Travel (VKT) of different vehicle categories in megacity Delhi. VKT data for megacity Delhi has been taken from Goyal (2007), which have been considered for future years also (Table 5.2). For external commercial vehicles (e.g., buses, taxis, three wheelers, LCVs and HCVs) different VKT values have been taken, because mostly external commercial vehicles either pass through the city or just enter and leave a destination. For this reason average of length (52 km) and width (48 km) of Delhi area have been used to compute a VKT of 50 km.

Table 5.2: Annual mileage (km) for different vehicle categories

Vehicle type	**VKT (km/day)**
2 Wheelers	27
3 Wheelers	110
Passenger cars	41
Taxis	82
Multi utility vehicles	101
Buses	164
LCVs	110
HCVs	82
External Vehicle	
Buses	50
LCVs	50
HCVs	50

5.2.1.5. Population

Delhi has an area of 1,483 km^2 confined by maximum length and width of ~52km and ~48km, respectively. Delhi has population density of about 11,126 per km^2 (ESD, 2006). Present population of Delhi has been taken from Census of India (1991, 2001), while projected data is taken from Delhi Statistical Abstract (DSA, 2008) (Fig. 5.3). As visible from Fig. 5.3, Delhi's population showed a steep rise from 9.4 million in 1991 to about 18.5 million in 2010, which is further forecasted to reach 24 million in 2020; indicating an average annual growth of 4.5% as compared to national average of 2.1% (Fig. 5.3). Besides, it is estimated that about 0.2–0.3 million migrants settle in Delhi every year.



Source: DSA (2008), Census of India, (1991, 2001)

Fig.5.3: Present and projected population of megacity Delhi

5.2.1.6. Vehicle Population Saturation Level

The growth in vehicles per 1000 persons over time typically follows a sigmoid or S-shaped curve (Dargay et al., 2007). As discussed in Chapter 3, Gompertz function forecasts how and when a given growth system will reach its saturation level. Some studies have given saturation level based on a reasonably assumed value or data derived from relevant studies of other countries (Singh 2000). However, most of them have described saturation level externally by applying a rule of thumb, e.g., one car per family (Palelink, 1960), one driving member per family (Tanner 1978), or per capita vehicle ownership (Button et al., 1993; Peter et al., 2003; Das, 2010). In present study seating capacity of passenger commercial vehicles (Das, 2010) and one car plus two wheelers per family are assumed to be the saturation levels (Tanner, 1978). In Delhi normal family size is of 5 members, hence each family is assumed to have a car and a two-wheeler. The seating capacities of auto rickshaws and taxis are 3 and 5, which imply that the saturation levels per 1000 persons are assumed to be 330 and 200, respectively (Das, 2010). However, the seating capacity of buses ranges from 11 (LCVs buses) to 60 (HCVs buses). Therefore, it was assumed that the saturation level for buses is 20 for 1000 persons. In the case of goods vehicles, the saturation level is assumed to be 20 per 1000 persons (Das, 2010).

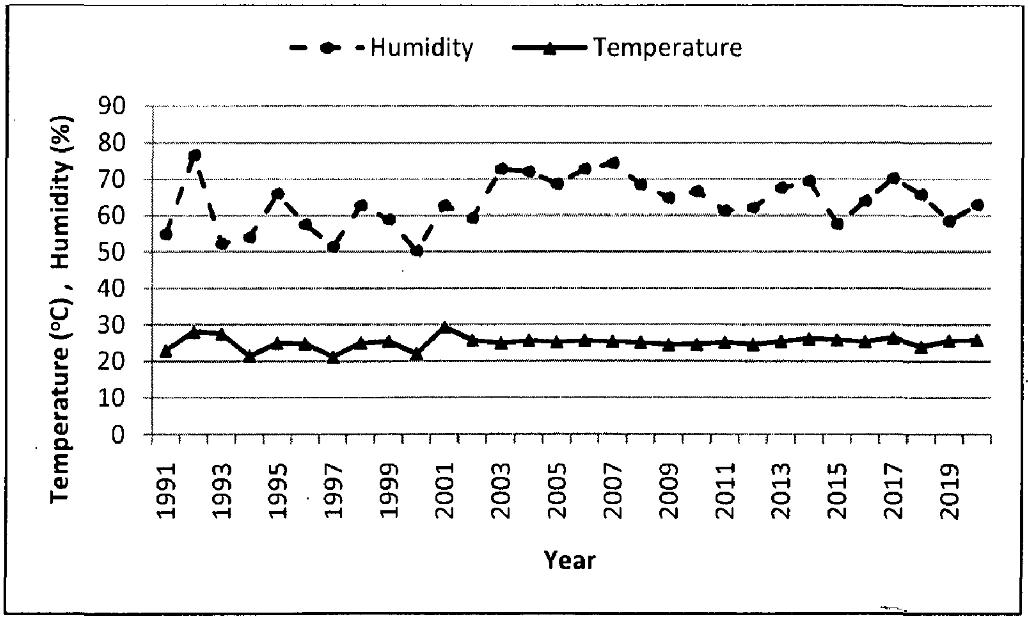
Table 5.3: Per thousand vehicles saturation level in megacity Delhi

	2-Ws	3-Ws	Car	Taxis	Buses	LCVs	HCVs
Per 1000	200	330	200	200	20	20	20

Source: Das, 2010

5.2.1.7. Altitude, Temperature, Humidity:

Delhi is located between 28° 24' 17" N to 28° 53' 00" North and 76° 50' 24" to 77° 20' 37" East in northern part of India with at elevation of 225m above the mean sea level (MSL) (DSA, 2008). Ambient temperature and relative humidity have been taken from DSA (2006, 2008). Based on historical data, future temperature and humidity are randomly predicted for Delhi (Fig. 5.4) by using Crystal Ball 11.1.1.1 software.



Source: DSA, 2008

Fig.5.4: Present and predicted temperature and humidity for megacity Delhi

5.2.2. Policies and other parameters Considered in Study

From time to time, Government of Delhi has implemented various norms and policies for reducing traffic emissions in megacity Delhi. In VAPI model most of the norms and policies are considered indirectly due to the use of country specific emission factors and policies oriented vehicle population use in the model. Following are the norms and policies, which VAPI model considers for emission estimations (Table 5.4).

Table 5.4: Policies considered in study

	Policies	Implementation
1	Bus Rapid Transit System (BRTS)	Implemented in year 2008, already included in bus population and post 2005 emission factor used for it
2	CNG vehicles Population	Implemented in year 2002 for all commercial passenger vehicles and from 2006 for new LCVs population
3	Emission Norms	Emission factors used in the study is based on emission norms implemented in various years (1991-1996, 1996-2000, 2000-2005 and post 2005)
4	Improvement in the quality of Fuel	Emission factors used in the study are based on improvement in the quality of fuel between following years (1991-1996, 1996-2000, 2000-2005 and post 2005)
5	Phasing Out of vehicles	Model requires age of vehicle for phasing out of old vehicles. Before 2002 phasing out age was natural age while 2002 onwards it is based on government norms

5.2.2.1. Bus Rapid Transit System (BRTS)

Government of Delhi launched first phase of BRTS in 2008. In comparison to buses the population of BRTS buses in Delhi is very less. As far as emission factors are concerned there is no difference between normal buses and BRTS bus. Because BRTS buses are new technology buses, the post 2005 emission factors given by IARI (2007) have been used for calculating emissions from BRTS buses in VAPI model (Table 3.1, 3.2).

5.2.2.2. CNG vehicles Population

Government of Delhi implemented CNG program in 2002 for all commercial passenger vehicles and in 2006 for new LCVs population. VAPI model considers CNG vehicles population separately.

5.2.2.3. External Vehicles VKT

There are several external vehicles that enter into and/or leave from Delhi while some of vehicles pass through the bypass of Delhi (Fig. 5.1). For estimating emissions from these types of vehicles, VAPI model considers VKTs accordingly (Table 5.2).

5.2.2.4. Emission Norms

Emission factors used in VAPI model for calculating emissions of various pollutants from the vehicles in Delhi are based on various emission norms introduced by the government during study period (Table 3.1, 3.2) (IARI, 2007).

5.2.2.5. Improvement in the quality of Fuel

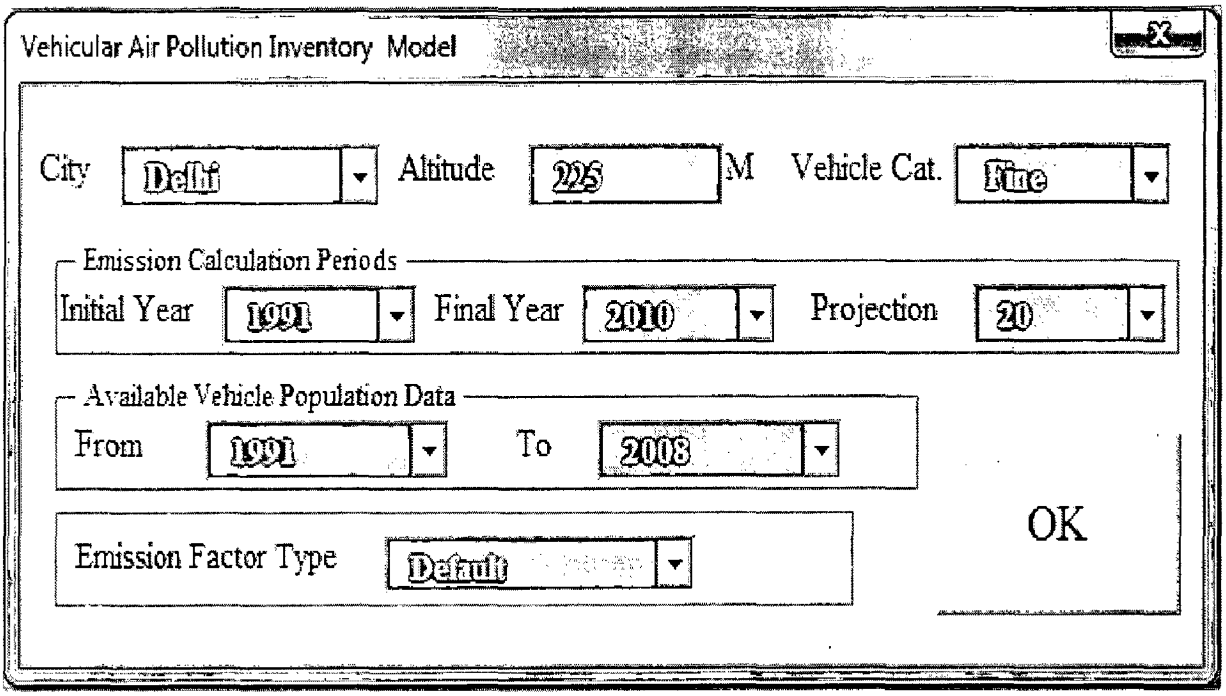
Emission factors developed by IARI for different vehicles already consider improvement of fuel quality norms introduced by the Government of Delhi (Table 3.1, 3.2) (IARI, 2007).

5.2.2.6. Phasing Out of vehicles

After certain age (Table 5.1) vehicles get phased out from the road. VAPI model require phasing out age of vehicles as input parameter and based on that the model calculates on-road vehicle population.

5.2.3. Calculation

As shown in Fig. 5.5, for estimating on-road traffic emissions from 1991 to 2020 in megacity Delhi, 225 m altitude has been entered in input data form followed by fine vehicle category. Input data of vehicle population are available for 1991 to 2008 only. However, period of emission calculation is given from initial year 1991 to final year 2010 with future projections for 10 years from 2011 onwards. Simultaneously, fine category wise vehicle population, GDP, vehicle age, per 1000 vehicle saturation level, humidity and temperature have been inserted in their respective tables in VAPI model.



City: Delhi
Altitude: 225 M
Vehicle Cat.: Fine

Emission Calculation Periods
Initial Year: 1991
Final Year: 2010
Projection: 20

Available Vehicle Population Data
From: 1991
To: 2008

Emission Factor Type: Default

Fig. 5.5: Initial input parameter for VAPI model for calculation emissions from 1991-2020

5.2.4. Future Vehicle Population Projection

For estimating future vehicle population through Gompertz function, number of vehicles per thousand human populations is required. VAPI model also calculates number of vehicles per 1000. As discussed in Chapter 3, since the relationship between growth of vehicle ownership and per-capita income is highly non-linear, VAPI model uses Gompertz function to calculate future vehicle population. This implies that vehicle ownership increases slowly at the lowest income levels, and then more rapidly as income rises, and finally slows down as saturation is approached. Based on Gompertz function regression between GDP/PCI and vehicle ownership has been carried out by VAPI model for all vehicle categories for future projection. For best fitting relationship between GDP/PCI and vehicle ownership, appropriate adjustments have been done in intercept and slope for all vehicle categories. Fig. 5.6 shows the on-road vehicle population projected by VAPI model.

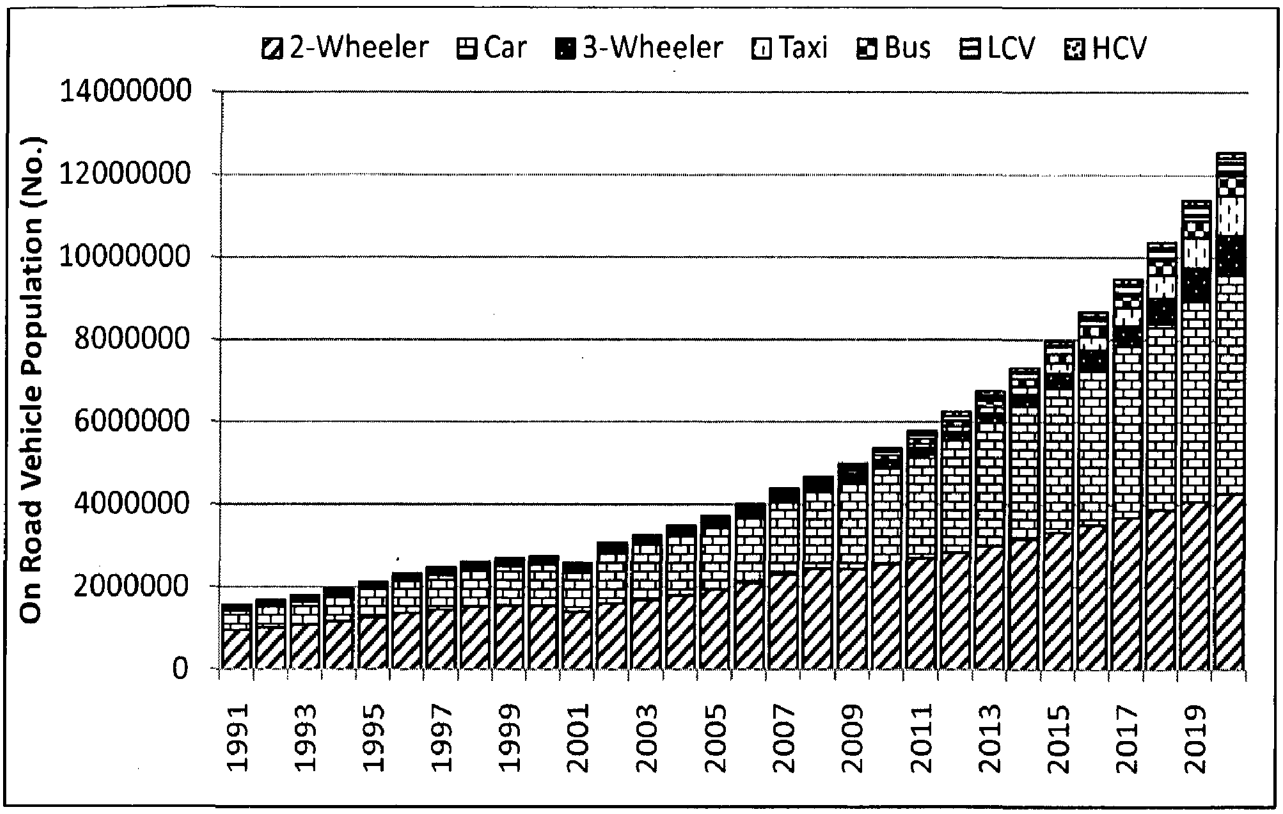


Fig.5.6: On-road vehicle population in megacity Delhi

5.3. RESULTS AND DISCUSSION

Based on VAPI model output, emission loads from transport sector of megacity Delhi during 1991 to 2010 for the compounds CO, HC, NO_x, CO_2, PM, Benzene, 1-3 Butadiene, Formaldehyde, Acetaldehyde, total Aldehyde, and total PAH are presented in this chapter. Whereas emission loads from 2011 to 2020 are discussed in Chapter 6. Furthermore, non-exhaust emissions from various sources such as evaporative, break, tire and resuspended dust are described in Chapter 7.

5.3.1. CO emissions

As visible from Fig. 5.7, CO emissions from 1991 to 2010 show an irregular trend. CO emissions from various vehicle categories are 178 Gg in 1991 and the emission trend shows an average growth of 6% from 1991 to 1999. It reflects impacts of increasing vehicle population in Delhi. During 1991 to 1999 highest change (~ 10%) in emissions is observed between 1994 (218 Gg) and 1995 (239 Gg), while least emission growth (~2.4%) is observed between 1998 (278 Gg) to

1999 (284 Gg). Less emissions between 1998 and 1999 might be due to implementation of new norms in 1996 for newly introduced vehicles, (CPCB, 2006; ARAI, 2007). CO emissions in 1999 and 2000 are observed to be 284 Gg and 273 Gg, the reduction in 2000, might be due to phasing out program started by the government for vehicles in 1999. Similarly negative trend has been observed between 2000 and 2002 because of same reason. After 2002, CO emissions from all vehicle categories show a positive trend till 2006, because of increasing on-road population of vehicles. Between 2006 and 2007 about 13% decline is observed, due to phasing out of 1991 and pre-1991 vehicles (especially two-wheelers) in 2007 due to their retirement age (15 year). After 2007, CO emissions from vehicles show an increasing trend till 2010. As per contribution, two wheelers shared highest percentage (44-51%) during most of the period (1991- 2006), while car is the second largest contributor (23-38%) during same period. After 2006, however, car population shows their dominancy in CO emissions, followed by two wheelers. It is observed that contributions of two wheelers decreased gradually from 1991 to 2010, due to less emission factor for new technology two wheelers (Table 3.2) (ARAI, 2007).

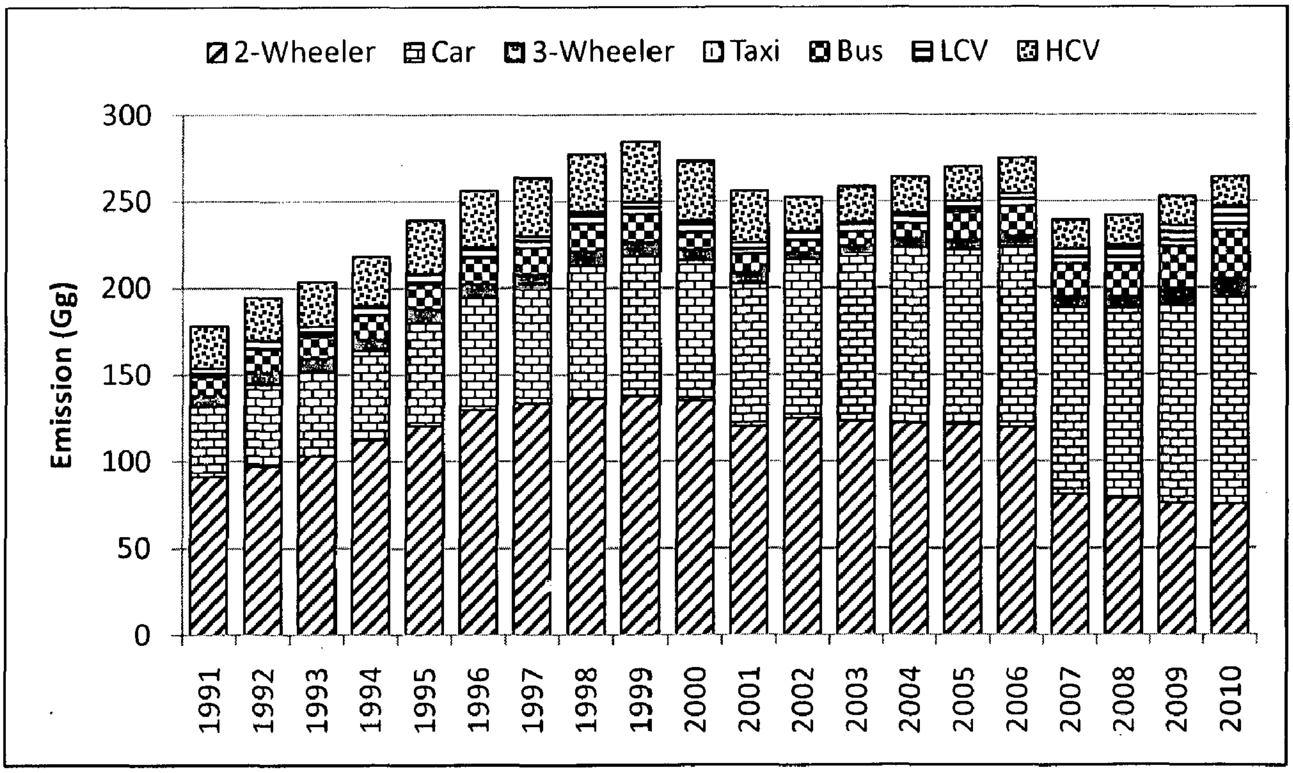


Fig. 5.7: CO emission from various vehicle categories in megacity Delhi during (1991-2010)

5.3.1.1. *Two Wheelers*

Two wheelers accounted for about 29-51% of CO emissions during 1991 to 2010. In 1991, CO emissions from two wheelers were about 92 Gg, with continuous increase it became ~138 Gg in 1999. About 2% decrease is observed in CO emissions between 1999 and 2000 from two wheelers. Nevertheless, due to phasing out of old technology of two wheelers, 11% decline is observed in CO emissions from 2000 to 2001. Between 2001 and 2002 about 4% growth in CO emission is observed; while from 2003 emissions follow a decreasing trend due to phasing out of old technology vehicles with higher emission factors. Due to phasing out of 1991 and pre-1991 two-wheeler population shows a sudden decrease in CO emission during the year 2007 (Fig. 5.8). After 2007, CO emissions decline until 2010 because of continuous phasing out of 1992, 1993 and 1994 two-wheeler population that were having higher emission factors. Estimations suggest that two-stroke moped is the highest CO contributor (31-42%) among all two wheelers during 1991 to 2006, while from 2007 to 2010 two stroke motorcycles contribute the most (29-30%) of the CO emissions.

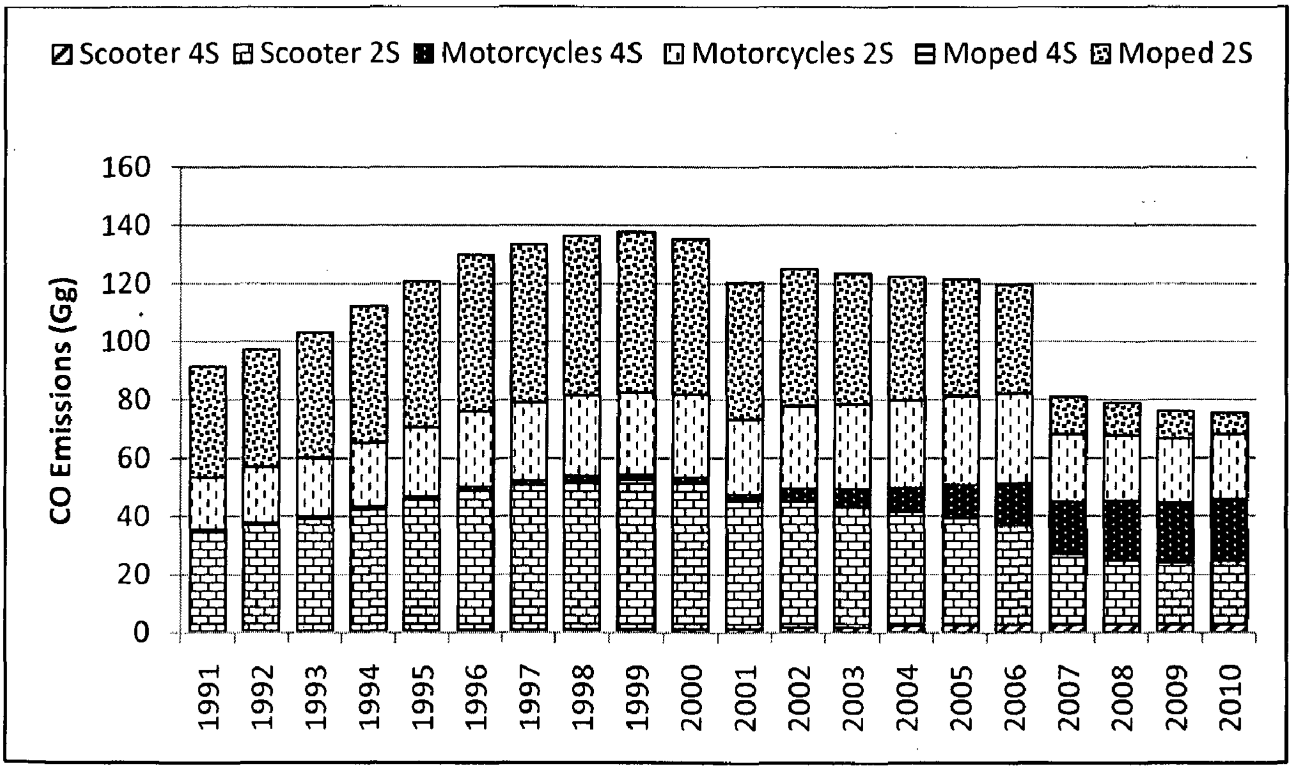


Fig. 5.8: CO emissions from two wheelers in megacity Delhi during 1991-2010

5.3.1.2. Cars

Fig. 5.9 shows the CO emission from car population in megacity Delhi during 1991-2010. Petrol driven personal car is the major contributor of CO emissions among all categories of cars in Delhi, sharing about 98-99% of total floating cars during 1991 to 2010. Fig. 5.9 indicates that CO emissions from car population are rising from 1991 to 2010, with little fluctuations in growth rates. The reason of fluctuation in growth rates is phasing out of old age vehicle and implementation of new norms and change in emission factors in various years (e.g., 1996, 2000, 2005). CO emissions from car population are about 40 Gg in 1991, 59 Gg in 1995, followed by 81 Gg in 2000 and 101 Gg in 2005. For year 2010, VAPI model predicted that emissions will become nearly 119 Gg. It is observed that CO emissions from car population rise with average growth rate of about 4% per annum. However, about 2% of decline in CO emission has been observed between 2004 and 2005. Phasing out of pre 1991 car population is expected to be responsible for this change during 2004-2005.

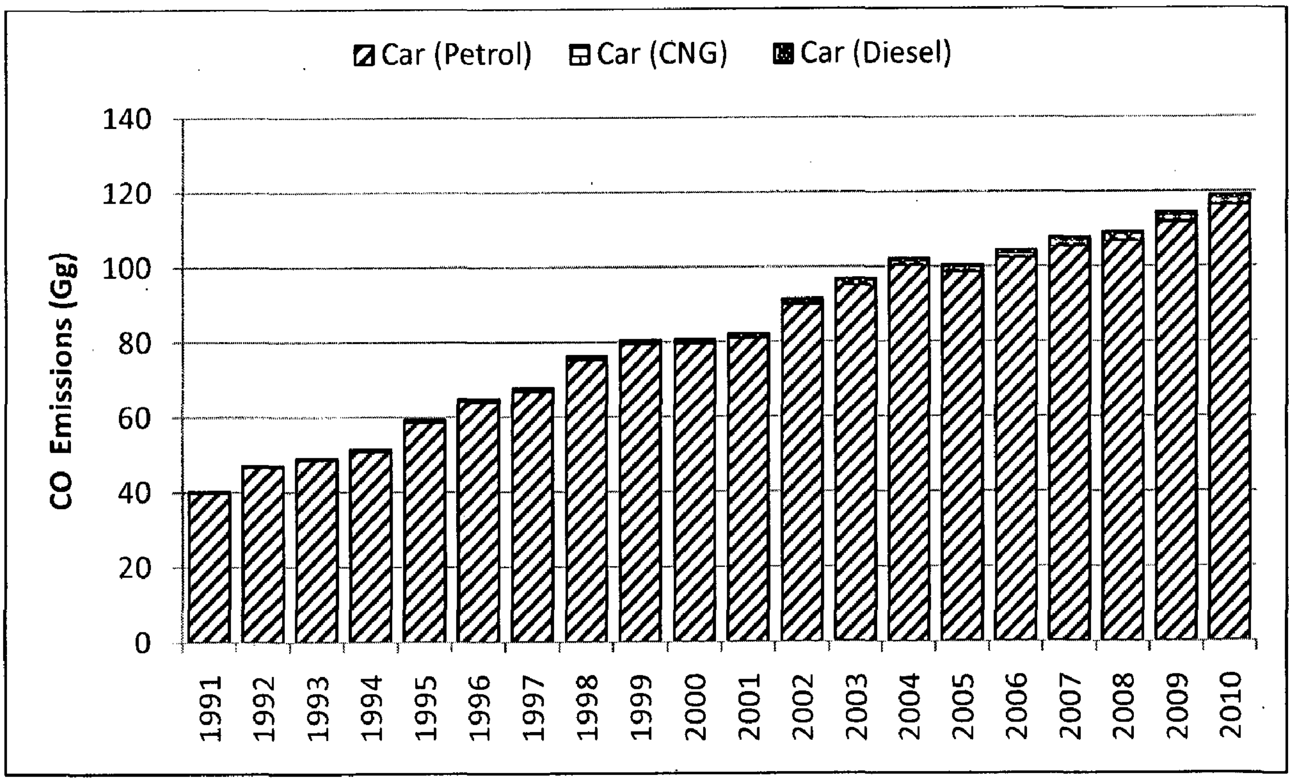


Fig. 5.9: CO emissions from the cars in megacity Delhi during 1991-2010

5.3.1.3. Three Wheelers

Fig. 5.10 illustrates the emissions of CO from three-wheelers during 1991 to 2010 in Delhi. It shows CO emissions from petrol driven 2-stroke and 4-stroke three-wheelers during 1991 to 1999. In 2001 government strictly implemented norms to convert all kinds of three wheelers to CNG and stopped registration of two-stroke three-wheelers. In 1991, CO emissions from three wheelers were ~6 Gg and increased with ~19% growth rate between 1991 and 1992. After this about 1.4% decrease is observed between 1992 and 1993 because of decrease in on-road three wheelers population. Approximately 17% of growth is observed between 1994 (~6 Gg) and 1995 (~7 Gg). This might be due to ~8% growth in on-road three wheelers population in 1995. After 1995, however, negative trend is observed in CO emissions from three wheelers during the years 1996 and 1997. Decline in on-road three wheelers population (2.4% and 7%) in year 1996 and 1997, respectively, is responsible for this change. About 28% growth is observed in CO emissions during 1997 (~6 Gg) and 1998 (~8 Gg). Increase in on-road three wheelers population (18%) might be responsible for this change. In 2001, emissions of CO showing ~7.4% increment and similar to previous increment change in on-road three wheelers (47%) are responsible for it. About 48% decrease in CO emission from three-wheelers is observed between 2001 (~6 Gg) and 2002 (~3 Gg) due to a complete shift of petrol driven four-stroke and two-stroke three wheelers to four-strokes CNG driven three-wheelers. After 2002, however, CO emissions show an increasing trend until 2010. In between 2004 (~3 Gg) and 2005 (~5 Gg), about 40% growth in emissions is observed due to growth of ~ 37% in on-road three wheelers. Because of the same reason steep increase is observed between years 2008 and 2009. Fig. 5.10 shows that initially (1991-2001) the contribution of two-stroke petrol driven three-wheelers is higher, followed by four-stroke petrol driven three-wheelers, and after 2002, most of the CO is emitted by CNG driven three wheelers.

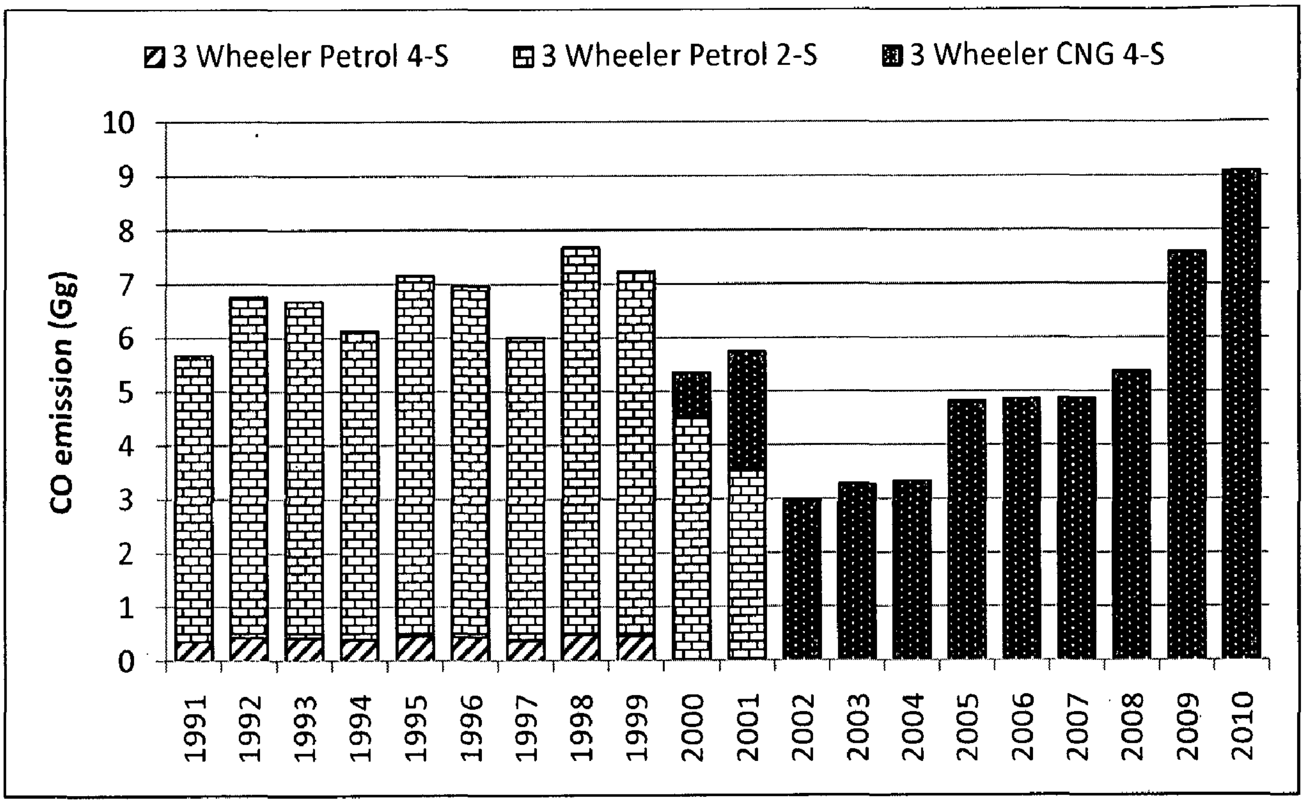


Fig. 5.10: CO emissions from the 3-wheelers in megacity Delhi during 1991-2010

5.3.1.4. Taxis

Fig. 5.11 shows the emission of CO from taxi population in megacity Delhi during 1991 to 2010. Initially in 1991, CO emissions were ~0.4 Gg, followed by ~0.5 Gg in 1995 and 0.70 Gg in 2000. From 1991 to 2001, CO emissions from taxi population show a similar trend. From 2000 to 2001, sudden increase in CO emissions is observed because of 16% increase in taxi population during 2000 and 2001. In between 2001 and 2002 about 43% decline has been observed, which might be due to phasing out of all old age taxis and strict implementation of CNG norms for commercial vehicles including taxis. In 2005, emission of CO from taxis population was ~0.7 Gg and in 2010 it increased to ~1.4 Gg. Before 2002, the contribution of petrol driven taxis was higher (66-69%), followed by diesel taxis (31-34%). After CNG implementation in 2002 contribution of CNG taxi population in CO emissions started to increase.

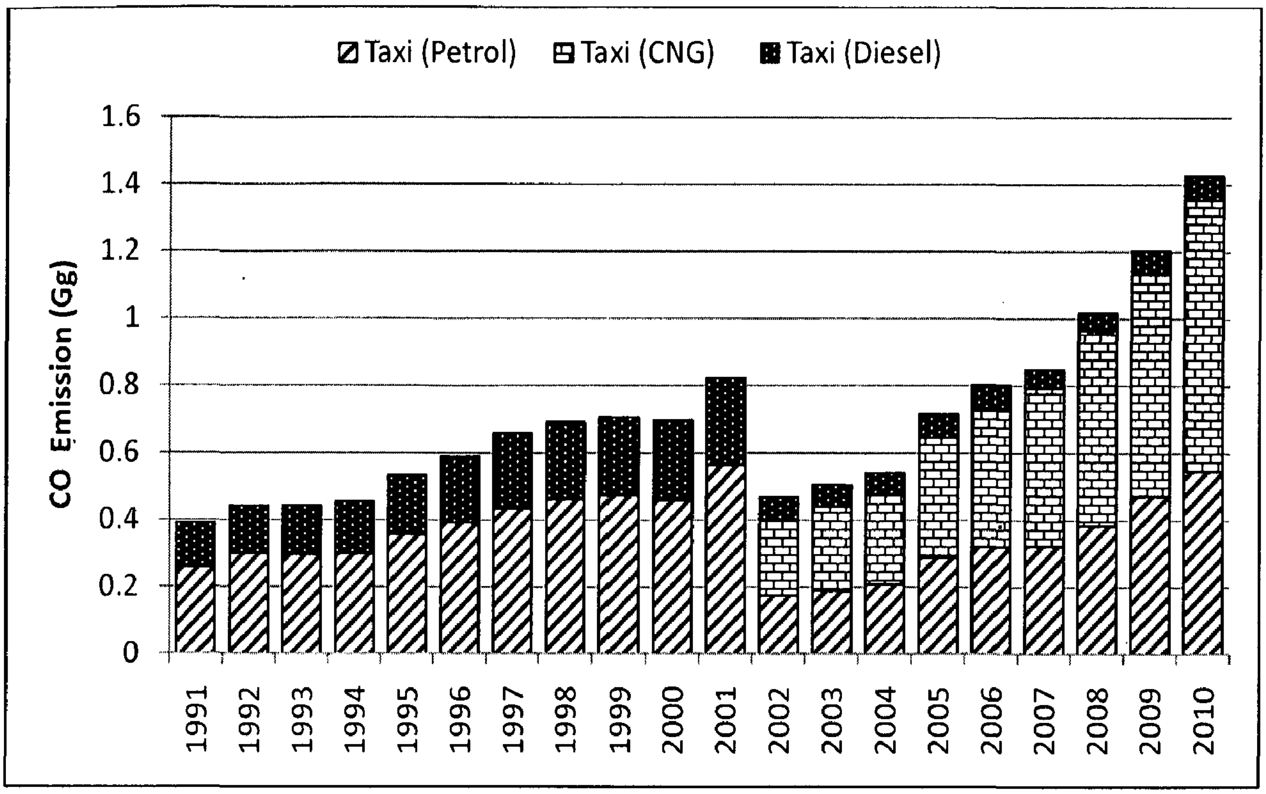


Fig. 5.11: CO emissions from the taxis in megacity Delhi during 1991-2010

5.3.1.5. Buses

Fig. 5.12 illustrates the emissions of CO from CNG and diesel driven buses in megacity Delhi during 1991 to 2010. Estimates show that CO emissions from buses increase ~2.6 times from 11 Gg in 1991 to 28 Gg in 2010. From 1991 to 1999 emission trend of CO follows a similar pattern, while sudden decrease (39%) is observed between 1999 (~16 Gg) and 2000 (~10 Gg). This is due to phasing out of old technology (high emission factor) buses (1991 and pre-1991 models) in 2000. Decrease of 31.4% is observed in emissions between 2001 and 2002 because of strict conversion of all internal (i.e. registered in Delhi) diesel driven buses to CNG and phasing out of old age (8 years) buses. Noticeable growth rate (~89%) is observed between 2004 (8.8 Gg) and 2005 (16.7 Gg) due to entry of 19000 buses in 2005 (DSA, 2008). Slight negative change is observed between 2007 and 2008, due to change in emission factors in 2008 for newly 2006 to 2008 model and phasing out of old age buses. As per emissions contribution, diesel buses dominated (99-100%) from 1991 to 2001, while after 2001 contribution of CNG buses increased significantly (86-88%) (Fig. 5.12).

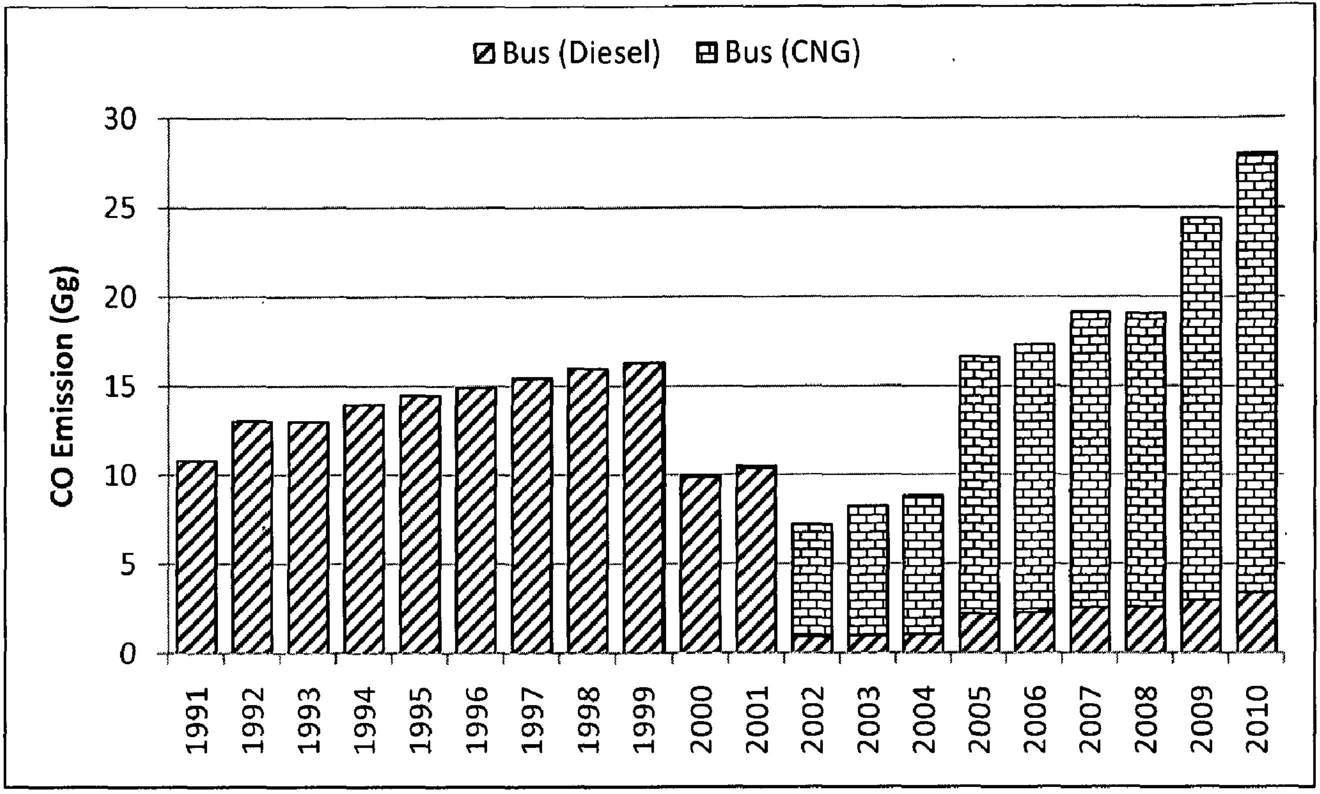


Fig. 5.12: CO emissions from the buses in megacity Delhi during 1991-2010

5.3.1.6. LCVs

CO emissions from LCVs between 1991 (5 Gg) and 1999 (7 Gg), shows similar trend with 1-9% growth rate (Fig. 5.13). Between 2000 and 2001, CO emissions decreased by 7.7%, which is 16% between 2001 (~6.4 Gg) and 2002 (~5.4 Gg). The reason behind this negative growth rate is phasing out of old age (15-17 year) LCVs, less entry of new LCVs and conversion of LCVs from diesel to CNG. In year 2005, emission from LCVs again decreased due to phasing out of pre-1991 diesel driven LCVs's. From 2005 to 2008 CO emissions increased with slightly higher growth rate due to rapid growth in CNG driven LCVs population in same period. In 2010, emission of CO from LCVs was ~14.2 Gg. Between 1991 to 2007, contribution of diesel driven LCVs is higher and ranged between 56-100%, while from 2008 to 2010 contribution of CNG driven LCVs became higher (54-63%).

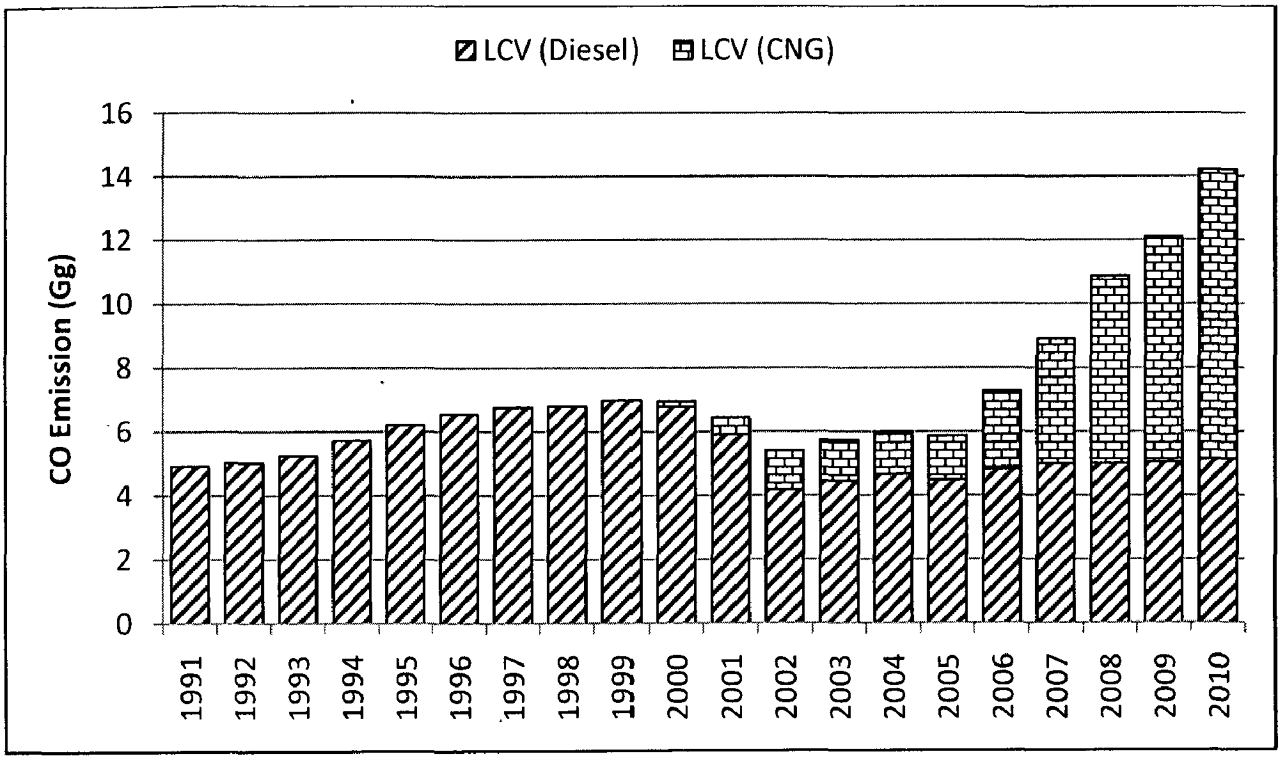


Fig. 5.13: CO emissions from the LCVs in megacity Delhi during 1991-2010

5.3.1.7. HCVs

CO emissions from HCVs population in megacity Delhi was 24.4 Gg in 1991, 30.8 Gg in 1995 and 34.2 Gg in 2000. As visible from Fig. 5.14, CO emissions from HCVs increased from 1991 to 1999 in megacity Delhi, while negative growth rate has been observed from 2000 to 2002. In 2000, CO emissions from HCVs population were 34.2 Gg, but declined to 30.1 Gg in 2001. Similarly about 33% decrease is recorded between 2001 and 2002. Phasing out program of Delhi government for old HCVs is responsible for this decline. Negative change in CO emissions has been observed between 2006 and 2007 (~19%). The reason behind this trend is the phasing out of pre-1991 model HCVs population in 2007 (more fraction, and high emission factor; 19.3g/km), and introduction of more newly HCVs (less emission factor; 6 g/km).

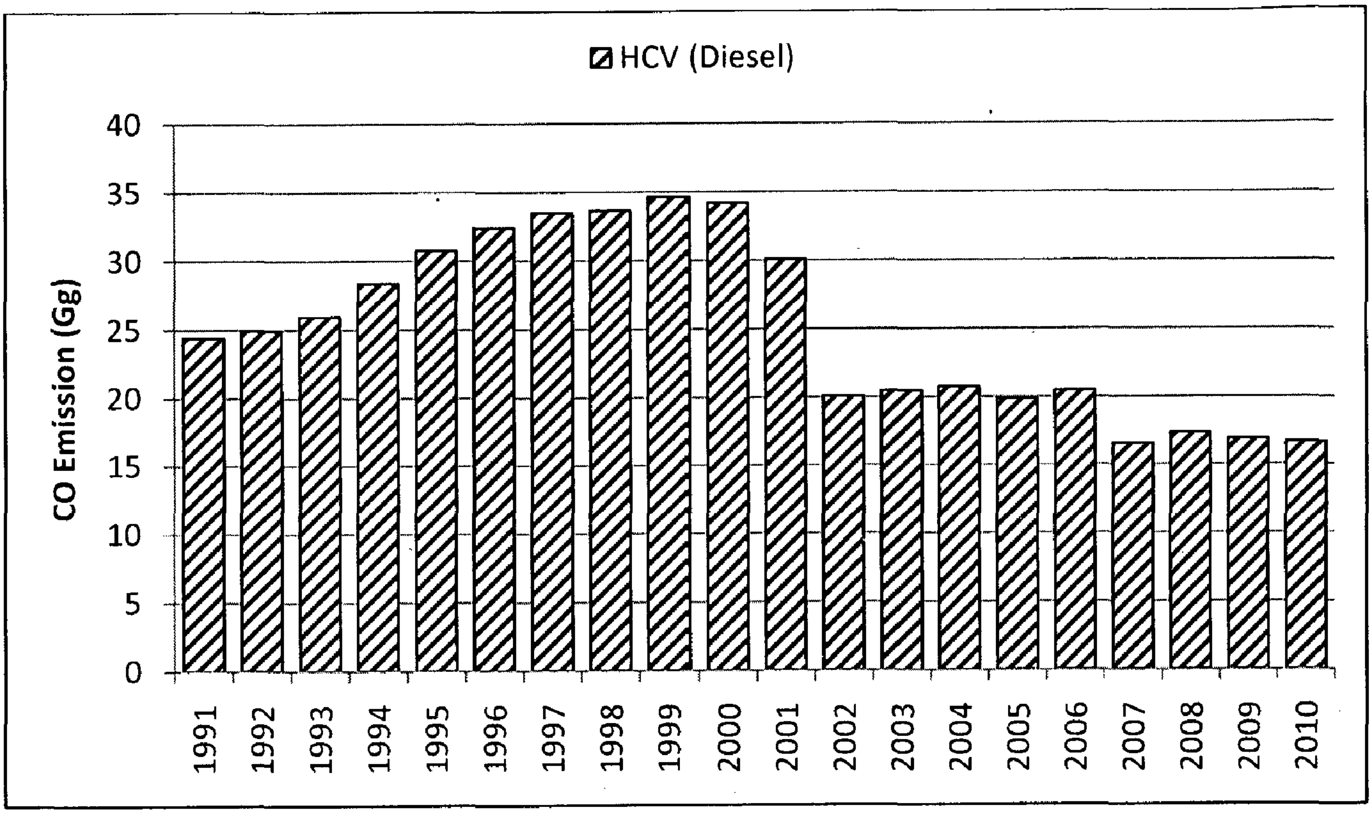


Fig. 5.14: CO emissions from the HCVs in megacity Delhi during 1991-2010

5.3.2. CO_2 emissions

CO_2 emissions from various vehicle categories in Delhi for the period 1991 to 2010 are presented in Fig. 5.15. CO_2 emissions show an increasing trend from 1991 to 2010, with annual average growth rate of 8%. In 1991, CO_2 emission from all vehicle categories in megacity Delhi was 2954 Gg, which became 3921 Gg in 1995, followed by 5058 Gg in 2000 and 7148 Gg in 2005. Quite similar growth rates (3.5-9%) have been observed between 1991 and 2001. About 4.4% decrease is observed between 2001 and 2002 because of phasing out program (Table 5.1) by the government of Delhi for commercial vehicles in 2001 and 2002. Initially from 1991 to 1995 contribution of HCVs population is highest (28-29%) among all other vehicles, while from 1996 to 2010 Car population has emerged as highest CO_2 contributor (28-42%).

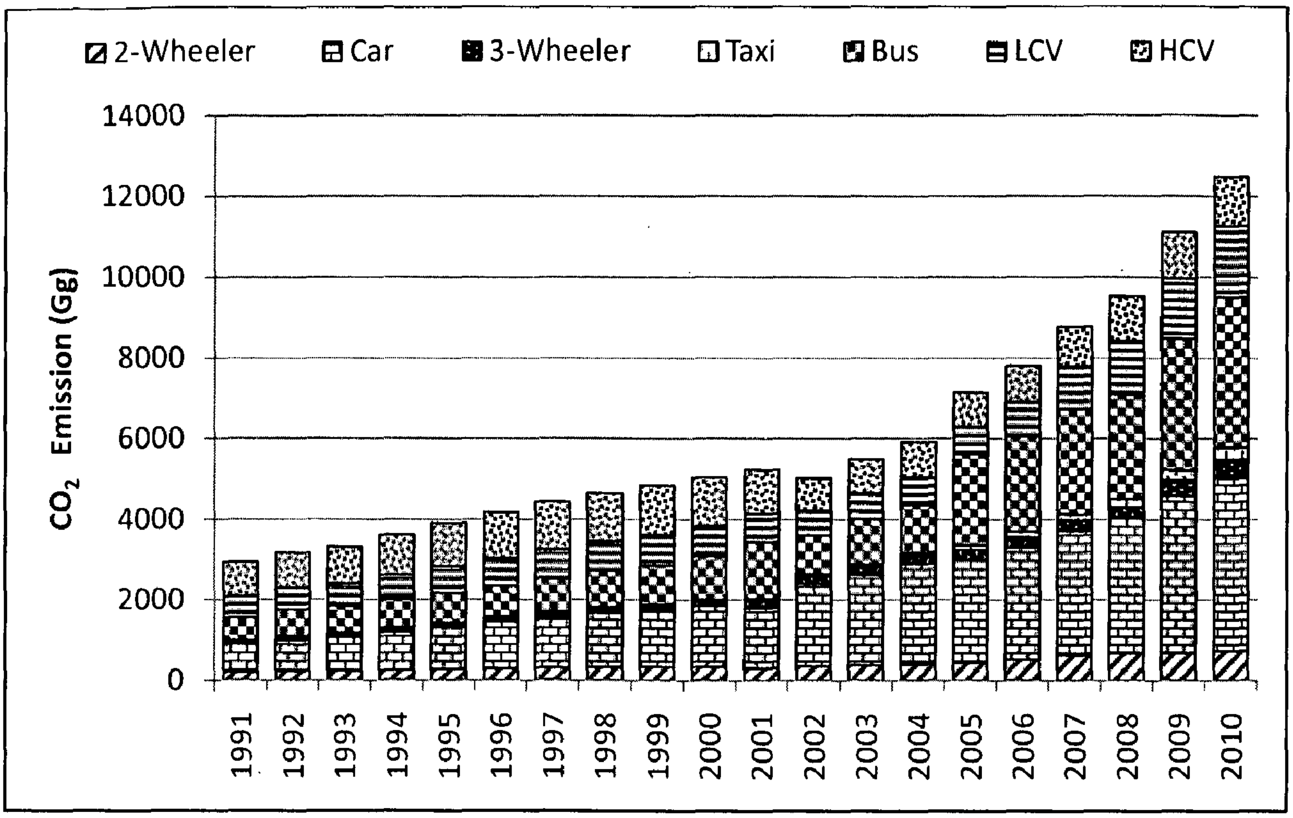


Fig. 5.15: CO_2 emission from various vehicle categories in megacity Delhi during 1991-2010

5.3.2.1. Two wheelers

Two wheelers accounted about 6-7% of CO_2 of all vehicles in megacity Delhi during 1991-2010 (Fig. 5.16). Initially in 1991, emission of CO_2 from two wheelers was 211 Gg, and reached to 280 Gg in 1995 with annual growth between 6-9%. In 2000 emissions of CO_2 was 349 Gg and between 2000 and 2001 emissions decreased by 9% and reached to 318 Gg. The reason behind this decrement is phasing out of vehicles in 2001. After 2001, CO_2 emissions continuously increased till 2010, while some noticeable increments have been observed between some years. For instance, between 2001 and 2002 (16%), 2005- 2006 (12%) and 2006-2007 (23%) the emission growth was higher because of relatively high population growth of two-wheelers in these years . Nevertheless, in 2008 the impact of phasing out of 1991 and pre-1991 model two wheelers is not noticeable because of their less emission factors. Among all two-wheeler categories, the contribution of two stroke scooters (29-49%) is higher during 1991-2004, followed by two-stroke motorcycles (17-27%). Contribution trend in Fig. 5.16 suggests that contribution of 4-stroke scooters and motorcycles is increasing while contribution of 2-stroke scooters and motorcycles is decreasing.

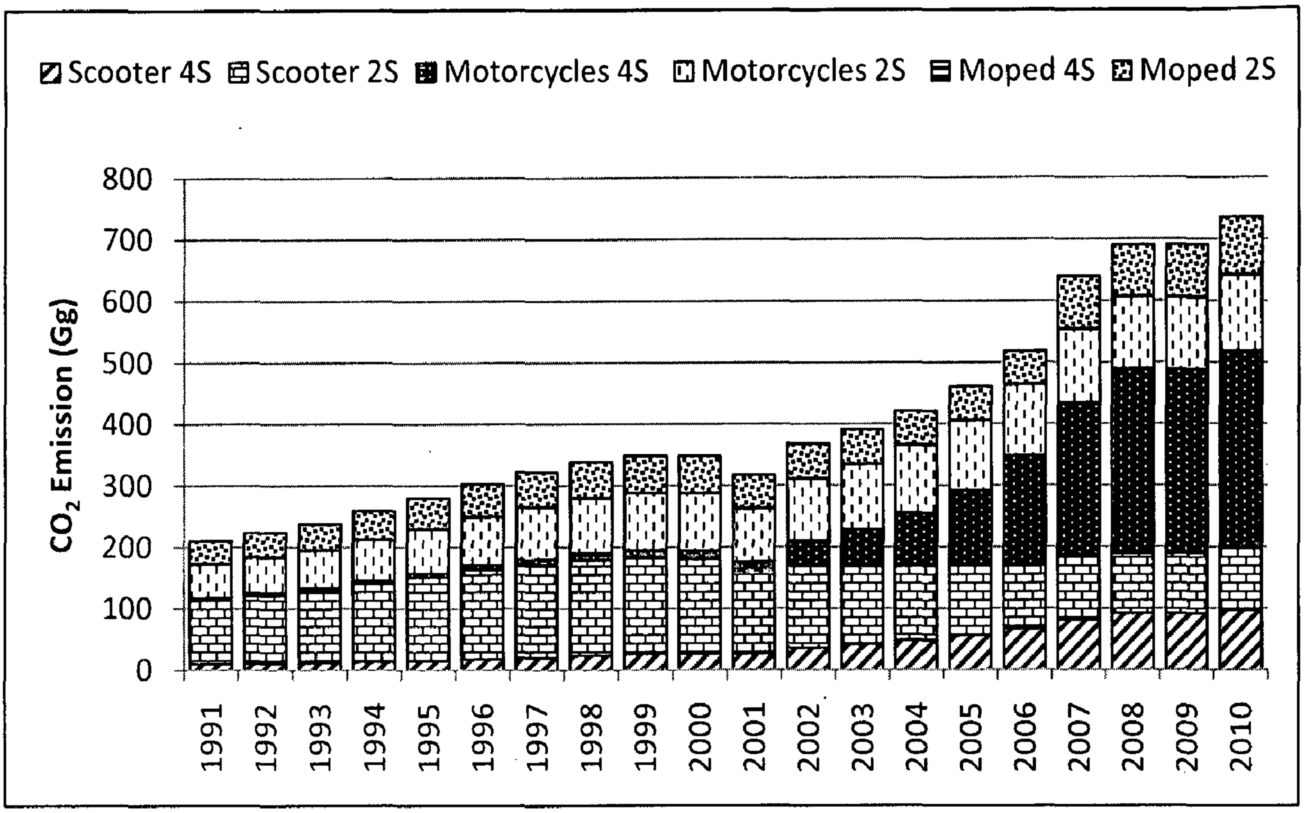


Fig. 5.16: CO_2 emission from two wheelers in megacity Delhi during 1991-2010

5.3.2.2. Cars

Emissions of CO_2 from car population in megacity Delhi shows an increasing trend from 1991 to 2010 (Fig.5.17). In 1991, CO_2 emissions from car population was 713 Gg, which reached to 1038 Gg in 1995, followed by 1509 Gg in 2000 and 2531 Gg in 2005. From 1991 to 2000, CO_2 emissions from cars show a steady trend with 6-12% annual growth rate. Between 2000 and 2001, CO_2 emissions reduced about 1.3%, because of less population of cars in 2001 than 2000. After 2001, emissions of CO_2 increased with car population. VAPI model based estimations of CO_2 for 2010 is ~4301 Gg. As per contribution, accountability of petrol driven cars is higher (80-89%) throughout the study period (1991-2010), followed by diesel driven cars, while contribution of CNG driven cars are found to be gradually increasing from the year 2002 onward.

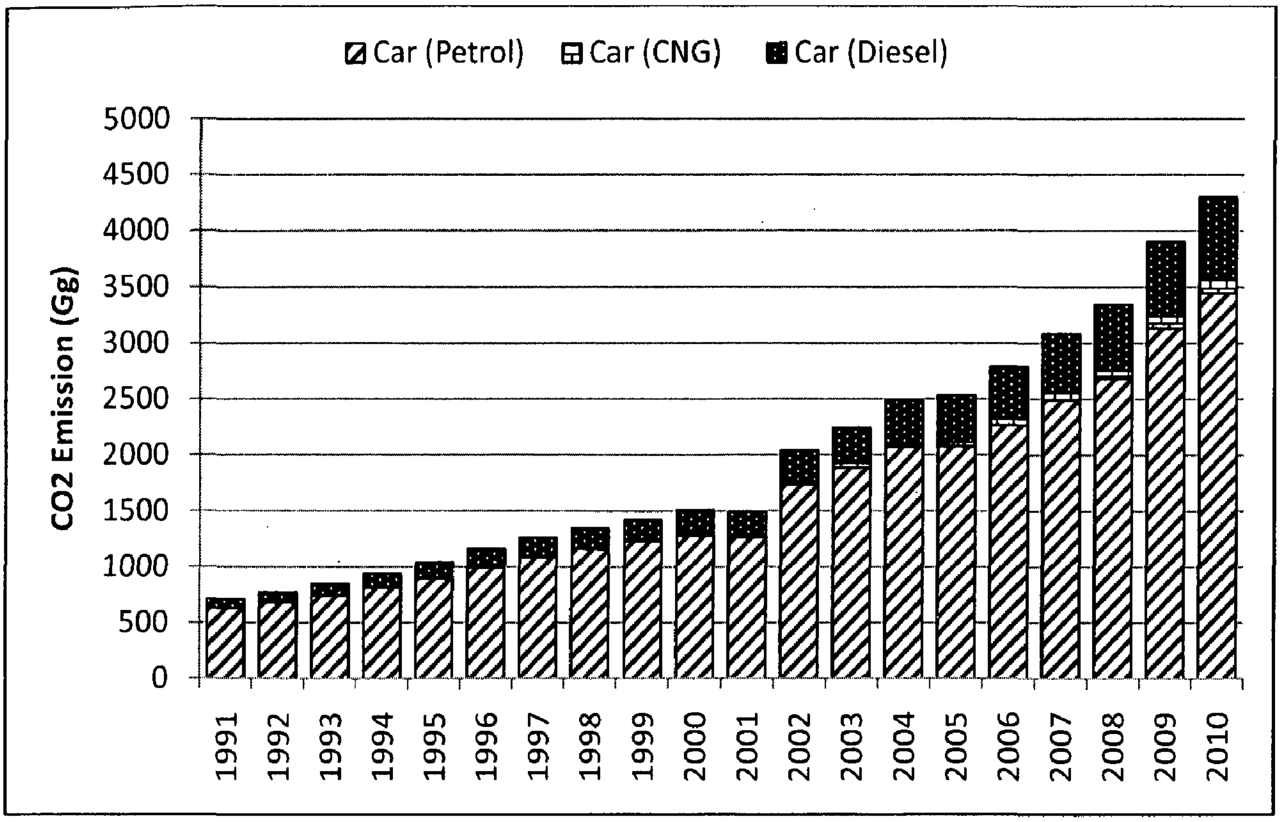


Fig. 5.17: CO_2 emissions from cars in megacity Delhi during 1991-2010

5.3.2.3. Three-Wheelers

Emissions of CO_2 from three-wheelers in megacity Delhi for the duration of 1991 to 2010 have been shown in Fig. 5.18. Initially the emissions of CO_2 from three wheelers were 62 Gg in 1991, which increased to 75 Gg in 1995. Fig. 5.18 shows emission of petrol driven four-stroke three wheelers from 1991 to 1999 and of petrol driven two-strokes from 1991 to 2001. After 2001, most of the three wheelers are CNG equipped due to CNG implementation. From 1991 to 1999 the contribution of four-stroke petrol driven three wheelers was 11%, while that of two-stroke petrol driven three wheelers was 89%. From 2002, onwards all three wheelers are converted to CNG and old three wheelers phased out from the road. Between 2000 to 2002 and 2004 to 2005 higher growth rate was observed, due to higher growth in CNG fueled three wheelers (higher emission factor). CO_2 emissions from CNG equipped three wheelers in 2002 were 178 Gg, which reached to 262 Gg in 2005 followed by 451 Gg in 2010. From 2002 to 2008 emission trend of CO_2 from three wheelers are quite fluctuated, because of variations in vehicle population, model year and emission factors. This is inferred that contribution of two-stroke three wheelers is higher during 1991 to 1999, while emissions from CNG driven three wheelers dominate after 1999.

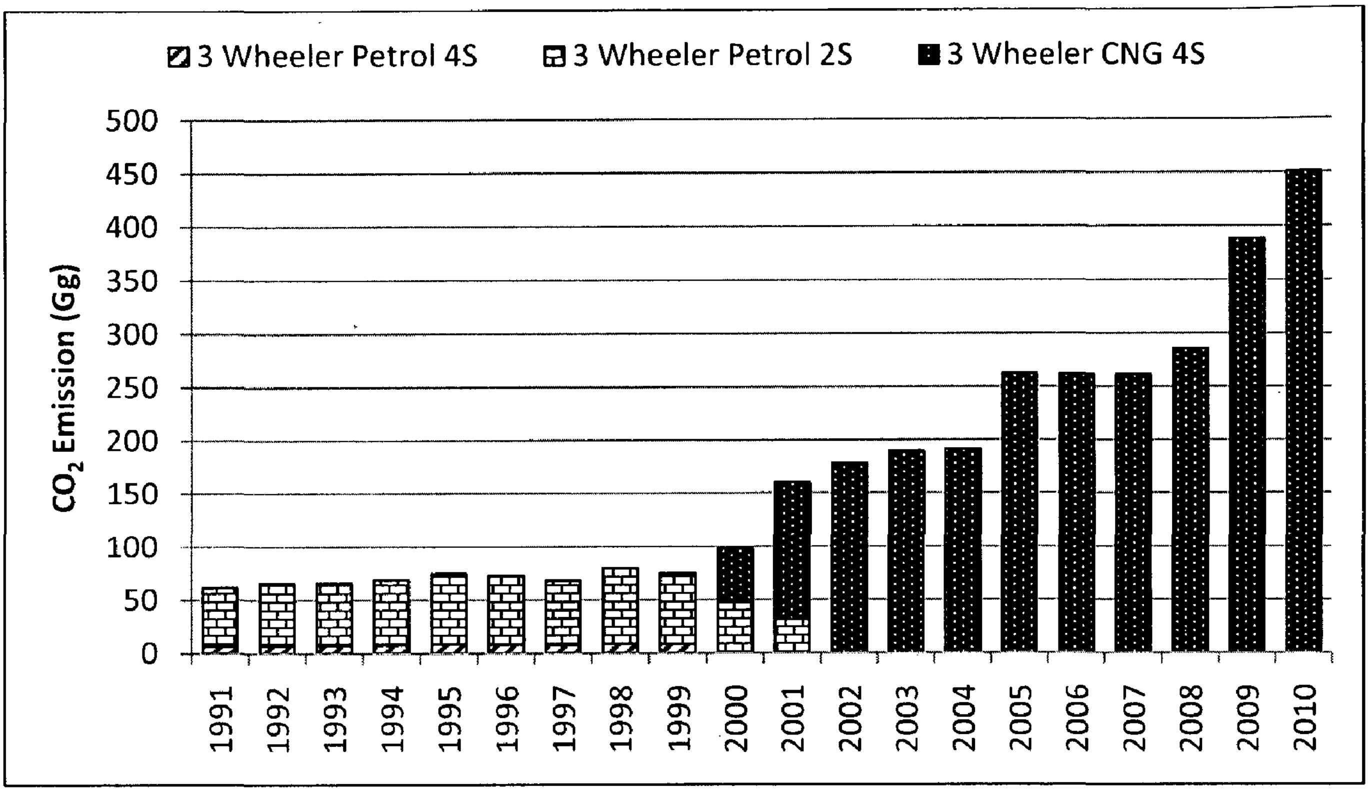


Fig. 5.18: CO_2 emissions from 3-wheelers in megacity Delhi during 1991-2010

5.3.2.4. Taxis

CO_2 emissions from taxi population were 30 Gg in 1991, and reached to 39 Gg in 1995, followed by 53 Gg in 2000. From 1991 to 2001, emission of CO_2 increased with growth rate ranging between 1-17% (Fig. 5.19). Whereas between 2001 and 2002, decline (~-0.6%) is observed in CO_2 emissions from taxis due to phasing out of pre 1991 taxis and CNG conversion program in Delhi. In comparison to other pollutants this change is less because of lower emission factor for old model taxis. In 2005, emission of CO_2 from taxi population was 111 Gg and increased to 303 Gg in 2010. About 43% of growth rate has been observed in CO_2 emissions between 2004 and 2005 due to increase in taxi population in 2005. Initially from 1991 to 2001 the contribution of diesel driven taxis was highest (84-86%), followed by petrol driven taxis (14-16%). Similarly, after CNG implementation from 2002 to 2010, CNG driven taxis played a dominant (68-81%) role for CO_2 emissions followed by diesel taxis.

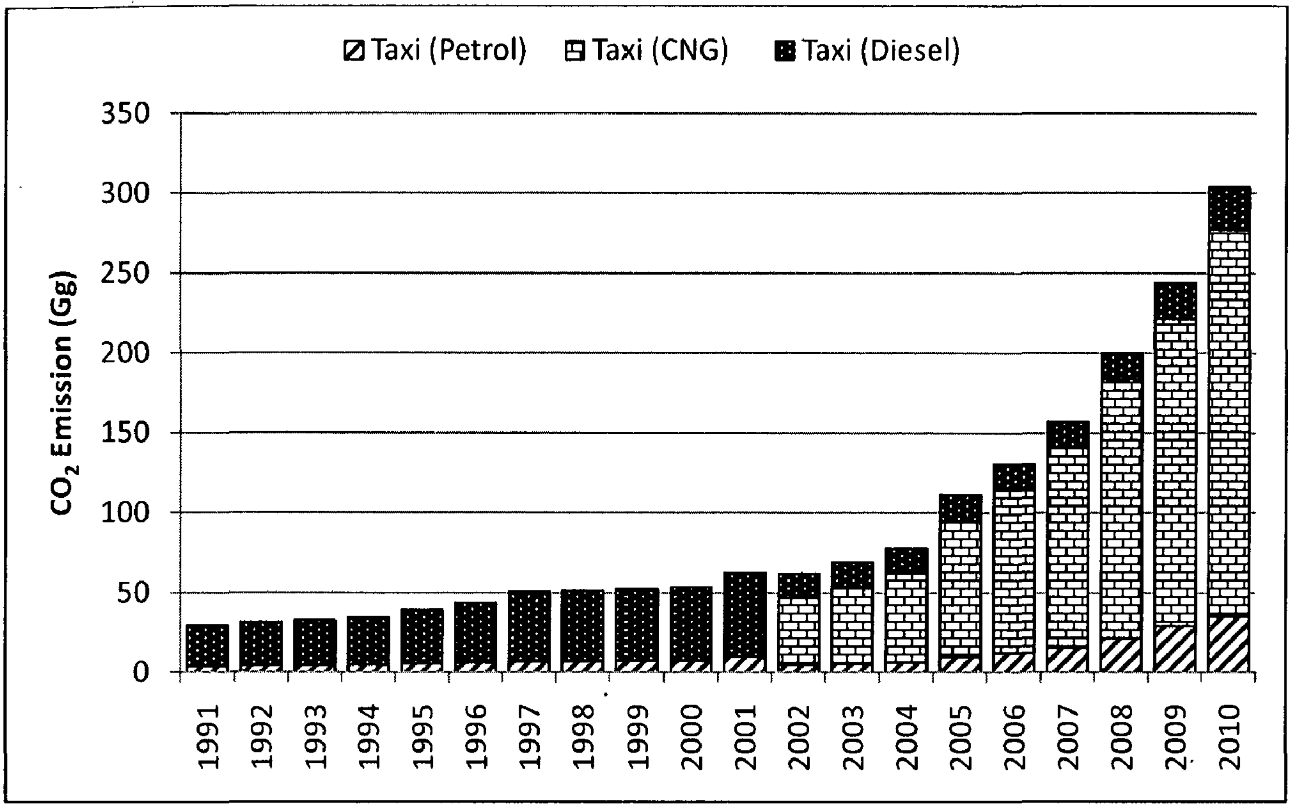


Fig. 5.19: CO_2 emissions from the taxis in megacity Delhi during 1991-2010

5.3.2.5. Buses

Bus is one of the major modes of public transport in Delhi. The contribution of bus population for CO_2 emissions is 17-29% in among all vehicle categories in megacity Delhi. In 1991, emissions of CO_2 from buses were 550 Gg and in 1995 it became 738 Gg (Fig. 5.20). Between 1992 and 1993, CO_2 emissions have decreased about 0.1% because of phasing out of old buses and less entry of new buses. Similarly, in between 2001 and 2002 about 32% of decline is observed because of strictly phasing out of old age buses and CNG conversion program. In 2004, CO_2 emissions from buses were 1197 Gg. With very drastic growth rate of 90% it became 2271 Gg in 2005. This is because of more entry of new buses in 2005. In between 2007 and 2008, about 0.45% of decrease is observed, followed by 26.24% of increase between 2008 and 2009. Less increment in bus population between 2007 and 2008 is responsible for negative growth in emission, while higher bus population growth between 2008 and 2009 is responsible for higher growth rate. Initially from 1991 to 2001 contribution of bus population was higher (99-100%), while after CNG implementation by government of Delhi contribution of diesel driven buses decreased gradually. From 2002 to 2010 contribution of CNG driven buses is increased to rise from 84-87%. Fig. 5.20 shows diesel driven buses after 2001, which are actually external buses coming from other states.

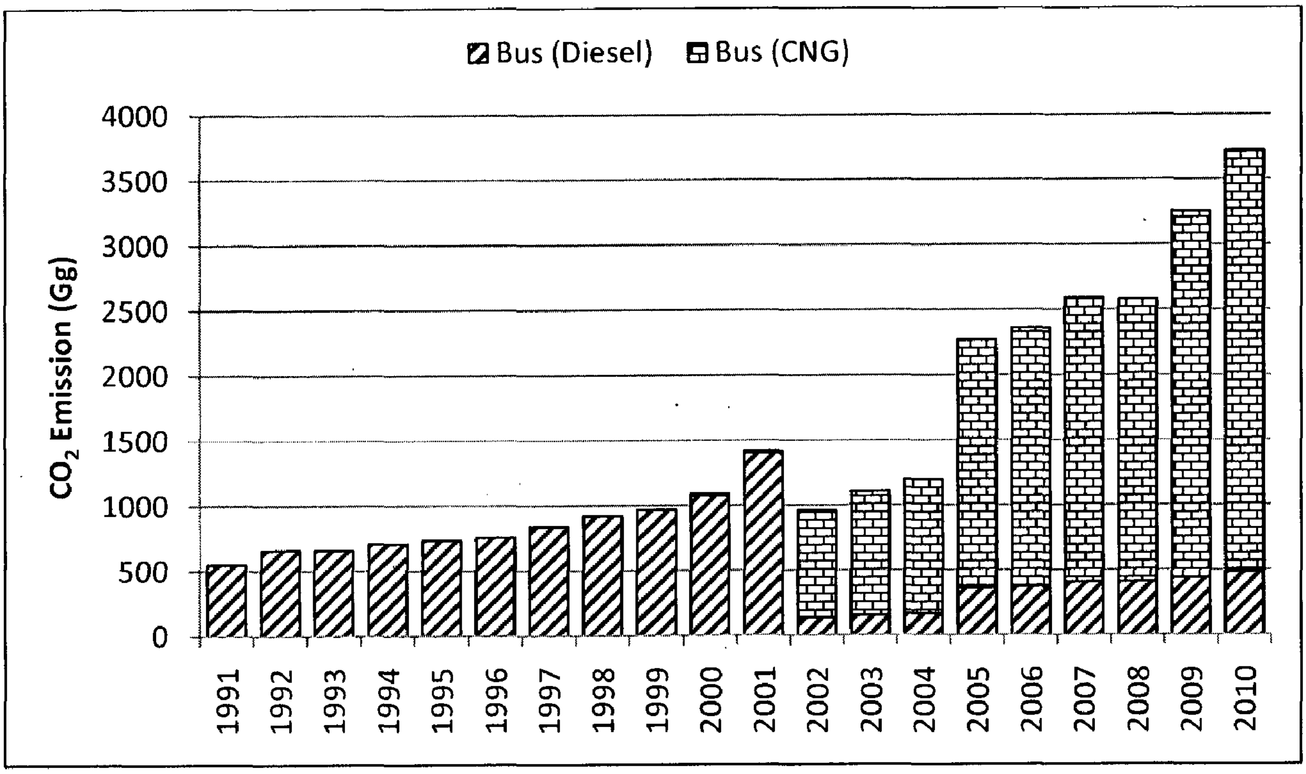


Fig. 5.20: CO_2 emissions from the buses in megacity Delhi during 1991-2010

5.3.2.6. LCVs

In megacity Delhi, LCVs play very important role for transportation of goods etc. and contributes about 9-18% of road transports induced CO_2 emissions. In 1991, CO_2 emissions from LCVs were 526 Gg and in 1995 it reached to 663 Gg (Fig. 5.21). In 2000, CO_2 emissions from LCVs were 750 Gg. During 2000 to 2002 continuous decrement has been observed in CO_2 emissions from LCVs because of CNG conversion program and phasing out of old age vehicles (pre 1991). CO_2 emissions have been estimated to be 668 Gg and 1758 Gg in 2005 and 2010, respectively. Initially the contribution of CNG driven LCVs was very less (0-10%). However, in 2006 the Government of Delhi launched CNG norms for all new LCVs, hence share of CNG driven LCVs contribution increased. after 2006 in comparison with diesel driven LCVs. From 1991 to 2007, the contribution of diesel driven LCVs in CO_2 emissions was 51-100%, whereas after 2007 the contribution of CNG driven LCVs started to rise and ranged between 59-68%.

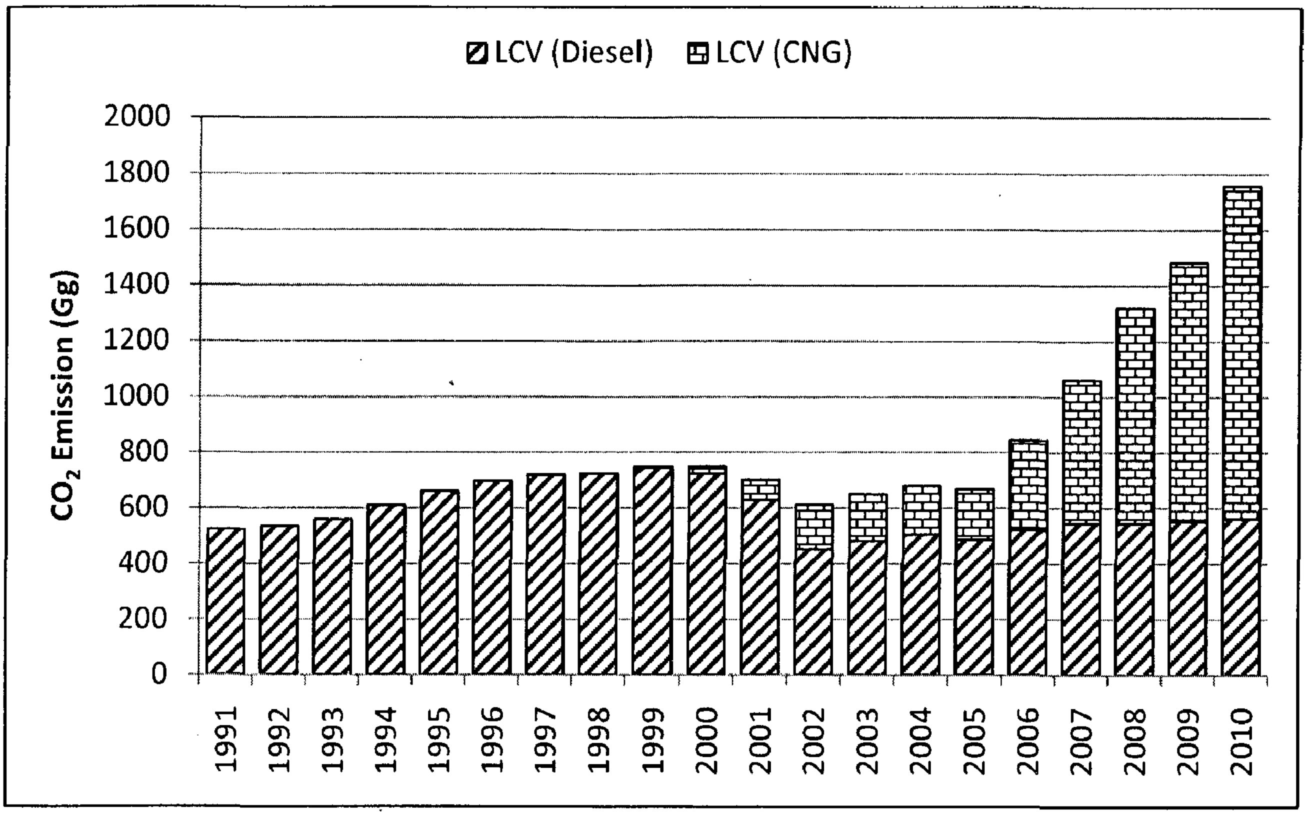


Fig. 5.21: CO_2 emissions from the LCVs's in megacity Delhi during 1991-2010

5.3.2.7. HCVs

Emissions of CO_2 from HCVs show an increasing trend with slight fluctuations (Fig. 5.22). The contribution of HCVs among all on-road vehicles ranged between 10-29%. Initially in 1991, CO_2 emission from HCVs was 863 Gg, followed by1087 Gg in 1995 and 1207 Gg in 2000. From 1991 to 1999 emission trend of CO_2 shows a positive growth rate ranging between 1-9% per annum. Emissions of CO_2 from HCVs population decreased from 2000 to 2002. In between 1999 and 2000 a decline of about 1.4% declines is recorded followed by 10% decrease between 2000 and 2001 and 26% decline between 2001 and 2002. High decline between 2001 and 2002 shows the impact of phasing out program in megacity Delhi. Emissions of CO_2 from HCVs in 2005 were 841 Gg that increased to 1214 Gg in 2010.

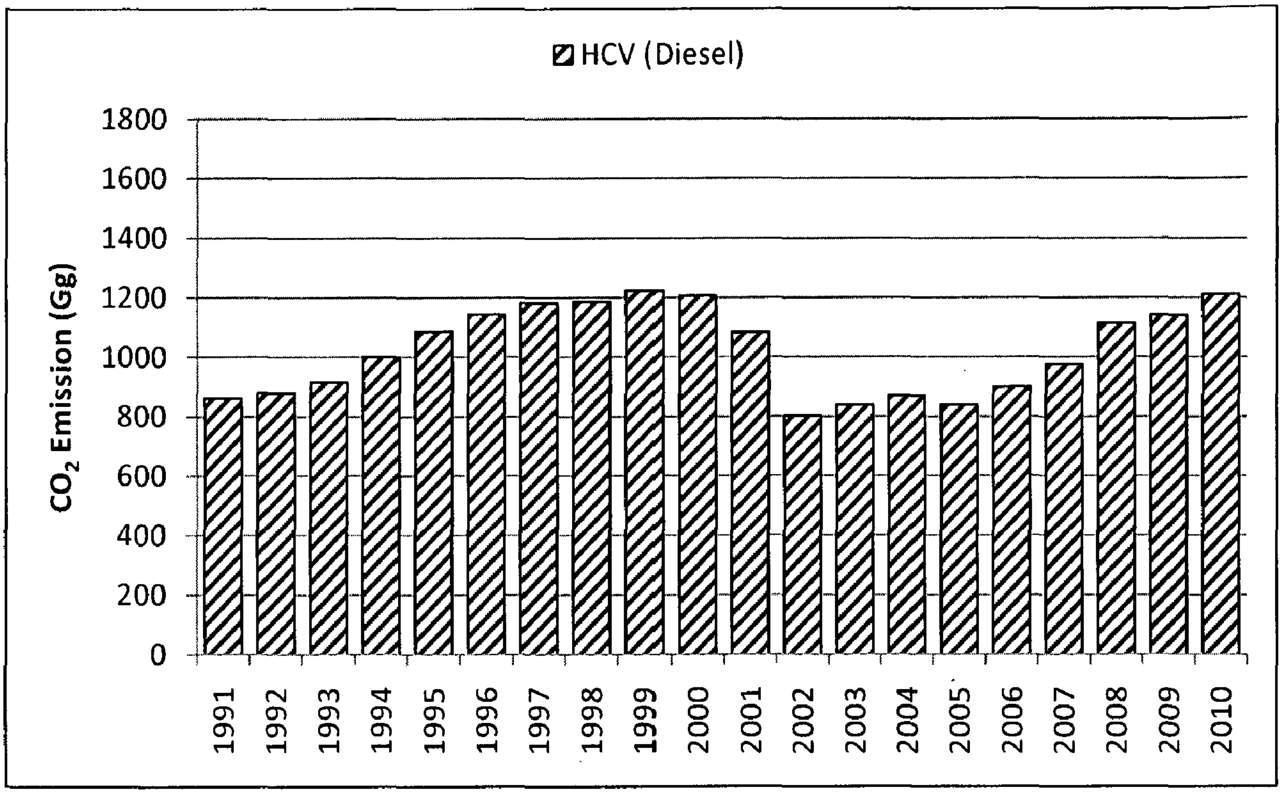


Fig. 5.22: CO_2 emissions from the HCVs's in megacity Delhi during 1991-2010

5.3.3. NO_x emissions

Fig. 5.23 shows the emission trend of NO_x from various vehicle categories in megacity Delhi. It follows an increasing trend between 1991 and 2010 except a sharp dip during 2002. From 1991 to 2011, NO_x emissions increase with 6% annual average growth rate. In 1991, NO_x emissions from all on-road vehicles were 35 Gg which reached to 46 Gg in 1995 and 60 Gg in 2000 followed by 59 Gg in 2005 and 87 Gg in 2010 (Fig. 5.23). A decline of about 30% is observed in NO_x emissions between 2001 to 2002 because of phasing out of old age vehicles and CNG conversion program for commercial vehicles in 2002. Between 2004 and 2005, highest change in growth rate (22.5%) of NO_x emission has been observed, which might be due to increased entry of new buses in 2005. After 2002 emission trend rises until 2010. From 1991 to 2006 contribution of HCVs population was highest (22-42%) among all vehicle categories except during the year 2001, while from 2007 to 2010 bus population is dominating the NO_x emissions.

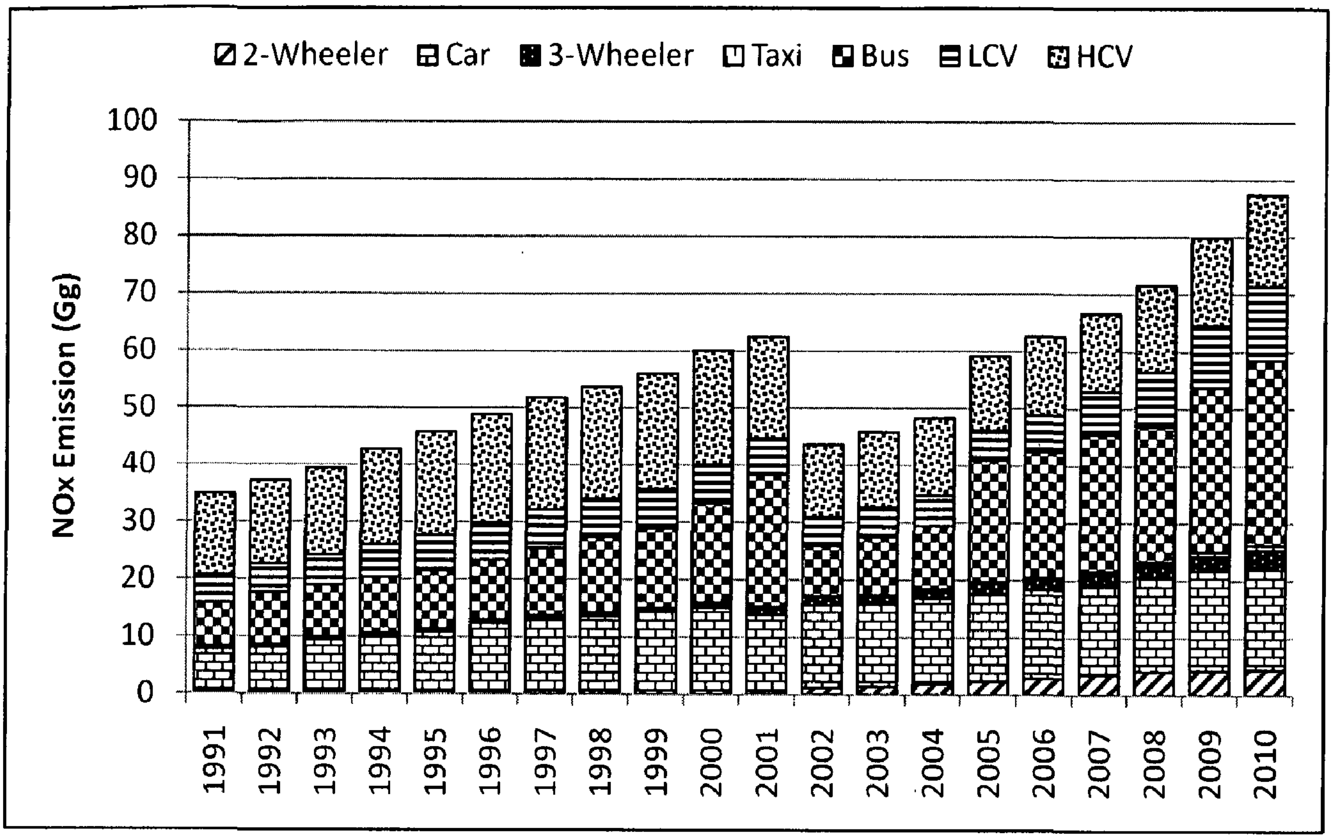


Fig. 5.23: NO_x emission from various vehicle categories in megacity Delhi during 1991-2010

5.3.3.1 Two wheelers

In 1991 emission of NO_x from two wheelers were 363 Mg (Fig. 5.24), and reduced to 329 Mg in 1992 with a decline of 9.4%. Further, about 16.5% decrease is noticed between 2000 and 2001 because of phasing out of old age two wheelers in 2001. In 2000, emission of NO_x from two wheelers was 809 Mg, which reached to 2538 Mg in 2005, followed by 4504 Mg in 2010. Four-stroke scooters (29-34%) contributed highest NO_x during 1991 to 2001, while from 2002 to 2010 four-stroke motorcycles contributed highest share (44-79%).

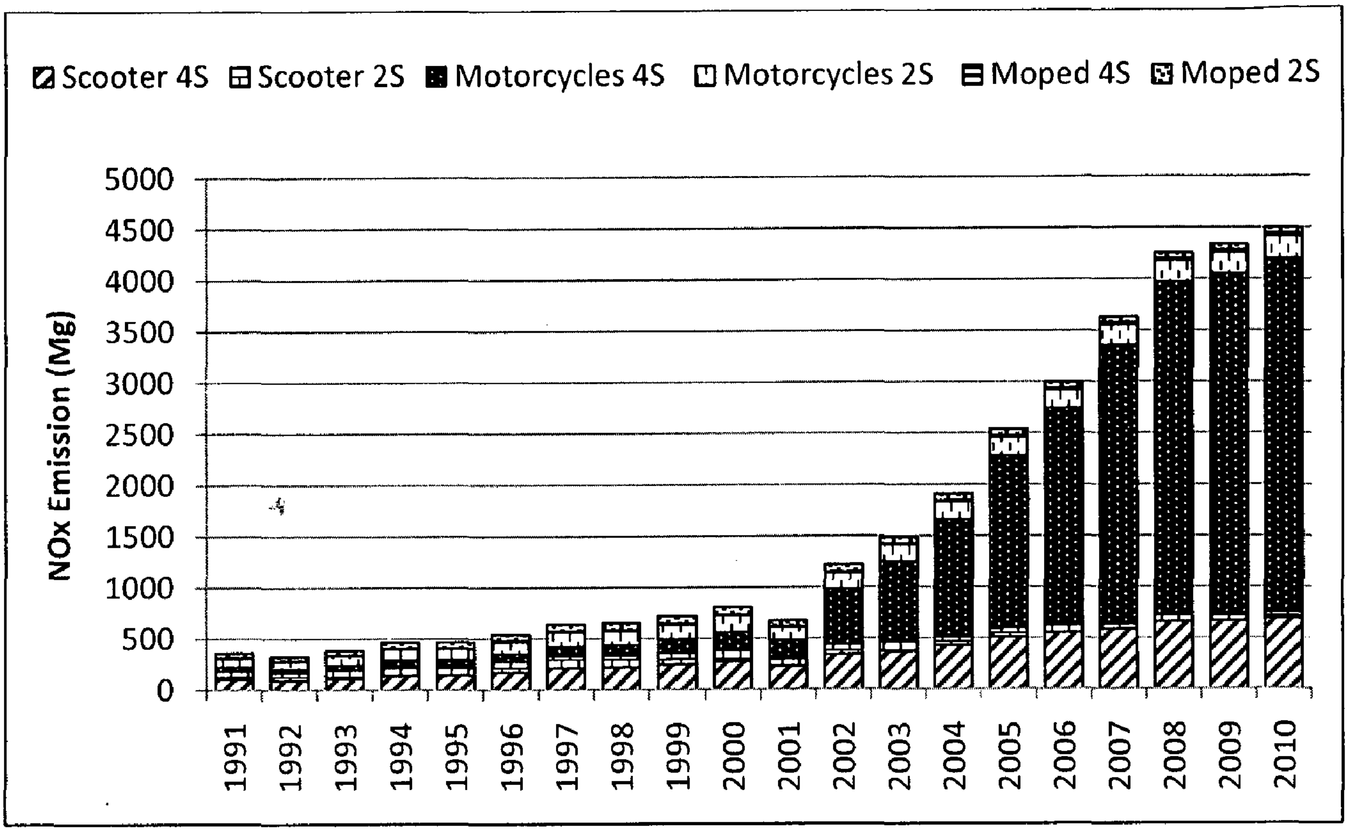


Fig. 5.24: NO_x emissions from the two wheelers in megacity Delhi during 1991-2010

5.3.3.2. Cars

Emission of NO_x from car population was 7.5 Gg in 1991 and reached to 10.5 Gg in 1995. No decline has been found in NO_x emission from 1991 to 2000. Between 2000 and 2001, however, about 7.2% decline has been observed in NO_x emissions. Phasing out of old age cars and fewer new vehicles might be responsible for this decline. In 2000, emission of NO_x from car population was 14.4 Gg and in 2005 it was 15.2 Gg. From 2006 onwards, emissions increased with 1 to 5% growth rate and reached to 18 Gg in 2010. As per NO_x emission contribution of petrol driven car is highest during 1991-2010, but its emission contribution decreased from ~96% in 1991 to ~83% in 2010.

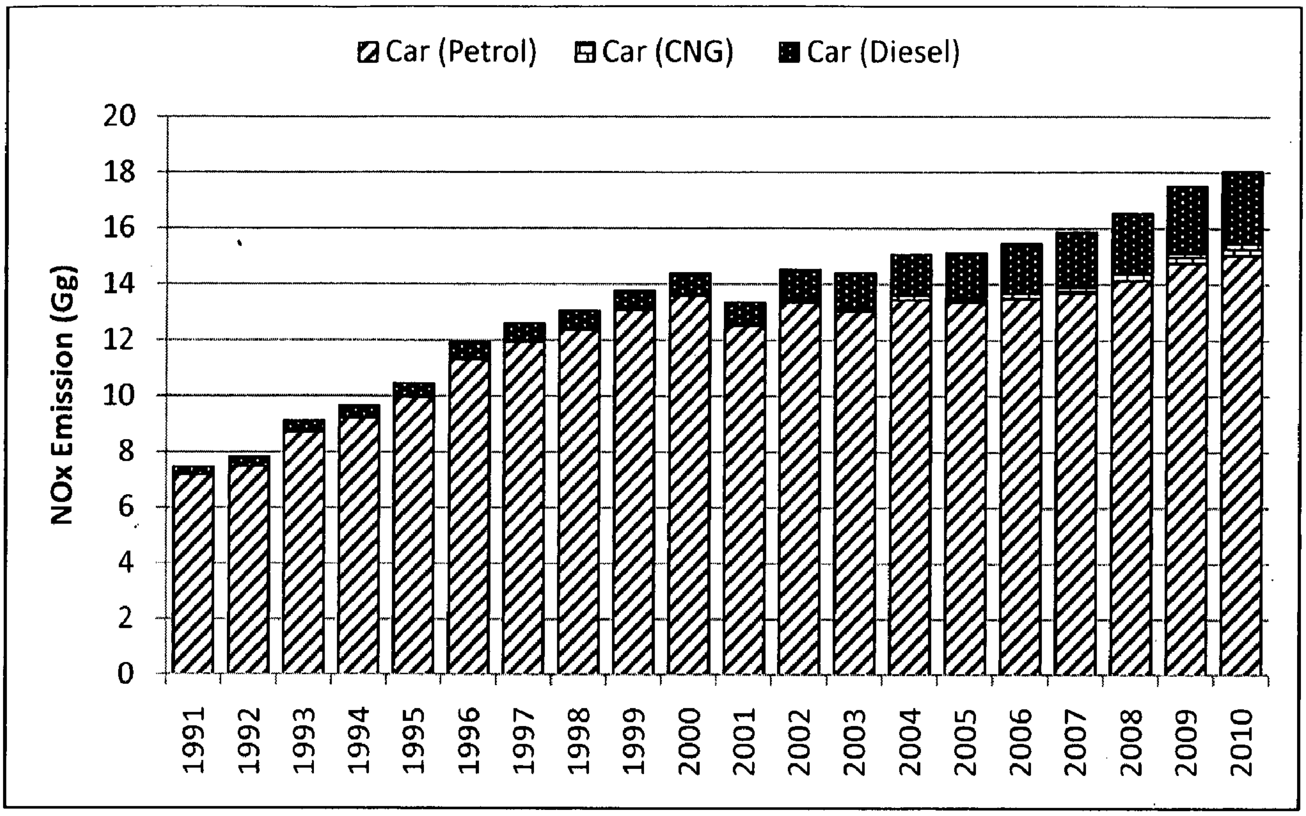


Fig. 5.25: NO_X emissions from the car population in megacity Delhi during 1991-2010

5.3.3.3. Three wheelers

In 1991, NO_X emission from three wheelers was only 331 Mg and with 9% decline, it became 301 Mg in 1992. In 1995, emissions reached 371 Mg, followed by 633 Mg in 2000. In 2001 Delhi government implemented CNG norms for three wheelers, and from 2002 onwards all three wheelers had been converted to CNG driven four-stroke three-wheelers. Nevertheless, instead of decrease this policy measure resulted in increase of NO_X emissions from three-wheelers between 2001 and 2002 (Fig. 5.26). This could be because of higher emission factors of CNG driven four-stroke three wheelers in comparison to petrol driven two- and four-stroke three wheelers. NO_X emissions from three wheelers in Delhi were 1769 Mg in 2005 and 2830 Mg in 2010. Higher growth in NO_X emissions is observed between 2004 and 2005 due to increase in three wheeler population in 2005. Negative trends are observed between 2005 and 2007. Phasing out of three wheelers and variation in emission factors is responsible for this change. As per share of emissions, the contribution of two-stroke petrol driven three wheelers is higher before 2000, while after 2000 contribution of CNG driven four-stroke three wheelers is found to be more dominating.

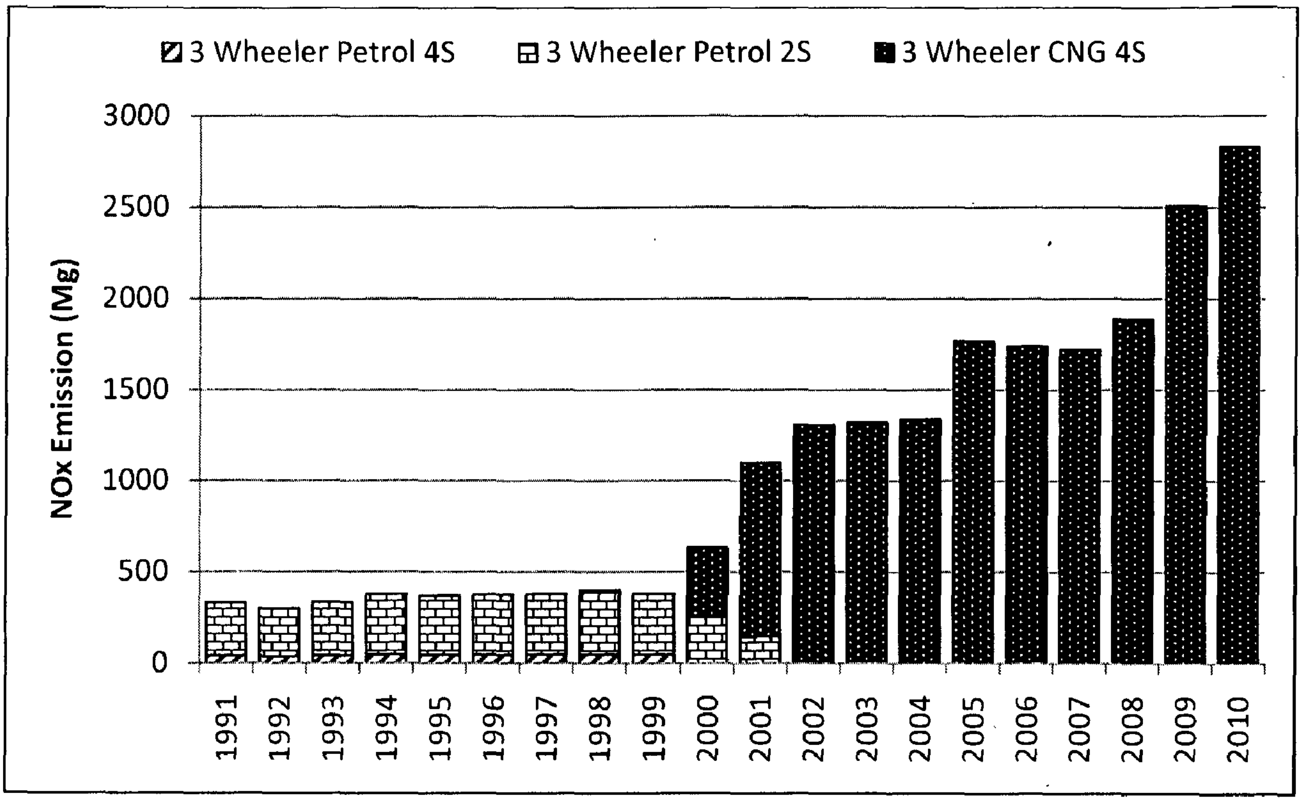


Fig. 5.26: NO_x emissions from the three wheelers in megacity Delhi during 1991-2010

5.3.3.4. Taxis

Fig. 5.27 illustrates the NO_x emissions from taxis in megacity Delhi. It shows that NO_x emissions gradually increase from 1991 (138 Mg) to 2001 (277 Mg), while a sudden decrease of 16% is observed between 2001 (277 Mg) and 2002 (234 Mg). In 2005, emissions of NO_x from taxi population are estimated to be 380 Mg and 871 Mg in 2010. After 2002, no further decline has been observed. Fig. 5.27 also shows that the contribution of diesel and petrol driven taxis through 2002-2010 is decreasing gradually, while that of CNG driven taxis is increasing. Initially from 1991 to 2001, contribution of diesel driven taxis was highest (65-70%) followed by petrol driven taxis. During 2002 to 2010, CNG driven taxis emerged as highest NO_x contributor (66-85%) among all types of taxi population in megacity Delhi (Fig. 5.27).

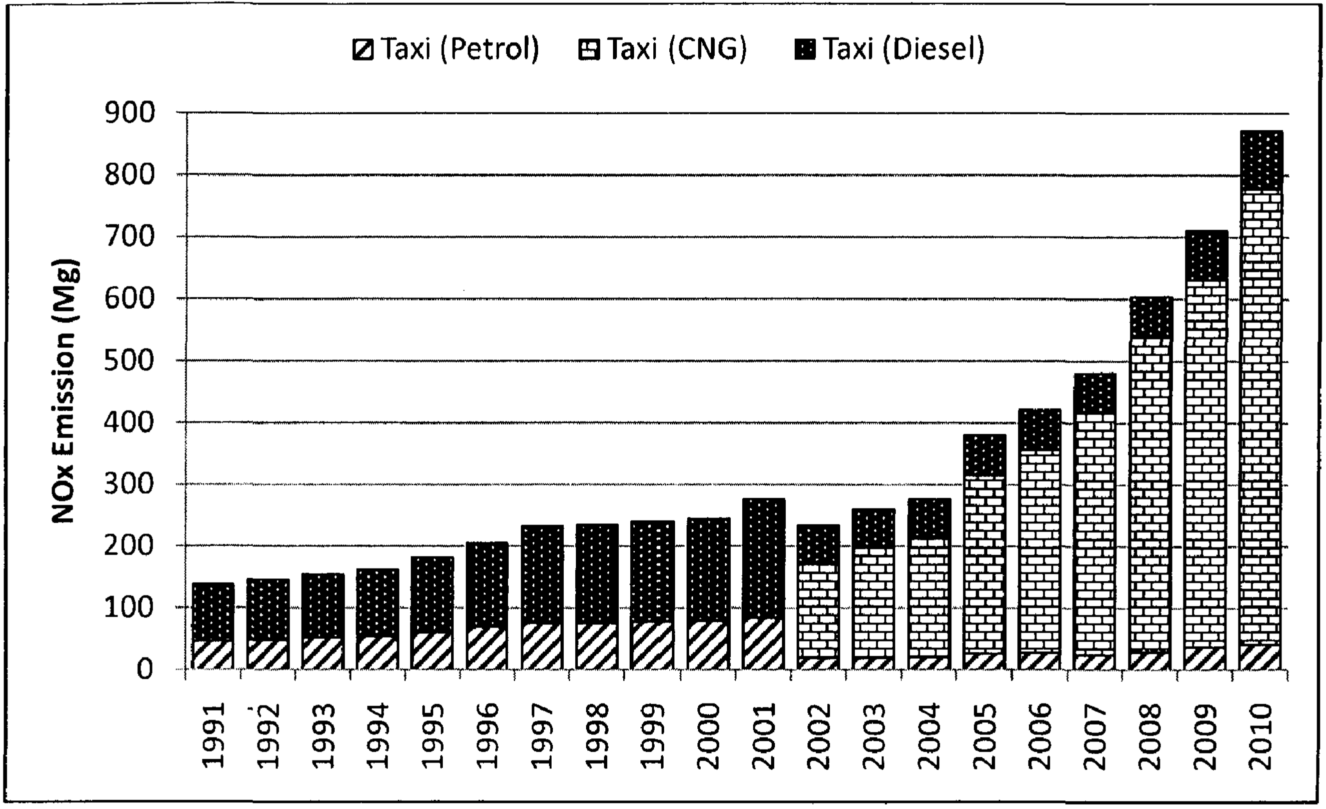


Fig.5.27: NO_x emissions from the taxis in megacity Delhi during 1991-2010

5.3.3.5. Buses

Buses account for major share of NO_x emissions among on-road vehicles in megacity Delhi. In 1991, NO_x emissions from bus population in Delhi were 7.6 Gg (Fig. 5.28), which increased to 10.2 Gg in 1995 followed by 17.3 Gg in 2000. These emissions were estimated to be 21.2 Gg and 32.3 Gg in 2005 and 2010, respectively. Approximately 33% of increase is observed between 2000 and 2001 because of enhancement in bus population in 2001. About 62% decline is found in between 2001 and 2002 because of CNG conversion and phasing out of old buses (8 year) by the Government of Delhi. While about 93% increase is observed between 2004 and 2005 in NO_x emission because of more entry of buses in 2005 in Delhi. From 1991 to 1998 contribution of diesel driven buses was 100%, due to absence of CNG driven buses in New Delhi. From 1999 buses started to convert in CNG and in 2001 government of Delhi strictly implemented CNG norms for buses, leading to a shift in emission contribution, with diesel buses declining gradually from 1999 while the CNG buses increasing simultaneously (Fig. 5.28).

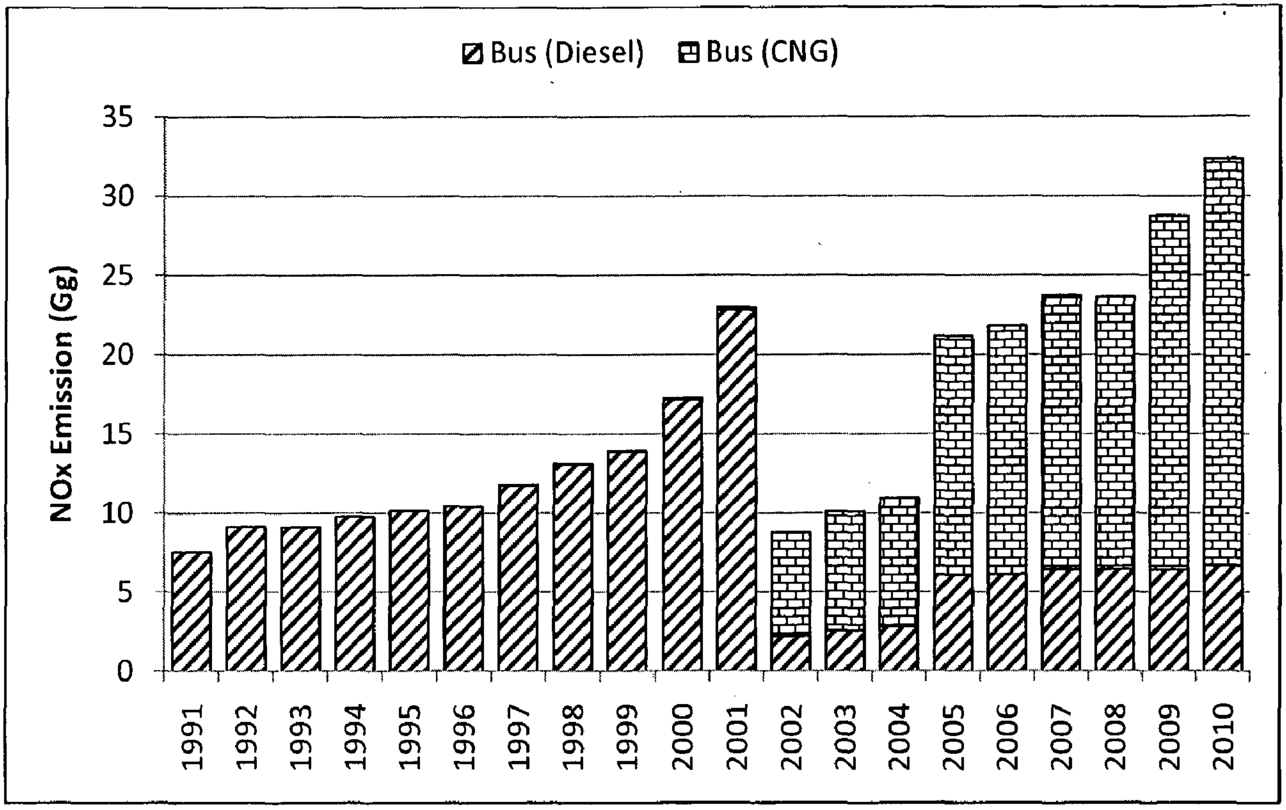


Fig. 5.28: NO_x emissions from the buses in megacity Delhi during 1991-2010

5.3.3.6. LCVs

Fig. 5.29 shows the contribution of CNG and diesel LCVs. It indicates that initially from 1991 to 2006 contribution of diesel driven LCVs is higher (61-100%), while from 2007 to 2010 CNG driven LCVs emerged as the dominating one (54-74%). During 1991 and 1995 emission of NO_x from LCVs was 4.9 Gg and 6.1 Gg. NO_x emissions from LCVs showed an increasing trend from 1991 to 1999 with growth rate ranging between 1-9%. From 1999 to 2001, however, negative trend has been observed, which might be due to the strict phasing out of old age LCVs and less entry of LCVs in 2000 and 2001. Emission of NO_x from LCVs is 5.2 Gg in 2005, which increased to 12.8 Gg in 2010.

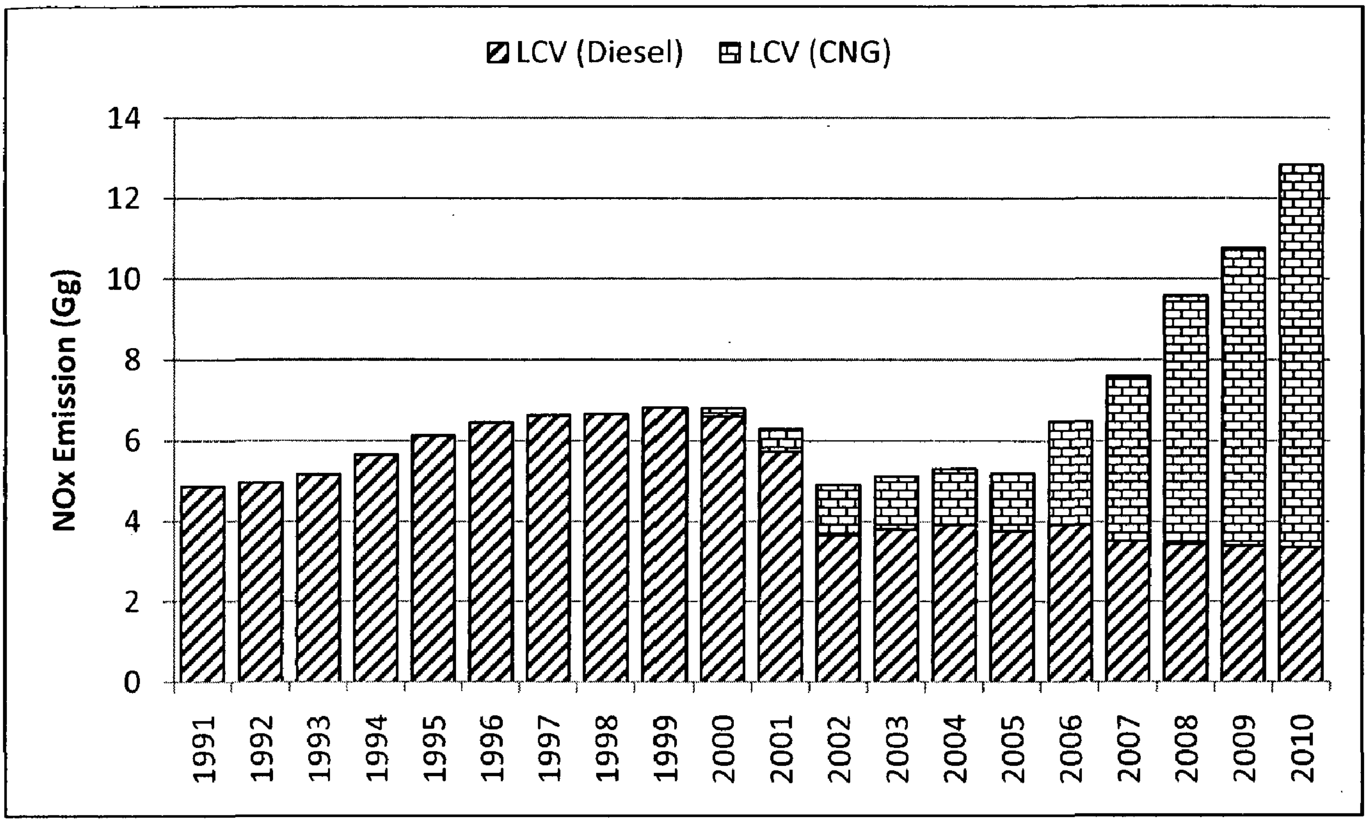


Fig. 5.29: NO_x emissions from the LCVs in megacity Delhi during 1991-2010

5.3.3.7. HCVs

HCVs are the largest contributor (24-43%) of NO_x during most of the study period among all vehicle categories in megacity Delhi. NO_x emissions were 14.3 Gg and 18 Gg during 1991 and 1995 from HCVs (Fig. 5.30). However, there was a declining trend between 1999 to 2002. Maximum decline (29%) is observed between 2001 and 2002, due to phasing out of HCVs and less entry of new vehicles in 2002. In 2005, emission of NO_x from HCVs was 13 Gg which increased to 16 Gg in 2010. Decreasing trend is observed between 2004 and 2005 in NO_x emission from HCVs because of phasing out of 1991 and pre-1991 HCVs population during this year.

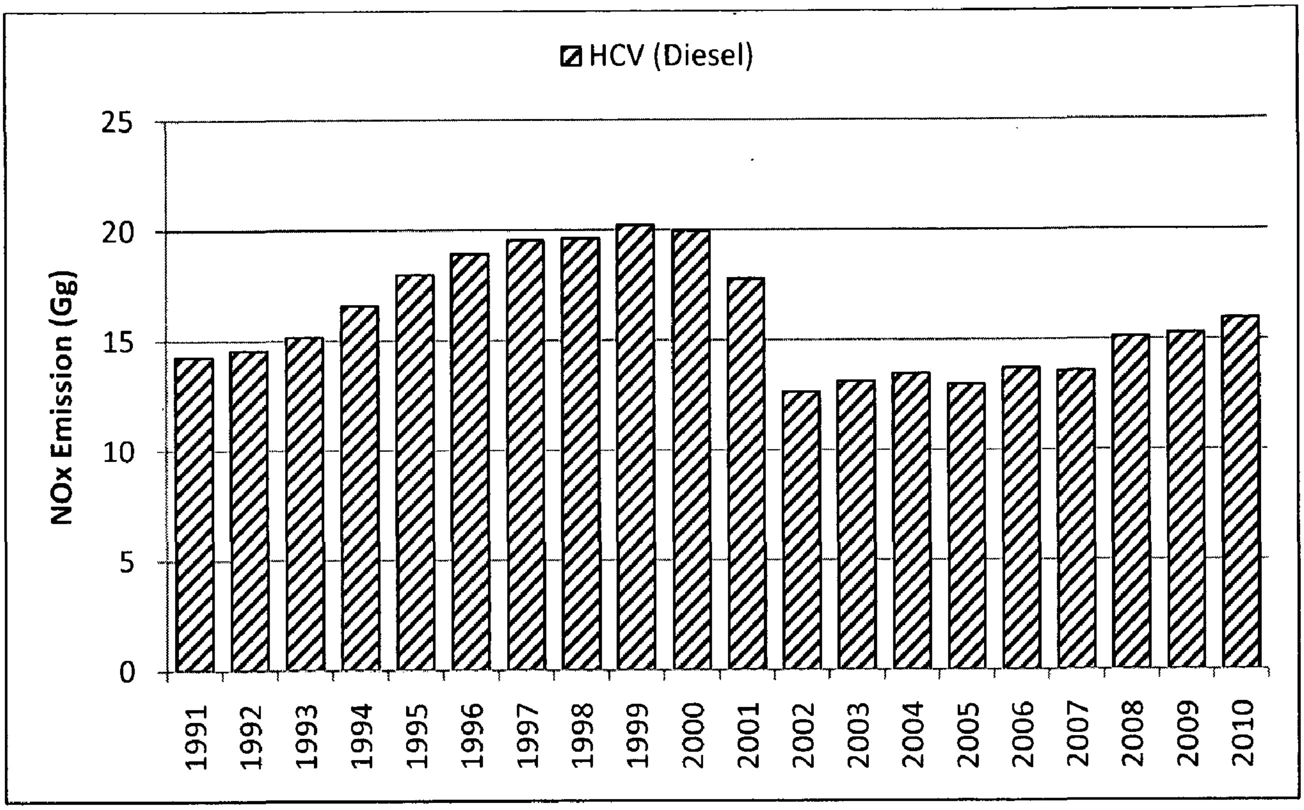


Fig. 5.30: NO_x emissions from the HCVs in megacity Delhi during 1991-2010

5.3.4. HC emissions

Fig. 5.31 shows the emissions of HC from various vehicle categories in megacity Delhi during 1991 to 2010. In 1991, emission of HC from vehicles was 61 Gg, which arrived at 80 Gg in 1995, followed by 89 Gg in 2000. HC emissions show an increasing trend during 1991 to 1999, while decline is observed between 1999 and 2002. This is because of phasing out program of commercial vehicles in 2001 and 2002 by the Government of Delhi. After 2002, however, HC emissions started to increase until 2006. After that major decrement (18%) is observed between 2006 and 2007 because of phasing out of pre-1991 and 1991 vehicles especially two-wheelers. HC emissions were 82 Gg in 2005, followed by 75 Gg in 2010. As per share the contribution of two wheelers (45-73%) is highest among all vehicles for HC emission in megacity Delhi.

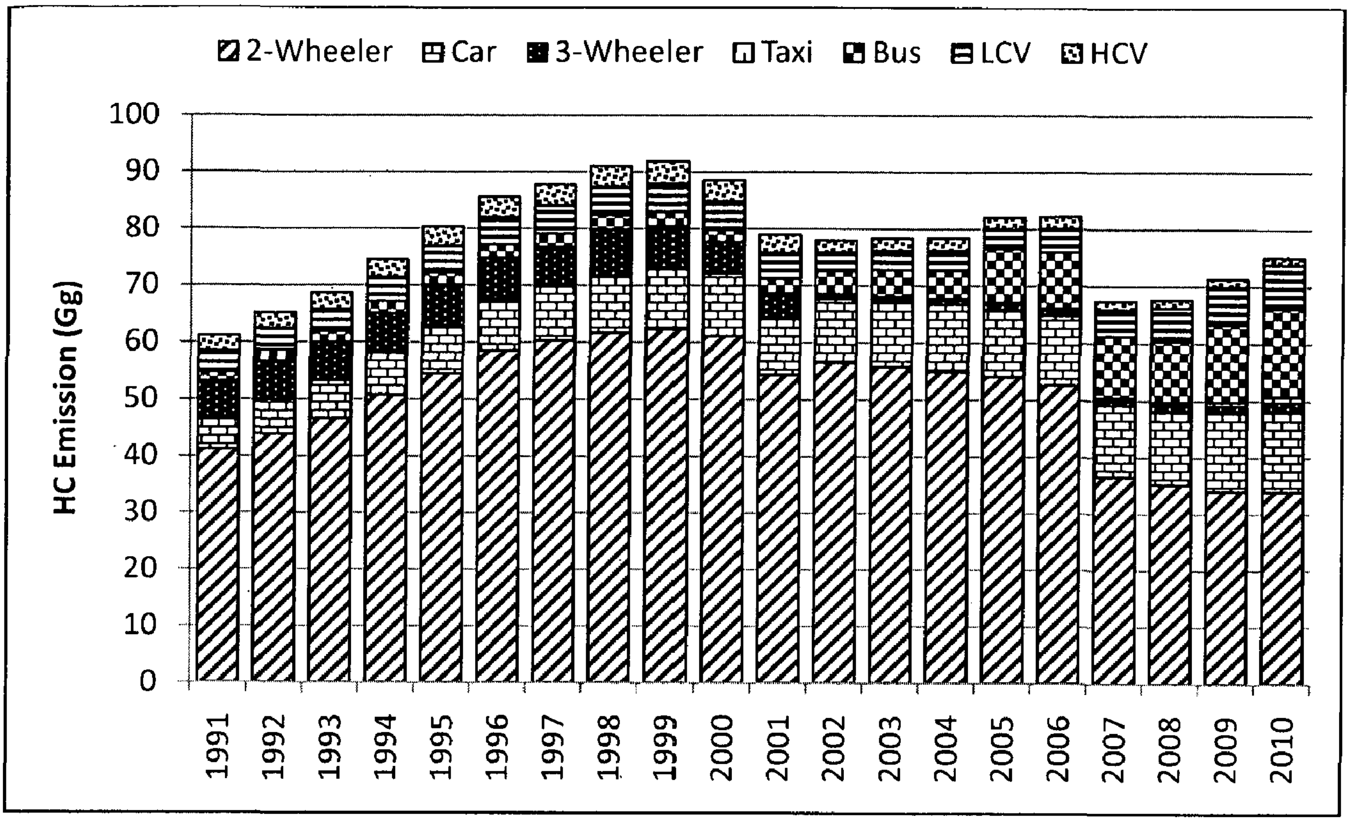


Fig. 5.31: HC emission from various vehicle categories in megacity Delhi during 1991-2010

5.3.4.1. Two Wheelers

HC emissions were 41 Gg from two wheelers in 1991 and reached to 54 Gg in 1995 with 6 to 9% growth rate (Fig. 5.32). Because of phasing out population of old age two wheelers decrease is observed between 1999 and 2001. About 2% decline is observed between 1999 and 2000, while it is 11% between 2000 and 2001. In 2000, HC emissions from two wheelers were 61 Gg and in 2005 it was 54 Gg. After 2006, major decline is observed in NO_x emissions because of phasing out of 1991 and pre-1991 old two wheelers from megacity Delhi. Because of continuous decline in HC, emissions from two wheelers reached to 34 Gg in 2010. Among all two-wheeler categories contribution of two-stroke mopeds is highest (37-46%) during 1991 to 2006, while contribution of two-stroke motorcycles is highest (34-37%) during 2007 to 2010.

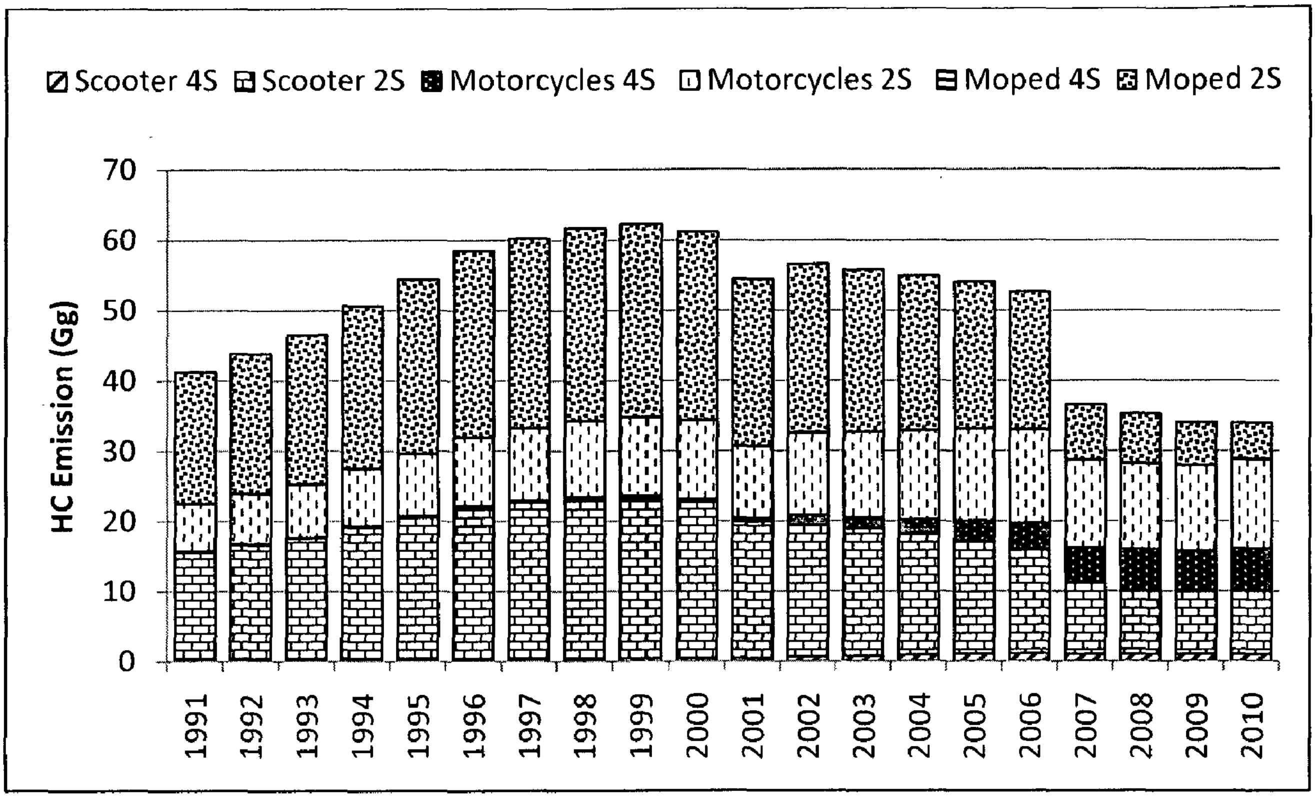


Fig. 5.32: HC emissions from the two wheelers in megacity Delhi during 1991-2010

5.3.4.2. Cars

Emissions of HC from cars in Delhi was 5.7 Gg in 1991 and with 9.7% average annual growth it reached to 8.1 Gg in 1995 (Fig. 5.33). In 2000, Car HC emissions increased to 11 Gg, while between 2000 and 2001 it decreased by 7.3% because of phasing out of old age cars. In 2005, HC emission from car population was 11.79 Gg, which reached to 14.35 Gg in 2010. From contribution/share viewpoint, petrol driven cars accounted for highest percentage (91-98%) of HC emissions during 1991 to 2010.

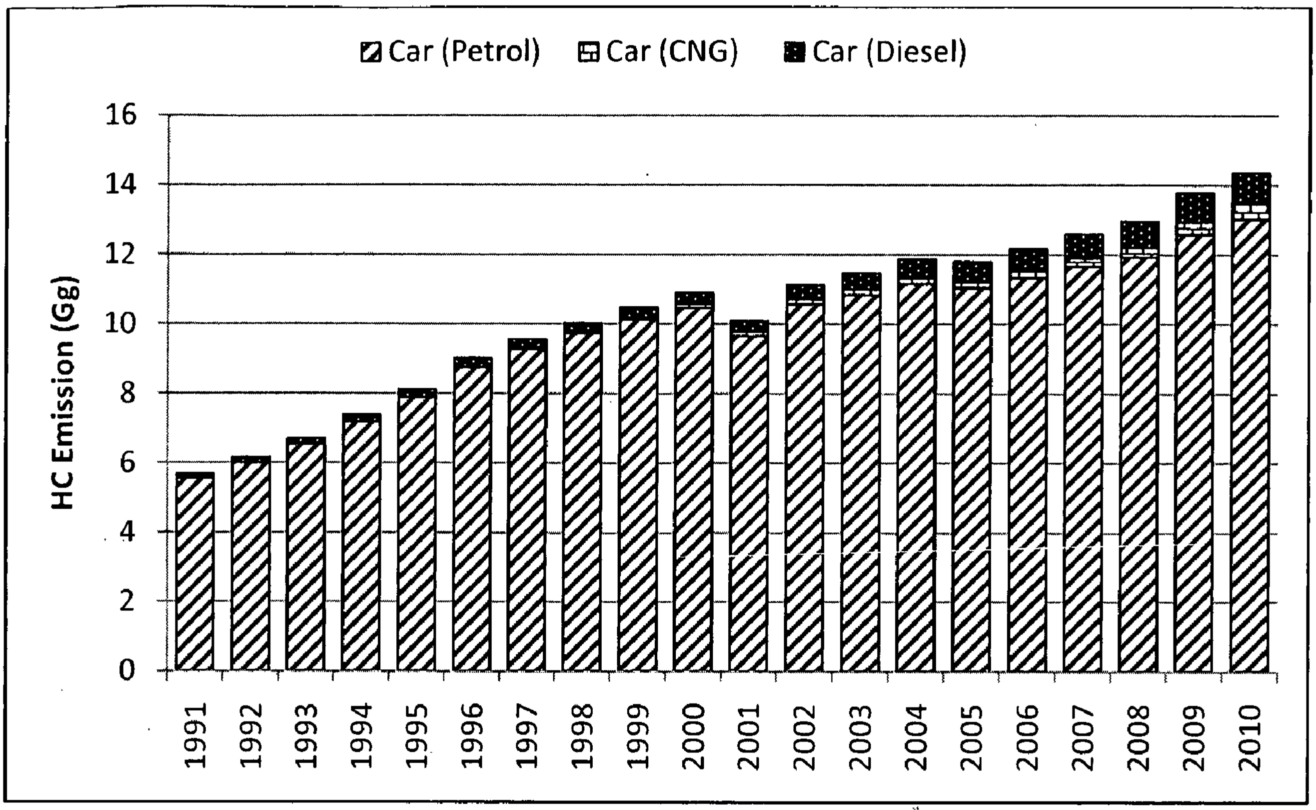


Fig. 5.33: HC emissions from the cars in megacity Delhi during 1991-2010

5.3.4.3. Three Wheelers

As visible from Fig. 5.34, HC emissions from three wheelers were 6.2 Gg in 1991, and 7.5 Gg and 5.5 Gg in 1995 and 2000, respectively. Before 2002 most of the three wheelers were petrol driven. Because of this emissions of HC are higher before 2002 due to their high emission factors. HC emissions started to decrease from 2000, with 85% decline between 2001 and 2002, due to low emission factors for CNG driven three wheelers. After 2002, however, HC emissions rise again due to constant increase in population of CNG driven three-wheelers. Emissions of HC were 0.9 Gg in 2005, followed by 1.5 Gg in 2010. Before 2000 share of petrol driven two-stroke three wheelers in HC emissions was higher, this has been dominated by CNG driven four-stroke three wheelers after 2001. Nevertheless, HC emissions from CNG driven four-stroke three-wheelers are much lower than the pre-2001 period.

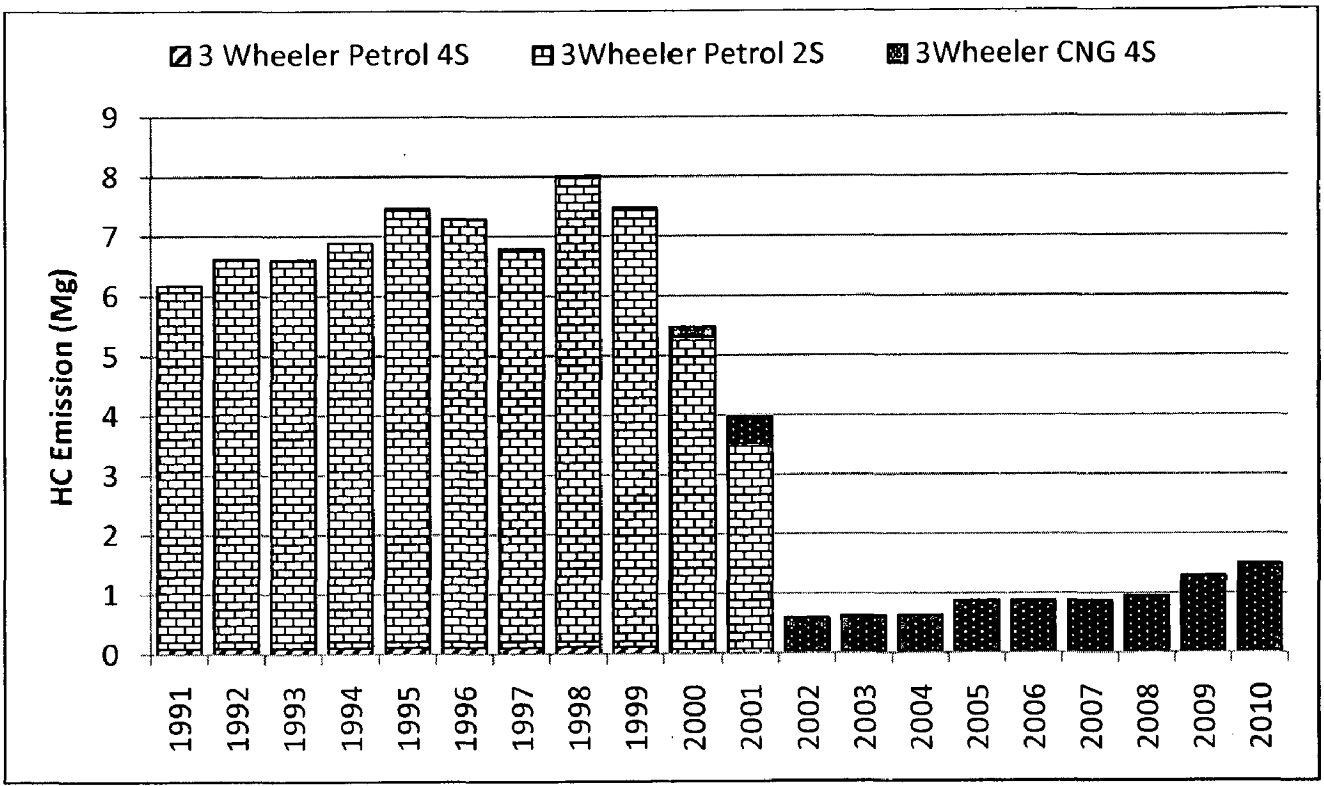


Fig. 5.34: HC emissions from the three wheelers in megacity Delhi during 1991-2010

5.3.4.4. Taxis

Fig. 5.35 demonstrates the emissions of HC from taxis in megacity Delhi. In 1991, emission of HC from taxis was 77 Mg and with 5 to 12% annual growth rate reached to 102 Mg in 1995. In 2000, emission of HC from taxi population was 134 Mg. About 77% increase is observed between 2001 (147 Mg) and 2002 (224 Mg) because of higher emission factor for HC from CNG driven taxis. In 2005 emission of HC from taxis are estimated to be 362 Mg and 850 Mg in 2010 (Fig. 5.35). Fig. 5.35 suggests that contribution of CNG taxis in Delhi is increasing annually, while that of petrol and diesel driven taxis is decreasing. It shows that during the initial study years (1991 to 2001) contribution of diesel driven taxi is higher (53-55%), while from 2002 to 2010 CNG driven taxis show their dominancy (83-91%).

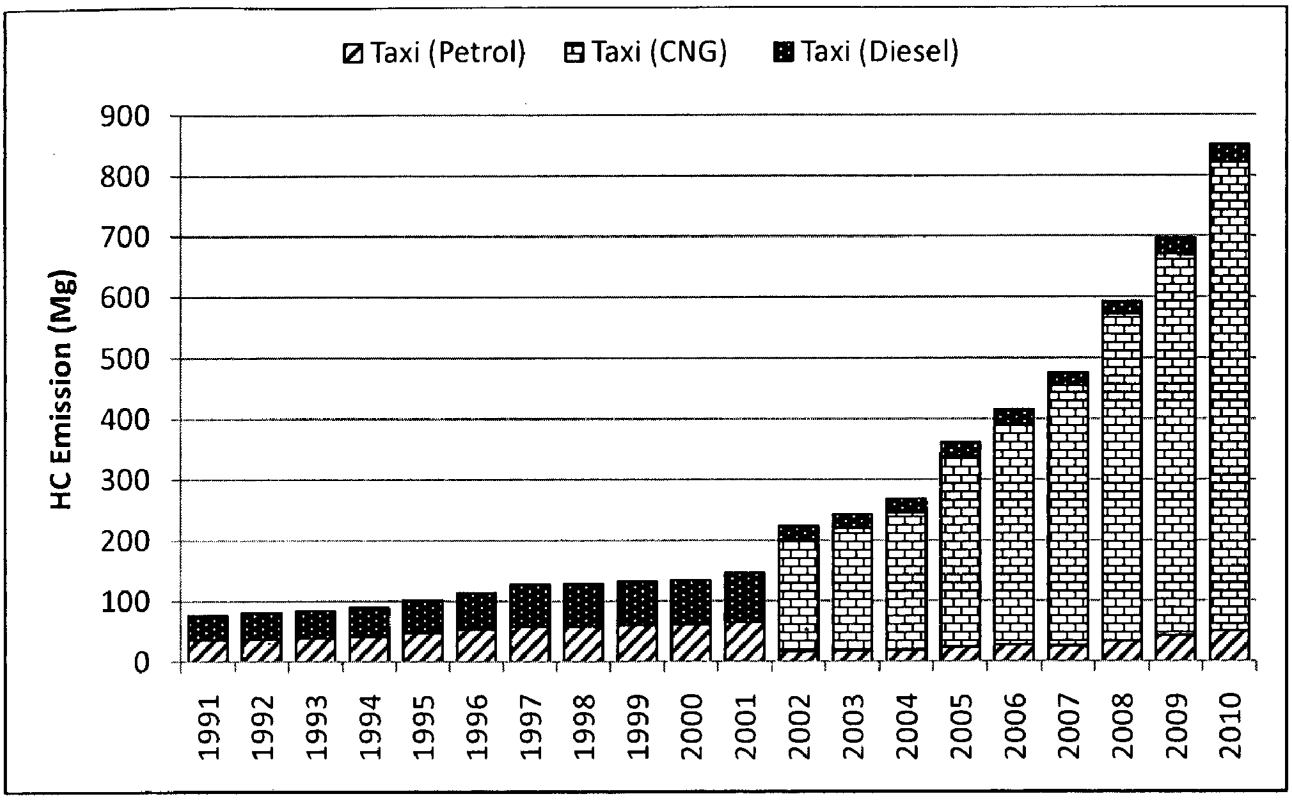


Fig. 5.35: HC emissions from the taxis in megacity Delhi during 1991-2010

5.3.4.5. Buses

Emissions of HC from buses in megacity Delhi were 1.6 Gg in 1991, followed by 2.2 Gg in 1995 (Fig. 5.36). Slight decline (~0.1%) has been observed between 1992 and 1993 because of phasing out of old age buses and less entry of new buses. However, about 18.6% of decline has been observed between 1999 (2.6 Gg) and 2000 (2.1 Gg) because of retirement of more old technology buses in 2000. In between 2001-2002, there is a sharp decrease in HC emissions from diesel driven buses but substantial increase from CNG driven buses because of more population and high emission factors of CNG buses. High growth (87%) is observed between 2004 (5 Gg) and 2005 (9.4 Gg). Sudden growth in the number of new buses in 2005 is responsible for this increment. Results suggest that contribution of diesel buses (96-100%) is higher during 1991 to 2001, while that of CNG buses is higher (95-97%) during 2002 to 2010 (Fig. 5.36).

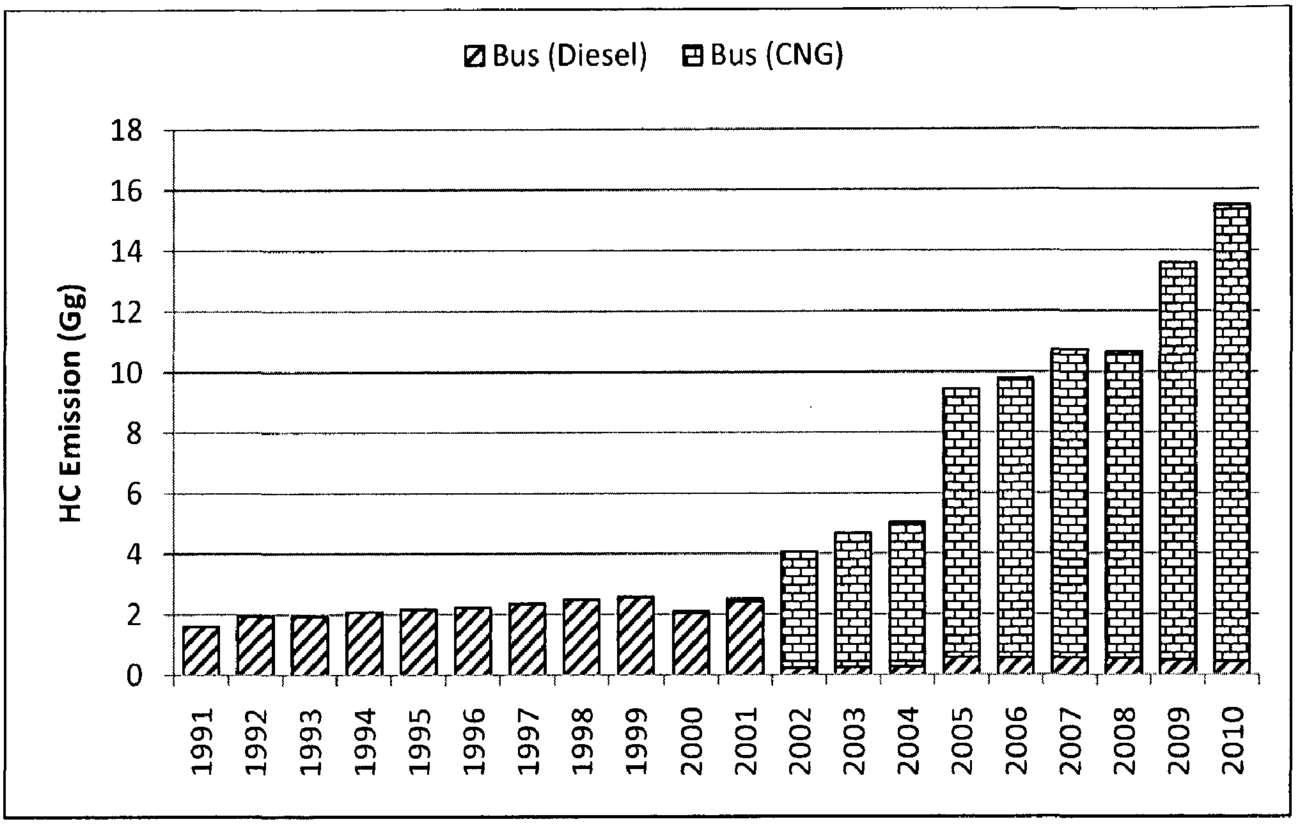


Fig. 5.36: HC emissions from the buses in megacity Delhi during 1991-2010

5.3.4.6. LCVs

LCVs contribute about 4 to 10% of HC among all on-road vehicles in Delhi. In 1991, HC emission from LCVs was 3.7 Gg which reached to 4.6 Gg in 1995 (Fig. 5.37). Between 1999 and 2002 decline in HC emission has been noticed, because of phasing out of old age LCVs. In 2000 HC emission was estimated to be 5 Gg and 3.4 Gg in 2005. About 2.3% of decline was again observed between 2004 and 2005 because of old LCVs retirement and less entry of new LCVs. In 2010, HC emission from LCVs is 7.7 Gg. Fig. 5.4 shows that contribution of CNG driven LCVs is increasing rapidly since 2006 and that of diesel driven is decreasing during same period. Initially from 1991 to 2006, the contribution of LCVs diesel was 64-100%, while from 2007 to 2010 the contribution of CNG driven LCVs is estimated to be 51-72%.

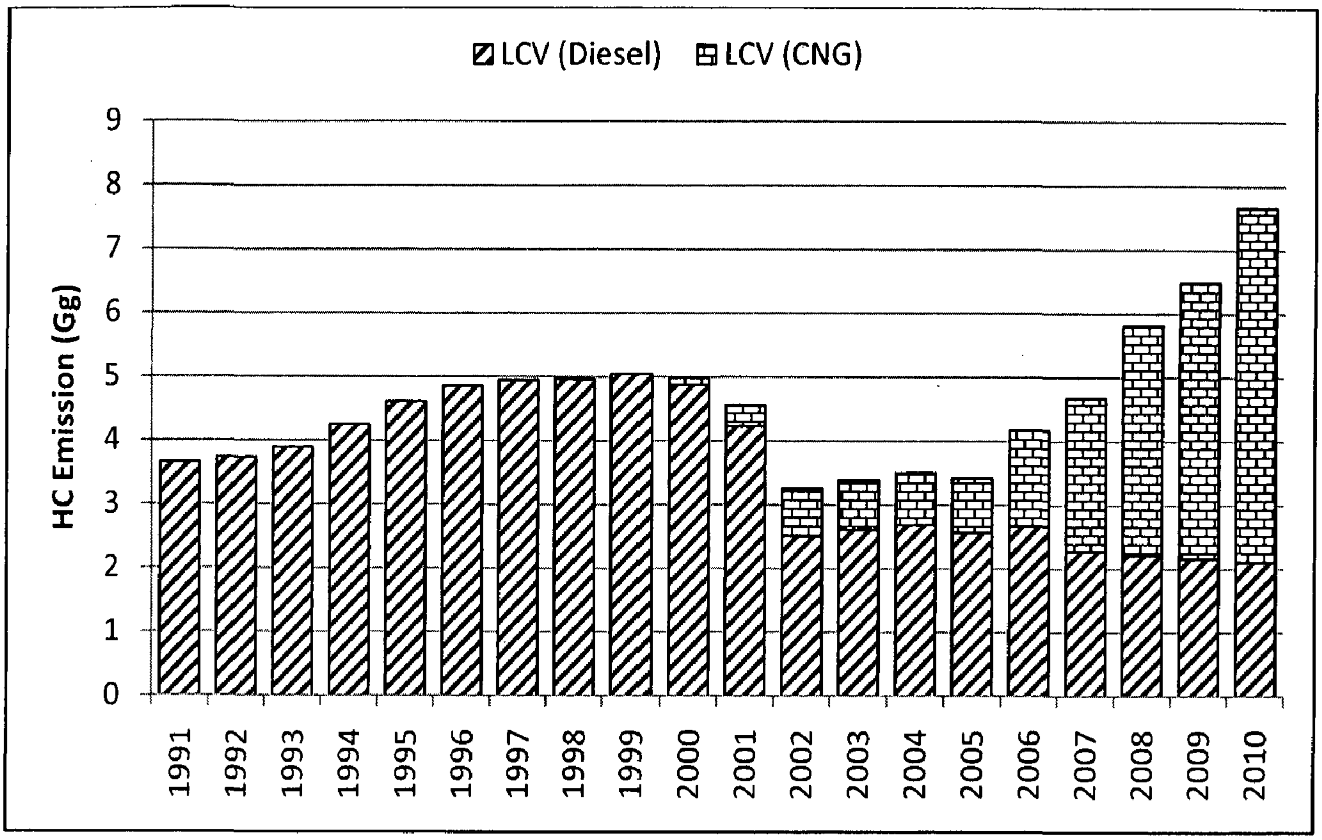


Fig. 5.37: HC emissions from the LCVs in megacity Delhi during 1991-2010

5.3.4.7. HCVs

Fig. 5.38 gives HC emission trend from HCVs in megacity Delhi, which are estimated to be 2.7 Gg in 1991 and 3.4 Gg in 1995. Similar to other vehicles, HCV emissions have decreased between 1999 and 2002 because of phasing out and change in emission factors of old age HCVs. About 35.5% decline is observed between 2001 and 2002, due to the phasing out program by the Delhi government in 2002. In 2005, emission of HC was 2.1 Gg, while in 2004 it was 2.2 Gg. Phasing out of old age HCVs and less entry of new HCVs is responsible for it. Between 2006 and 2007 about 30% of decline is observed due to phasing out of 1991 and pre-1991 HCVs (high emission factor, Table 3.1). From 2007 to 2010, emissions show a decreasing trend because of low emission factor values for new HCVs and phasing out of old age HCVs population (Fig. 5.38).

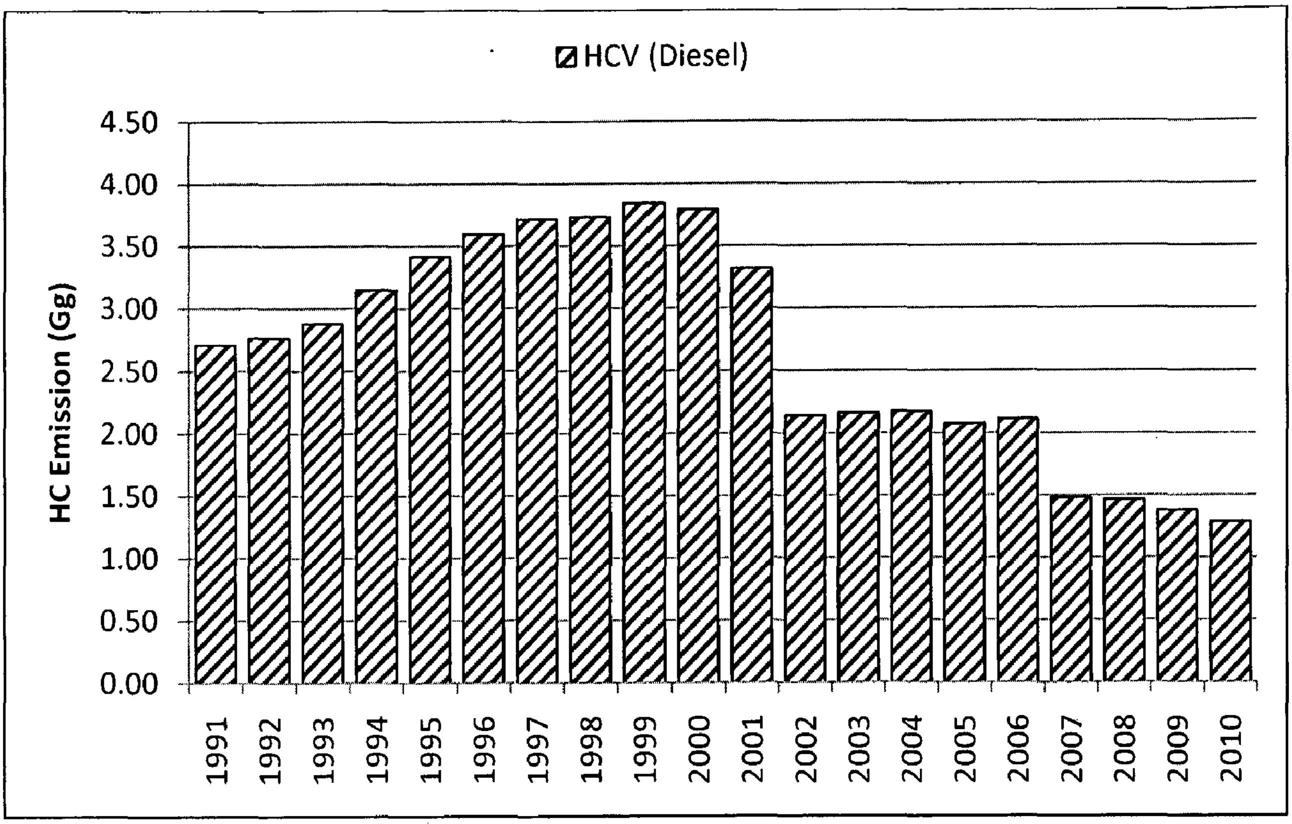


Fig. 5.38: HC emissions from the HCVs in megacity Delhi during 1991-2010

5.3.5. PM emissions

Particulate Matter (PM) is among the six criteria pollutants, and the most important in terms of adverse effects on human health. According to VAPI model calculations, PM emissions from vehicles in 1991 are estimated to be 6 Gg, followed by 7.5 Gg in 1995 and 8 Gg in 2000 (Fig. 5.39). Continues decline is observed from 2000 to 2002 in PM emission. Maximum decrease (43%) is observed between 2001 and 2002, because of phasing out of vehicles and CNG conversion program. Slight declining trend is observed during 2006 and 2007 because of the same reason. Emission of HC in 2010 is 5 Gg, while during whole study period (1991-2010) the contribution of HCVs population is highest (33-43%). LCVs population is the second largest contributor of PM pollutants during 1991 to 2010 (Fig. 5.39).

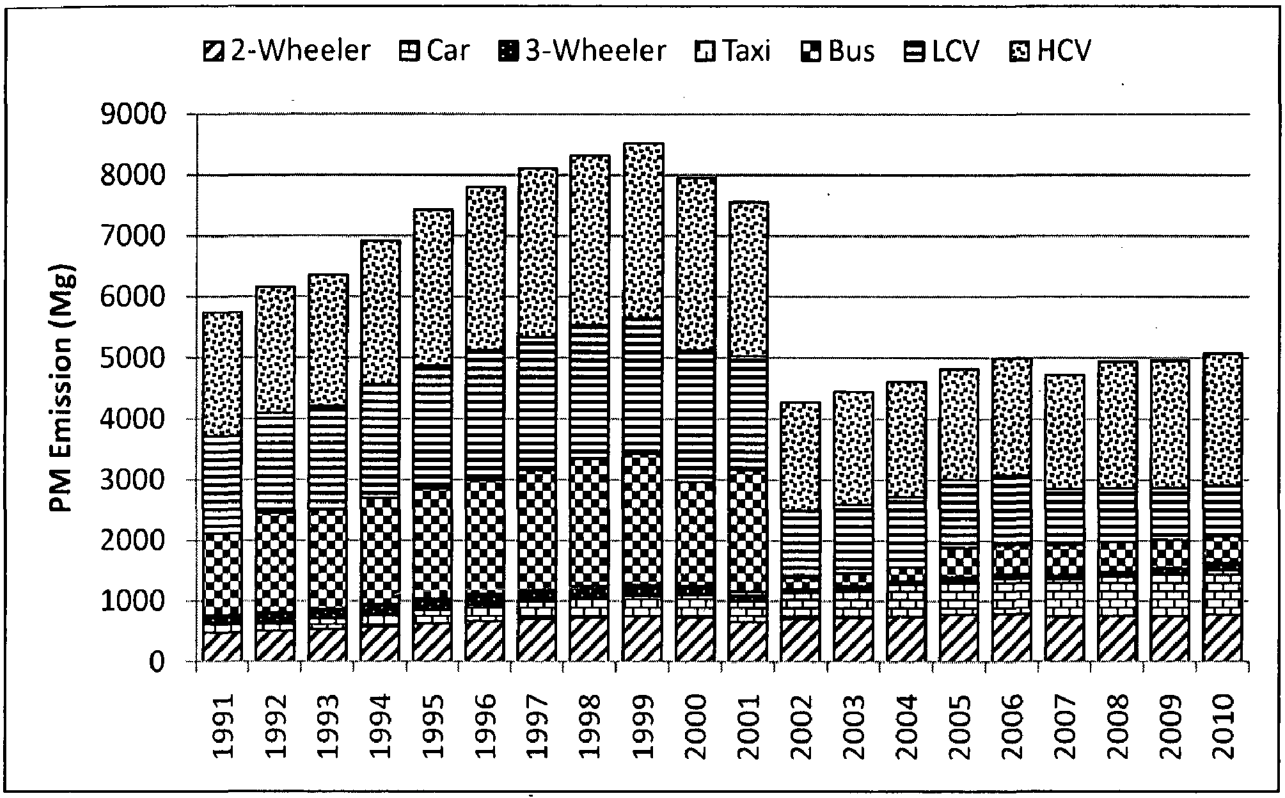


Fig. 5.39: PM emission from various vehicle categories in megacity Delhi during 1991-2010.

5.3.5.1. Two Wheelers

Emissions of PM from two wheelers in megacity Delhi is given in Fig. 5.40. It shows that in 1991, PM emissions from two wheelers are 483 Mg, followed by 635 Mg in 1995. From 1991 to 1999 emissions show an increasing trend, while between 1999 and 2001 decline is observed. In 2000, emissions of PM are estimated to be 741 Mg and 782 Mg in 2005. A decline is observed between 2006 and 2007 due to phasing out of 1991 and pre-1991 two wheelers in 2007. In 2010, PM emissions are 778 Mg. Among all types of two-wheelers the two-stroke scooters account for highest percentage (~38- 64%) from 1991 to 2006, while a shift is observed from 2007 to 2010 to four-stroke motorcycles (34- 40%).

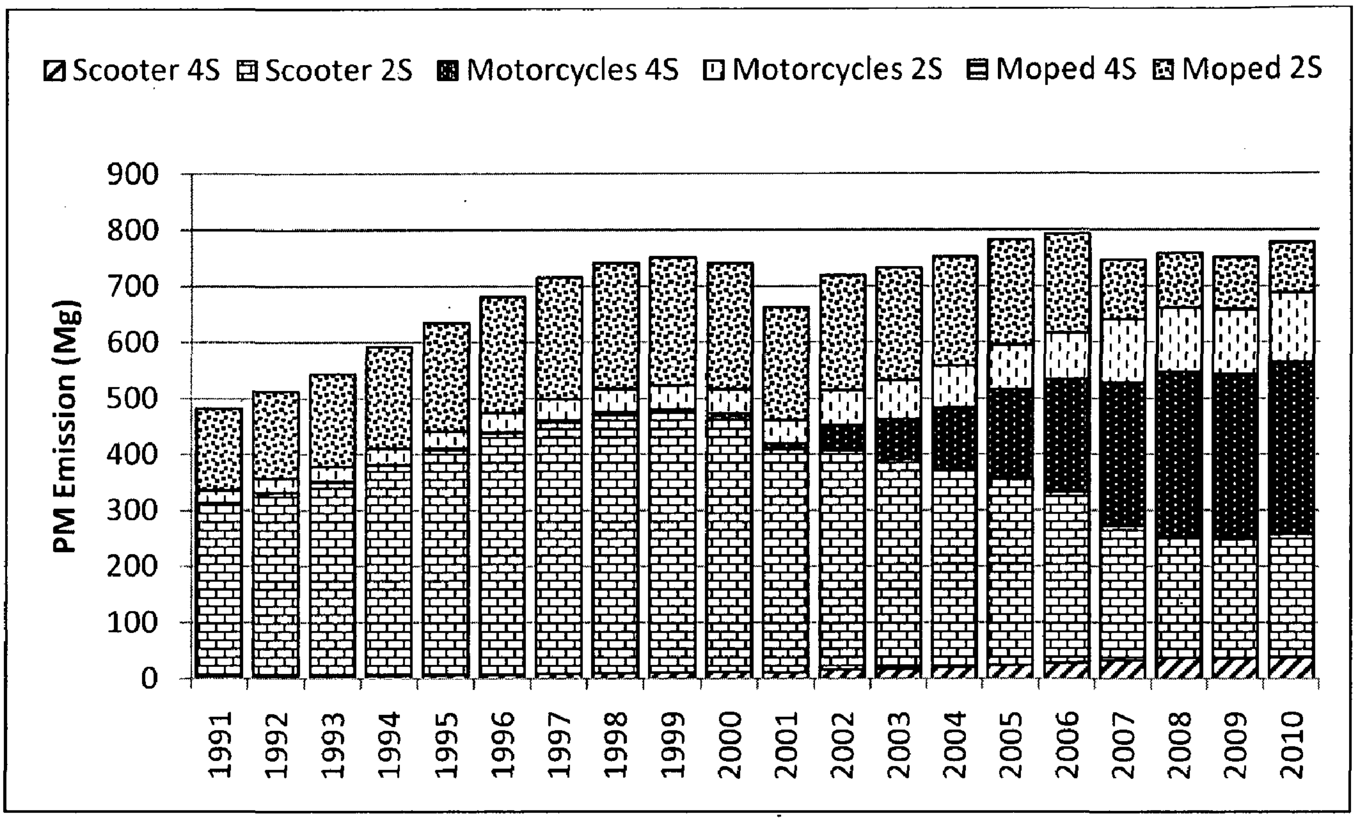


Fig. 5.40: PM emissions from the two wheelers in megacity Delhi during 1991-2010

5.3.5.2. Cars

PM emissions from car population in megacity Delhi are given in Fig. 5.41. In 1991 PM emissions are estimated to be ~140 Mg and 230 Mg in 1995. A decline of about 3% in PM emissions from cars has been observed between 2000 and 2001 because the number of old cars phased out was more than the entry of new cars during that period. PM emissions from cars are 362 Mg in 2000, and 555 Mg and 743 Mg in 2005 and 2010 respectively (Fig. 5.41). Estimations show that contribution of diesel driven cars is highest (61-72%) among all types of cars, followed by petrol driven cars (28-39%).

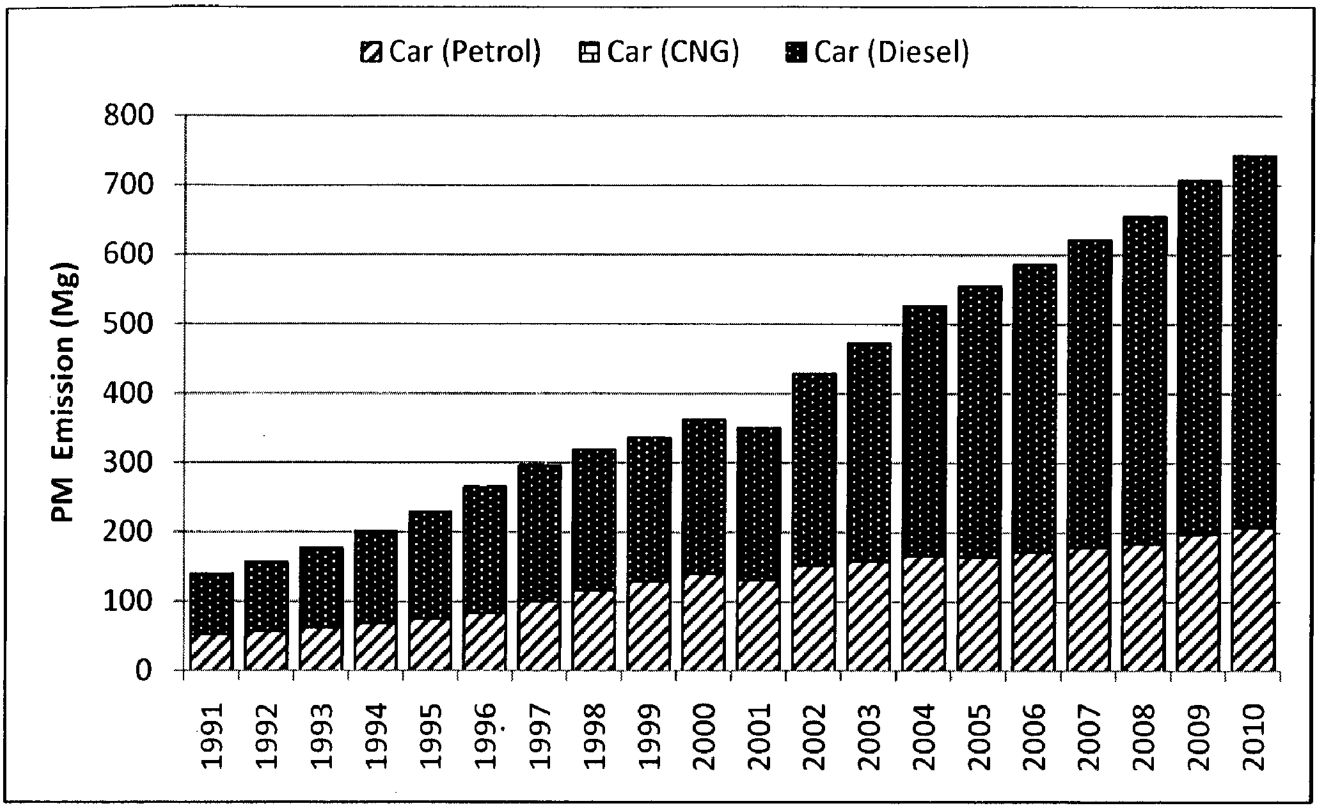


Fig. 5.41: PM emissions from the car population in megacity Delhi during 1991-2010

5.3.5.3. Three Wheelers

Emission of PM from three-wheelers is shown in Fig. 5.42. PM emissions from three wheelers are 114 Mg in 1991, which increased to 138 Mg in 1995 and 148 Mg. However, this declined to ~34 Mg in 2002 because of CNG conversion program implemented after 2000. PM emissions from three-wheelers are estimated to be 51 Mg in 2005 and 87 Mg in 2010. Fig. 5.42 suggests that before CNG implementation the share of petrol driven three wheelers was higher in PM emissions while after 2001 it completely shifted to CNG driven three wheelers.

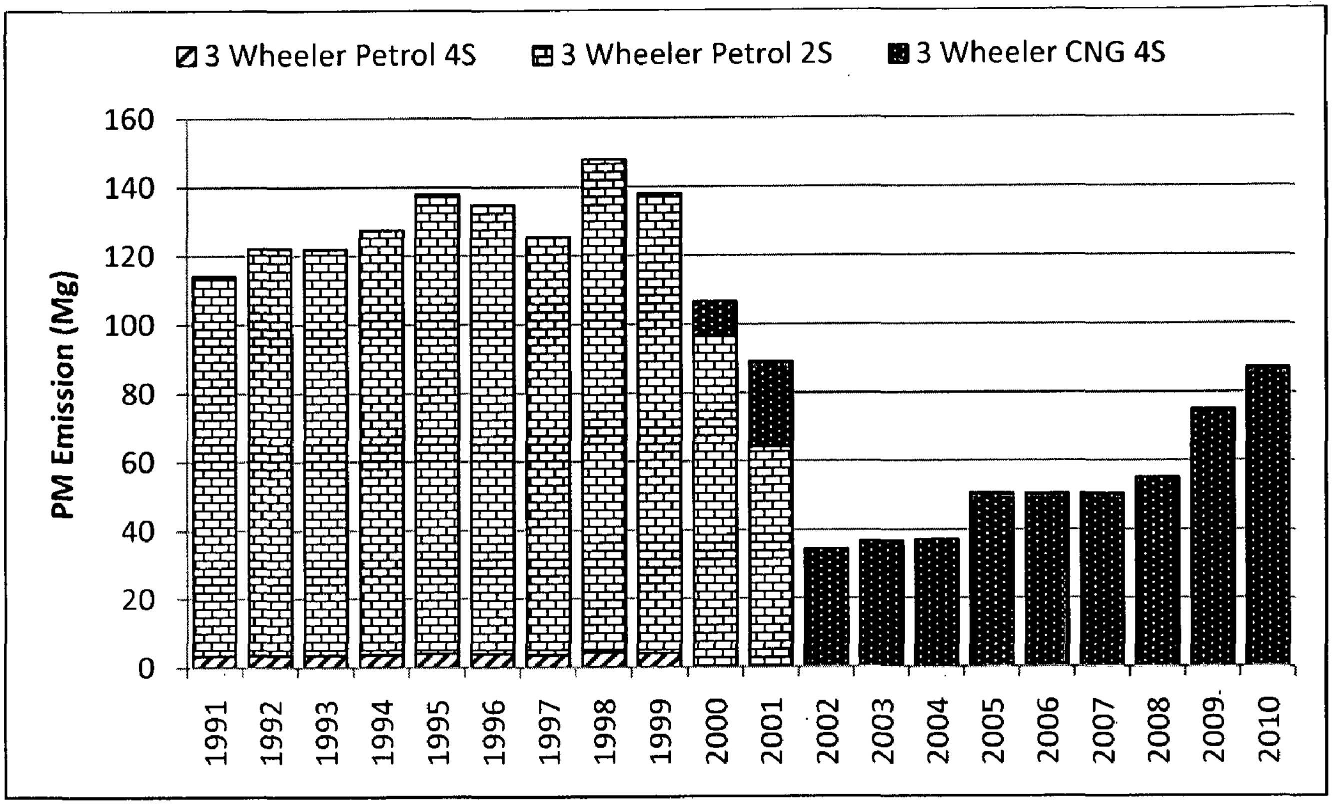


Fig. 5.42: PM emissions from the three wheelers in megacity Delhi during 1991-2010

5.3.5.4. Taxis

As shown in Fig. 5.43, in 1991, PM emissions from taxis are estimated to be 28 Mg, followed by 38 Mg in 1995 and 51 Mg in 2000. Emission from 1991 to 2001 follow a similar trend with average annual growth rate of about 7%. A sudden decrease of about 73% is observed in emissions during 2002, due to phasing out and CNG conversion programs for commercial vehicles in Delhi. In 2005, PM emission from taxi is observed to be 18 Mg and 25 Mg in 2010. In between 2006 and 2007 negative growth rate (-12%) is observed because of phasing out of very old age (Pre-1991 and 1991) vehicles in this year. Fig. 4.43 suggests that contribution of diesel driven taxis for PM emission is highest (68-99%) because of external diesel taxis and their higher emission factor (17 to 163 times higher than CNG taxis) (Table 3.2).

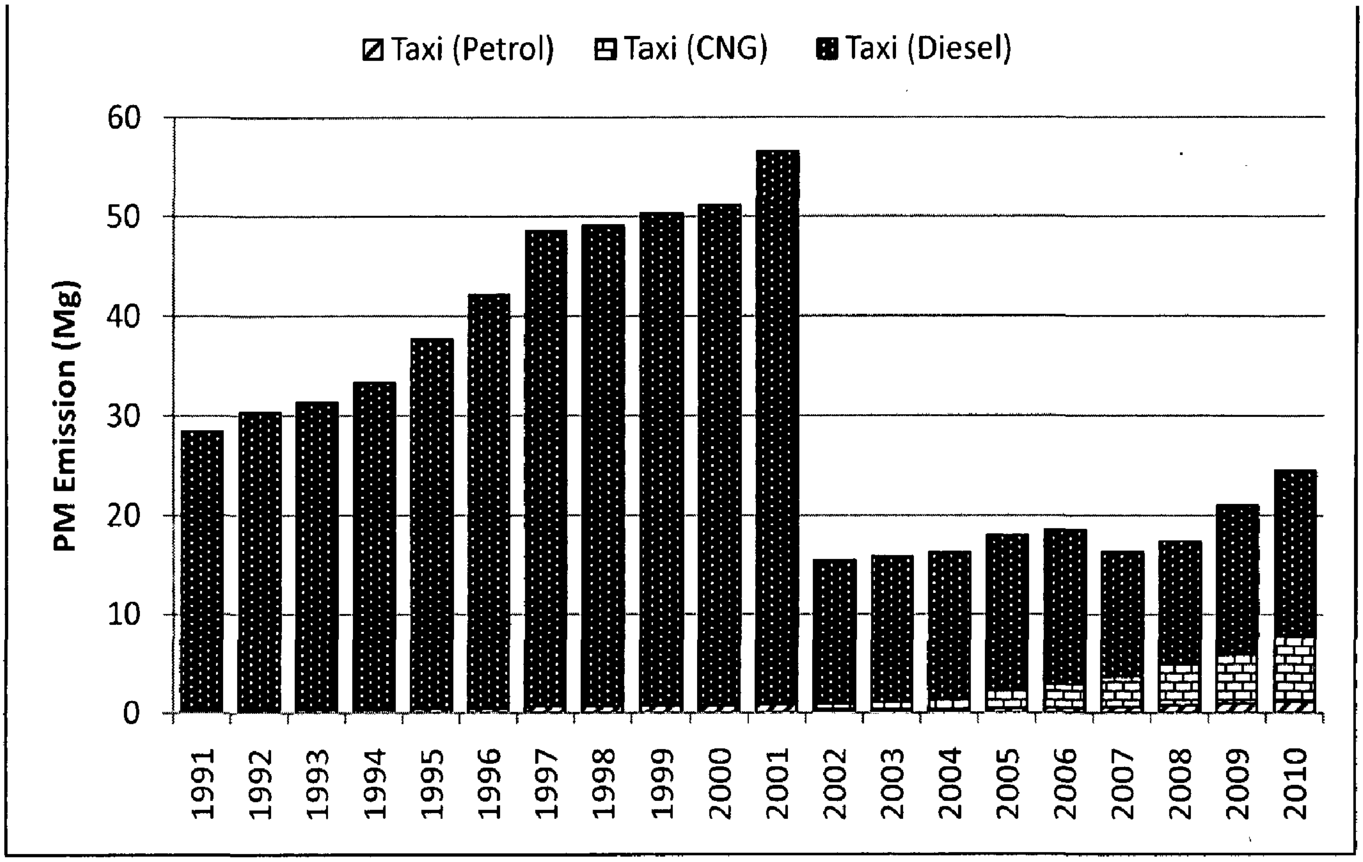


Fig. 5.43: PM emissions from the taxi population in megacity Delhi during 1991-2010

5.3.5.5. Buses

Buses contribute about 4 to 27% of total PM vehicular emissions in megacity Delhi. Fig. 5.44 shows that PM emissions from buses are 1353 Mg in 1991, while 1817 Mg in 1995. Decline of about 21% is observed between 1999 (2158 Mg) and 2000 (1707 Mg) because of retirement of older (1991 and pre-1991) buses in the year 2000. Furthermore, reduction of about 90% is observed between 2001 and 2002 because of phasing out of old age buses and CNG (very less emission factor , Table 3.2) conversion program. Between 2004 (230 Mg) and 2005 (489 Mg), about 112% growth has been observed in PM emissions because of more entry of new buses in 2005. Fig. 5.44 shows that in 2010 emission of PM is ~452 Mg. Because of very high emission factor of PM for external diesel buses than CNG buses (Table 3.2) (ARAI, 2007), the contribution of diesel vehicles is much higher throughout the study period (Fig. 5.44).

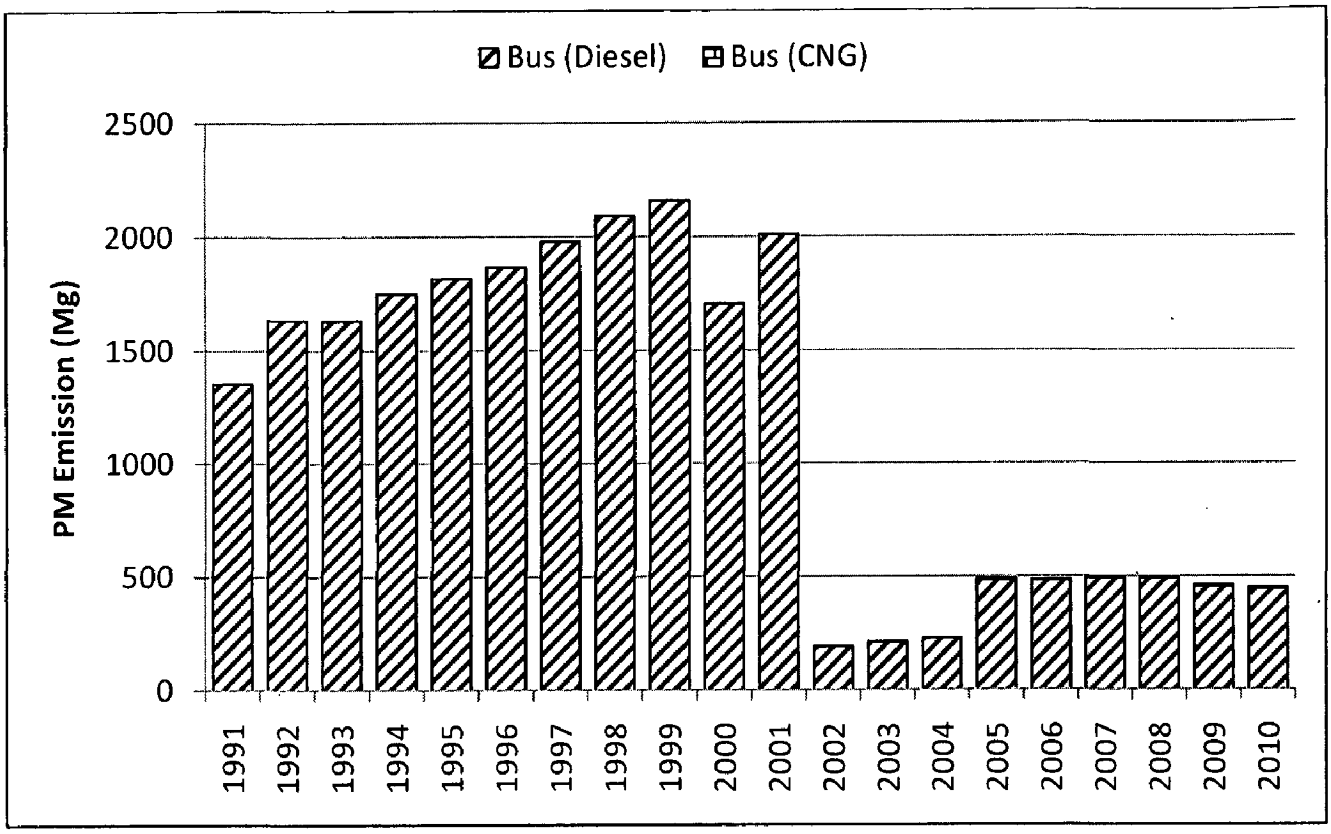


Fig.5.44: PM emissions from the bus population in megacity Delhi during 1991-2010

5.3.5.6. LCVs

As visible from Fig. 5.45 emission of PM from LCVs are 1603 Mg in 1991, which reached to 2021 Mg in 1995. No negative trend has been observed till 1999 in PM emission from LCVs. Because of phasing out of older vehicles, decrease is observed between 1999 (2224 Mg) and 2002 (1102 Mg), with major decline (41%) between 2001 and 2002. After 2002 emission of PM from LCVs shows a positive trend, while between 2004 (2537 Mg) and 2005 (2421 Mg) again negative trend is observed which continues till 2010 due to phasing out of older LCVs and decreasing emission factor for new LCVs. After 2006 emissions of PM follow a decreasing trend because of less emission factor of the respective year models of LCVs. Because of external diesel LCVs and their very high emission factor (Table 3.2) the contribution of diesel LCVs are higher even after CNG policy implementation.

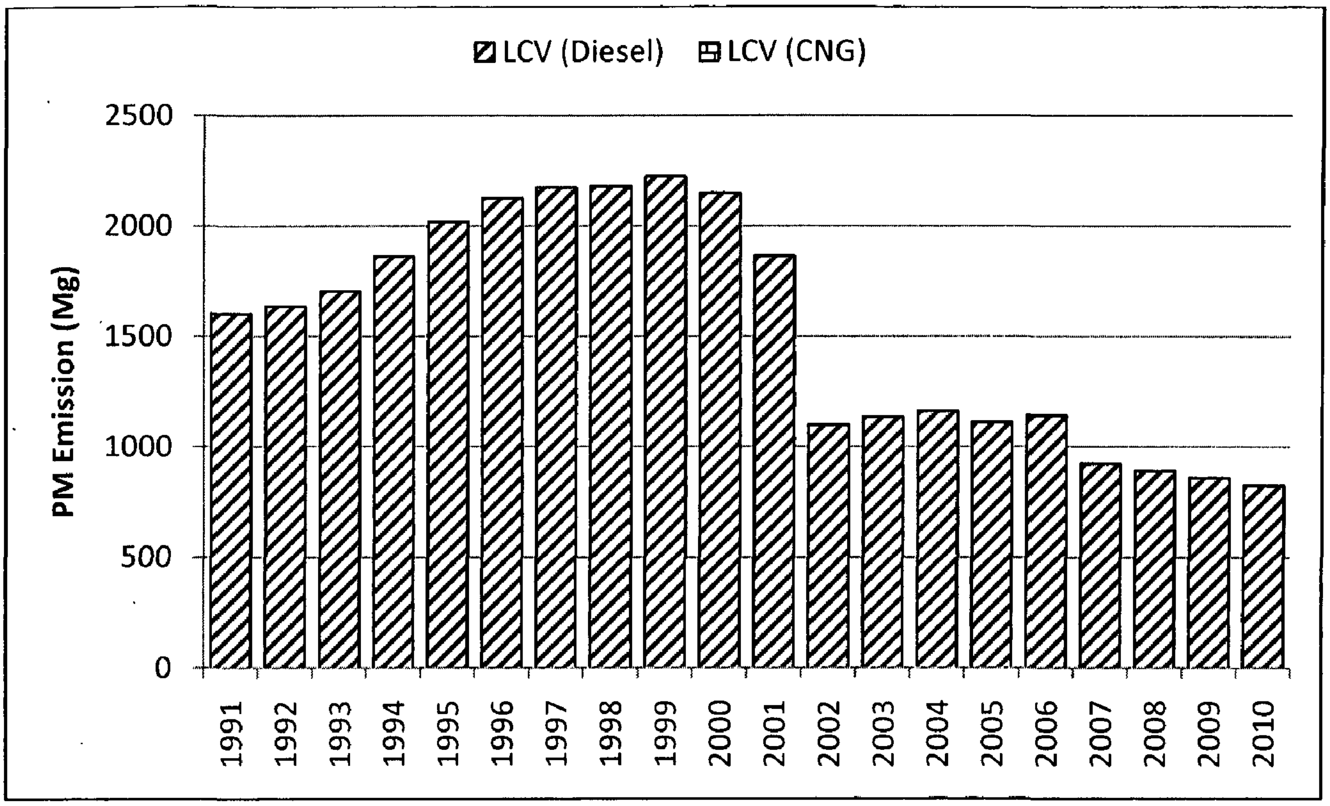


Fig. 4.45: PM emissions from the LCVs in megacity Delhi during 1991-2010

5.3.5.7. HCVs

Fig. 4.46 illustrates the emission of PM from HCVs during 1991 to 2010 in megacity Delhi. In 1991 PM emission from HCVs are 2024 Mg, which became 2552 Mg in 1995. Similar to other vehicles emission of HCVs have decreased between 1999 and 2002, with major decreasing trend (29%) observed between 2001 (2521 Mg) and 2002 (1781 Mg). In 2000 emissions from HCVs are 2831 Mg that decreased between 2004 (1891Mg) and 2005 (1820Mg) with ~4% growth rate because of less entry of new HCVs in 2005. In 2010, emission of PM from HCVs is 2164Mg.

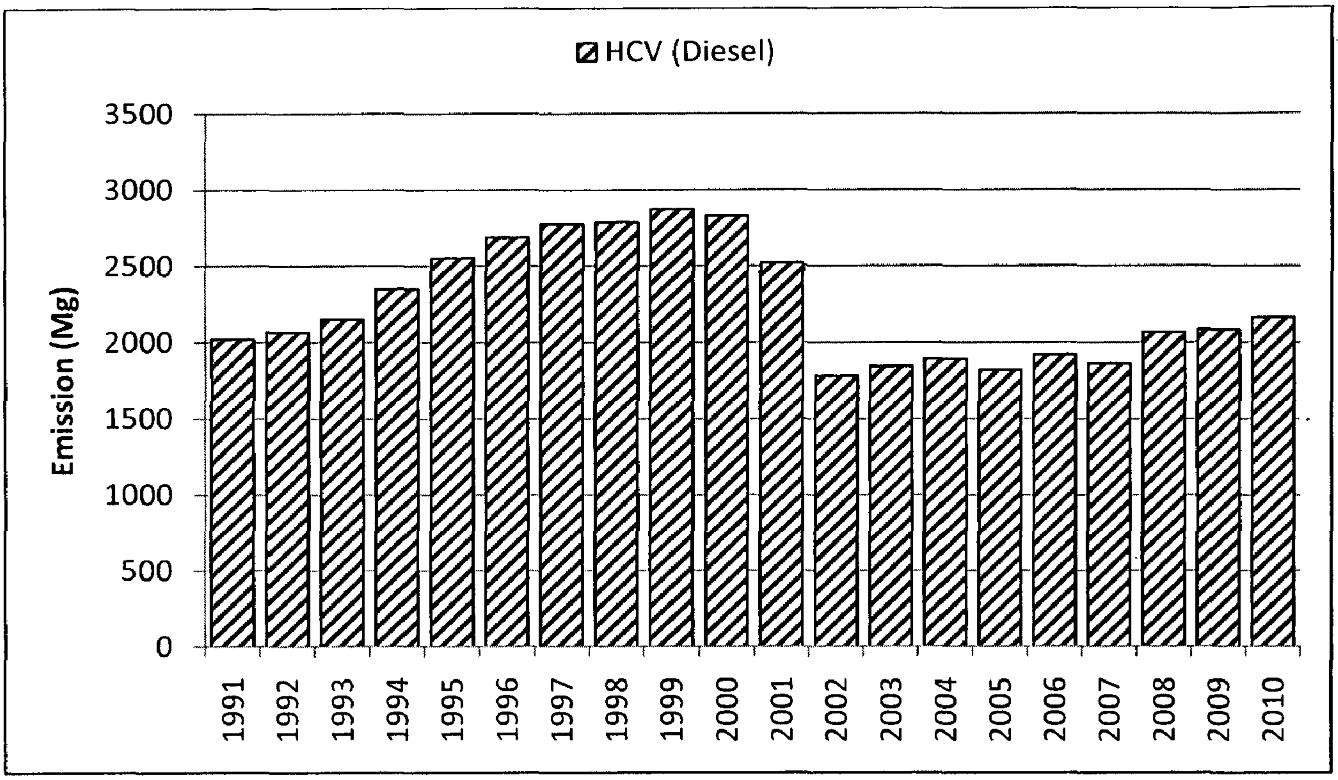


Fig. 5.46: PM emissions from the HCVs in megacity Delhi during 1991-2010

5.3.6. 1-3 Butadiene emissions

1-3 Butadiene is one of the harmful gases, which adversely affect human health. Emissions of 1-3 Butadiene have been calculated by VAPI model with country specific emission factors. Emission of 1-3 Butadiene from vehicles is very less in comparison to other pollutants, while it's potentiality is higher than other pollutants. In 1991 emission of 1-3 Butadiene from all on-road vehicle categories are estimated to be 1253 kg, which increased to 1805 kg in 1995. Negative trend in 1-3 Butadiene emission have been observed between year 1999 and 2001 due to phasing out of various types of vehicles (e.g., two wheelers and cars). In 2000 emission of 1-3 Butadiene from all on-road vehicles are 2095 kg, whereas 2180 kg in 2005 and 2608 kg in 2010. According to VAPI model results contribution of car population is higher (72-89%) during 1991 to 2010.

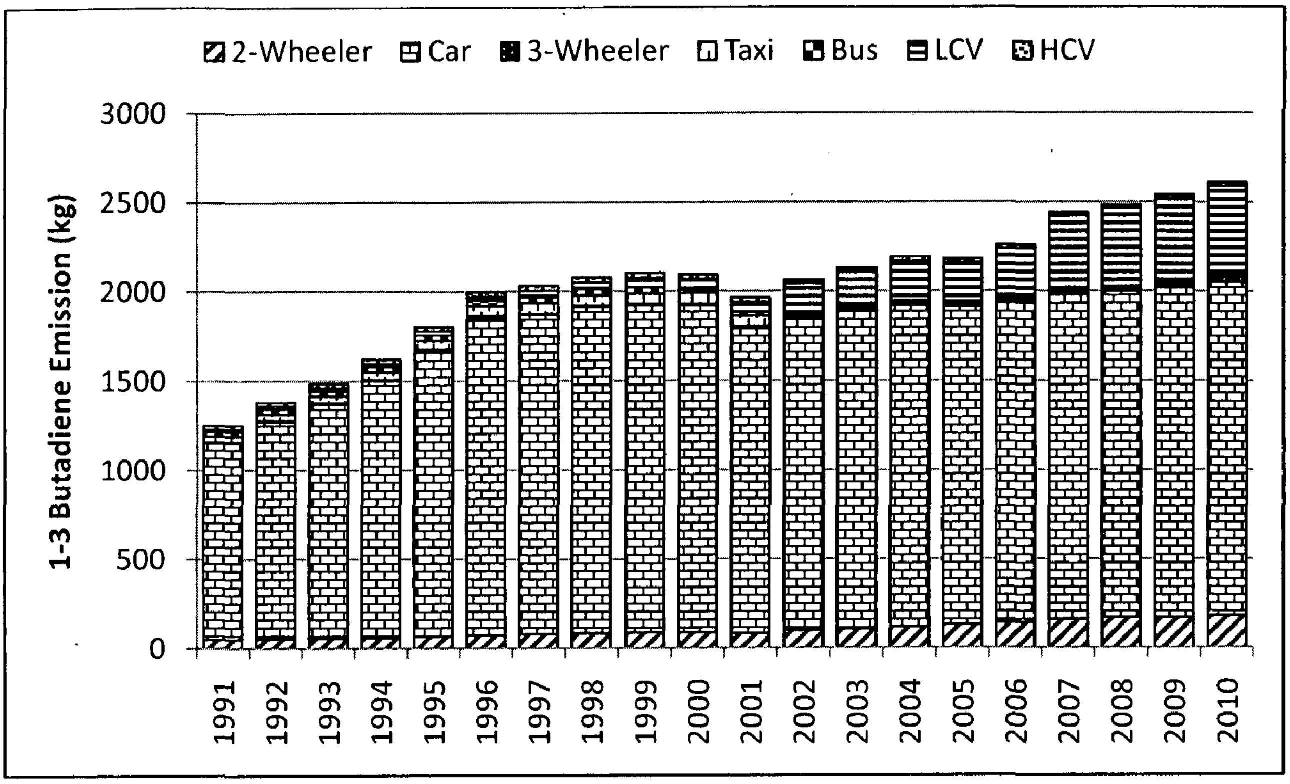


Fig. 5.47: 1-3 Butadiene emissions from various vehicles in megacity Delhi during 1991-2010

5.3.6.1. Two Wheelers

Emission of 1-3 Butadiene from two wheelers is increasing year by year (Fig. 5.48). In 1991 and 1995 the emissions are 51 kg and 69 kg, respectively, followed by 89 kg in 2000. Between 1999 and 2001, 1-3 Butadiene emissions have decreased from 89 kg to 84 kg because of phasing out of two-wheeler population. After 2001 emission of 1-3 Butadiene show positive growth rate till 2010. In 2005 emission of 1-3 Butadiene are 134 kg and 180 kg in 2010. Among all two-wheeler categories contribution of two-stroke motorcycles is highest (30 to 41%) from 1991 to 2006, while after 2006 four-stroke motorcycles emerged as second highest contributor (31-34%).

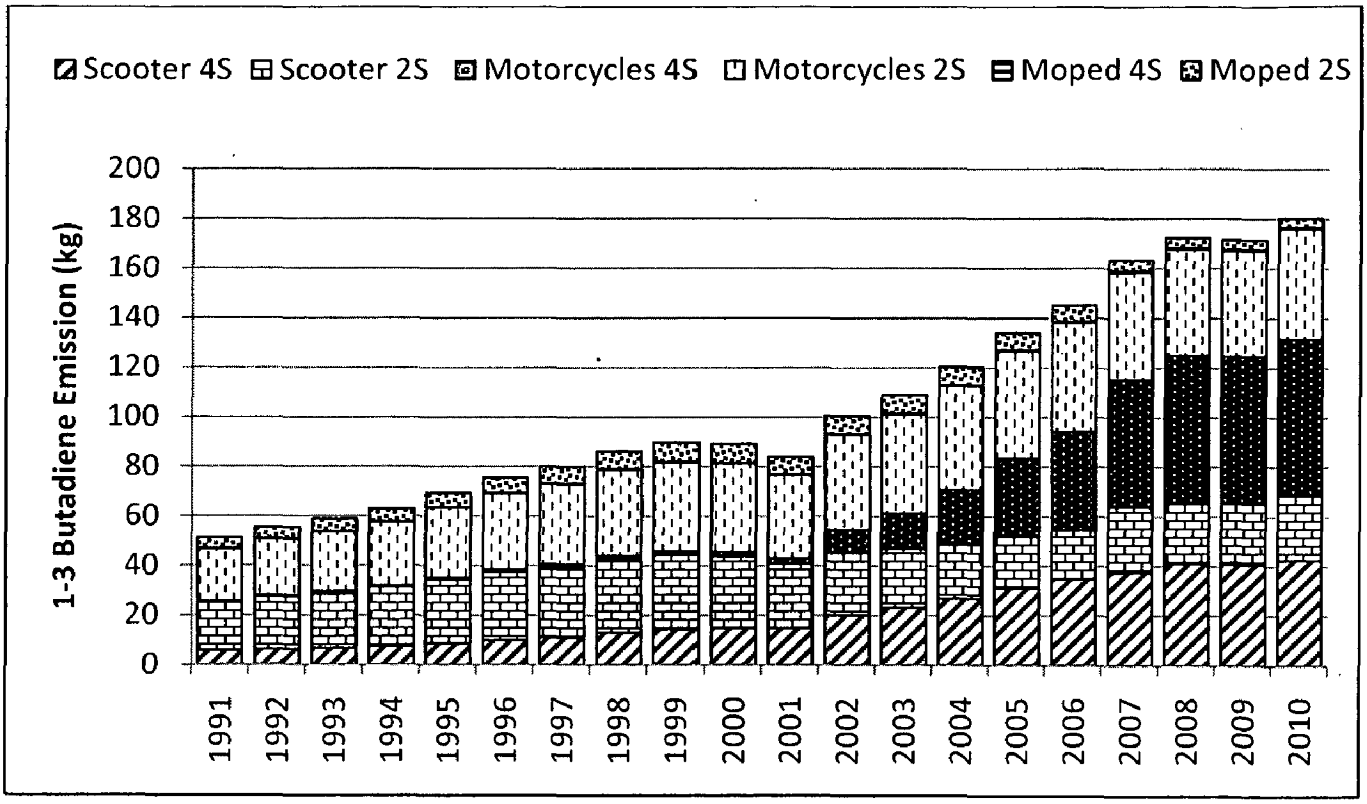


Fig. 5.48: 1-3 Butadiene emissions from two wheelers in megacity Delhi during 1991-2010

5.3.6.2. Cars

Fig. 5.49 shows the emission trend of 1-3 Butadiene from car population in megacity Delhi. Initially, emission of 1-3 Butadiene from car population are 1101 kg in 1991, followed by 1605 kg in 1995 and 1833 kg in 2000. Decline has been observed between 2000 and 2001 because of phasing out of car population and change in emission factors for available car population in 2001. In 2005, emission of 1-3 Butadiene is estimated to be 1778 kg followed by 1869 kg in 2010. With concern to contribution accountability of petrol driven car is highest (85-92%) among all car categories during 1991 to 2010.

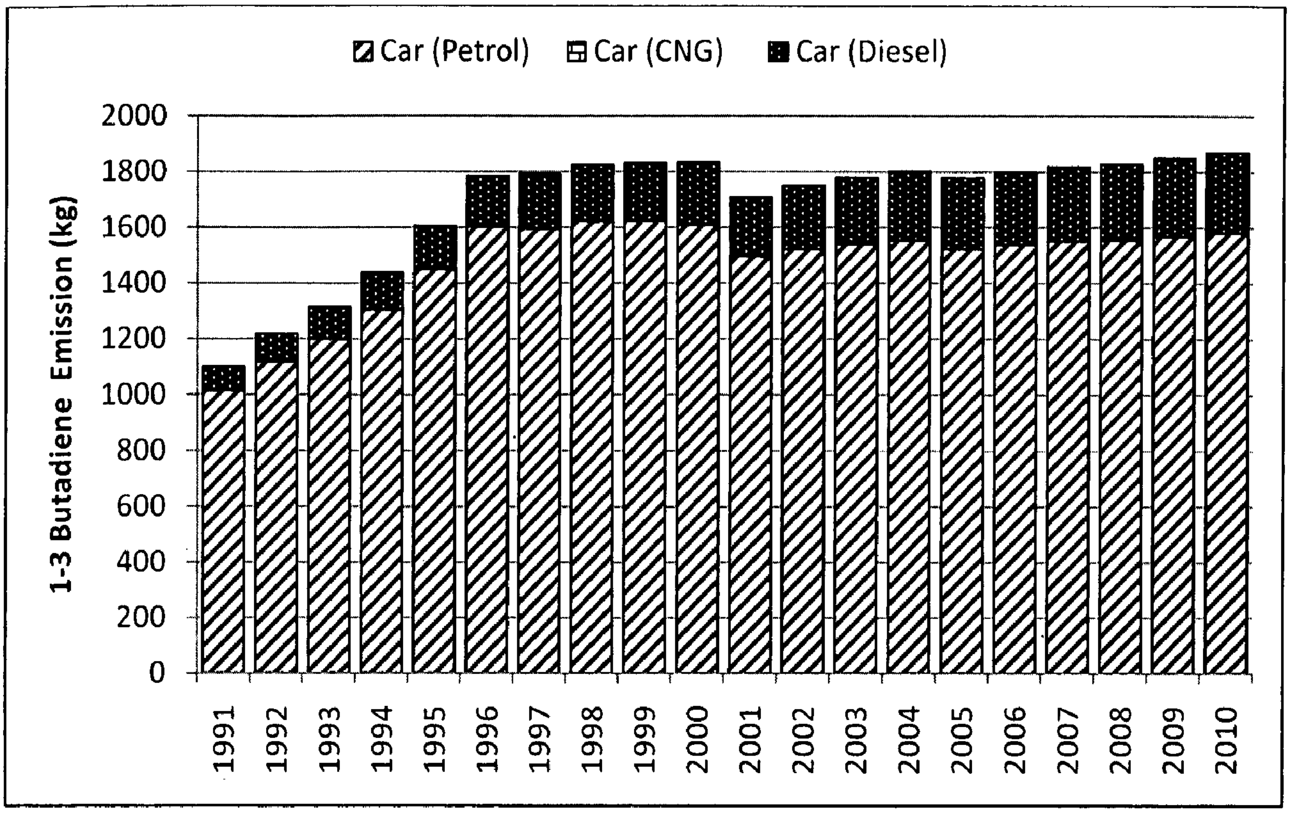


Fig. 5.49: 1-3 Butadiene emissions from car population in megacity Delhi during 1991-2010

5.3.6.3. Three Wheelers

Emissions of 1-3 Butadiene from three-wheelers are given in Fig 5.50. It shows that emission of 1-3 Butadiene are dominated by petrol driven three-wheelers before 2001, and shifts to CNG driven three wheelers after 2001. Emissions of 1-3 Butadiene from three wheelers are estimated to be ~6 kg in 1991 and 7 kg in 1995. In comparison to other pollutants, there is negligible decline in case of 1-3 Butadiene emissions between 2001 and 2002 because of high emission factor for CNG driven three wheelers rather than other fuels. In 2005, emissions of 1-3 Butadiene were ~16 kg that increased to ~28 kg in 2010.

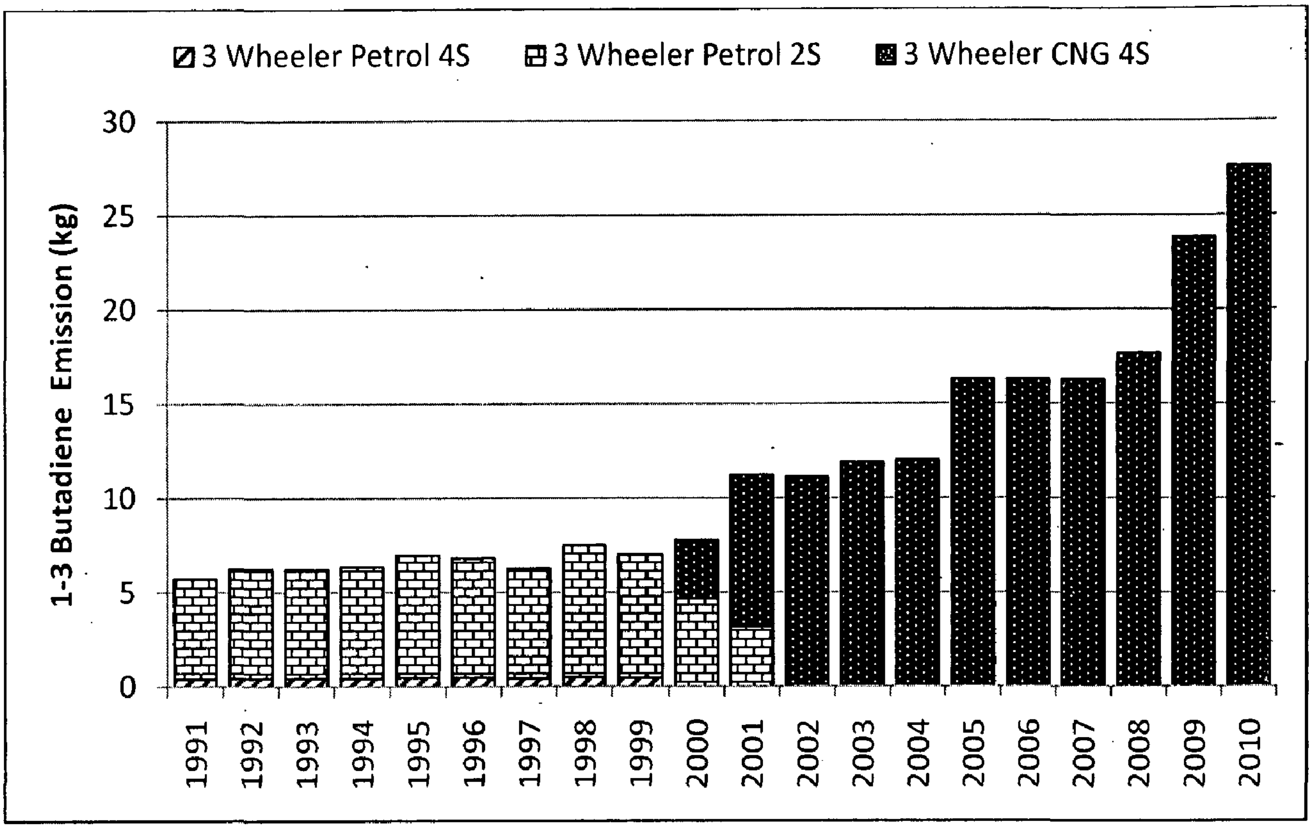


Fig. 5.50: 1-3 Butadiene emissions from three wheeler population in megacity Delhi during 1991-2010

5.3.6.4. Taxis

Emission of 1-3 Butadiene from taxis are 35 kg during 1991 and 46 kg in 1995, followed by 60 kg in 2000 (Fig. 5.51). Similar to other commercial vehicles a decline of about 79% has been observed between 2001 and 2002 because of phasing out of diesel taxis and conversion of diesel taxis to CNG program by the Government of Delhi. In 2005, emissions of 1-3 Butadiene from taxi population were 13 kg that decreased to 7.5 kg in 2010. Because of phasing out of 1991 and pre-1991 taxis, a decline is observed in emissions between 2006 and 2007. It is observed that among all types of taxis contribution of diesel driven taxis remain maximum (80-84%) throughout the study period (1991-2010). After CNG conversion the contribution of diesel taxis remain higher because of external diesel taxis and their very higher emission factor compared to CNG taxis (Table 3.2).

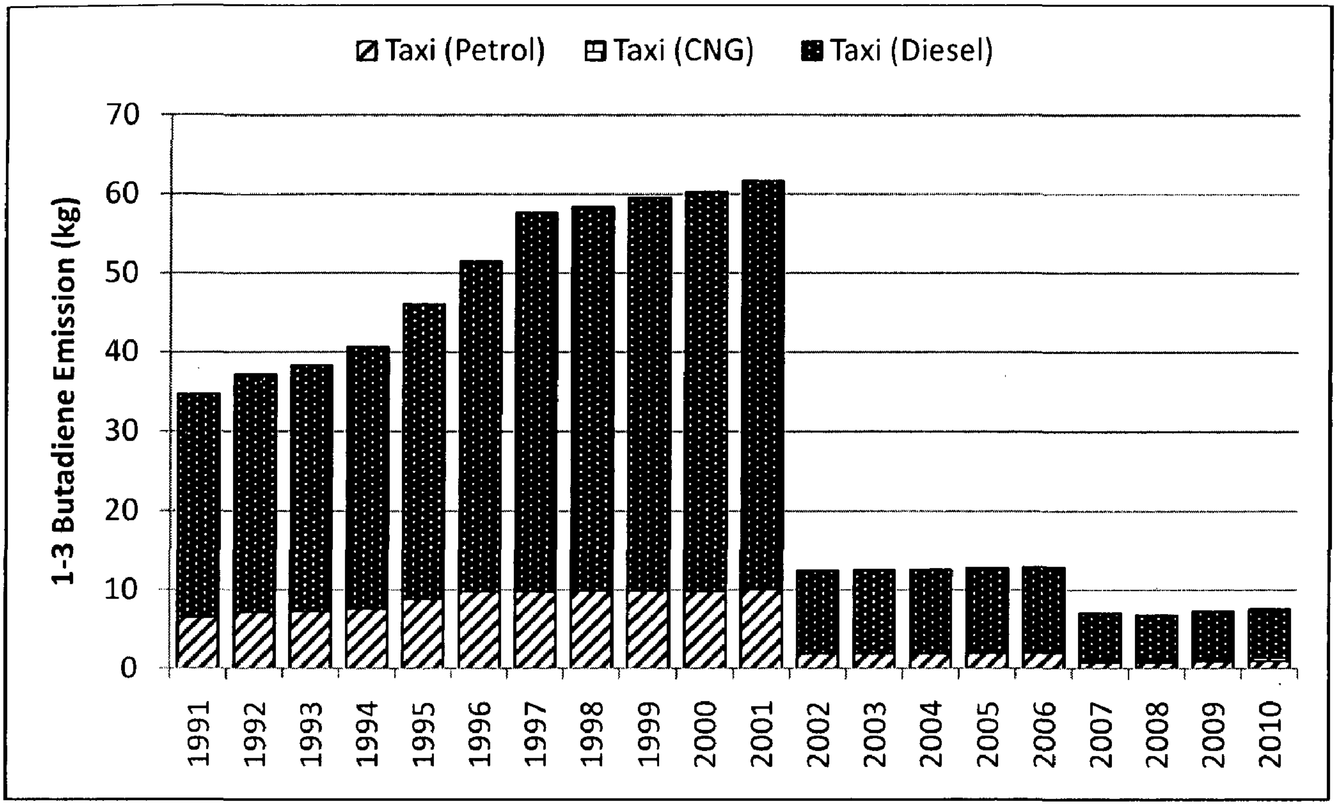


Fig. 5.51: 1-3 Butadiene emissions from taxi population in megacity Delhi during 1991-2010

5.3.6.5. Buses

Emissions of 1-3 Butadiene from bus population in 1991 and 1995 are 24 kg and 33 kg (Fig. 5.52). A significant reduction of about 43% in 1-3 Butadiene emission is observed between 1999 (36 kg) and 2000 (21 kg). Decline of ~91% is further observed between 2001 and 2002 because of phasing out program of diesel buses by the Government of Delhi in 2002. However, an increase of about 107% has been observed between 2004 and 2005. The reason behind this change is sudden increase in population of internal and external buses during 2005 (DSA, 2008). As per contribution, share of emissions from diesel buses is higher because of external diesel buses and their very high emission factor (Table 3.2) in comparison to CNG buses.

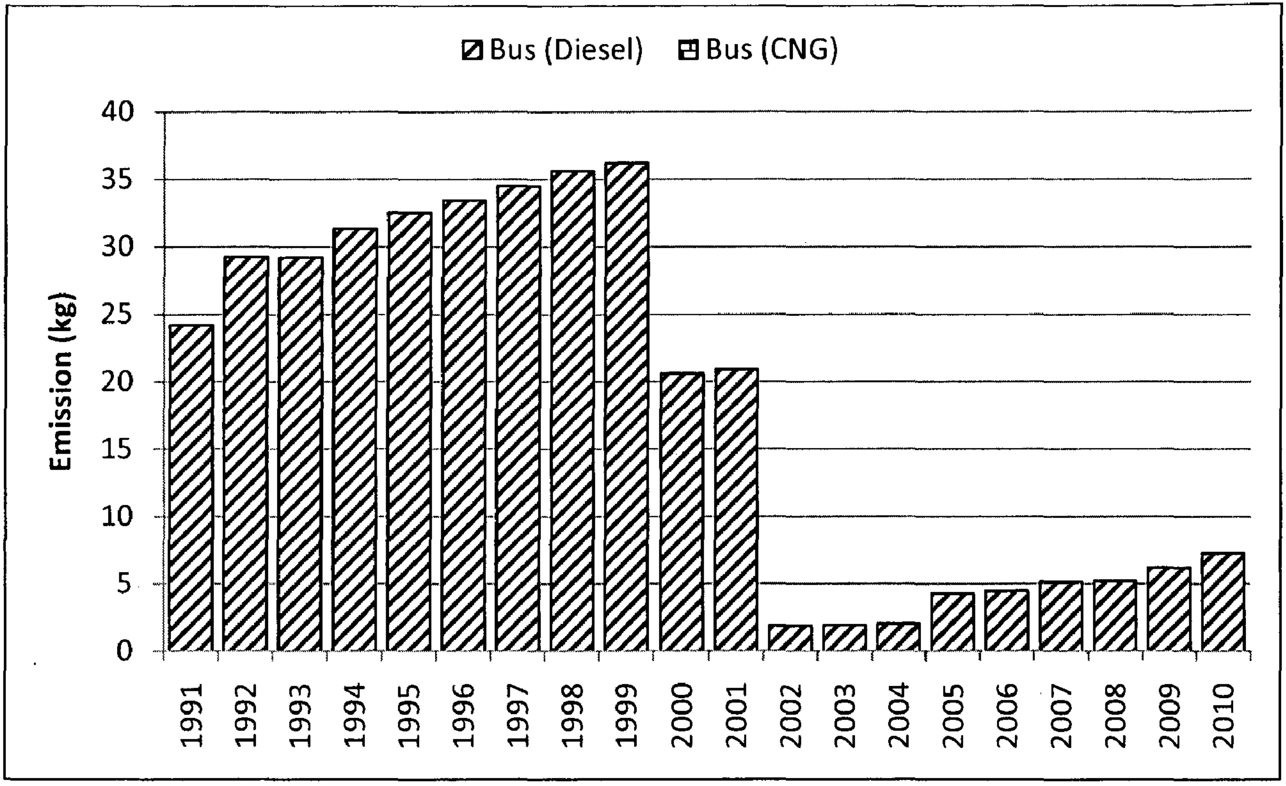


Fig. 5.52: 1-3 Butadiene emissions from bus population in megacity Delhi during 1991-2010

5.3.6.6. LCVs

Emissions of 1-3 Butadiene from LCVs are observed to be 15 kg in 1991 and 19 kg in 1995. Emissions during the year 2000 are 54 kg. A sudden growth of (218%) in 1-3 Butadiene emissions has been observed between 2001 and 2002 due to high emission factor for 2002 onward model LCVs (Table 3.2). Similar to 2002 major hike in LCVs population is observed in 2007, leading to an increase in 1-3 Butadiene emissions also. According to Fig. 5.53 in 2010 emission of 1-3 Butadiene is ~500 kg. Emission factors of 1-3 Butadiene used for the years 1991-1996 of are less than those used during 1997-2010, hence the emissions are less in the previous years and higher in subsequent years. Due to very less value of 1-3 Butadiene emission factors for CNG driven LCVs, no significant contribution is observed in total 1-3 Butadiene emission (Table 3.2).

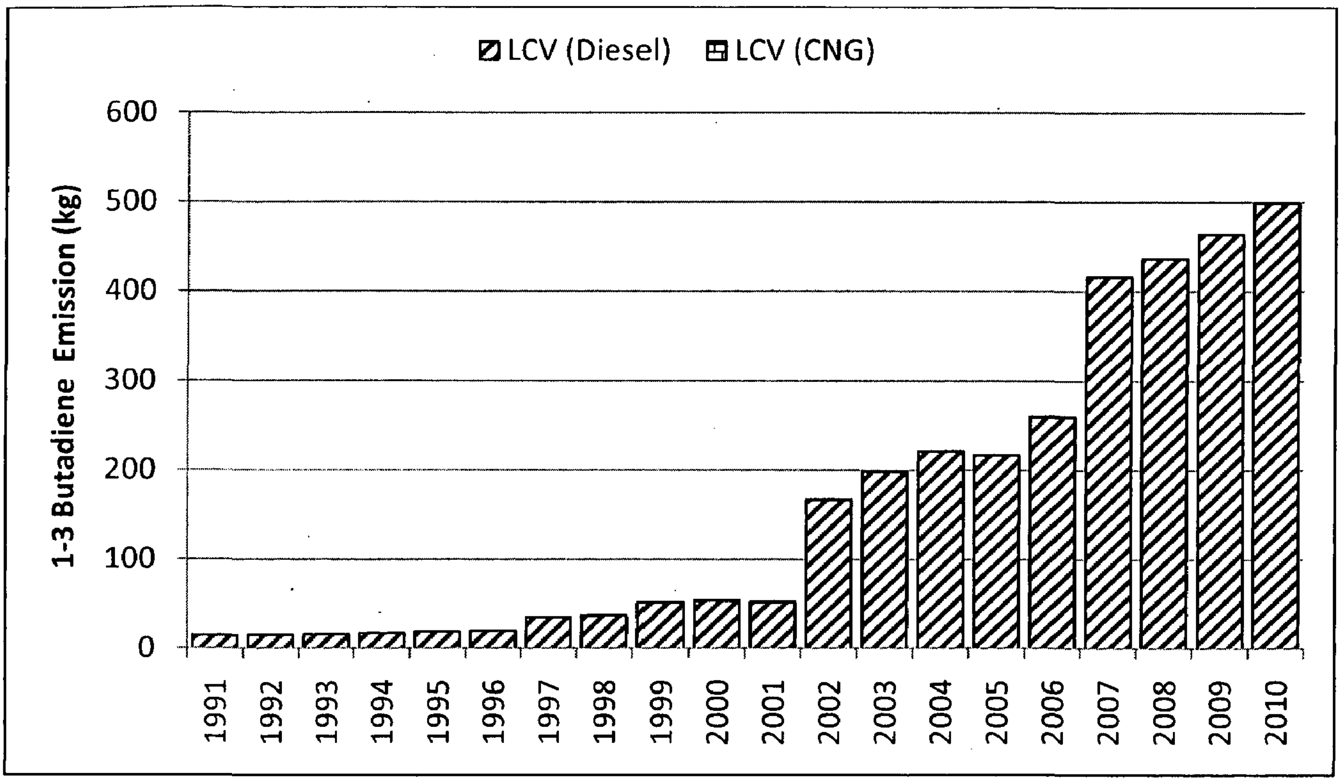


Fig. 5.53: 1-3 Butadiene emissions from LCVs population in megacity Delhi during 1991-2010

5.3.6.7. HCVs

In 1991 emission of 1-3 Butadiene are 21 kg and 26 kg in 1995. Similar to other pollutants, emission of 1-3 Butadiene have declined between 1999 and 2002 because of phasing out old age HCVs in this period. In between 1999 and 2000 about 1.4% decline has been observed followed by 11.7% during 2000 to 2001 and 32% during 2001 to 2002. In 2000 emission of 1-3 Butadiene was 29 kg followed by 17 kg in 2005. Again negative trend has been observed between 2004 and 2005 because of phasing out of HCVs and less entry of new HCVs. Similar status has been observed between 2006 and 2007 due to phasing out of pre-1991 and 1991 old technology HCVs.

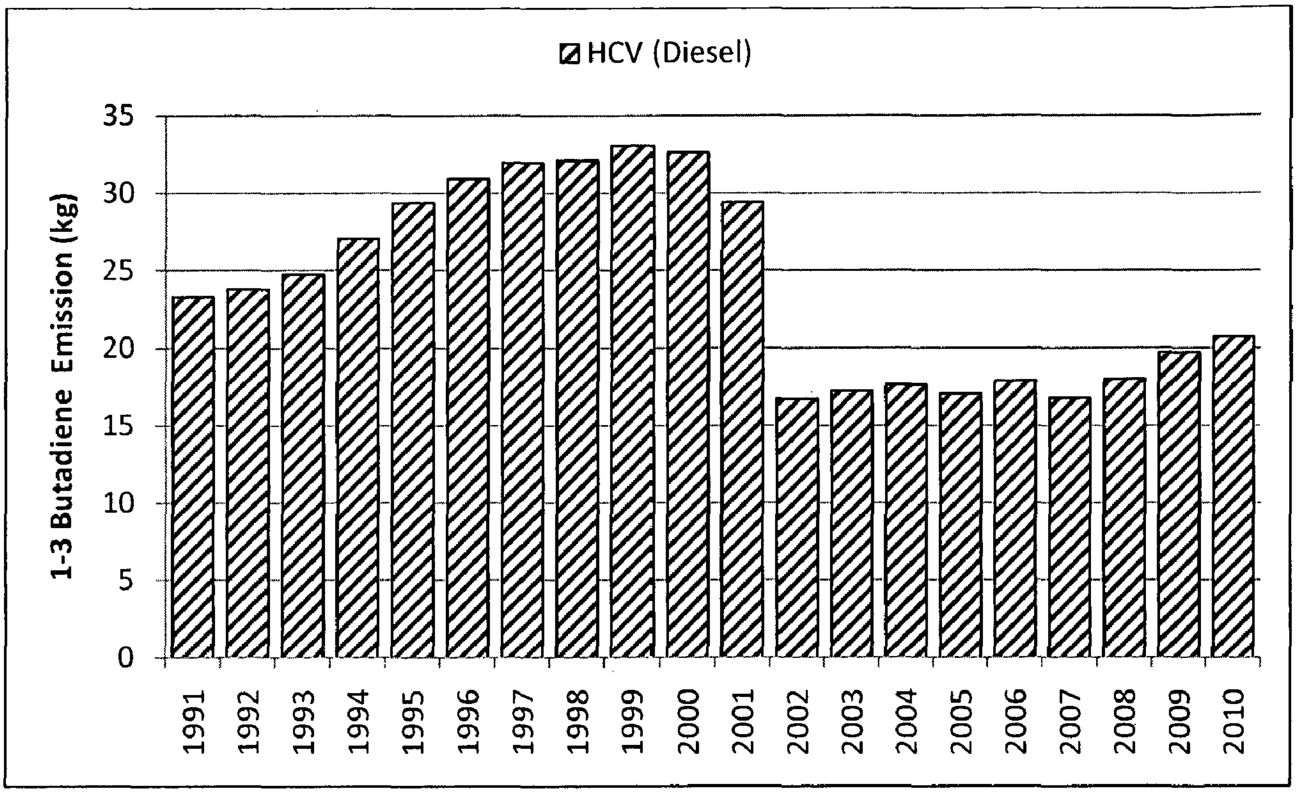


Fig. 5.54: 1-3 Butadiene emissions from HCVs population in megacity Delhi during 1991-2010

5.3.7. Acetaldehyde emissions

Fig. 5.55 shows the emission of Acetaldehyde from various vehicle categories in megacity Delhi. Emission of Acetaldehyde from all on-road vehicles are 291 kg in 1991 and 391 kg in 1995. Similar to other pollutants, negative trend is observed between 1999 (436 kg) and 2002 (352 kg) because of phasing out of more vehicles between these years. In 2000 emission of Acetaldehyde are 414 kg, which decreased (17%) to 340 kg in 2005, followed by 455 kg in 2010. As per contribution, accountability of two wheelers (47-51%) is highest throughout the study period, followed by cars (29-40%) and HCVs population (6-8%).

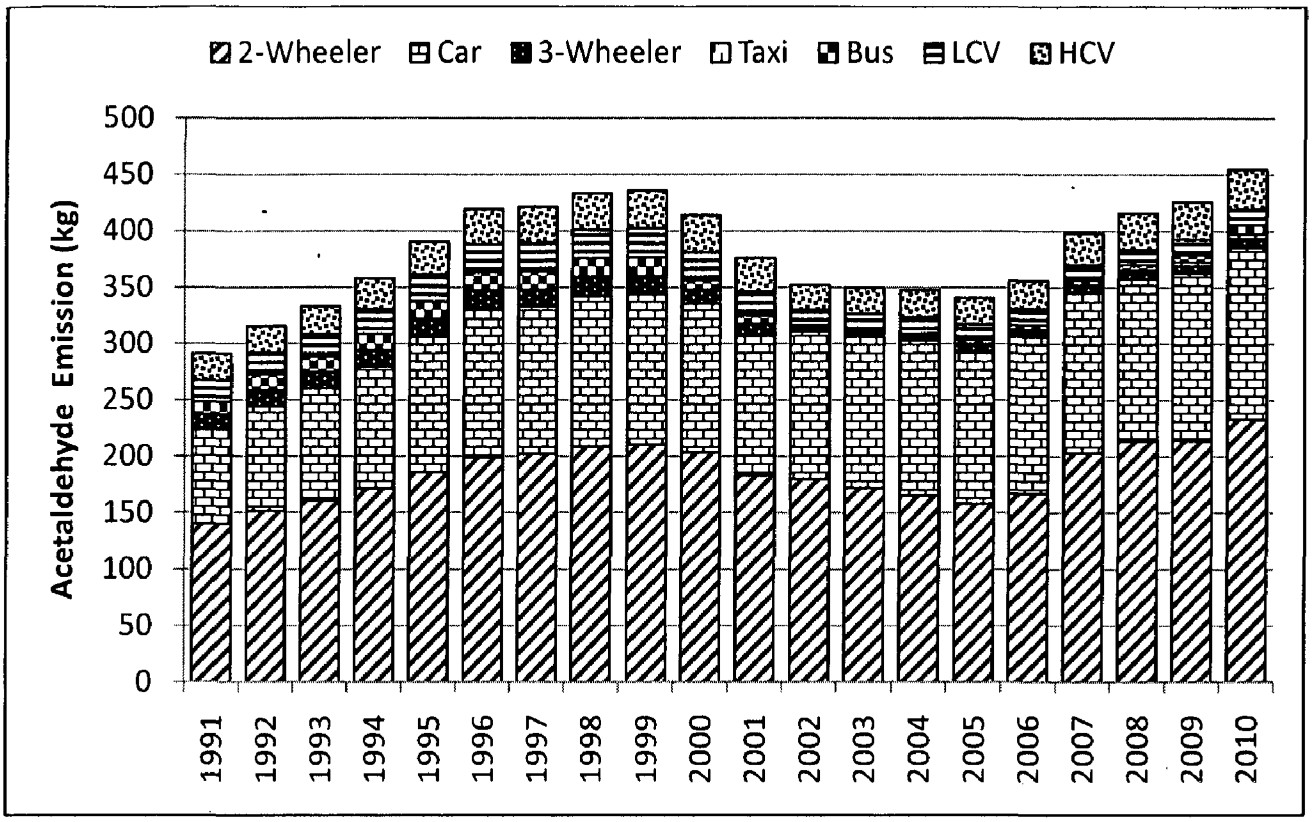


Fig. 5.55: Acetaldehyde emissions from various vehicles in megacity Delhi during 1991-2010

5.3.7.1. Two Wheelers

Two wheelers population is responsible for a major part of Acetaldehyde emissions among various on-road vehicle categories during 1991 to 2010. In 1991 emission of Acetaldehyde from two wheelers was 141 kg followed by 186 kg in 1995. Decline in Acetaldehyde emission has been observed between 1999 and 2005 because of less emission factor of two wheelers in respective years. Acetaldehyde emissions in year 1999 are 211 kg, which reduced to 158 kg in 2005 and again increased to 233 kg in 2010. After 2005 emissions started to increase and about 21% of growth is observed between 2006 and 2007 because of phasing out of pre-1991 and 1991 two-wheelers that had low emission factors (ARAI, 2007) and increasing new vehicle population (high emission factors). Two-stroke scooters are responsible for highest share (39-55%) in total emission from two-wheelers, followed by two-stroke moped (13-47%), four-stroke motorcycles and four-stroke scooters.

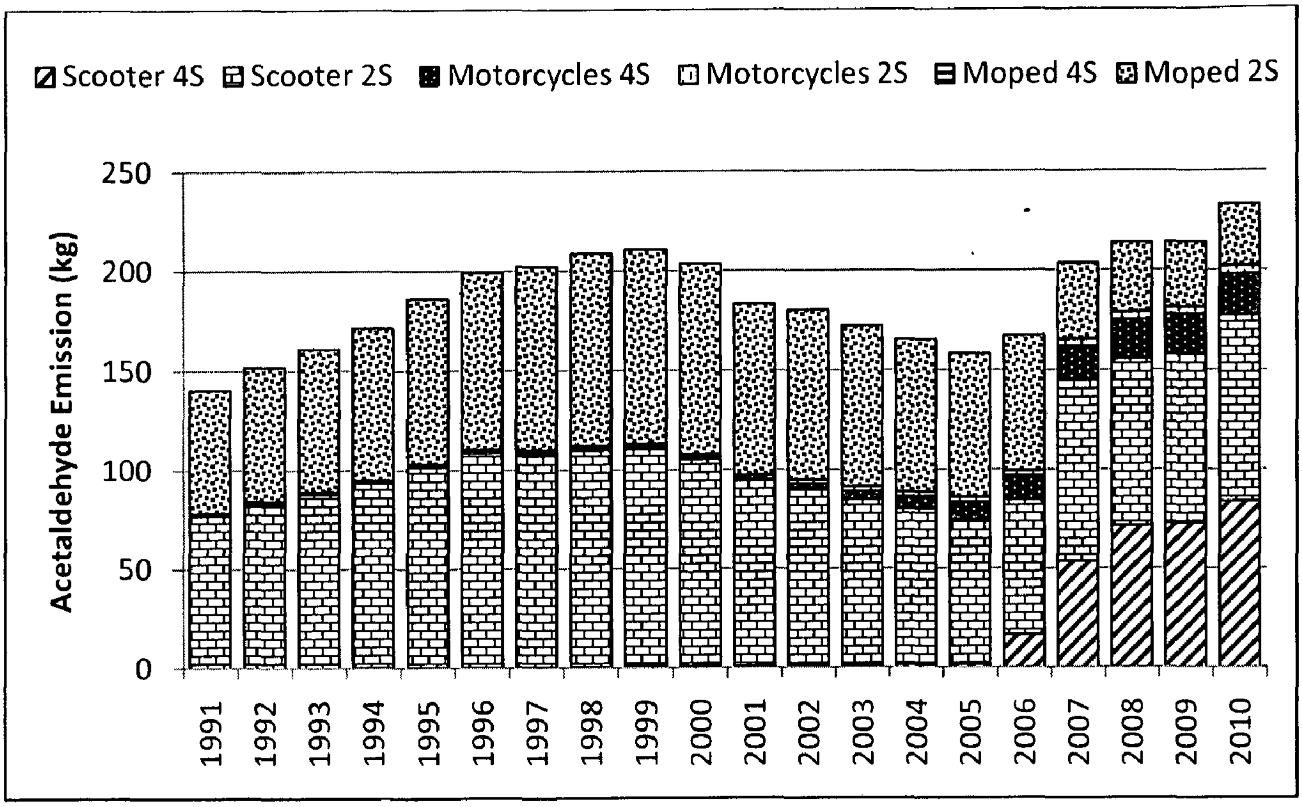


Fig. 5.56: Acetaldehyde emissions from two wheelers population in megacity Delhi during 1991-2010

5.3.7.2. Cars

Emissions of Acetaldehyde from car population in megacity Delhi are shown in Fig. 5.57. Emissions of Acetaldehyde from cars in 1991 were 84 kg, which increased to 120 kg (~43%) in 1995. Growing trend of Acetaldehyde emission from car population is observed between 1991 and 1996. A reduction in emissions is observed between 2000 and 2001 due to decrease in car population. Acetaldehyde emissions in 2000 are 132 kg followed by 136 kg in 2005 and 153 kg in 2010. Petrol driven cars share about 93-100% of Acetaldehyde emissions during the study period (1991-2010), while share of CNG and petrol driven car is very less.

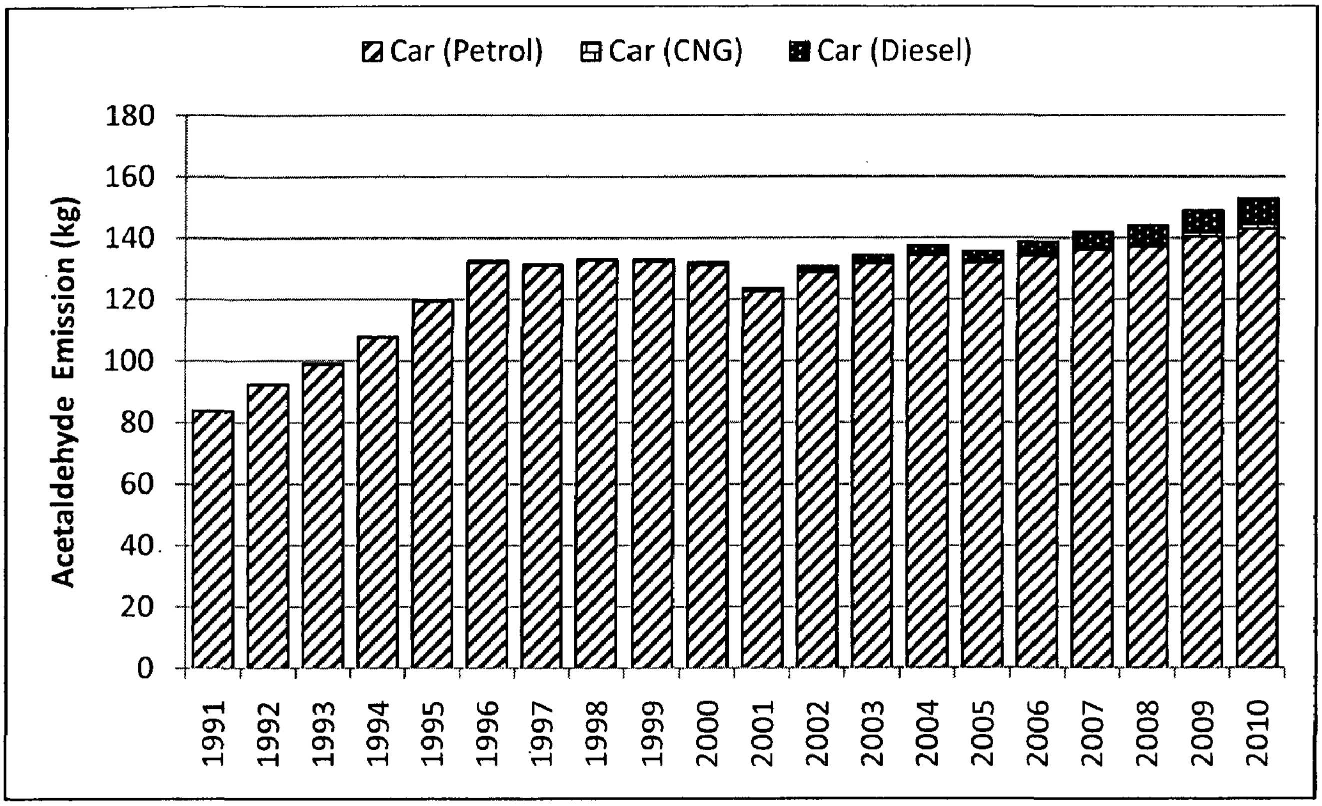


Fig. 5.57: Acetaldehyde emissions from car population in megacity Delhi during 1991-2010

5.3.7.3. Three Wheelers

Three wheelers share about 1 to 4% of Acetaldehyde emissions among all on-road vehicles in megacity Delhi. In 1991 Acetaldehyde emissions from three-wheelers are 12.4 kg and with 9% annual growth rate reached to 13.5 kg in 1992. Major decline in Acetaldehyde emissions (~67%) has been observed between 2001 and 2002 due to shifting of all three wheelers from other fuels to CNG and phasing out of old age three wheelers. Emissions of Acetaldehyde from three wheelers are observed to be 15 kg in 1995 and 12 kg in 2000. In 2005 emission of Acetaldehyde are 4.7 kg while increased to 8 kg in 2010. After 2006 emissions started to increase because of similar emission factors for respective year's two-wheeler models.

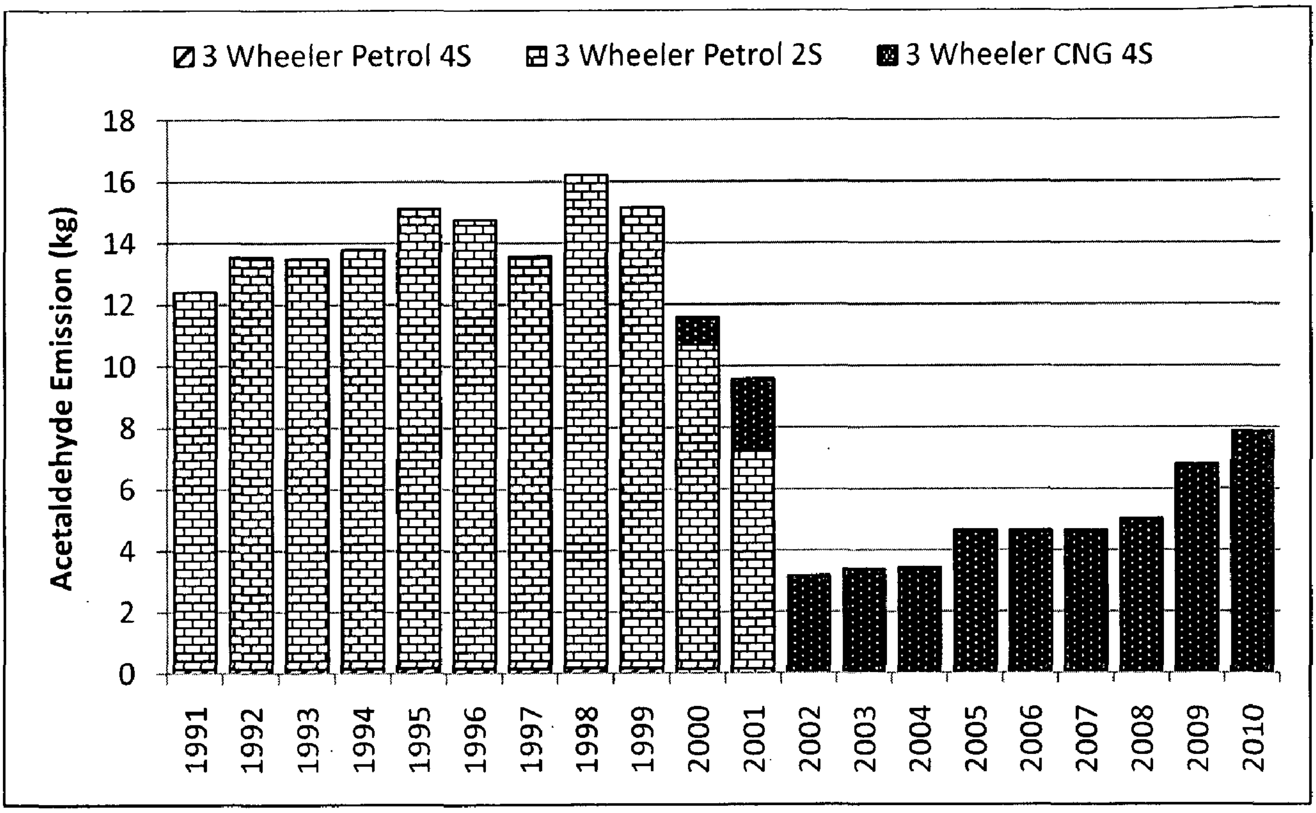


Fig. 5.58: Acetaldehyde emissions from three-wheeler population in megacity Delhi during 1991-2010

5.3.7.3. Taxis

Fig. 5.59 shows the emission of Acetaldehyde from taxi population in megacity Delhi. In 1991 emissions of Acetaldehyde from taxis are 0.6 kg and became 0.8 kg in 1995. Decline of about 22% is observed in Acetaldehyde emissions during 2001 (~1.1 kg) and 2002 (0.8 kg) because of phasing out program of commercial vehicles. In 2000 emission of Acetaldehyde are ~0.9 kg, followed by 1.5 kg in 2005, and 3.8 kg in 2010. From 1991 to 2001, share of petrol driven taxis was higher (81-89%) while after 2001 contribution of CNG driven taxis (65-83%) increased.

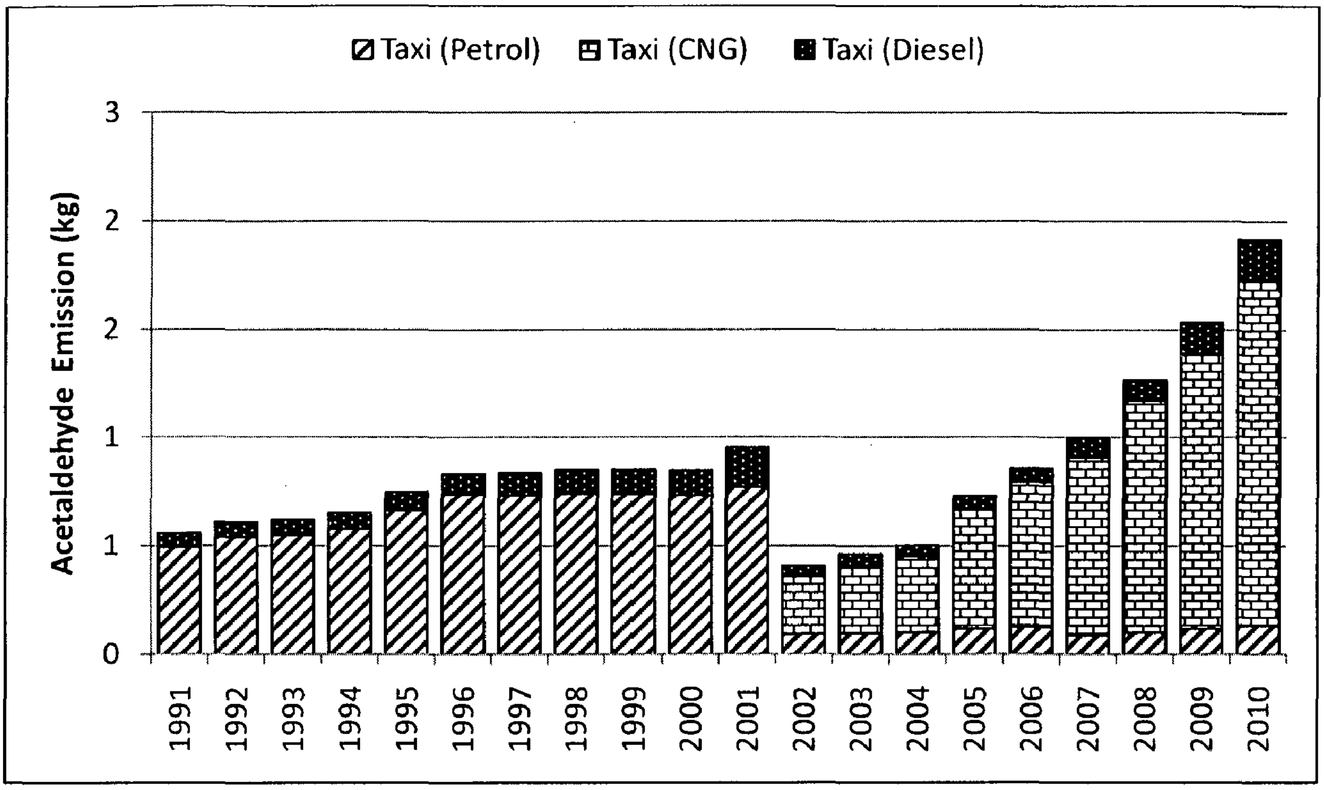


Fig. 5.59: Acetaldehyde emissions from taxi population in megacity Delhi during 1991-2010

5.3.7.5. Buses

Approximate 0.4 to 4% of total vehicular Acetaldehyde emissions come from buses in megacity Delhi. Emissions of Acetaldehyde are 11 kg in 1991 and 15 kg in 1995 A decrease of about 51% is noticed between 1999 and 2000 because of phasing out of older age (1991 and pre-1991) bus population in 2000. Emissions of Acetaldehyde are observed to be 8.2 kg in 2000 and 3.5 kg in 2005. Furthermore, sharp decrease between 2001 and 2002 is due to CNG conversion program. After 2002 emissions show a positive trend. Sudden increase (~93%) in Acetaldehyde emissions has been observed between 2004 and 2005 because of immediate increase in bus population in 2005. In 2010, emission is 8.4 kg and as per emission share contribution of diesel driven buses is higher before 2001 while after 2001 CNG driven buses emerge as a higher contributor (Fig. 5.60). Even though the population of diesel buses is less after 2001 (external buses only), their contribution is higher because of their higher emission factors (Table 3.2).

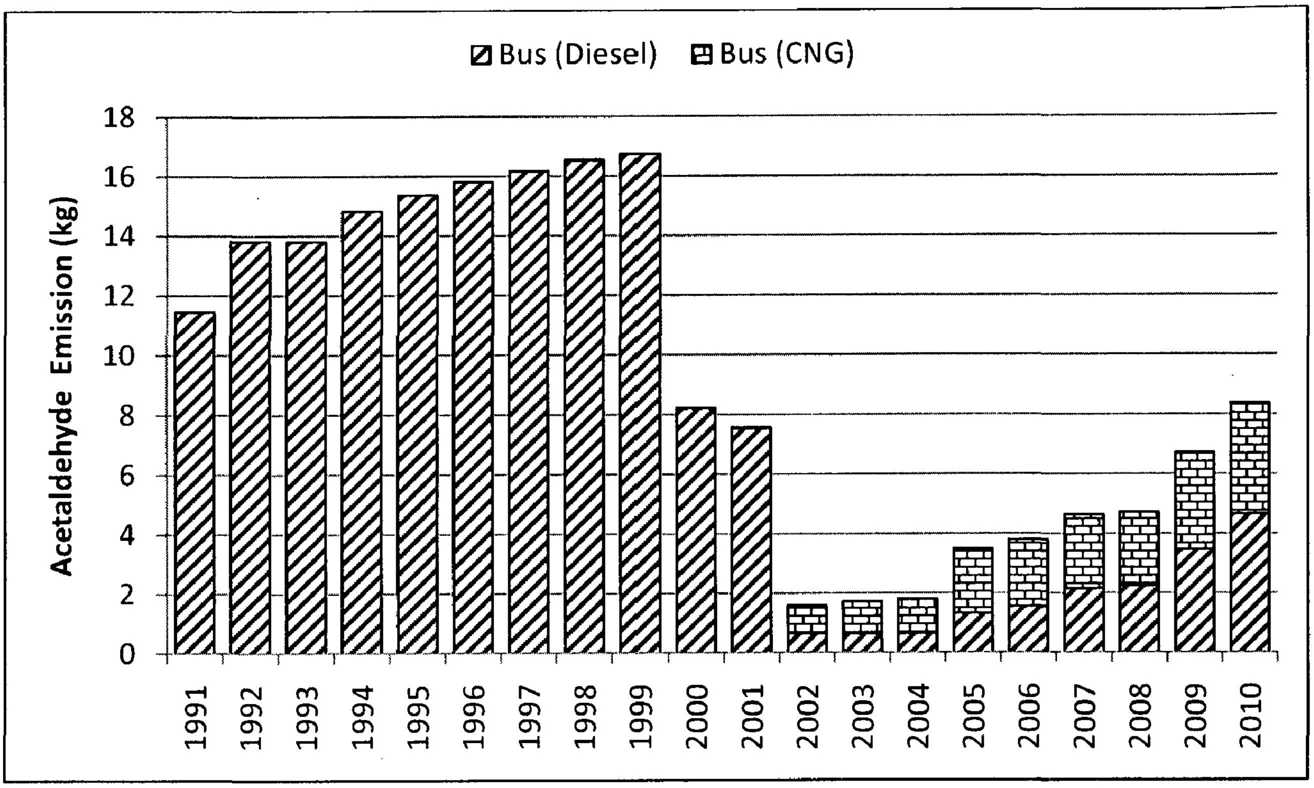


Fig. 5.60: Acetaldehyde emissions from bus population in megacity Delhi during 1991-2010

5.3.7.6. LCVs

Acetaldehyde emissions from LCVs population in megacity Delhi are 19 kg and 24 kg in 1991 and1995, respectively. According to Fig. 5.61, emissions of Acetaldehyde show an increasing trend from 1991 to 1999 while after 1999 decline has been observed with a sharp decrease between 2001 and 2002 because of phasing out of LCVs population. In 2004 emissions of Acetaldehyde from LCVs are 14.3 kg and 14 kg in 2005 due to less entry of new LCVs and phasing out of old LCVs. In 2006 slight growth is there because of increasing vehicle population while in 2007 emissions again decrease due to phasing out of pre-1991 and 1991 LCVs population (having higher emission factors). In 2010, emission of Acetaldehyde is 13.5 kg. During the study period, contribution of diesel driven LCVs is ~92-100%, while CNG driven LCVs are responsible for ~0-8% emissions.

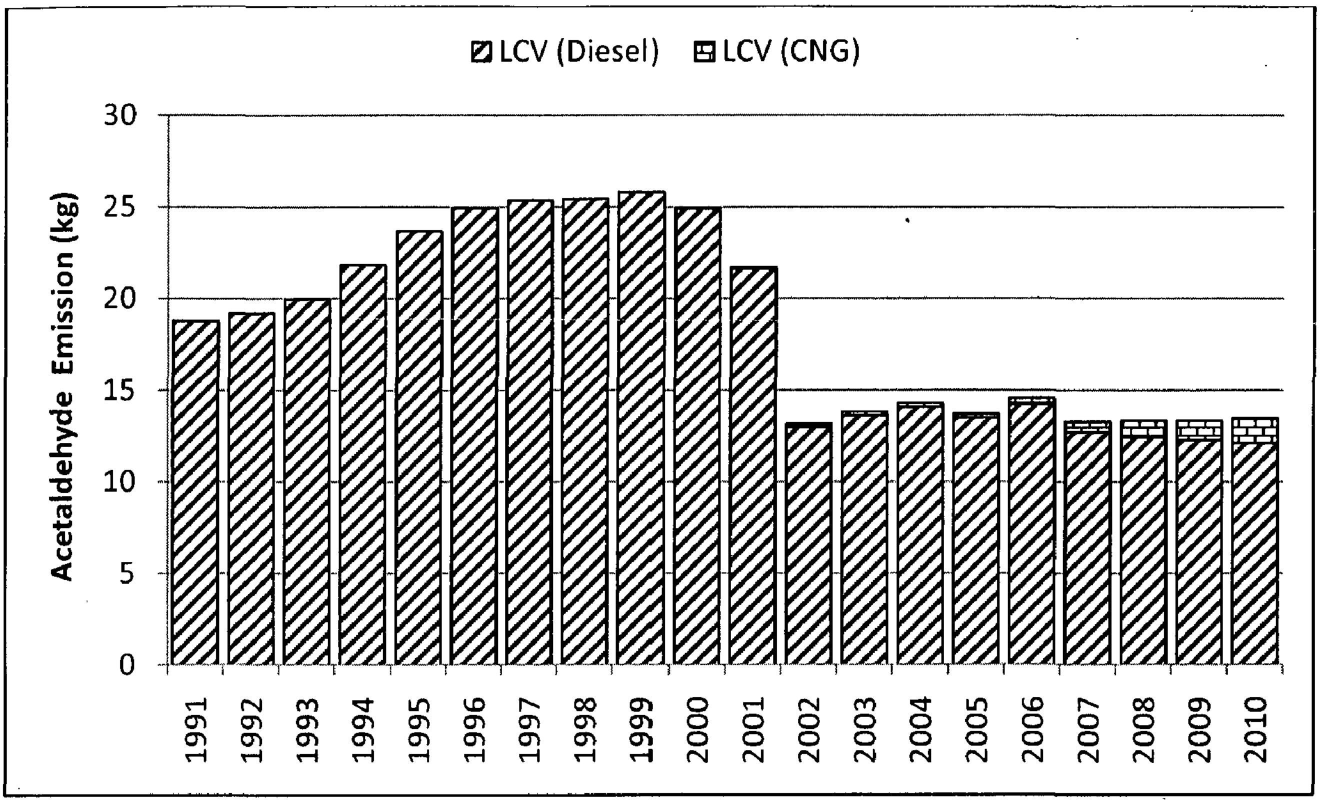


Fig. 5.61: Acetaldehyde emissions from LCVs population in megacity Delhi during 1991-2010

5.3.7.7. HCVs

In 1991 emission of Acetaldehyde from HCVs population are 23 kg, which constantly increase to about 34 kg in 1999 (Fig. 5.62). A declining trend is observed between 1999 and 2002 because of phasing out of HCVs. Acetaldehyde emission in 2000 are 33 kg. Again decline has been observed between 2004 (24 kg) and 2005 (23 kg) due to more retirement of old age vehicles and less increment in new HCVs population. However, Acetaldehyde emissions from HCVs again increase (from 25 kg to 35 kg) during 2006 to 2010.

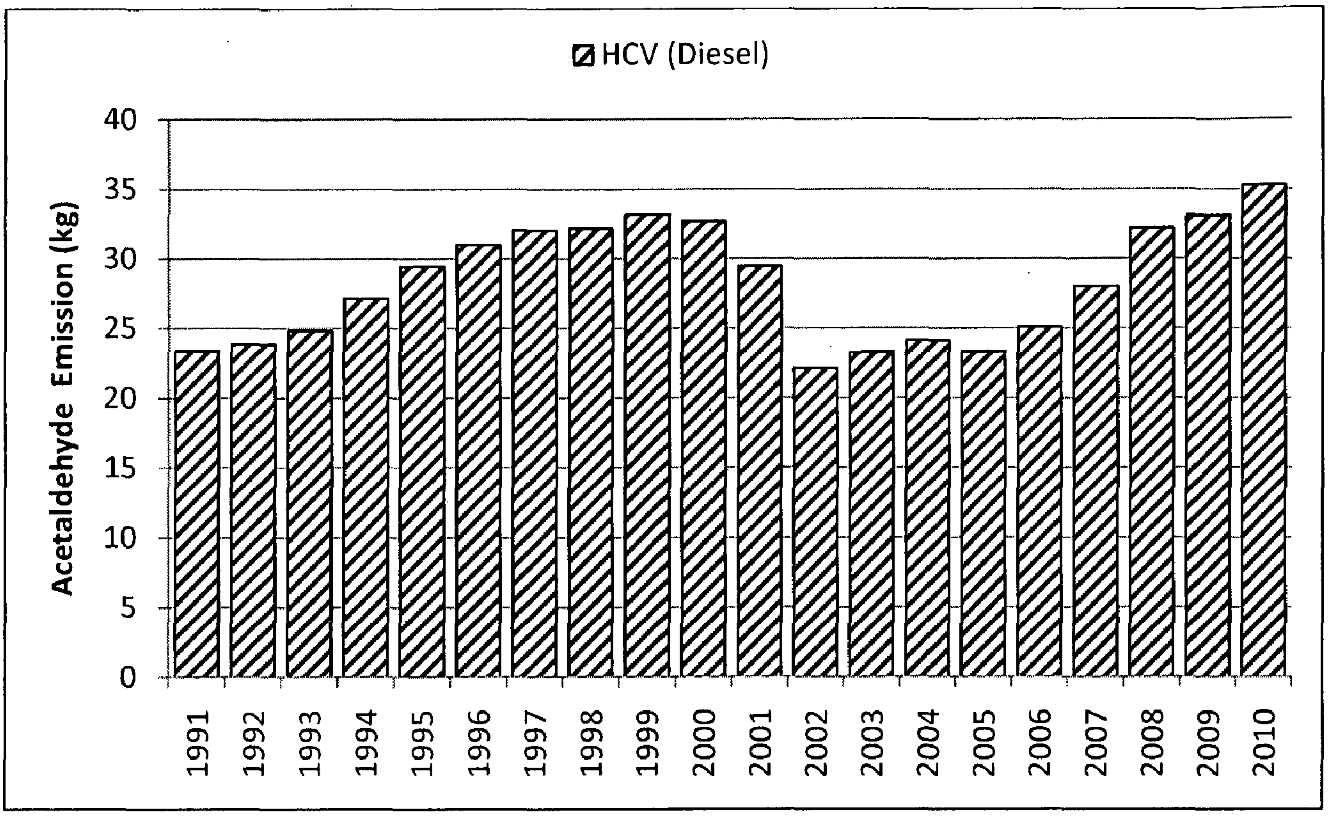


Fig. 5.62: Acetaldehyde emissions from HCVs population in megacity Delhi during 1991-2010

5.3.8. Benzene emissions

Fig. 5.63 shows emission of Benzene from various vehicle categories in megacity Delhi. In 1991 Benzene emissions are 3043 kg and 4299 kg in 1995, followed by 4994 kg in 2000. From 1991 to 2000 emissions follow a positive trend, while similar to other pollutants decline has been observed between 2000 and 2001 (7.2%) and 2001 to 2002 (15.7%). Benzene emissions are 4017 kg in 2005 and 3971 kg in 2010. Change in emission factors because of change in technology and retirement of old technology equipped vehicles is responsible for this negative trend. It is observed that among all vehicle categories Benzene emission contribution of car population is highest (61-82%) followed by LCVs (9-29%) during 1991 to 2010.

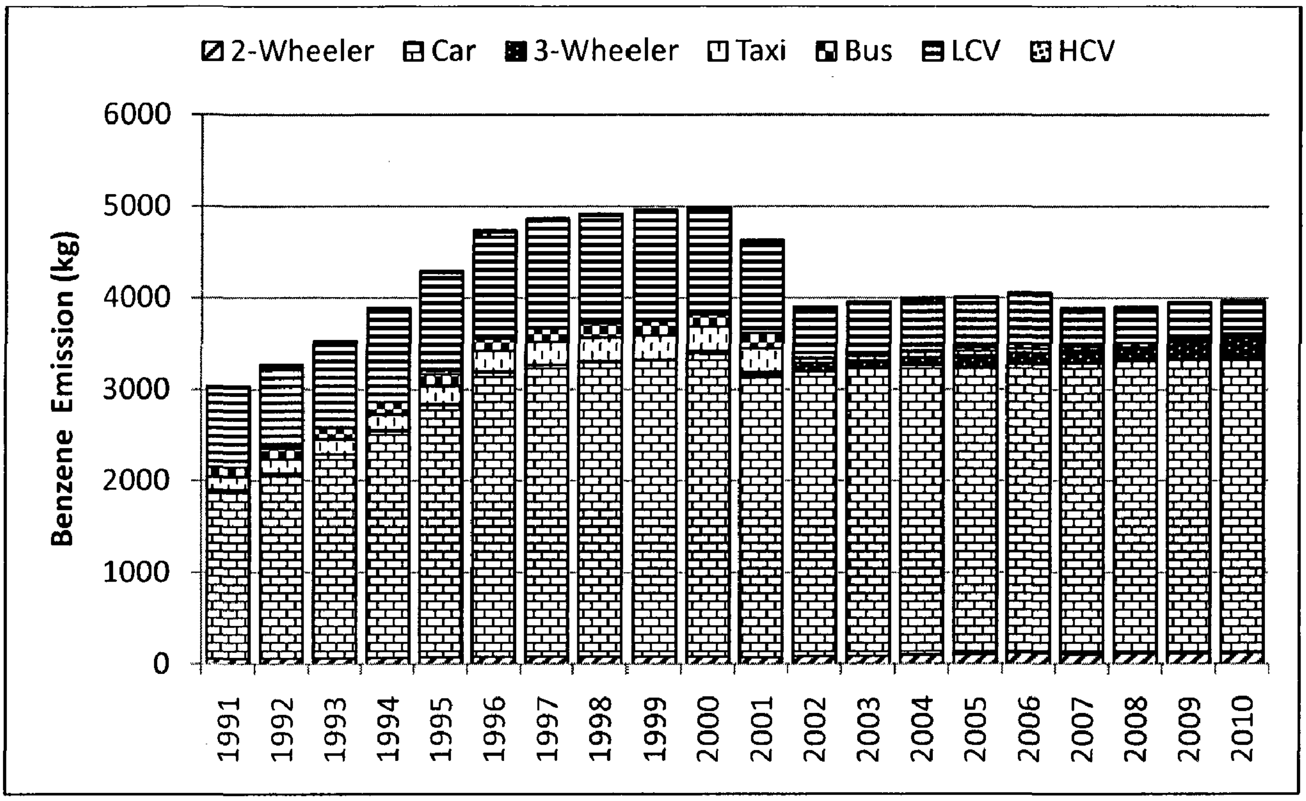


Fig. 5.63: Benzene emissions from various vehicles in megacity Delhi during 1991-2010

5.3.8.1. Two Wheelers

Emissions of Benzene from two wheelers population have an overall increasing trend between 1991-2010 except two sharp dips during 2000-2001 and 2006-2007. (Fig. 5.64). These sharp declines correspond to phasing out of old age two-wheelers and less entry of new two-wheelers during these years. As per contribution, two-stroke scooters dominate between 1991 and 2003, while four-stroke motorcycles are major contributors after 2003.

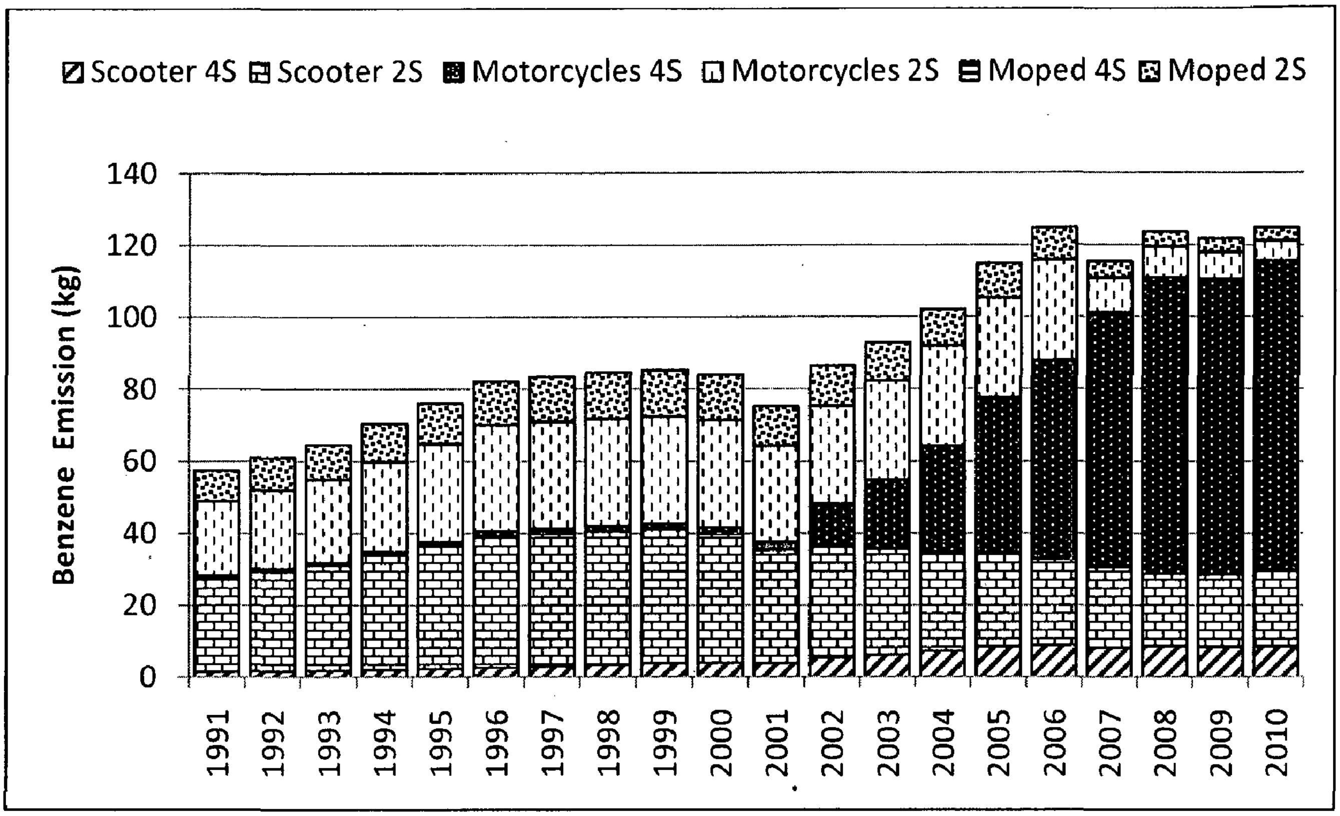


Fig. 5.64: Benzene emissions from two wheelers population in megacity Delhi during 1991-2010

5.3.8.2. Cars

Fig. 5.65 shows emission trend of Benzene from car population in megacity Delhi. There is a rapid increase in emissions during 1991-1996; thereafter there is slow increase until 2001. This is because of increasing population and decreasing emission factor. Emissions of Benzene from car population are 1836 kg in 1991 and 2757 kg in 1995, followed by 3310 kg in 2000. Similar to other pollutants, emissions of Benzene from car population have decreased between 2000 and 2001 (7.8%), thereafter it has an overall but slow and steady increasing trend until 2010. Fig. 5.65 shows that petrol driven cars are major source of Benzene emissions throughout the study period followed by diesel driven cars, while contribution of CNG cars is negligible.

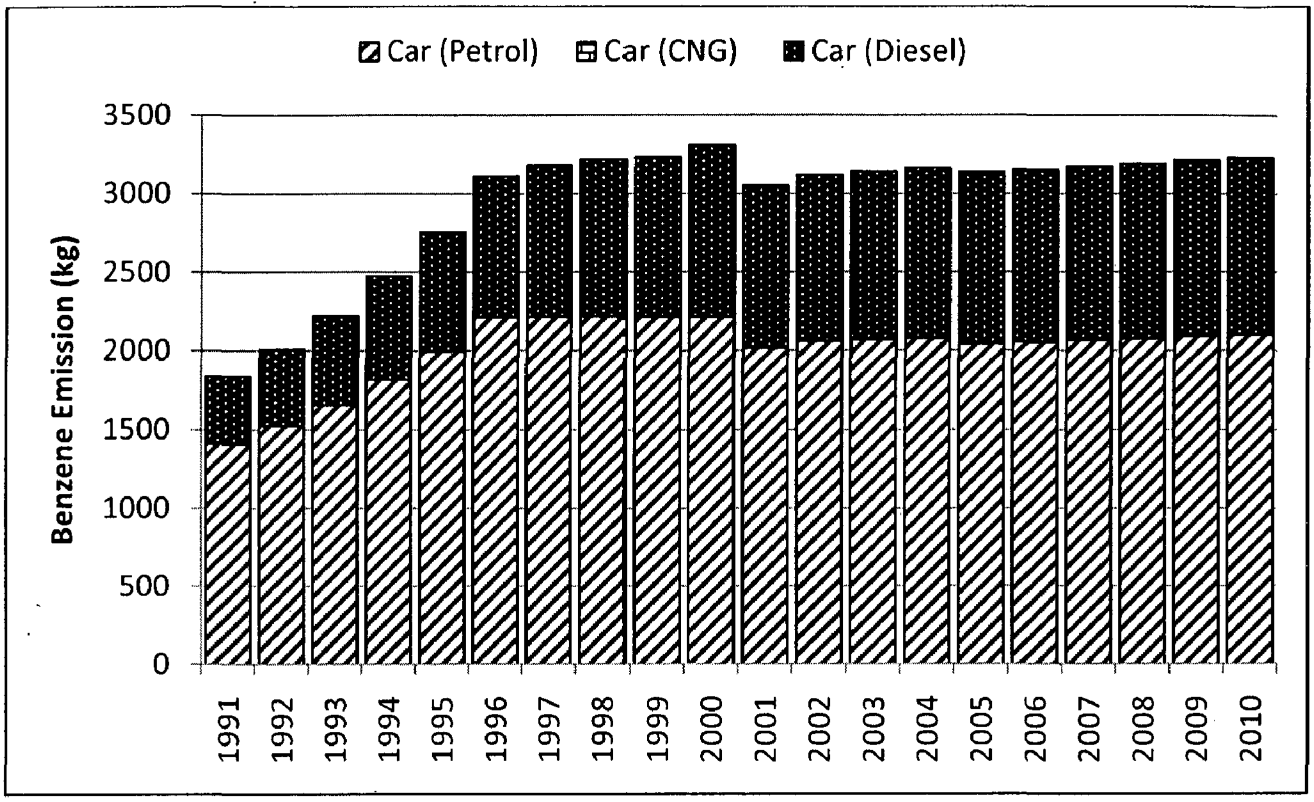


Fig. 5.65: Benzene emissions from car population in megacity Delhi during 1991-2010

5.3.8.3. Three Wheelers

Emissions of Benzene from three wheelers during 1991 to 2010 in megacity Delhi are shown in Fig. 5.66. During 1991-1999 Benzene emissions from three-wheelers population are almost constant. Before 2000 there are no CNG driven three wheelers running on the roads of Delhi, hence petrol driven two-stroke three wheelers contributed higher Benzene emissions (94%) compared to petrol driven four-stroke three wheelers (6%) during this period. After implementation of CNG norms in Delhi all three-wheelers have been converted to CNG and are responsible for Benzene emission in Delhi. In 2000 emission of Benzene from three wheelers are 29 kg and increased to 121 kg in 2005, followed by 208 kg in 2010. After 2000 huge growth in Benzene emission has been observed because of high emission factor for CNG driven three wheelers. Benzene emission rate of petrol driven three wheelers is very less than CNG driven three wheelers (ARAI, 2007).

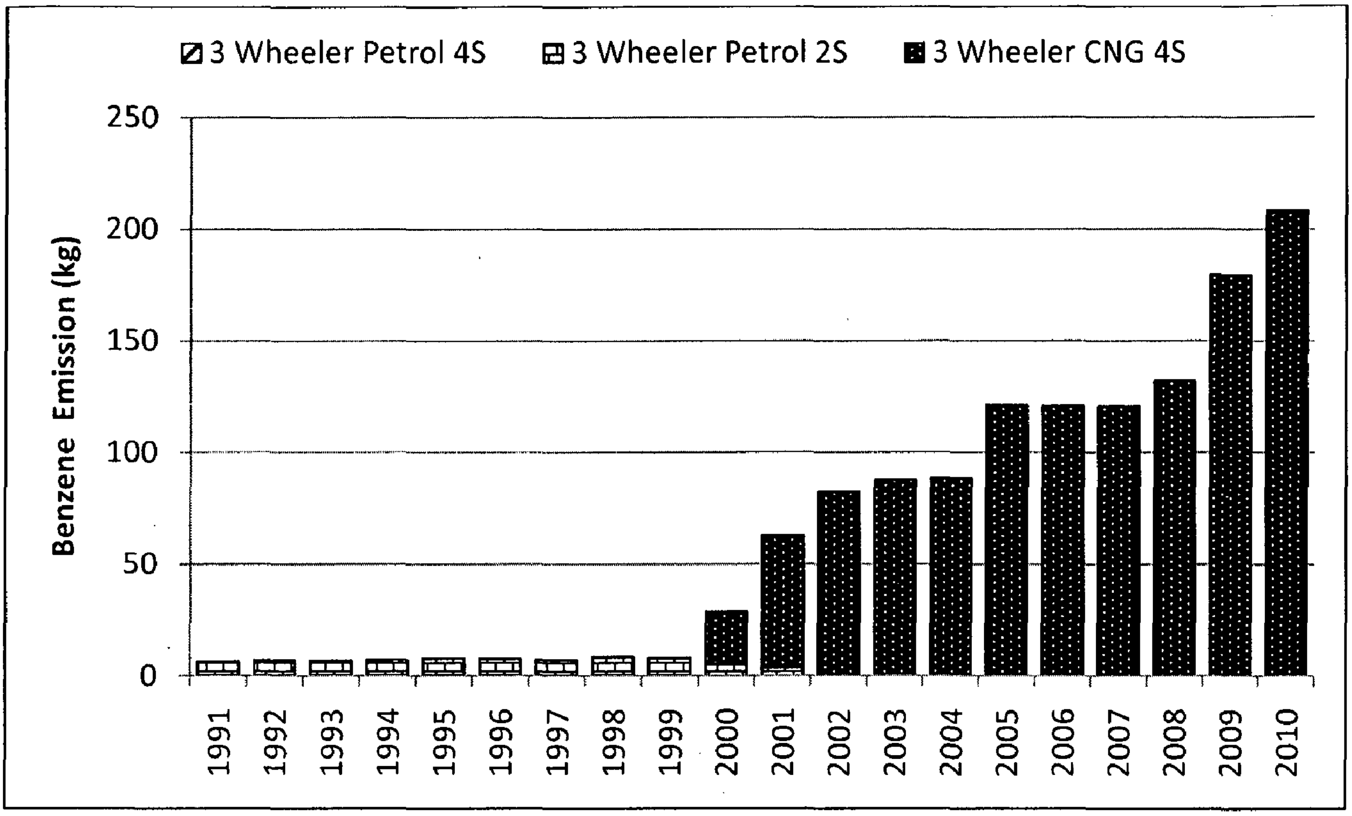


Fig. 5.66: Benzene emissions from three-wheeler population in megacity Delhi during 1991-2010

5.3.8.4. Taxis

Emissions of Benzene from taxis are shown in Fig. 5.67. It shows that emissions of Benzene in 1991 from taxi population are 147 kg, followed by 195 kg in 1995 and 262 kg in 2000 depicting an increasing trend from 1991-2000. Decrease of about 81% has been observed in Benzene emission from taxi population between 2001 and 2002, because of phasing out program by the Delhi Government and change in emission factors. However, emissions during 2002-2006 are almost constant. A decreasing trend in Benzene emission is further observed from 2007 to 2010 because of phasing out of 1991 and pre-1991 modeled taxis and change in emission factors for newly registered taxis. Estimations suggest that diesel driven taxis contributed highest amount (92- 95%) of Benzene among all types of taxis followed by petrol and CNG driven taxis.

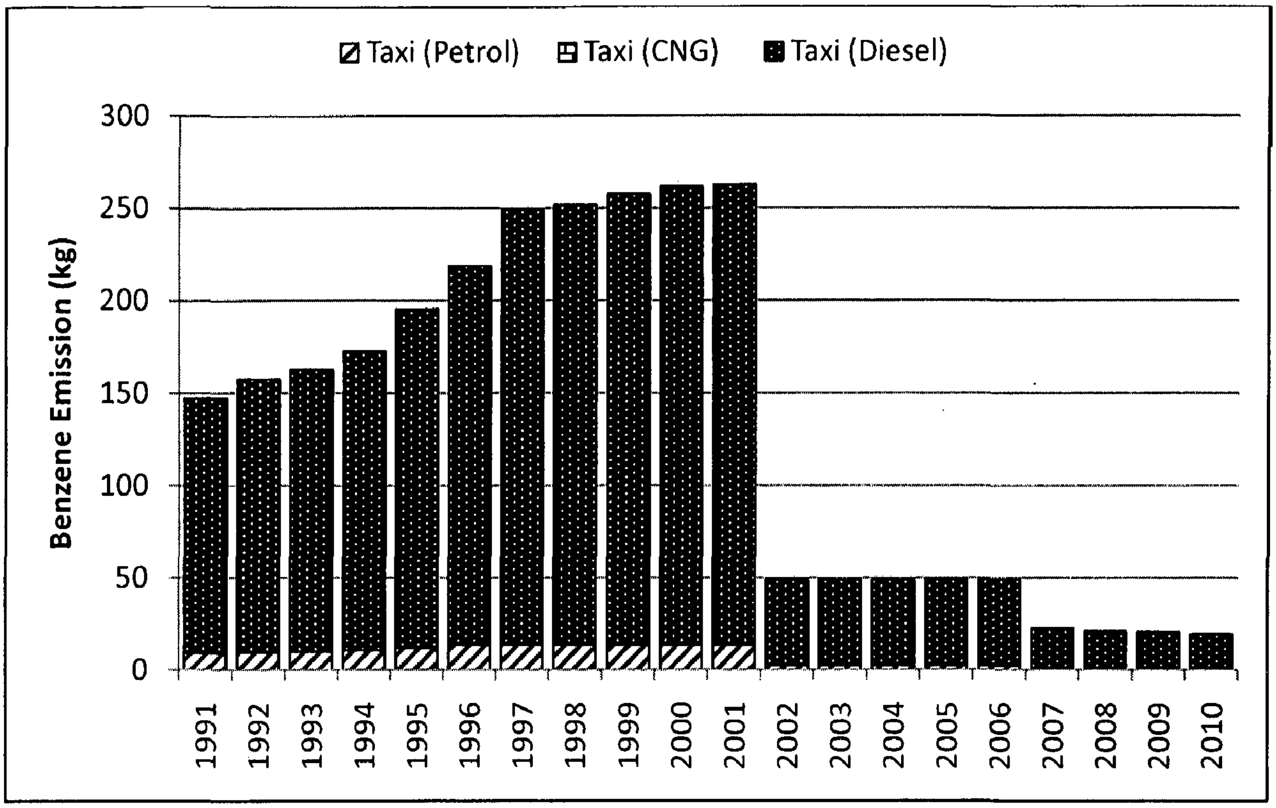


Fig. 5.67: Benzene emissions from taxi population in megacity Delhi during 1991-2010

5.3.8.5. Buses

Fig. 5.68 shows emission of Benzene from bus population in megacity Delhi. Benzene emissions from buses in megacity Delhi are 103 kg in 1991, which increase to about 166 kg in 1999. There was a dip in emissions in 2000 but increased in 2001 almost to 1999 level. There is a sharp decrease of about 17% and 90% between 1999-2000 and 2001-2002 because of phasing out of old age buses. In 2004 Benzene emissions from buses in Delhi are 20 kg which almost doubled (42 kg) in 2005 because of immediate growth in bus population in megacity Delhi during 2005. After 2005, emissions of Benzene again decreased until 2010 because of less emission factor of newly introduced models, phasing out of old buses and less entry of new buses. Due to low value emission factors the contribution of CNG driven buses is very less and thus diesel driven buses have much larger share in Benzene emissions.

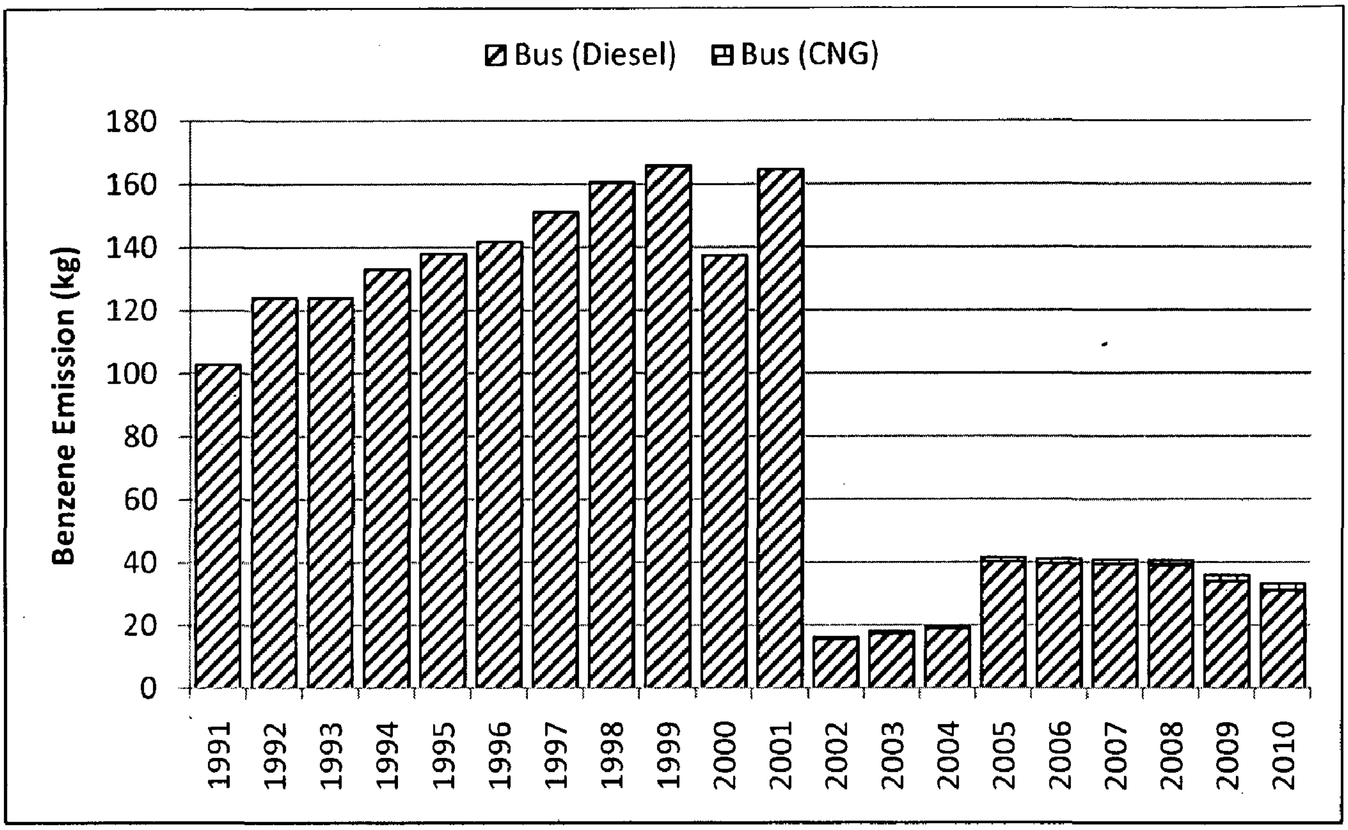


Fig. 5.68: Benzene emissions from bus population in megacity Delhi during 1991-2010

5.3.8.6. LCVs

Fig. 5.69 shows the emission of Benzene from LCVs. It suggests that emissions of Benzene from LCVs increase from 1991-1999 and then decrease until 2010. Benzene emissions are estimated to be 872 kg in 1991 and ~1190 kg in 1999. In 2000 emission of Benzene from LCVs are 1144 kg followed by 539 kg in 2005. Between 2001-2002 and 2006-2007 there are sharp dips in emissions because of less entry of new LCVs, and phasing out of old age LCVs. From 2007 onwards there is continuous decrease in emissions due to phasing out of 1991 and pre-1991 (which had large population) LCVs and change in emission factor according to technology. Because of low value emission factors the contribution of CNG driven LCVs is almost insignificant as compared to diesel driven LCVs.

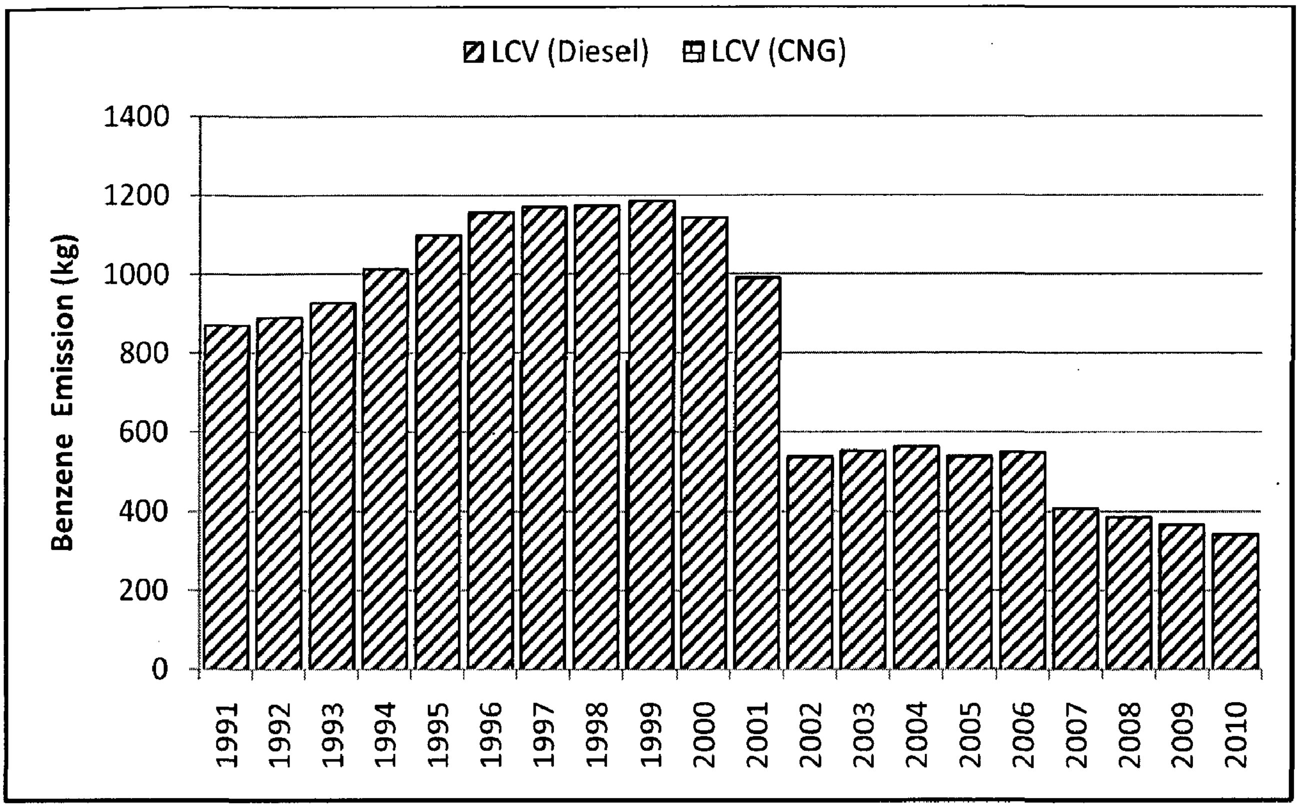


Fig. 5.69: Benzene emissions from LCVs population in megacity Delhi during 1991-2010

5.3.8.6. HCVs

Annual trend of Benzene emission from HCVs is shown in Fig. 5.70. It follows a trend similar to Benzene emissions from LCVs. Emissions of Benzene in 1991 from HCVs population were 20 kg and became 26 kg in 1995 followed by 29 kg in 2000. There is increasing trend in Benzene emissions between 1991 and 1999, while it decreases after 1999 until 2010. There is large decrease in emissions between 1999 and 2002 because of phasing out program by the Government of Delhi. In 2005 Benzene emissions from HCVs are 16 kg, which decline to 12 kg in 2010. In between 2006 and 2007 a decrease of 23% has been observed in Benzene emissions because of phasing out 1991 and pre-1991 (high number) HCVs and less entry of new HCVs population.

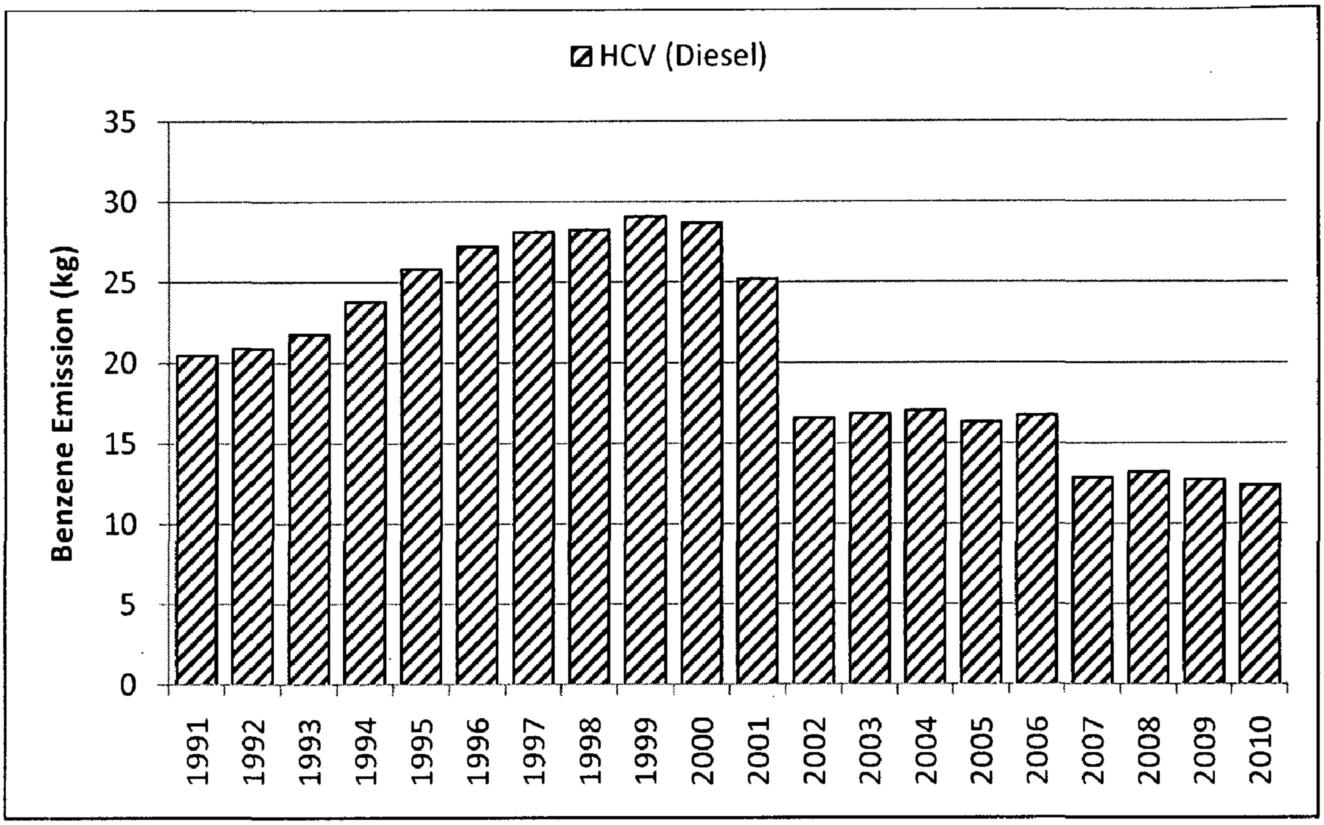


Fig. 5.70: Benzene emissions from HCVs population in megacity Delhi during 1991-2010

5.3.9. Formaldehyde emissions

Fig. 5.71 shows the emission of Formaldehyde from various vehicle categories in megacity Delhi. It indicates that emission trend of Formaldehyde from vehicles follow an increasing trend from 1991 to 1999 after that it decrease with a sharp decline from 2001-2002. However, Formaldehyde emissions increase again during 2002-2010. Formaldehyde emissions from all vehicle categories are 727 kg in 1991 and about 1080 kg in 1999. In between 1999 and 2002, a sharp decrease is observed because of CNG conversion and phasing out program undertaken by the Government of Delhi. In 2005 emissions of Formaldehyde from vehicles are 748 kg followed by 1171 kg in 2010. Between 2006 and 2007, higher growth rate (18%) has been observed in Formaldehyde emissions because of change in emission factors for two wheelers during 2007. With concern to emission contribution, accountability of LCVs population is higher (36-44%) from 1991 to 2001, while cars dominate (39-43%) after 2001.

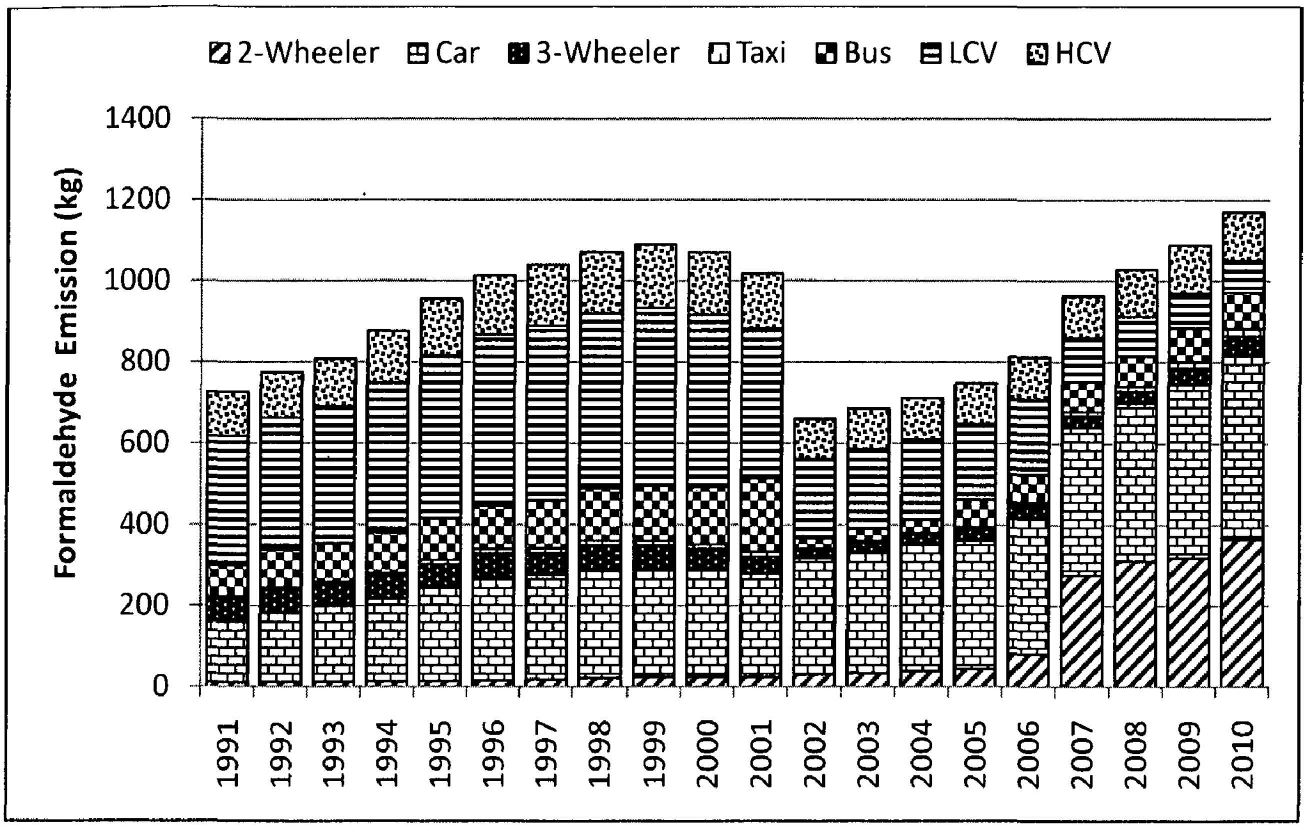


Fig. 5.71: Formaldehyde emissions from various vehicles in megacity Delhi during 1991-2010

5.3.9.1 Two Wheelers

Fig. 5.72 shows the emissions of Formaldehyde from two wheelers in megacity Delhi. Emissions are increasing throughout from 1991-2010 with a very sharp increase from 2006-2007. Formaldehyde emissions from two-wheelers are 11 kg in 1991, 15 kg in 1995, followed by 26 kg in 2000. Formaldehyde emissions from two wheelers are observed to be 45 kg in 2005 and 364 kg in 2010. In 2007 all pre-1991 and 1991 modeled two wheelers (less emission factor) have been phased out and more post-2005 model two wheeler population is entered (that have higher emission factor), due to this change the Formaldehyde emissions show a sudden rise from 81 kg in 2006 to 277 kg in 2007. As per contribution, share of two-stroke motorcycles is highest among all two wheelers during 1991 to 2001, which shifted to four-stroke scooters as prominently visible during 2006-2010.

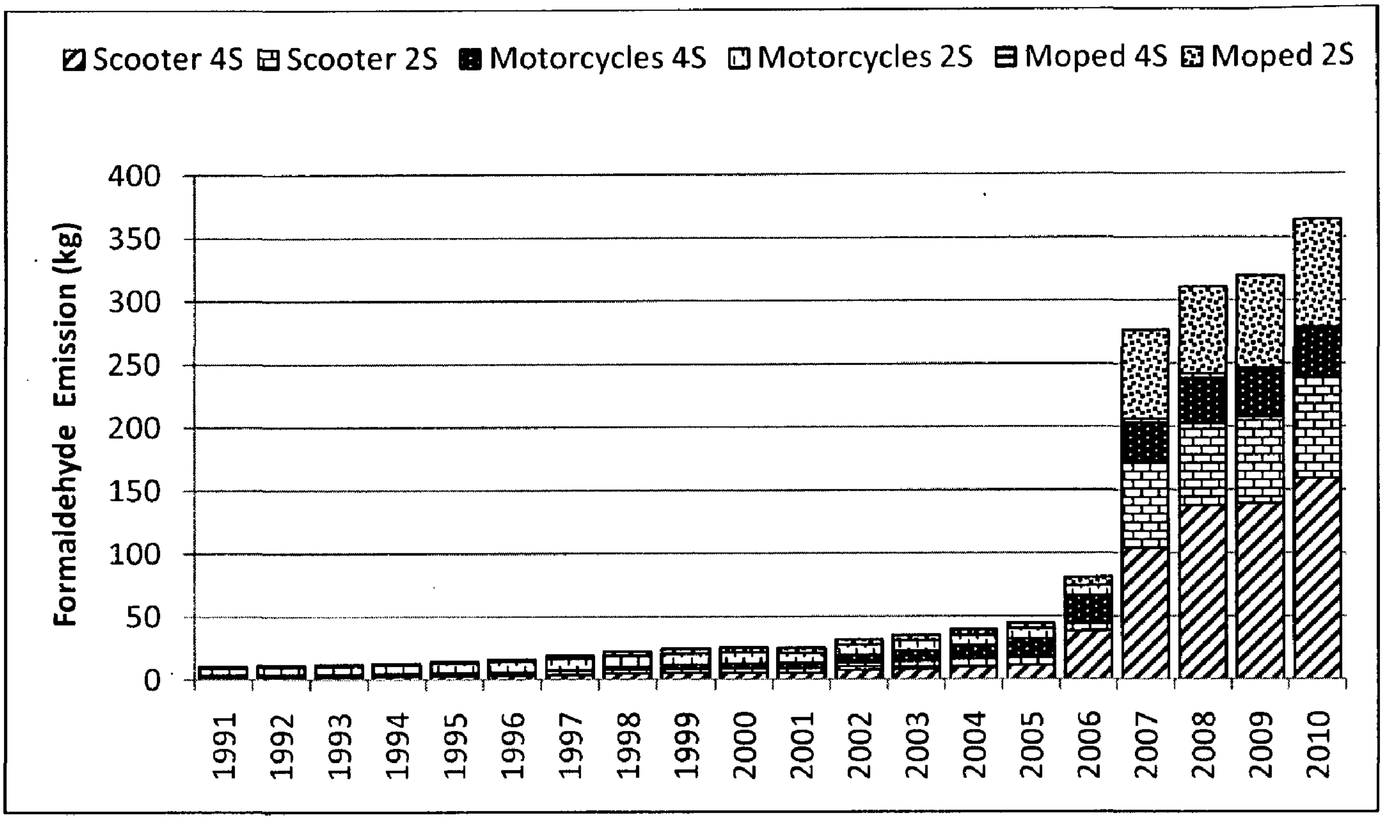


Fig. 5.72: Formaldehyde emissions from two-wheeler population in megacity Delhi during 1991-2010

5.3.9.2. Cars

Formaldehyde emissions from cars have constantly increased between 1991-2010 except a slow growth during 1996-2000 (156 kg to 453 kg) and a decline (~5%) between 2000-2001 (Fig. 5.73). This is because of decline in population (-3%) in between 2000-2001. Petrol driven cars contribute about 59 to 89 % of Formaldehyde emissions during 1991 to 2010, followed by diesel driven cars (11-40%).

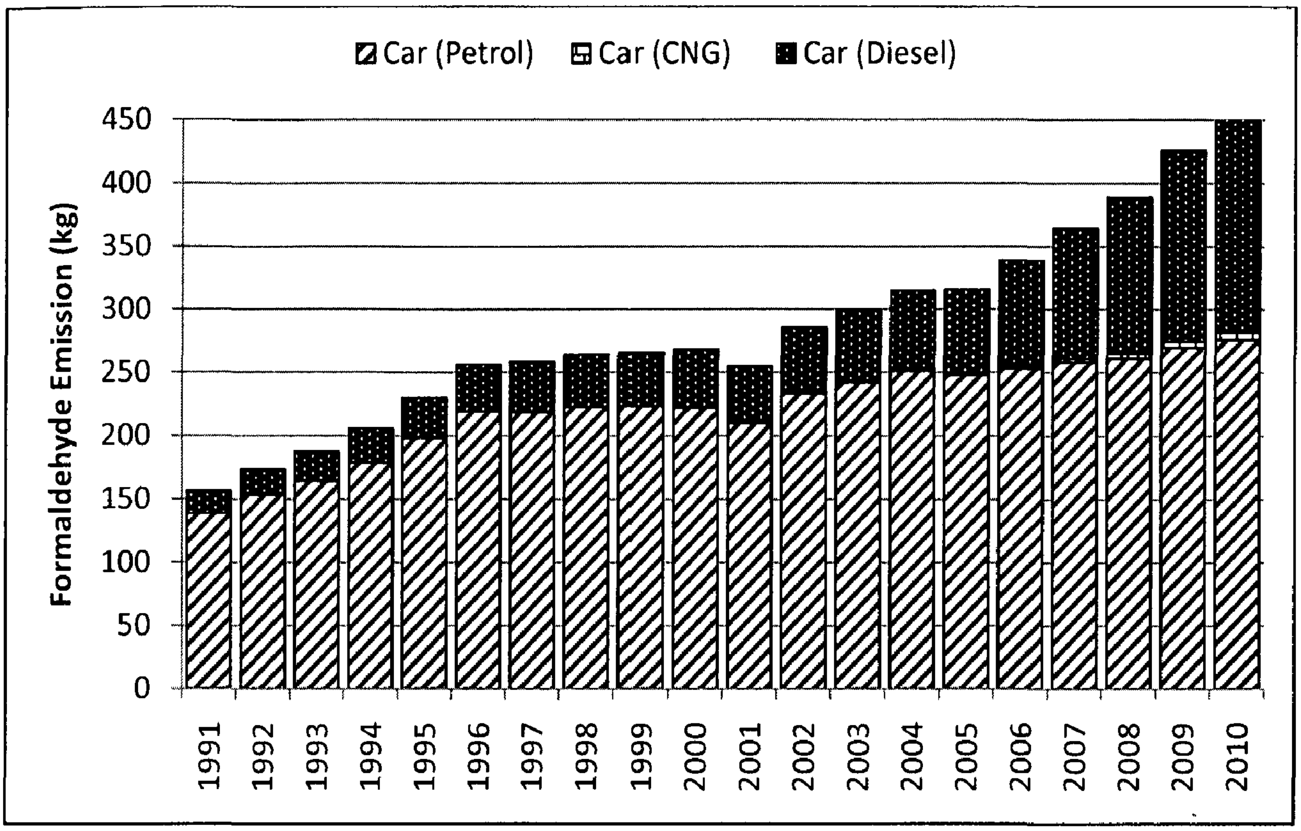


Fig. 5.73: Formaldehyde emissions from car population in megacity Delhi during 1991-2010

5.3.9.3. Three Wheelers

Fig. 5.74 shows the emission of Formaldehyde from three-wheelers in megacity Delhi during 1991 to 2010. Formaldehyde emissions from three wheelers are 48 kg in 1991 and 59 kg in 1995. Occasional declines have been observed between 1992-1993, 1995-1997, 1999-2002 and 2006-2007 due to phasing out of more old age three wheelers and less entry of new three wheelers. In between 2001-2002 about 55% decline has been noticed due to shifting of three wheelers from petrol (gasoline) to CNG. In 2000 and 2005 Formaldehyde emission from three wheelers are 47 kg and 28 kg, respectively. From 2005 to 2008 emissions show a slow growth rate thereafter rapid increase (~35%) is observed.

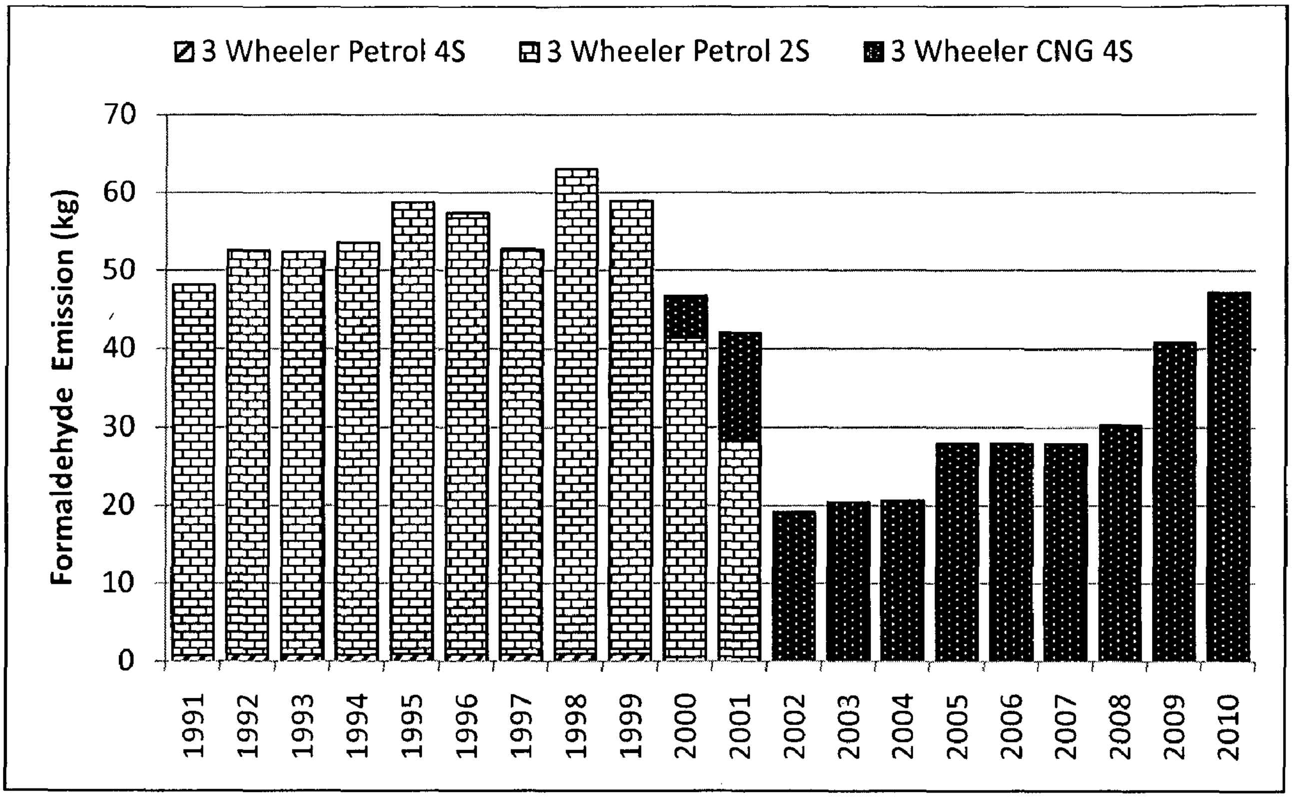


Fig. 5.74: Formaldehyde emissions from three-wheeler population in megacity Delhi during 1991-2010

5.3.9.4. Taxis

Fig. 5.75 shows the emission of Formaldehyde from taxis in megacity Delhi during 1991 to 2010. It shows that emissions of Formaldehyde from taxi population increases from 6.5 kg in 1991 to about 12.1 kg in 2001. There is sharp decrease (-61%) in emissions between 2001-2002. Phasing out and CNG conversion program by the government of Delhi might be responsible for that. Thereafter emissions again increase until 2010. It is also observed that emission contribution of diesel driven taxis is highest (47-88%) during 1991 to 2004, while it is shifted to CNG driven taxis from 2005 onwards.

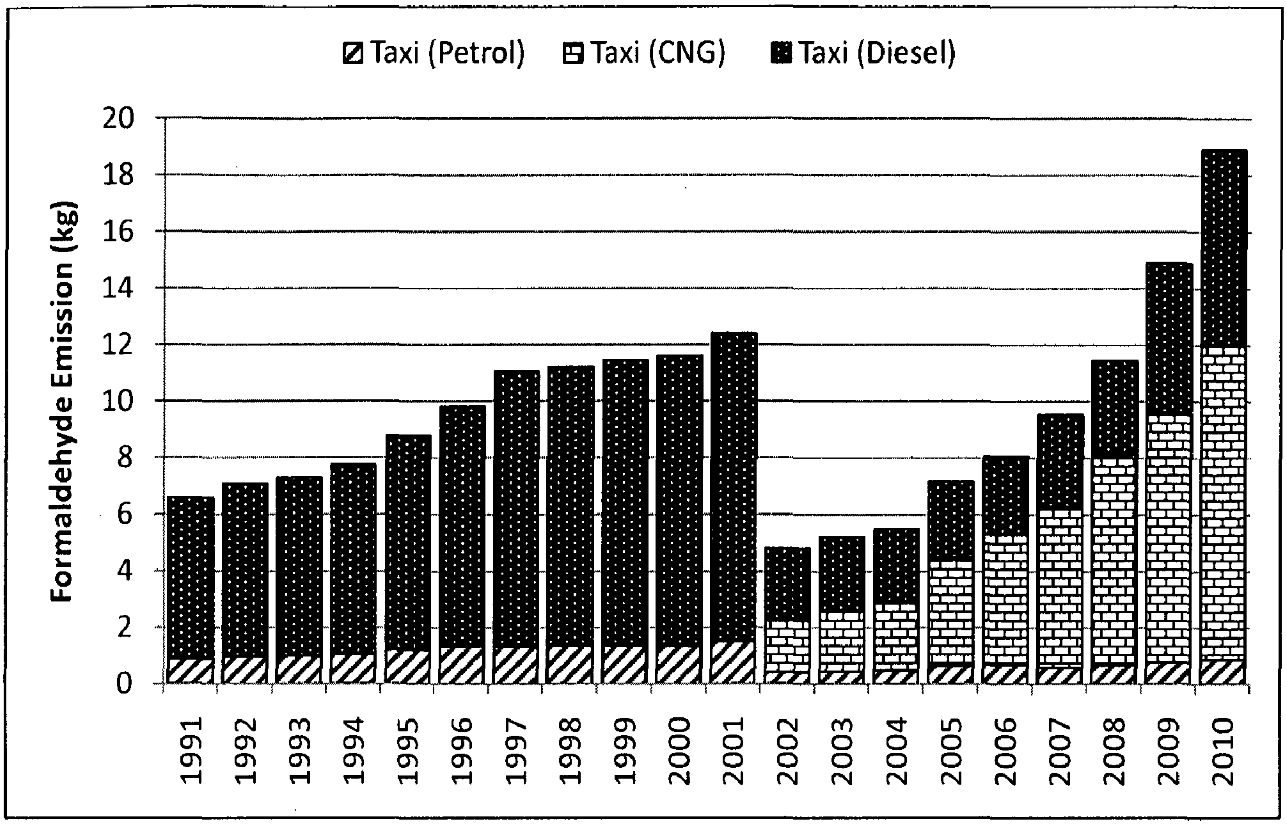


Fig. 5.75: Formaldehyde emissions from taxi population in megacity Delhi during 1991-2010

5.3.9.5. Buses

Fig. 5.76 shows Formaldehyde emissions from buses in megacity Delhi that follow almost similar trend that of taxis during 1991 to 2010. There is clear impact of phasing out of older buses and CNG conversion program in between 2001 and 2002 with sudden decrease in Formaldehyde emission. While sudden increase in Formaldehyde emissions is observed between 2004 and 2005 because of entry of more new buses during this period. During 2005 Formaldehyde emissions from buses are 67 kg followed by 90 kg in 2010. Diesel driven buses play a dominating role for Formaldehyde emissions in megacity Delhi, while contribution of CNG buses is quite less (Fig. 5.76). This might be because of high emission factors for diesel driven buses than CNG driven buses.

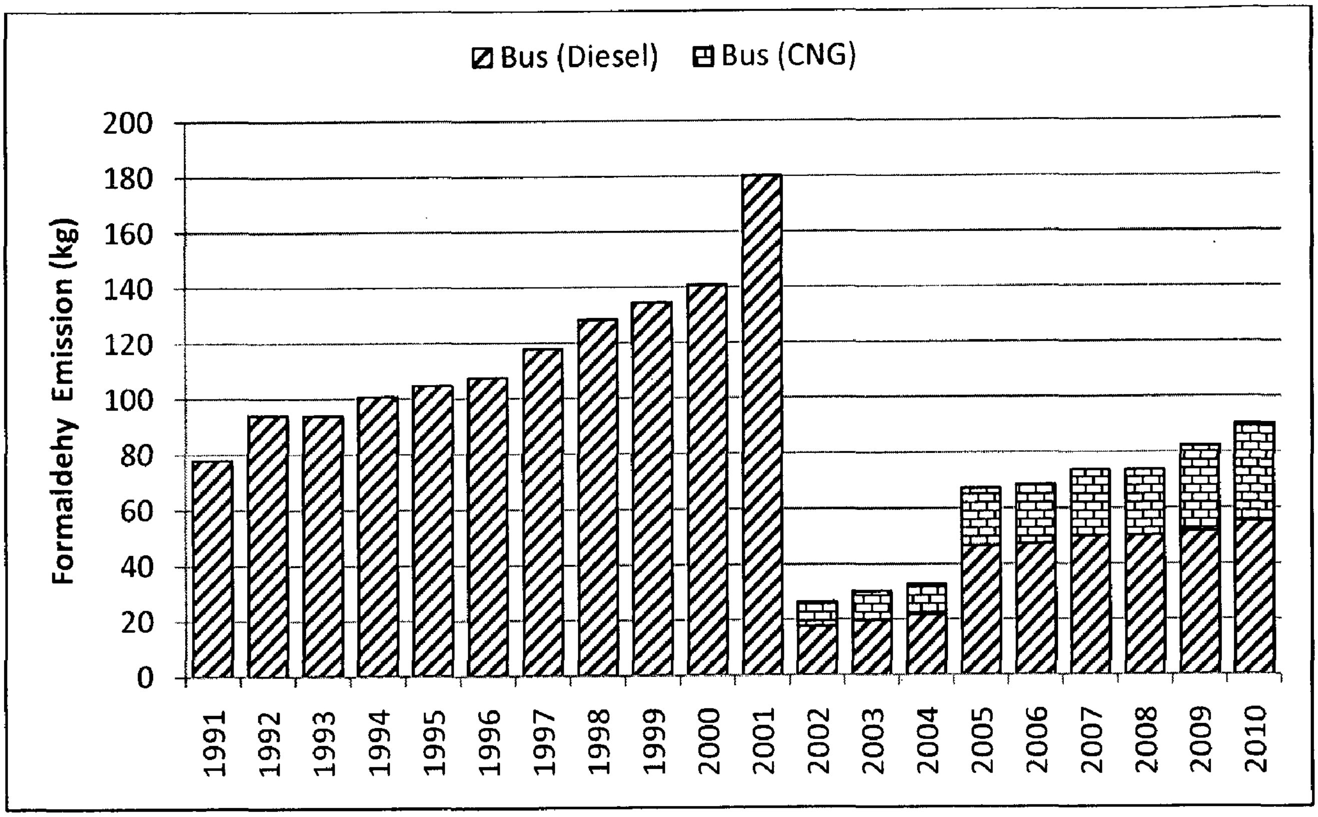


Fig.5.76: Formaldehyde emissions from bus population in megacity Delhi during 1991-2010

5.3.9.6. LCVs

Fig. 5.77 presents annual emission of Formaldehyde from LCVs. It indicates that initially (1991-1999) emission shows an increasing trend, while after 1999 decrease in emission trend is noticed. In 1991 emission of Formaldehyde from LCVs is 317 kg and 400 kg in 1995 followed by 424 kg in 2000. In between 1999-2002 decrease in emission trend is noticed because of phasing out of LCVs in 2001 by Delhi Government. Corresponding to less entry of new LCVs and phasing out of old LCVs, there is sharp decline in emissions during 2001-2002 and 2006-2007. During 2007, for example, all old aged (pre-1991 and 1991) LCVs having more emission factor (0.1975 mg/km) of Formaldehyde than post-2000 model (0.0028 mg/km) were phased out. It is observed that diesel driven LCVs contribute major part to Formaldehyde emissions while contribution of CNG driven LCVs is very less mainly due to substantial difference in their emission factors.

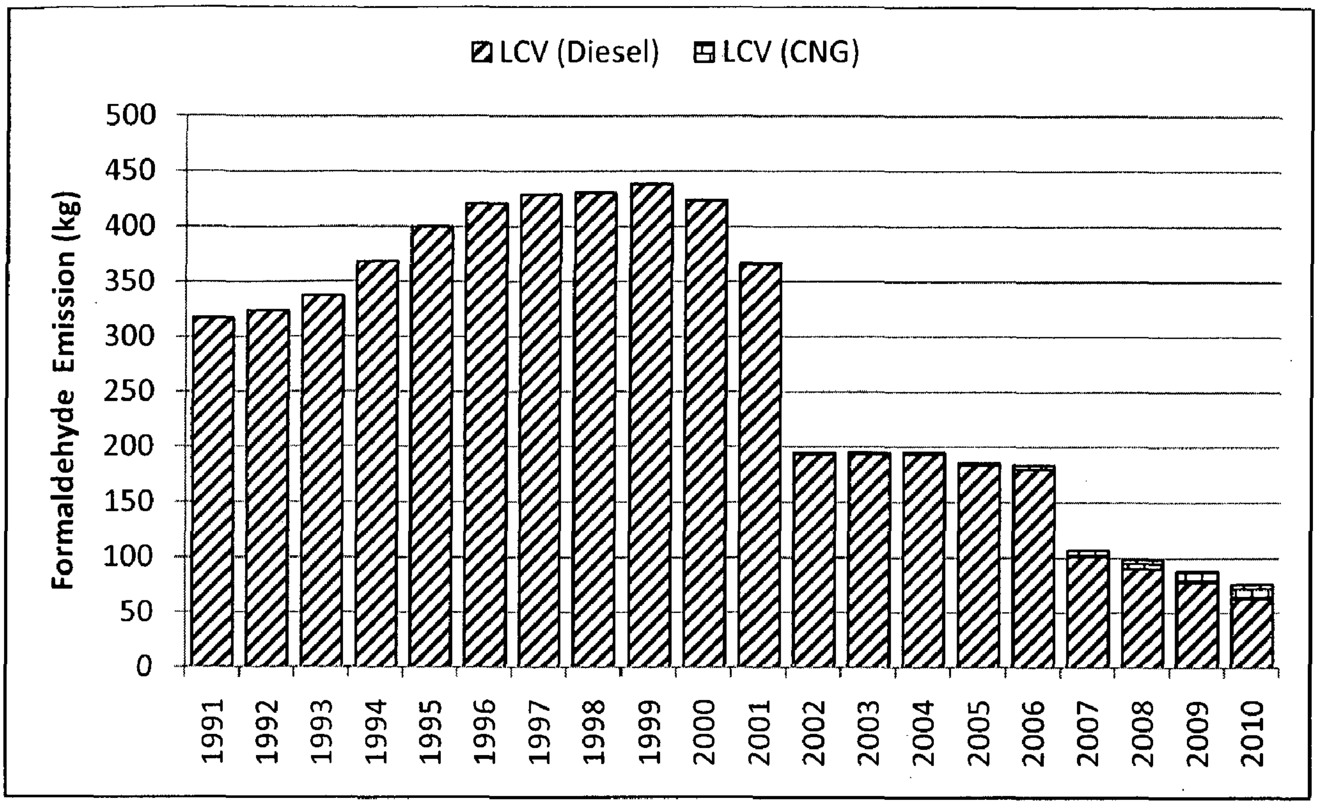


Fig. 5.77: Formaldehyde emissions from LCVs population in megacity Delhi during 1991-2010

5.3.9.7. HCVs

Fig. 5.78 shows emission of Formaldehyde from HCVs in megacity Delhi depicting an increasing trend between 1991-1999 (110 kg to 155 kg) and then decreasing until 2002 (~97 kg) followed by an increasing trend between 2002-2010 (24%). Decrease in emissions corresponds to less entry of new HCVs and more phasing out of old HCVs.

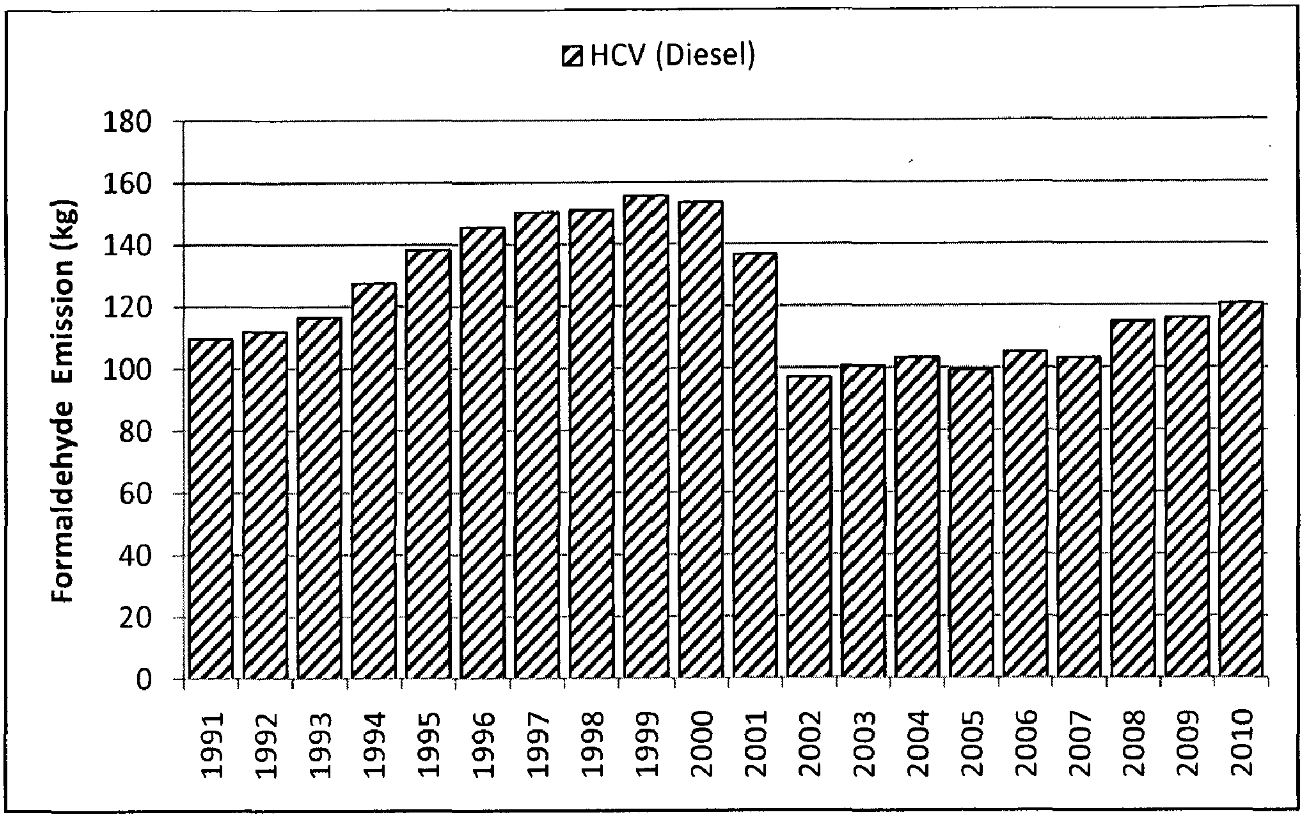


Fig. 5.78: Formaldehyde emissions from HCVs population in megacity Delhi during 1991-2010

5.3.10. Total Aldehyde emissions

Fig. 5.79 shows the emission of total Aldehyde from various vehicle categories in Delhi during 1991 to 2010 that follow almost same trend as discussed in previous section. Similar to other pollutants decrease is observed between 1999 and 2002 corresponding to phasing out of old vehicles. In between 1991-2000 LCVs contributed highest percentage (32-36%), followed by cars and two wheelers. During 2001-2010, however, cars dominate (32-52%) by emitting maximum share of total Aldehyde in megacity Delhi (Fig. 5.79).

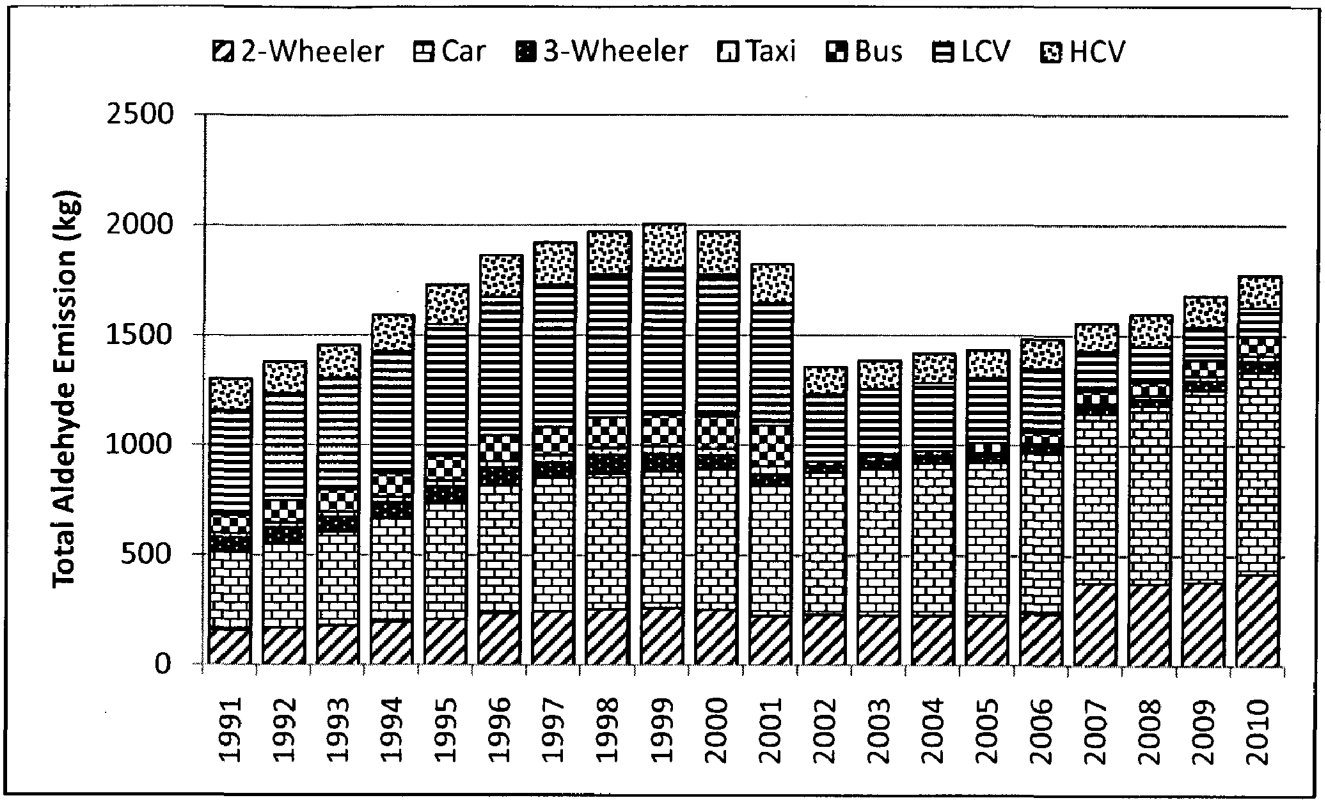


Fig. 5.79: Total Aldehyde emissions from various vehicles in megacity Delhi during 1991-2010

5.3.10.1. Two wheelers

Total Aldehyde emissions from two wheelers in megacity Delhi during 1991 to 2010 are shown in Fig. 5.80. Total Aldehyde emissions first increase between 1991-1999 followed by decreasing trend until 2005, where decline from 1999-2001 is due to phasing out of old age two wheelers during this period. In 2005 emission of total Aldehyde from two wheelers are 230 kg, whereas 420 kg in 2010. Sudden growth in total Aldehyde emissions has been observed during 2006 and 2007 due to high emission factors of some categories of latest technology two wheelers. It is observed that during the whole study period (1991-2010) contribution of two-stroke scooters is highest (47-80%) followed by four-stroke motorcycles and two-stroke moped.

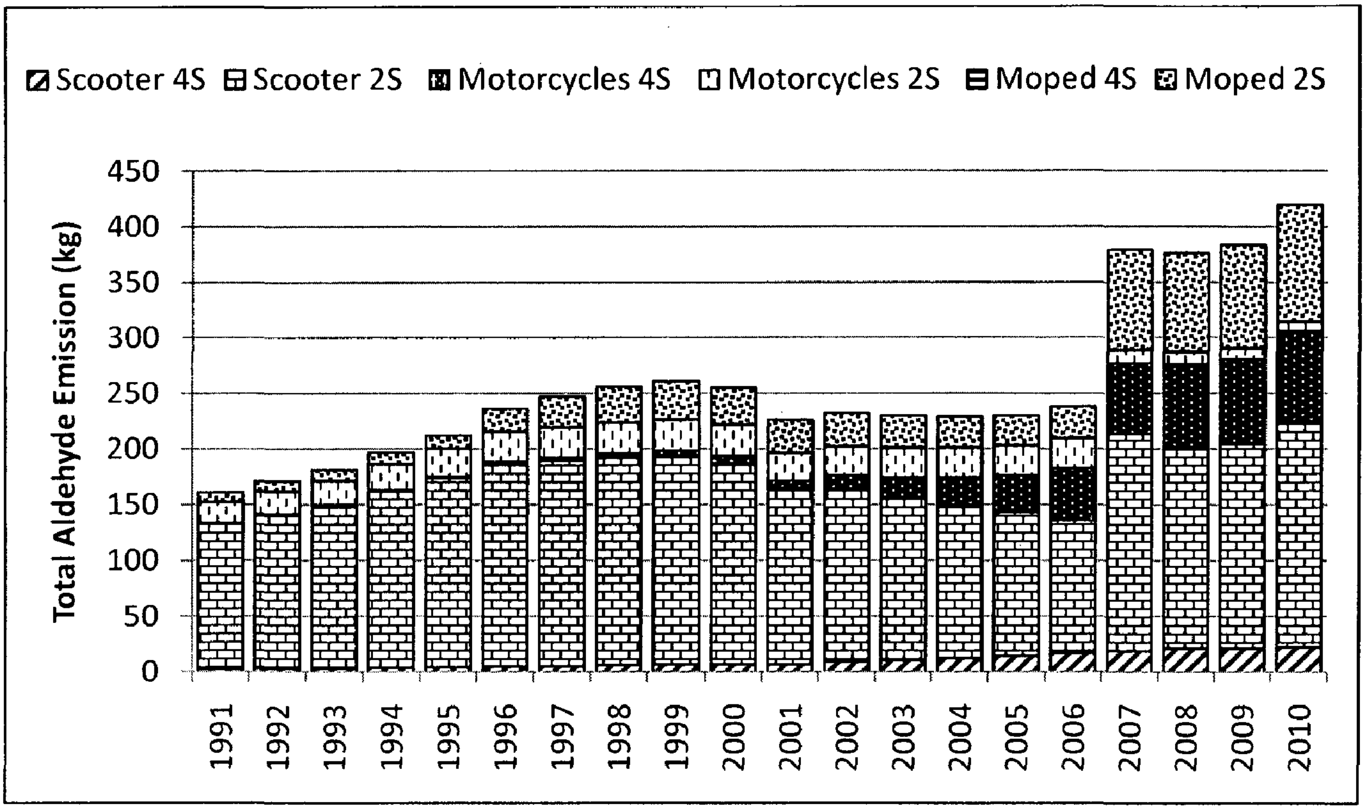


Fig. 5.80: Total Aldehyde emissions from two wheeler population in megacity Delhi during 1991-2010

5.3.10.2. Cars

Total Aldehyde emissions from car population are shown in Fig. 5.81 with an overall increasing trend throughout 1991-2010. It indicates that in 1991 emission of total Aldehyde are 355 kg and 533 kg in 1995, followed by 638 kg in 2000. Similar to other pollutants emissions have decreased between 2000 and 2001 (~7%). After 2001 emissions show a positive growth rate until 2010. Total Aldehyde emissions are estimated to be 695 kg in 2005, while 916 kg in 2010. Among all categories of cars, petrol driven cars contributed highest percentage (67-84%) of total aldehyde, followed by diesel driven cars (15-32%) while contribution of CNG driven cars is very less.

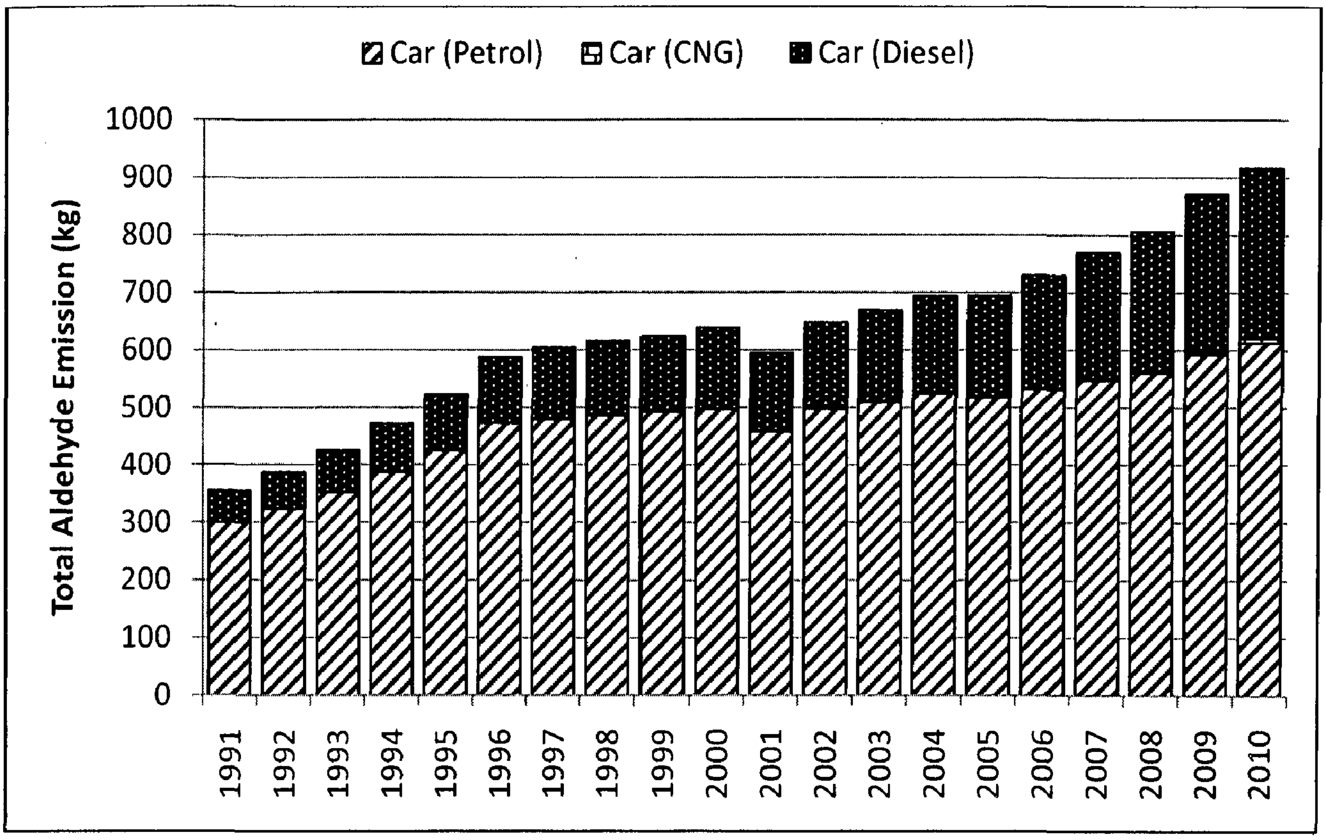


Fig. 5.81: Total Aldehyde emissions from car population in megacity Delhi during 1991-2010

5.3.10.3. Three Wheelers

According to Fig. 5.82 emission of total Aldehyde from three wheelers are 65 kg in 1991 and 79 kg in 1995, followed by 60 kg in 2000. Because of yearly variations in total number of three-wheelers due to less entry of new three wheelers and more phasing out of old modeled three wheelers occasional decrease in total Aldehyde emissions in the years 1993, 1996, 1997 and 1999. Furthermore, shifting of three wheelers from petrol to CNG caused sharp decline in emissions in 2000 and subsequent years of 2001 and 2002. Thereafter, however, increasing number of CNG driven three-wheelers caused increasing trend in emissions. Total Aldehyde emissions from three wheelers were 29 kg in 2005 and 49 kg in 2010. Before the implementation of CNG norms, share of petrol driven two-stroke three wheelers was higher than four-stroke three wheelers while after implementation of CNG in 2000-2001 the CNG driven three wheelers became responsible for most of the total Aldehyde emissions.

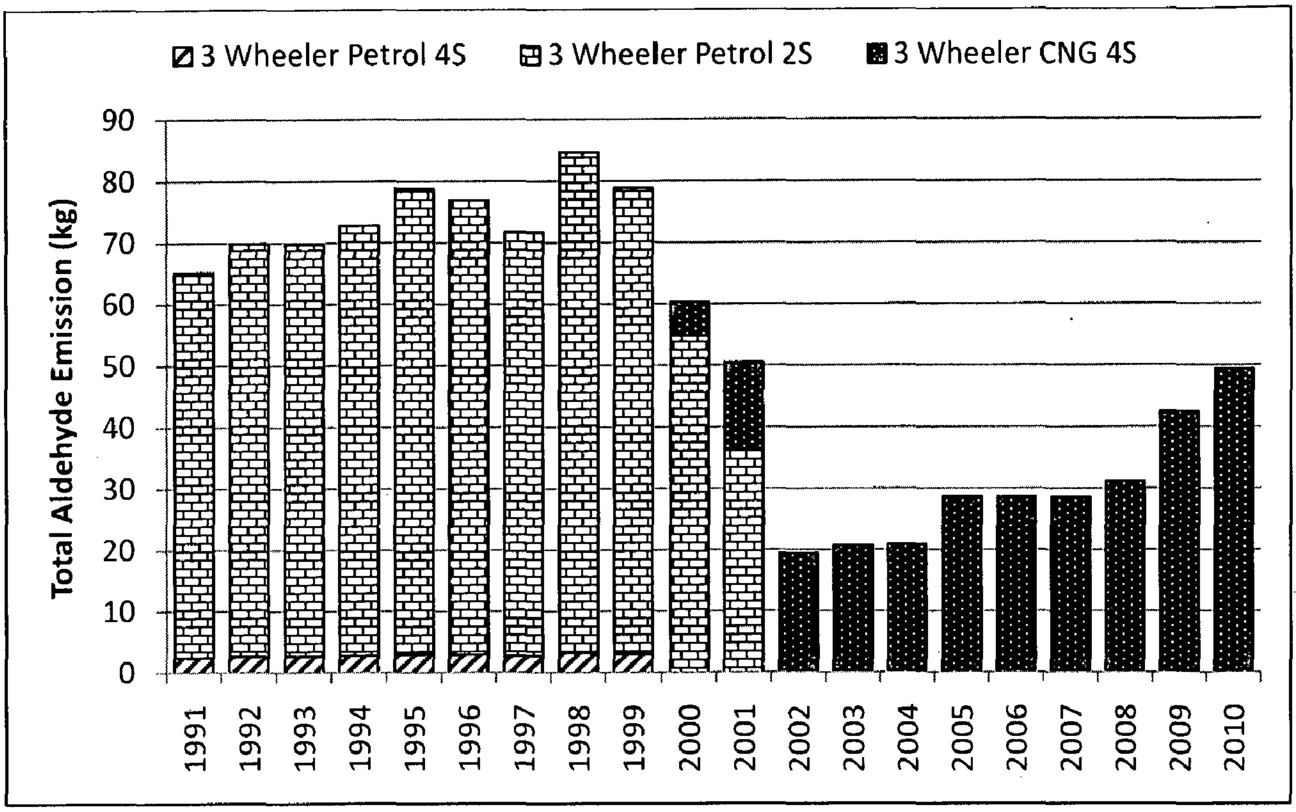


Fig. 5.82: Total Aldehyde emissions from three wheeler population in megacity Delhi during 1991-2010

5.3.10.3. Taxis

Total Aldehyde emissions from taxis are given in Fig. 5.83. Total Aldehyde emissions from taxis are 20 kg in 1991, followed by 26 kg in 1995 and 35 kg in 2000. During 1991-2001, emissions showed an increasing trend, while sharp decline of about ~72% is observed during year 2002 because of phasing out of old taxis and CNG conversion programs by the Government of Delhi. Decline of about ~2% is observed in year 2007, which might be due to phasing out of pre-1991 and 1991 model taxis and less entry of new taxis in 2007. After 2007, emissions again show a positive growth rate till 2010 (25 kg). Diesel driven taxis are responsible for most of total Aldehyde emission before 2006, while CNG driven taxis emerge as a major contributor from 2007 onwards.

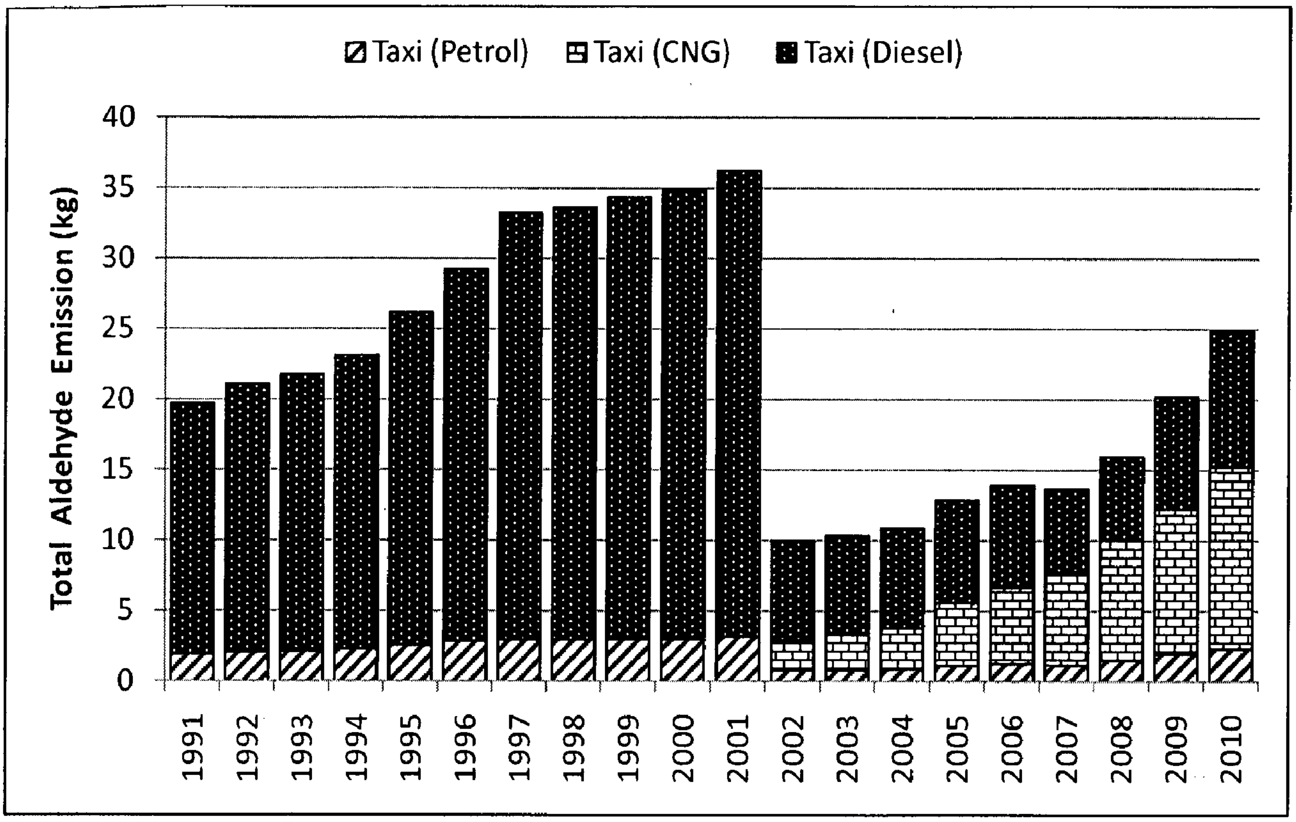


Fig. 5.83: Total Aldehyde emissions from taxi population in megacity Delhi during 1991-2010

5.3.10.5. Buses, LCVs and HCVs

Due to unavailability of emission factors, total Aldehyde emissions are not calculated for CNG driven buses, LCVs and HCVs. Fig. 5.84-5.86 presents the emissions of total Aldehyde from diesel driven buses, LCVs and HCVs, respectively. Total Aldehyde emissions from buses are 85 kg in 1991, 114 kg in 1995 and 146 kg in 2000. Major decline (90%) is observed between 2001 and 2002 due to CNG conversion and phasing out program by the government of Delhi. From 2003 onwards emissions slowly increase, while in 2005 major increase is observed in total Aldehyde emissions because of entry of major number of buses in this year. Again major rise is observed between 2008 and 2009 due to high population and emission factors for new technology buses (ARAI, 2007). In 2005 emission of total Aldehyde from buses are 48 kg followed by 91 kg in 2010.

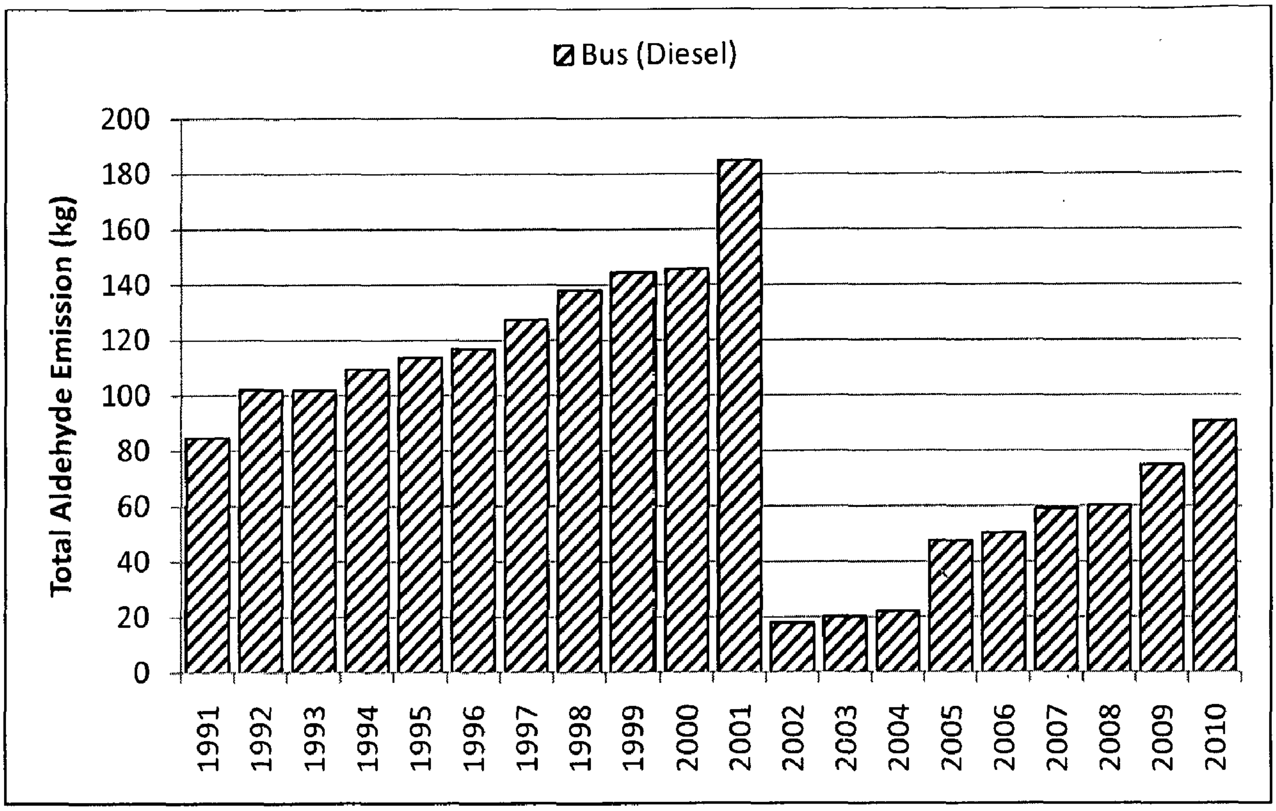


Fig. 5.84: Total Aldehyde emissions from diesel bus population in megacity Delhi during 1991-2010

As visible in Fig. 5.85, emissions of total Aldehyde from LCVs population increase during 1991-1999 followed by a decreasing trend until 2010. Emissions are 475 kg in 1991, 599 kg in 1995, 641 kg in 2000, 294 kg in 2005 and 125 kg during 2010. Most of the decrease is due to phasing out of LCVs and entry of new LCVs, while changed emission factors according to the vehicle model year are also responsible for a minor decline.

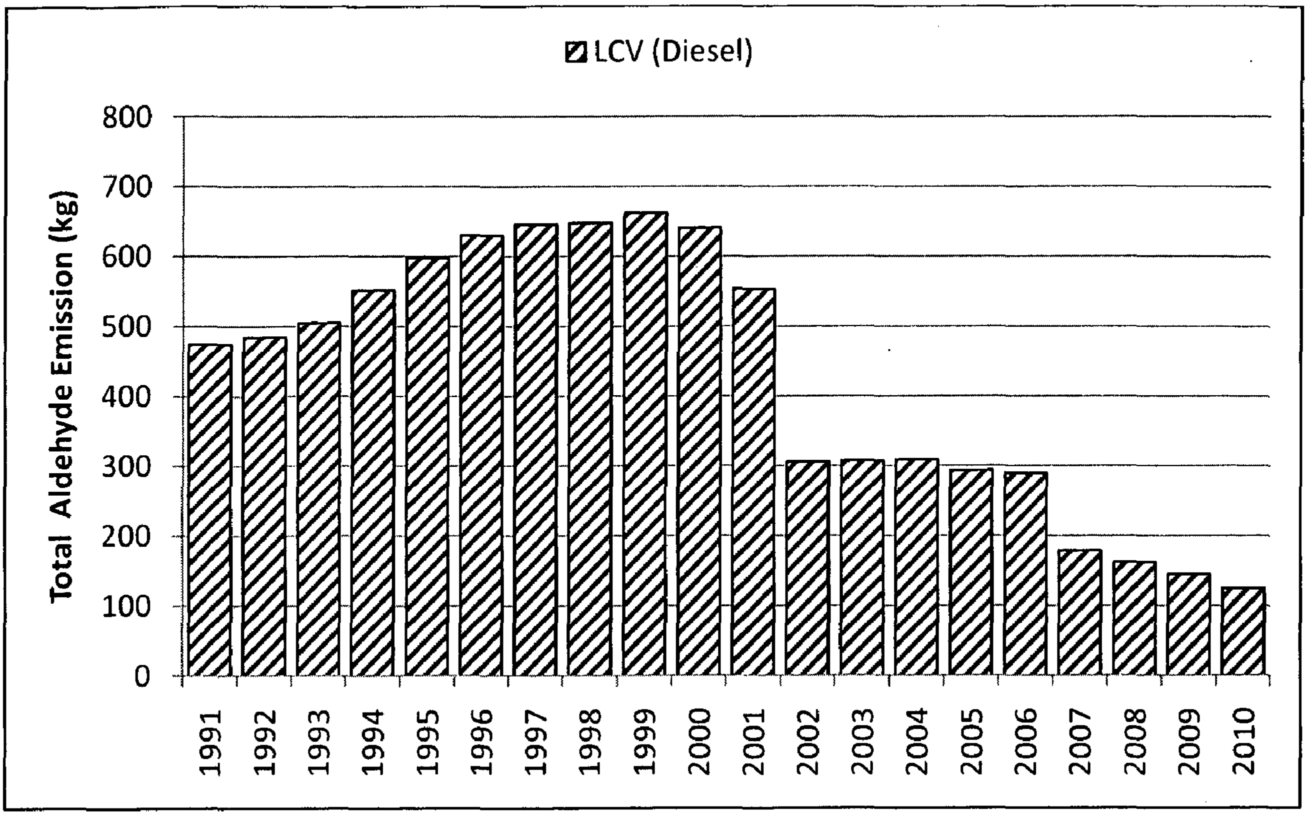


Fig. 5.85: Total Aldehyde emissions from diesel LCVs population in megacity Delhi during 1991-2010

Total Aldehyde emissions from HCVs population are 142 kg in 1991, 200 kg in 1995, followed by 178 kg in 2000 (Fig. 5.86). During the study years (2000-2002, 2005 and 2007) decline is observed in total Aldehyde emissions from HCVs. The reason behind these trends are phasing out of old age HCVs and change in emission factors according to change in technology. In 2005 emission of total Aldehyde from HCVs are 126 kg and 148 kg in 2010.

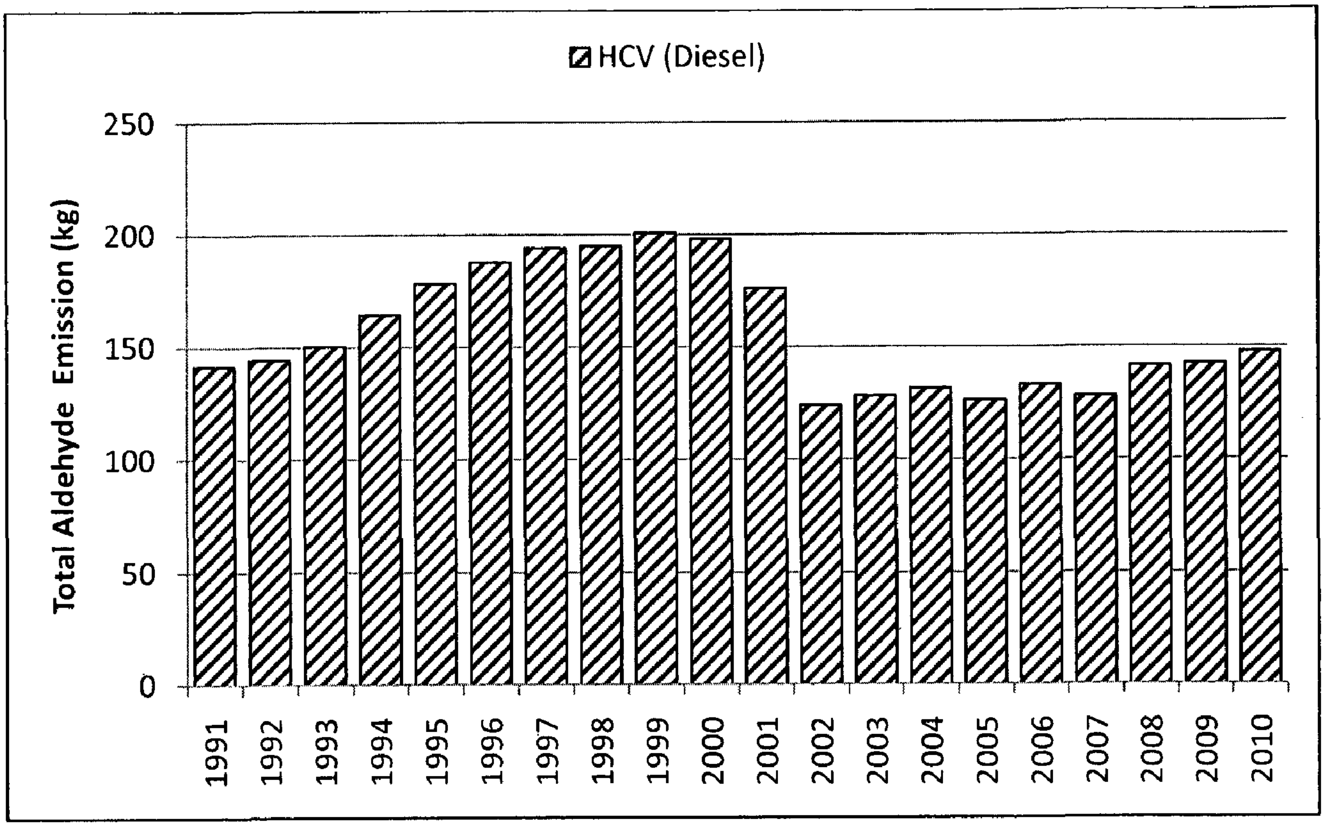


Fig. 5.86: Total Aldehyde emissions from diesel HCVs population in megacity Delhi during 1991-2010

5.3.11. Total PAH emissions

Fig. 5.87 shows that emission trend of PAHs follow an increasing trend, with slight fluctuations during the study period. Initially, emissions of total PAH from various vehicles are 31 Mg during 1991, 40 Mg in 1995 and 45 Mg in 2000. About 7% and 30% decrease is observed between 2000-2001 and 2001-2002 respectively, due to phasing out of old age vehicles. Emissions of total PAH from vehicles in megacity Delhi are estimated to be 33 Mg in 2005 and 39 Mg in 2010. It is observed that initially from 1991 to 2001 LCVs contributed (36- 42%) highest total PAH among all vehicle categories, while from 2002 onwards contribution of two wheelers dominated (37- 42%).

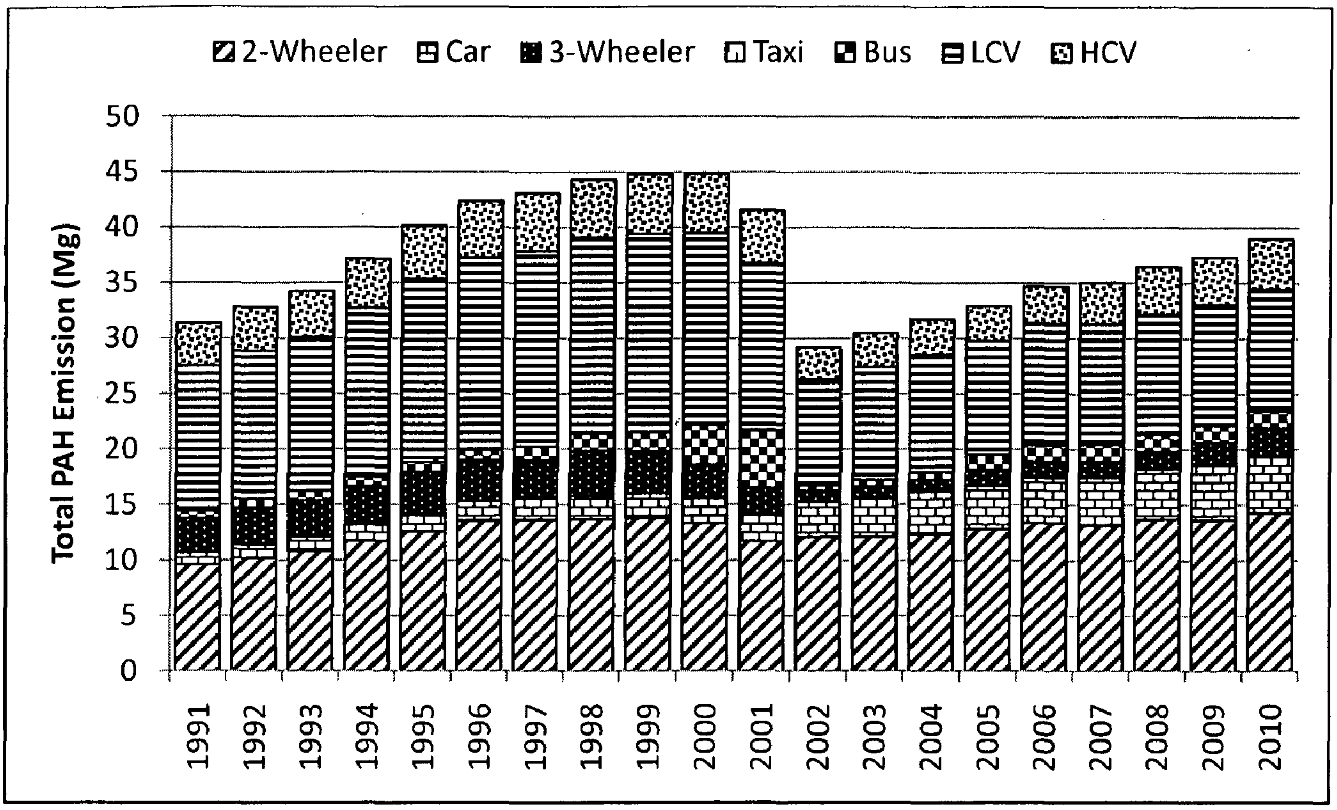


Fig. 5.87: Total PAH emissions from various vehicles population in megacity Delhi during 1991-2010

5.3.11.1. Two Wheelers

Total PAH emissions from two wheelers are presented in Fig. 5.88. Total PAH emissions from two wheelers are 9628 kg in 1991, followed by 12635 kg in 1995 and 13348 kg in 2000. There is decrease in emissions during 1999 to 2001 and 2006 to 2007. Total PAH emissions from two wheelers are 12841 kg in 2005 and 14289 kg in 2010. From 1991 to 2007 contribution of two-stroke scooters is highest while from 2008 the four-stroke motorcycle is responsible for higher total PAH emission. Two-stroke mopeds also emerge as major source of total PAH emissions from 2007 onwards.

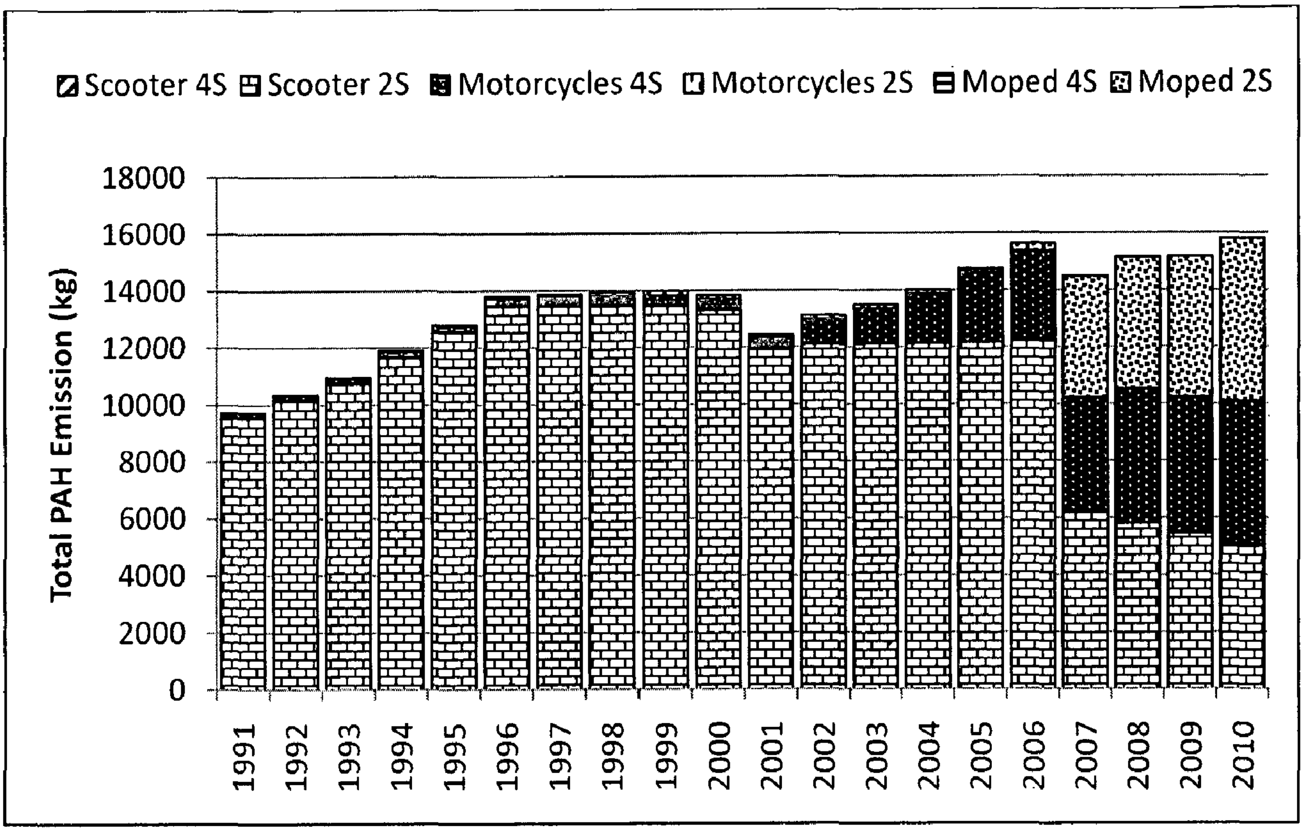


Fig. 5.88: Total PAH emissions from two wheelers population in megacity Delhi during 1991-2010

5.3.11.2. Cars

Emissions of total PAH from car population are shown in Fig. 5.89 with an overall increasing trend from 1991-2010. Total PAH emissions from cars are 1107 kg in 1991, followed by 1590 kg in 1995 and 2351 kg in 2000. A slight decline of about 1.3% has been observed between 2000 and 2001 but there is sharp increase between 2001-2002 due to increase in car population (29%) and higher emission for 2002 model car (Table 3.2). Emissions of total PAH from car population are estimated to be 3912 kg in 2005 and 5223 kg in 2010. It is observed that share of petrol driven car for total PAH is highest throughout the study period among all types of cars.

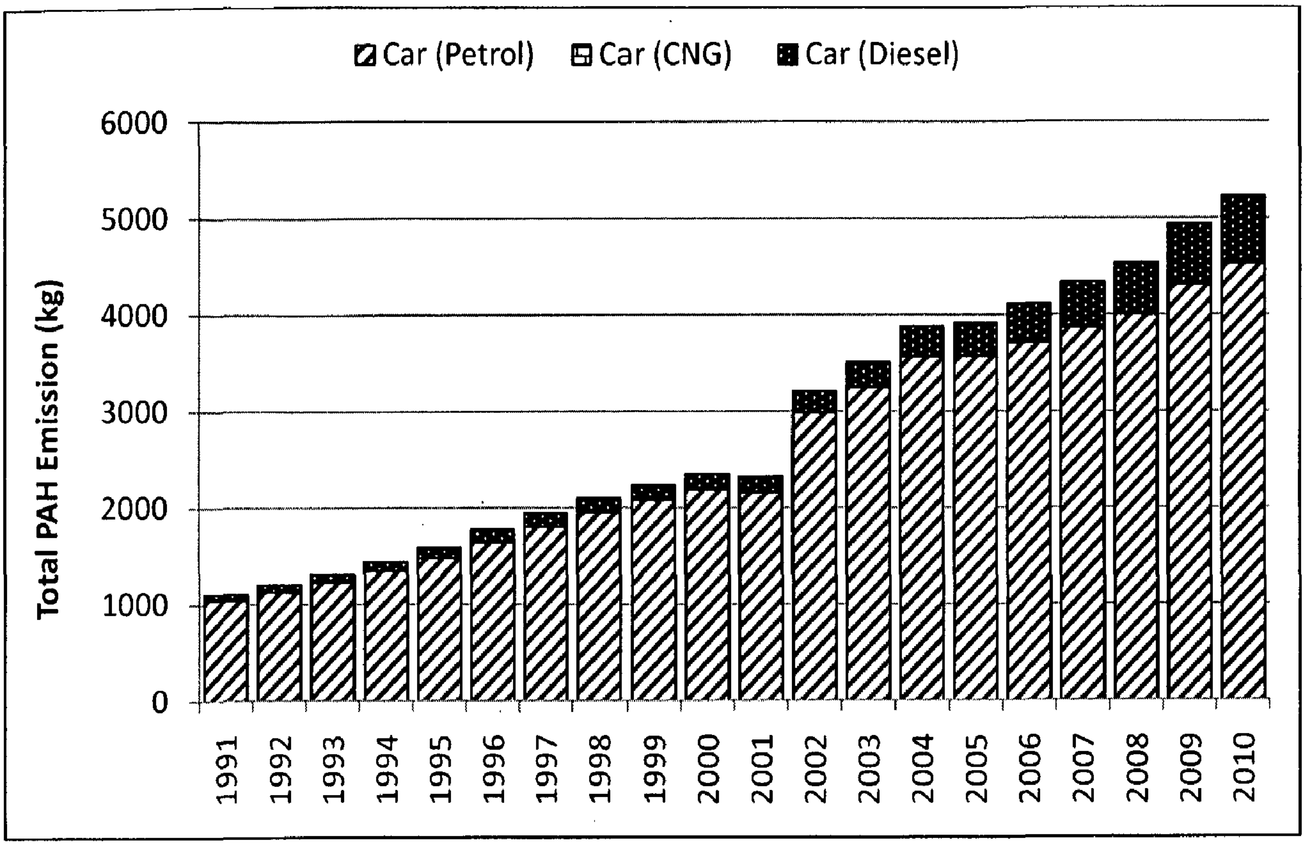


Fig. 5.89: Total PAH emissions from car population in megacity Delhi during 1991-2010

5.3.11.3. Three Wheelers

Fig. 5.90 shows the total PAH emissions from three wheelers in megacity Delhi during 1991 to 2010. It suggests that total PAH emissions from three wheelers in Delhi during 1991 are 3054 kg, followed by 3692 kg in 1995 and 2881 kg in 2000. Decrease is observed in PAH emissions during 1996-1997, and during1998 to 2002. Phasing out, less entry of new three wheelers, and variation in emission factors of CNG driven three wheelers are found to be the responsible reasons for all these decreasing trends but constantly increasing number of there-wheelers population cause increasing trend in emissions from 2003 onwards. Emissions of PAH from three wheelers are observed to be 1363 kg in 2005 and 2343 kg in 2010. Initially from 1991 to 2001 petrol driven two-stroke three wheelers dominate for total PAH emissions, while from 2002 CNG driven four-stroke three wheelers are responsible for 100% emissions of three wheelers.

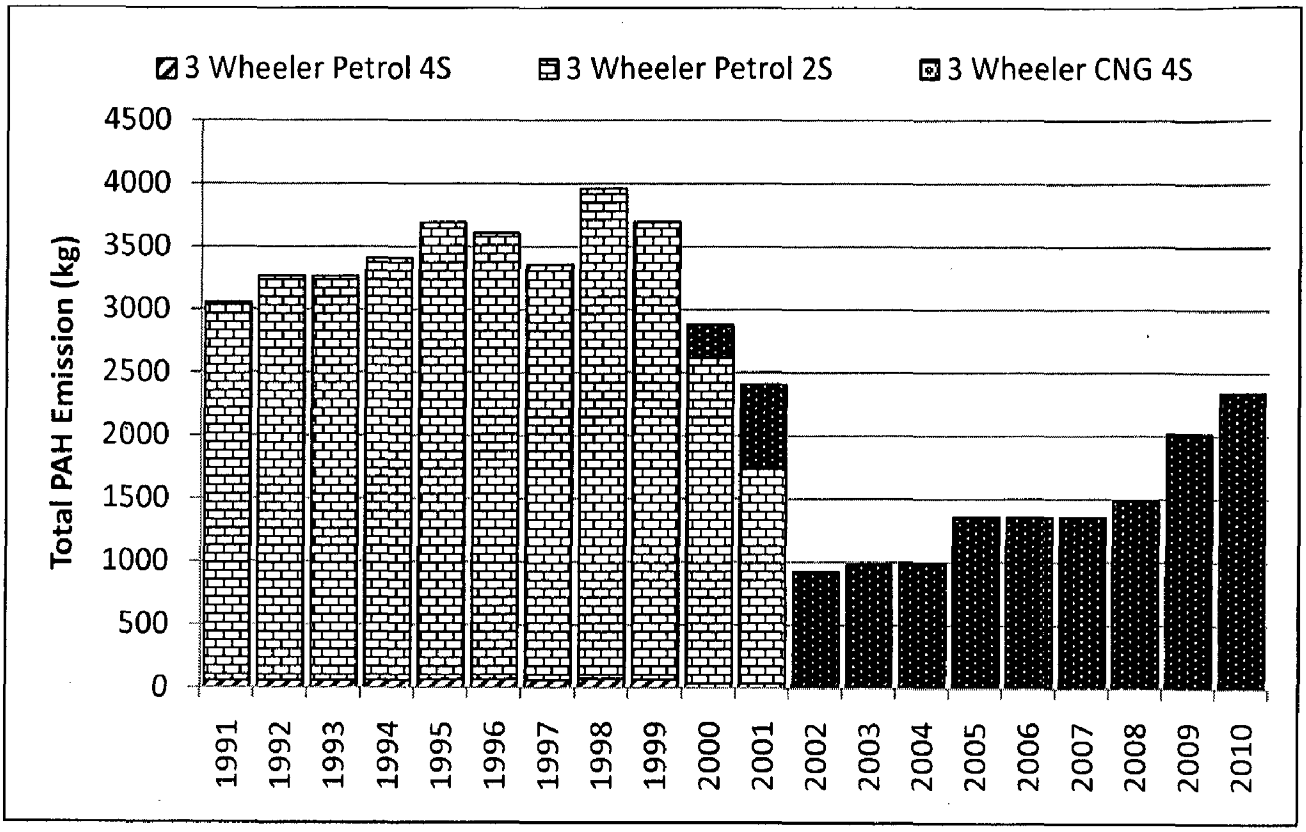


Fig. 5.90: Total PAH emissions from three wheeler population in megacity Delhi during 1991-2010

5.3.11.4. Taxis

Total PAH emissions from taxis in megacity Delhi are shown in Fig. 5.91, which shows that there is overall increase in emissions between 1991-2010 except a sudden drop (56%) between 2001-2002 corresponding to CNG conversion program. Emissions of total PAH are 27 kg in 1991 and 36 kg in 1995, followed by 48 kg in 2000. Total PAH emissions in 2005 are estimated to be 40 kg in 2005 and 87 kg in 2010. For total PAH emissions initially diesel driven taxis have played a major role from 1991-2003 while after 2004 petrol driven taxis show their dominance along with increasing share of CNG driven taxis.

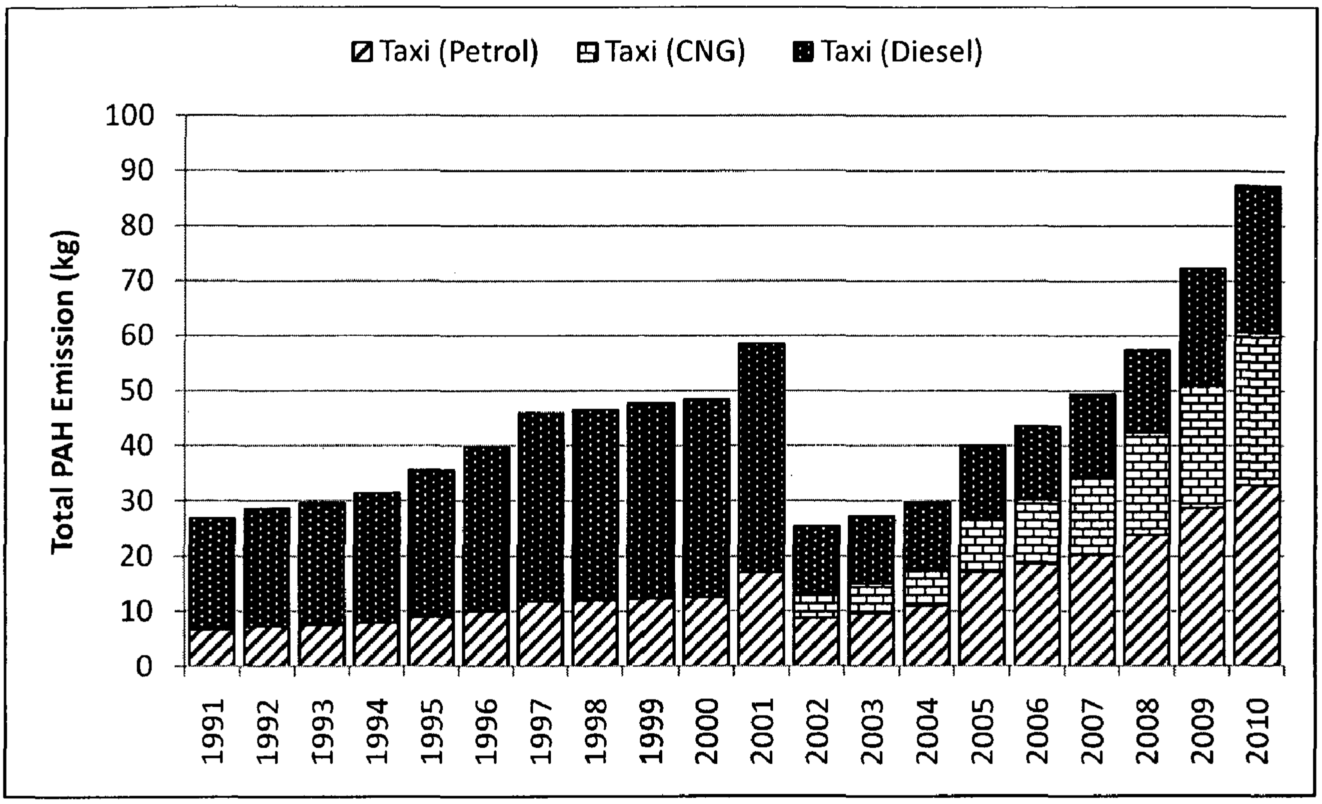


Fig. 5.91: Total PAH emissions from taxis population in megacity Delhi during 1991-2010

5.3.11.5. Buses, LCVs and HCVs

Due to unavailability of emission factors for CNG driven buses, LCVs and HCVs; emissions are calculated for diesel driven buses, LCVs and HCVs only. Total PAH emission from diesel driven buses, LCVs and HCVs are given in Fig. 5.92-5.94. In 1991 emissions of total PAH from diesel buses are 681 kg and 914 kg in 1995, followed by 3598 kg in 2000. From 1997 to 2001 sudden increase in emissions is observed due to high emission factors for 1997 to 2001 model buses. Nevertheless, there is sharp decline between 2001 and 2002 because of phasing out and CNG conversion program by the Government of Delhi. There is also sudden increase in emissions between 2004 and 2005 because of increased number of buses on road due to entry of new buses. PAH emissions from diesel buses are 1528 kg in 2005 and 2104 kg in 2010.

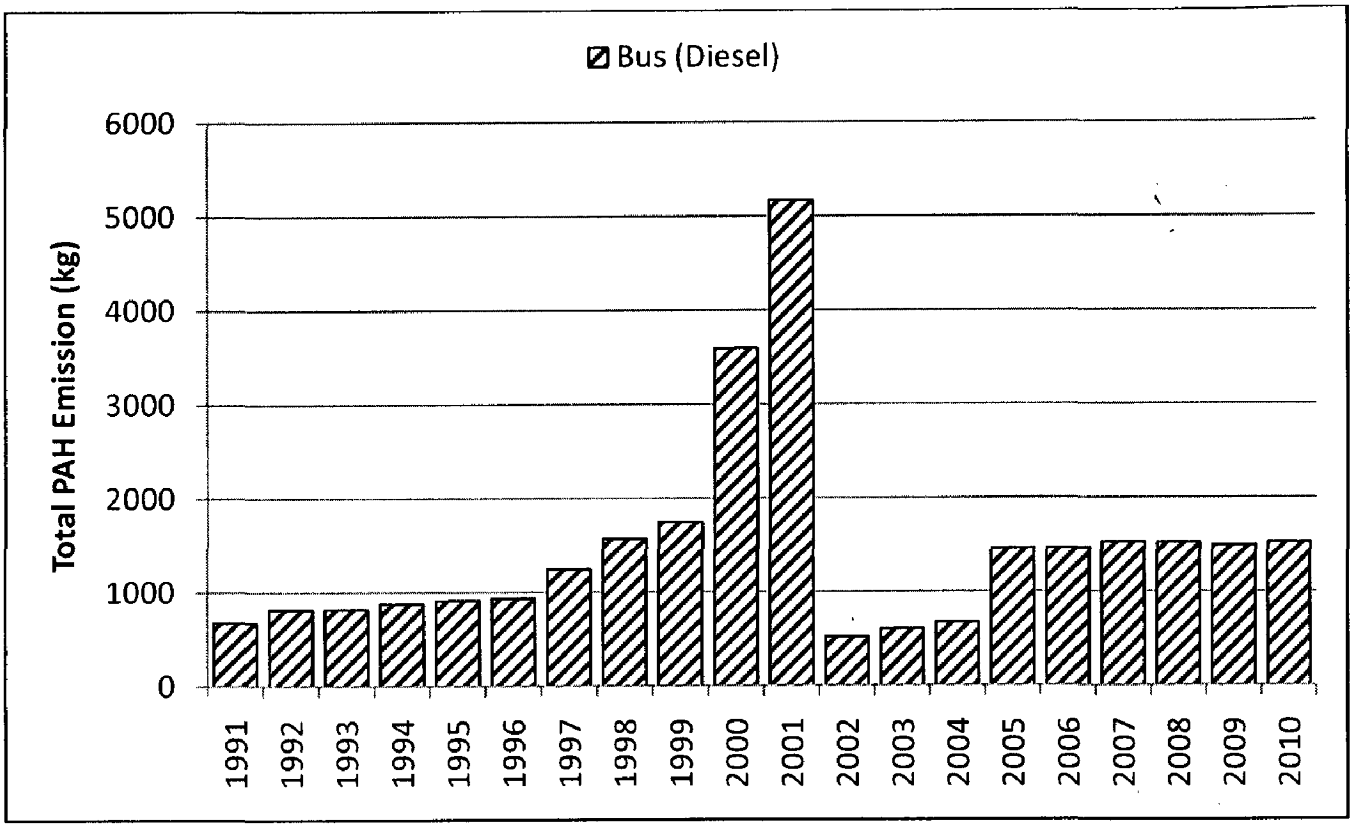


Fig. 5.92: Total PAH emissions from bus population in megacity Delhi during 1991-2010

Emissions of total PAH from LCVs are presented in Fig. 5.93. It shows that in 1991 emission of PAH from LCVs is 13 Mg, 16 Mg in 1995 and 17.26 Mg in 2000. Few negative trends have been observed during 1999-2002 and 2004-2005 because of phasing out of old technology LCVs. In 2005 emission of total PAH from LCVs are estimated to be 10 Mg and 12 Mg in 2010.

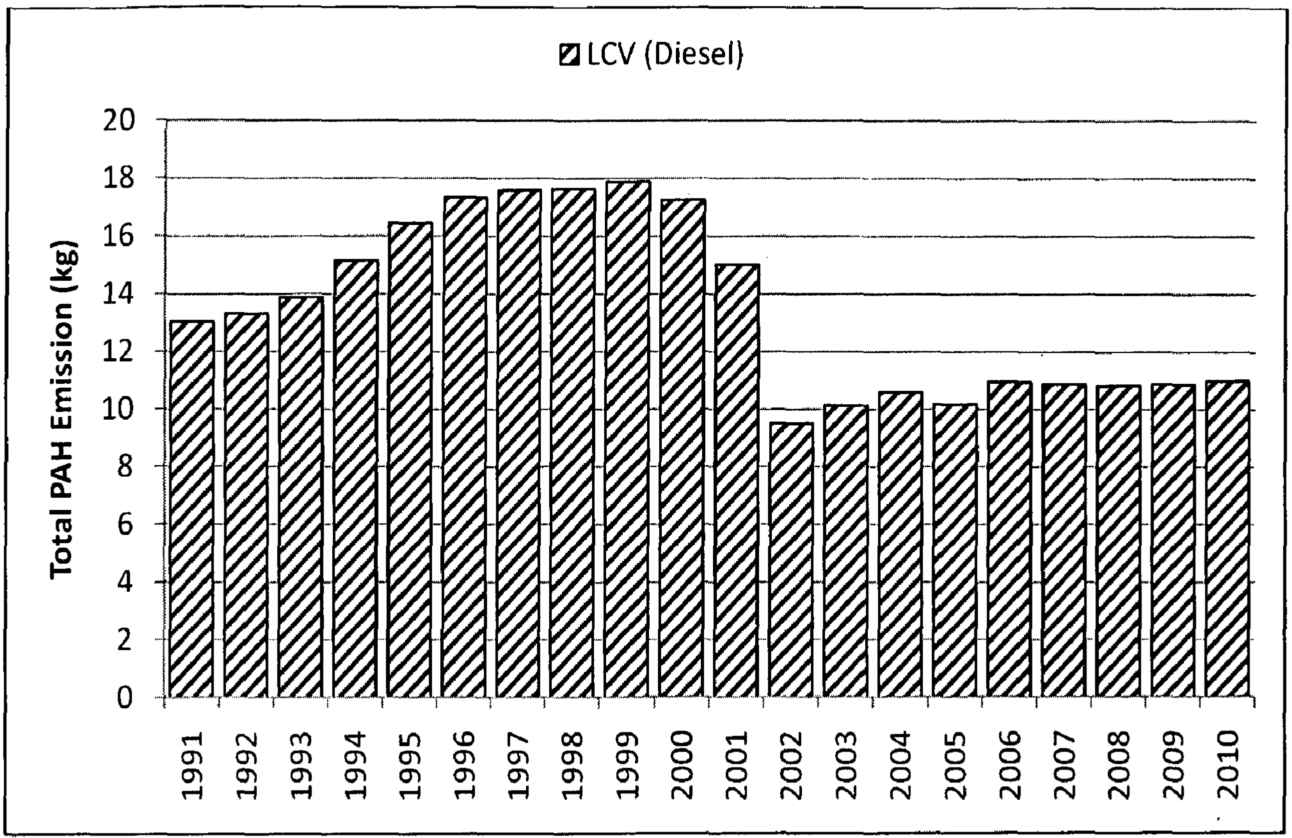


Fig. 5.93: Total PAH emissions from LCVs population in megacity Delhi during 1991-2010

Fig. 5.94 shows the emission of total PAH from HCVs in megacity Delhi during 1991 to 2010. It is observed that emissions of total PAH from HCVs are 3826 kg in 1991 and 4823 kg in 1995, followed by 5355 kg in 2000. Similar to LCVs negative trend is observed during 2000-2002 and 2004-2005 because of phasing out of old age HCVs and less entry of new HCVs. Total PAH emissions from HCVs are estimated to be 3090 kg in 2005 and 4592 kg in 2010.

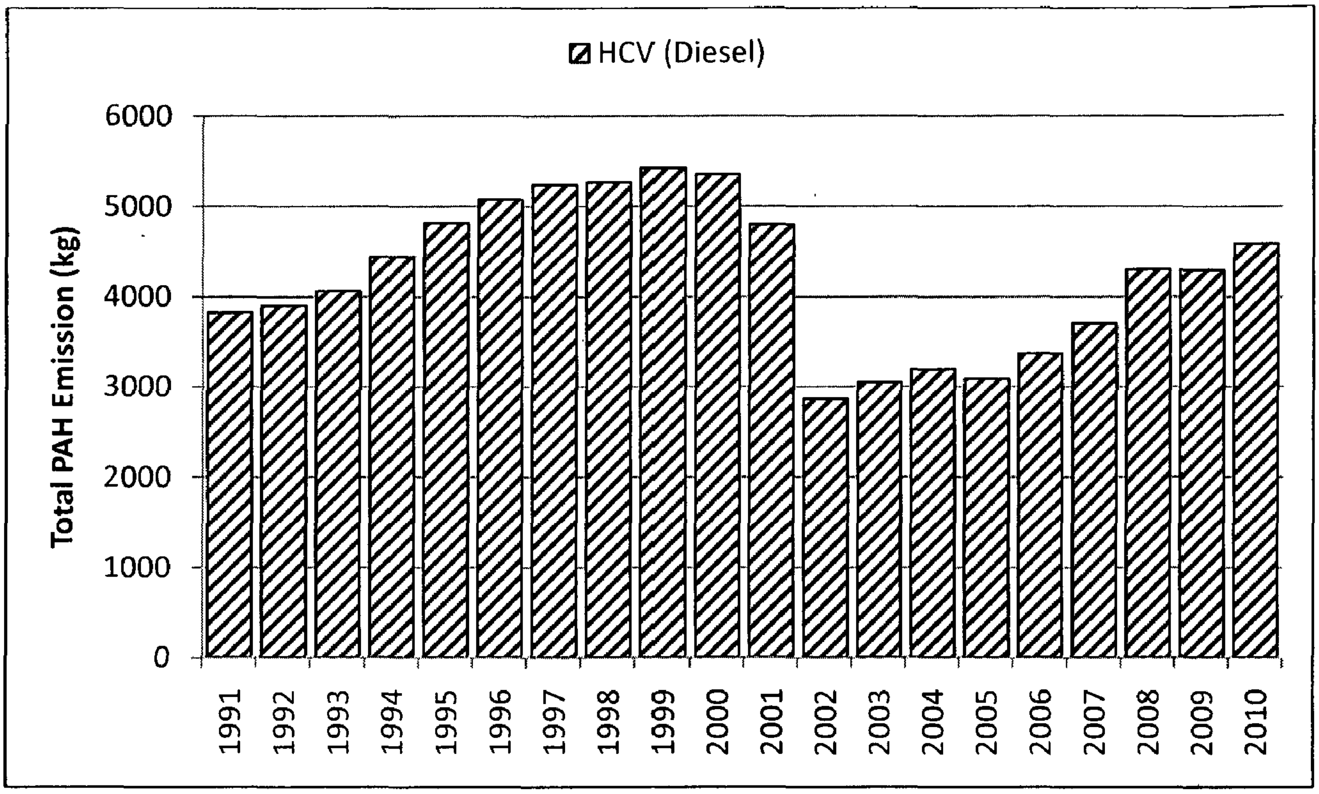


Fig. 5.94: Total PAH emissions from HCVs population in megacity Delhi during 1991-2010

5.4. EVALUATION AND VALIDATION OF MODEL RESULTS

In this section evaluation and validation of VAPI model results have been carried out. For this purpose, both qualitative (e.g., trend analysis of emissions and ambient air concentrations) and quantitative (e.g., computation of correlation coefficient) techniques have been used. According to Gurjar et al. (2004) transport sector is responsible for 80% of CO and NO_x emissions in megacity Delhi. Therefore, CO and NO_x can be considered as good indicator pollutants that can represent degree of air pollution emitted by road transport sector. Keeping this concern and data availability in mind, evaluation and validation of VAPI model has been done by comparing the estimated emissions of CO and NO_x with their ambient air concentrations in megacity Delhi. Ambient air concentrations of CO and NO_x observed at air quality monitoring stations managed by Central Pollution Control Board (CPCB) have been used for this purpose.

5.4.1. Comparison of estimated emissions and observed ambient air concentrations of NO_x

NO_x concentration data is available for six monitoring stations of Central Pollution Control Board (CPCB) and three of National Environmental Engineering Institute (NEERI) in Delhi (CPCB, 2010), which cover and collectively represent entire megacity Delhi. During analysis and evaluation exercise, a few anomalies were found in concentration data of three monitoring stations namely, Najafgarh Road, Netaji Nagar and Town hall. According to Saksena et al. (2003) the biasness in the data of mentioned stations are due to problem with monitoring stations, hence we have removed biased data of the above mentioned three monitoring stations. Average of all monitoring stations (except biased data of Najafgarh Road, Netaji Nagar and Town hall) concentration data have been taken for comparison and evaluation/validation of NO_x emissions from vehicles in megacity Delhi (Fig. 5.95-5.99).

Fig. 5.95a and b show the concentration and emission trends of NO_x from two wheelers and car population in megacity Delhi. As it can be seen in Fig. 5.95a, emission of NO_x from 1991 to 2000 increases and also its ambient air concentration follows a rising trend during the same period. During 1991-2000, about 10% average growth in NO_x emissions is observed whereas about 5% growth in their concentration is noticed. After 2002, NO_x emission from two wheelers and concentration in megacity Delhi are following rising trend until 2009.

As visible in Fig. 5.95b, emissions and concentration of NO_x from car population follow similar trends in megacity Delhi. From 1991 to 2000 emission of NO_x increases with 7.6% average growth rate, whereas concentration increases with 5%. From 2001 to 2009 emission trend of NO_x from car population increases with 2.3% growth rate and concentration increases with 3% growth rate.

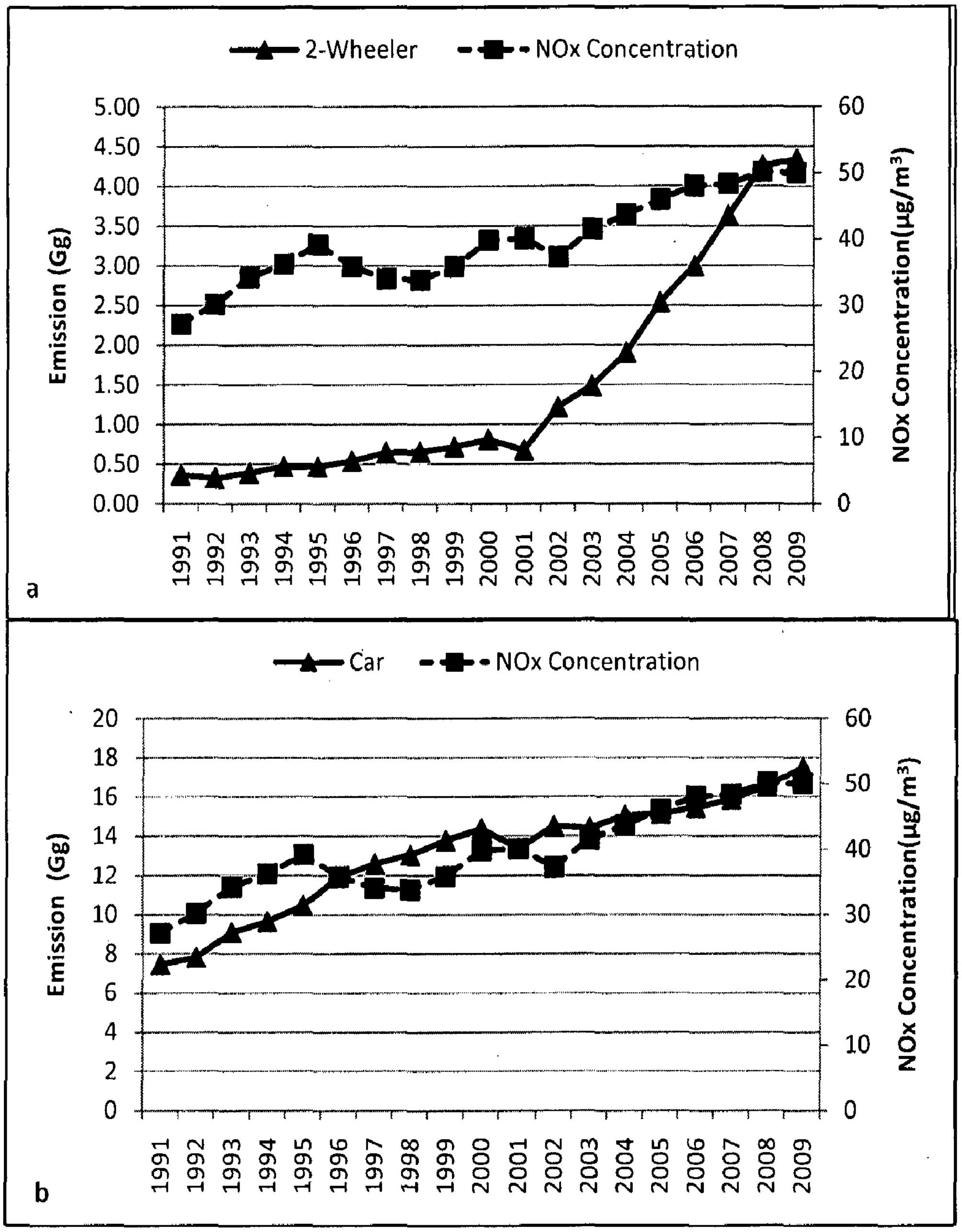


Fig. 5.95: NO_X concentration versus emission of NO_X from (a) two wheelers and (b) cars in megacity Delhi

Fig. 5.96a and b show the emissions of NO_X from three-wheelers and taxis and ambient air concentration of NO_X in megacity Delhi. Emissions of both three-wheelers and taxis are rising from 1991 to 2000. From 1991 to 2009 the average growth rate of NO_X emissions from three-wheelers and taxis are 9% and 7% respectively and concentration increases with 5%. During 1991-2009, except a few minor variations associated with some particular years (e.g., 1995) overall trend of NO_X emissions from both three wheelers and taxis has much similarity with that of NO_X concentrations in ambient air of megacity Delhi. This may be noted that here the emission estimates correspond only to road transport sector whereas ambient air concentration values of NO_x are a product of emissions from all sectors and liable to greatly influenced by meteorological parameters. Given that this is highly unlikely that emissions and concentrations trends will follow exactly similar pattern. However, an overall similar trend between two indicates that model estimations might be representing actual emissions.

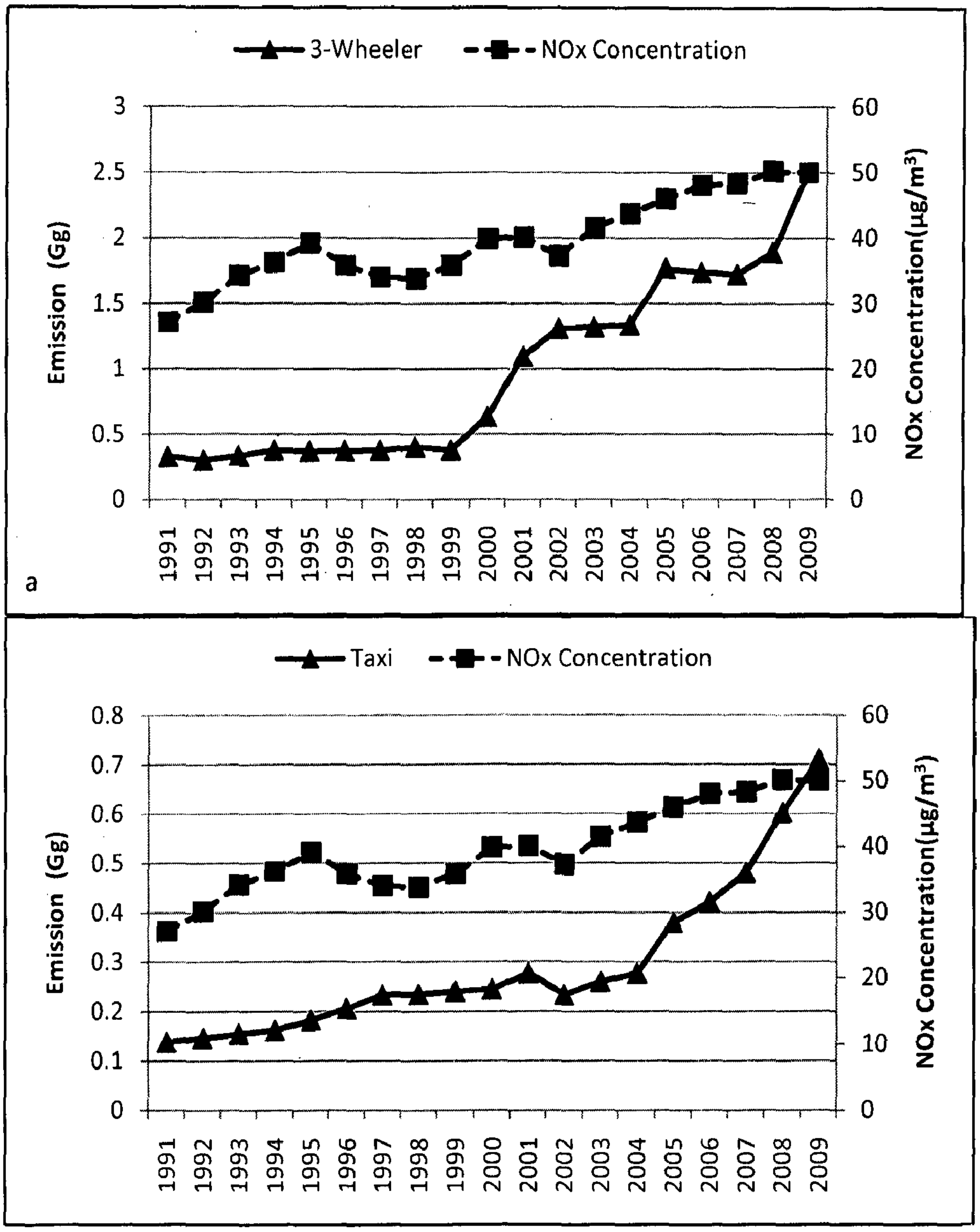


Fig. 5.96: NO_x concentration versus emission of NO_x from (a) three-wheelers and (b) taxis in megacity Delhi

Emissions of NO_x from buses and LCVs versus NO_x concentration in megacity Delhi are shown in Fig. 5.97a and 5.97b. Emissions of NO_x from buses and LCVs have increased 10% and 4% respectively from 1991 to 2000 in megacity Delhi and concentration increased 5% during same period. From 2001 to 2009 emissions of NO_x from buses and LCVs and their concentration are continuously increasing. About 13% growth is observed in emission of NO_x from buses between 2001 and 2009, which is 6% for LCVs, while concentration increased about 3% during the same period.

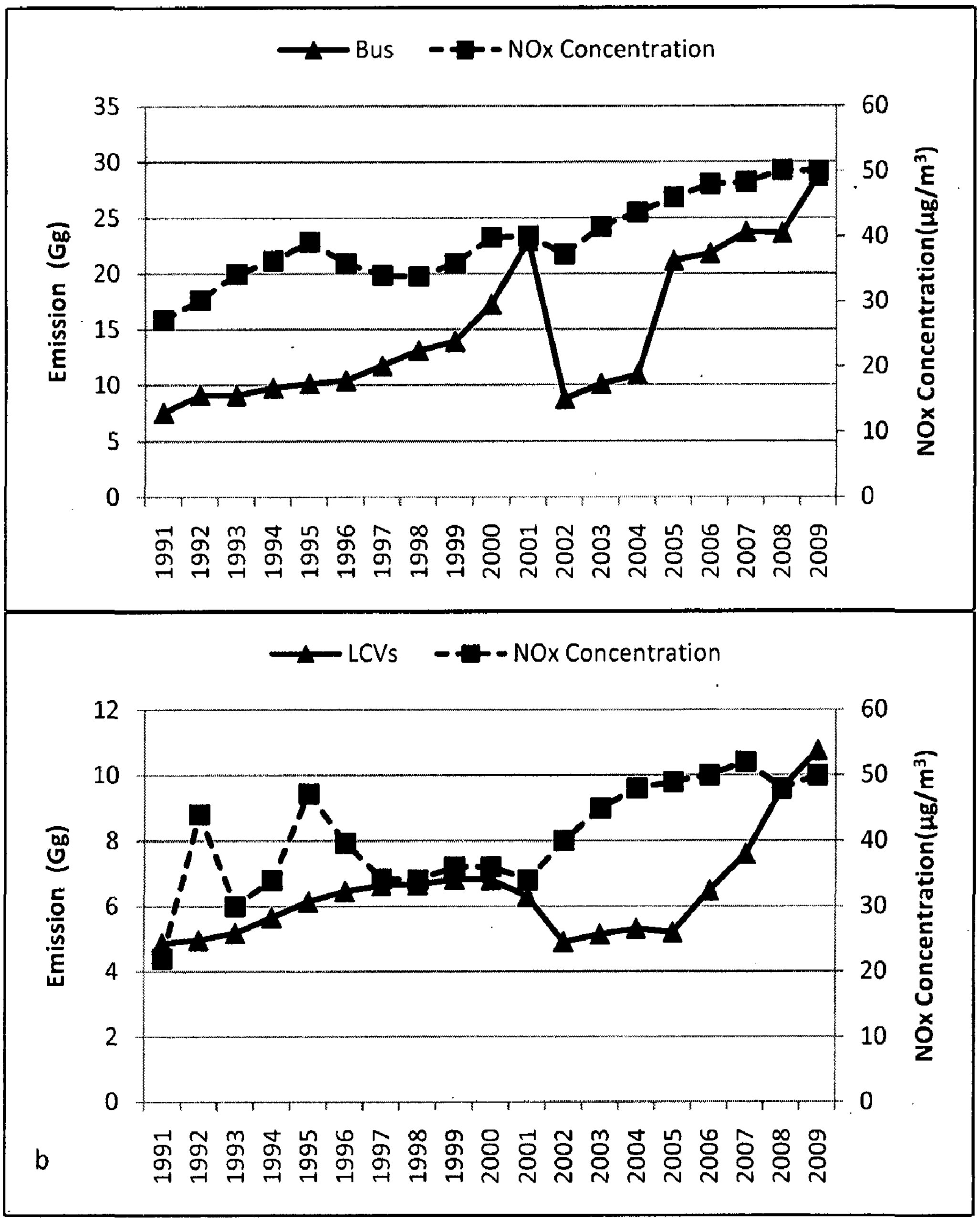


Fig. 5.97: NO_x concentration versus emission of NO_x from (a) bus and (b) LCVs in megacity Delhi

Emissions of NO_x from HCVs population and concentration of NO_x have been shown in Fig. 5.98a. It indicates that from 1991 to 1995 both emissions and concentration are increasing whereas during 1995-2000 the emissions follow increasing trend but ambient air concentration first decrease until 1998 and then increase again. As an overall, both emissions and concentrations increase from 1991-2000. About 4% of growth is observed in NO_x emissions from HCVs, which is 5% for NO_x concentration during 1991 to 2000. Although increasing and decreasing rates may vary, during 2001 to 2009 both emissions and concentrations tend to follow an overall similar trend.

Fig. 5.98b shows the emission of NO_x from all vehicle categories in megacity Delhi and NO_x concentration during 1991 to 2009. From 1991 to 2000 emission of NOx increased about 7% which is 3% for NO_x concentration. Between 2001 and 2009 this change is 4% and 3% for both NO_x emissions and concentrations respectively. Fig. 5.99 shows the coefficient correlation between NO_x emissions and concentration. The coefficient of determination (r^2) value of NO_x emission from all vehicles and ambient air concentration of NO_x is found to be good (~0.68). From above-mentioned qualitative discussions (i.e. overall trend based analysis) and quantitative estimation of correlation coefficient indicate that a good relation is found between NO_x emissions from vehicles calculated by VAPI model and their ambient air concentrations observed in megacity Delhi.

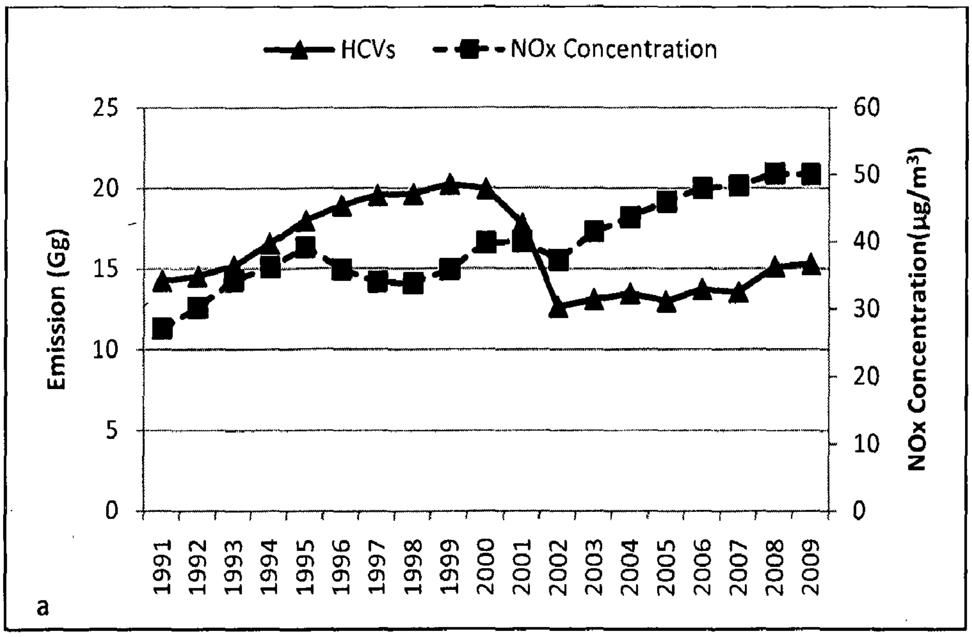


Fig. 5.98a: NO_x concentration versus emission of NO_x from (a) HCVs in megacity Delhi

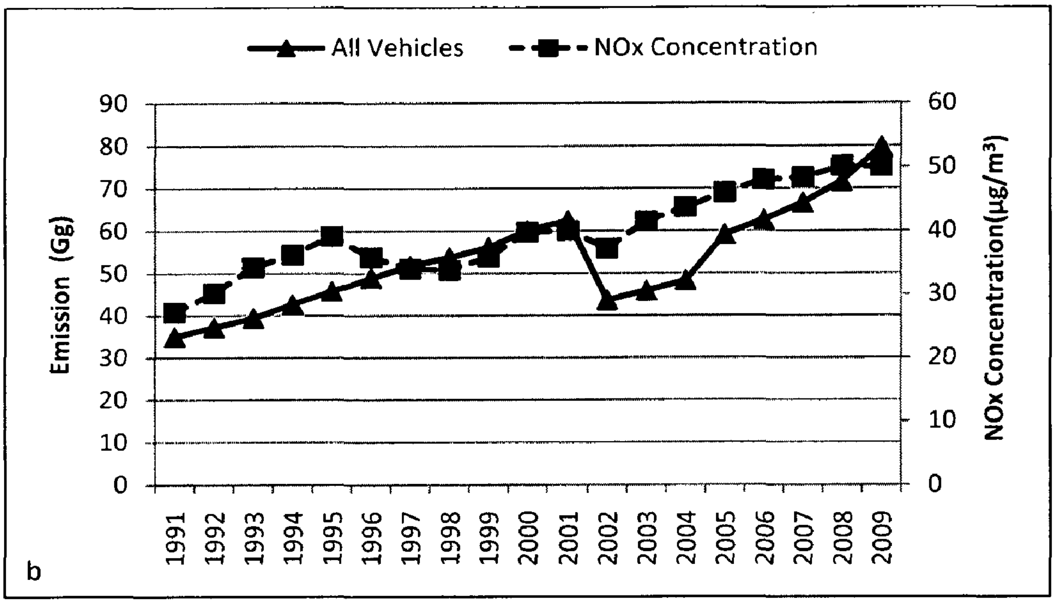


Fig. 5.98b: NO_x concentration versus emission of NO_x from all vehicle categories in megacity Delhi

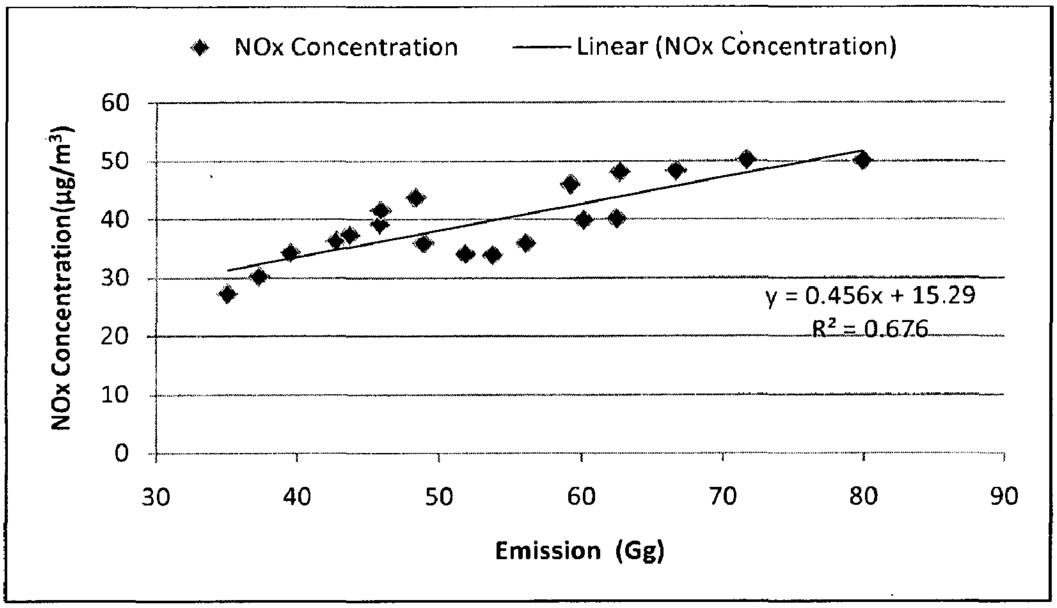


Fig. 5.99: Coefficient correlation between NO_x emissions and Concentration in megacity Delhi from 1991 to 2009

5.4.2. Comparison of estimated emissions and observed ambient air concentrations of CO

Due to data limitations, emissions of CO were validated with only one site i.e. ITO monitoring station concentration data from 1996 to 2009. For comparison, evaluation and validation of model estimates of CO emissions with respect to CO concentrations observed at ITO traffic junction makes a plausible selection because at this is one of the most busy traffic junction. VAPI model estimate CO emissions at ITO junction according to the traffic composition of ITO station, which have been taken from traffic volume survey data near ITO station obtained from DUDGD (2006). Emissions of CO are calculated by VAPI model according to the traffic composition in ITO station in 1 km distance. After estimation of CO emissions, it is compared with ambient concentration trend of CO monitored at ITO station during 1996-2009.

Table 5.5: Traffic Volumes on ITO Bridge (BSZ Road) in Delhi

Duration (Hours)	Traffic Volume	Traffic Composition(in percentage)				
		Cars	Auto	2Ws	Bus	Goods
16	166175	32.34	12.73	45.28	7.21	2.44

Fig. 5.100a and 5.100b show emissions of CO from two wheelers, cars, and taxis and concentrations of CO at ITO traffic station. Emission of CO from two wheelers at ITO station was 158 kg in 1996 and with approximately 4% decline reached to 134 kg in 2000; similarly CO concentration shows 3% decline during the same period. From 2001 to 2009, both emission and concentration of CO at ITO station have declined with 8% average decreasing rate (Fig. 5.100a). About 4% decline is observed in CO emissions from cars and taxis during 1996 to 2009, which is quite similar to decline in CO concentration (6%) during the same period (Fig. 5.100b).

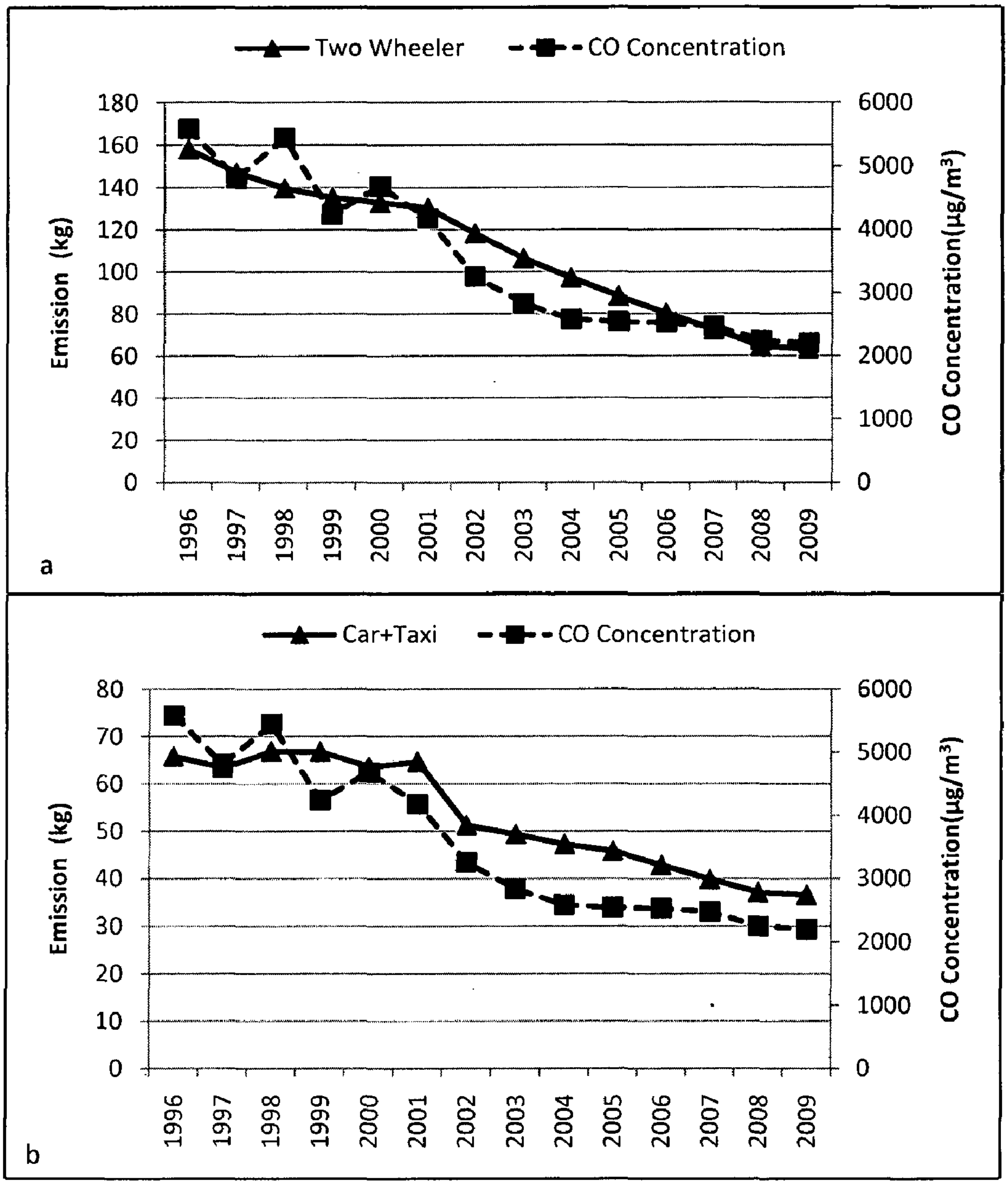


Fig. 5.100: CO concentration at ITO station versus emission of CO from (a) two wheelers and (b) car, taxi in ITO station in megacity Delhi

Emission of CO from three wheelers at ITO station have decreased by about 8% during 1996-2000 from 1996 to 2000 and this negative growth rate is similar (~8%) between 2001 and 2009. CO concentration trend also follows a similar trend between 1996 and 2000 (3% decline) and 2001 and 2009 (8% decline) (Fig.101a). Emissions of CO from buses have shown 7% decline during 1996 to 2009, which is similar to decrease in CO concentration during same period (Fig. 101b).

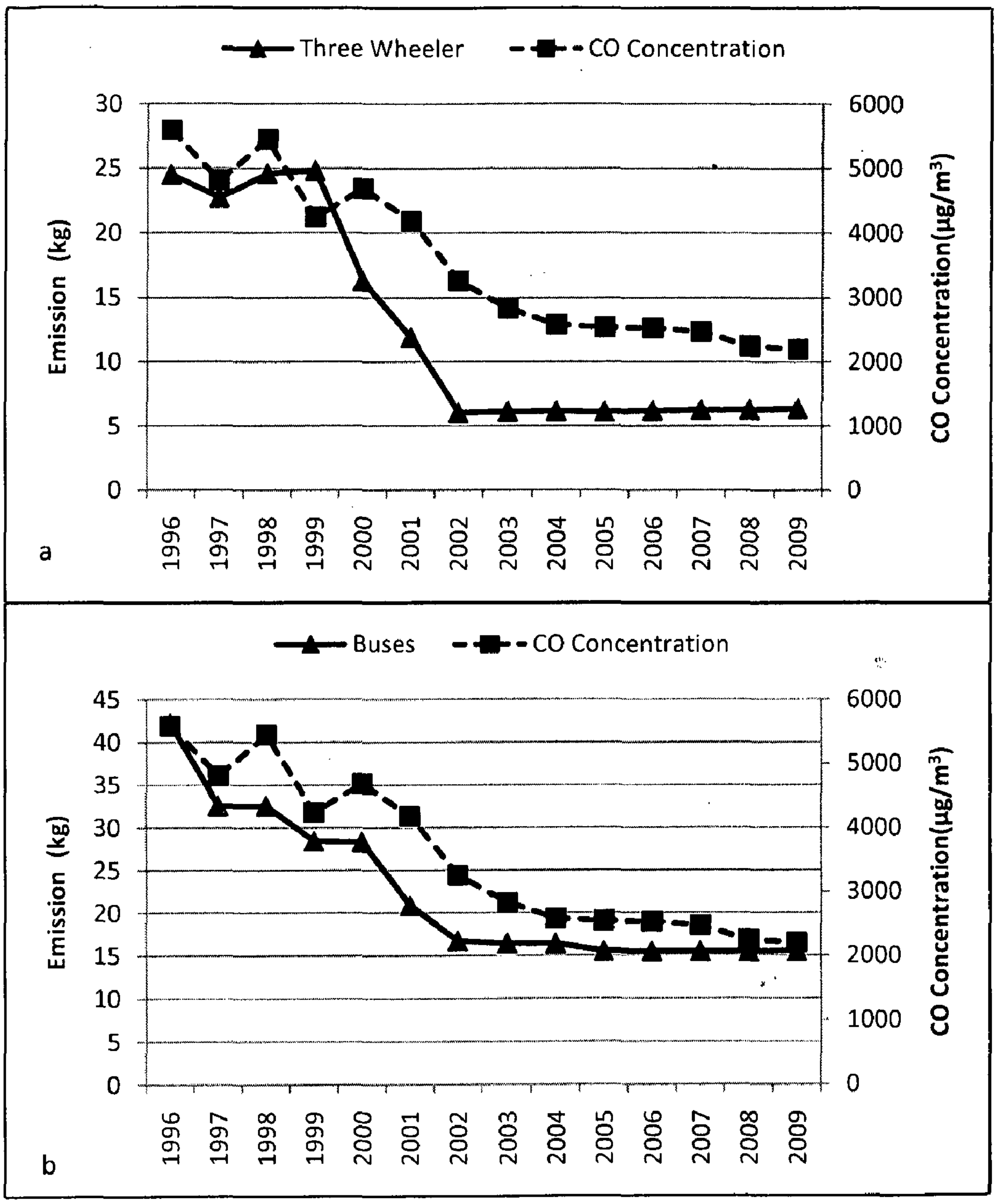


Fig. 5.101: CO concentration at ITO station versus emission of CO from (a) Three wheelers and (b) buses in ITO station in megacity Delhi

Emissions of CO from goods vehicle population and CO concentration at ITO monitoring station of megacity Delhi have been shown in Fig. 5.102a. It indicates that from 1996 to 2009 though emission and concentration trends do not show a much similar trend, still the both have decreased during the same period. About 3% decline is observed in CO emissions from goods vehicles which is 6% for CO concentration during 1996 to 2009. Fig. 5.102b shows the emission of CO from all vehicle categories at ITO station of megacity Delhi and CO concentration during 1996 to 2009. From 1996 to 2000 CO emissions decreased about 4%, while concentration decreased by 3%. Between 2001 and 2009 this change i.e.,7% and 8% for both CO emission and concentration, respectively, at ITO station of megacity Delhi. Fig. 5.103 shows the coefficient correlation between CO emissions and concentration. The coefficient of determination (r^2) value of CO emission from all vehicles and ambient air concentration is found to be very strong (0.94). Thus, a very good agreement found between CO emissions from vehicles calculated by VAPI model and their concentration in ITO monitoring station of megacity Delhi.

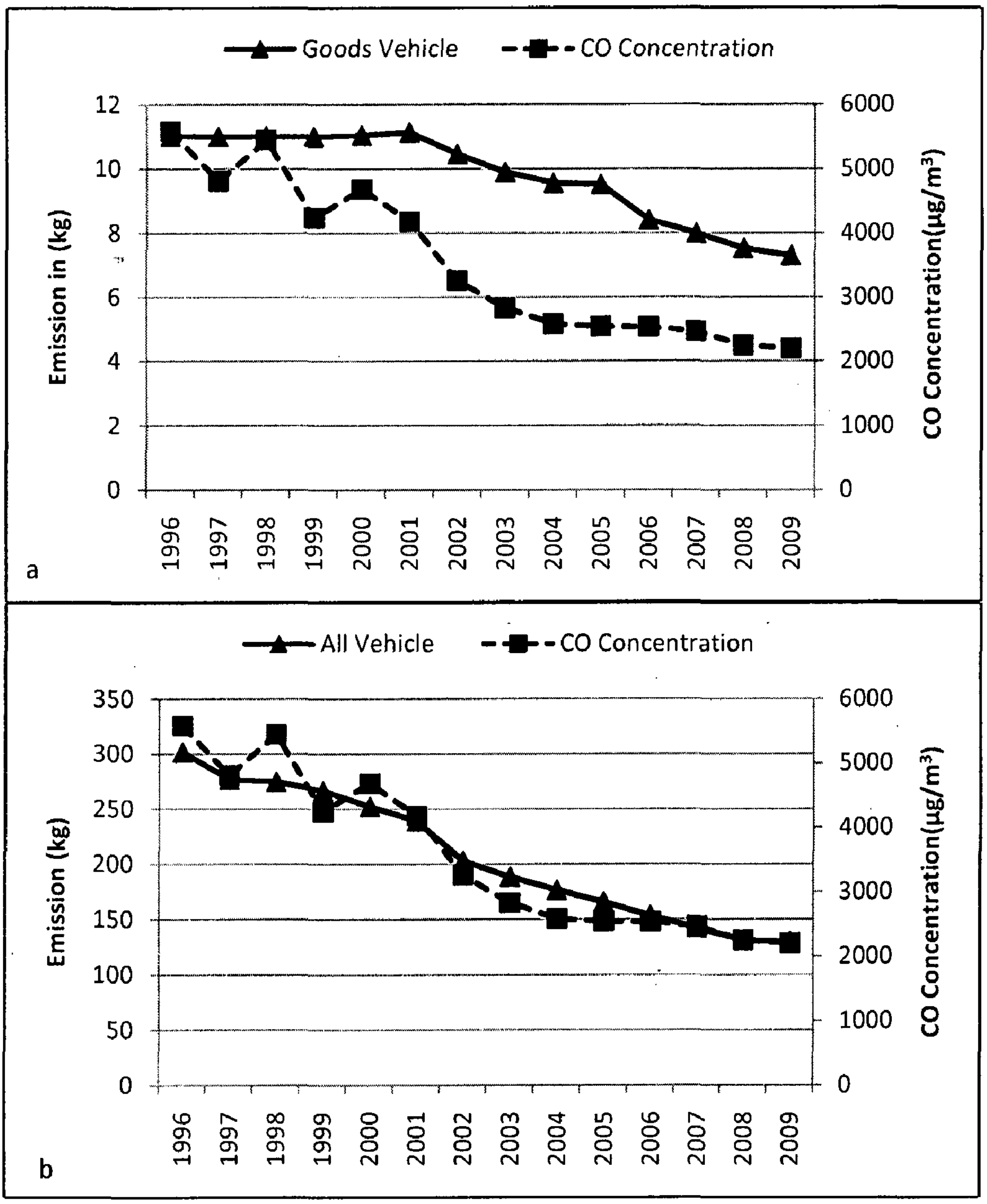


Fig. 5.102: CO concentration at ITO station versus emission of CO from (a) goods and (b) all vehicles in ITO station in megacity Delhi

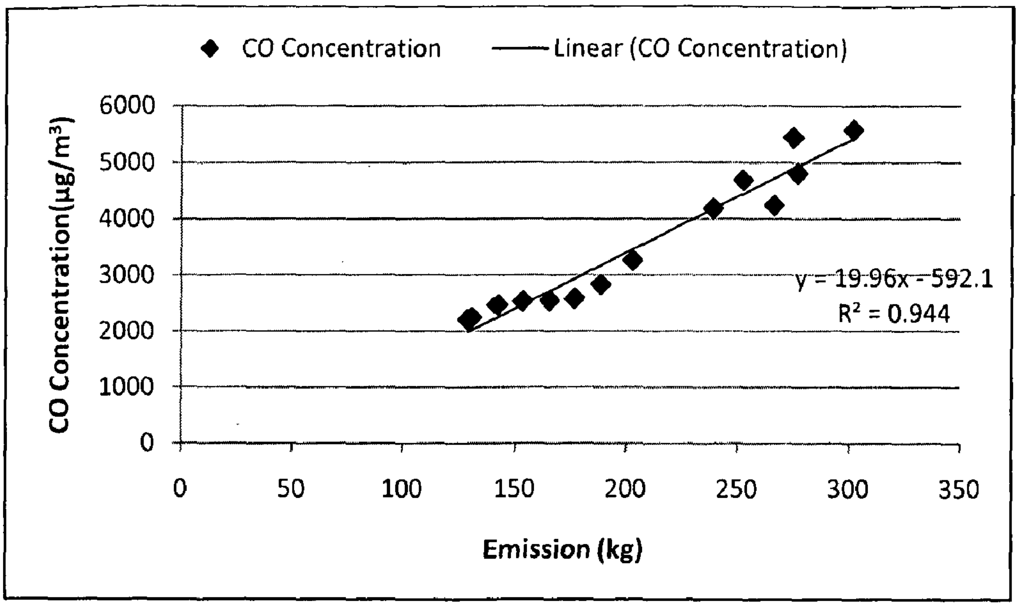


Fig. 5.103: Coefficient correlation between CO emissions and Concentration in megacity ITO monitoring station of Delhi from 1996 to 2009

5.5. CONCLUSION

Comprehensive emission inventories of eleven categories of pollutants from different vehicles have been developed for megacity Delhi. For two wheelers, emissions of different pollutants follow almost similar trend from 1991 to 2001. Emissions of all pollutants from two wheelers decrease in 2001 because of phasing out of two wheelers. Emission trends of all pollutants from cars show increasing trend from 1991 to 2010. Noticeable decrease in emissions of various pollutants from cars is observed in year 2001, phasing out of car population is responsible for it. In case of three wheelers, emission trend of different pollutants are not similar because of change in emission factors according to pollutants and model of three wheelers in each year. For all commercial vehicles sudden fall in emission of various pollutants is observed in year 2002 because of phasing out of old age vehicles and CNG conversion program in megacity Delhi. In case of some vehicle categories (e.g., car) no change is observed during year 2002 because of high emission factors of available vehicle model in 2002. Sudden increase in emissions from buses is observed in year 2005 in all categories of pollutants because of entry of 19000 buses in megacity Delhi in 2005. Evaluation and validation of VAPI model results with the help of existing ambient air concentration of NO_x and CO has thus been carried out. On the basis of results and discussions described in Section 5.4, this can be said that an overall good agreement exists between estimated emissions and observed concentrations.

CHAPTER 6

Future Vehicular Emission Scenarios for Megacity Delhi (2011-2020)

6.1. INTRODUCTION

Vehicular Air Pollution Inventory (VAPI) model can estimate emissions from 1991 to 2030. It estimates future emissions based on past, present and future Gross Domestic Product (GDP) or Per Capita Income (PCI) and their relation with past and present vehicle populations. Introduction of emission norms, clean fuel technology, impact of external vehicles etc. are some of the factors which affect the emissions of pollutants from on road vehicles in Delhi. This chapter estimates emissions for the period of 2011-2020 considering two scenarios; i) Business as Usual (BAU) Scenario, and ii) Best Estimates Scenario (BES).

6.1.1. Business as Usual (BAU) Scenario

VAPI model has already considered many policies for estimation of emissions along with their input parameters and emission factors discussed in Chapter 5 (Section 5.2.2) for the years 1991 to 2010. BAU scenario is the extension of Chapter 5 study (1991-2010) for the years 2011 to 2020.

6.1.2. Best Estimate Scenario (BES)

Apart from policy measures considered in BAU scenario there might be some other policy interventions which may affect vehicular emissions in megacity Delhi in future years. To consider also the possible future policy programs in addition to policies used in BAU scenario, emissions of pollutants have been calculated for the years 2011 to 2020 by using VAPI model under the Best Estimated Scenario (BES). Policies considered in BES scenario are discussed in Table 6.1.

Table: 6.1. Policies considered in BES scenarios

	Policies	Implementation
1	Bus Rapid Transit System (BRTS)	Implemented in year 2008, already included in bus population and post-2005 emission factors have been used for it
2	CNG vehicles population	Implemented in year 2002 for all commercial passenger vehicles and from 2006 for new LCVs population
3	Emission Norms	It is found from the IARI (2007) and TERI (2011) studies that Indian vehicles technology are more efficient than norms introduced by government due to this post-2005 emission factors given by IARI (2007) have been used for emissions estimation of post-2011 model vehicles in the study
4	Improvement in the quality of Fuel	Emission factors used in the study are based on the quality of fuel improved during following years (1991-1996, 1996-2000, 2000-2005 and post-2005)
5	Phasing-Out of vehicles	VAPI model requires age of vehicle for phasing-out of old vehicles. Before 2002 phasing out age was natural age while 2002 onwards it is based on Government norms
6	Shift of two-wheelers from two-stroke to four-stroke	From 2011 onwards
7	Metro Rail	From 2002 onwards, reduction of passenger vehicles from 2002 to 2005 is 13 to 20%, 2005 to 2010 is 21%, 2010 to 2015 is 24-39% and after 2005 it is 39% (Murty et al., 2007)

6.1.2A. Shift of two-wheelers from two-stroke to four-stroke

Among various means of road transportation, two-wheelers are a popular mode of transportation, but at the same time, they have been a major source of air pollution in megacity Delhi. In the early 1991, on road two-wheelers in Delhi numbered about 0.96 million. Their number increased at a rate of 5-15% per annum and constituted almost 48 to 61 % of the total fleet of vehicles during 1991 to 2010. Until the mid 2000s, a large majority of the two-wheelers were 2-stroke. Two-wheelers with two-stroke engines emit twice as much hydro-carbons (HCs) and suspended particulate matter (SPM) as do the four-stroke types (Chongpeerapien, 1991). It is being increasingly realized that the two-wheeler industry is moving towards the production of two-wheelers with four-stroke engines in India. Moreover, given the progress towards implementing stricter emission norms in India, there is a possibility that in future the Government may consider to ban two-stroke machines in megacities like Delhi. With this consideration in mind, emissions from two-wheelers have been estimated according to possible future population of two-stroke and four-stroke two-wheelers.

6.1.2B. Impact of Metro Rail on vehicles

Delhi Metro railway has not just made travelling easy and comfortable but also made significant environmental impact on megacity Delhi. Since the beginning of Metro rails in December 2002, there has been a progressive increase in the reduction of daily vehicle demand as the people made shift towards the Metro rail for commuting. Till 2005, the Metro rail has replaced 338418 number of vehicles and this share is projected to increase approximately to 2920065 for all other modes of travel such as cars, buses, two wheelers and auto-rickshaws by the end of 2020 (Murty et al. 2007). Significant impact will be observed in future on vehicular emissions due to shifting of commuters from on road to metro rail (Table 6.1). Looking at this important issue, emissions of pollutants from vehicles of Delhi have been estimated by reducing the number of vehicles replaced by metro rail. As described hereinafter, for estimating emission of various pollutants in BES scenario vehicle population is projected by considering above-mentioned issues.

6.1.2.1. Two Wheelers

As per Iyer (2007) it is assumed that all new two-wheeler purchases from 2011 are in the 9:1 ratio of four- and two-stroke two-wheelers. VAPI model only gives the future annual on road vehicles population and not the annual newly registered vehicles. For estimating future annual newly registered two-wheelers, average ratios of present annual registered two-wheeler populations have been taken. To assess impact of Delhi Metro Rail on two-wheelers population data given by Murty et al. (2007) has been taken for reduction of numbers of this segment of vehicular population.

6.1.2.2. Cars

Car is the prominent source of pollutants in megacity Delhi. Conversion of other fuels used in car to CNG is increasing day by day in Delhi (IGL, 2010). In BES, CNG equipped car population is similar to BAU scenario (discussed in Chapter 5) while impact of metro rail on car population has been considered according to Murty et al. (2007).

6.1.2.3. Three-Wheelers

After 2002 all three-wheelers were converted to CNG in megacity Delhi. In BES, population of CNG driven three-wheelers are considered similar to BAU scenario, while reduction of three-wheelers due to metro is considered according to Murty et al. (2007).

6.1.2.4. Taxis/Buses/LCVs-HCVs

In BES, impact of metro on taxis/buses/LCVs-HCVs populations have been considered according to Murty et al. (2007) while other policies and norms are considered according to BAU scenario discussed in Chapter 5.

6.2. RESULTS AND DISCUSSION

In this section emissions from different vehicle categories, their contribution, and emission trend from 2011 to 2020 in BAU and BES scenarios have been discussed.

6.2.1. CO emissions

CO emissions from various vehicle categories in BAU and BES scenarios are presented in Fig. 6.1 (a and b). Fig 6.1a suggests that in BAU scenario CO emission in 2011 will be 274 Gg and with 6% decline will be 258 Gg in 2012 due to phasing out of 1991 car population in the year 2012 and higher emission factors for cars registered in 1991. In 2015, CO emission from vehicles in BAU scenario will be 314 Gg, followed by 477 Gg in 2020. As per the emission contribution, share of car population is highest among all vehicles in BAU scenario (25-45%), followed by two wheelers (22-29%) and buses (11-21%).

According to BES scenario, CO emission from vehicles in Delhi will be 247 Gg in 2011 and similar to BAU scenario emissions will decrease between 2011 (247 Gg) and 2012 (227 Gg) because of the same reason as stated in the above-mentioned description. In 2015, however, emission of CO from vehicles in BES scenario will be 260 Gg followed by 393 Gg in 2020. Similar to BAU, in BES scenario contribution of car for CO emission will be higher (23-45%) throughout the study period followed by two-wheelers and buses. As compared to BAU scenario, emission of CO from BES scenario will be 10-18% less in future years (2011-2020). Moreover, during the same period, highest reduction is observed in emissions from taxis (13-37%).

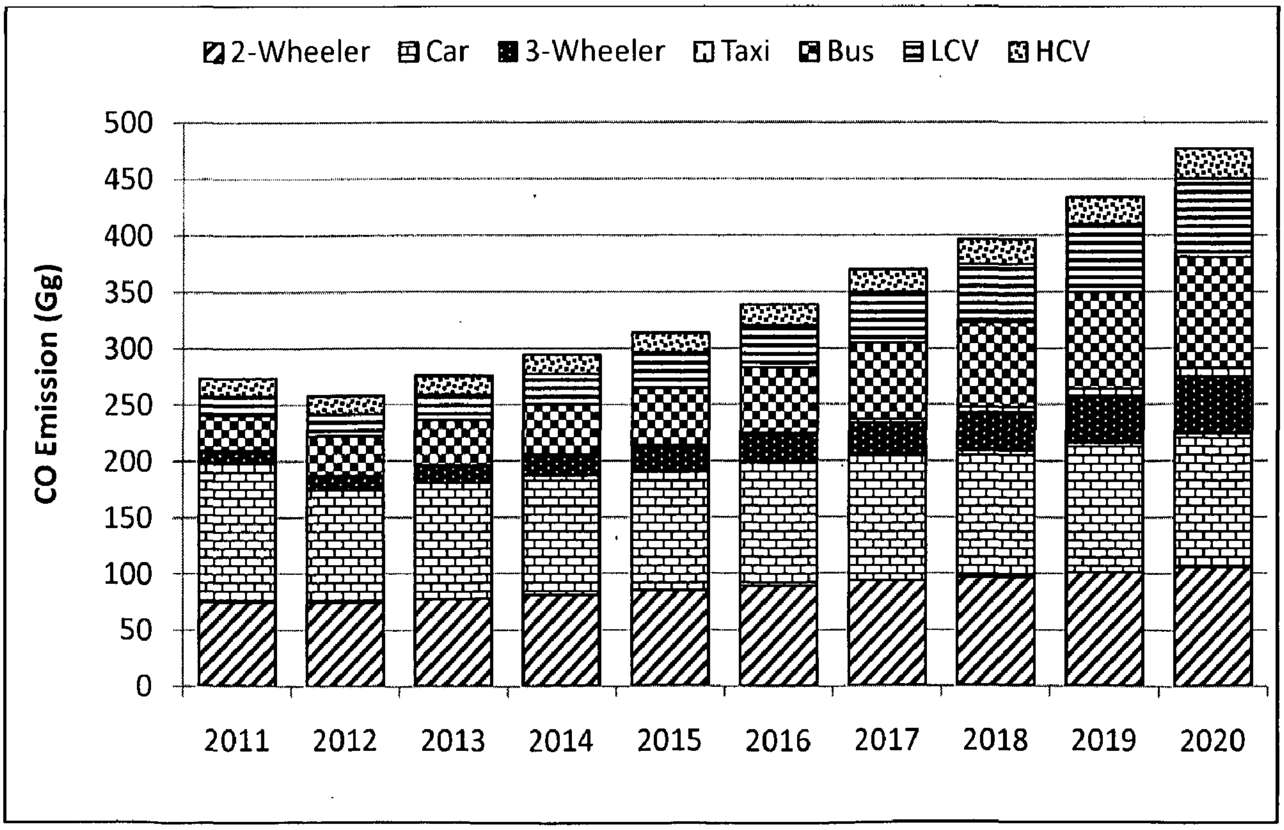


Fig. 6.1a: CO emissions as per BAU scenario from vehicles in megacity Delhi

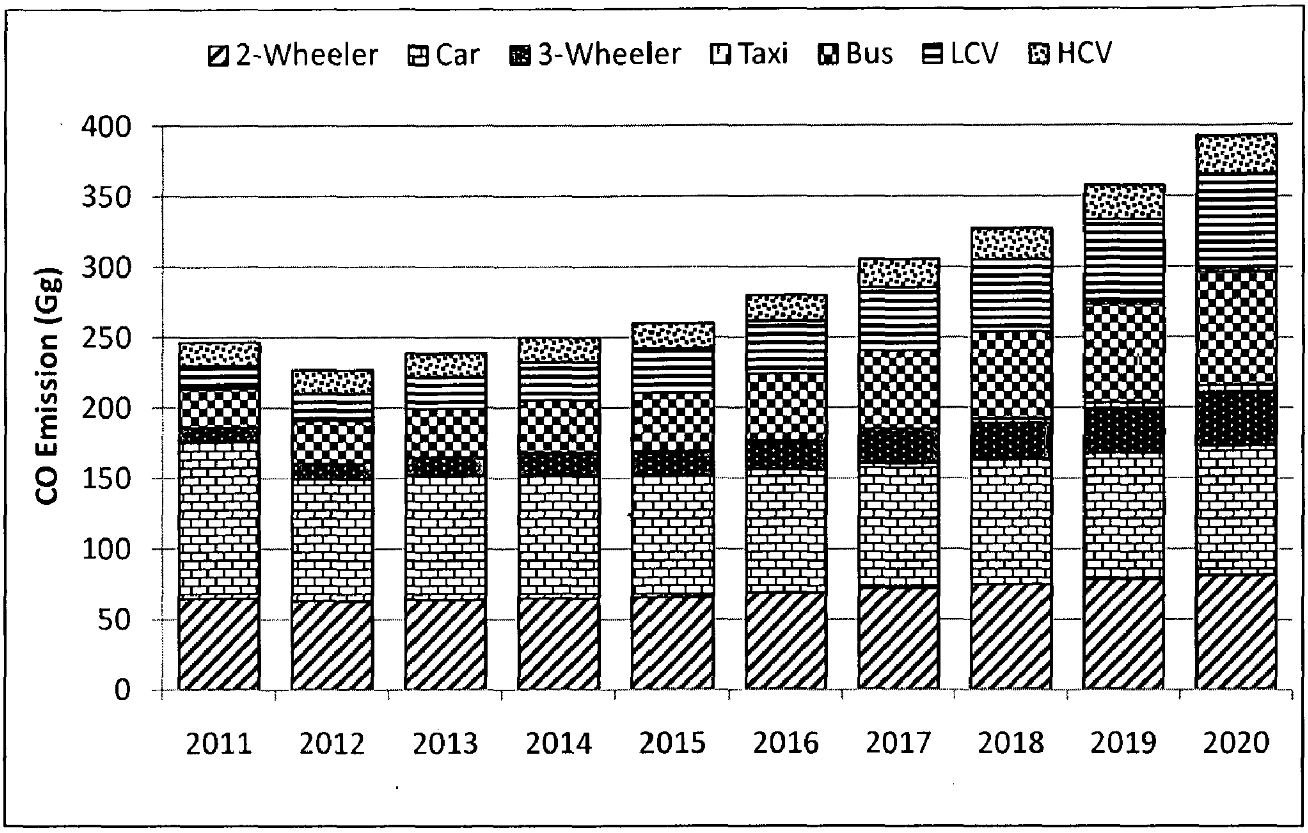


Fig. 6. 1b: CO emissions as per BES scenario from vehicles in megacity Delhi

6.2.1.1. Two-Wheelers

It is projected that about 75 Gg of CO will be emitted from two wheelers in megacity Delhi during 2011 in BAU scenario. With 0.69% decline emissions will be 75 Gg in 2012. In 2015, CO emissions from vehicles in Delhi will be 85 Gg, followed by 105 Gg in 2020 (Fig. 6. 2a). Among all types of two wheelers, contribution of two-stroke motorcycles is highest (30-33%), followed by four-stroke motorcycles and two-stroke scooters during 2011 to 2020. In BES scenario, CO emissions from two wheelers are expected to be 65 Gg in 2011, 66 Gg in 2015 and 82 Gg in 2020 (Fig. 6. 2b). Share of two-stroke motorcycles is highest (31-33%) for CO emissions in megacity Delhi. In comparison to BAU, CO emissions from two-wheelers are 14 to 23% less in BES scenario.

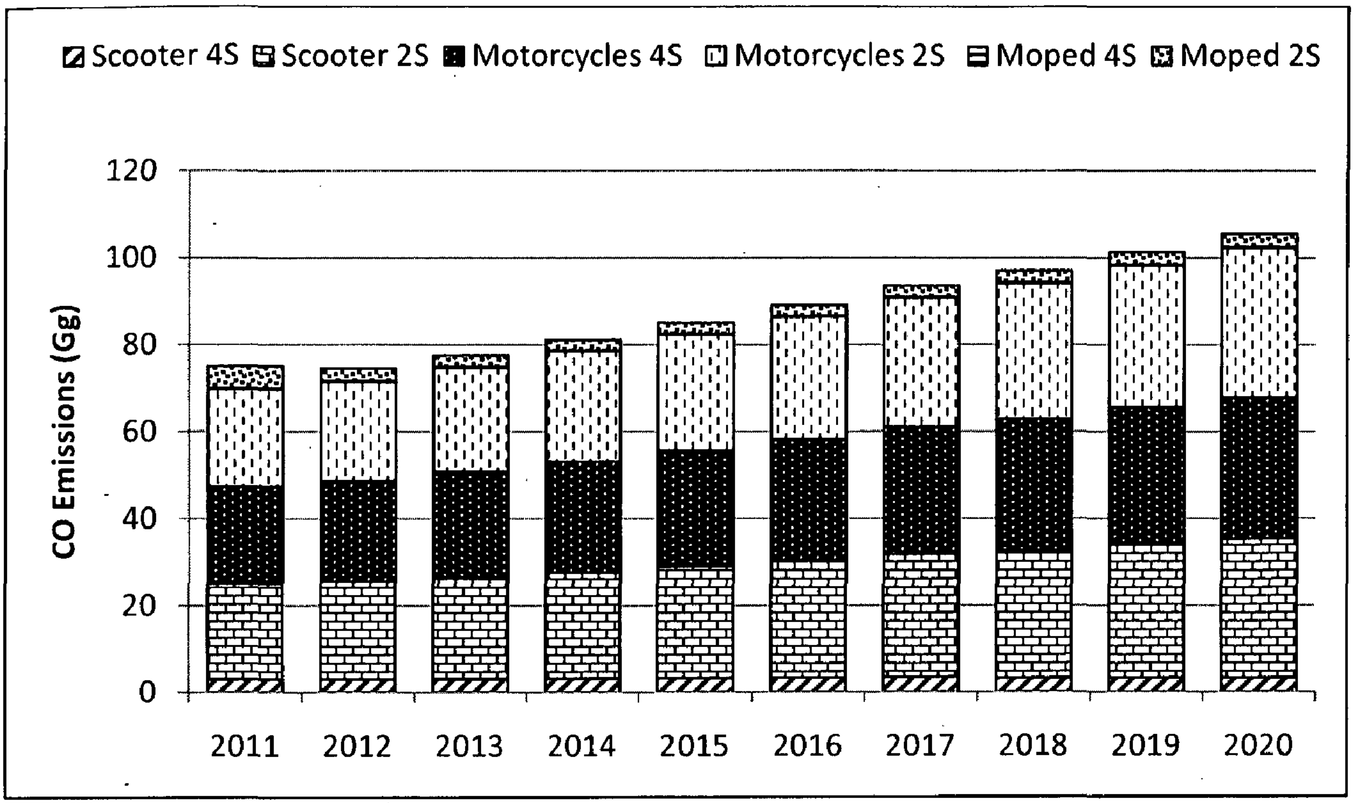


Fig. 6.2a: CO emissions as per BAU scenario from two wheelers in megacity Delhi

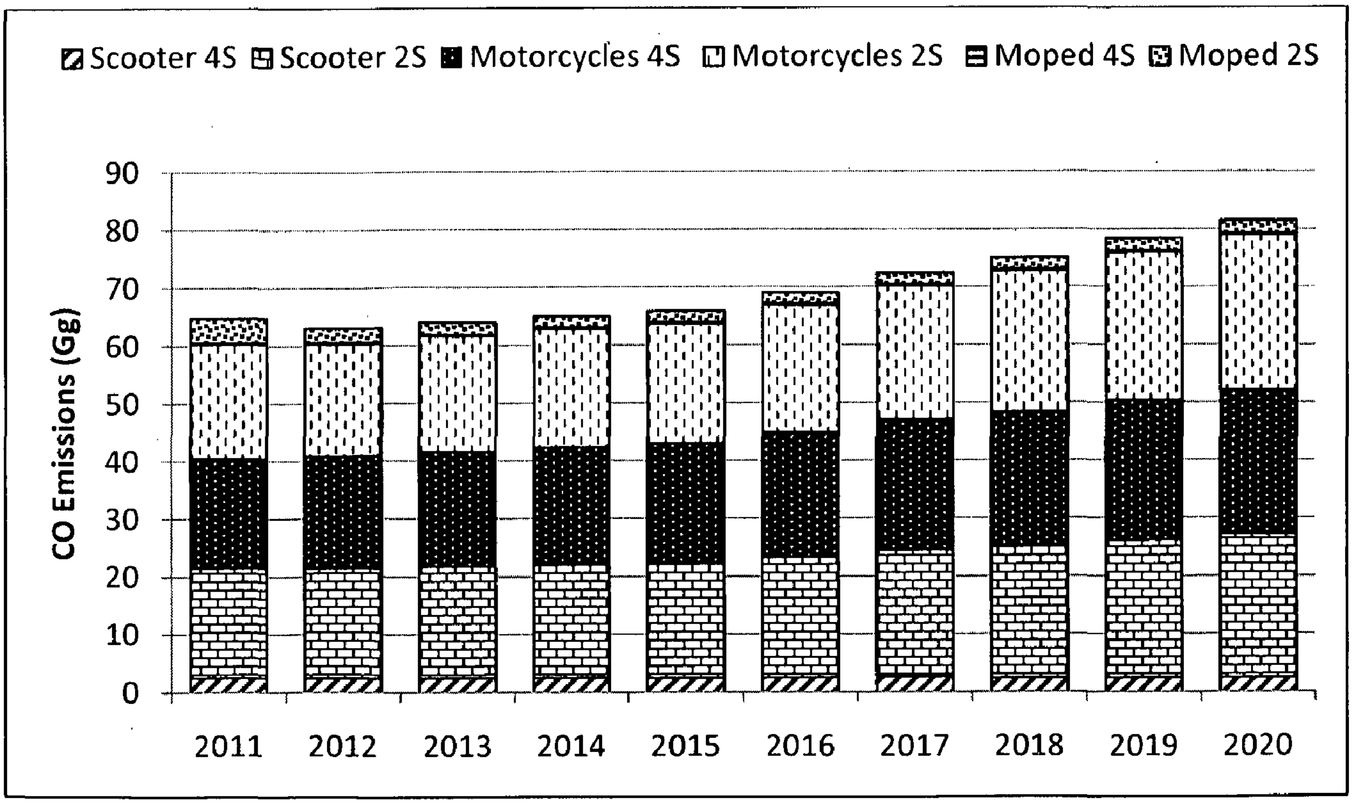


Fig. 6.2b: CO emissions as per BES scenario from two wheelers in megacity Delhi

6.2.1.2. Cars

Fig. 6.3 (a and b) presents the emissions of CO from car population in BAU and BES scenorios. In 2011 CO emissions from cars in BAU scenario will be 123 Gg, while in 2012 it will be 99 Gg (with 19% decline). Phasing out of 1991 and pre-1991 car population (that had higher emission factors) are responsible for this declining trend. In BAU scenario, CO emissions are projected to be 107 Gg and 119 Gg from cars in 2015 and 2020 respectively. Similar to BAU, CO emissions from cars in BES scenario decrease from 112 Gg in 2011 to 87 Gg in 2012 (~22% decline). In 2015 emissions of CO from cars in BES scenario will be 86 Gg which is 19% less than BAU scenario, while in 2020 it will be 91 Gg which is 23% less in comparison to BAU. It is observed that CO emissions in BES scenario are about 10-23% less as compared to BAU scenario. Share of petrol driven cars is highest for CO emissions in both BAU and BES scenarios while because of less population and emission factor, contribution of CNG and diesel driven car is very less.

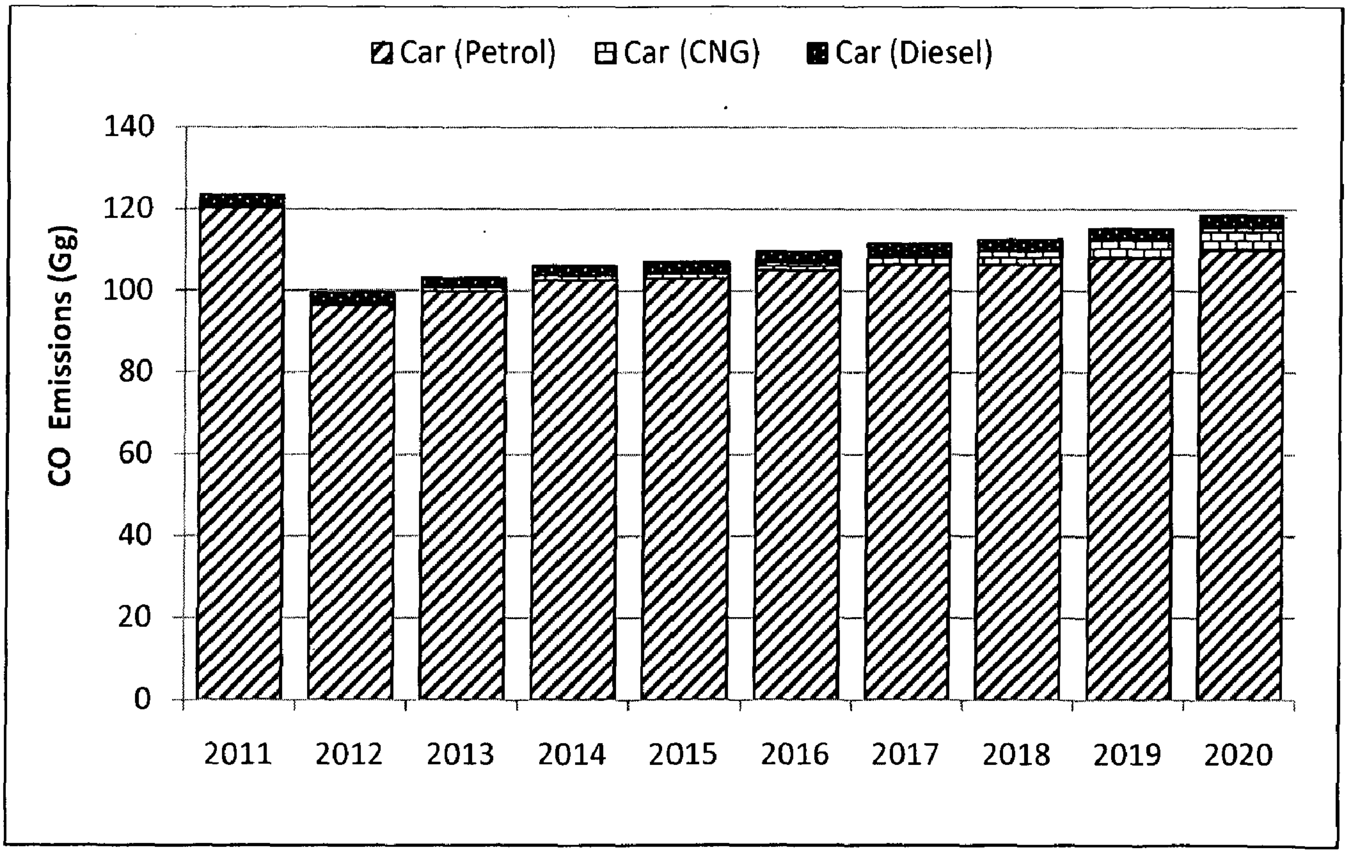


Fig. 6.3a: CO emissions as per BAU scenario from cars in megacity Delhi

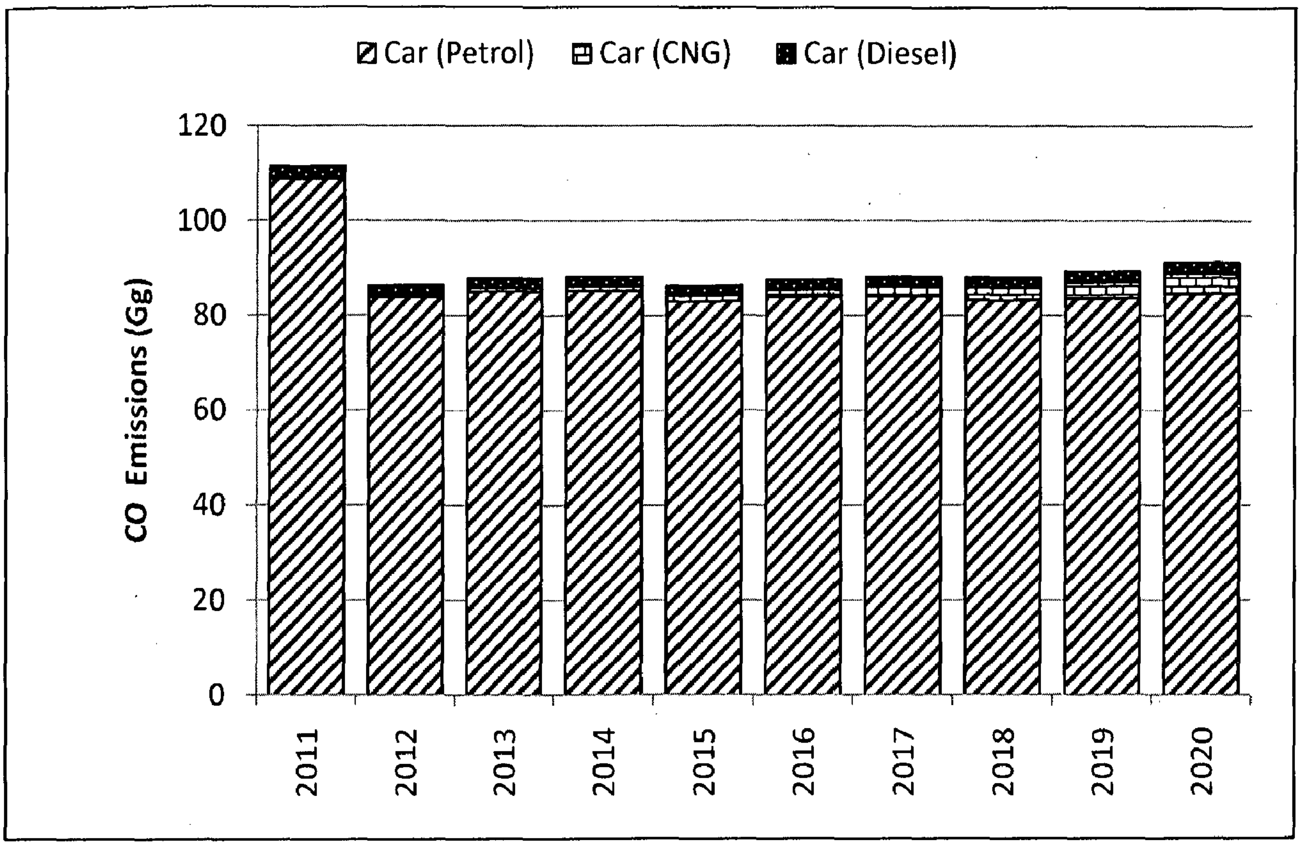


Fig. 6.3b: CO emissions as per BES scenario from cars in megacity Delhi

6.2.1.3. Three Wheelers

Fig. 6.4 (a and b) shows the emission of CO from three wheelers in megacity Delhi as per BAU and BES scenarios. CO emissions from three wheelers in BAU scenario are projected to be 10 Gg in 2011, 20 Gg in 2015 and 51 Gg in 2020. In BES scenario, CO emissions from three wheelers in 2011 will be 9 Gg which is about 13% less than BAU. In 2015 it is projected to be 16 Gg which is about 21% less in comparison to BAU scenario, while in 2020 BES emission will be 38 Gg which is 24% lesser than BAU scenario. It is observed that CO emission in BES scenario is ~13-24% lesser than BAU scenario during 2011 to 2020.

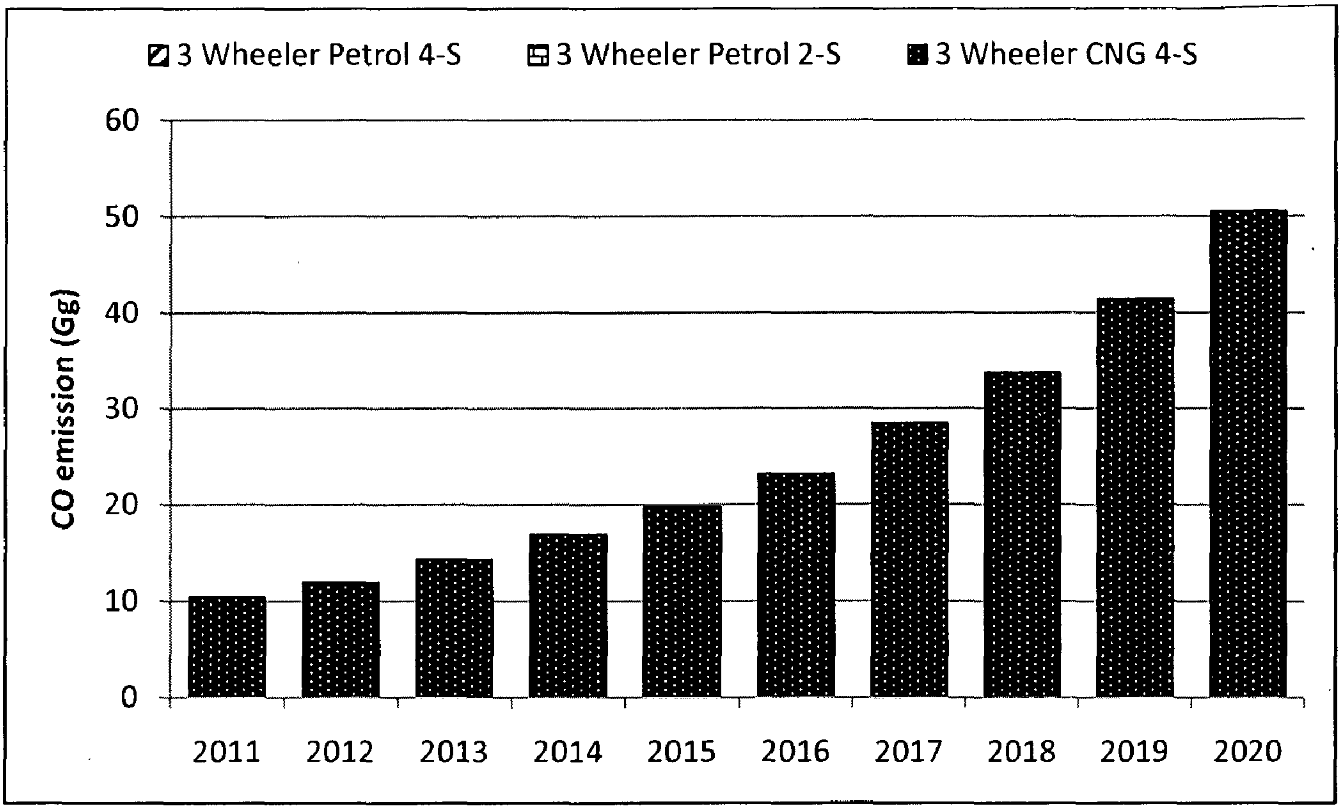


Fig. 6.4a: CO emissions as per BAU scenario from three wheelers in megacity Delhi

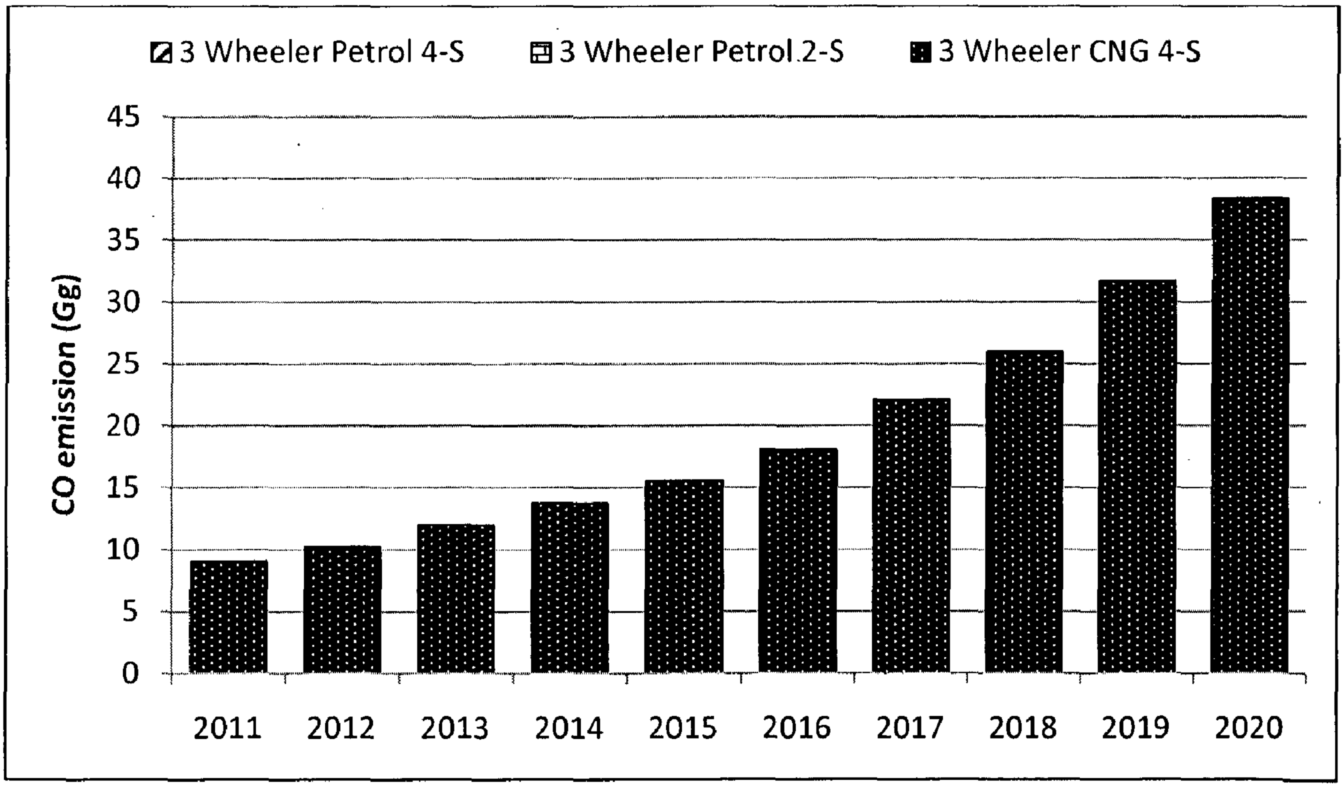


Fig. 6.4b: CO emissions as per BES scenario from three wheelers in megacity Delhi

6.2.1.4. Taxis

Fig 5 (a and b) suggest the possible scenarios of CO emission from taxis in megacity Delhi. Fig. 6.5a indicates that in 2011 emission of CO from taxis in BAU scenario will be 0.86 Gg and in 2015 it will be 2 Gg followed by 8 Gg in 2020. BES scenario is also showing similar trend for CO emissions from taxis, while emissions in BES scenario are much less compared to BAU. In 2011 emissions from taxis in BES scenario are projected to be 0.75 Gg which is 13% less than BAU scenario. In 2015 emission of CO from BES scenario will be 1.48 Gg followed by 5 Gg in 2020. About 13-37% of difference has been observed between BAU and BES scenario. Initially emission difference between BAU and BES scenario is 13% in 2011 followed by 29% in 2015 and 37% in 2020. Fig. 6.5 (a and b) presents the share of petrol and diesel driven taxis in CO emissions due to external taxis (petrol and diesel) population.

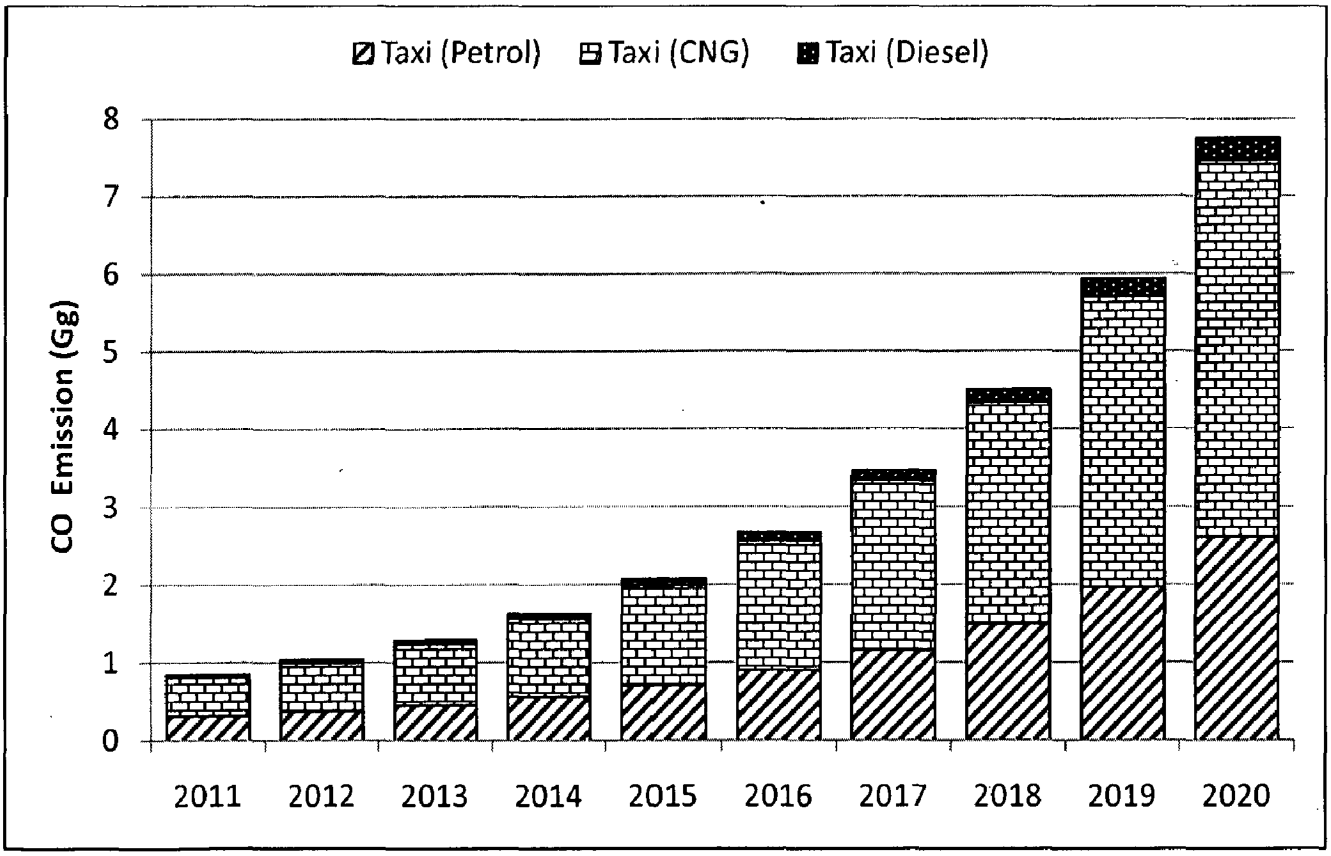


Fig. 6.5a: CO emissions as per BAU scenario from taxis in megacity Delhi

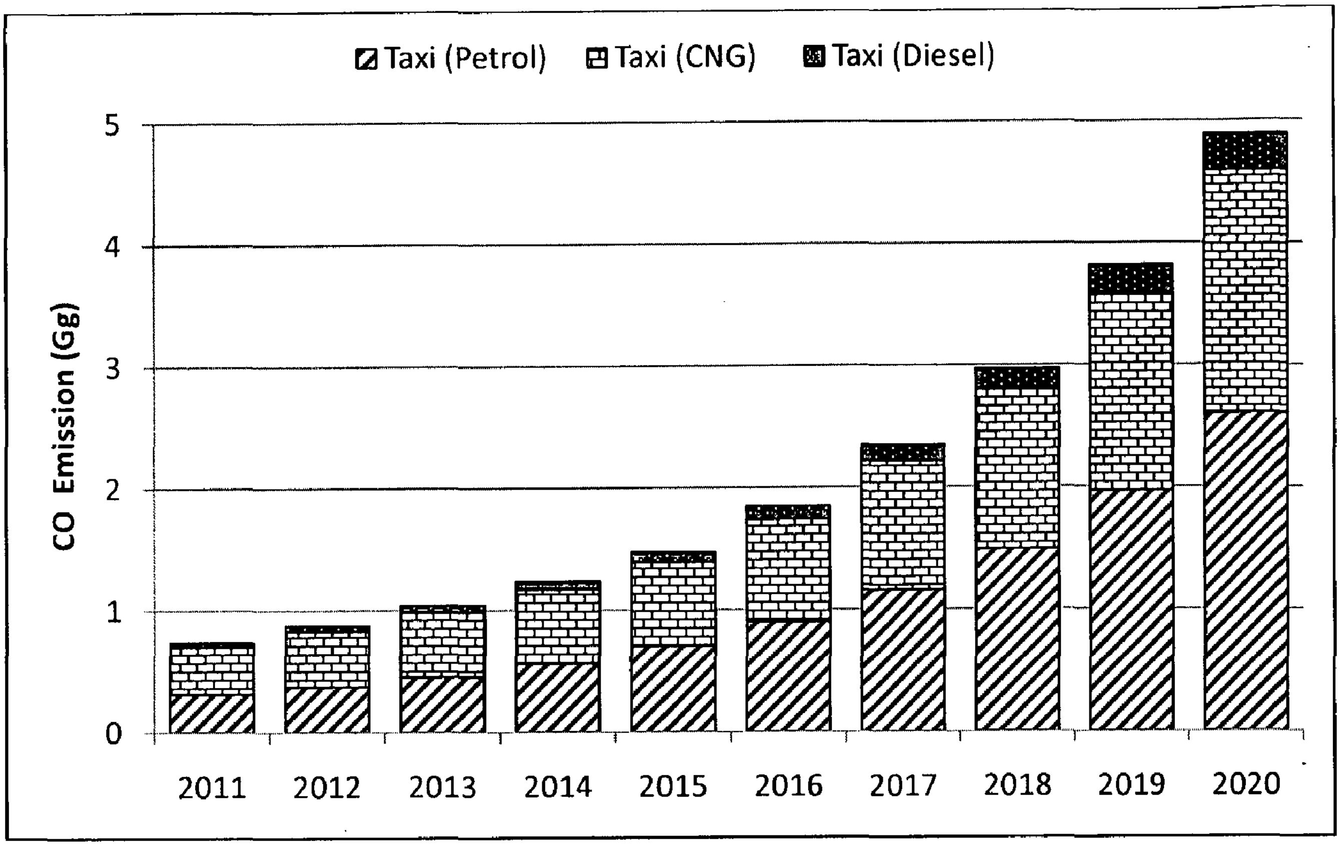


Fig. 6.5b: CO emissions as per BES scenario from taxis in megacity Delhi

6.2.1.5. Buses

Buses are prominent source of public transportation in megacity Delhi. Fig. 6.6 (a and b) shows the emission of CO from buses in BAU and BES scenarios in Delhi. Estimations suggest that CO emissions from bus population in BAU scenario will be 31 Gg in 2011 and 51 Gg in 2015 followed by 100 Gg in 2020. During 2011 to 2020 contribution of diesel driven external buses will be 13-18% while that of CNG driven buses will be 82-87% in BAU scenario. CO emission trend in BES scenario follows a similar trend to that of BAU scenario. CO emissions from buses in BES scenario are estimated to be 28 Gg in 2011, 41 Gg in 2015 and 81 Gg in 2020. As per emission contribution the share of CNG population is higher (78-86%) followed by diesel buses (14-22%) during 2011 to 2020 in BES. It is observed that emission difference between BAU and BES scenario is ~12% in 2011 and ~18% in 2015 and in 2020.

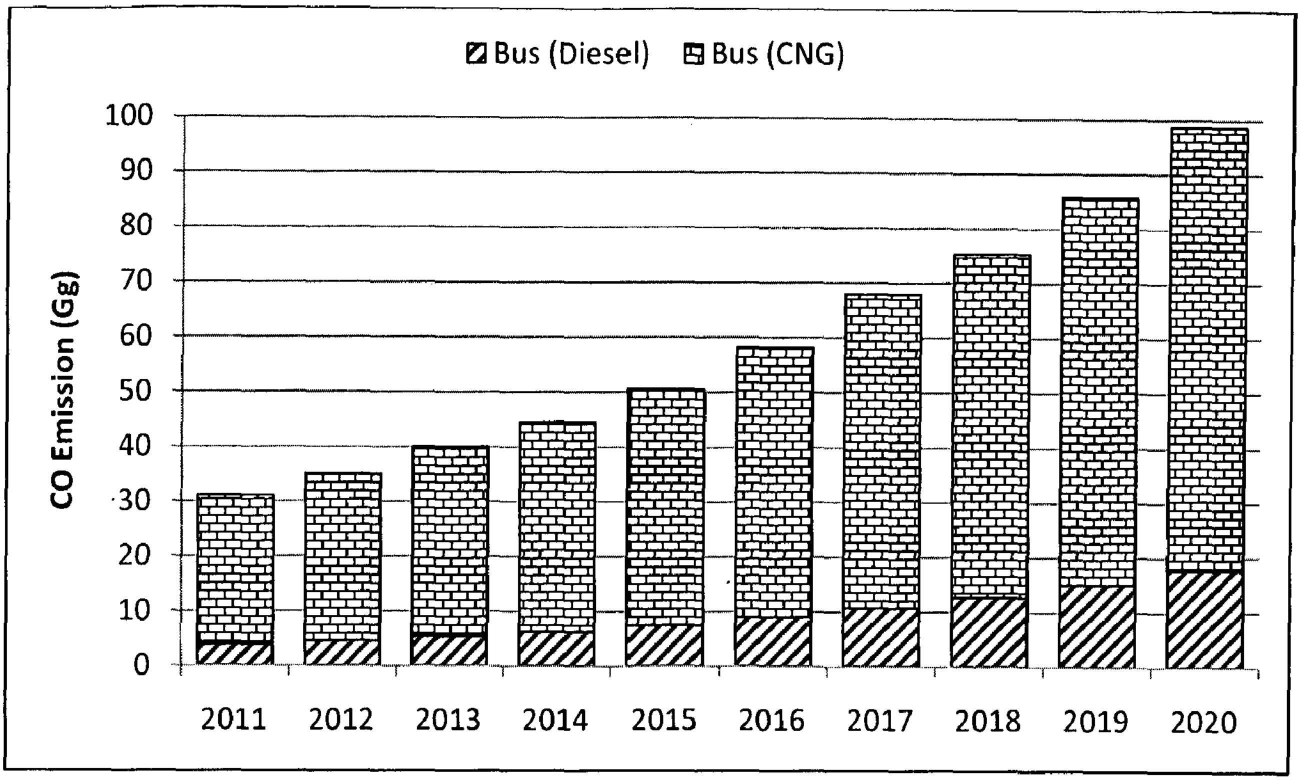


Fig. 6.6a: CO emissions as per BAU scenario from buses in megacity Delhi

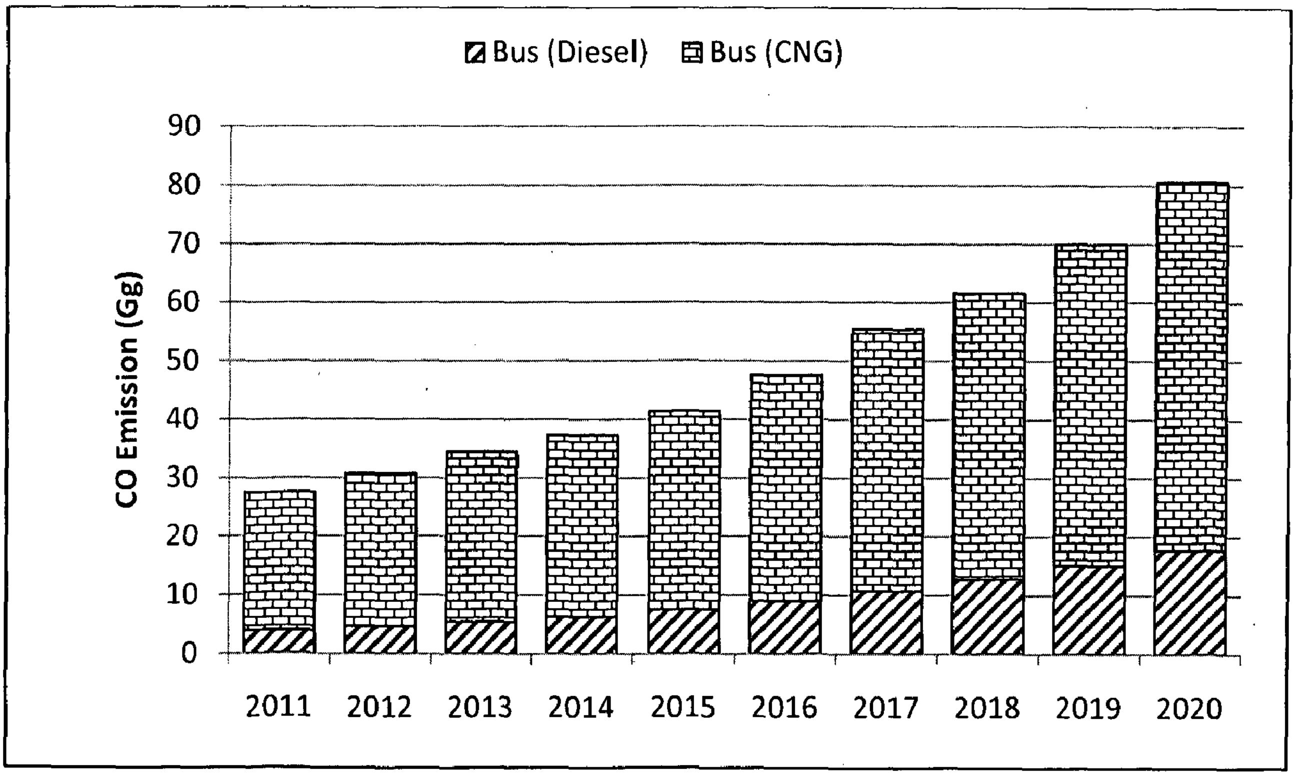


Fig. 6.6b: CO emissions as per BES scenario from buses in megacity Delhi

6.2.1.5. LCVs/HCVs

No BES scenario estimation has been done for LCVs and HCVs as CNG population norms are already considered in BAU scenario. Similarly external LCVs and HCVs and their vehicle kilometer travelled are already considered in BAU scenario. Fig. 6.7 shows the emission of CO from LCVs during 2011 to 2020. In 2011 emission of CO from LCVs are projected to be 16 Gg followed by 32 Gg in 2015 and 69 Gg in 2020. A growth rate of 15-19% has been observed in CO emission trend during 2011 to 2020. With comparison to contribution of LCVs driven by CNG is higher and increasing annually, while share of diesel driven LCVs is less and decreasing. Fig. 6.8 shows the emission trend of CO from HCVs in megacity Delhi during 2011 to 2020. In 2011 emission of CO from HCVs are estimated to be 17 Gg in 2011, 18 Gg in 2015 and 27 Gg in 2020. Initially from 2011 to 2016 emission growth rate of CO is somewhat slow (~0.3% to 3.5% annually), whereas after 2016 it increased to ~9-11% because of change in vehicle population.

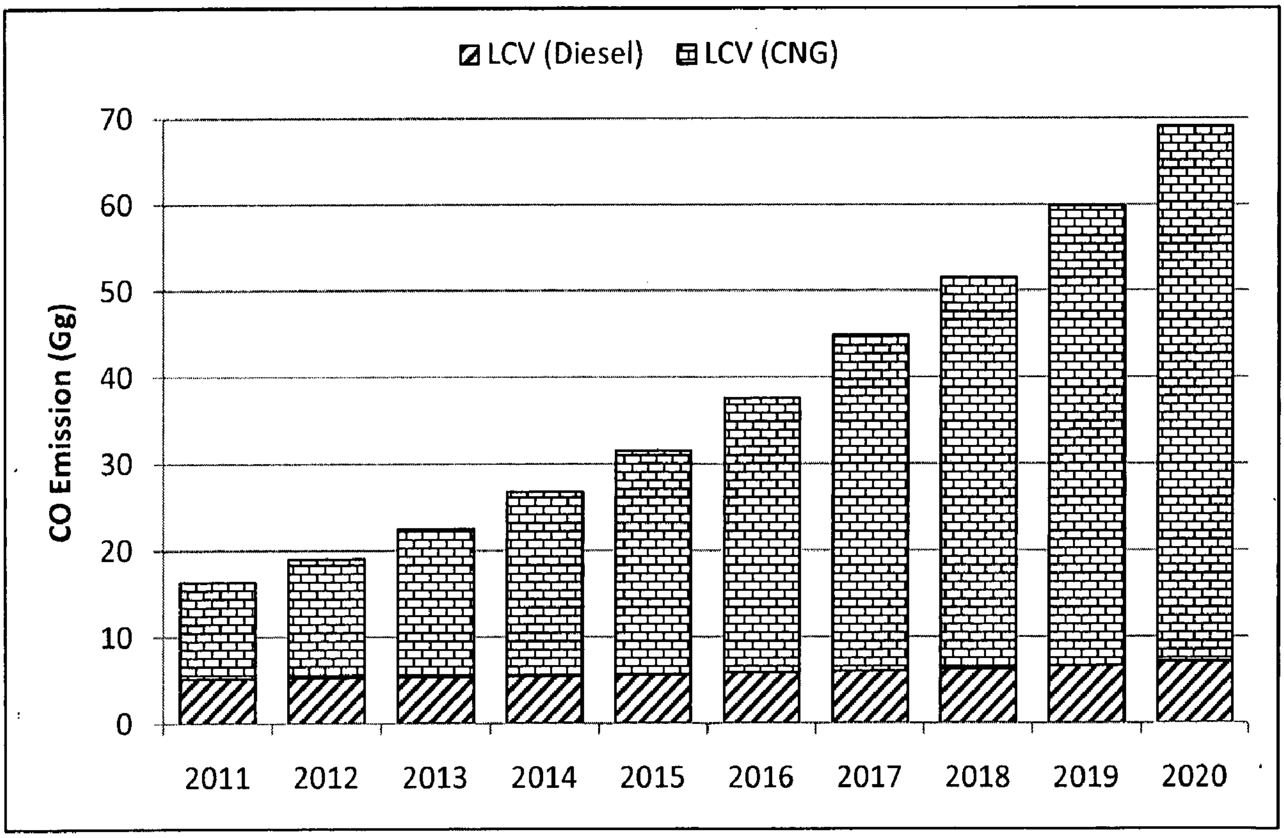


Fig. 6.7: CO emissions as per BAU scenario from LCVs in megacity Delhi

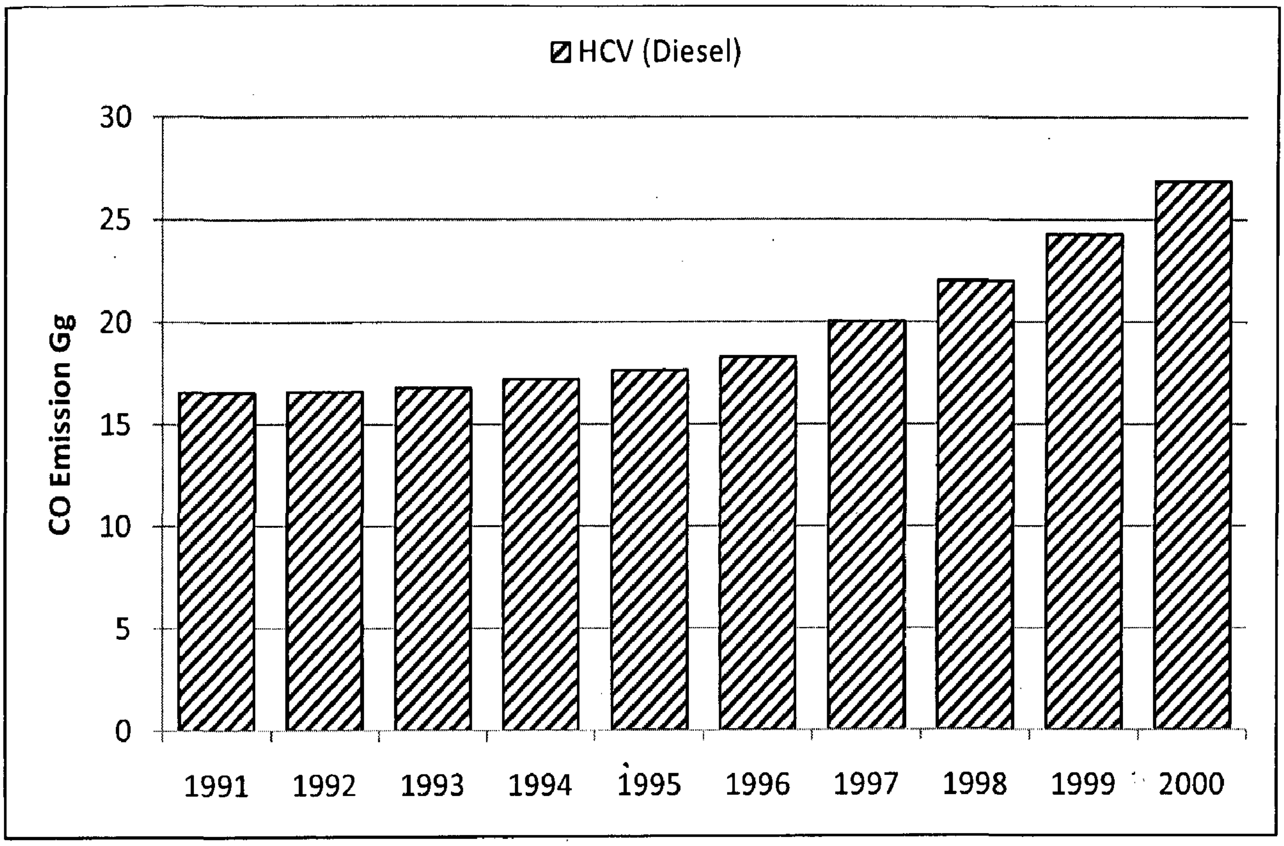


Fig. 6.8: CO emissions as per BAU scenario from HCVs in megacity Delhi

6.2.2. CO_2 emission

Emissions of CO_2 from various vehicle categories in BAU and BES scenario are shown in Fig. 6.9 (a and b). CO_2 emissions from various vehicle categories in BAU scenario are projected to be 13928 Gg in 2011, 23825 Gg in 2015 and 46565 Gg in 2020. About 14% annual average growth rates have been observed in CO_2 emissions in BAU scenario in megacity Delhi. Fig. 6.9a suggest that cars are the highest contributor (30-34%) for CO_2 emission during 2011 to 2015, while from 2016 buses will contribute maximum (32-33%). Almost similar trend is observed in BES scenario. In 2011 emission of CO_2 from various vehicles in BES scenario will be 12475 Gg, followed by 19941 Gg in 2015 and 39001 Gg in 2020. As per estimations, cars are the largest contributor in BES scenario during 2011 to 2013, while from 2014 buses are expected to be the largest contributor. About 10.4% difference is observed in between CO_2 emissions between BAU and BES scenario in 2011. Similarly ~16% differences are observed during 2015 and 2020.

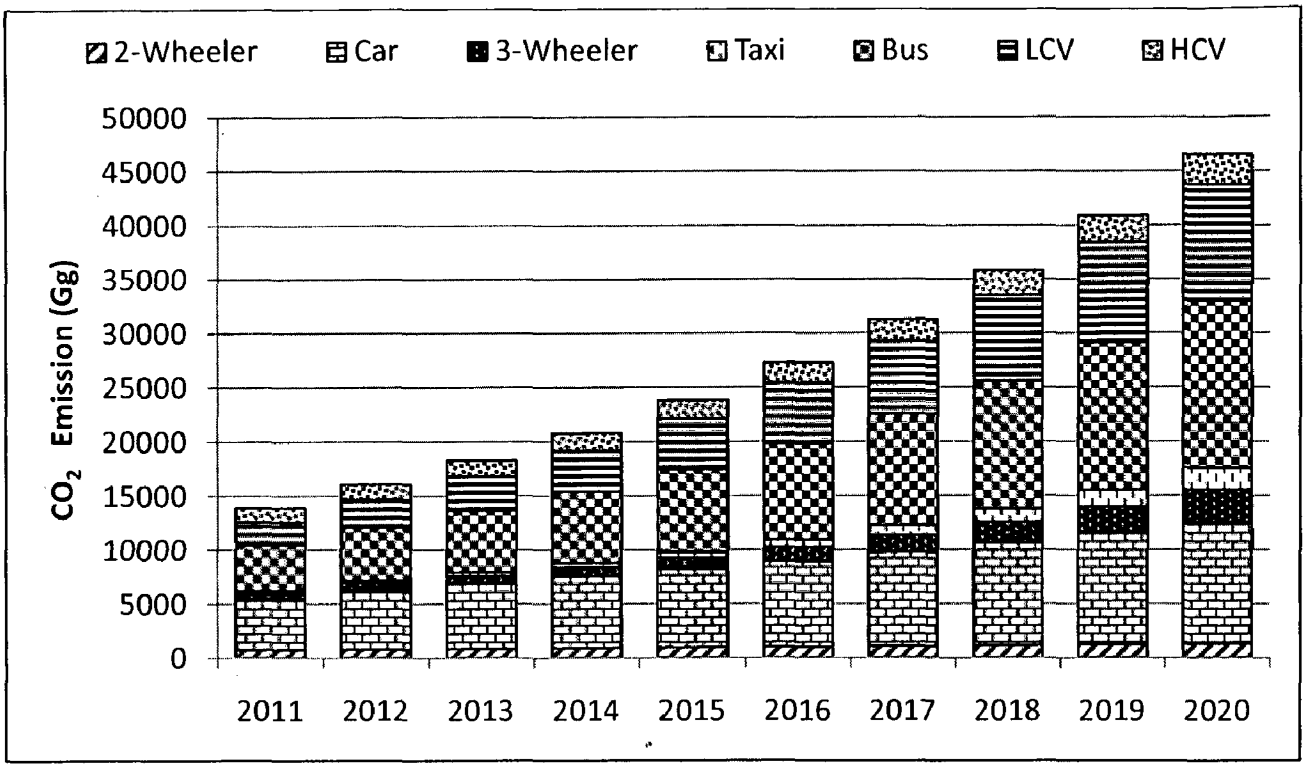


Fig. 6.9a: CO_2 emissions as per BAU scenario from vehicles in megacity Delhi

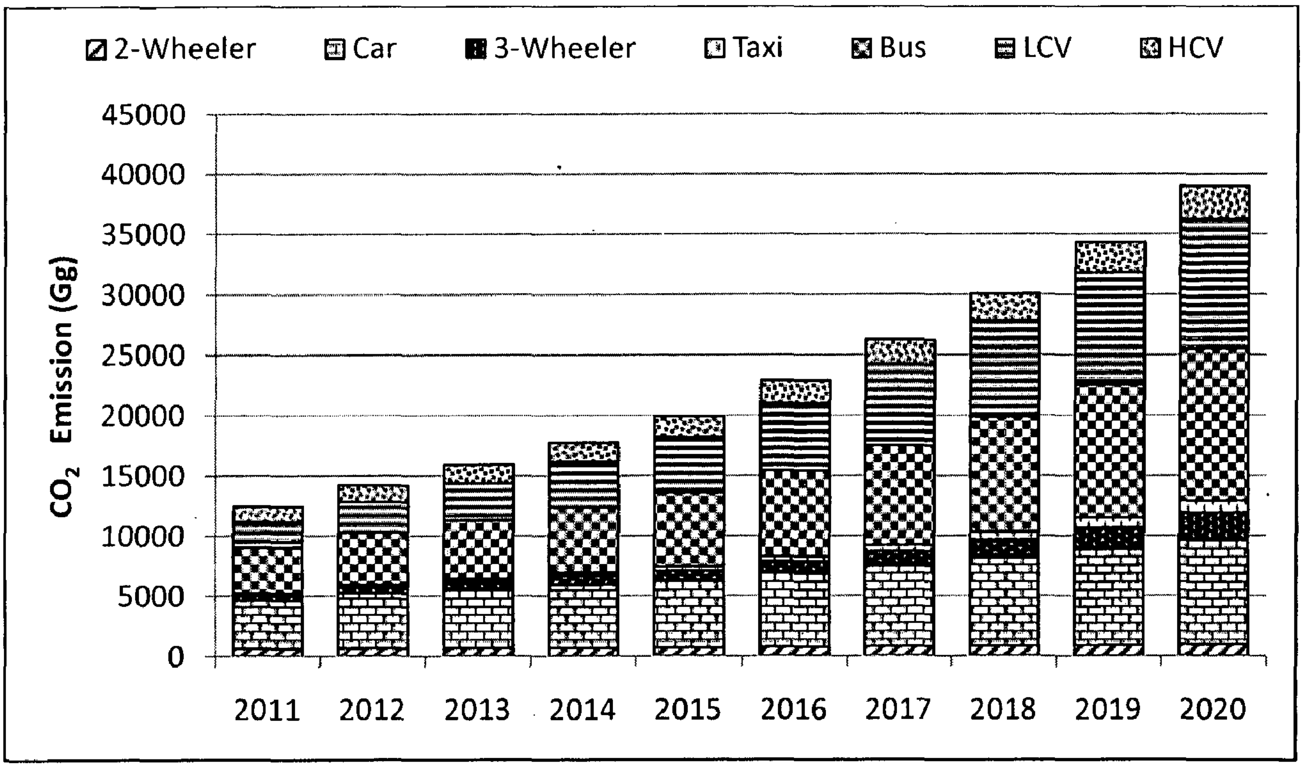


Fig. 6.9b: CO_2 emissions as per BES scenario from vehicles in megacity Delhi

6.2.2.1. Two Wheelers

Fig. 6.10 (a and b) shows the emissions of CO_2 from two wheelers in BAU and BES scenario. Fig 10a indicates that CO_2 emission in 2011 from two wheelers in BAU scenario will be 783 Gg, followed by 993 Gg in 2015 and 1319 Gg in 2020. It is observed that four-stroke motorcycles are the highest CO_2 contributor (42-43%) during 2011 to 2020, followed by two-stroke motorcycles (15-16%). Estimations show that CO_2 emission from two wheelers in 2011 will be 670 Gg, followed by 757 Gg in 2015 and 1010 Gg in 2020 in BES. As per contribution, share of four-stroke motorcycles is highest followed by two-stroke motorcycles. After observing Fig. 6.10 (a and b) it is concluded that emissions are less in BES than BAU.scenario. About 14.5% of difference has been observed during 2011 in CO_2 emissions between BAU and BES scenarios, this difference becomes ~23-24% in 2015 and 2020.

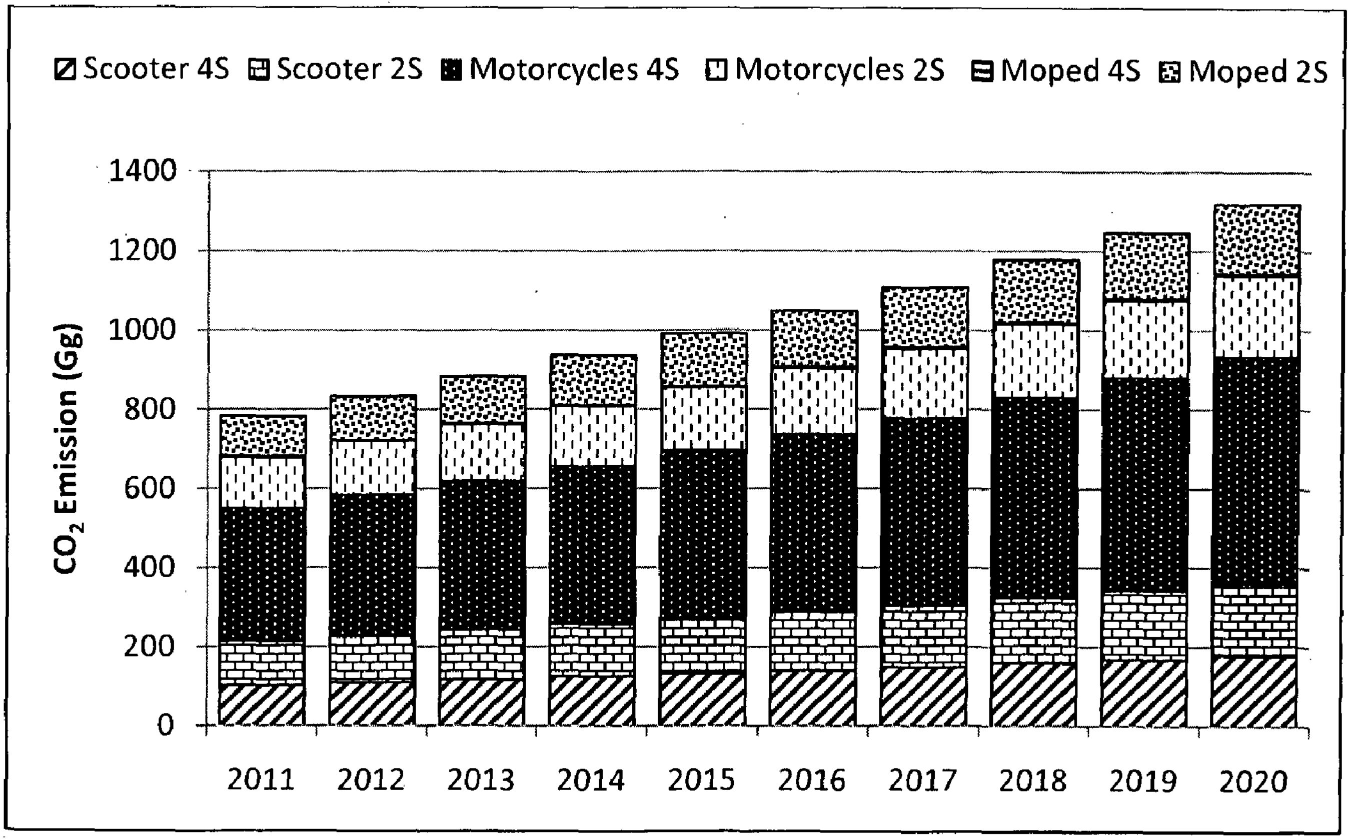


Fig. 6.10a: CO_2 emissions as per BAU scenario from two wheelers in megacity Delhi

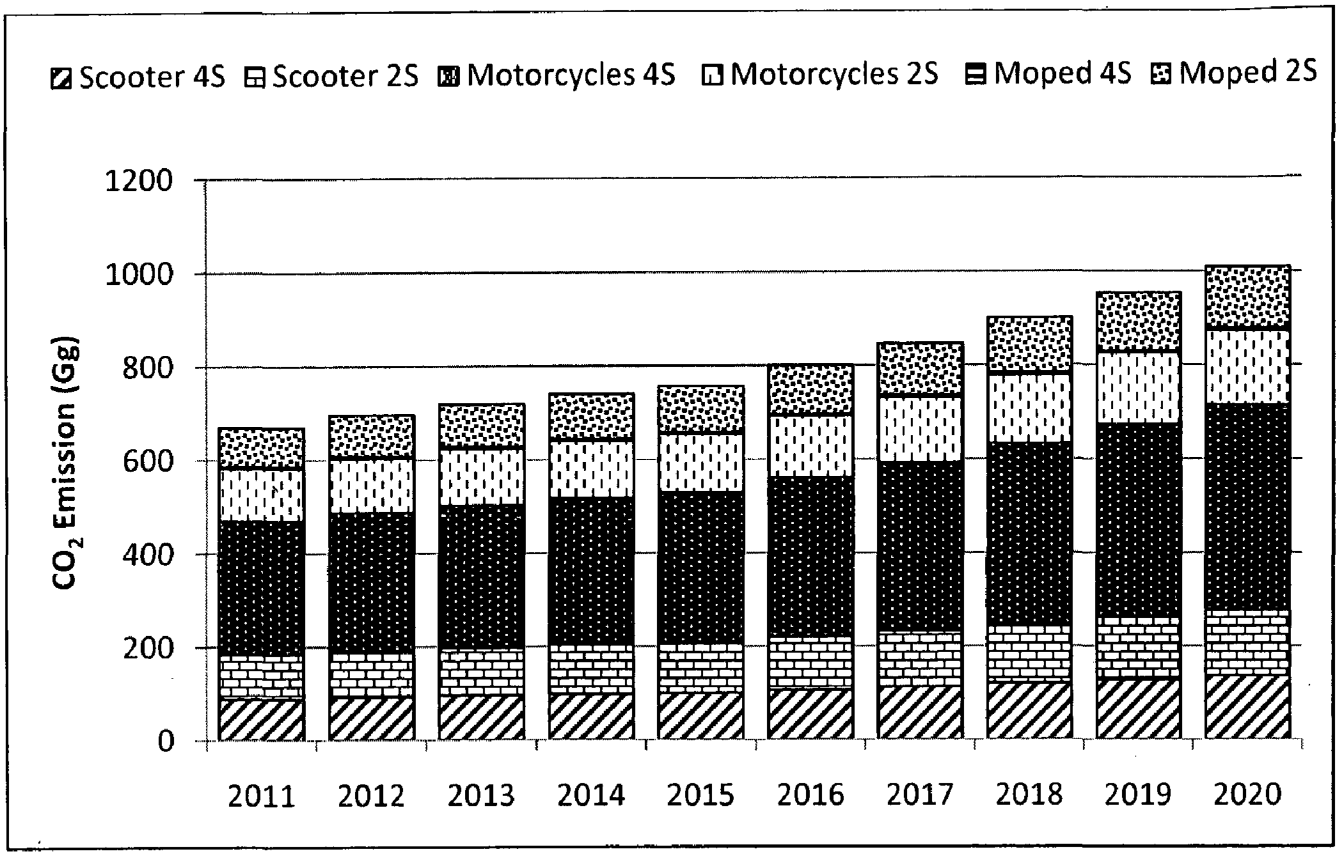


Fig. 6.10b: CO_2 emissions as per BES scenario from two wheelers in megacity Delhi

6.2.2.2. Cars

CO_2 emissions from car population in BAU and BES scenario are given in Fig. 6.11 (a and b). In BAU scenario emissions of CO_2 in 2011 will be 4736 Gg, followed by 7259 Gg in 2015 and 11263 Gg in 2020. Among all types of cars, contribution of petrol driven is projected to be highest (71-81%) followed by CNG and diesel cars. In BES scenario CO_2 emissions show a similar trend as that to BAU scenario. CO_2 emissions in 2011 will be 4007 Gg in 2011, followed by 5541 Gg in 2015 and 8658 Gg in 2020. Similar to BAU, contribution of petrol driven cars is highest among all types of cars in BES scenario. About 15.4% of difference has been observed in CO_2 emission between BAU and BES scenario during 2011. This difference will become ~23-24 % in 2015and 2020.

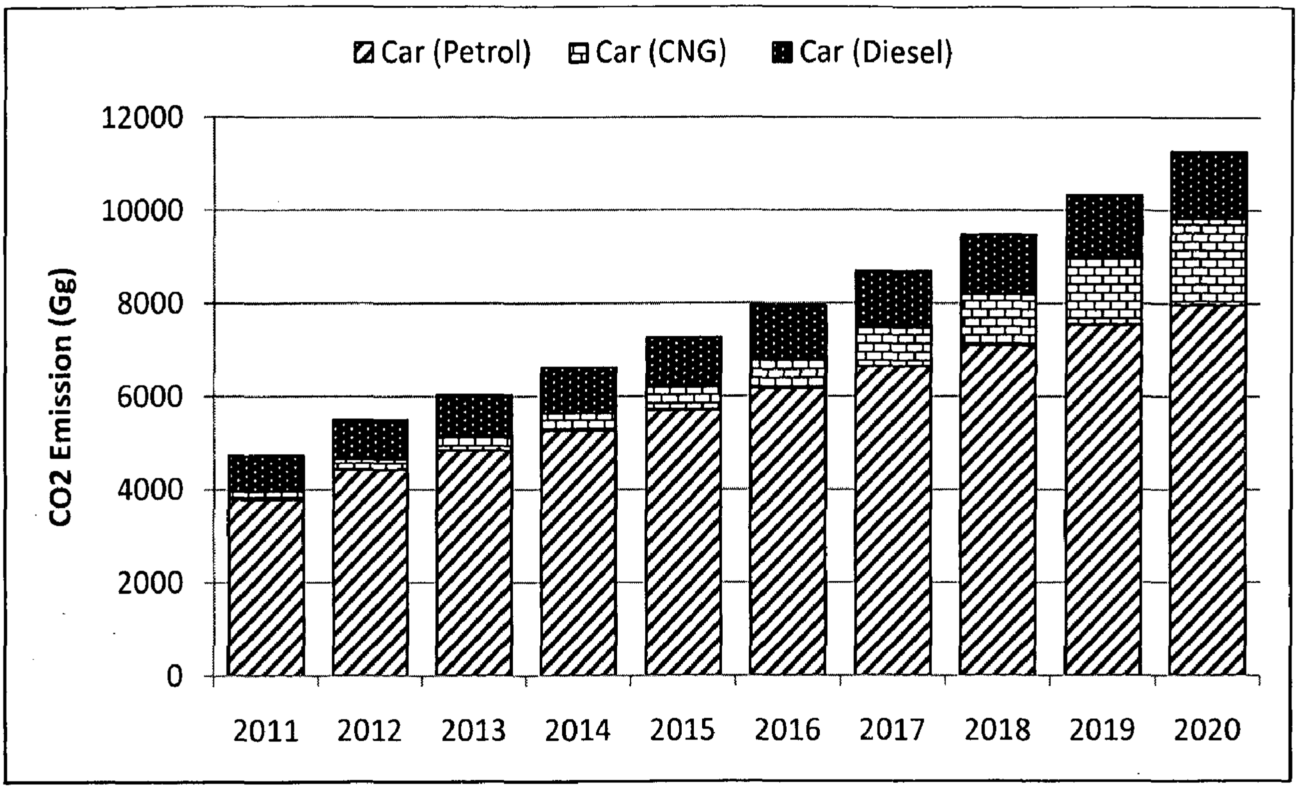


Fig. 6.11a: CO_2 emissions as per BAU scenario from cars in megacity Delhi

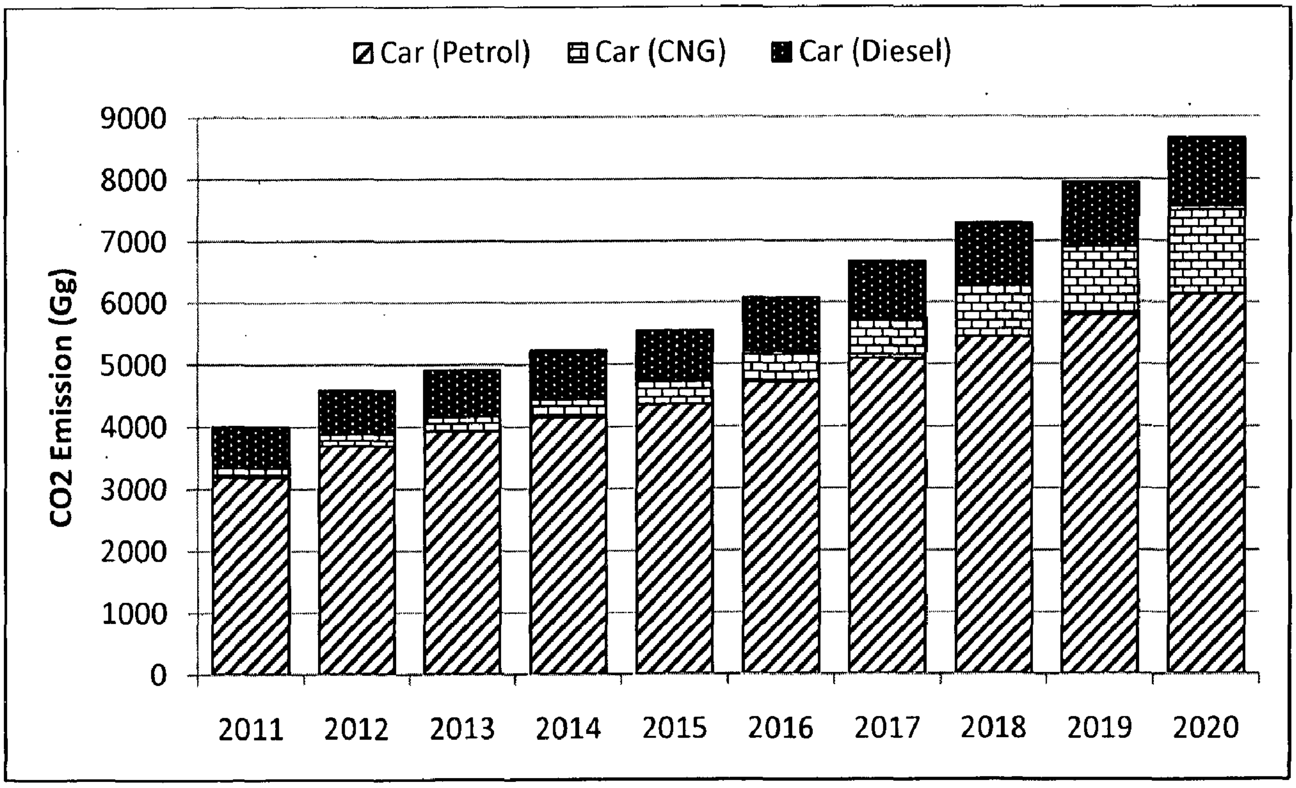


Fig. 6.11b: CO_2 emissions as per BES scenario from cars in megacity Delhi

6.2.2.3. Three Wheelers

CO_2 emissions from three wheelers in megacity Delhi in BAU scenario are given in Fig. 6.12a. It indicates that in 2011 CO_2 emissions from three wheelers will be 528 Gg, followed by 1071 Gg in 2015 and 2976 Gg in 2020. Emissions will increase with 18 to 24% growth rate from 2011 to 2020. Because of CNG implementation in 2002 it is assumed that all three wheelers running in Delhi are CNG equipped. BES scenario shows similar trend to BAU, though emissions of BES scenario are ~13-24% less in comparison to BAU scenario. CO_2 emissions from three wheelers in BES scenario will be 461 Gg in 2011, followed by 832 Gg in 2015 and 2254 Gg in 2020 (Fig. 6.12b).

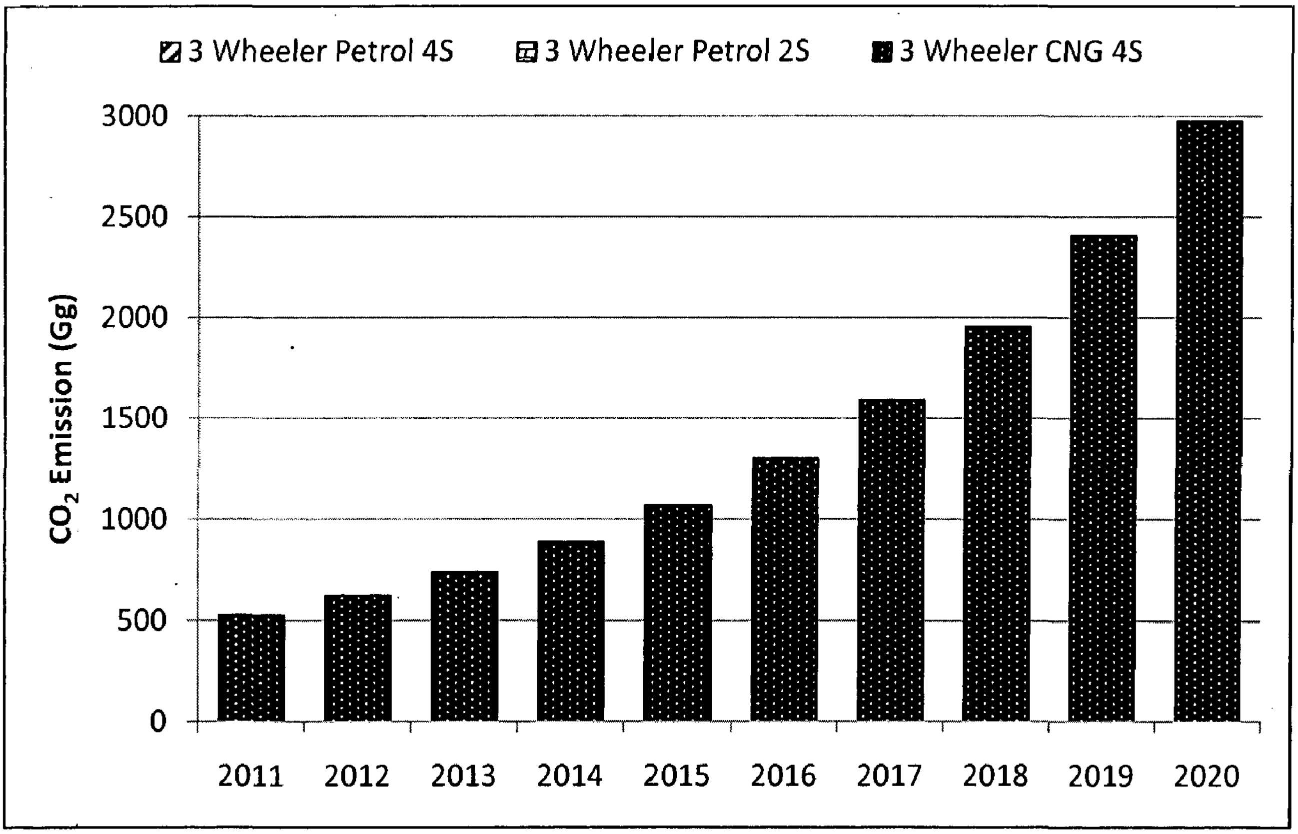


Fig. 6.12a: CO_2 emissions as per BAU scenario from three wheelers in megacity Delhi

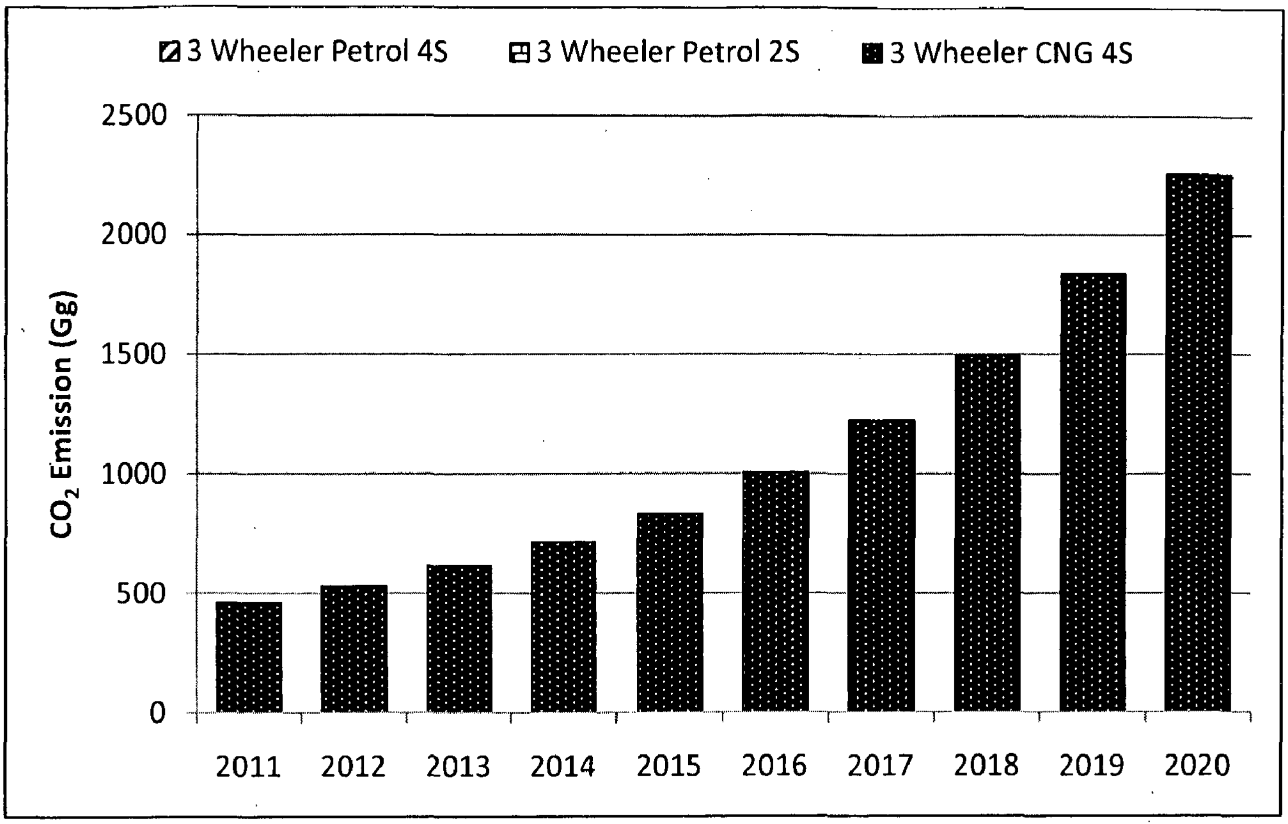


Fig. 6.12b: CO_2 emissions as per BES scenario from three wheelers in megacity Delhi

6.2.2.4. Taxis

About 191 Gg of CO_2 is projected to be emitted from taxis in BAU scenario during 2011, followed by 523 Gg in 2015 and 2012 Gg in 2020 (Fig. 6.13a). Fig. 6.13a indicates that CNG driven taxis contribute highest share of CO_2 among all types of taxis in megacity Delhi, while contribution of diesel taxis and petrol taxis are very less. Fig. 6.13b shows the BES scenario emission of CO_2 from taxis in megacity Delhi. It shows that CO_2 emissions from taxis will be 154 Gg in 2011, followed by 321 Gg in 2015 and 1042 Gg in 2020. Similar to BAU scenario contribution of CNG driven taxis is highest, followed by diesel and petrol driven taxis. CO_2 emissions in BES scenario are quite less in comparison to BAU scenario. In 2011 emission of CO_2 from BES scenario is 19% lesser than BAU scenario and this difference will be 39% in 2015 and 48% in 2020.

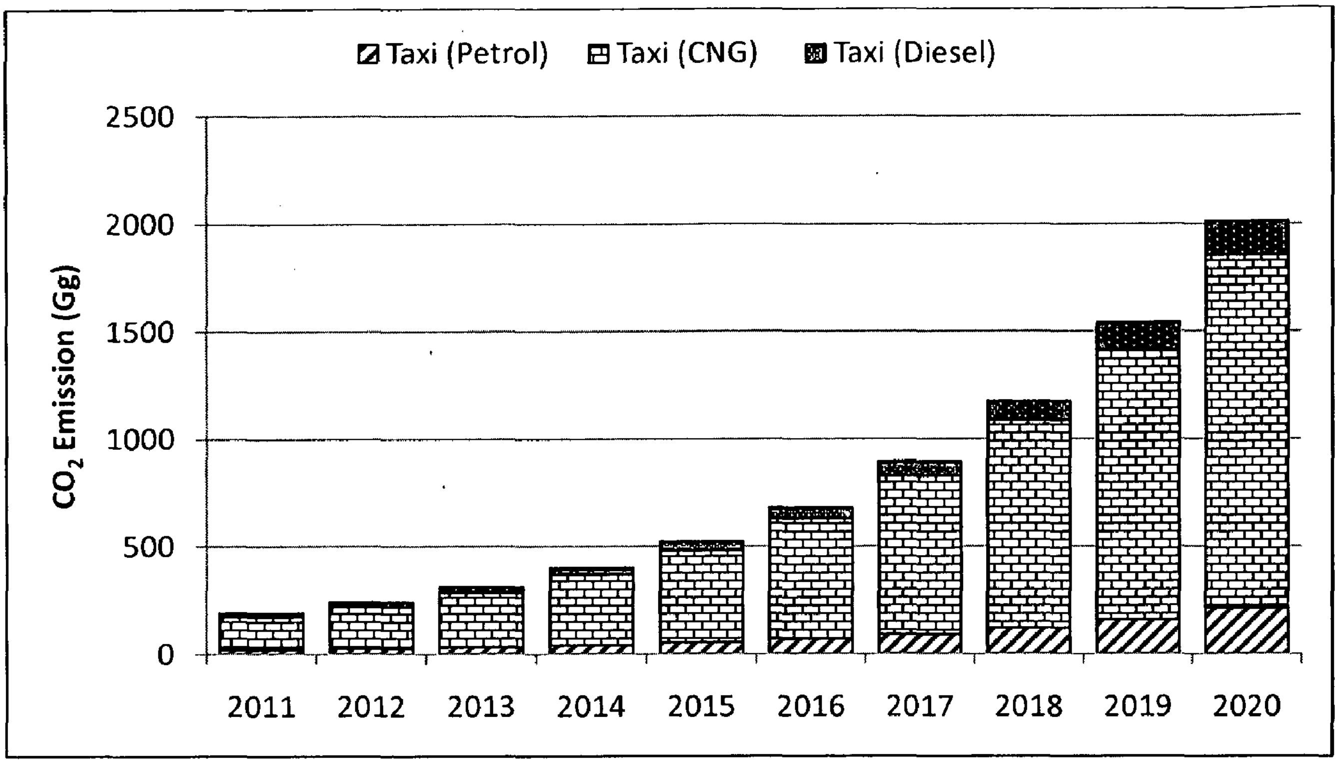


Fig. 6.13a: CO_2 emissions as per BAU scenario from taxis in megacity Delhi

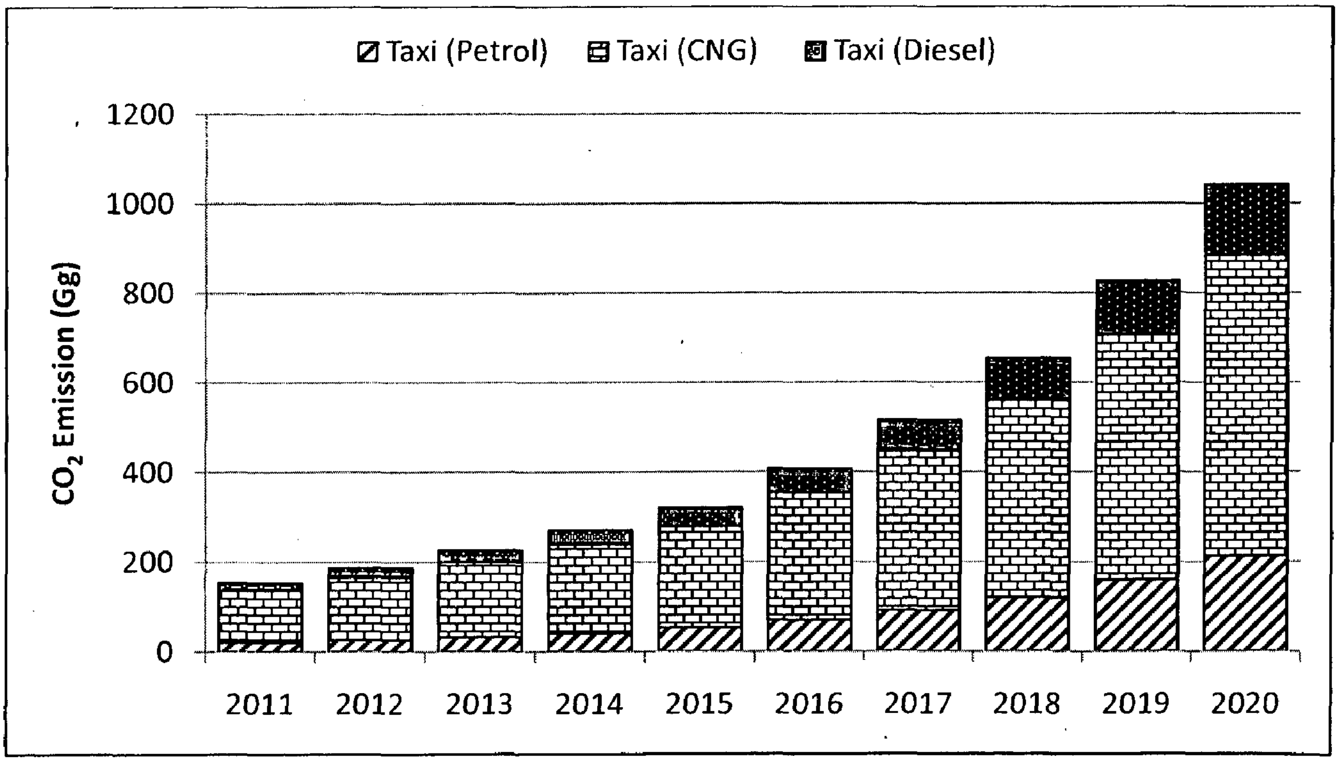


Fig. 6.13b: CO_2 emissions as per BES scenario from taxis in megacity Delhi

6.2.2.5. Buses

Emission of CO_2 from buses during 2011 to 2020 with BAU and BES scenario specifications are given in Fig. 6.14 (a and b). Fig. 6.14a shows that CO_2 emission in 2011 will be 4287 Gg, followed by 1067 Gg in 2015 and 1910 Gg in 2020. It is expected that CNG driven buses will be responsible for 86-88% of CO_2 during 2011 to 2020, while contribution of external diesel driven buses is comparatively less (~12-14%). In Fig. 6.14b CO_2 emissions from BES scenario indicates that emissions will be 3781 Gg in 2011, followed by 6151 Gg in 2015 and 1559 Gg in 2020. Similar to BAU contribution of CNG buses will be higher in future, while contribution of diesel buses will be less. Emission of CO_2 from BES scenario is 12% less than BAU scenario in 2011 followed by ~19% in 2015 and 2020.

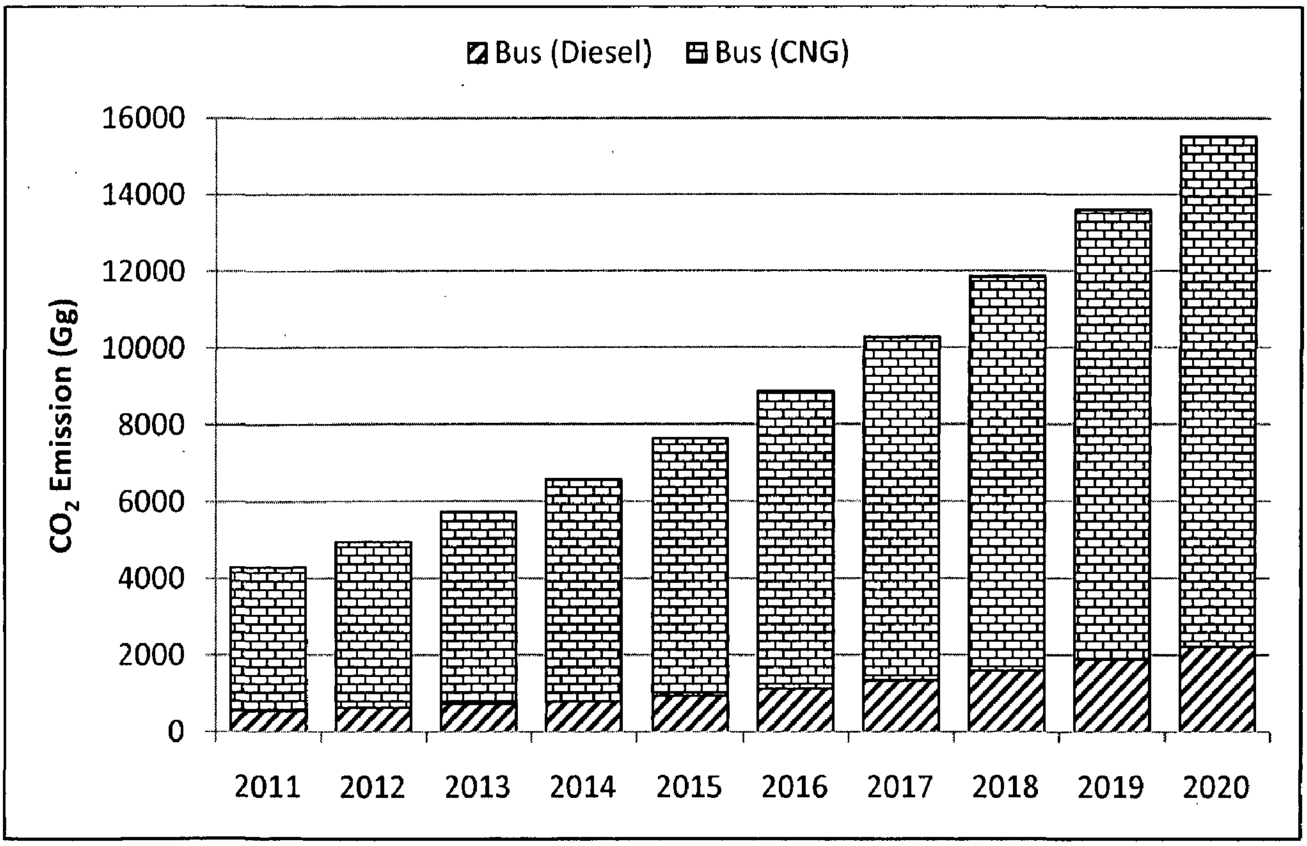


Fig. 6.14a: CO_2 emissions as per BAU scenario from buses in megacity Delhi

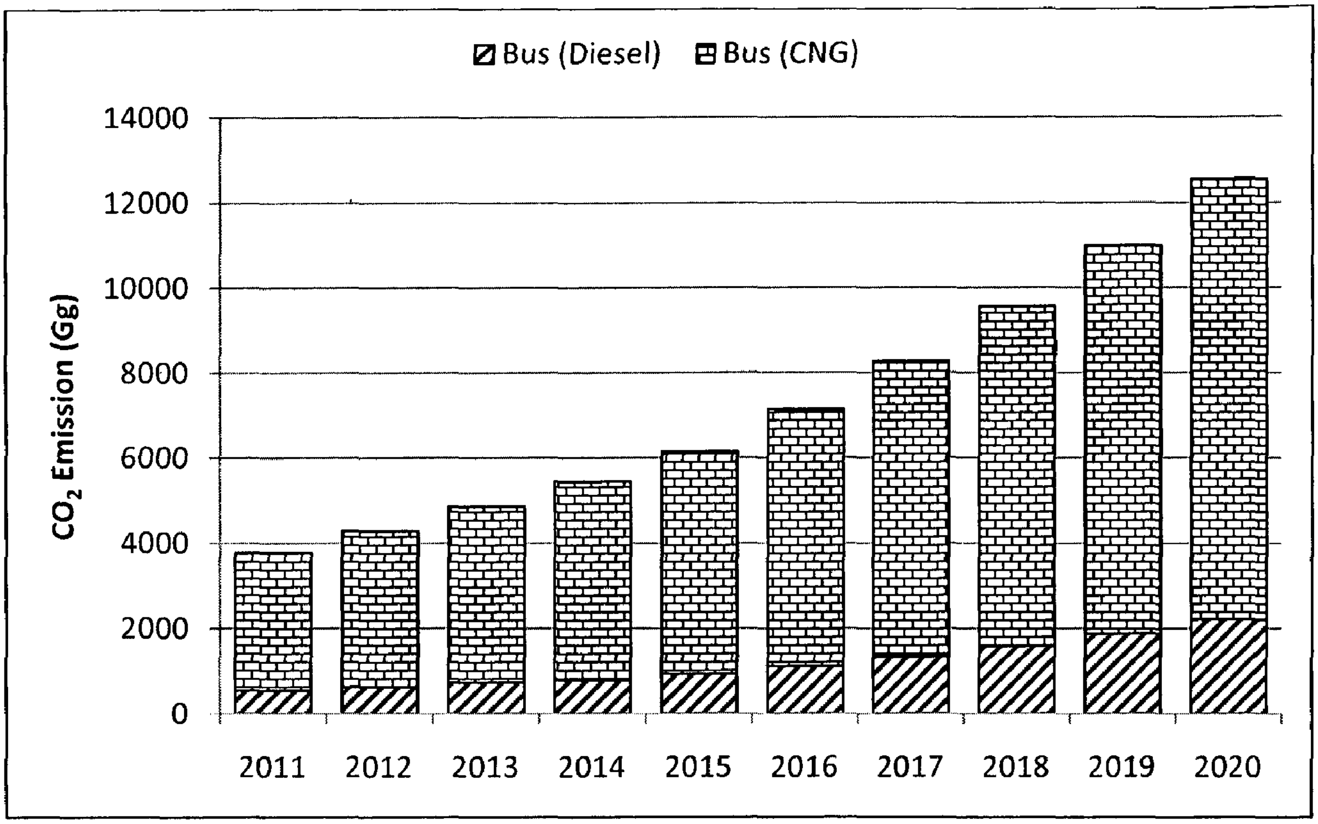


Fig. 6.14b: CO_2 emissions as per BES scenario from buses in megacity Delhi

6.2.2.6. LCVs/HCVs

About 2108 Gg of CO_2 is projected to be emitted by LCVs in 2011, followed by 4603 Gg in 2015 and 10709 Gg in 2020 (Fig. 6.15). CO_2 emissions from LCVs are rising between 2011 and 2020 with 20% growth rate. Between CNG and external diesel driven LCVs contribution of CNG driven LCVs is highest. Emission trend of HCVs is similar to that of LCVs (Fig. 6.16). In 2011 emission of CO_2 from HCVs will be 1293 Gg, followed by 1735 Gg in 2015 and 2774 Gg in 2020.

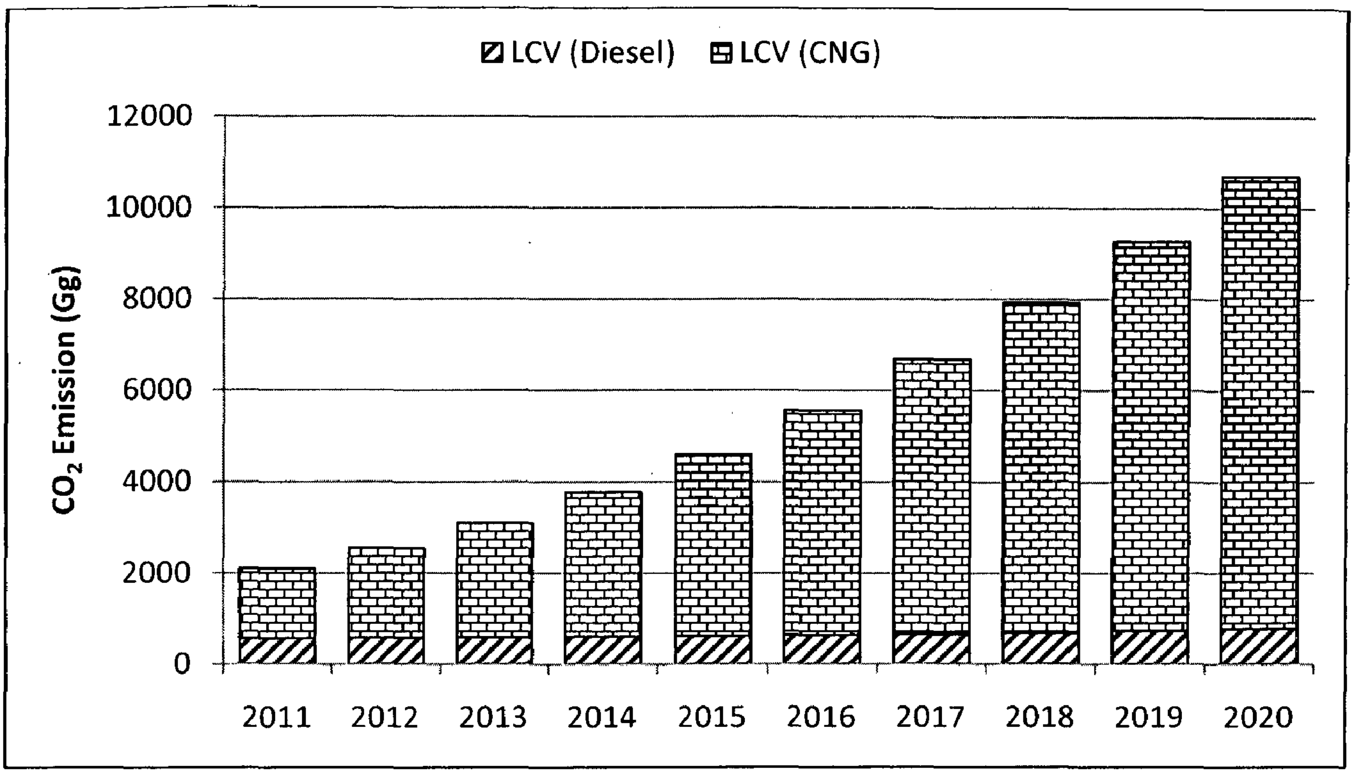


Fig. 6.15: CO_2 emissions as per BAU scenario from LCVs in megacity Delhi

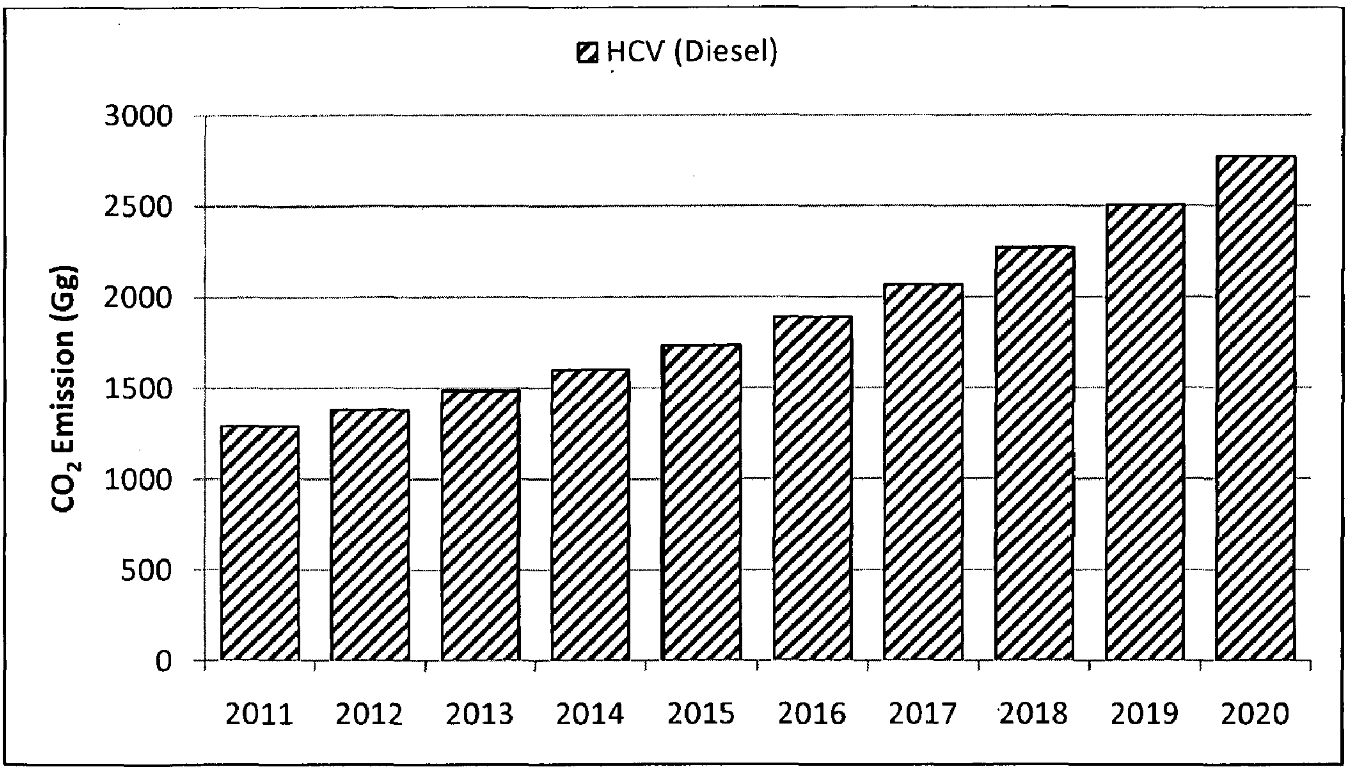


Fig. 6.16: CO_2 emissions as per BAU scenario from HCVs in megacity Delhi

6.2.3. NO_x emissions

NO_x emissions from various vehicle categories in megacity Delhi for BAU and BES scenario have been shown in Fig. 6.17 (a and b). In Fig. 6.17a, BAU scenario indicates that NO_x emissions will be 98 Gg in 2011, while it will be 156 Gg in 2015 followed by 317 Gg in 2020. NO_x emissions are growing with 14% annual average growth rate. Contribution of buses for NO_x emission is highest (38-44%) among all vehicle categories in BAU scenario, followed by LCVs and HCVs during the whole study period. In Fig. 6.17b BES scenario shows that emission of NO_x are 91 Gg in 2011 followed by 137 Gg in 2015 and 277 Gg in 2020. Similar to BAU scenario, contribution of buses is maximum (37-41%) followed by LCVs and HCVs. In 2011 NO_x emission in BES is 7% less than BAU scenario followed by 12-13% in 2015 and 2020.

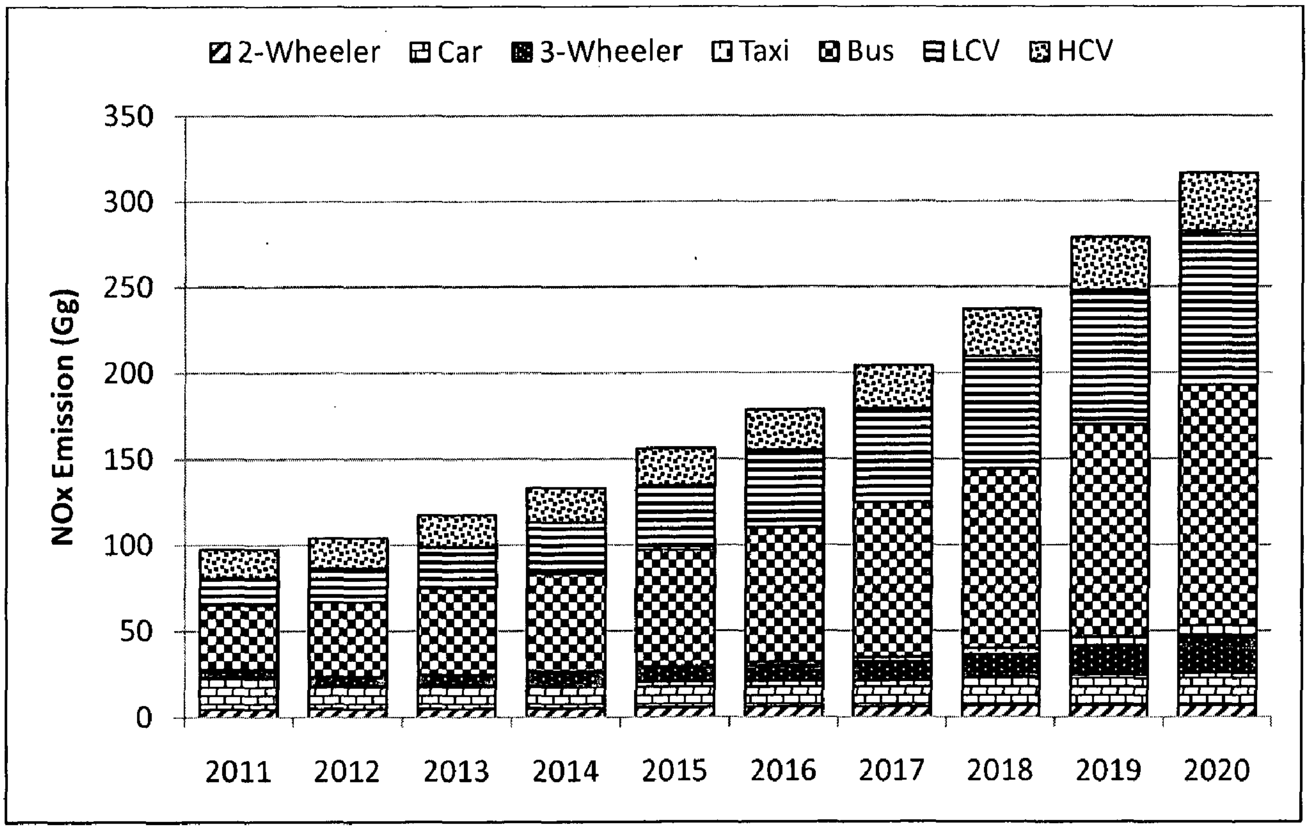


Fig. 6.17a: NO_x emissions as per BAU scenario from vehicles in megacity Delhi

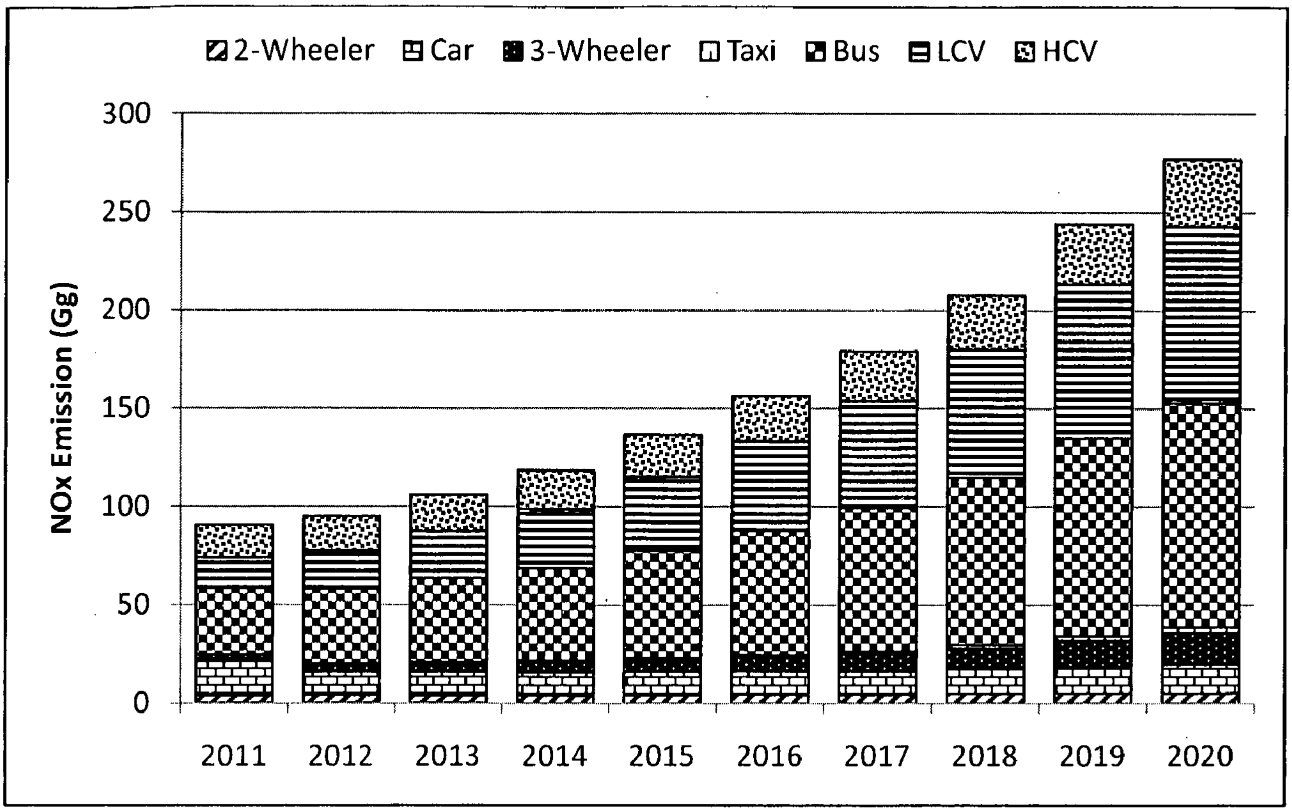


Fig. 6.17b: NO_x emissions as per BES scenario from vehicles in megacity Delhi

6.2.3.1. Two Wheelers

About 4787 Mg of NO_x is projected to be emitted from two wheelers in BAU scenario in megacity Delhi during 2011. It will be 5808 Mg in 2015 followed by 6886 Mg in 2020. The contribution of four-stroke motorcycles is highest (76-77%) among all types of two wheelers followed by four-stroke scooters. In BES scenario NO_x emissions in 2011 are projected to be 4108 Mg followed by 4497 Mg in 2015 and 5298 Mg in 2020. Similar to BAU, contribution of four-stroke motorcycles are highest for NO_x emissions among all two wheelers followed by four-stroke scooters. It is observed that emission of NO_x in BES is 14% less than BAU scenario during 2011, while in 2015 and 2020 it will be 23% less than BAU.

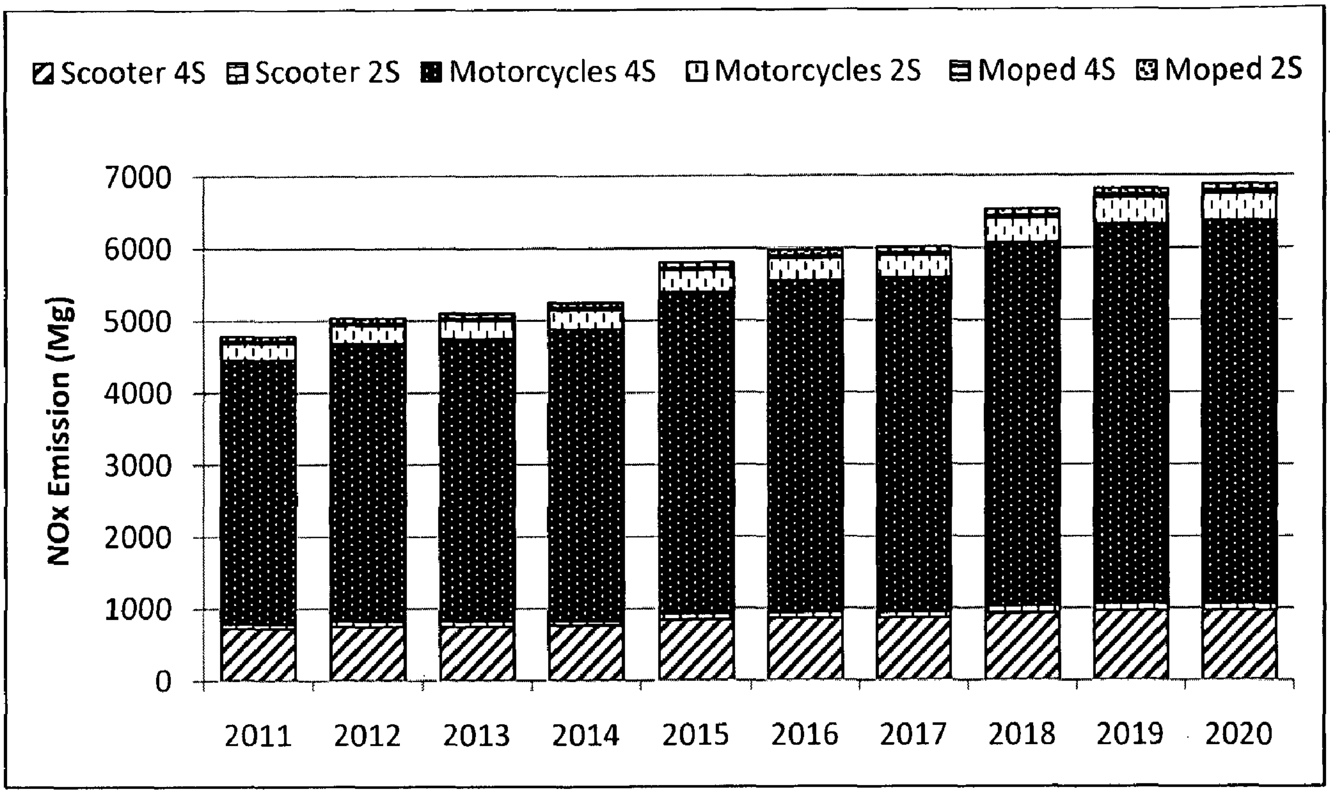


Fig. 6.18a: NO_x emissions as per BAU scenario from two wheelers in megacity Delhi

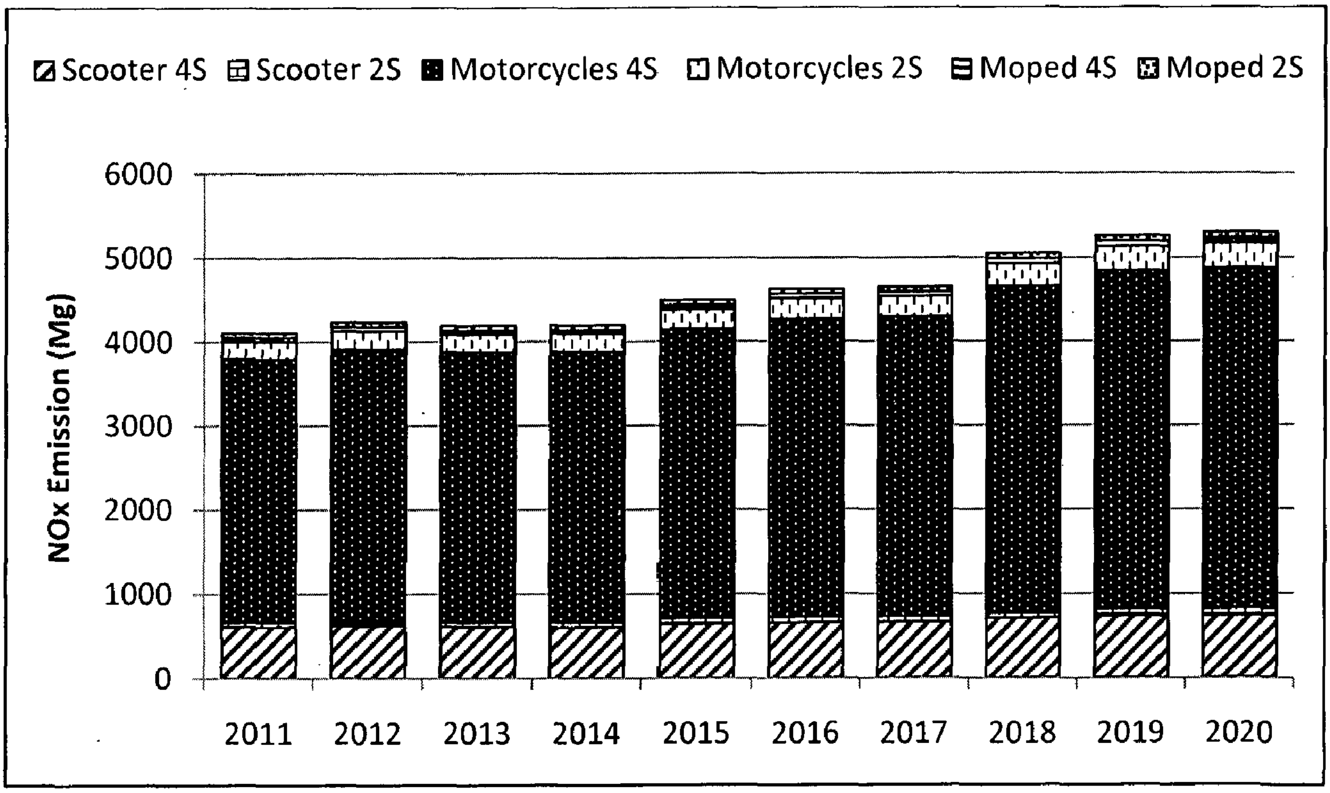


Fig. 6.18b: NO_x emissions as per BES scenario from two wheelers in megacity Delhi

6.2.3.2. Cars

Emissions of NO_x from cars in BAU scenario are given Fig. 6.19a. It indicates that in 2011 emissions of NO_x from cars will be 19 Gg, followed by 15 Gg in 2015 and 19 Gg in 2020. Between 2011 and 2012 about 28% decline is observed because of phasing out of 1991 model car population in 2012. Fig. 6.19b shows the NO_x emissions for BES scenario. In 2011 emissions of NO_x from BES scenario are projected to be 18 Gg, while in 2012 it will be 12 Gg with ~31% decline due to same reason as stated before. In 2015 NO_x emissions for BES scenario will be 12 Gg followed by 15 Gg in 2020. Similar to BAU scenario, petrol driven cars play a dominant role for NO_x emissions in BES scenario. In 2011 difference between BAU and BES scenario will be ~8%, followed by 18% in 2015 and 23% in 2020.

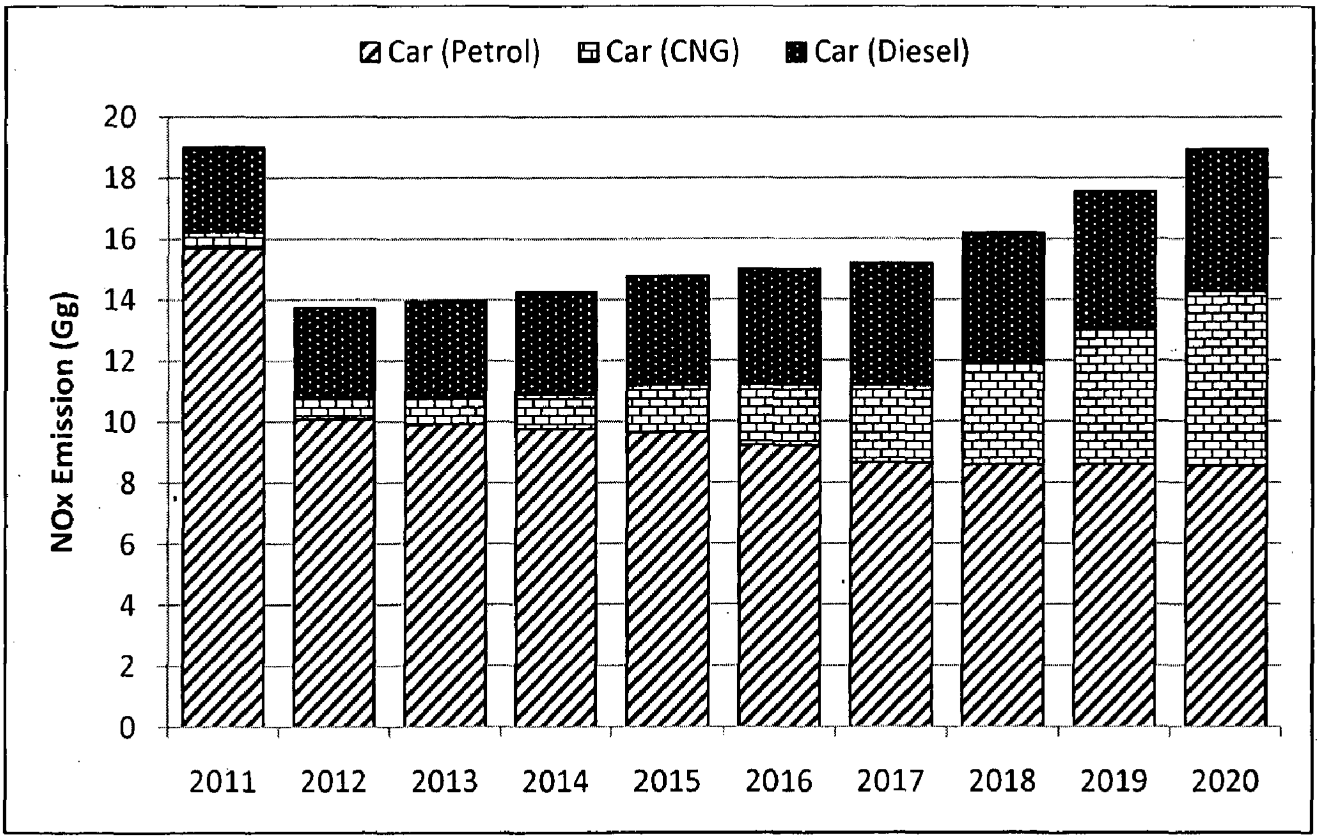


Fig. 6.19a: NO_x emissions as per BAU scenario from cars in megacity Delhi

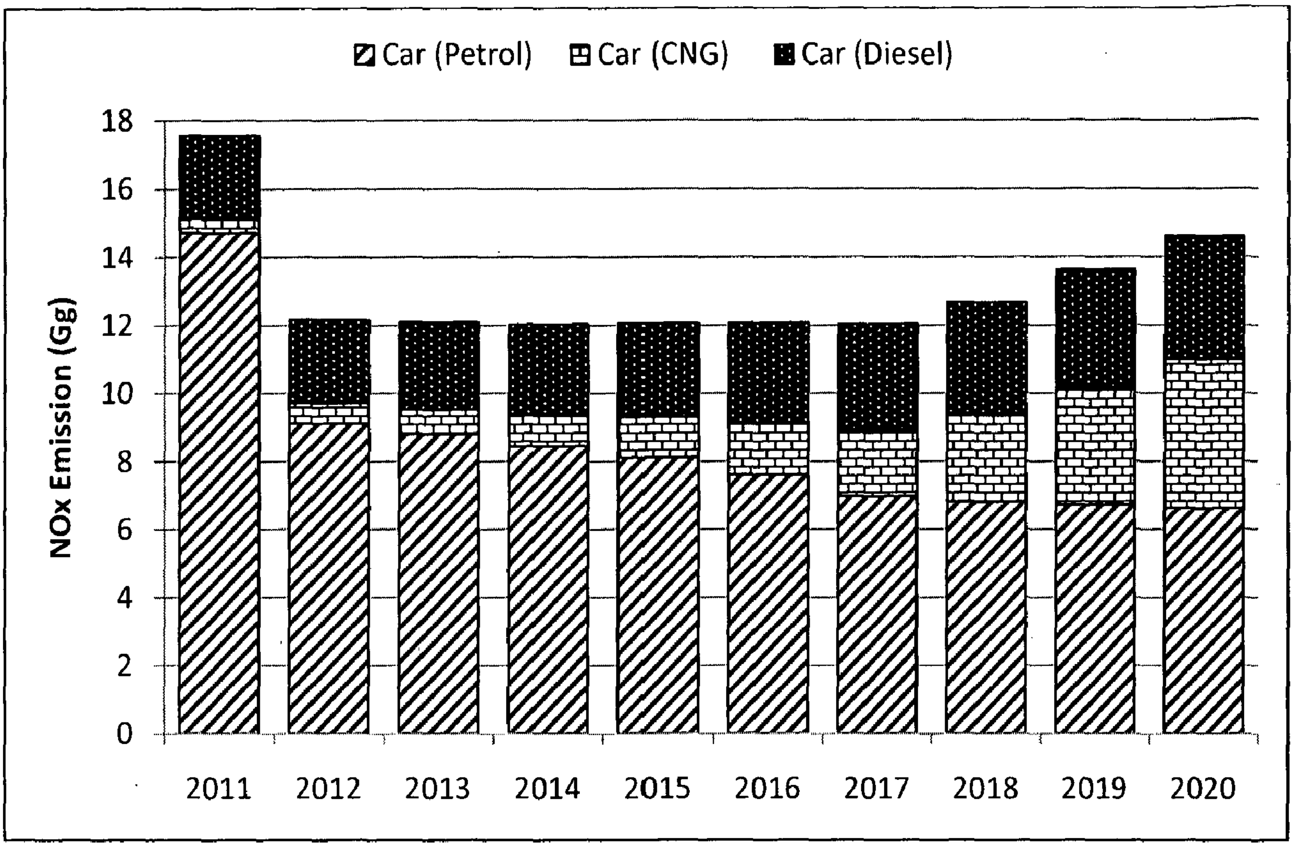


Fig. 6.19b: NO_x emissions as per BES scenario from cars in megacity Delhi

6.2.3.3. Three Wheelers

About 3 Gg of NO_x is projected to be emitted by three wheelers in 2011 according to calculations of BAU scenario. In 2015 emissions will be 7 Gg followed by 22 Gg in 2020. About 23% average growth rate is observed in NO_x emissions from three wheelers in BAU scenario during 2011 to 2020. In BES scenario NO_x emissions in 2011 will be 3 Gg followed by 6 Gg in 2015 and 16 Gg in 2020. Because of CNG implementation in megacity Delhi, all three wheelers are CNG driven. Emission of NO_x in BES is 13% less than BAU scenario in 2011 followed by 23% in 2015 and 24% in 2020.

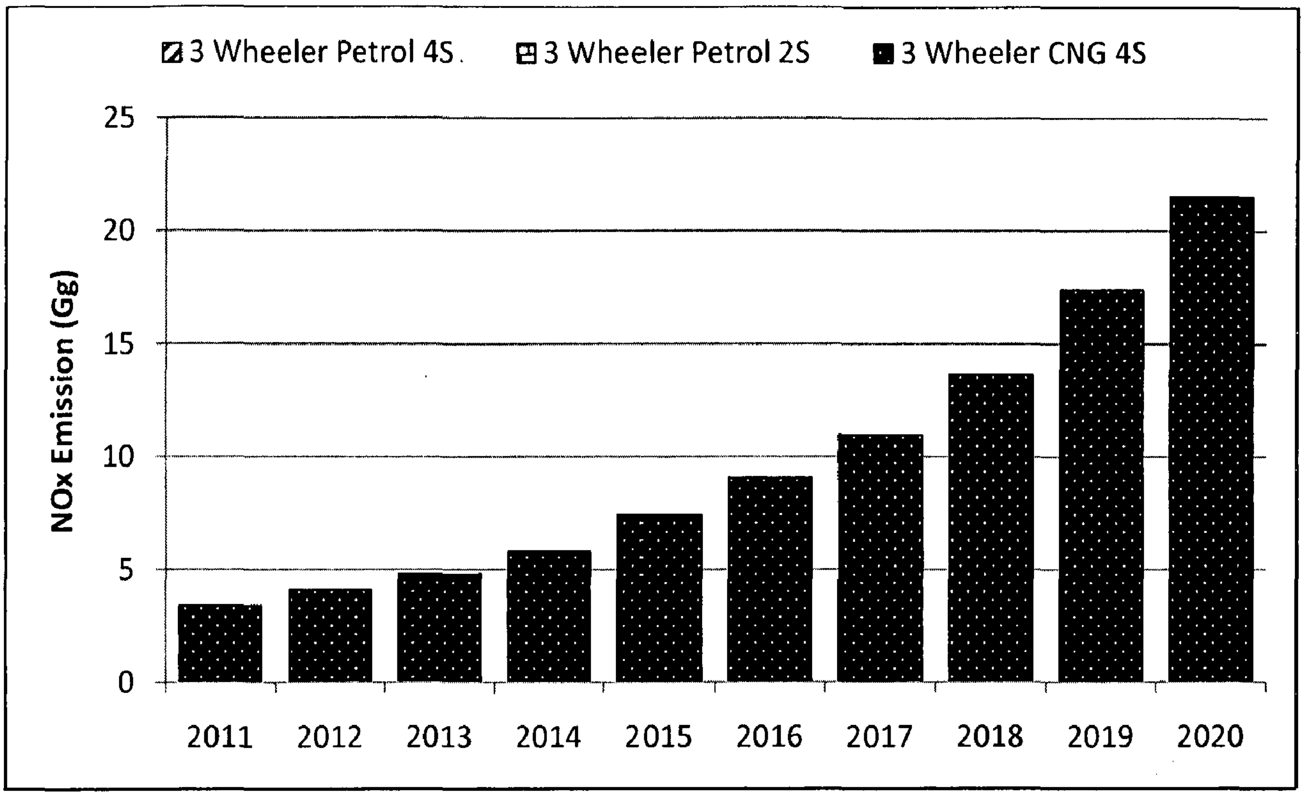


Fig. 6.20a: NO_x emissions as per BAU scenario from three wheelers in megacity Delhi

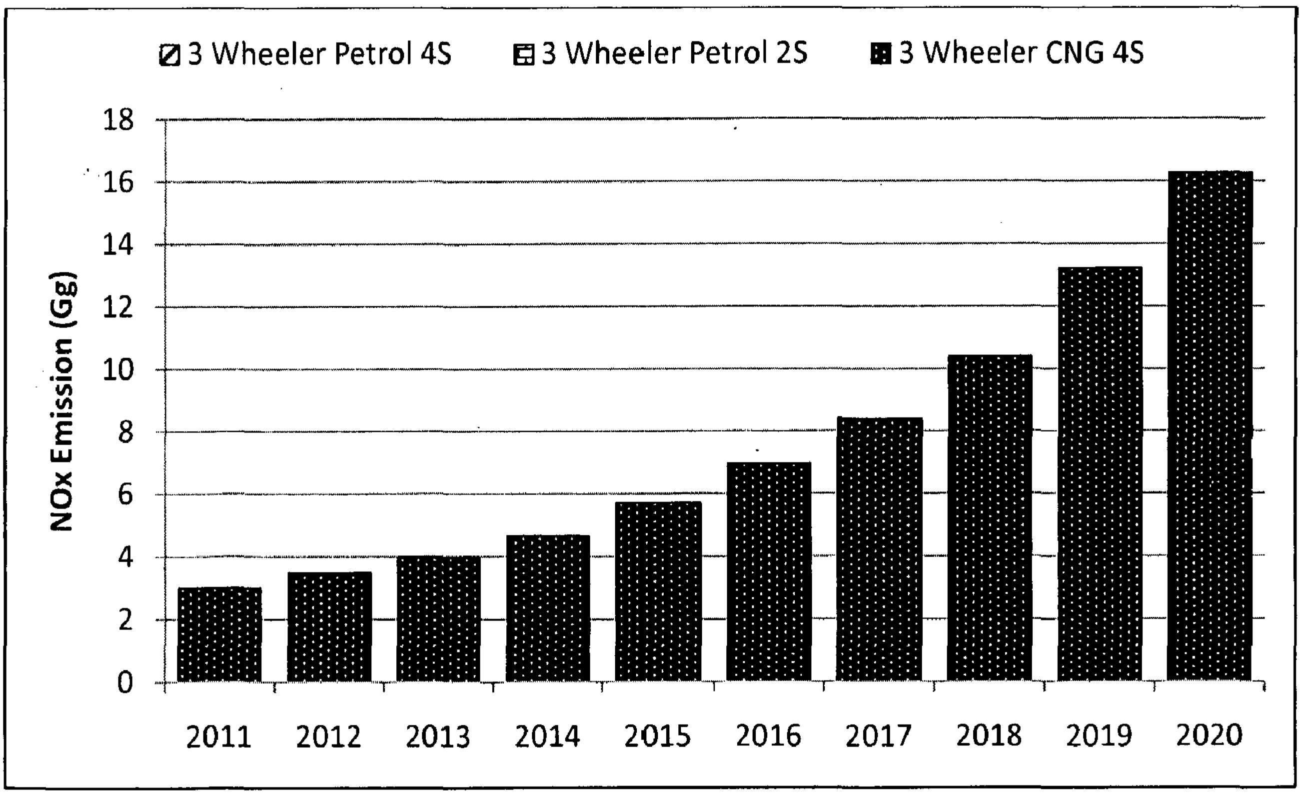


Fig. 6.20b: NO_x emissions as per BES scenario from three wheelers in megacity Delhi

6.2.3.4. Taxis

NO_x emissions from taxis in 2011 in BAU scenario will be 552 Mg followed by 1509 Mg in 2015 and 5615 Mg in 2020 (Fig. 6.21a). About 29% of annual average growth rate has been observed in NO_x emissions from BAU scenario during 2011 to 2020. As the population of CNG driven taxis is higher, its contribution in NO_x emissions is also highest (85-88%) among all type of taxis, while contribution of external taxis (diesel, petrol) is very less. NO_x emission from taxis in BES scenario is given in Fig. 6.21b. It indicates that in 2011 emissions will be 441 Mg followed by 885 Mg in 2015 and 2706 Mg in 2020. The annual average growth for increasing NO_x emissions from taxis in BES scenario is ~22%. Contribution of CNG driven taxis is projected to be highest (74-82%) among all taxis in BES scenario also. Emission of NO_x in BAU scenario is 20% higher than BES in 2011 and this percentage increases to 41% in 2015 and 52% in 2020.

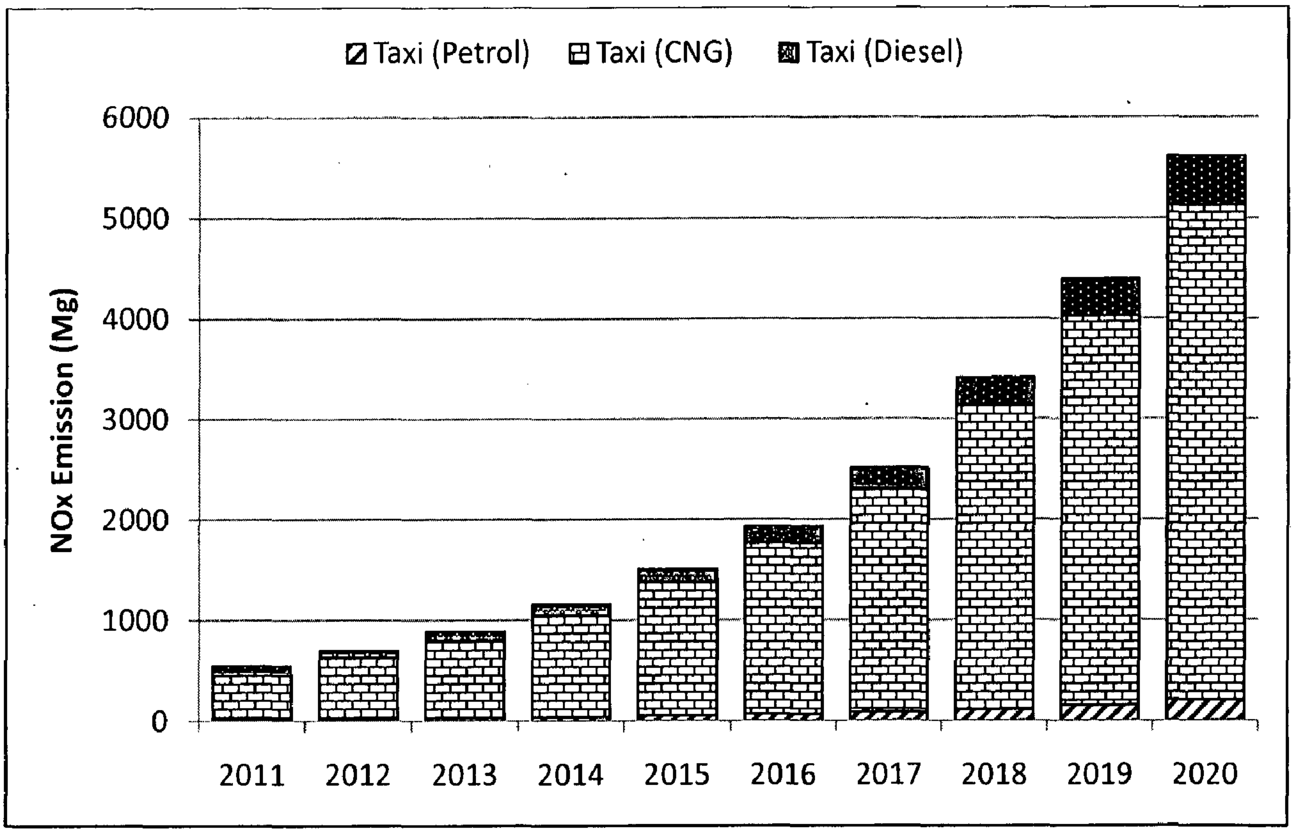


Fig. 6.21a: NO_x emissions as per BAU scenario from taxis in megacity Delhi

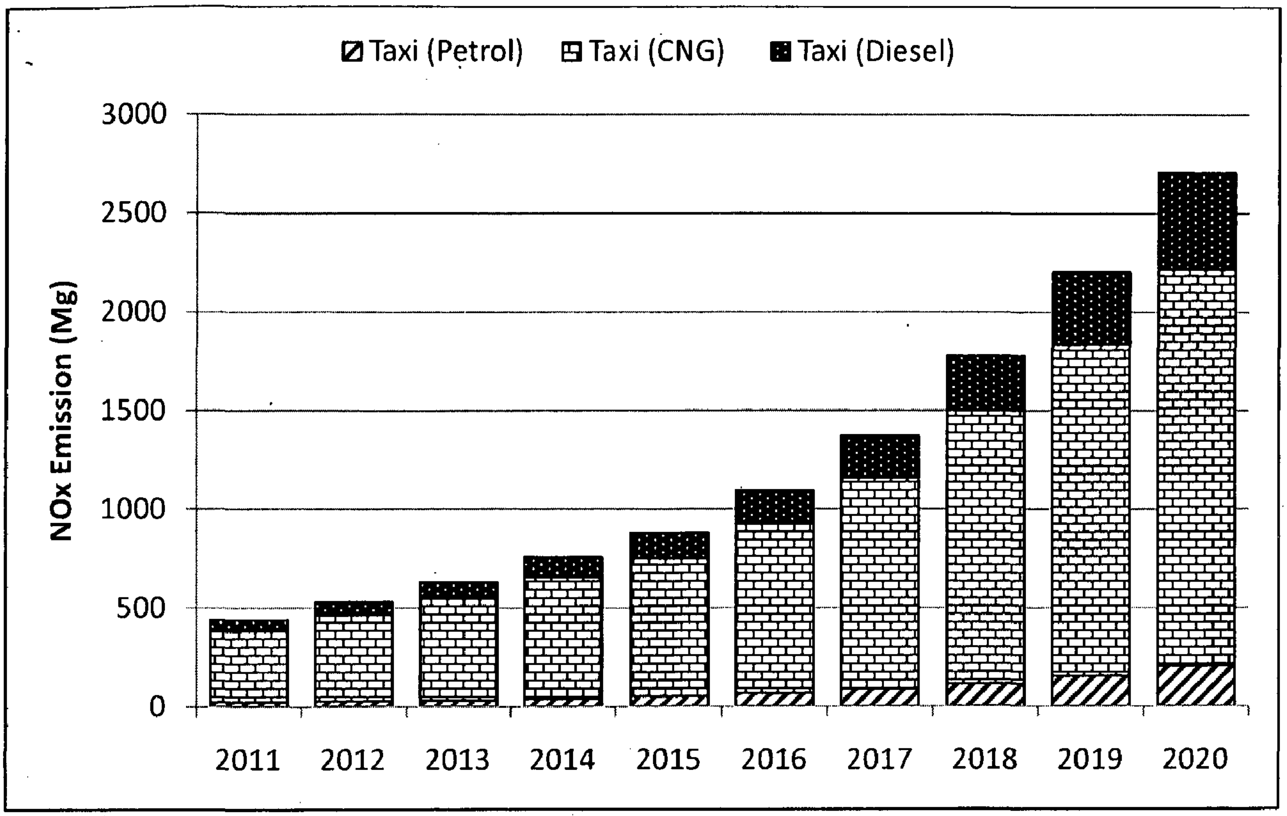


Fig. 6.21b: NO_x emissions as per BES scenario from taxis in megacity Delhi

6.2.3.5. Buses

In 2011 emissions of NO_x from buses in BAU scenario will be 38 Gg followed by 68 Gg in 2015 and 140 Gg in 2020. About 16% of average annual growth rate is expected during 2011 to 2020 in NO_x emissions. Contribution of CNG driven buses is higher in NO_x emission in BAU scenario. Emissions of NO_x from buses in BES scenario is given in Fig. 6.22a. It indicates that in 2011 emission will be 33 Gg followed by 55 Gg in 2015 and 114 Gg in 2020. Similar to BAU contribution of CNG buses is higher in BES scenario. Emission of NO_x from buses in BES is projected to be 11% less than BAU scenario and this percentage will be 18-19% in 2015 and 2020.

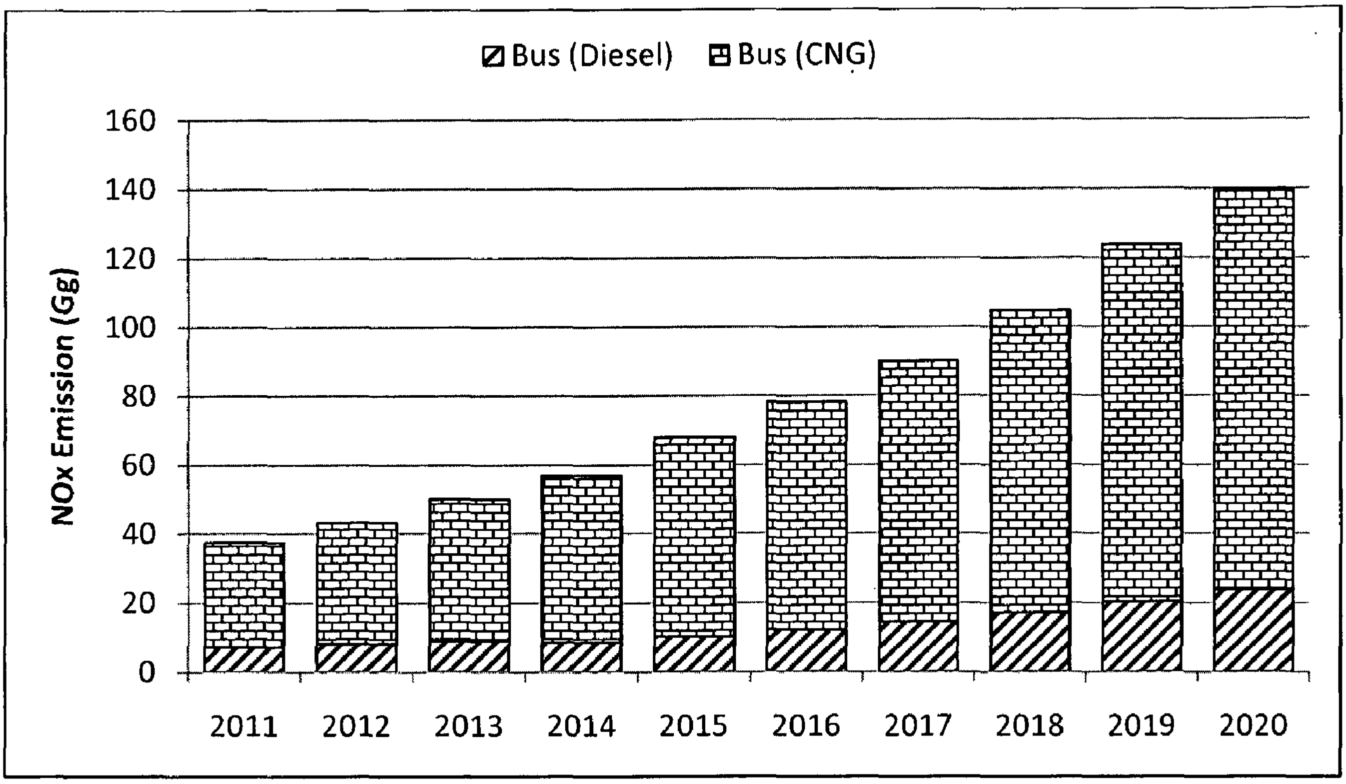


Fig. 6.22a: NO$_x$ emissions as per BAU scenario from buses in megacity Delhi

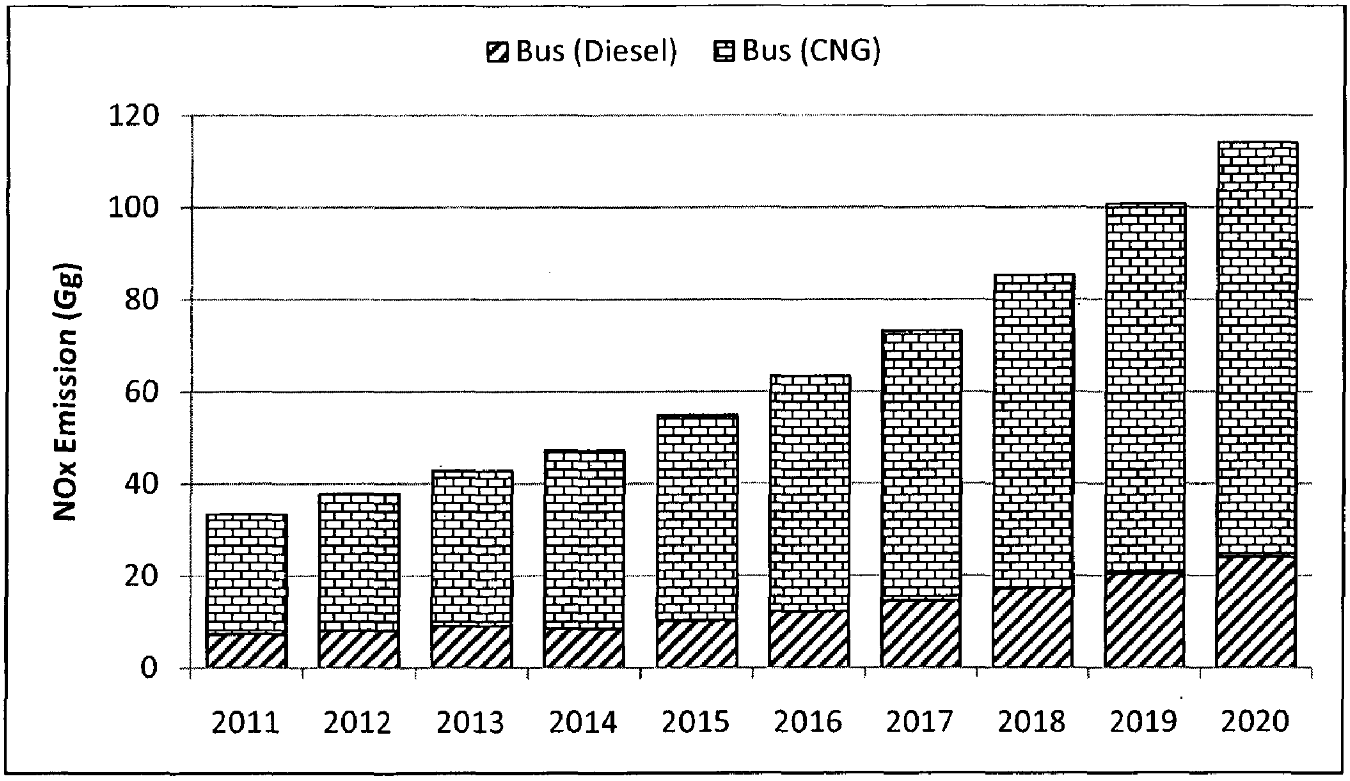


Fig. 6.22b: NO$_x$ emissions as per BES scenario from buses in megacity Delhi

6.2.3.6. LCVs/HCVs

Emissions of NO_x from LCVs and HCVs in megacity Delhi during 2011 and 2020 are given in Fig. 6.23 and 6.24. During 2011 NO_x emissions from LCVs are estimated to be 16 Gg followed by 37 Gg in 2015 and 90 Gg in 2020. About 29% of annual average growth rate is observed in NO_x emissions from LCVs during 2011 to 2020. Contribution of CNG driven LCVs is higher from 2011 to 2020. Fig. 6.24 shows the emissions of NO_x from HCVs population. It indicates that in 2011 NO_x emissions are ~17 Gg, ~21 Gg in 2015 and ~34 Gg in 2020.

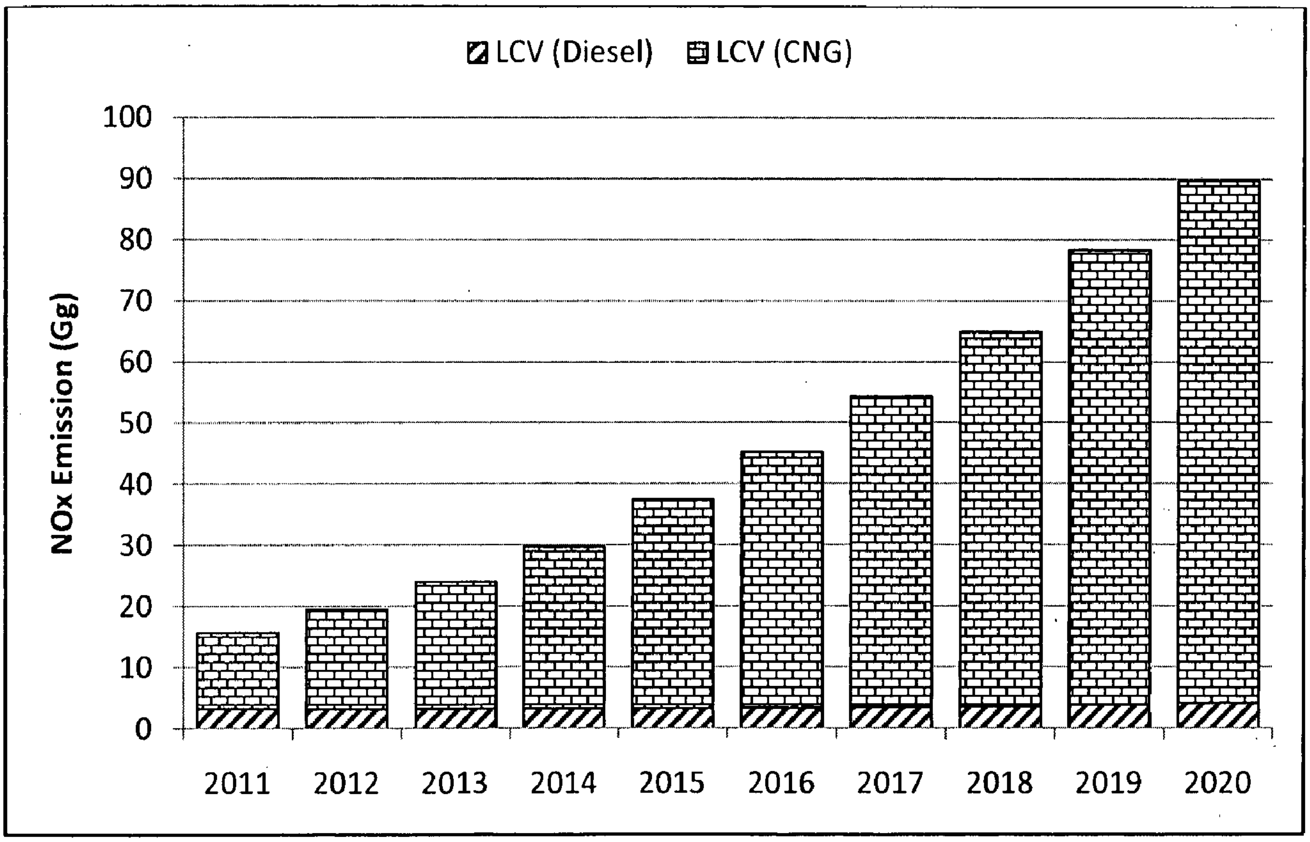


Fig. 6.23: NO_x emissions as per BAU scenario from LCVs's in megacity Delhi

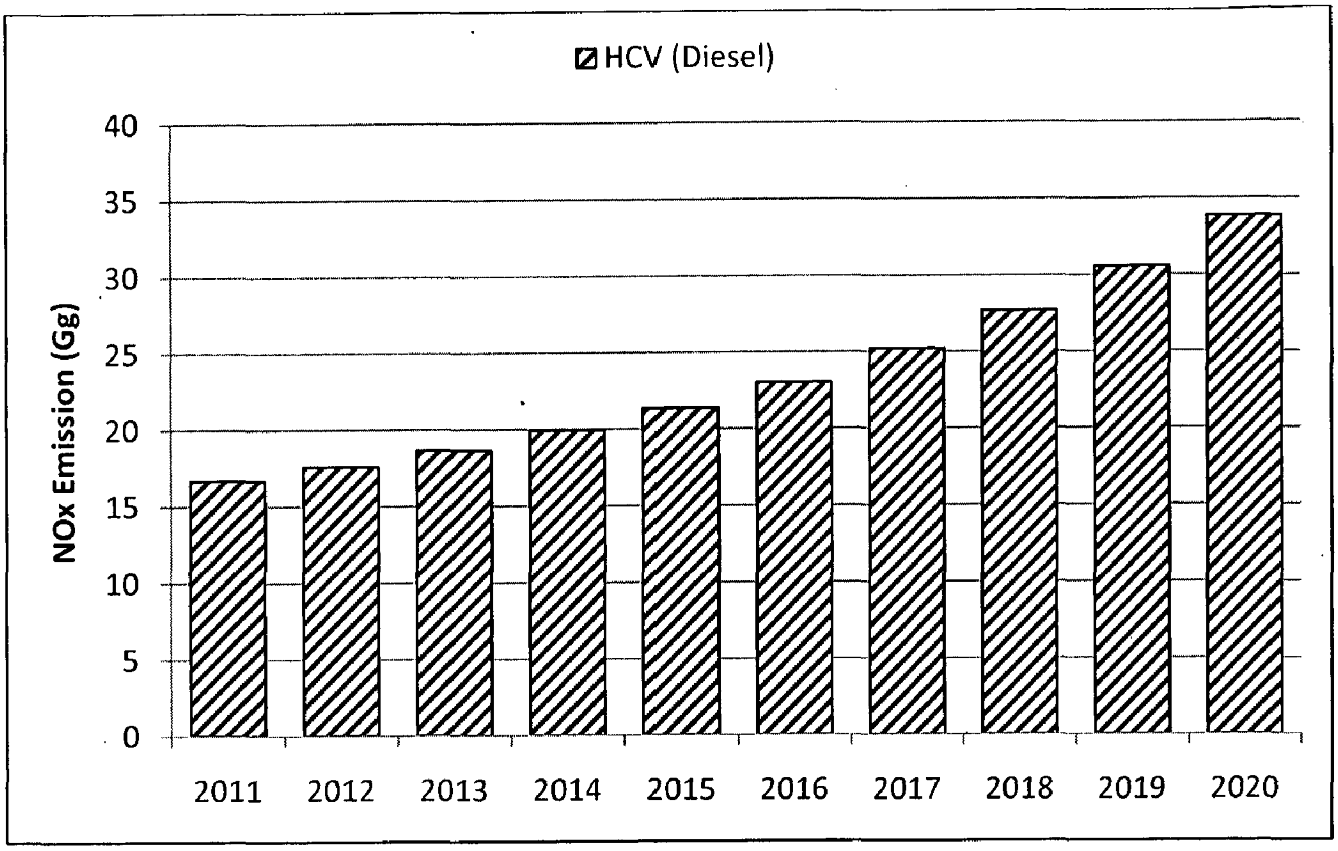


Fig. 6.24: NO_x emissions as per BAU scenario from HCVs's in megacity Delhi

6.2.4. HC emissions

Emissions of HC from various vehicle categories in BAU and BES scenario are shown in Fig. 6.25 (a and b). Fig.6.25a shows that HC emissions from various vehicles in megacity Delhi will be 80 Gg in 2011, 110 Gg in 2015 and 194 Gg in 2020. About 10.4 % of annual average growth rate is observed in HC emissions from vehicles in BAU scenario. Fig. 6.25b indicates that in 2011 HC emissions from vehicles in BES scenario will be 71 Gg, followed by 90 Gg in 2015 and 160 Gg in 2020. About 9.5% of annual average growth rate is observed in HC emissions during 2011 to 2020. Two wheelers are expected to play a dominant role for HC emissions from 2011 to 2017, followed by buses from 2018 onwards in both BES and BAU scenario. After comparing BAU and BES scenario it is found that in 2011 the difference between BAU and BES scenario is 10.5%, followed by 17.5% in 2015 and 2020.

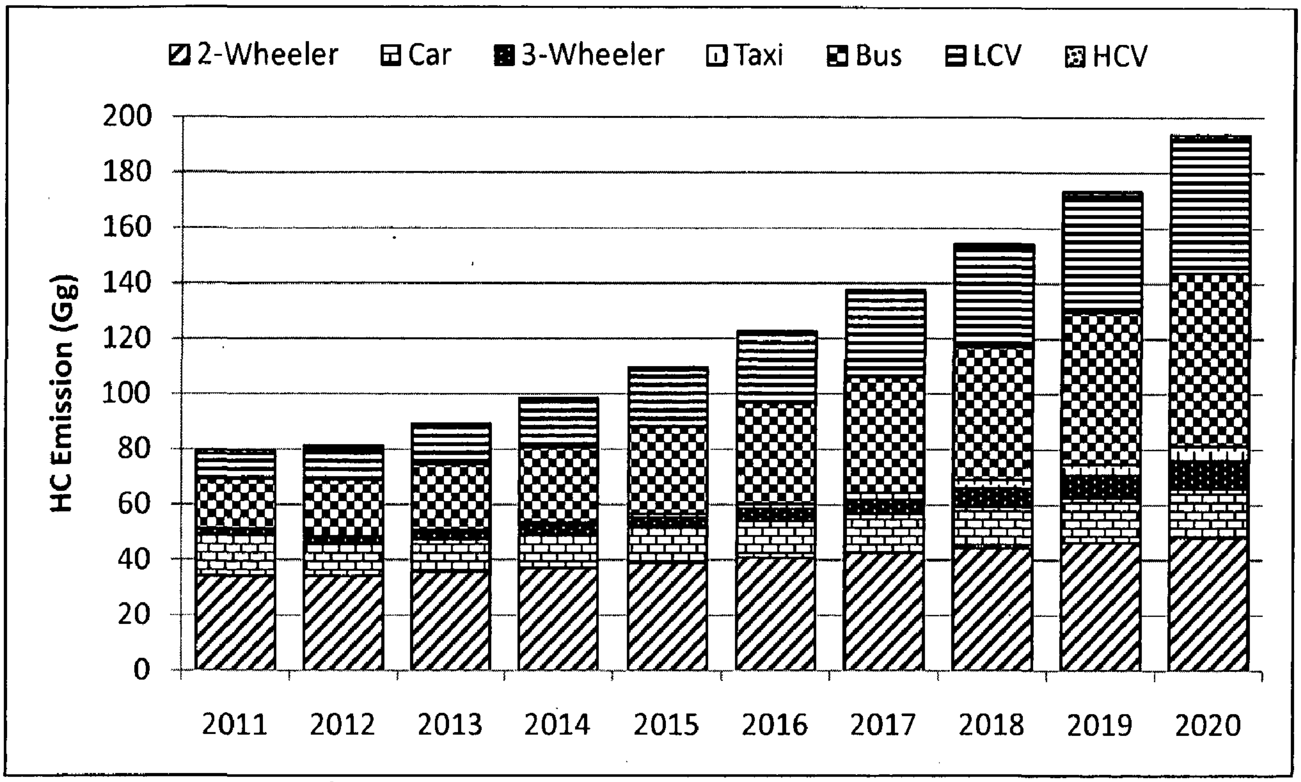


Fig. 6.25a: HC emissions as per BAU scenario from vehicles in megacity Delhi

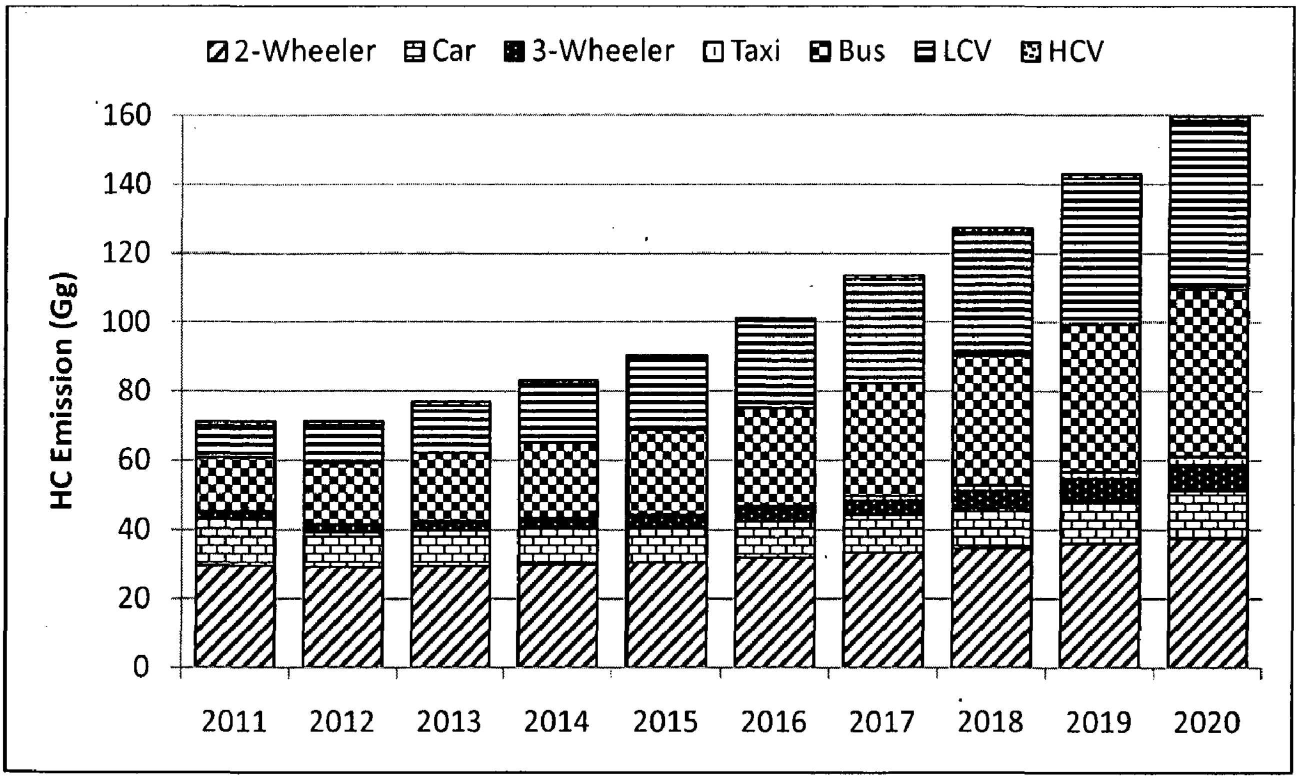


Fig. 6.25b: HC emissions as per BES scenario from vehicles in megacity Delhi

6.2.4.1. Two Wheelers

Emission of HC from two wheelers in BAU and BES scenario is presented in Fig. 6.26 (a and b). HC emissions from two wheelers in BAU scenario are projected to be 34 Gg in 2011 followed by 39 Gg in 2015 and 48 Gg in 2020. About 4% of annual average growth is observed during 2011 to 2020 in BAU scenario. Two-strokes have the highest share (39-43%) among all two wheeler types during the whole study period. Fig. 6.26b shows the emission of HC from two wheelers in BES scenario. In 2011 emissions will be 29.6 Gg followed by 30.4 Gg in 2015 and 37 Gg in 2020. About 3% of annual average growth rate has been found in HC emissions in BES scenario during 2011 to 2020. Emission of HC in BES is 13% less than BAU scenario in 2011 followed by 22-23% in 2015 and 2020.

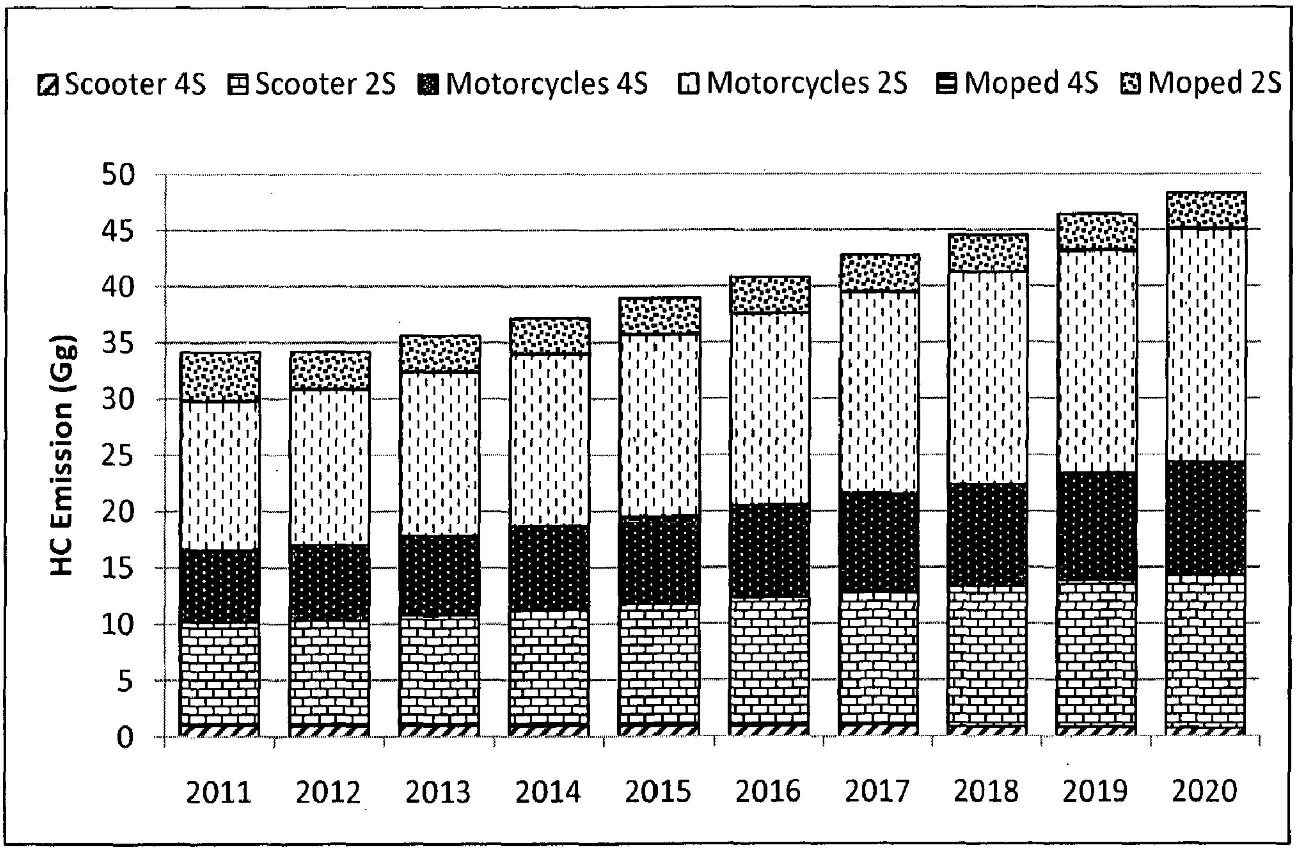


Fig. 6.26a: HC emissions as per BAU scenario from two wheelers in megacity Delhi

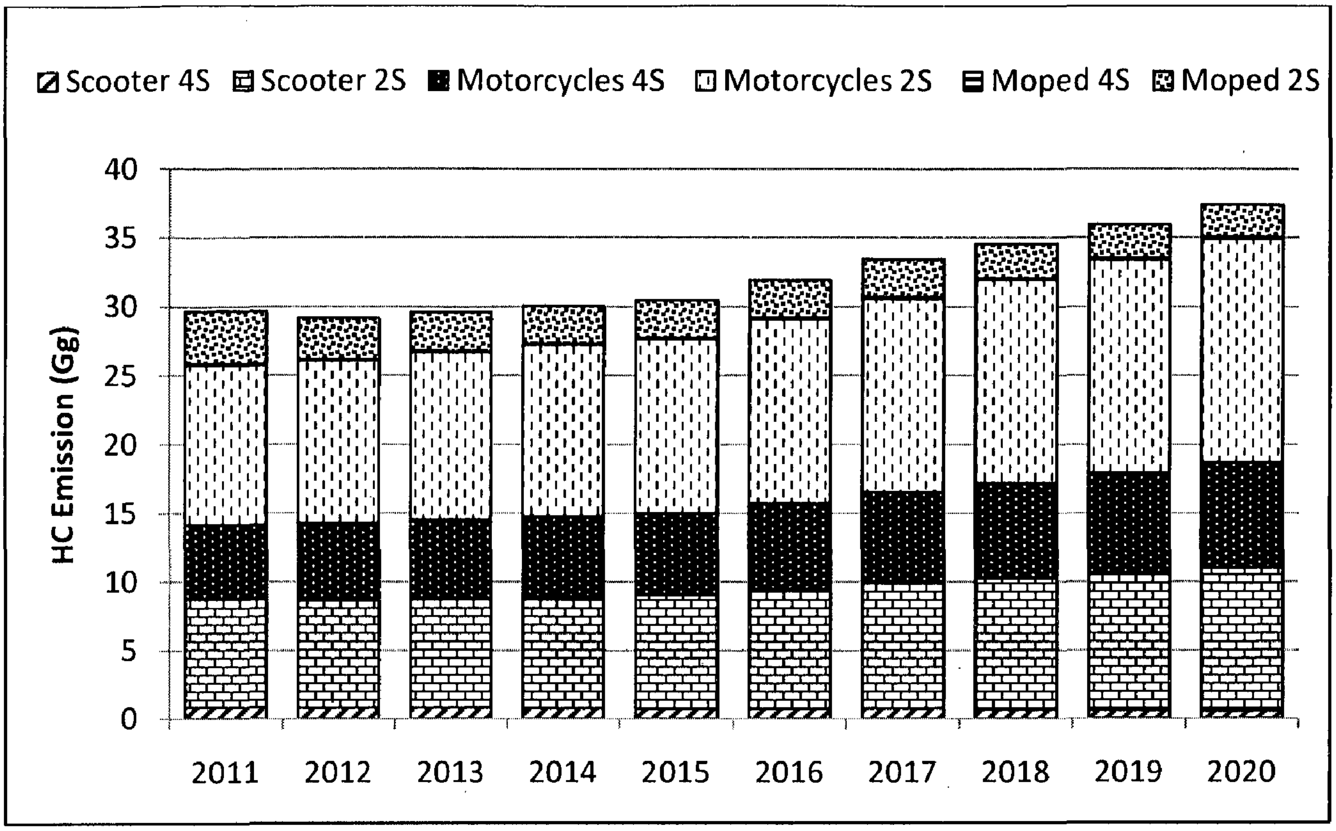


Fig. 6.26b: HC emissions as per BES scenario from two wheelers in megacity Delhi

6.2.4.2. Cars

In 2011 HC emissions from car population in BAU scenario will be 15 Gg followed by 13 Gg in 2015 and 18 Gg in 2020 (Fig. 6.27a). About 23% decrease is observed between 2011 and 2012 because of phasing out of 1991 model cars in year 2012. About 6% of average annual growth rate is observed between 2012 and 2020 in BAU scenario. In 2011 emission of HC from cars in BES scenario is projected to be 14 Gg followed by 10 Gg in 2015 and 14 Gg in 2020 (Fig. 6.27b). It is observed that among all cars petrol driven cars play a dominant role in both BES and BAU scenarios. Emission of HC in BES is 8% less than BAU scenario in 2011 and this figure is projected to become 19% in 2015 and 23% in 2020.

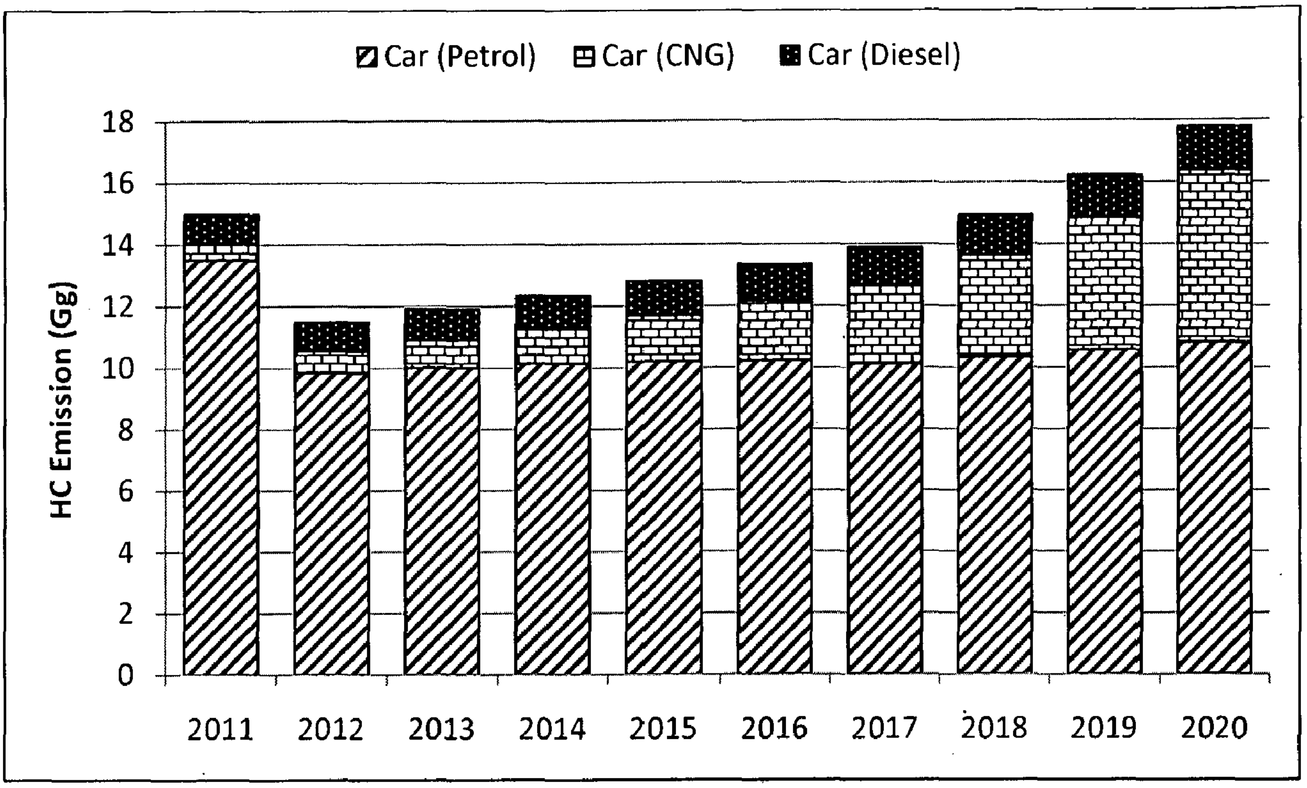


Fig. 6.27a: HC emissions as per BAU scenario from cars in megacity Delhi

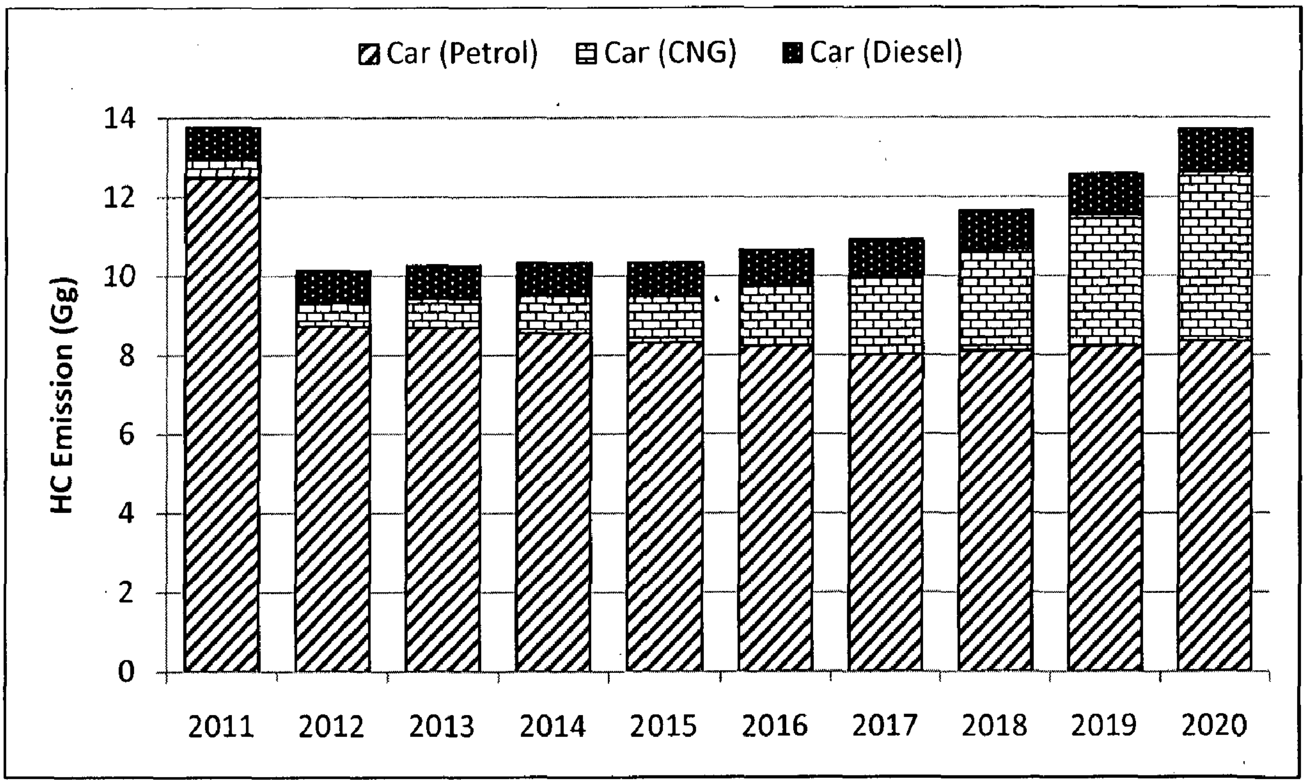


Fig. 6.27b: HC emissions as per BES scenario from cars in megacity Delhi

6.2.4.3. Three Wheelers

Fig. 6.28 (a and b) shows the emission of HC from three wheelers in BAU and BES scenario respectively. In 2011 HC emissions from BAU scenario are projected to be 2 Gg followed by 3.59 Gg in 2015 and 10 Gg in 2020. About 21% of average growth is estimated annually in HC emissions during 2011 to 2020. In BES scenario emission of HC from three wheelers will be ~1.5 Gg in 2011, 3 Gg in 2015 and 8 Gg in 2020. About 19% of annual average growth is estimated between 2011 and 2020. Emissions of HC in BAU scenario are 13% greater than BES scenario and this figure is estimated to become 22-24% in 2015 and 2020.

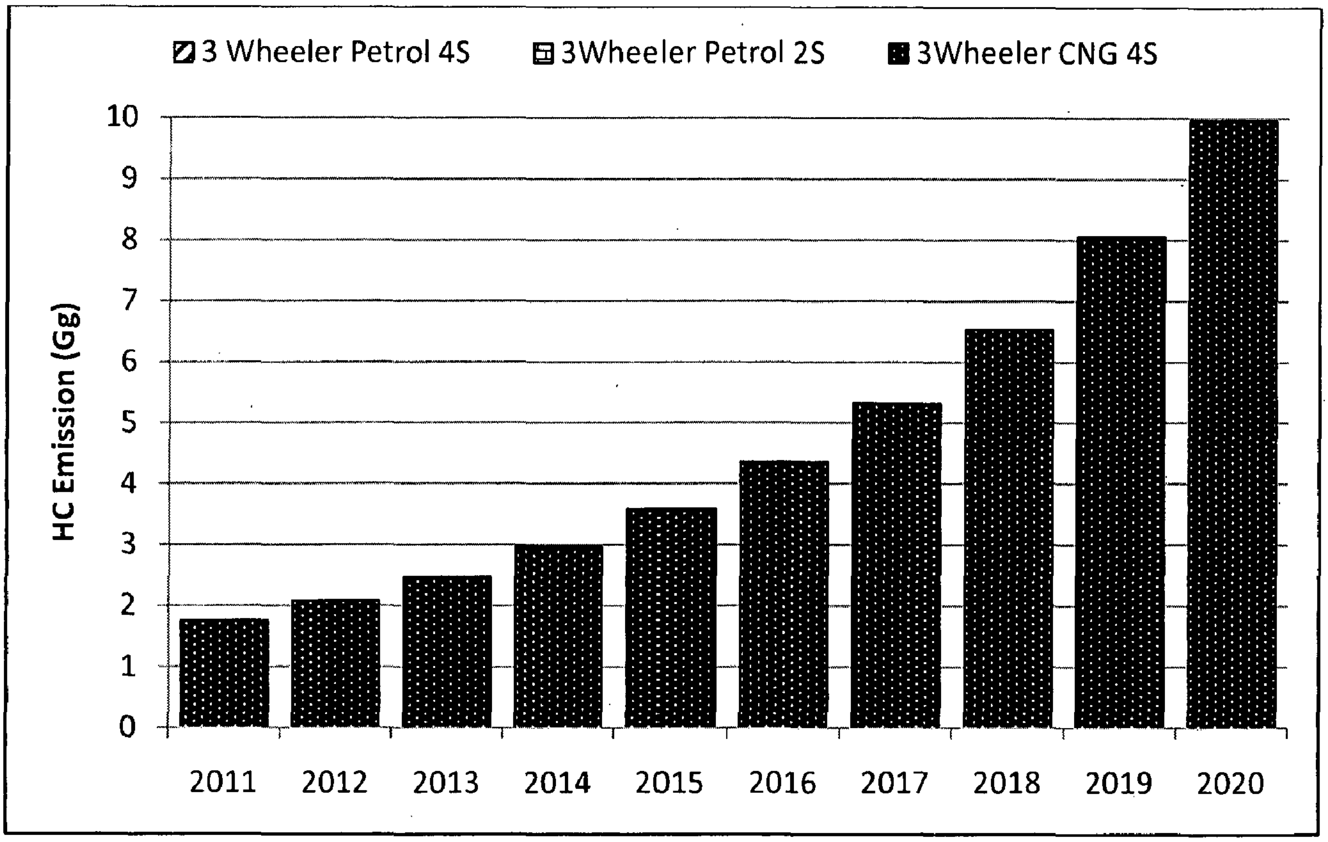


Fig. 6.28a: HC emissions as per BAU scenario from three wheelers in megacity Delhi

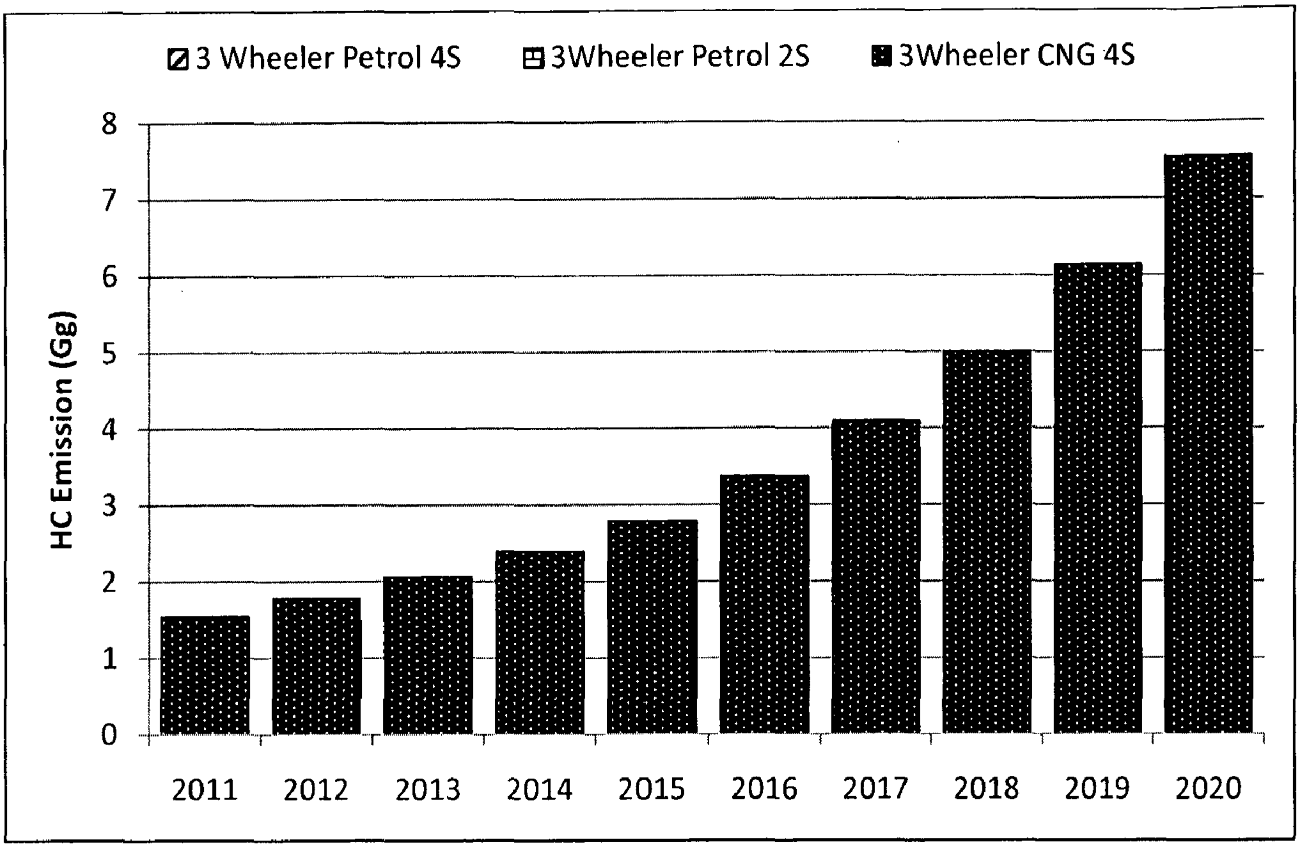


Fig. 6.28b: HC emissions as per BES scenario from three wheelers in megacity Delhi

6.2.4.3. Taxis

Estimated emissions of HC from taxis in BAU and BES scenario are given in Fig. 6.29 (a and b). Fig. 6.29a shows that in 2011 emissions are 527 Mg followed by 1394 Gg in 2015 and 5318 Gg in 2020. Fig. 6.29b shows that in 2011 HC emissions are to be 417 Mg followed by 791 Mg in 2015 and 2423 Mg in 2020. Contribution of CNG driven taxis is higher in both BAU and BES scenario, while that of petrol and diesel driven taxis is less. Emission of HC in BES is 21% less than BAU scenario and in 2015 this difference will be 43% followed by 54% in 2020.

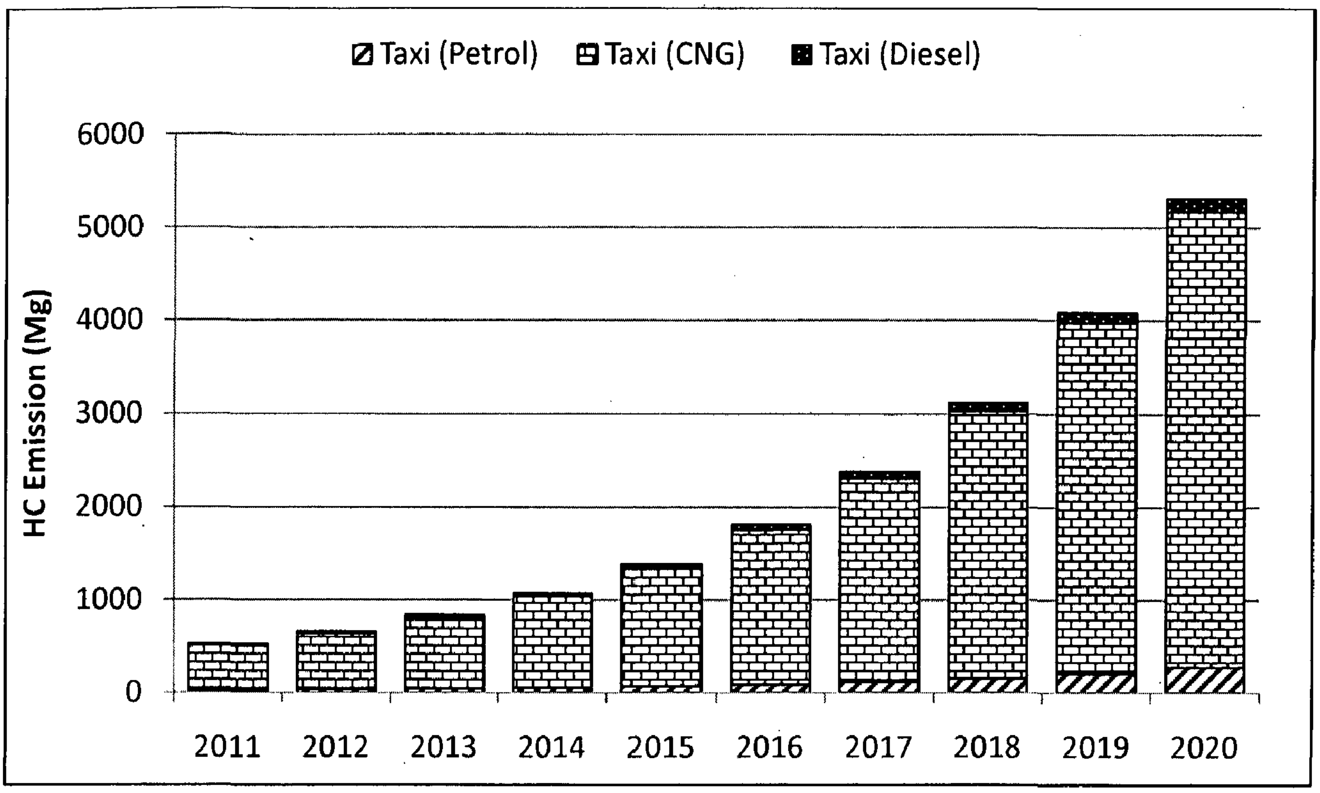


Fig. 6.29a: HC emissions as per BAU scenario from taxis in megacity Delhi

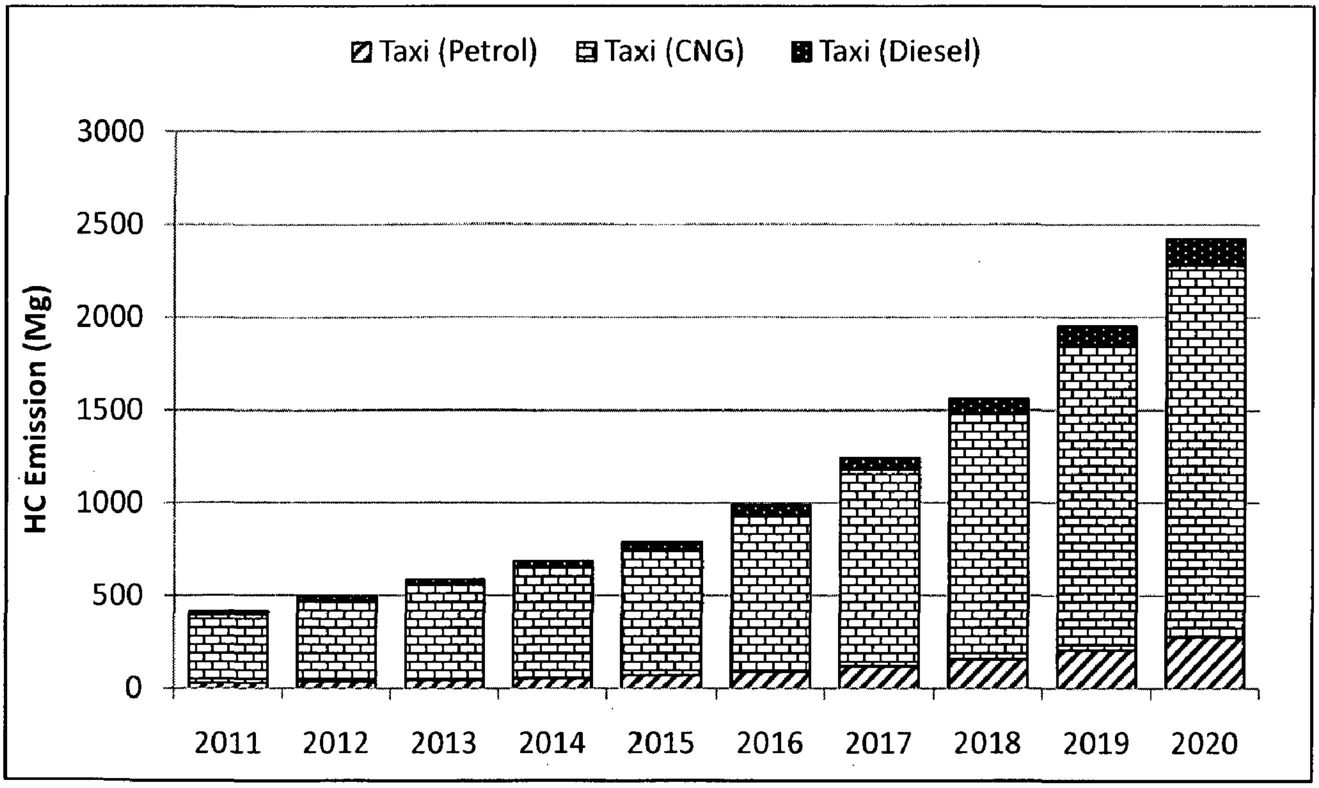


Fig. 6.29b: HC emissions as per BES scenario from taxis in megacity Delhi

6.2.4.5. Buses

Fig. 6.30a shows that in BAU scenario HC emissions from buses will be 18 Gg followed by 31 Gg in 2015 and 62 Gg in 2020. About 15% of average growth rate is projected annually in HC emissions during 2011 to 2020. Emissions of HC from BES scenario are shown in Fig. 6.30b. It indicates that in 2011 HC emissions will be 15 Gg in 2011 followed by 24 Gg in 2015 and 49 Gg in 2020. Emissions of HC from buses in BAU scenario are 13% higher than BES scenario for the year 2011 while for 2015 and 2020 it will be 22%. In both the scenarios, HC emissions are negligible from diesel buses in comparison to CNG buses.

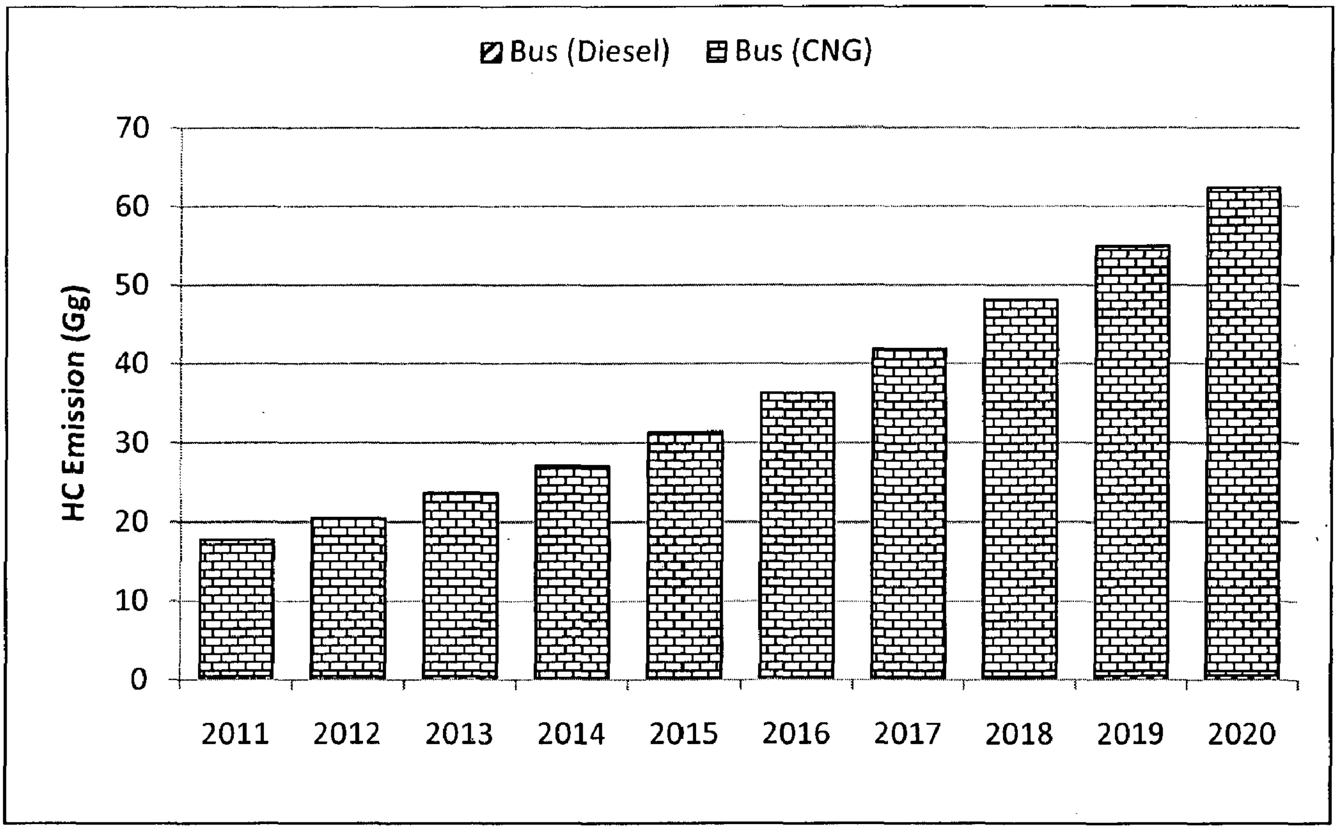


Fig. 6.30a: HC emissions as per BAU scenario from buses in megacity Delhi

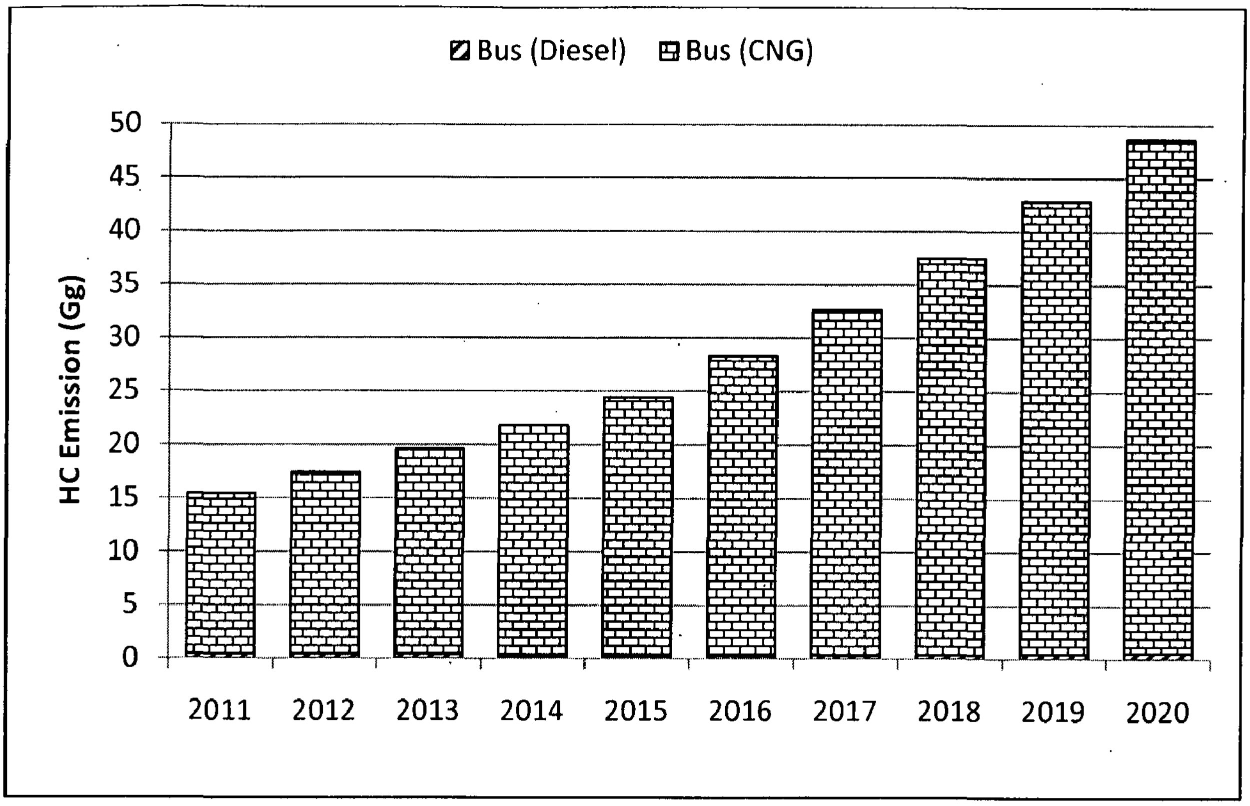


Fig. 6.30b: HC emissions as per BES scenario from buses in megacity Delhi

6.2.4.6. LCVs and HCVs

Emissions of LCVs and HCVs are presented in Fig. 6.31 and 6.32. HC emissions from LCVs are projected to be 9 Gg during 2011, 21 Gg in 2015 and 49 Gg in 2020. Contribution of CNG driven LCVs is higher than diesel driven LCVs (external population only). About an average 20.40% growth is observed in LCVs emissions during 2011 to 2020. HC emissions from HCVs population is quite less than LCVs because all HCVs are diesel driven (less emission factor). HCVs emissions (Fig. 6.32) are estimated to be 1.20 Gg in 2011 followed by 0.96 Gg in 2015 and 1.35 Gg in 2020.

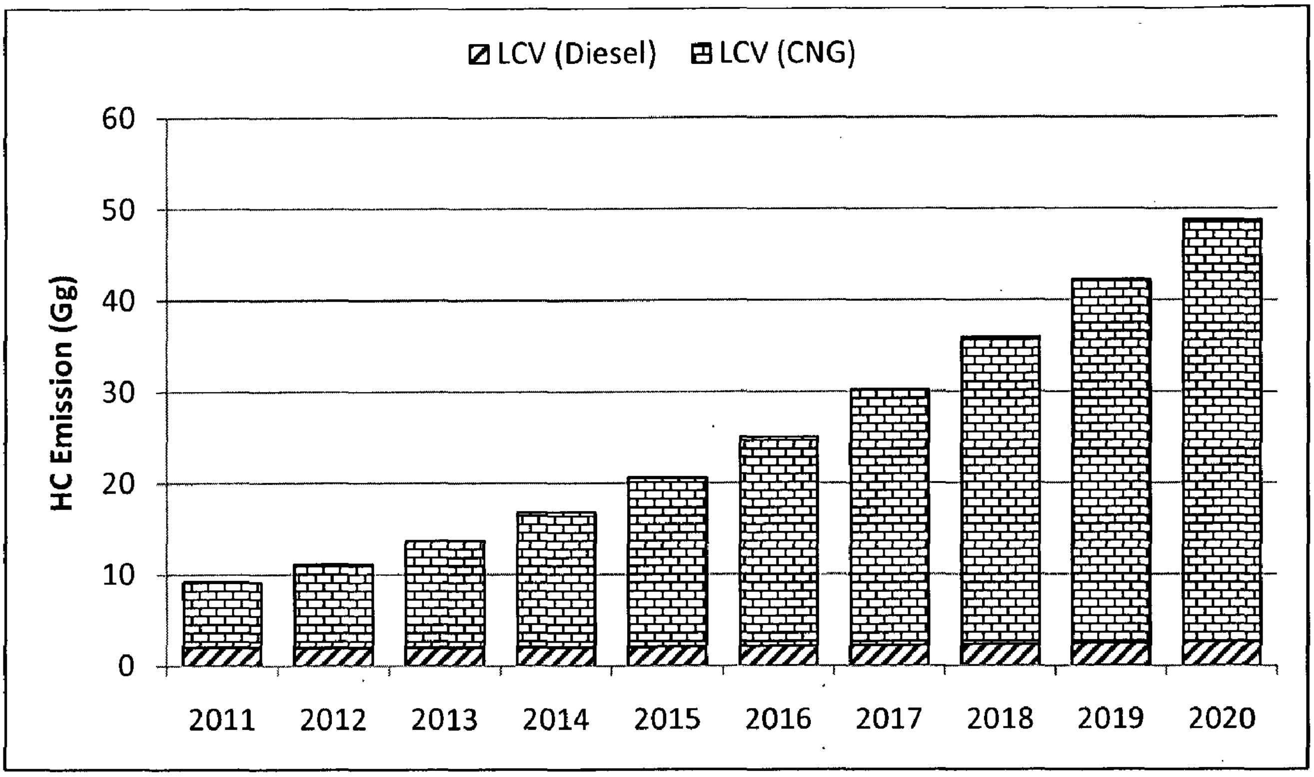


Fig. 6.31: HC emissions as per BAU scenario from LCVs in megacity Delhi

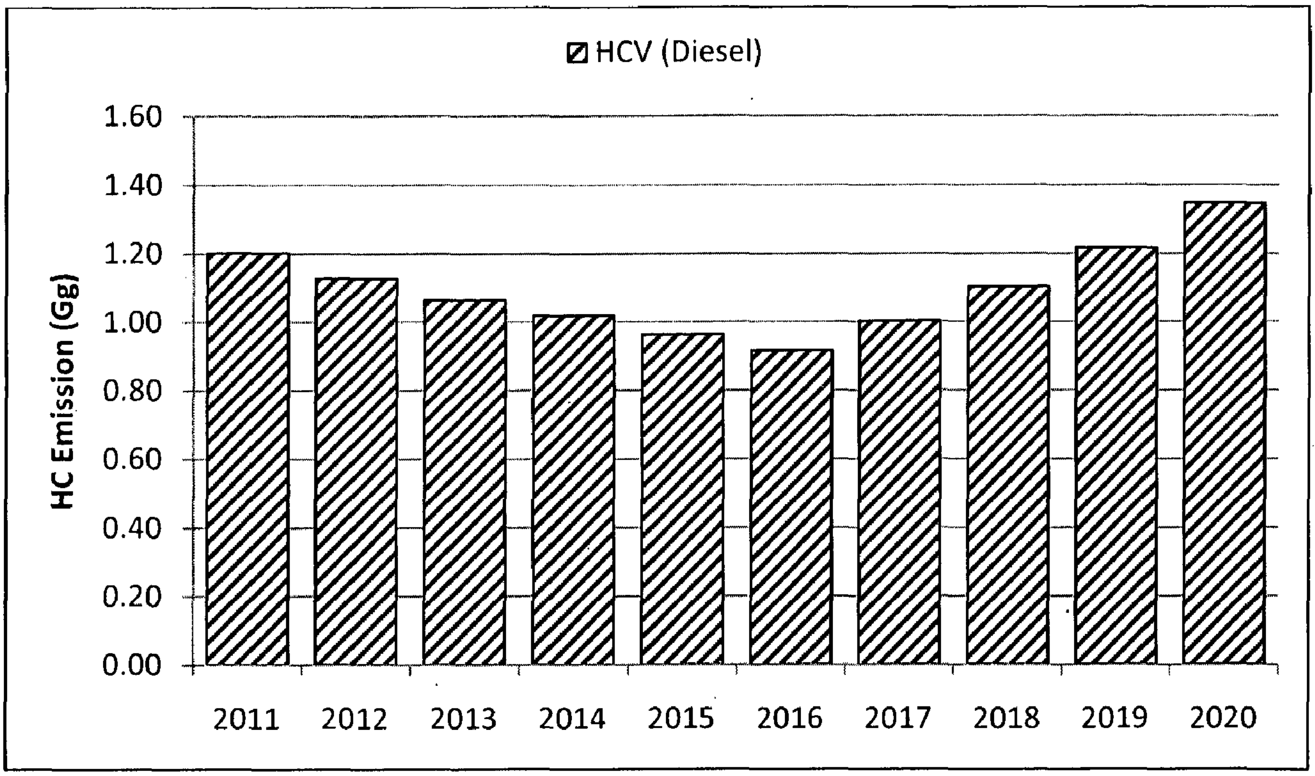


Fig. 6.32: HC emissions as per BAU scenario from HCVs in megacity Delhi

6.2.5. PM emissions

Fig. 6.33a indicates that from various vehicle categories PM emissions in BAU scenario will be 5242 Mg in 2011, 6166 Mg in 2015 and 9497 Mg in 2020. About 7% of annual average growth has been observed in estimation of PM emissions from various vehicles in BAU scenario during 2011 to 2020. Estimations show that HCVs population will be major (43-48%) contributor of PM emissions during 2011 to 2020. In Fig. 6.33b emission estimation of PM from 2011 to 2020 has been given for BES scenario. It suggests that in 2011 emissions will be 5018 Mg followed by 5717 Mg in 2015 and 8818 Mg in 2020. Among various vehicles, contribution of HCVs is highest followed by LCVs and two wheelers. As all HCVs in megacity Delhi are diesel driven, hence their contribution is highest in both BAU and BES scenarios. Emission of PM in BES is ~4% less than BAU scenario in 2011 and it will be ~7% less in 2015 and 2020.

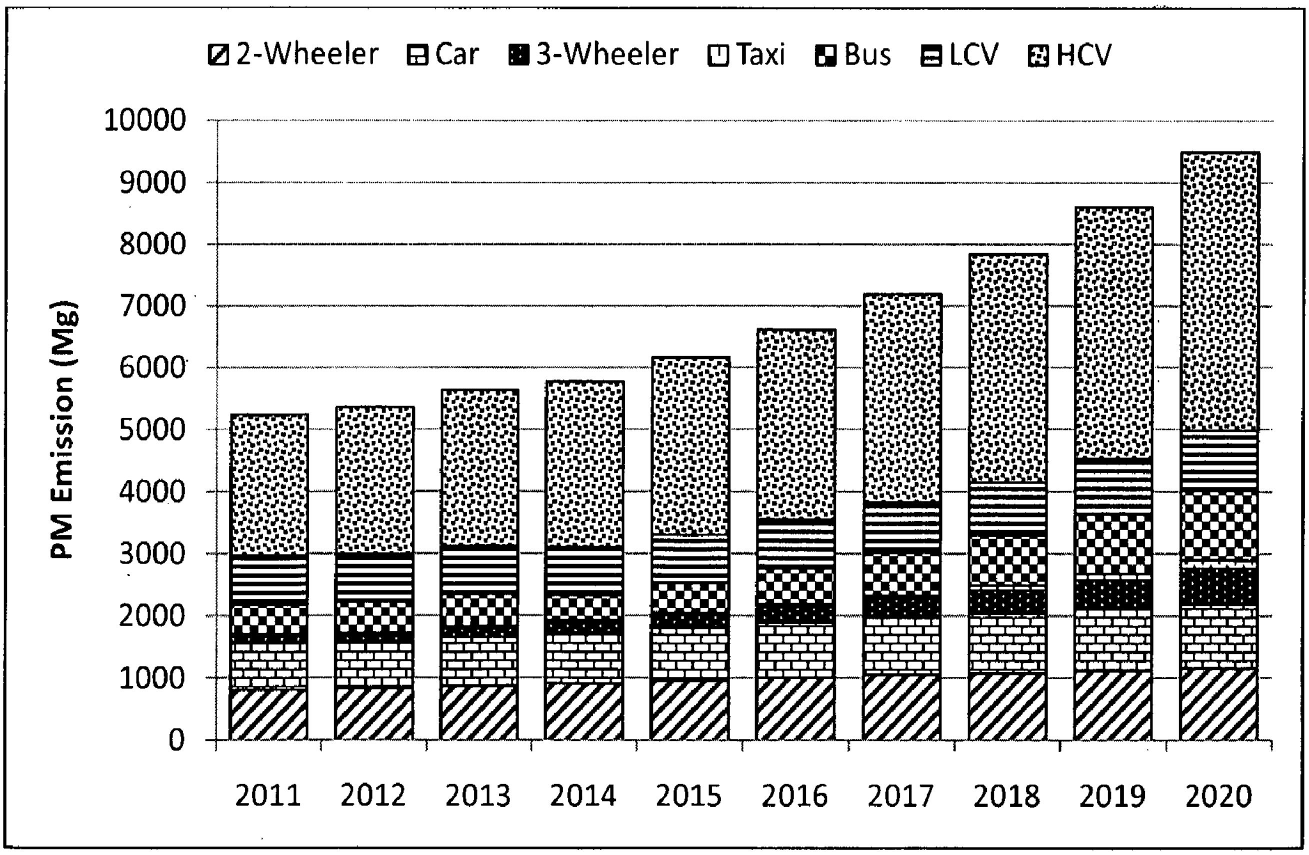


Fig. 6.33a: PM emissions as per BAU scenario from vehicles in megacity Delhi

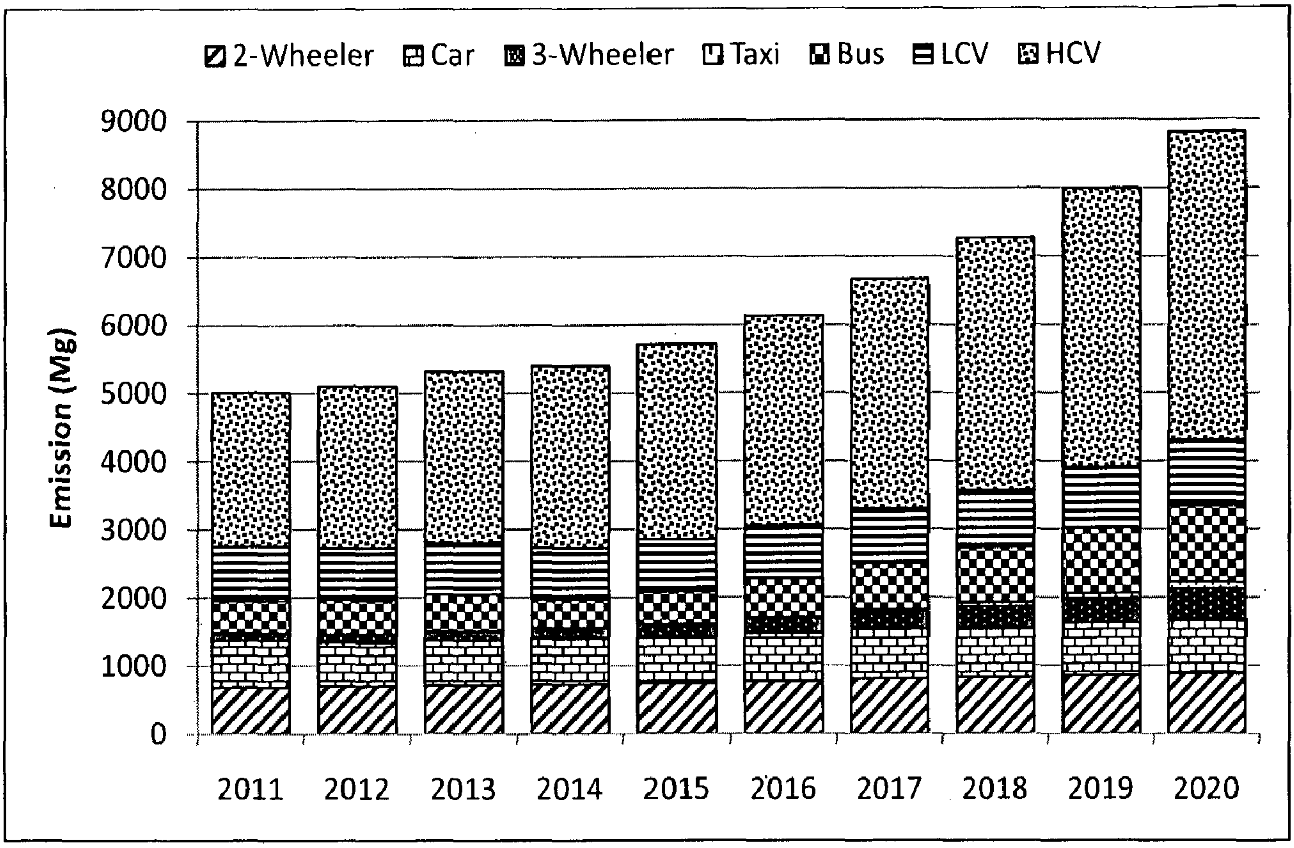


Fig. 6.33b: PM emissions as per BES scenario from vehicles in megacity Delhi

6.2.5.1. Two Wheelers

PM emissions from two wheelers in both BAU and BES scenarios are presented in Fig. 6.34 (a and b). Fig. 6.34a indicates that in 2011 PM emissions from BAU scenario will be 809 Mg, followed by 965 Mg in 2015 and 1159 Mg in 2020. Among all types of two wheelers contribution of four-stroke motorcycles is highest (39-40%) during 2011 to 2020. It is observed in Fig. 6.34b that in 2011 emission of PM from BES scenario will be 692 Mg followed by 747 Mg in 2015 and 892 Mg in 2020. Contribution of four-stroke motorcycles is again highest in BES scenario. Emission of PM from two wheelers in BES is less than BAU scenario. The difference between BAU and BES scenario for PM emissions from two wheelers is found to be 14.5% in 2011 and 22.5% in 2015 followed by 23% in 2020.

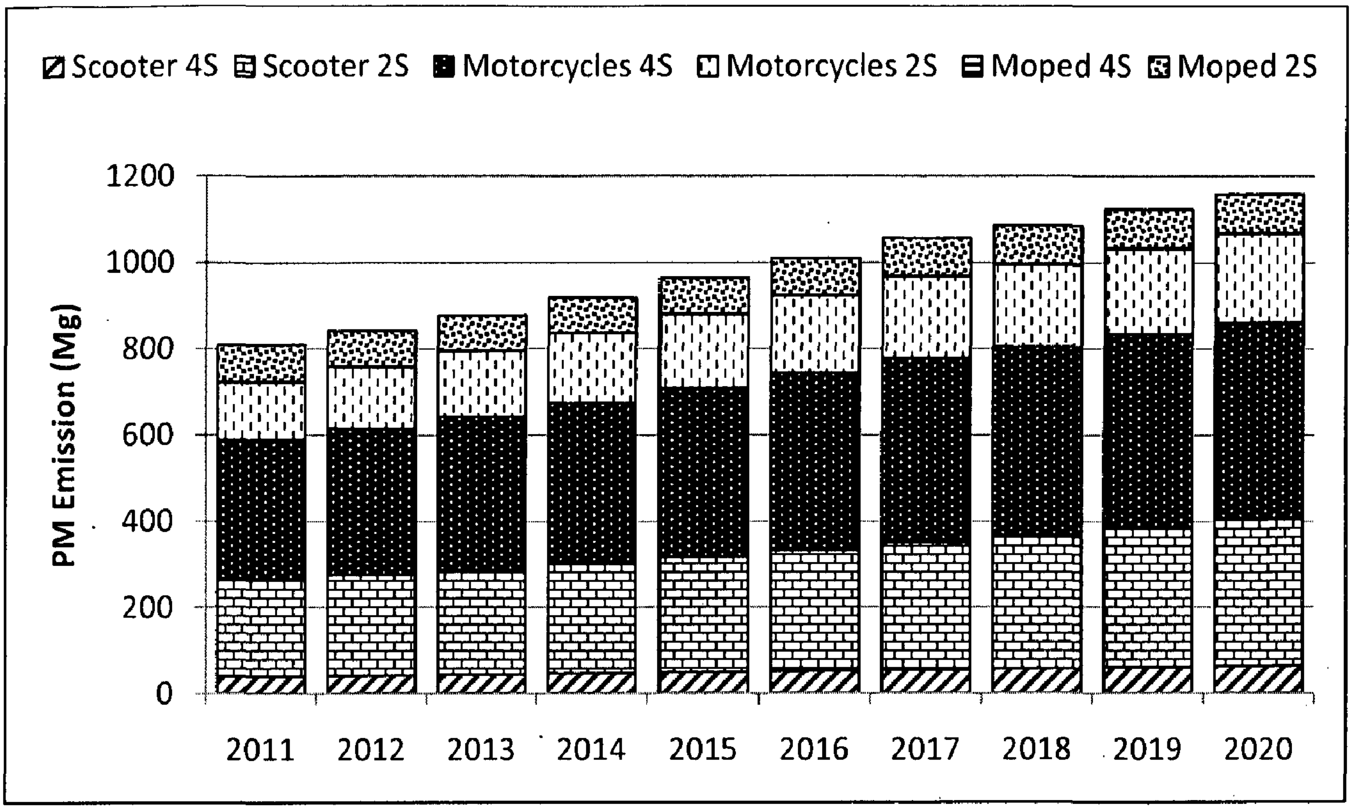


Fig. 6.34a: PM emissions as per BAU scenario from two wheelers in megacity Delhi

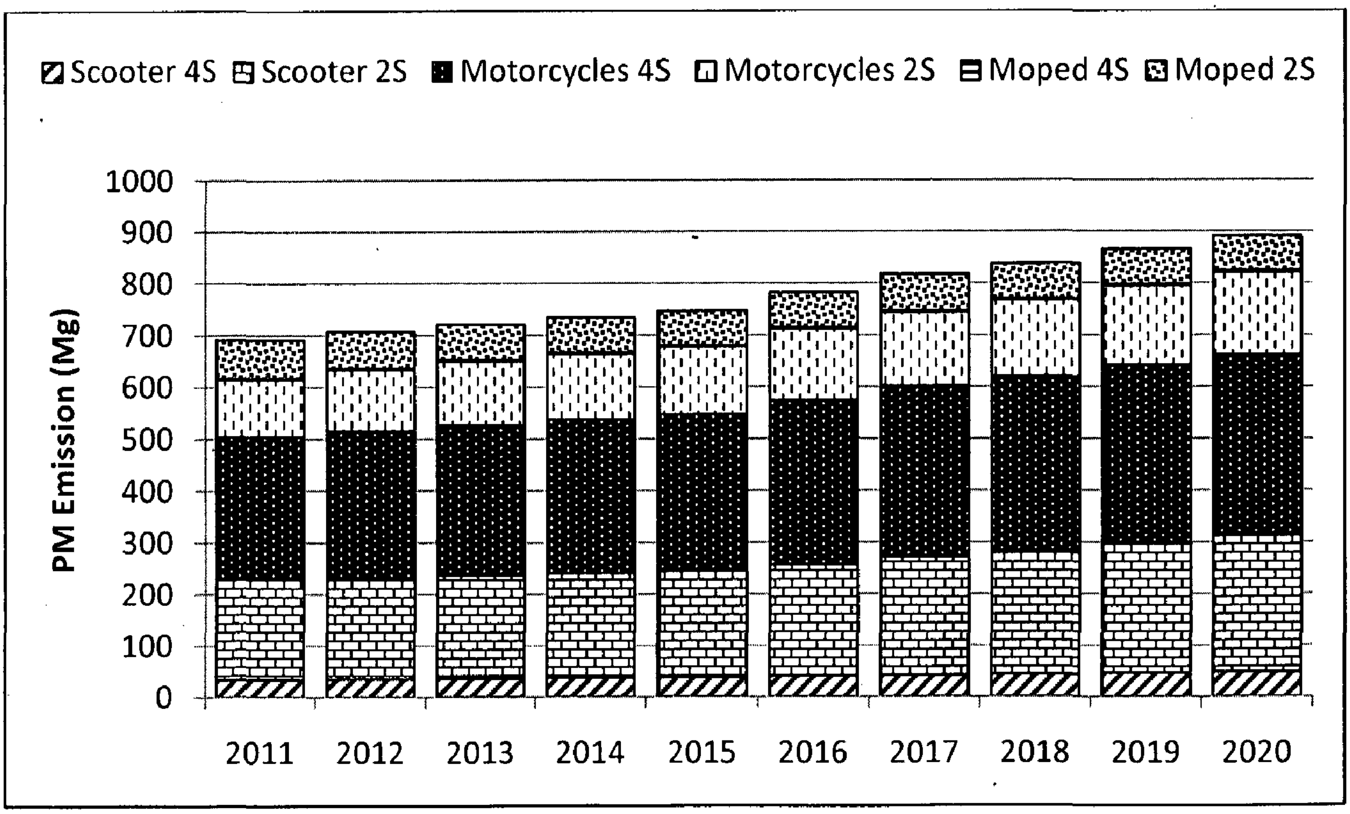


Fig. 6.34b: PM emissions as per BES scenario from two wheelers in megacity Delhi

6.2.5.2. Cars

About 782 Mg of PM is projected to be emitted from cars in 2011 in BAU scenario, while in 2015 and 2020 it will be 855 and 1039 Mg respectively (Fig. 6.35a). Between 2011 and 2012 very little difference is projected in PM emissions because of phasing out of 1991 and pre-1991 car population in 2012. Contribution of diesel driven cars is highest among all types of car in BAU scenario in megacity Delhi. Fig. 6.35b shows emission of PM from cars in BES scenario. In 2011 emission of PM from BES scenario will be 690 Mg followed by 481 Mg in 2015 and 570 Mg in 2020. Similar to BAU scenario slight decline is also observed between 2011 and 2012 due to same reason. Because of higher emission factors contribution of diesel is higher in BES scenario. Estimations suggest that PM emission in BES is quite lesser than BAU scenario. In 2011 difference between BAU and BES scenario are 12% followed by 21% in 2015 and 23% in 2020.

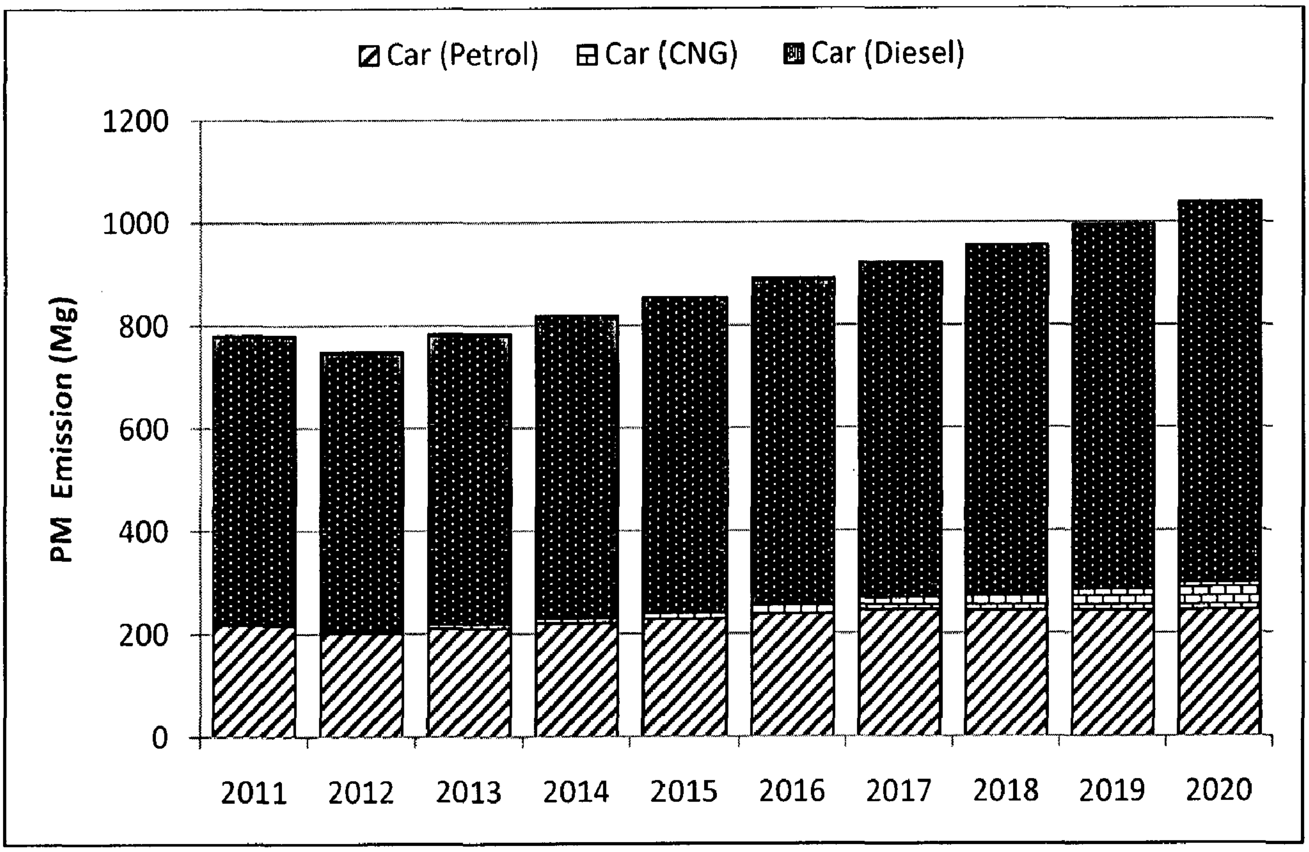


Fig. 6.35a: PM emissions as per BAU scenario from cars in megacity Delhi

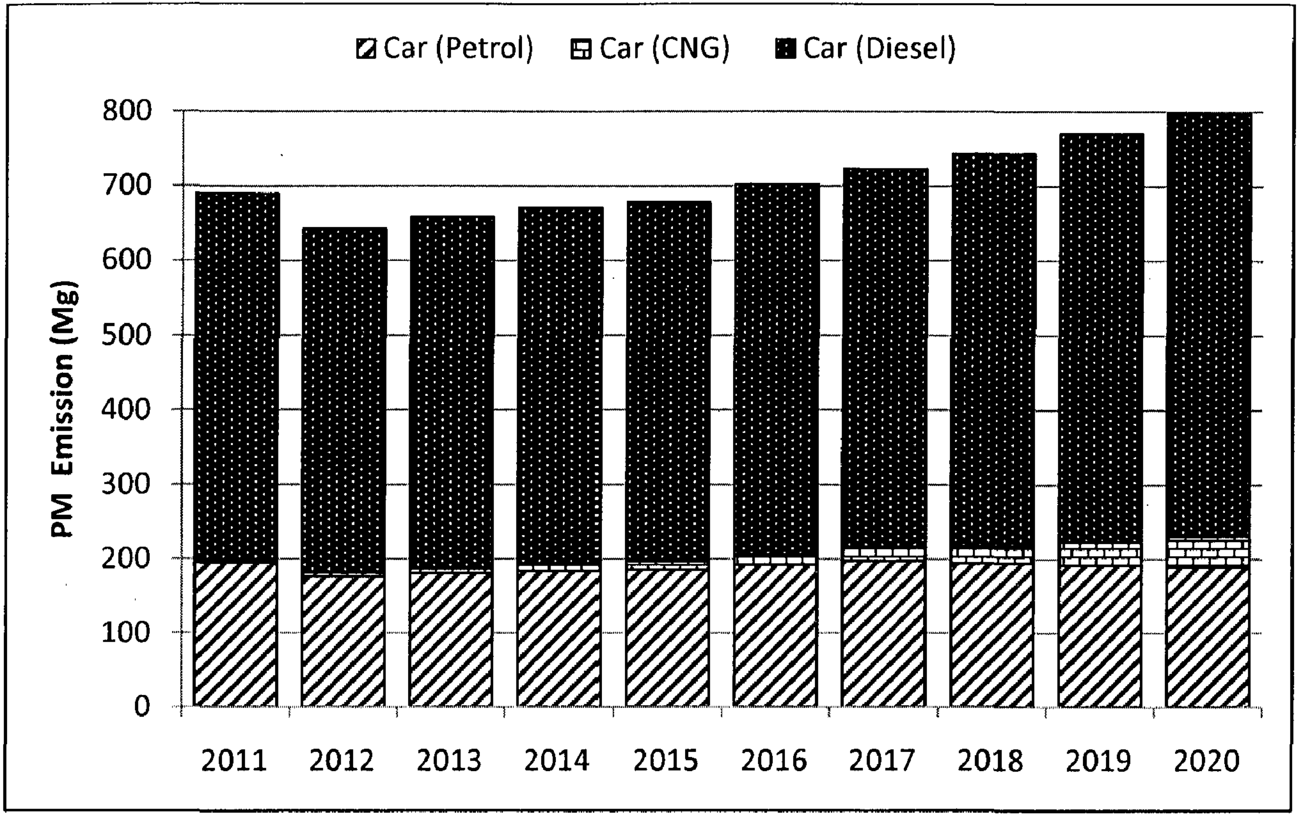


Fig. 6.35b: PM emissions as per BES scenario from cars in megacity Delhi

6.2.5.3. Three Wheelers

Emissions of PM from three wheelers in BAU scenario in 2011 will be 102 Mg followed by 207 Mg in 2015 and 575 Mg in 2020 (Fig. 6.36a). About 21% of annual average growth rate of PM is estimated for years 2011 to 2020. Fig. 6.36b shows the emissions of PM from three wheelers in BES scenario from 2011 to 2020. It suggests that in 2011 emissions will be 89 Mg followed by 161 Mg in 2015 and 4350 Mg in 2020. Estimations show that PM emission from three wheelers in BES scenario is 13% less than BAU scenario and this difference will be 22% in 2015 and 24% in 2020. In both the scenarios CNG driven four-stroke three-wheelers are dominant contributors in comparison to petrol driven four-stroke and two-stroke three-wheelers.

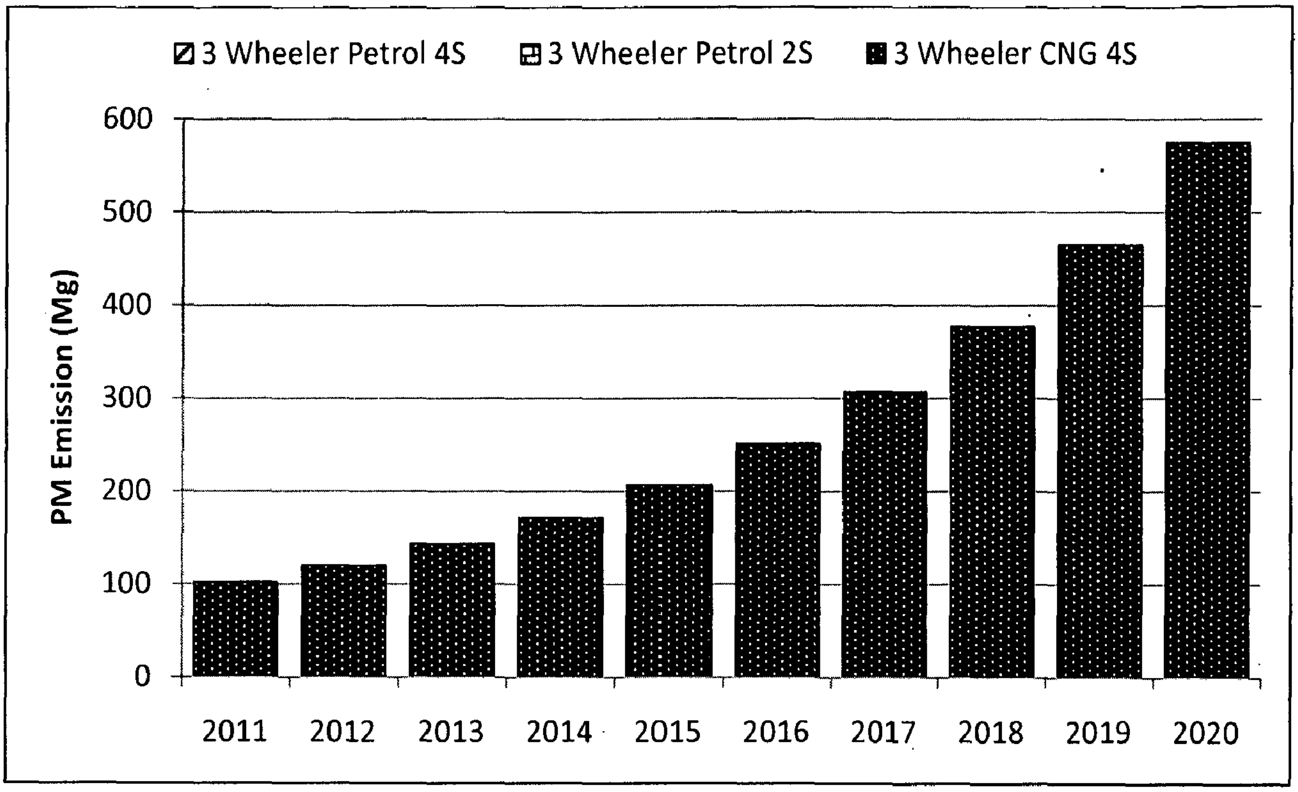


Fig. 6.36a: PM emissions as per BAU scenario from three wheelers in megacity Delhi

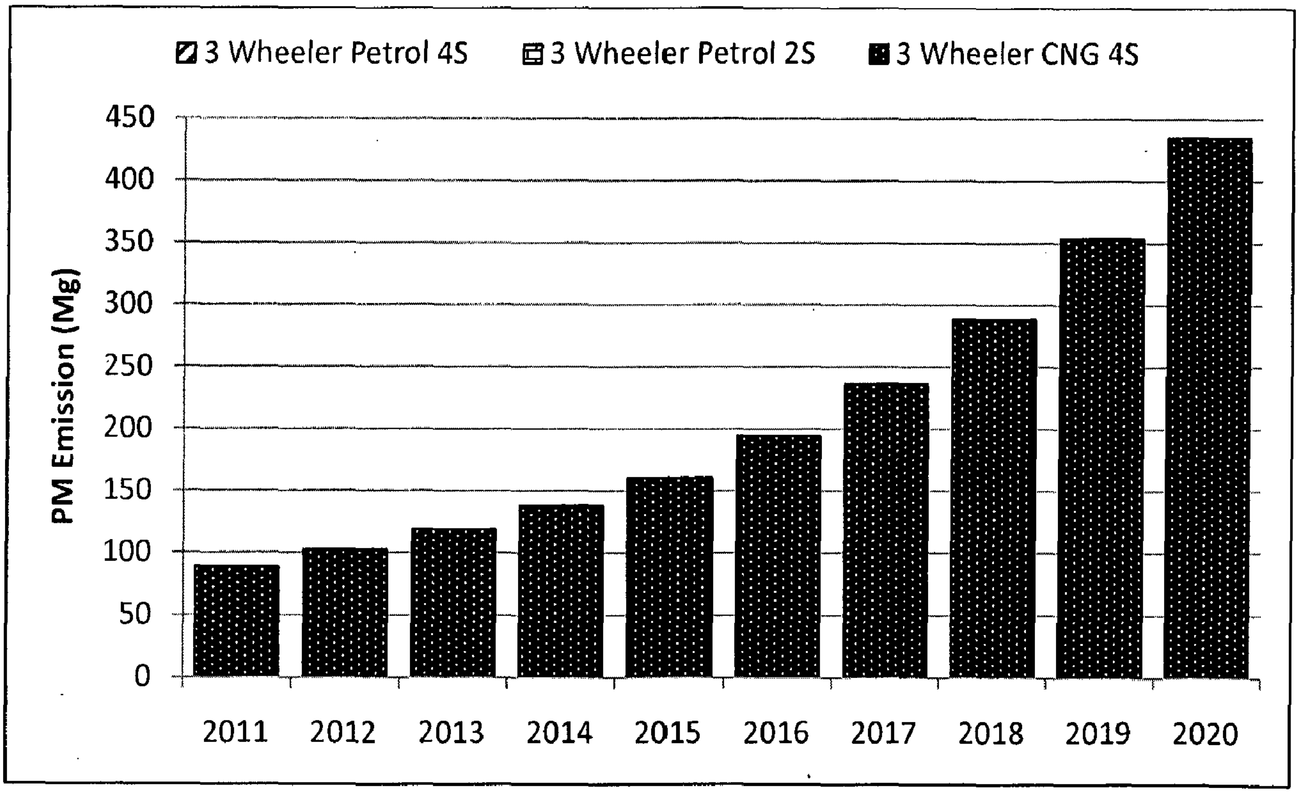


Fig. 6.36b: PM emissions as per BES scenario from three wheelers in megacity Delhi

6.2.5.4. Taxis

Fig. 6.37 (a and b) shows the emission of PM from taxis population in both BAU and BES scenario. Fig. 6.37a indicates that in 2011 emissions will be 14 Mg followed by 34 Mg in 2015 and 126 Mg in 2020. An average growth rate of about 27% is projected between 2011 and 2020. Due to very high emission factors (0.07 g/km) of diesel taxis in comparison to CNG driven ones (0.004 g/km), the diesel taxis (which are basically external population entering in Delhi from other states) contribute higher PM emissions in comparison to CNG driven taxis. According to Fig. 6.37b PM emissions will be 13 Mg in 2011 followed by 28 Mg in 2015 and 98 Mg in 2020. Similar to BAU share of diesel taxis is higher in BES emissions. Emission of PM in BES is 7% less than BAU scenario in year 2011 followed by 17% in 2015 and 22% in 2020.

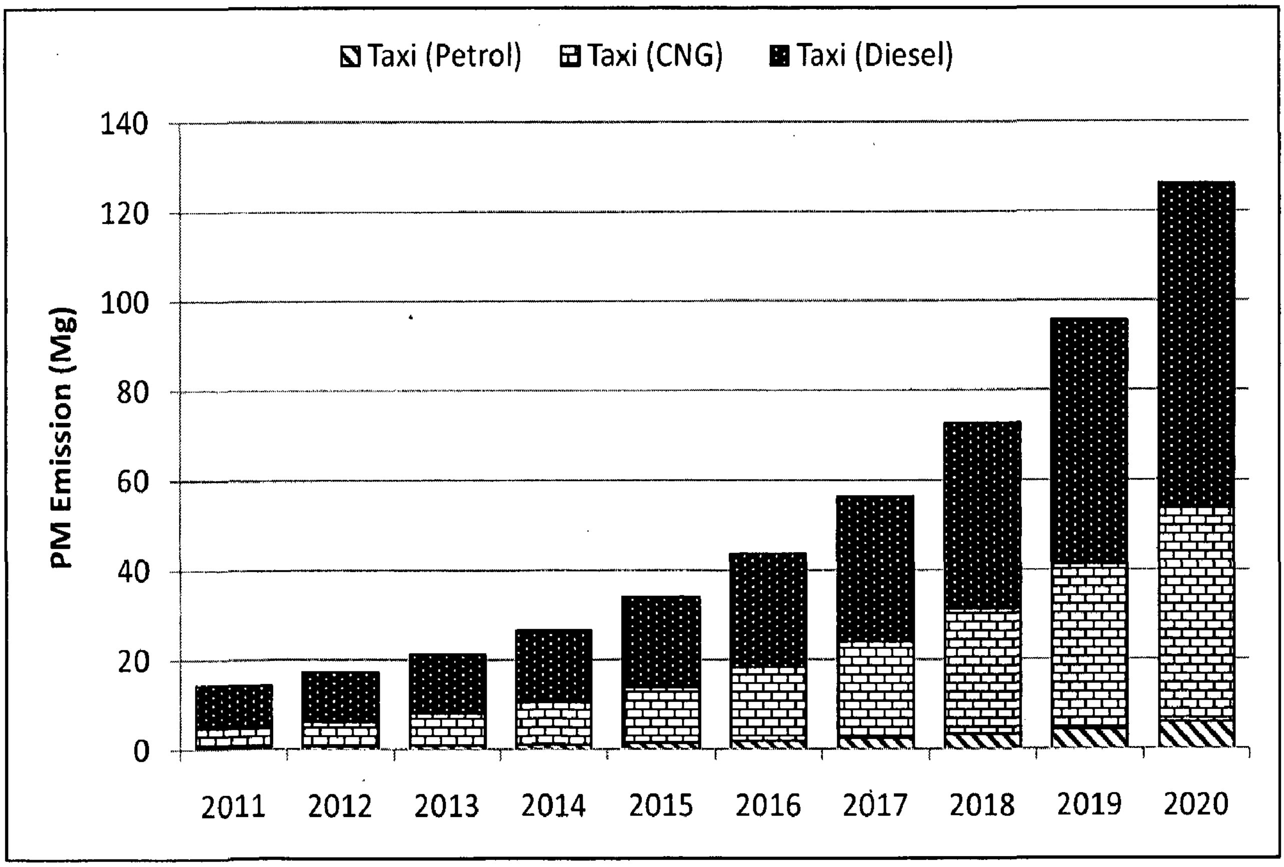


Fig. 6.37a: PM emissions as per BAU scenario from taxis in megacity Delhi

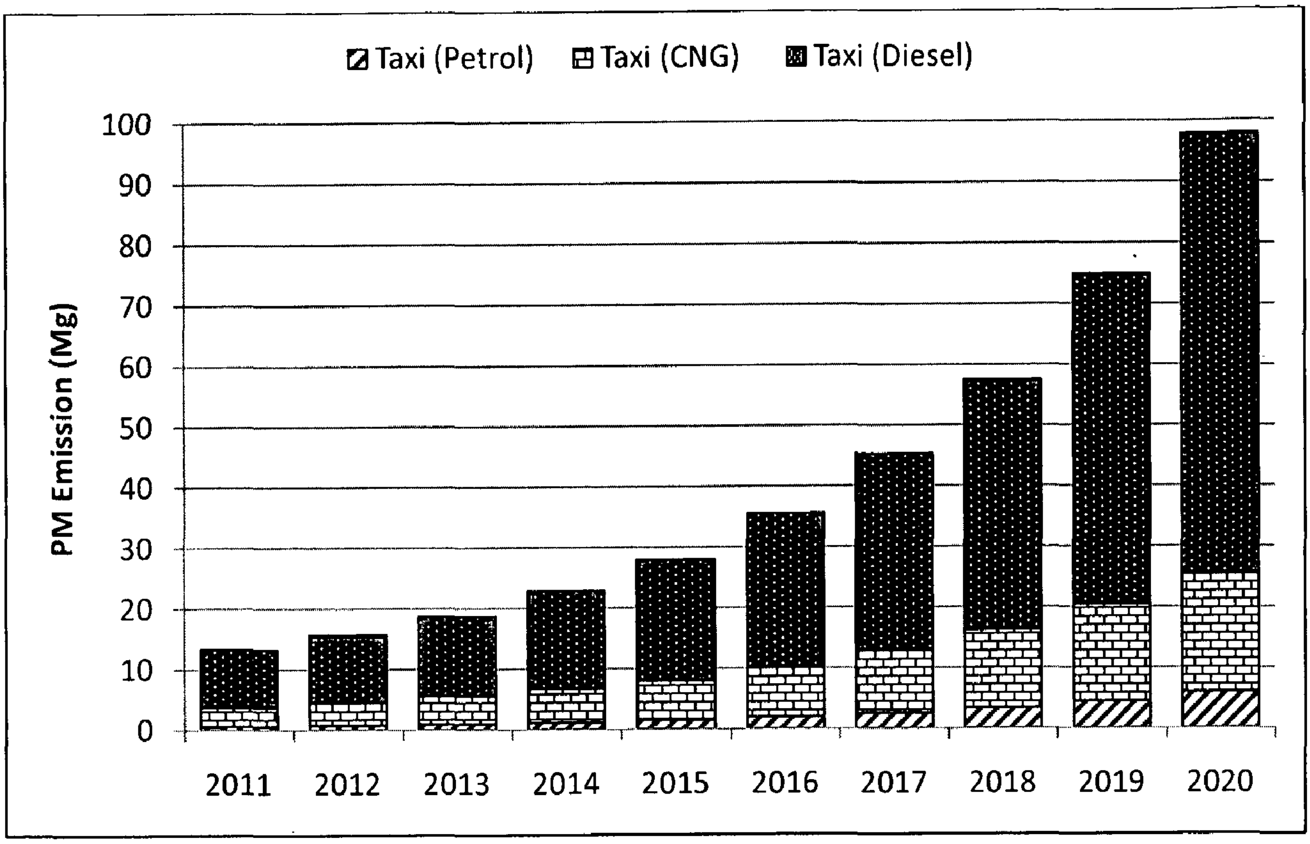


Fig. 6.37b: PM emissions as per BES scenario from taxis in megacity Delhi

6.2.5.5. Buses

Since 2002 internal buses running in Delhi are CNG equipped while all diesel buses come from outside of Delhi. In BAU scenario, PM emissions from buses in Delhi will be 482 Mg followed by 486 Mg in 2015 and 1132 Mg in 2020 (Fig. 6.38a). The contribution of internal CNG driven buses for PM emissions is only 1-3%, while external diesel driven buses are responsible for most of PM emissions because of higher emission factors (186 to 1000 times higher than CNG) for diesel buses (ARAI,2007, IVEM, 2010). In between 2013 and 2014 slight decrease in PM emissions is observed due to phasing out of 2005 model buses in 2014 (DSA, 2010). Fig. 6.38b shows the emission of PM from buses in BES scenario. In 2011 emission of PM from buses in BES scenario will be 481 Mg followed by 482 Mg in 2015 and 1126 Mg in 2020. Very little differences have been observed between BAU and BES scenario. For 2011 difference between BAU and BES is 0.21%, followed by 0.61% in 2015 and 0.52% in 2020.

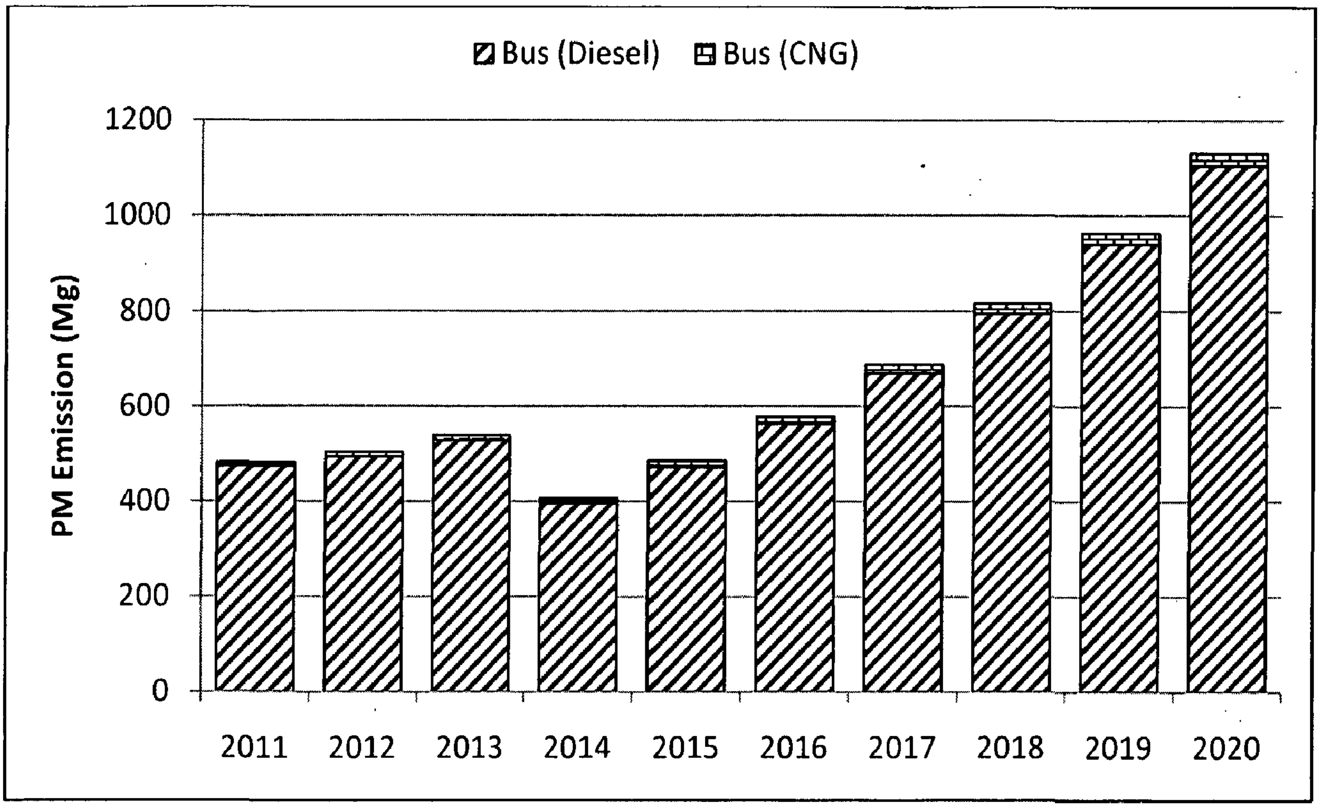


Fig. 6.38a: PM emissions as per BAU scenario from buses in megacity Delhi

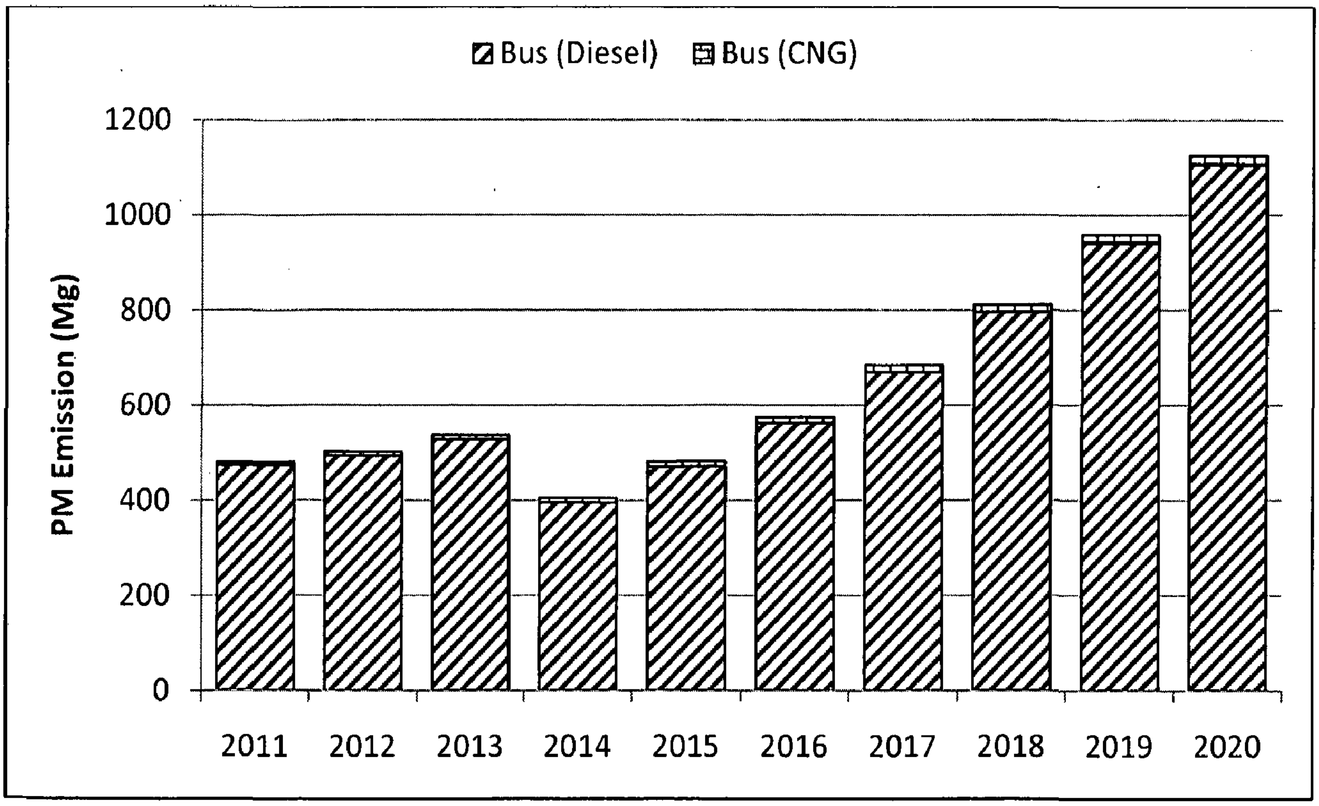


Fig. 6.38b: PM emissions as per BES scenario from buses in megacity Delhi

6.2.5.6. LCVs/HCVs

Emissions of PM from LCVs and HCVs between 2011 and 2020 have been given in Fig. 39 and 40 respectively. Fig. 6.39 indicates that PM emission from LCVs is 794 Mg in 2011, 764 Mg in 2015 and 953 Mg in 2020. In PM emission contribution of diesel driven LCVs is 98 to 99%, while contribution of CNG driven LCVs is very less. After observing Fig. 6.40 it is found that in 2011 emission of PM from HCVs population will be 2259 Mg followed by 2856 Mg in 2015 and 4512 Mg in 2020. About 8% of annual average growth has been found in PM emissions from HCVs during 2011 to 2020.

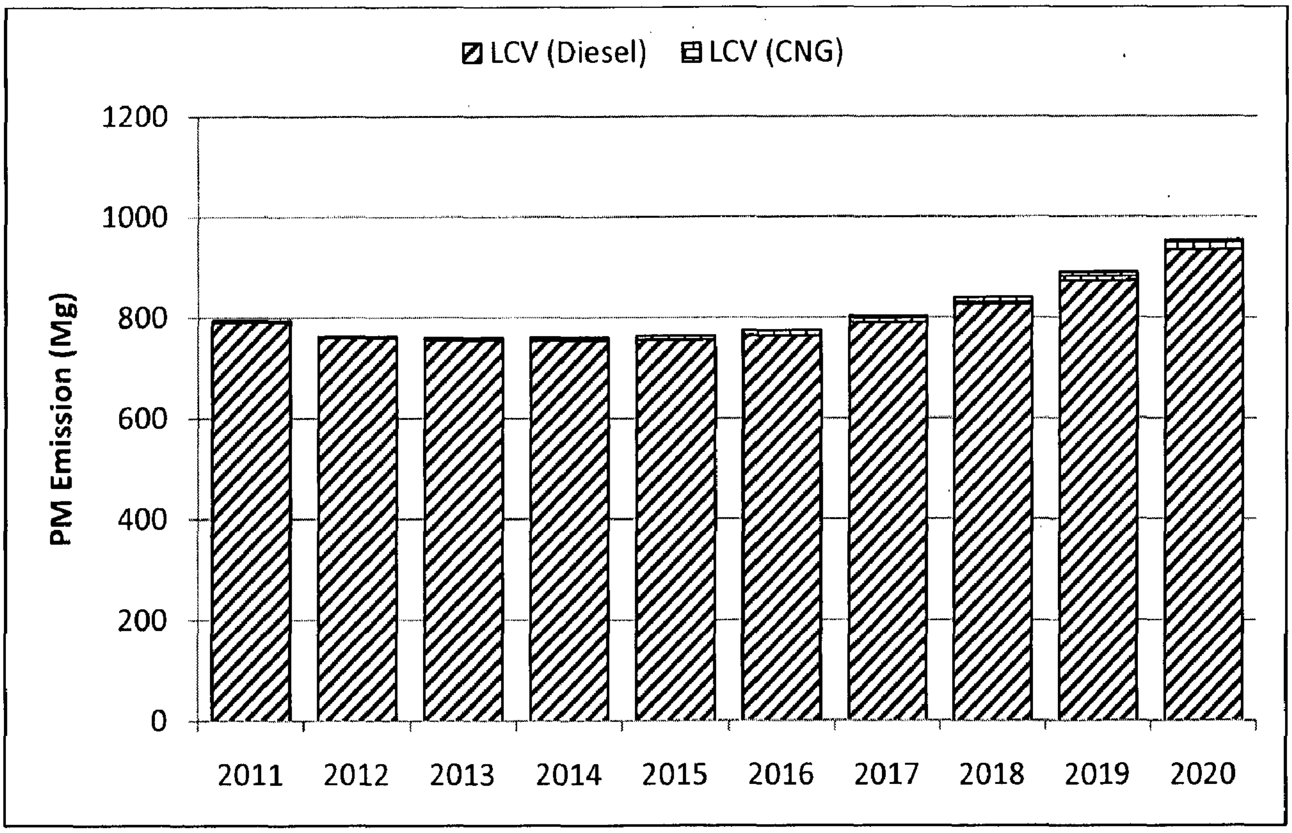


Fig. 6.39: PM emissions as per BAU scenario from LCVs in megacity Delhi

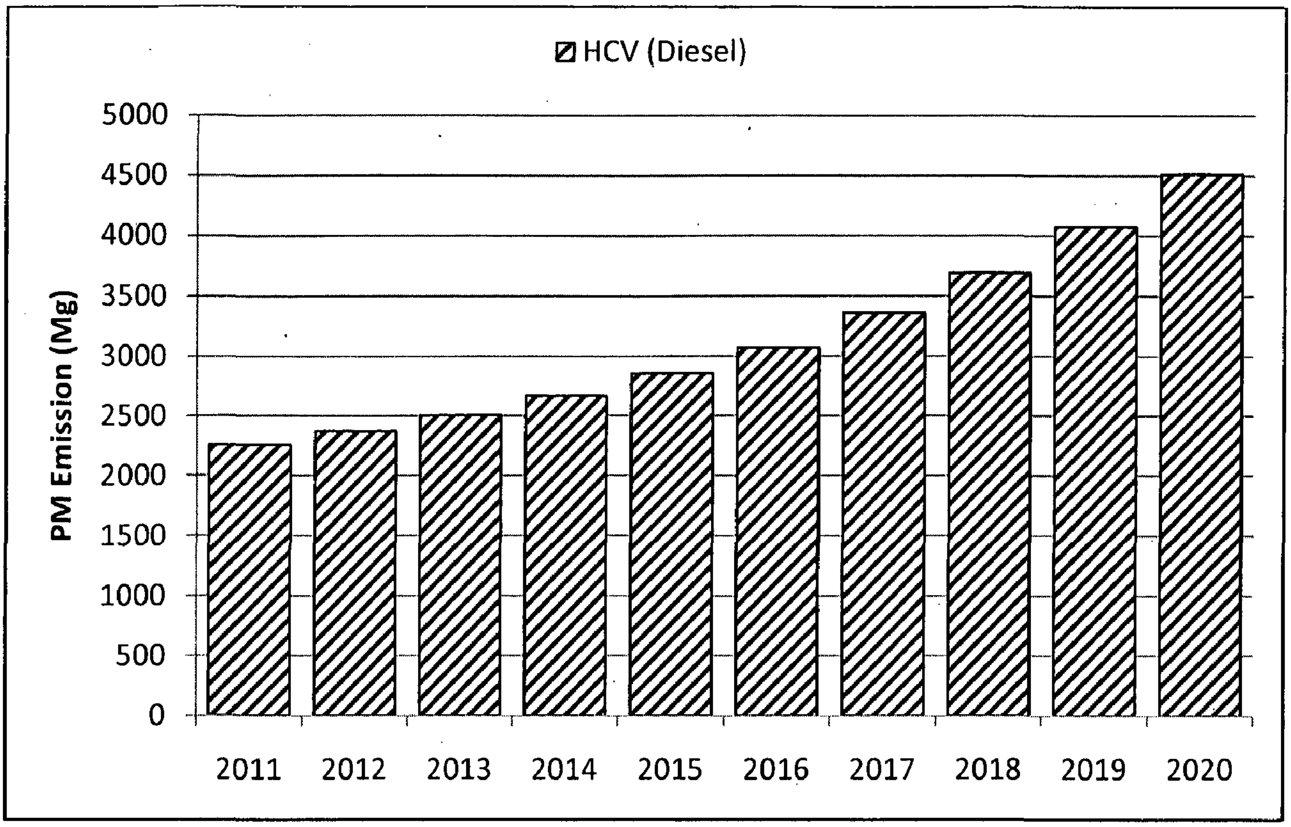


Fig. 6.40: PM emissions as per BAU scenario from HCVs in megacity Delhi

6.2.6. 1-3 Butadiene emissions

Emissions of 1-3 Butadiene from various vehicle categories during 2011 to 2020 in BAU and BES scenario are given in Fig. 6.41 (a and b). In 2011 emission of 1-3 Butadiene from various vehicles in BAU scenario will be 2671 kg, while in 2012 with 36% decline it will be 1703 kg, which is due to phasing out of 1991 modeled cars (having high emission factors). In 2015 emission of 1-3 Butadiene from various vehicles will be 1564 kg, followed by 1686 kg in 2020. Initially from 2011 to 2020 contribution of cars will be higher, followed by LCVs from 2015 to 2020. Similar to BAU scenario, emissions of 1-3 Butadiene in 2011 is higher (2581 kg) and with 37% decrease, the emissions are projected to be 1624 kg in 2012 (Fig. 6.41b). It is projected that cars and LCVs will be dominating for 1-3 Butadiene emissions in BES scenario in initial and later years respectively. In 2011 emissions in BAU scenario are higher than BES by about 3.4% followed by 8% in 2015 and 10.6% in 2020.

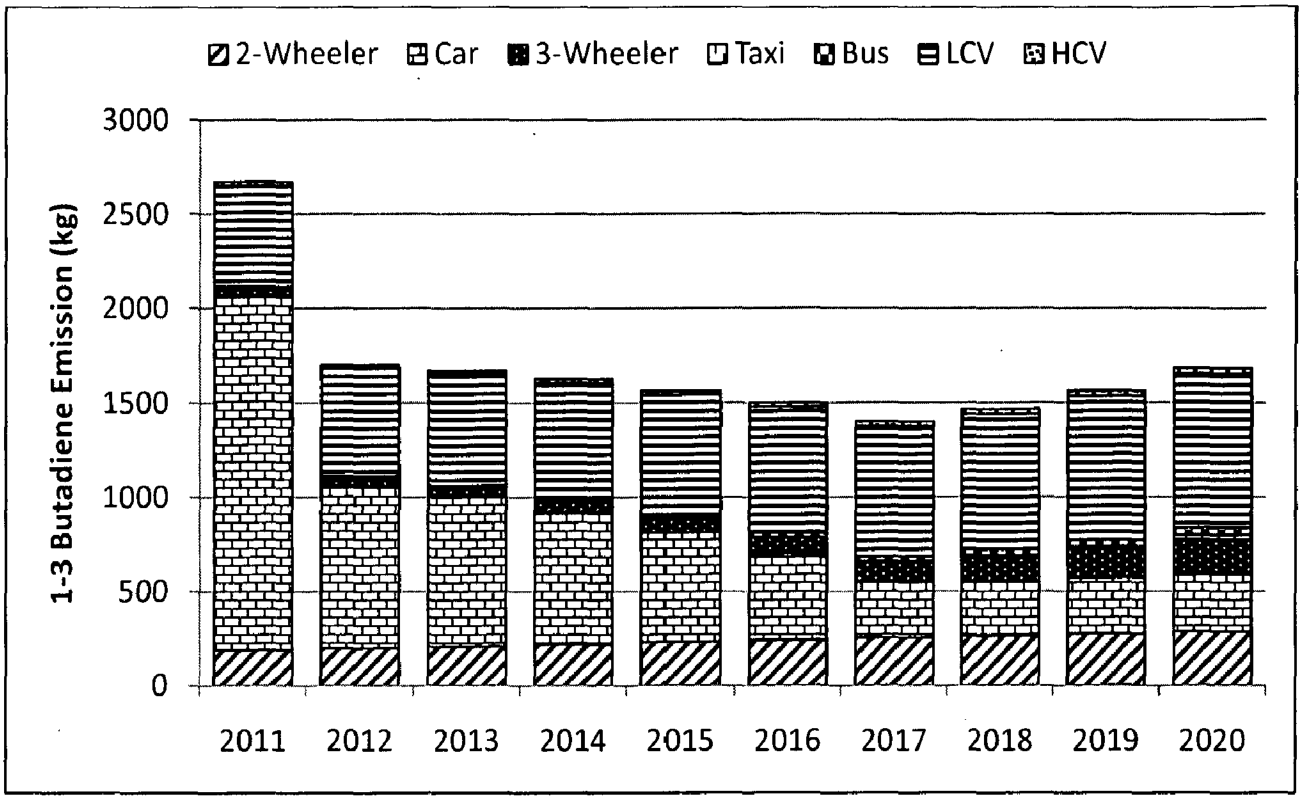


Fig. 6.41a: 1-3 Butadiene emissions as per BAU scenario from vehicles in megacity Delhi

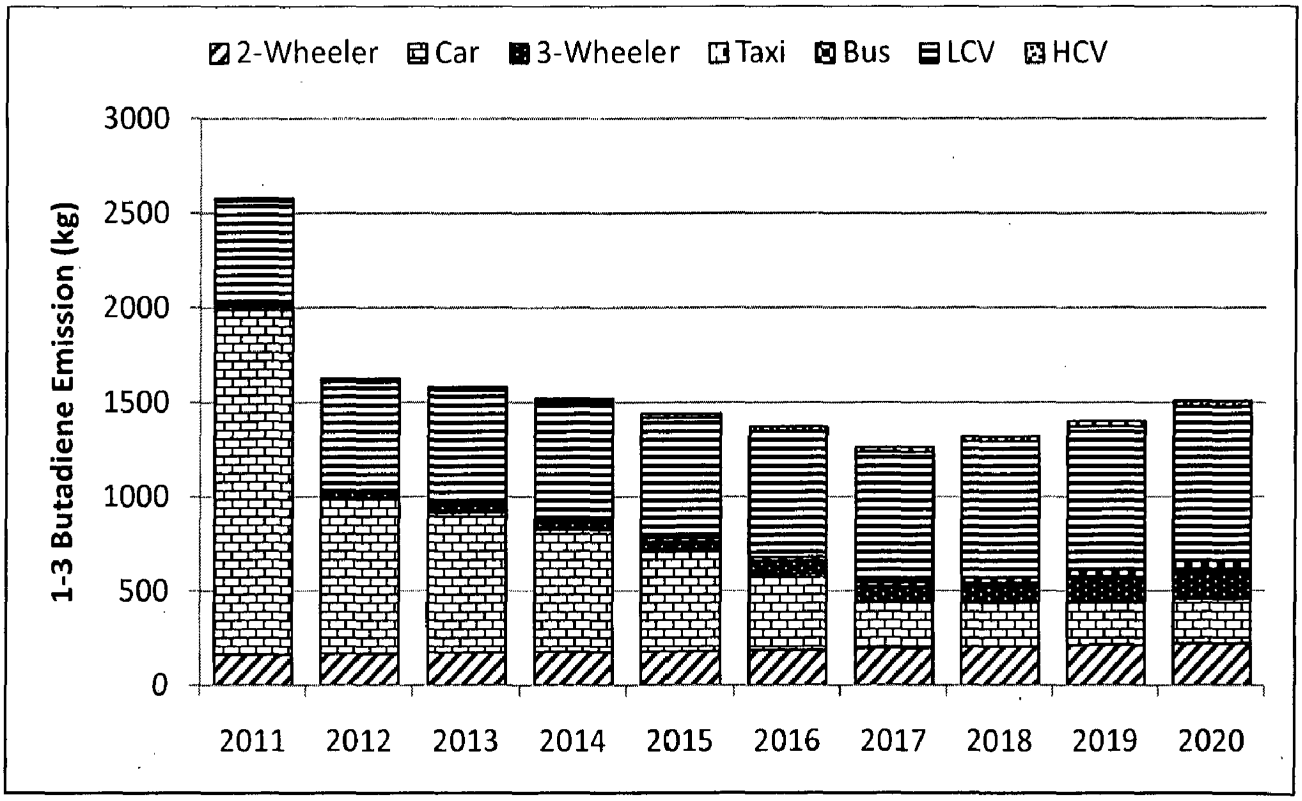


Fig. 6.41b: 1-3 Butadiene emissions as per BES scenario from vehicles in megacity Delhi

6.2.6.1. Two Wheelers

Emission trend of 1-3 Butadiene from two wheelers population in megacity Delhi from BAU and BES scenario is given in Fig. 6.42 (a and b). Emissions of 1-3 Butadiene from two wheelers in BAU scenario has been estimated to be 190 kg in 2011 followed by 232 kg in 2015 and 288 kg in 2020. Annual average growth in 1-3 Butadiene emission from BAU scenario is projected to be 4.7%. Estimation of 1-3 Butadiene emissions from BES scenario in 2011 is 164 kg, followed by 180 kg in 2015 and 222 kg in 2020, with projected annual average growth of 3.5%. With concern to contribution, share of four-stroke motorcycles is highest in both BAU and BES scenario. Emission of 1-3 Butadiene in BES is lesser than BAU scenario. In 2011 difference between BAU and BES scenario is ~9% in 2015 which suppose to become 12% in 2015 and 23% in 2020.

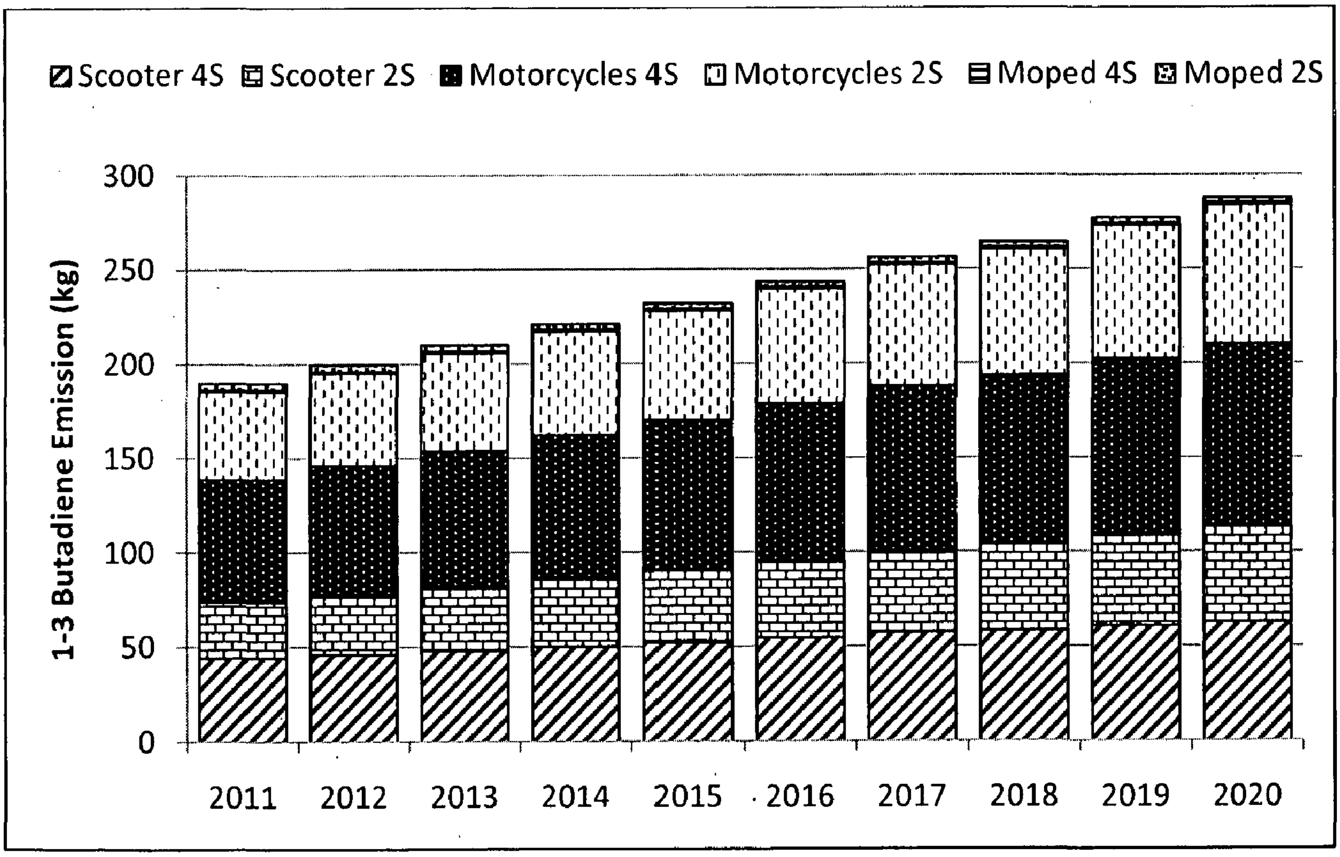


Fig. 6.42a: 1-3 Butadiene emissions as per BAU scenario from two wheelers in megacity Delhi

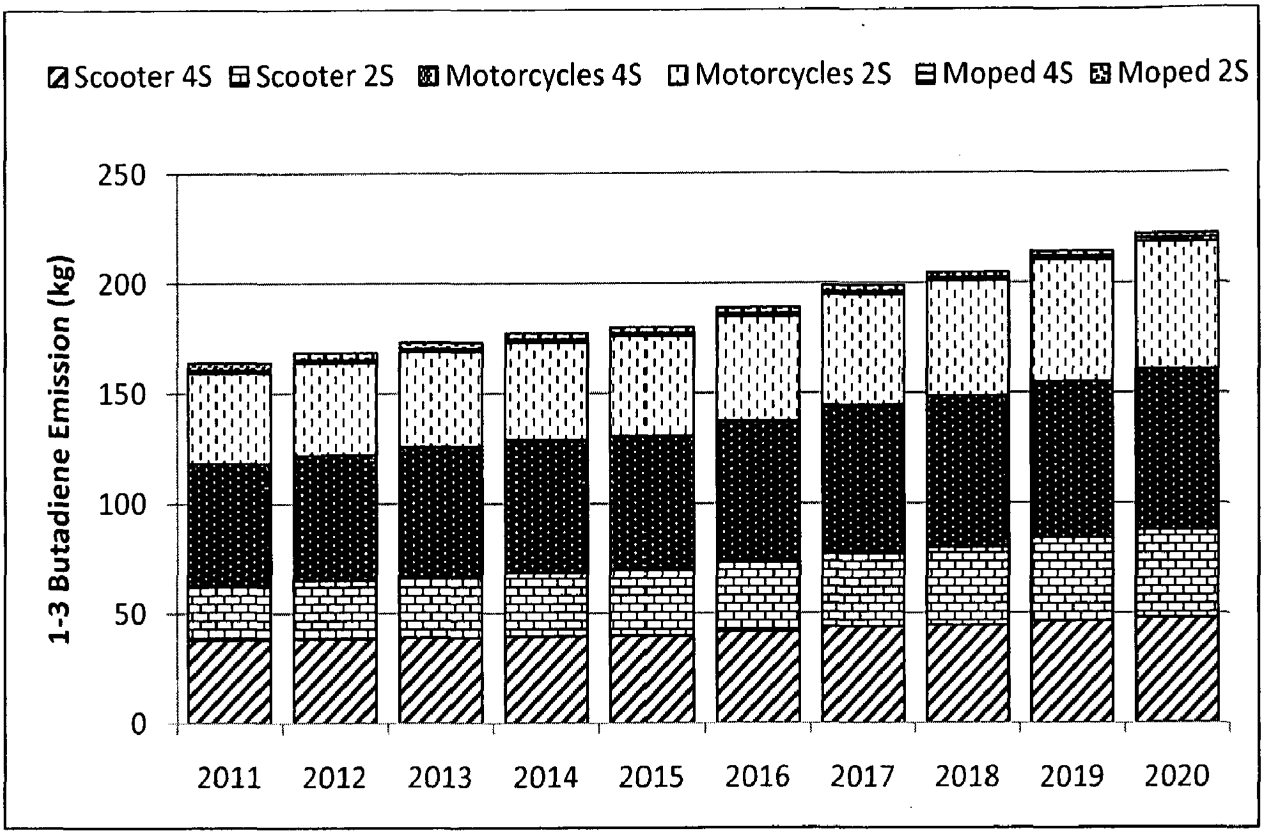


Fig. 6.42b: 1-3 Butadiene emissions as per BES scenario from two wheelers in megacity Delhi

6.2.6.2. Cars

1-3 Butadiene emissions from cars in BAU and BES scenario are presented in Fig. 6.43 (a and b). Figure shows that 1-3 Butadiene emissions in both the scenarios are much higher in 2011 than in other years. In the year 2012 emissions of 1-3 Butadiene are projected to decline due to phasing out of pre-1991 and 1991 model technology and high emission factor cars. It is projected that in both BAU and BES scenarios 1-3 Butadiene emissions will decrease due to gradual decline in emission factors. In BAU scenario 1-3 Butadiene emissions are estimated to be 1884 kg in 2011 followed by 584 kg in 2015 and 303 kg in 2020. Similarly in BES scenario 1-3 Butadiene emissions in year 2011 will be 1824 kg, 527 kg in 2015 and 236 kg in 2020. In BES scenario 1-3 Butadiene emissions are projected to be 3% less than that of BAU scenario in 2011 and in 2015 this difference will be 10% followed by 22% in 2020.

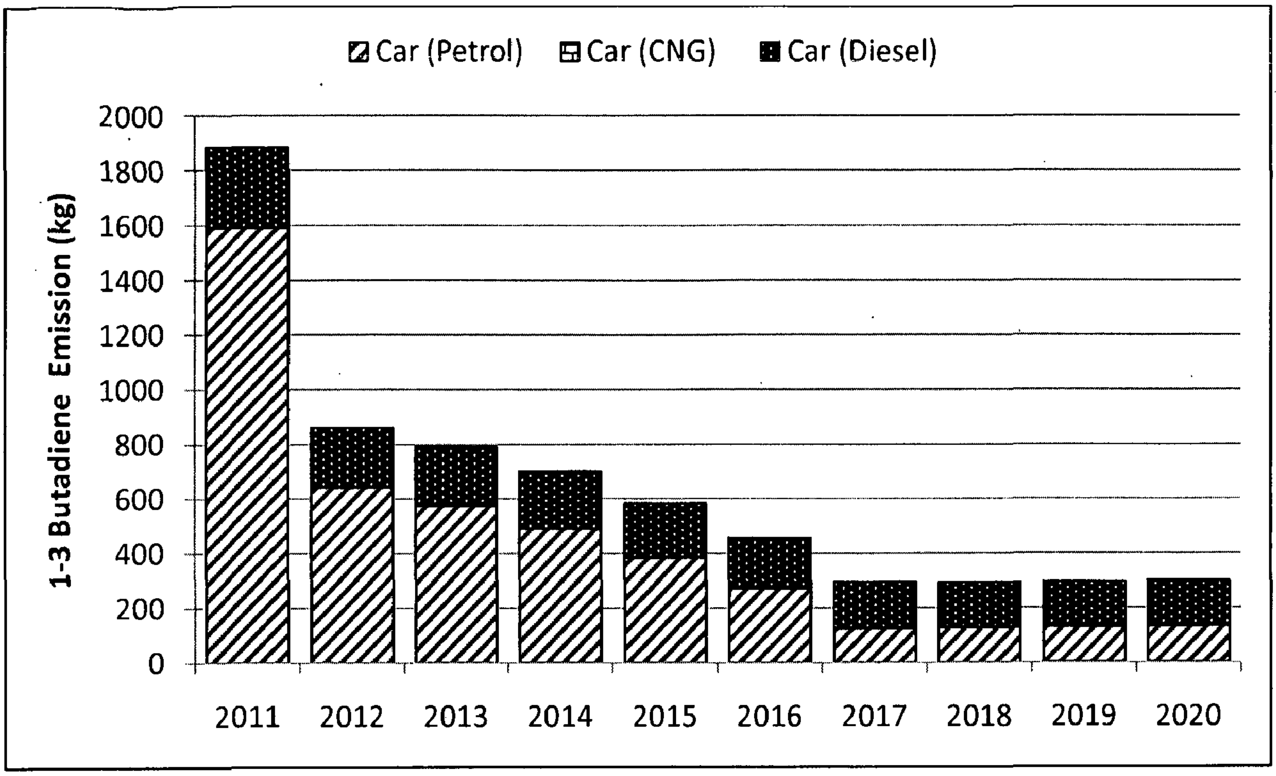


Fig. 6.43a: 1-3 Butadiene emissions as per BAU scenario from cars in megacity Delhi

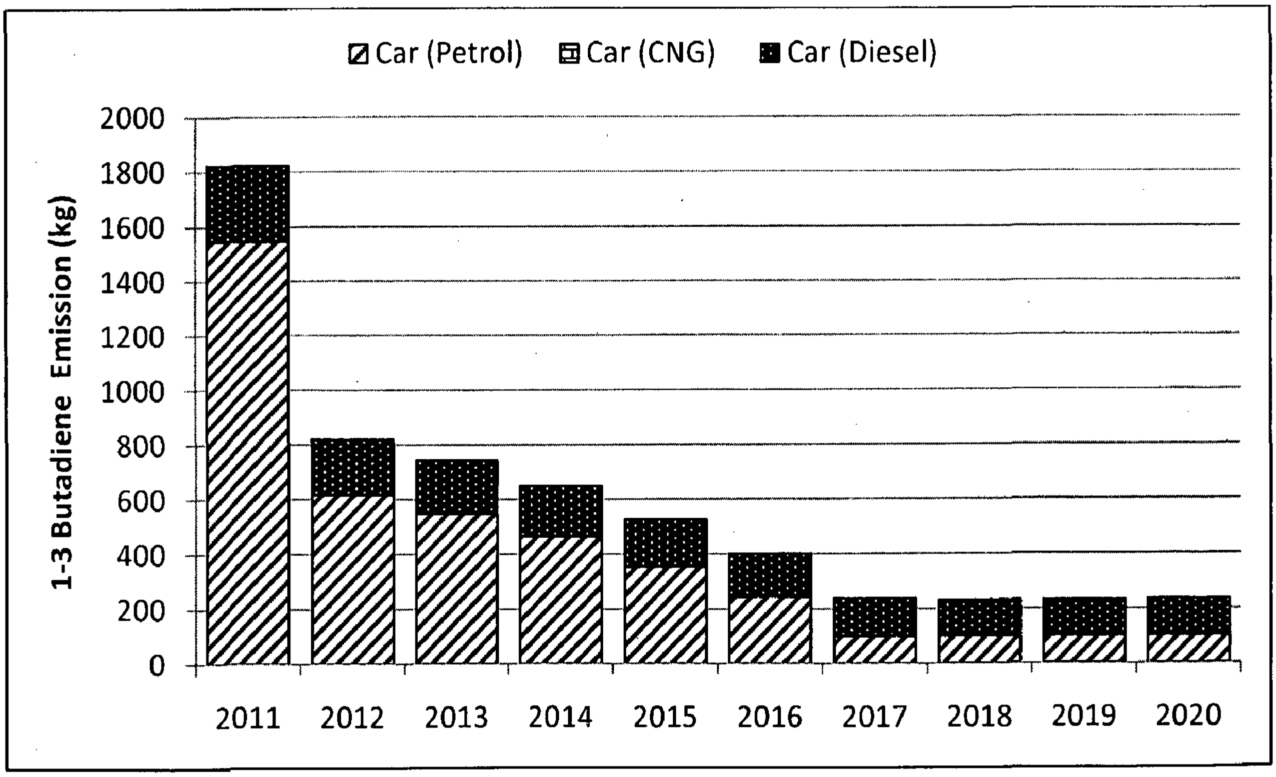


Fig. 6.43b: 1-3 Butadiene emissions as per BES scenario from cars in megacity Delhi

6.2.6.3. Three Wheelers

1-3 Butadiene emissions from three wheelers in megacity Delhi from 2011 to 2020 in BAU and BES scenario are given in Fig. 6.44 (a and b) respectively. This is evident that emissions from CNG driven four-stroke three-wheelers are predominant in both the scenarios. In BAU scenario, 1-3 Butadiene emission is estimated to be 32 kg in 2011, 66 kg in 2015, followed by 186 kg in 2020. An annual average growth of 21% is observed in 1-3 Butadiene from three wheelers in BAU scenario. Similar to BAU, 1-3 Butadiene emissions from three wheelers in 2011 is estimated to be about 28 kg, followed by 51 kg in 2015 and 141 kg in 2020 during BES scenario. About 20% of annual average growth is projected in 1-3 Butadiene emissions from 2011 to 2020. Emission of 1-3 Butadiene in BAU scenario is about 12-24% higher than BES during 2011 to 2020.

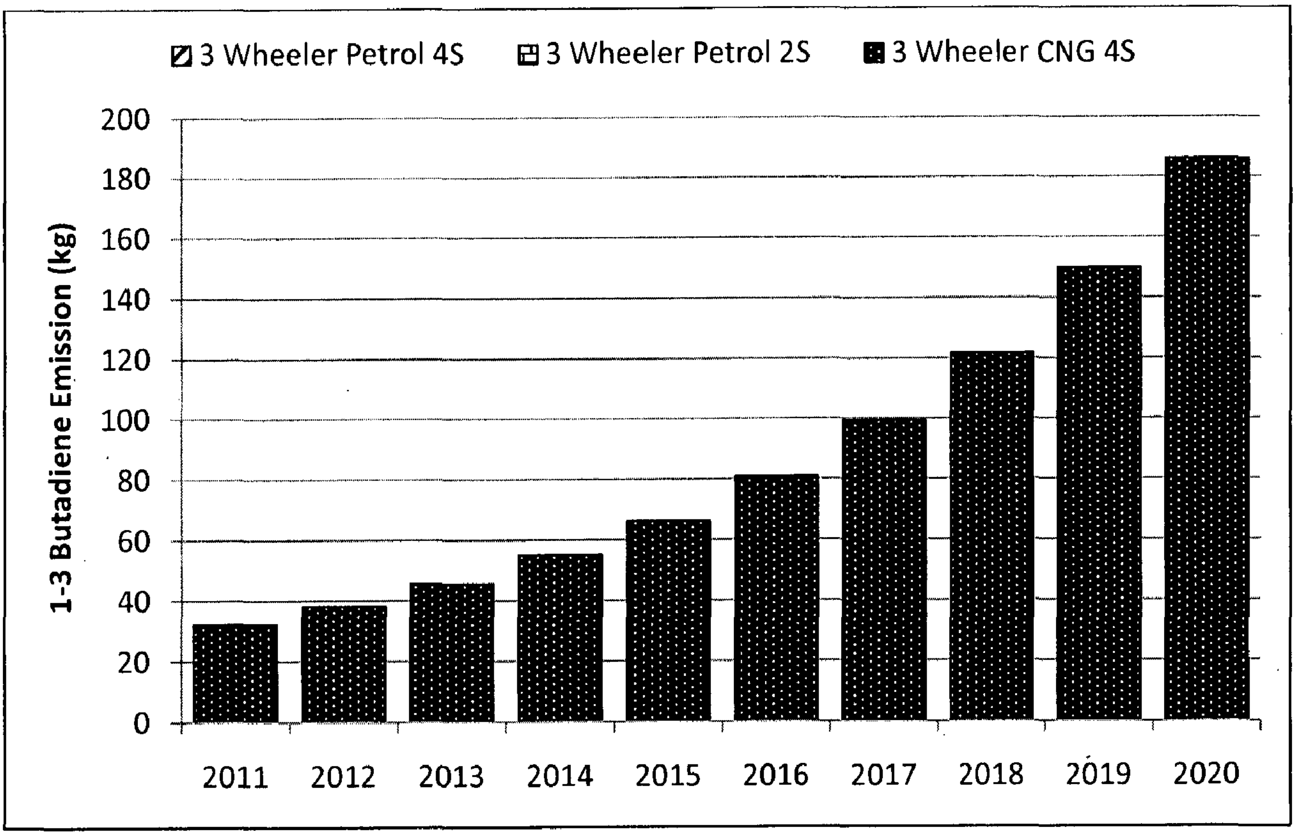


Fig. 6.44a: 1-3 Butadiene emissions as per BAU scenario from three wheelers in megacity Delhi

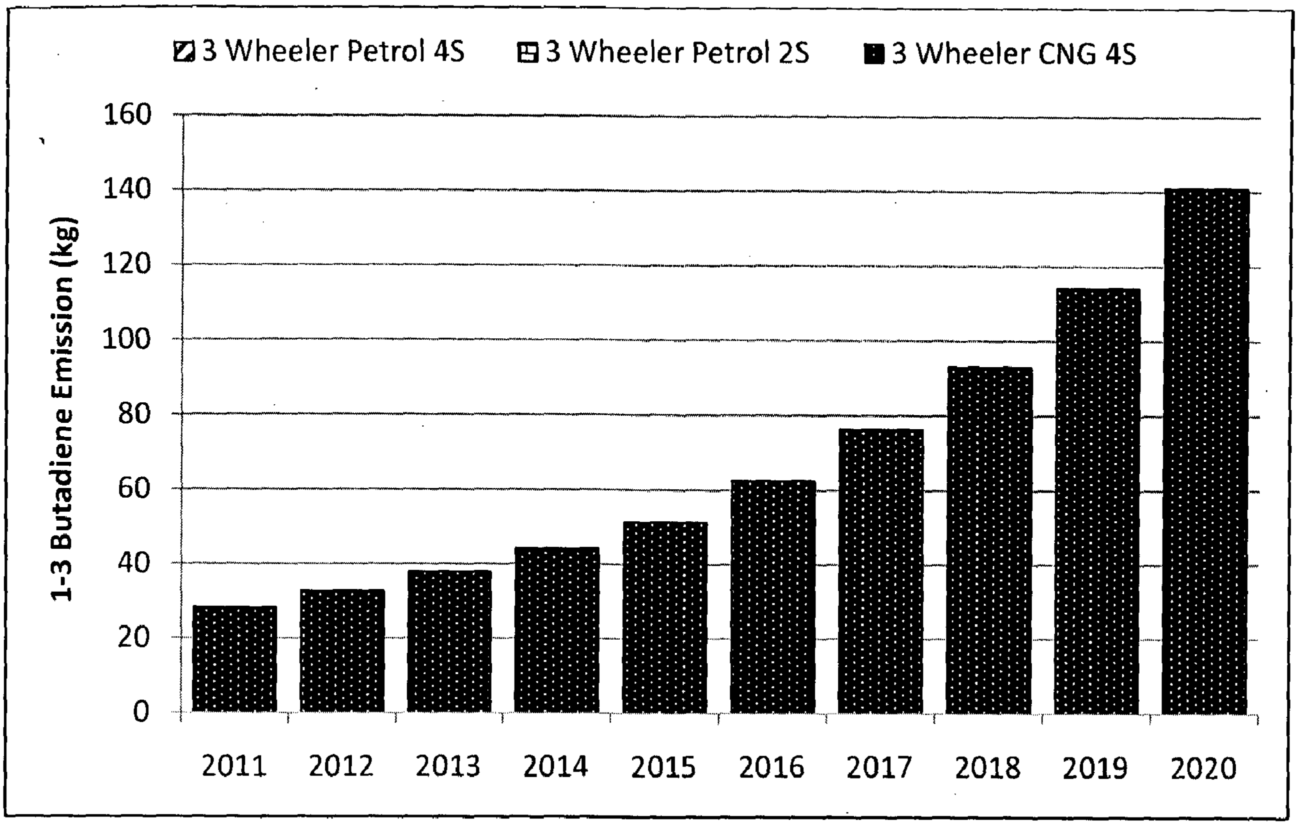


Fig. 6.44b: 1-3 Butadiene emissions as per BES scenario from three wheelers in megacity Delhi

6.2.6.4. Taxis

Fig. 6.45a shows the 1-3 Butadiene emission from BAU scenario during 2011 to 2020. It indicates that emissions in 2011 will be 3.7 kg and in 2015 it will be 5.9 kg followed by 21.4 kg in 2020. About 22% of annual average growth rate is observed in 1-3 Butadiene emissions from 2011 to 2020 in BAU scenario. Fig. 6.45b indicates the emission of 1-3 Butadiene according to BES scenario will be 3.7 kg in 2011, followed by 5.5 kg in 2015 and 19.4 kg in 2020. About 21% of annual average growth rate is observed in 1-3 Butadiene emissions from BES scenario from 2011 to 2020. In 2011 1-3 Butadiene emission in BES is 2% less than BAU scenario, while in 2015 and 2020 this difference will be 7% and 9% respectively.

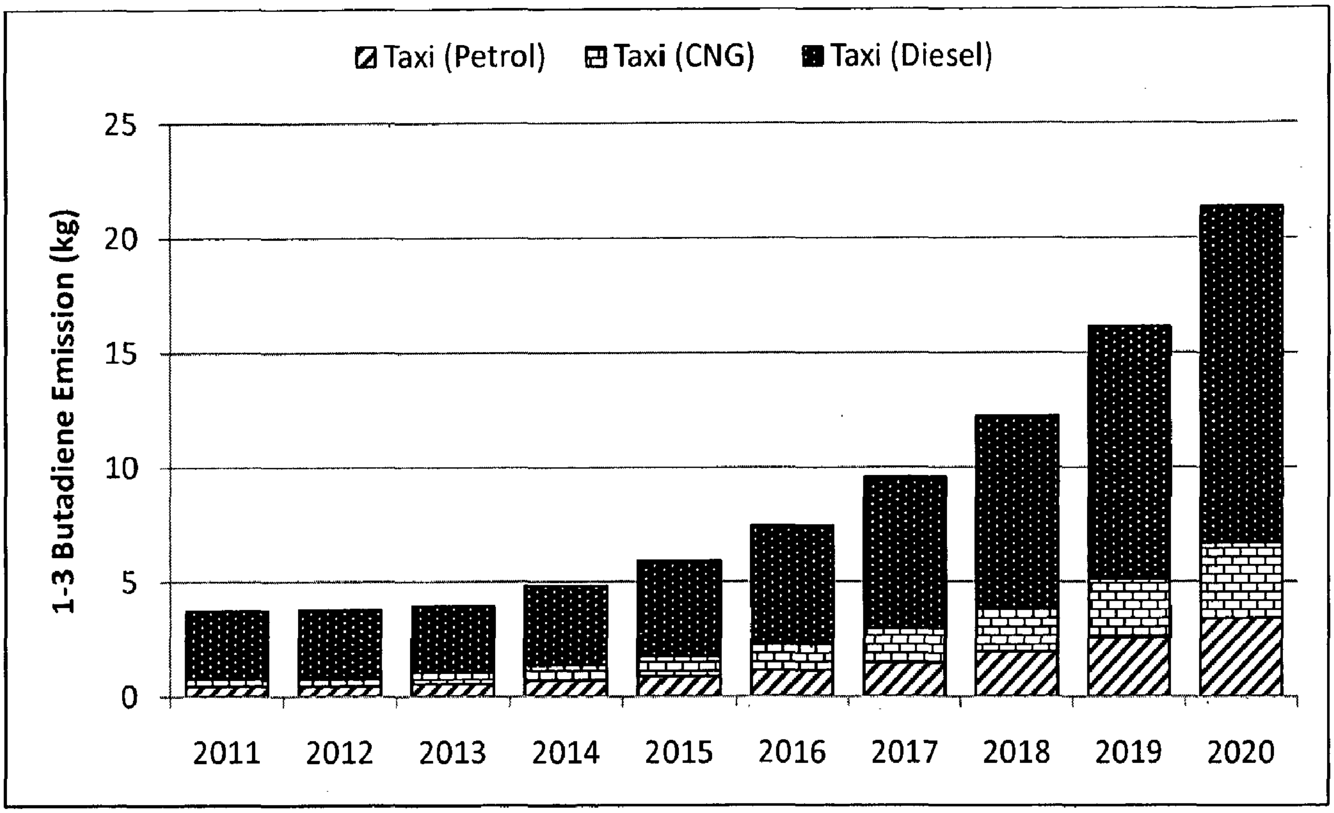


Fig. 6.45a: 1-3 Butadiene emissions as per BAU scenario from taxis in megacity Delhi

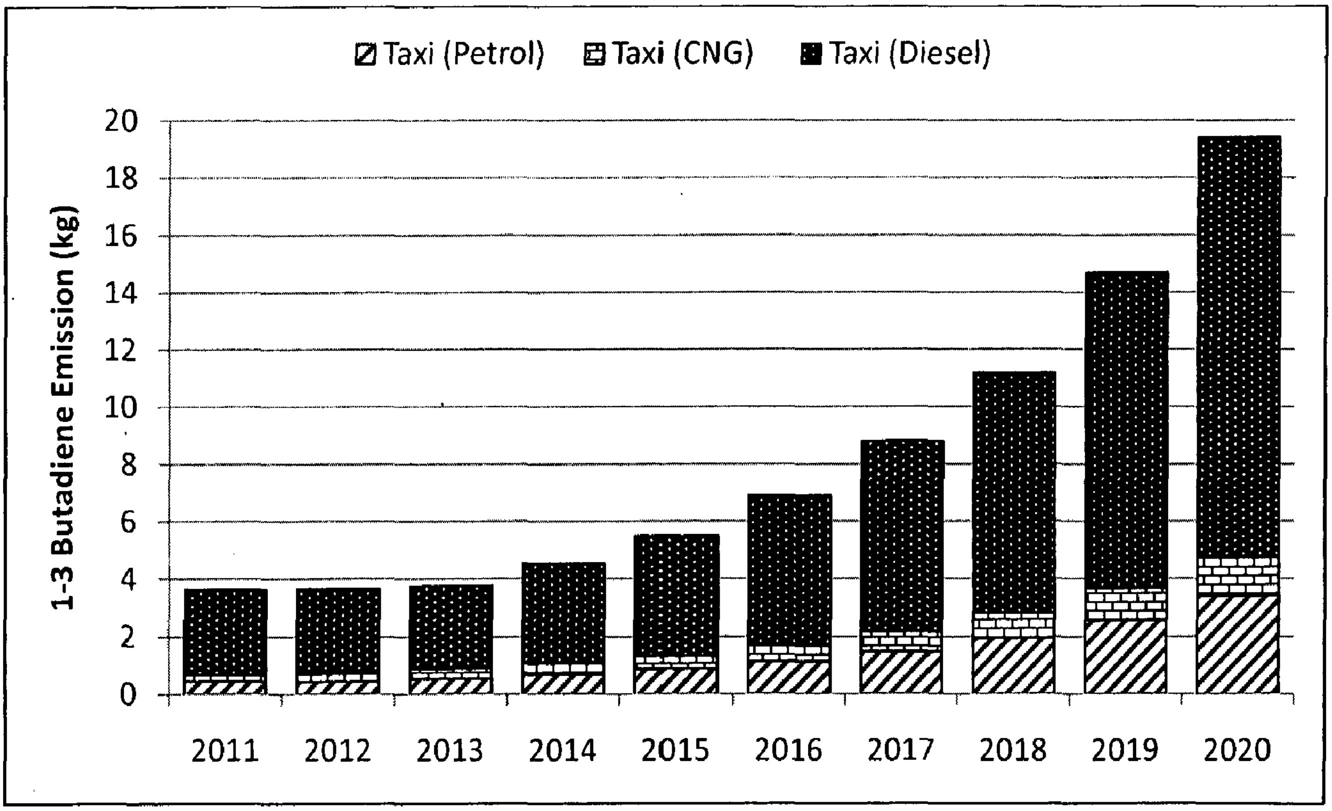


Fig. 6.45b: 1-3 Butadiene emissions as per BES scenario from taxis in megacity Delhi

6.2.6.5. Buses

1-3 Butadiene emissions from buses during 2011 to 2020 in BAU and BES scenario are presented in Fig 46 (a and b) respectively. It is projected that in 2011 emission of 1-3 Butadiene from buses will be 8.6 kg, while 17.4 kg and 40.7 kg in 2015 and 2020 respectively. Emissions of 1-3 Butadiene from buses in BES scenario (Fig. 6.46b) are 8.6 kg in 2011, followed by 17.4 kg in 2015 and 40.7 kg in 2020. Approximate 19% of annual average growth rate has been observed in 1-3 Butadiene emission from 2011 to 2020 in both BAU and BES scenarios. Contribution of CNG driven buses is very less for 1-3 Butadiene emission during 2011 to 2020 because of very less emission factor. Thus, external diesel buses are only the predominant source of 1-3 Butadiene emissions in Delhi.

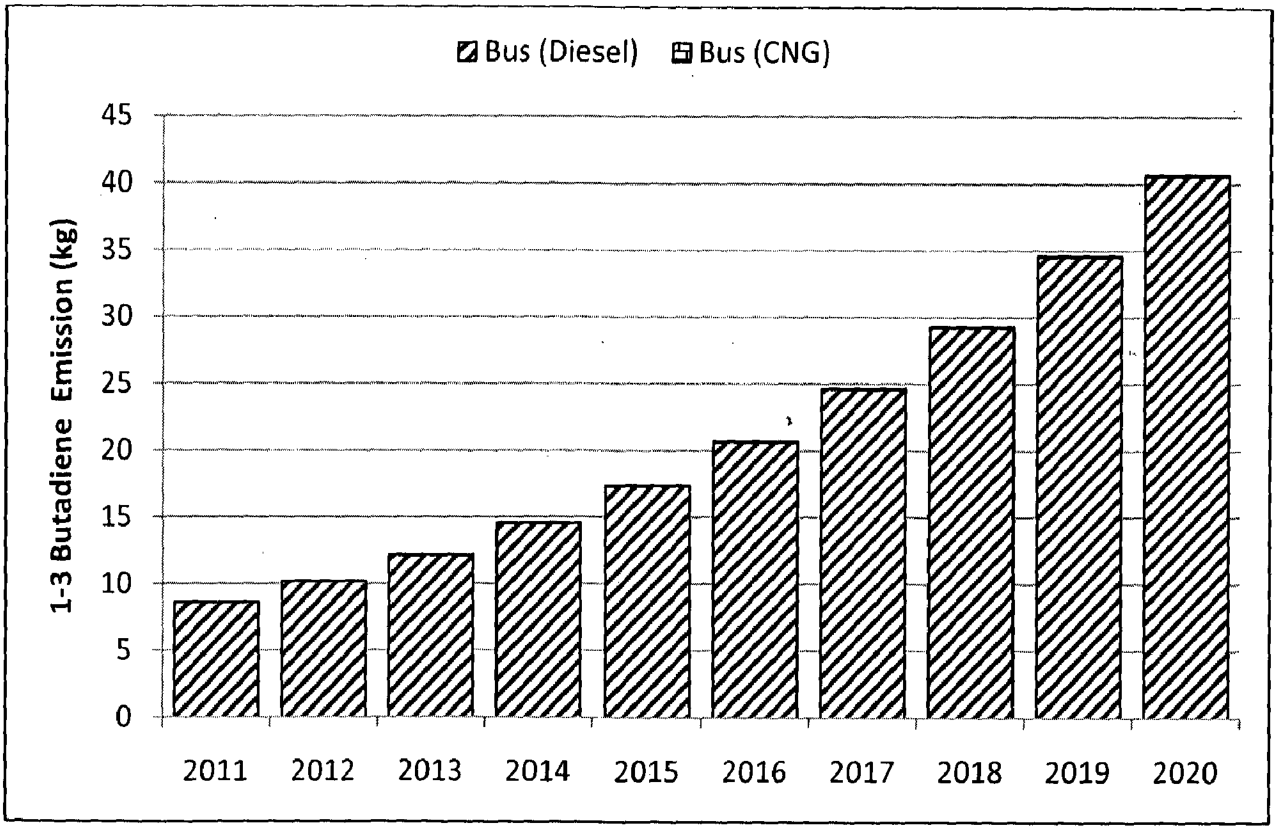


Fig. 6.46a: 1-3 Butadiene emissions as per BAU scenario from buses in megacity Delhi

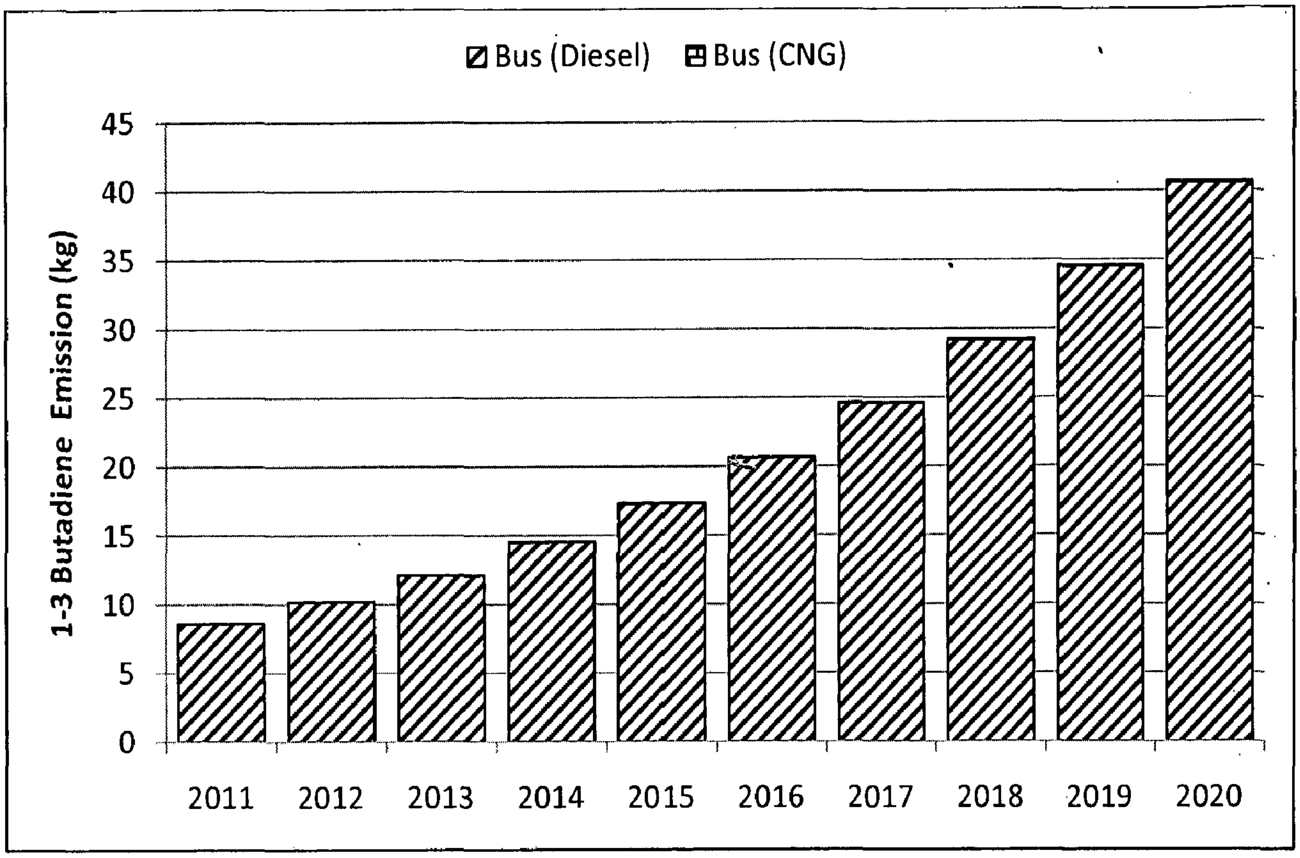


Fig. 6.46b: 1-3 Butadiene emissions as per BES scenario from buses in megacity Delhi

6.2.6.6. LCVs/HCVs

Fig 47 shows the emission of 1-3 Butadiene from LCVs during 2011 to 2020. Estimations suggest that emission of 1-3 Butadiene from LCVs will be 536 kg in 2011, 639 kg in 2015 and 827 kg in 2020. About 5% of annual average growth is observed in 1-3 Butadiene emissions from 2011 to 2020. Although all LCVs in Delhi are now CNG driven, the population of diesel drive external LCVs is enough to emit comparatively large emissions due to their very high emission factors (ARAI, 2007). Contribution of CNG driven LCVs is, therefore, negligible while diesel driven LCVs share major emissions of 1-3 Butadiene. Fig. 6.48 shows 1-3 Butadiene emissions from HCVs population during 2011 to 2020. In 2011 emissions are projected to be 17kg, followed by 20 kg in 2015 and 31 kg in 2020. About 6.76% of average growth is estimated annually in 1-3 Butadiene emissions from HCVs during 2011 to 2020.

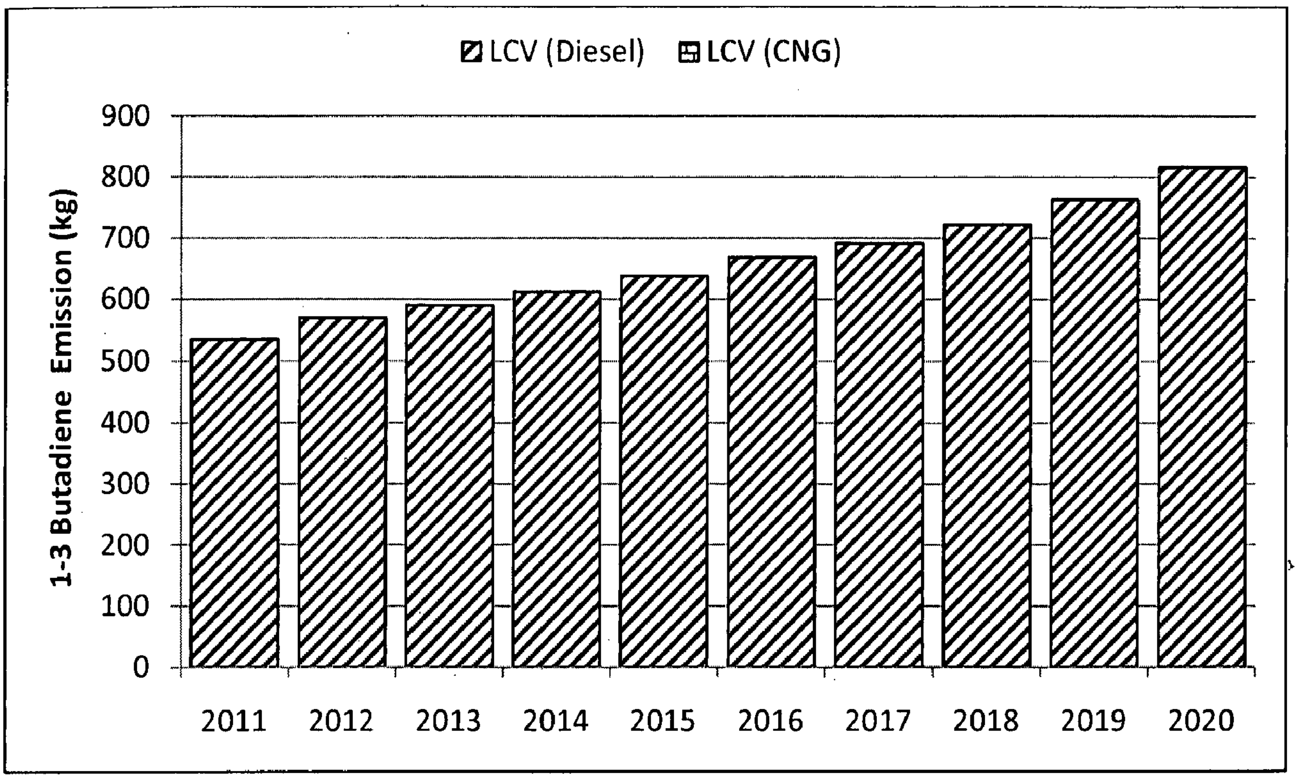


Fig. 6.47: 1-3 Butadiene emissions as per BAU scenario from LCVs in megacity Delhi

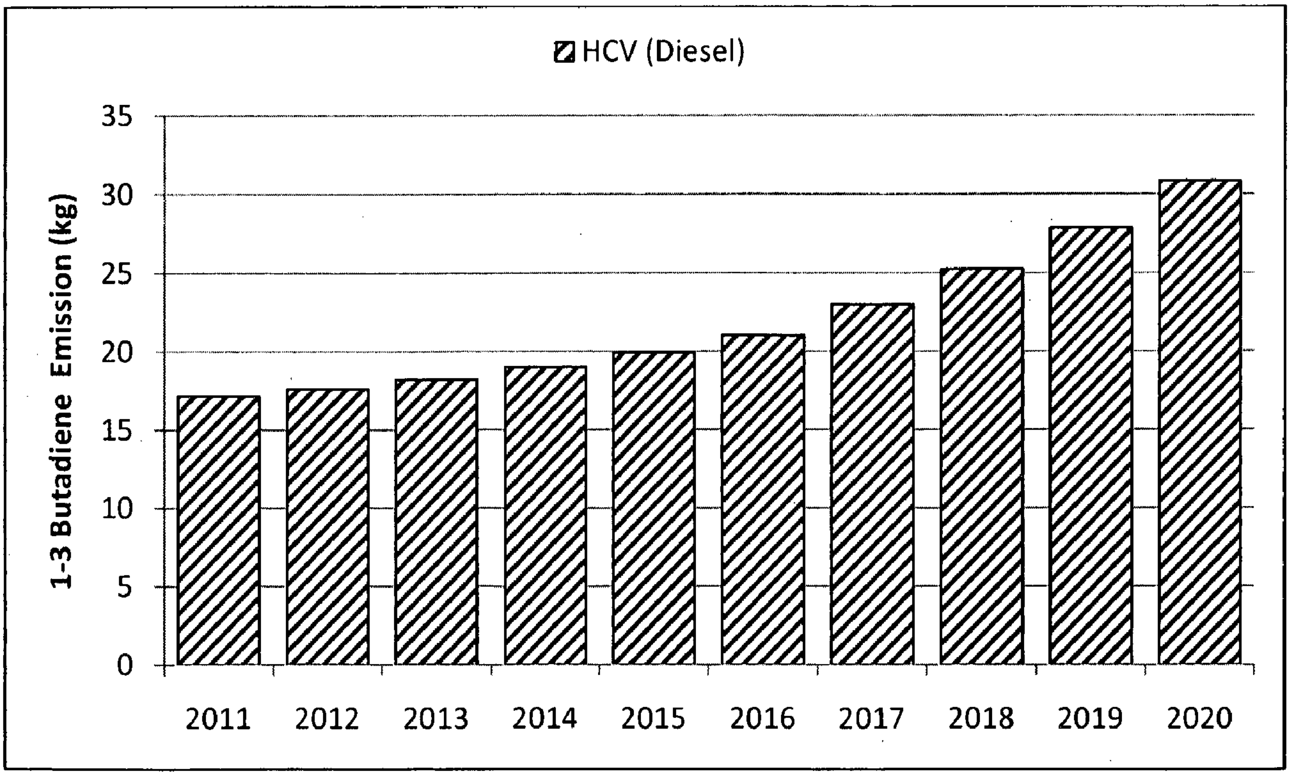


Fig. 6.48: 1-3 Butadiene emissions as per BAU scenario from HCVs in megacity Delhi

6.2.7. Acetaldehyde emissions

Emissions of Acetaldehyde from various categories of vehicles in BAU and BES scenario for megacity Delhi are given in Fig. 6.49 (a and b). BAU scenario indicates that Acetaldehyde emissions from various vehicle categories will be 484 kg in 2011, followed by 553 kg in 2015 and 870 kg in 2020. Between 2011 and 2012, decline of about 8% is projected due to phasing out of 1991 model cars (having high emission factor) in 2012. In 2011 emission of Acetaldehyde from various vehicle categories in BES scenario is projected to be 437 kg which is ~10% less than BAU estimation. Similarly in 2015 emission from BES is 444 kg and in 2020 it is 693 kg which are ~20% less than emissions during those years under BAU scenario. Two-wheelers are estimated to have the highest share of Acetaldehyde emissions in both BAU and BES scenarios.

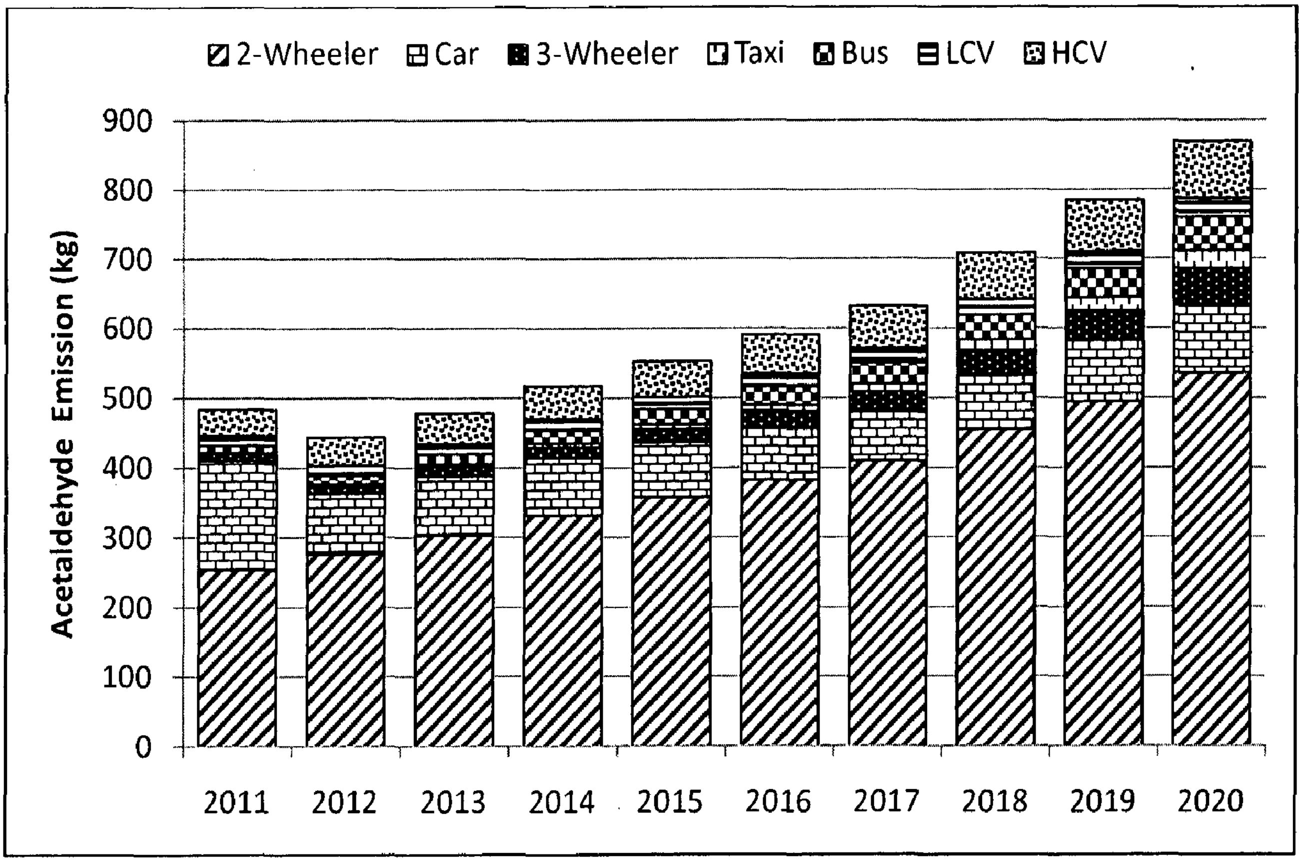


Fig. 6.49a: Acetaldehyde emissions as per BAU scenario from vehicles in megacity Delhi

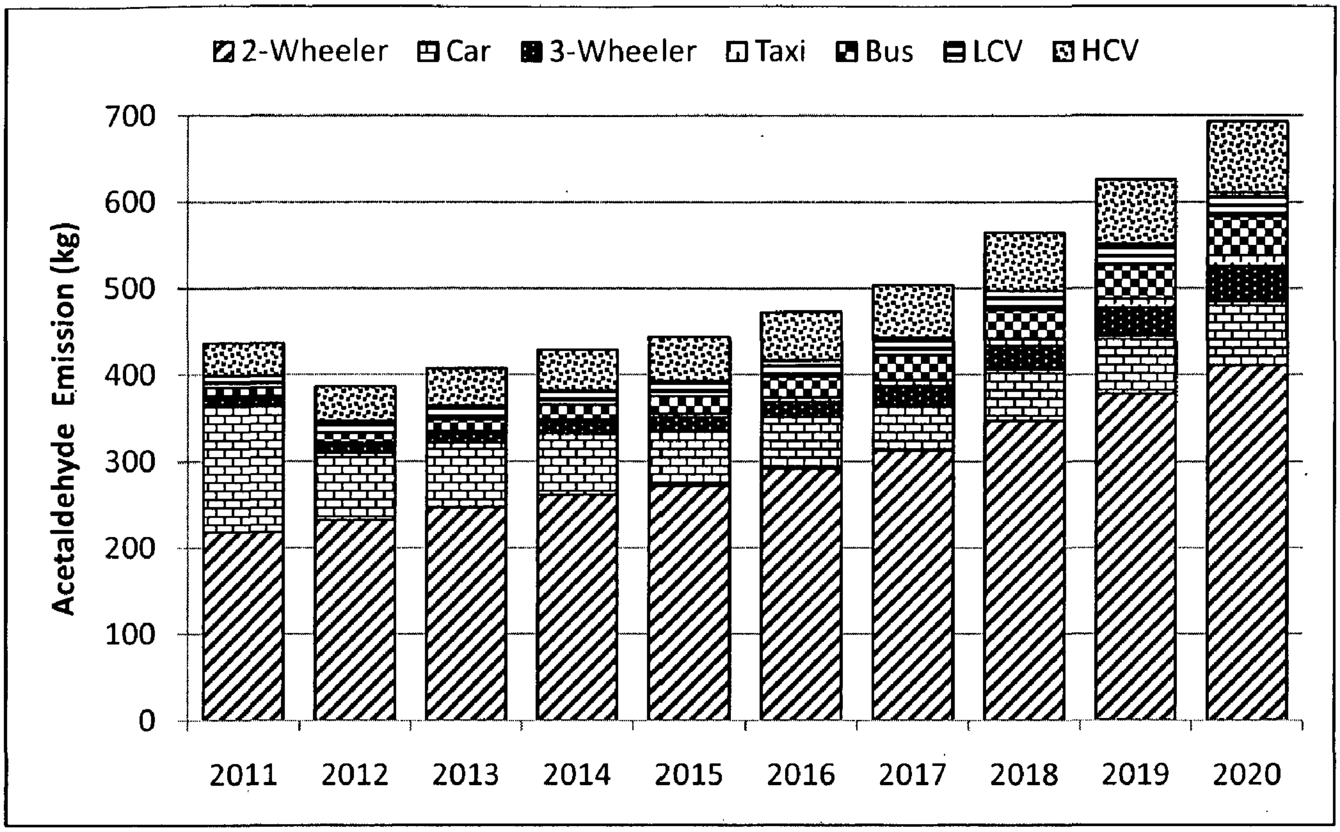


Fig. 6.49b: Acetaldehyde emissions as per BES scenario from vehicles in megacity Delhi

6.2.7.1. Two Wheelers

Fig. 6.50a indicates that Acetaldehyde emissions are projected to reach 255 kg in 2011, followed by 537 kg in 2020. About 8.6% of annual average growth rate is estimated in BAU scenario from 2011 to 2020. As per contribution, accountability of two-stroke and four-stroke scooters is highest. Fig. 6.50b shows the emission of Acetaldehyde from two wheelers during the time period of 2011 to 2020 in BES scenario. It indicates that in 2011 emissions will be 219 kg, while 272 kg in 2015 and 412 kg in 2020. Share of two-stroke and four-stroke scooters is also highest in BES scenario. In 2011 emission of Acetaldehyde in BES is 14% less than BAU scenario, followed by 23-24% in 2015 and 2020.

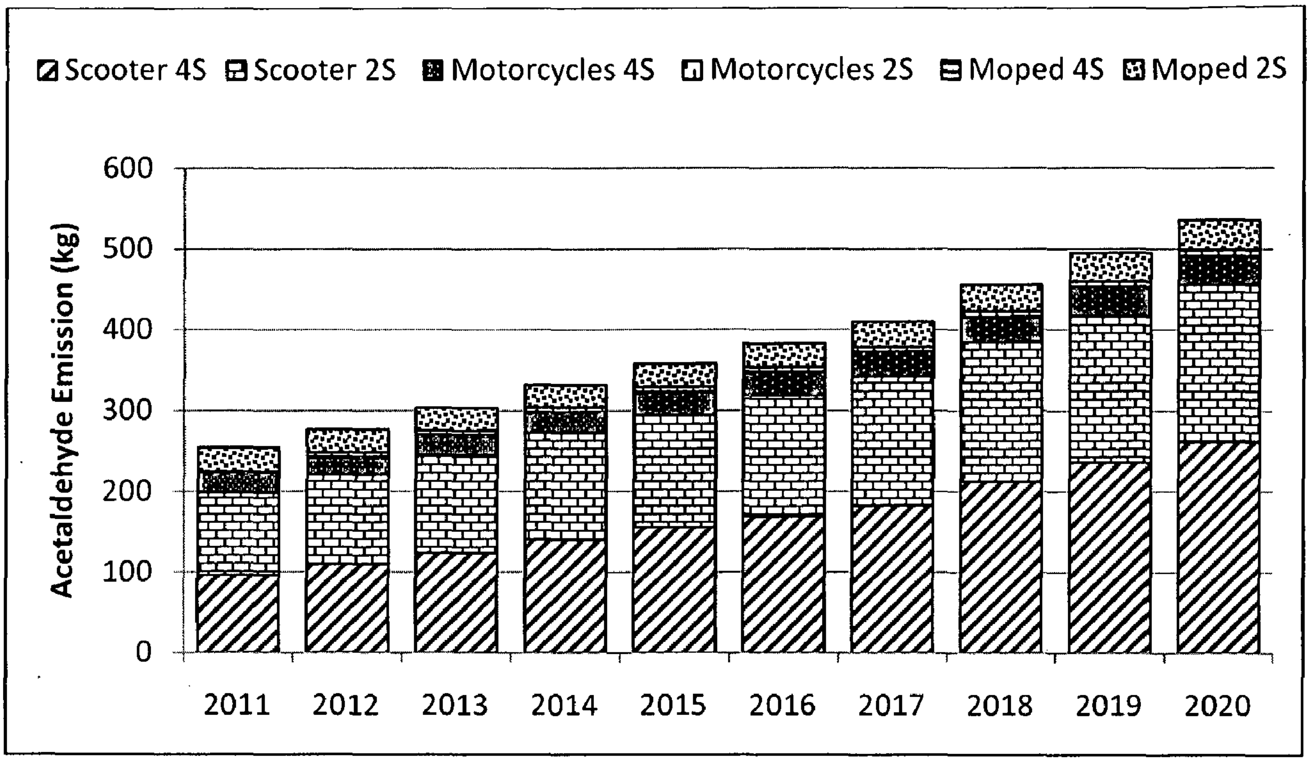


Fig. 6.50a: Acetaldehyde emissions as per BAU scenario from two wheelers in megacity Delhi

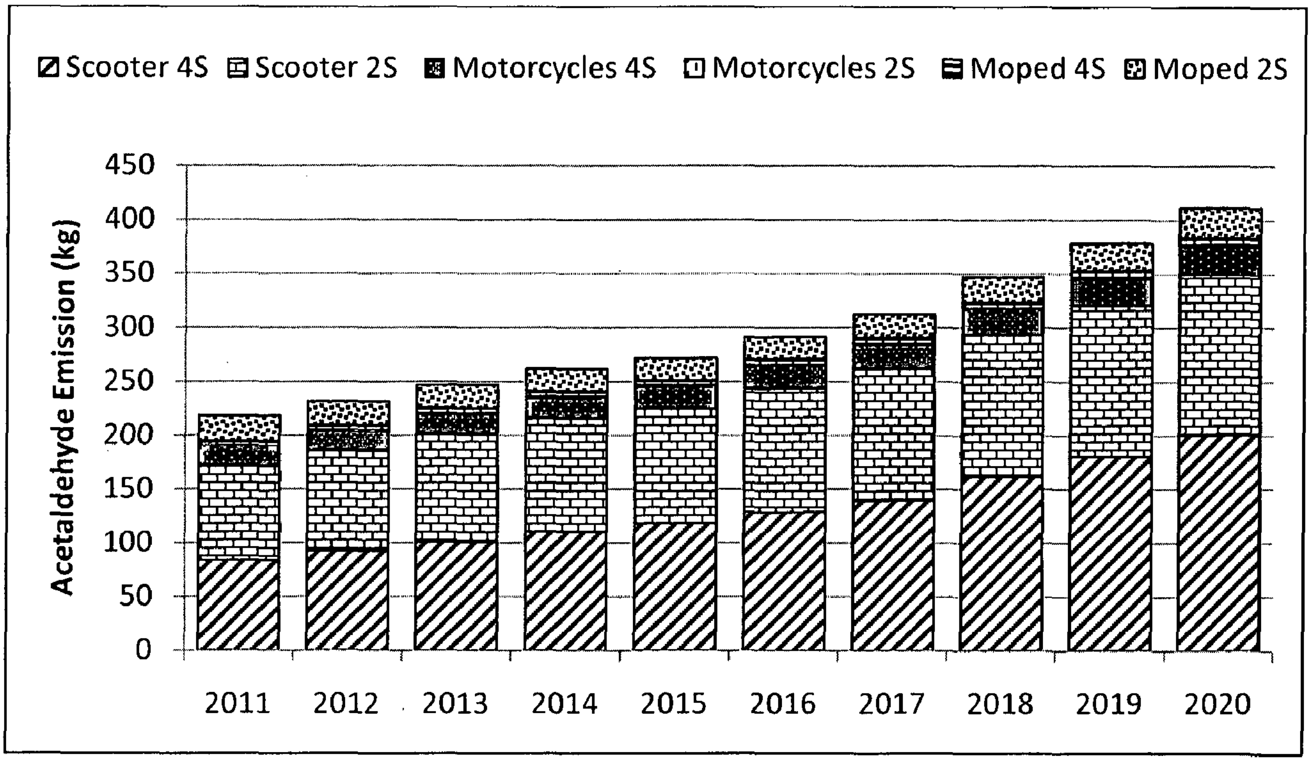


Fig. 6.50b: Acetaldehyde emissions as per BES scenario from two wheelers in megacity Delhi

6.2.7.2. Cars

Emissions of Acetaldehyde from cars are estimated to be 156 kg in BAU scenario in the year 2011. Sudden fall in Acetaldehyde emissions is observed between 2011 and 2012 in both BAU and BES scenarios due to phasing out of 1991 and pre-1991 cars (higher emission factor) in 2012. After 2012 emission of Acetaldehyde from cars are continuously decreasing till 2017 because of decreasing emission factor for new model cars and phasing out of old age cars having high emission factors. Acetaldehyde emissions from cars in BAU scenario are estimated to be 79 kg in 2015 and 97 kg in 2020. Emissions of Acetaldehyde from BES scenario in 2011 are estimated to be 147 kg and are projected to decrease during 2011 to 2017 due to same reason. In 2015 Acetaldehyde emission is 64 kg, followed by 74 kg in 2020. Emission of Acetaldehyde from BAU scenario in 2011 is 5.86% higher than BES and is projected to be 18.63% in 2015 and 23% in 2020. Although the emissions from petrol driven cars are maximum, their share is decreasing; while that of CNG and diesel driven cars is rising because of CNG conversion of internal cars and more external diesel driven cars.

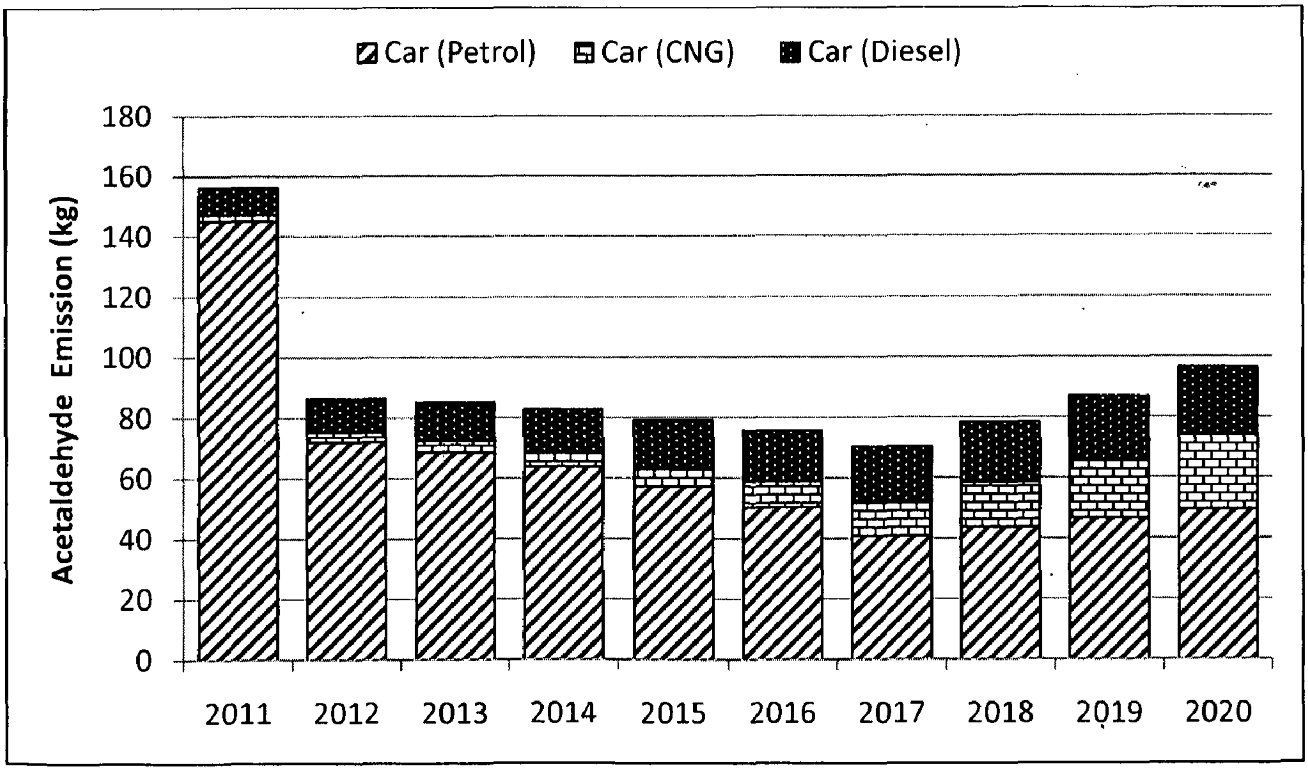


Fig. 6.51a: Acetaldehyde emissions as per BAU scenario from cars in megacity Delhi

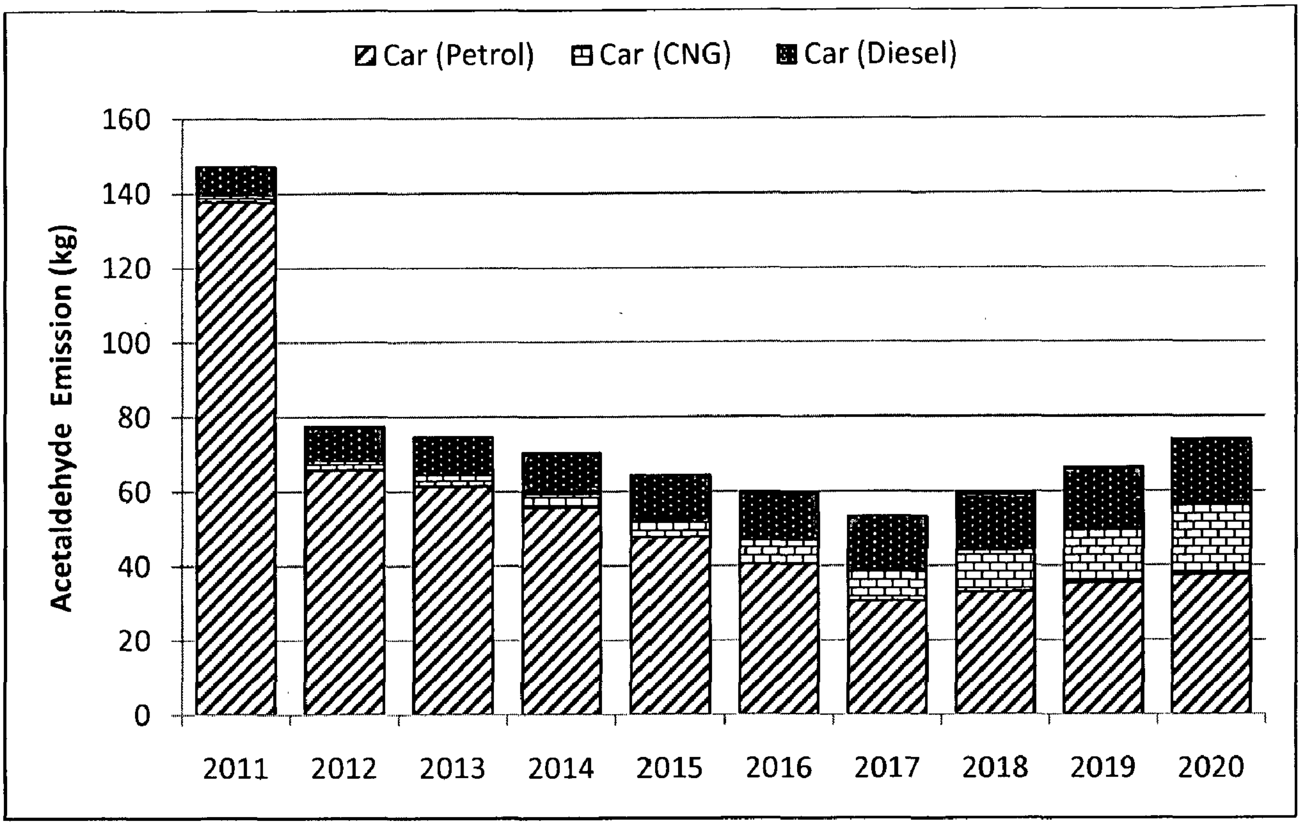


Fig. 6.51b: Acetaldehyde emissions as per BES scenario from cars in megacity Delhi

6.2.7.3. Three Wheelers

Acetaldehyde emissions from BAU and BES scenarios for three wheelers in megacity Delhi are given in Fig. 6.52 (a and b). These emissions are mainly from CNG driven four-stroke three-wheelers. Fig. 6.52a indicates that in 2011 emission of Acetaldehyde is 9 kg, followed by 19 kg in 2015 and 53 kg in 2020. About 21% of annual average growth is estimated in Acetaldehyde emissions from three wheelers in BAU scenario. Emissions of Acetaldehyde from three wheelers in BES scenario for the year 2011 is estimated to be 8 kg, 15 kg in 2015, followed by 40 kg in 2020. Emission of Acetaldehyde in BES is 13-24% less than BAU scenario during 2011 to 2020.

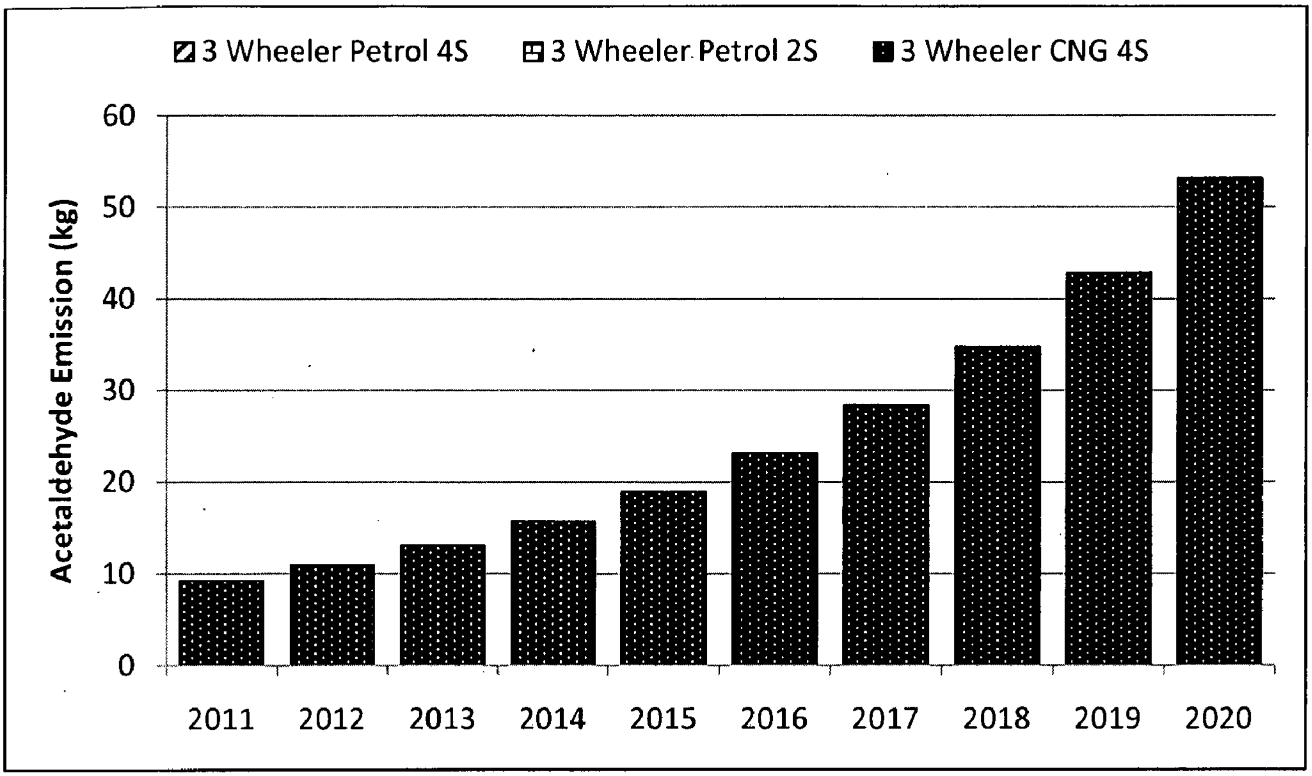


Fig. 6.52a: Acetaldehyde emissions as per BAU scenario from three wheelers in megacity Delhi

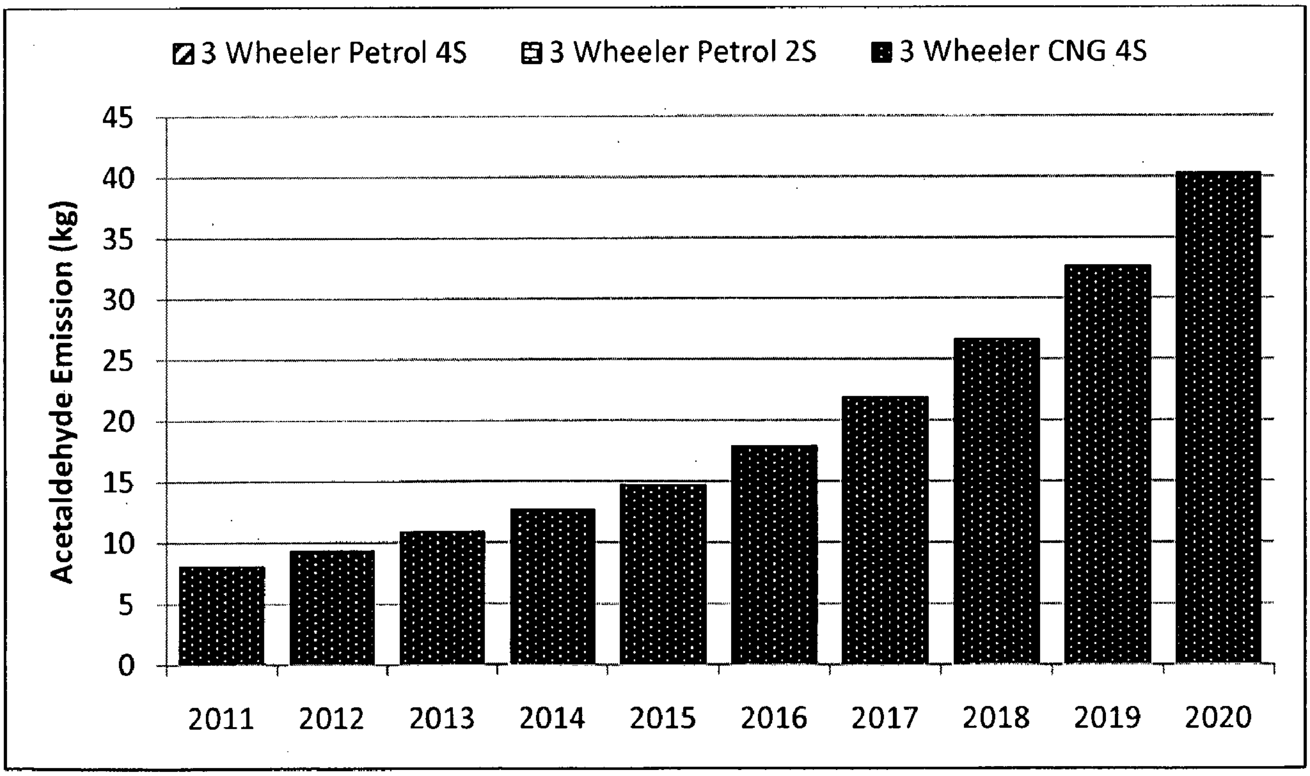


Fig. 6.52b: Acetaldehyde emissions as per BES scenario from three wheelers in megacity Delhi

6.2.7.4. *Taxis*

Acetaldehyde emissions from taxis for BAU and BES scenario are presented in Fig. 6.53 (a and b). Acetaldehyde emissions in BAU scenario for year 2011 are estimated to be 2.4 kg, 6.7 kg and 25.5 kg for the years 2015 and 2020 respectively. About 30% of annual average growth in Acetaldehyde emissions is estimated from 2011 to 2020. However, share is more from CNG and diesel driven taxis in comparison to the petrol driven taxis. Fig. 6.53b indicates that in 2011 Acetaldehyde emissions from taxis in BES scenario will be 1.93 kg, followed by 4 kg in 2015 and 12.71 kg in 2020. Emission of Acetaldehyde in BES is less than BAU scenario. In 2011, about 20% of difference is observed between BES and BAU scenario which will be ~40% in 2015 and 50% in 2020.

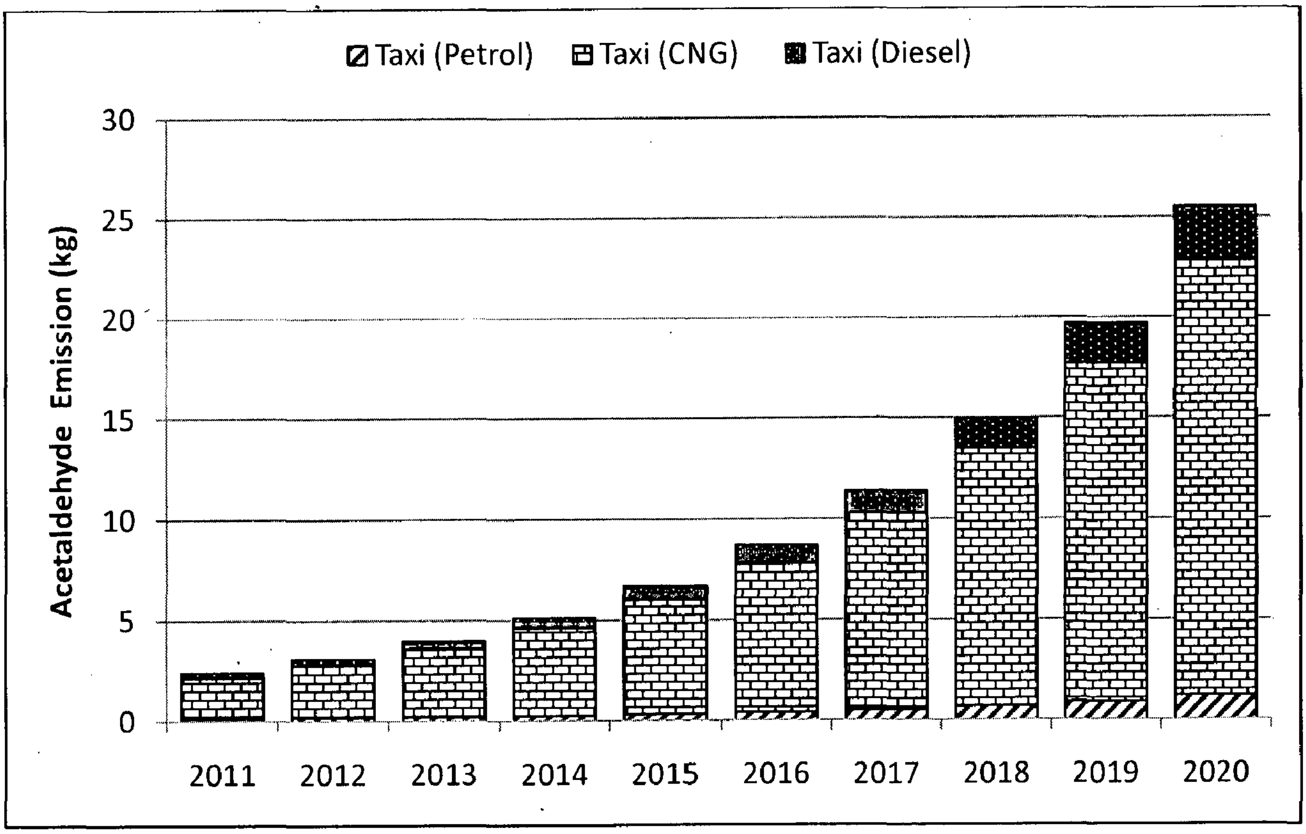


Fig. 6.53a: Acetaldehyde emissions as per BAU scenario from taxis in megacity Delhi

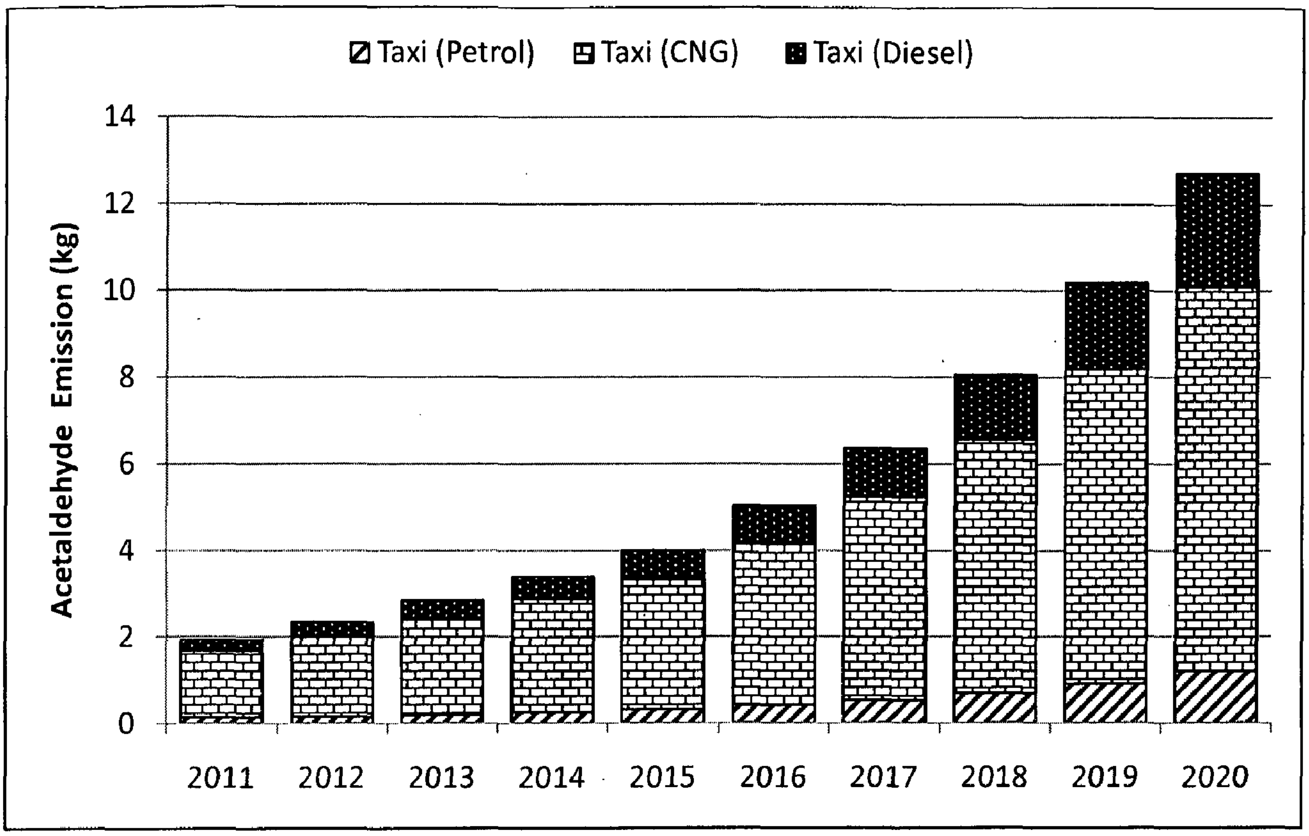


Fig. 6.53b: Acetaldehyde emissions as per BES scenario from taxis in megacity Delhi

6.2.7.5. Buses

Acetaldehyde emissions from buses in BAU scenario for the year 2011 is 10 kg (Fig. 6.54a) while in 2015 it is 22 kg followed by 48.65 kg in 2020. About 19.2% of annual average growth rate is estimated in Acetaldehyde emissions from buses in BAU scenario. Fig. 6.54b suggests that in 2011 Acetaldehyde emissions from buses for BES scenario will be 9.5 kg, followed by 20.4 kg in 2015 and 45.5 kg in 2020. Diesel driven external buses are expected to be the dominating source for Acetaldehyde emissions from 2011 to 2020 in both BAU and BES scenarios due to high emission factor (Table 3.2). Emission of Acetaldehyde from buses in BES scenario is 5.6% less than BAU scenario in 2011, and will be 6-7% in 2015 and 2020.

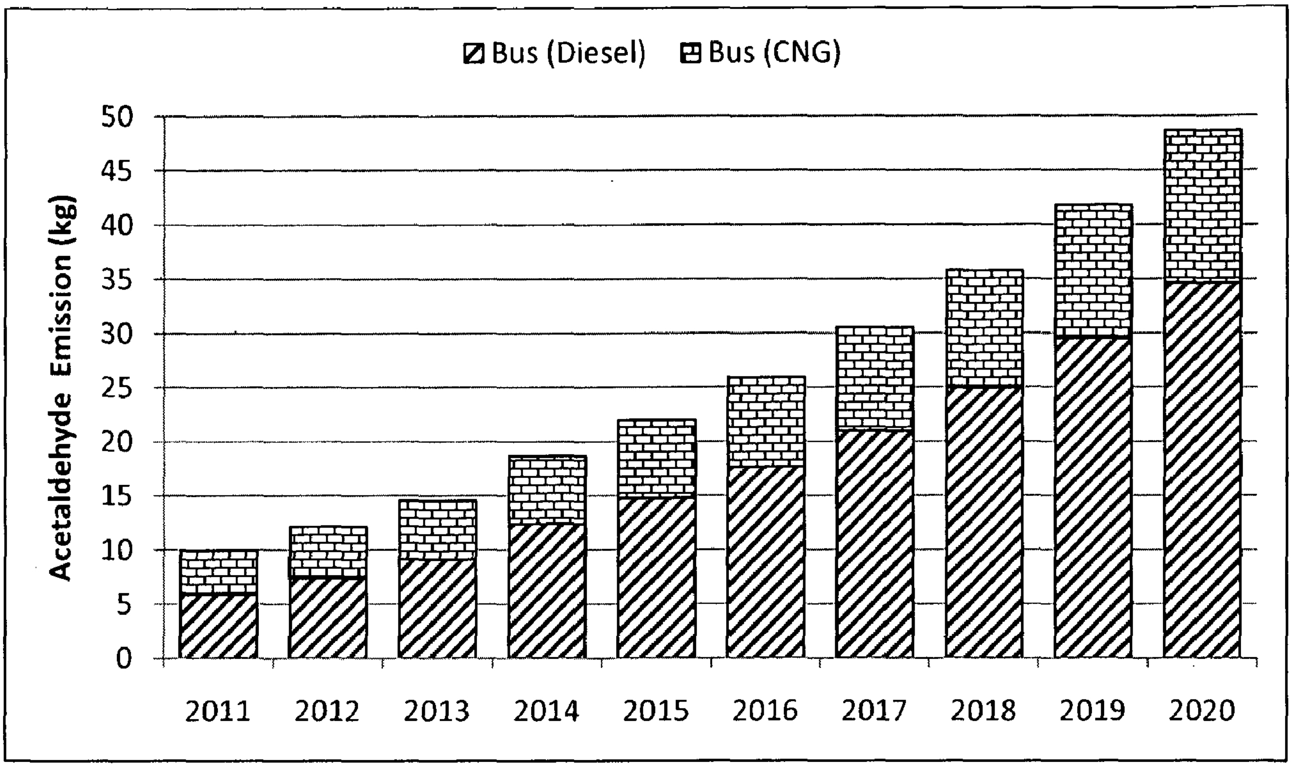


Fig. 6.54a: Acetaldehyde emissions as per BAU scenario from buses in megacity Delhi

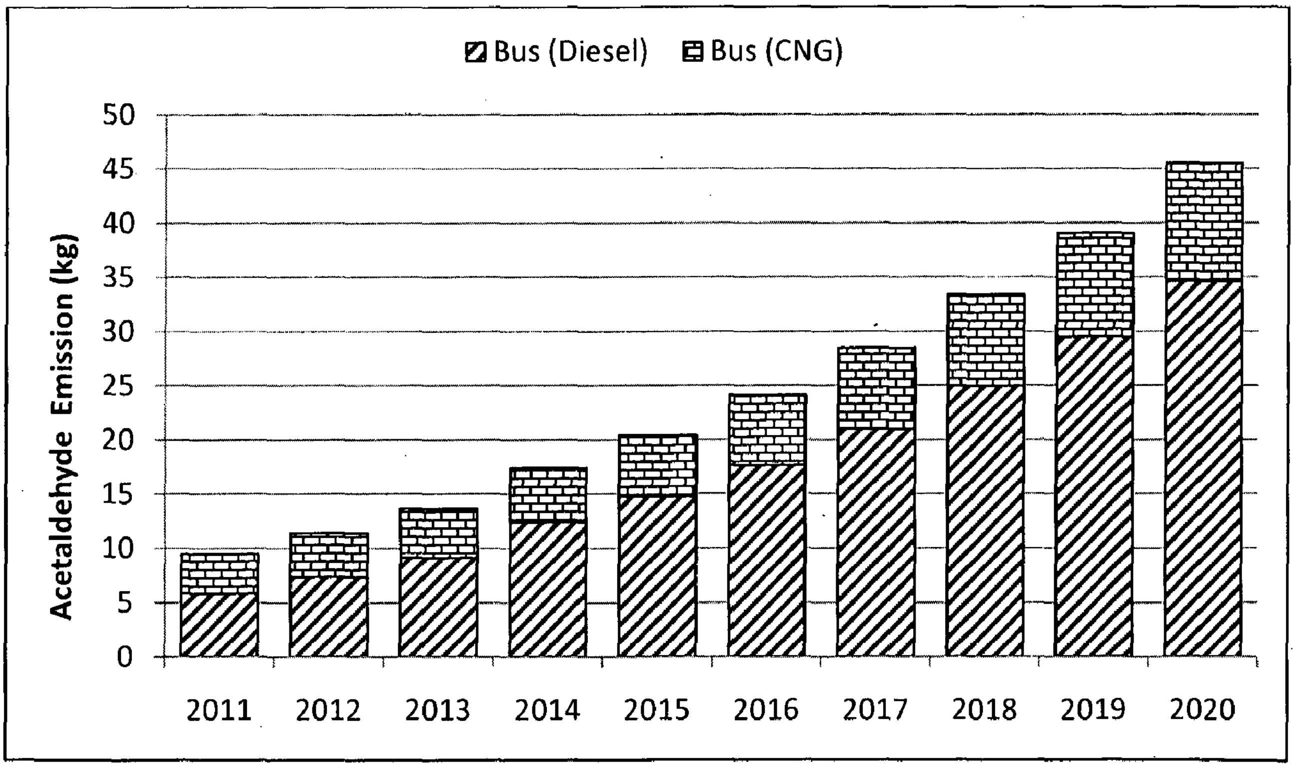


Fig. 6.54b: Acetaldehyde emissions as per BES scenario from buses in megacity Delhi

6.2.7.6. LCVs/HCVs

About 14 kg of Acetaldehyde is projected to be emitted from LCVs in 2011, followed by 17 kg in 2015 and 27 kg in 2020. An average growth rate of 8% is projected annually in Acetaldehyde emissions from LCVs from 2011 to 2020. The contribution of external diesel driven LCVs that visit and/or pass through Delhi is projected to be highest (61-87%) during 2011 to 2020 (Fig. 6.55). Fig 56 shows Acetaldehyde emissions from external diesel driven HCVs during the years 2011 to 2020. In 2011 emission of Acetaldehyde from HCVs population is 38 kg, followed by 51 kg in 2015 and 82 kg in 2020. About 9% of annual average growth rate is expected in Acetaldehyde emissions from HCVs during 2011 to 2020.

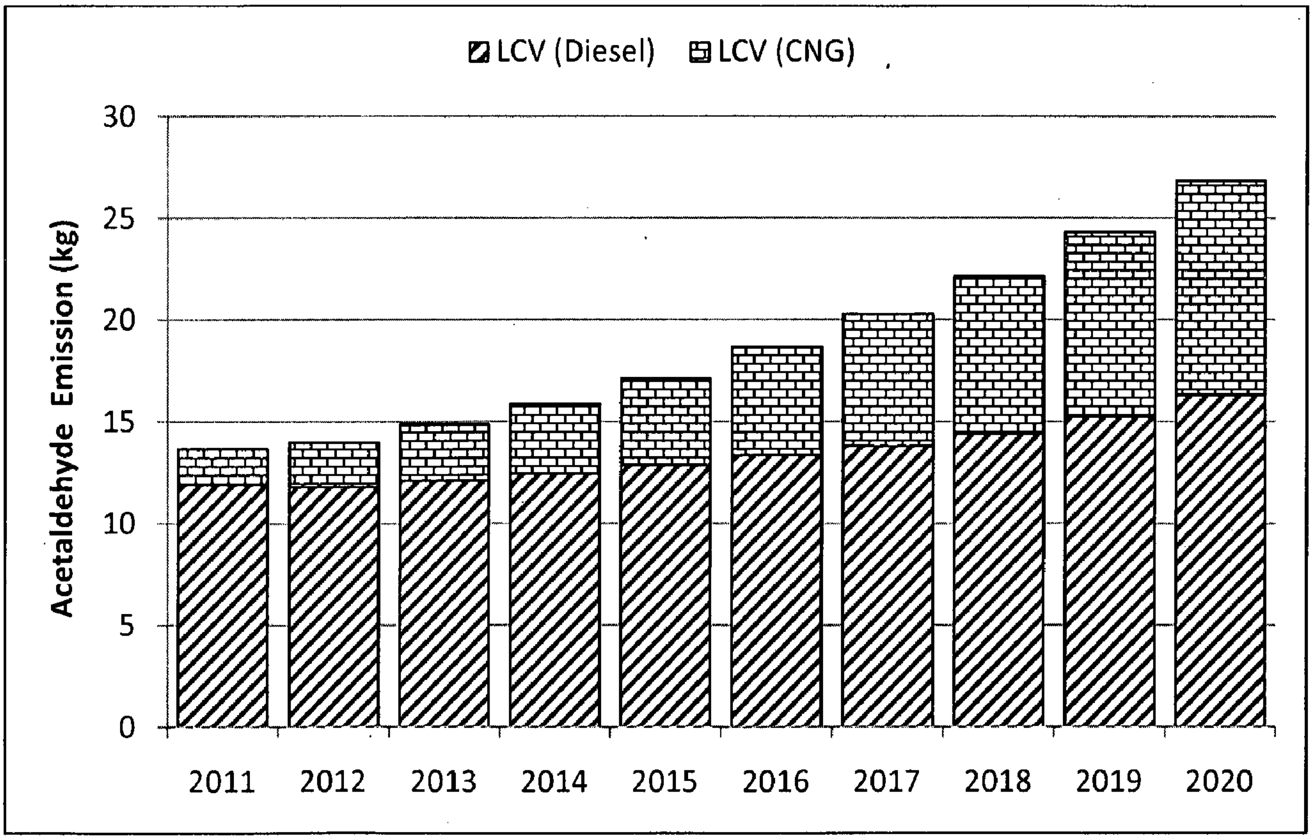


Fig. 6.55: Acetaldehyde emissions as per BAU scenario from LCVs in megacity Delhi

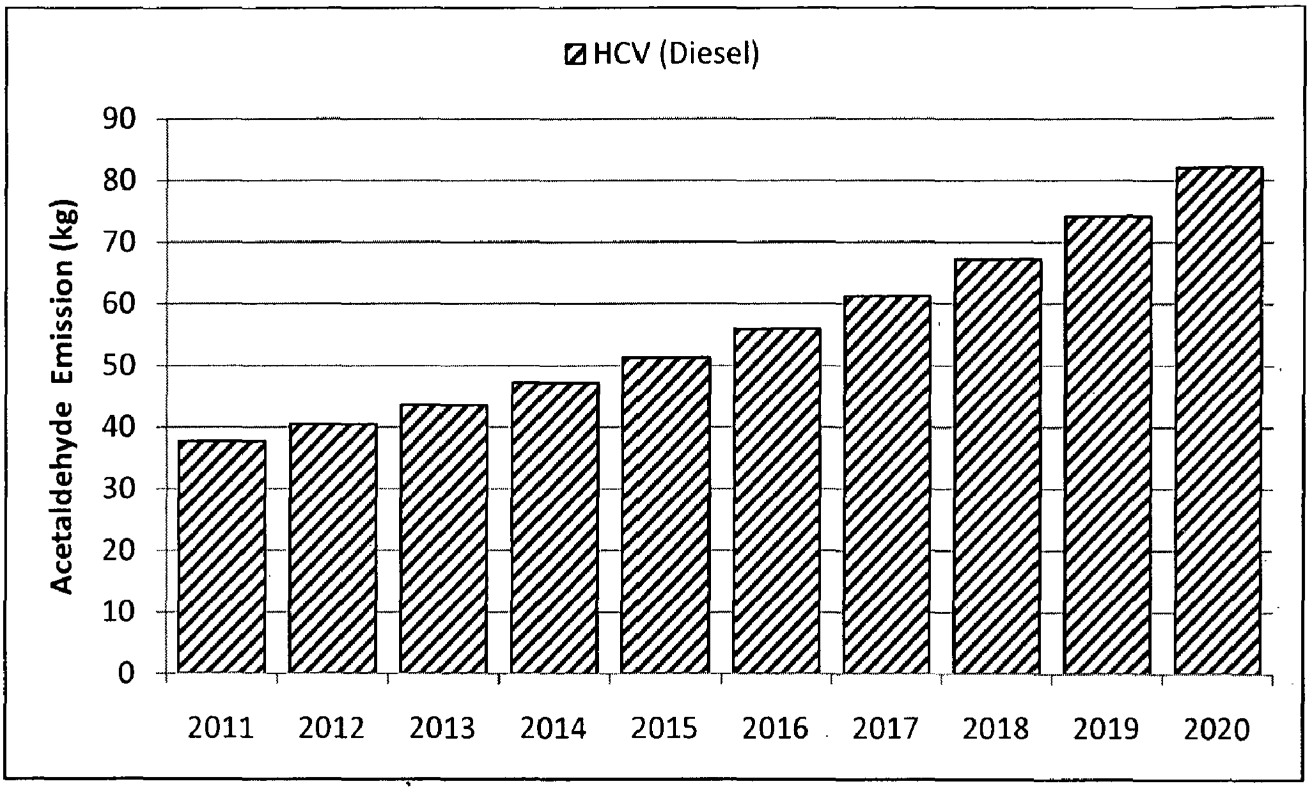


Fig. 6.56: Acetaldehyde emissions as per BAU scenario from HCVs in megacity Delhi

6.2.8. Benzene emissions

Benzene emissions from various vehicle categories in both BAU and BES scenarios are given in Fig. 6.57 (a and b). Benzene emissions from vehicles for BAU scenario is 3990 kg in 2011, while in 2012 it is 2272 kg. About 43% decrease is projected between 2011 and 2012. Phasing out of 1991 model (having higher emission factor) cars in 2012 is responsible for it. Cars are projected to be a dominating source of Benzene emissions during 2011 to 2015 and after 2015 three wheelers will supersede cars because of their increasing population. In 2015 emission of Benzene in BAU scenario is 1911 kg followed by 2252 kg in 2020. Fig. 6.57b shows the emission of Benzene from various vehicles in BES scenario. According to it Benzene emissions will be 3878 kg in 2011, followed by 1728 kg in 2015 and 1836 kg in 2020. Similar to BAU, Benzene emissions in BES scenario will decrease in 2012 because of same reason. Cars and three wheelers are the highest source of Benzene in BES scenario during 2011 to 2015 and post-2015 respectively. Emission of Benzene in BES is 3% less than BAU scenario in 2011 followed by 10% in 2015 and 18% in 2020.

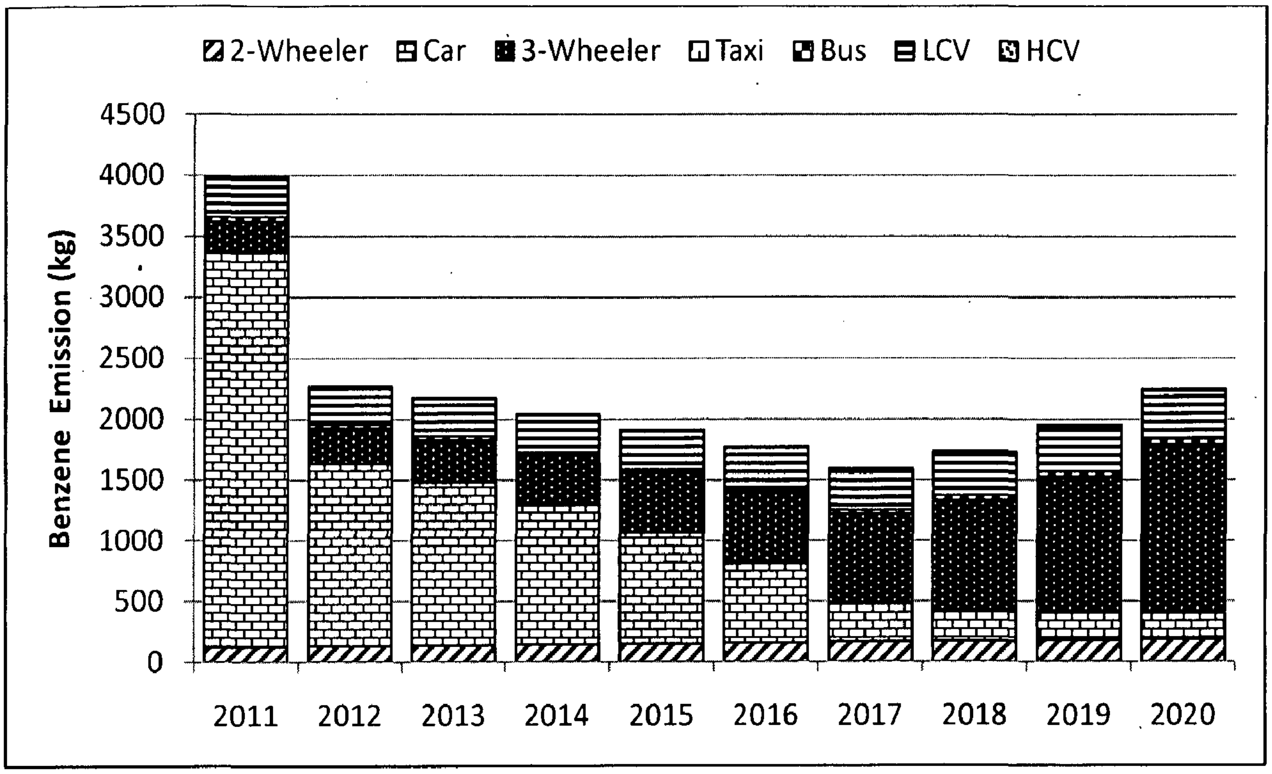


Fig. 6.57a: Benzene emissions as per BAU scenario from vehicles in megacity Delhi

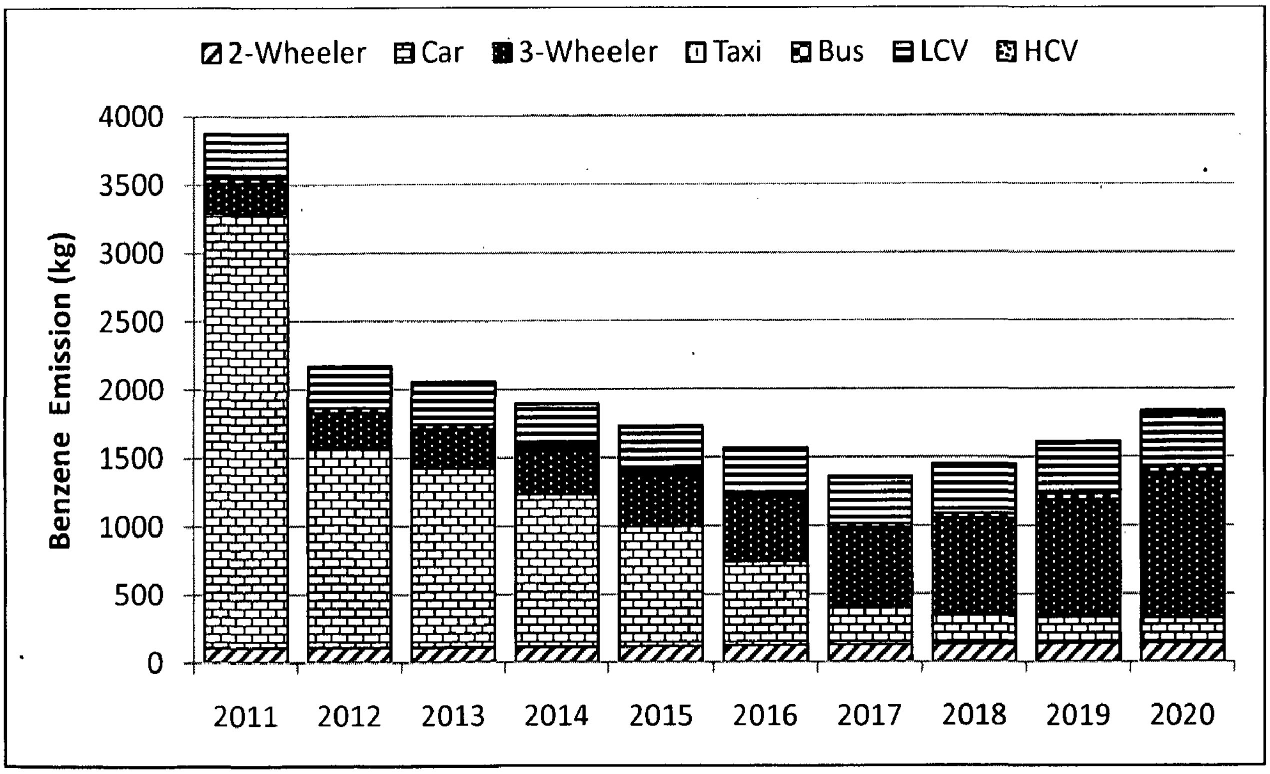


Fig. 6.57b: Benzene emissions as per BES scenario from vehicles in megacity Delhi

6.2.8.1. Two Wheelers

Emissions of Benzene from two wheelers in both BAU and BES scenarios are presented in Fig. 6.58 (a and b). In 2011 emission of Benzene from BAU scenario are estimated to be 128 kg, followed by 154 kg in 2015 and 185 kg in 2020. About 4.15% of average growth rate is expected annually in Benzene emissions from BAU scenario during 2011 to 2020. Fig. 6.58b shows that in 2011 emission of Benzene from two wheelers in BES scenario is 110 kg, while in 2015 it is 119 kg, followed by 142 kg in 2020. About 3% of annual average growth rate is observed in Benzene emissions in BES scenario from 2011 to 2020. Four-stroke motorcycles are expected to emerge as the highest source of Benzene emissions, followed by two-stroke scooters among all two wheelers in both BAU and BES scenario during 2011 to 2020. Emission of Benzene in BES is 14.44% less than BAU scenario in 2011, followed by 23% in 2015 and 2020.

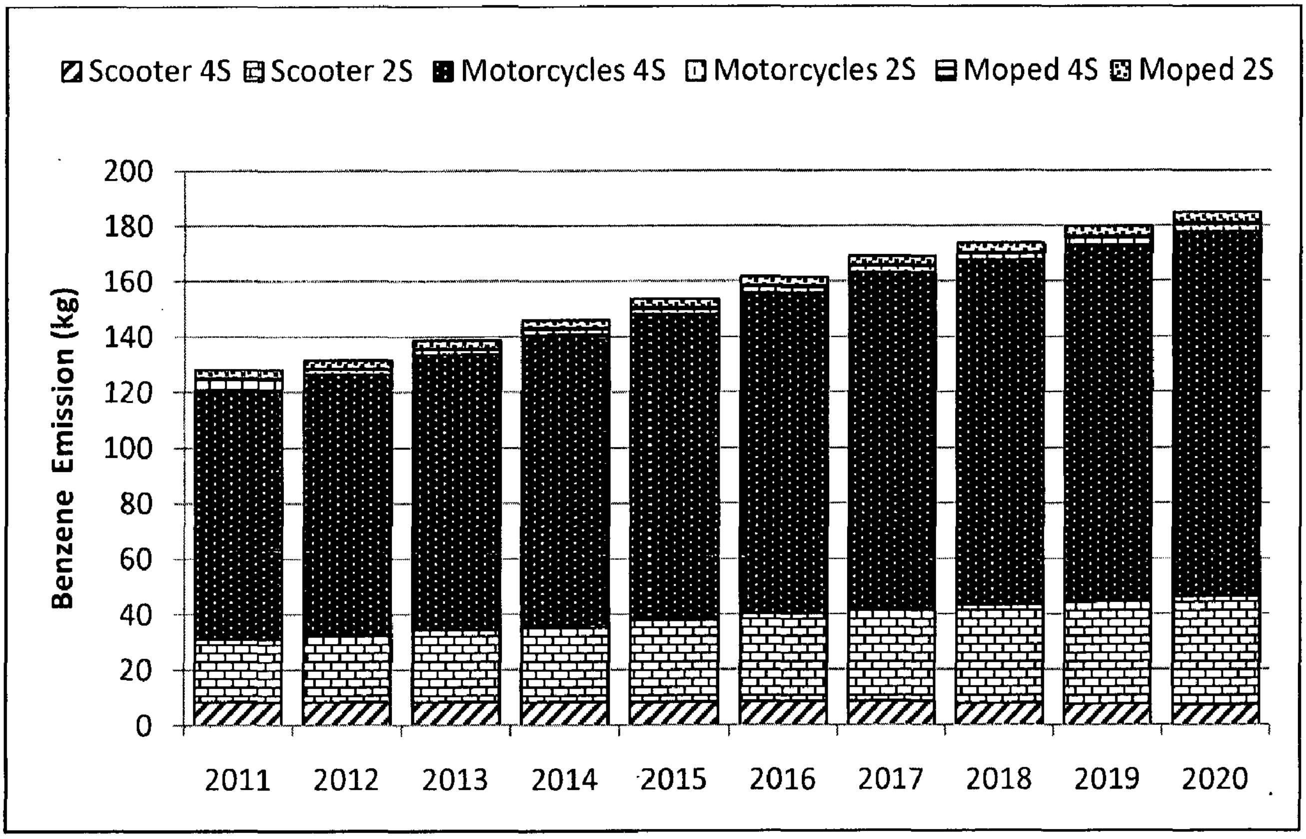


Fig. 6.58a: Benzene emissions as per BAU scenario from two wheelers in megacity Delhi

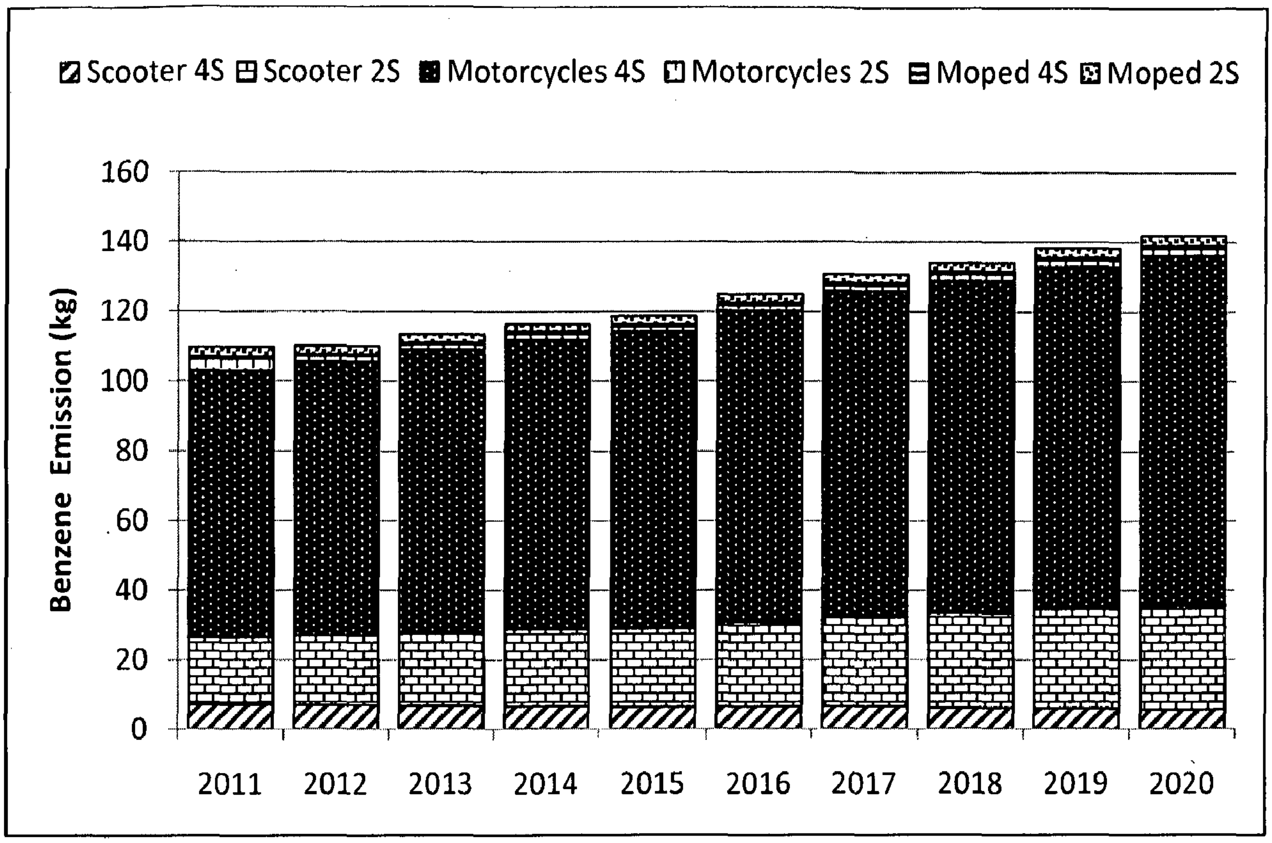


Fig. 6.58b: Benzene emissions as per BES scenario from two wheelers in megacity Delhi

6.2.8.2. Cars

Emission of Benzene from car population in both BAU and BES scenarios is decreasing from 2011 to 2020 because of gradual decrease in emission factor of 2001 to 2010 model car. Fig. 6.59a indicates that emission of Benzene from cars in 2011 is 3245 kg, followed by 914 kg in 2015 and 217 kg in 2020. Emission of Benzene from cars is decreasing 24% annually from 2011 to 2020. Fig. 6.59b shows the emission of Benzene from BES scenario from 2011 to 2020. In 2011 emission of Benzene from cars in BES scenario are projected to be 3183 kg in 2011, 879 kg in 2015 and 183 kg in 2020. Emissions projected in BES scenario are 2% less than BAU scenario in 2011 followed by 4% in 2015 and 15.5% in 2020.

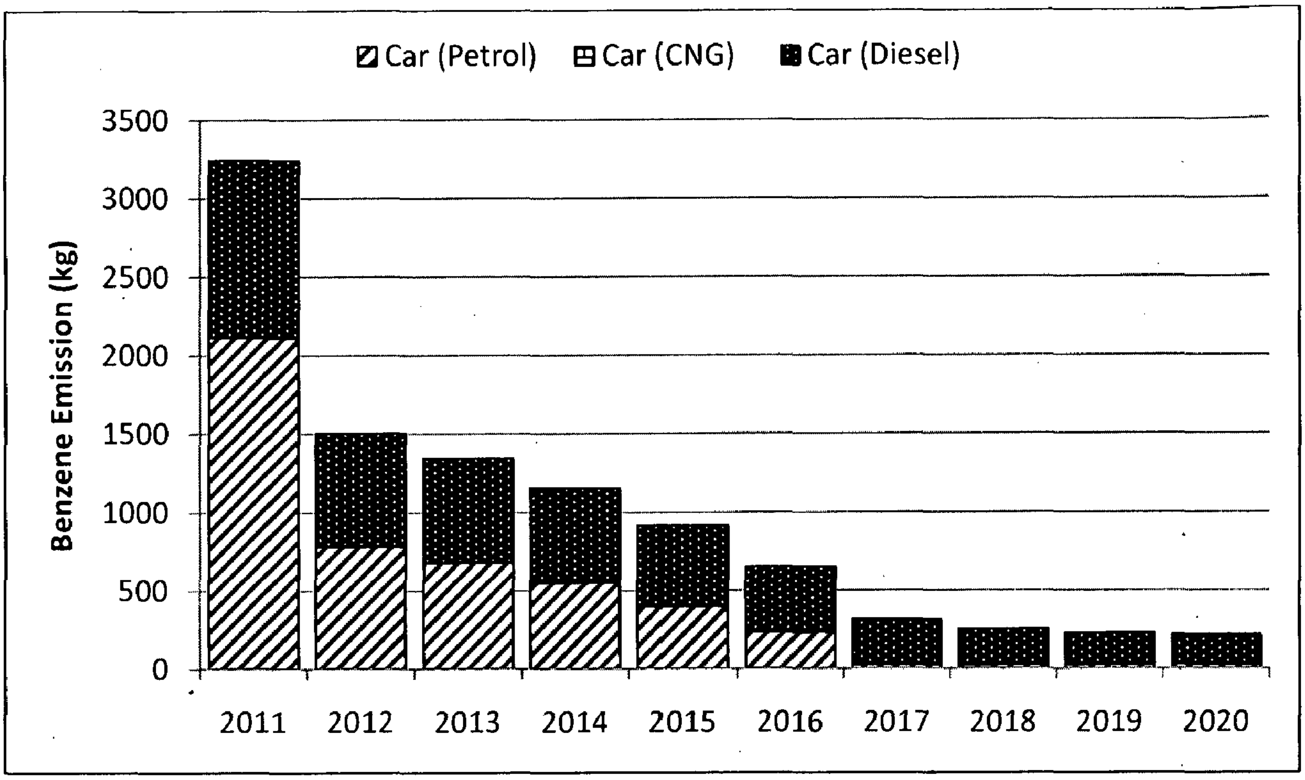


Fig. 6.59a: Benzene emissions as per BAU scenario from cars in megacity Delhi

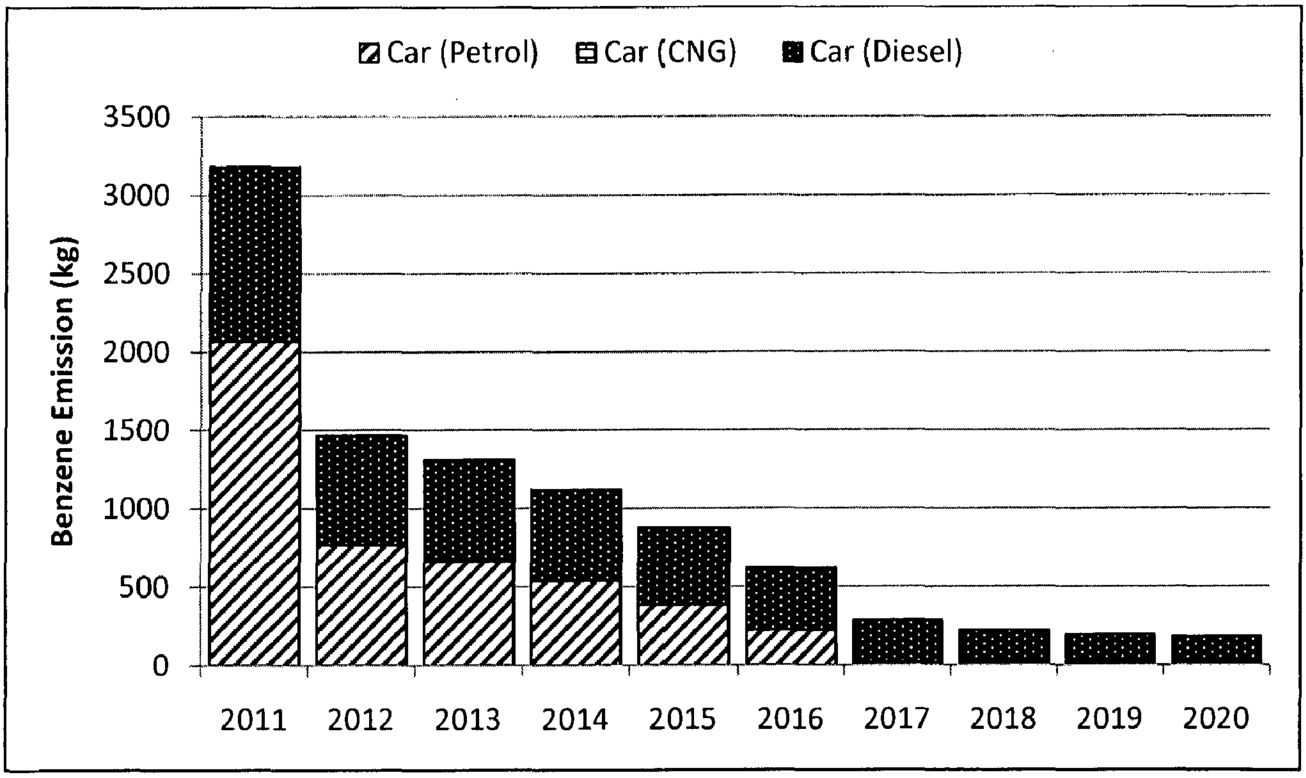


Fig. 6.59b: Benzene emissions as per BES scenario from cars in megacity Delhi

6.2.8.3. Three Wheelers

Emissions of Benzene from three wheelers from 2011 to 2020 in BAU and BES scenario are presented in Fig. 6.60 (a and b). Fig. 6.60a indicates that in 2011 Benzene emissions from three wheelers in BAU scenario is 244 kg, while in 2015 it is 495 kg, followed by 1375 kg in 2020. About 21% of annual average growth rate is estimated in Benzene emissions from three wheelers during 2011 to 2020 in BAU scenario. Fig. 6.60b shows that in 2011 emission of three wheelers in BES scenario will be 213 kg, 384 kg in 2015 and 1042 kg in 2020. Average growth of ~19% is projected annually in Benzene emissions from 2011 to 2020 in BES scenario. Emission of Benzene in BES is 13% less than BAU scenario in 2011 followed by 22% in 2015 and 24% in 2020.

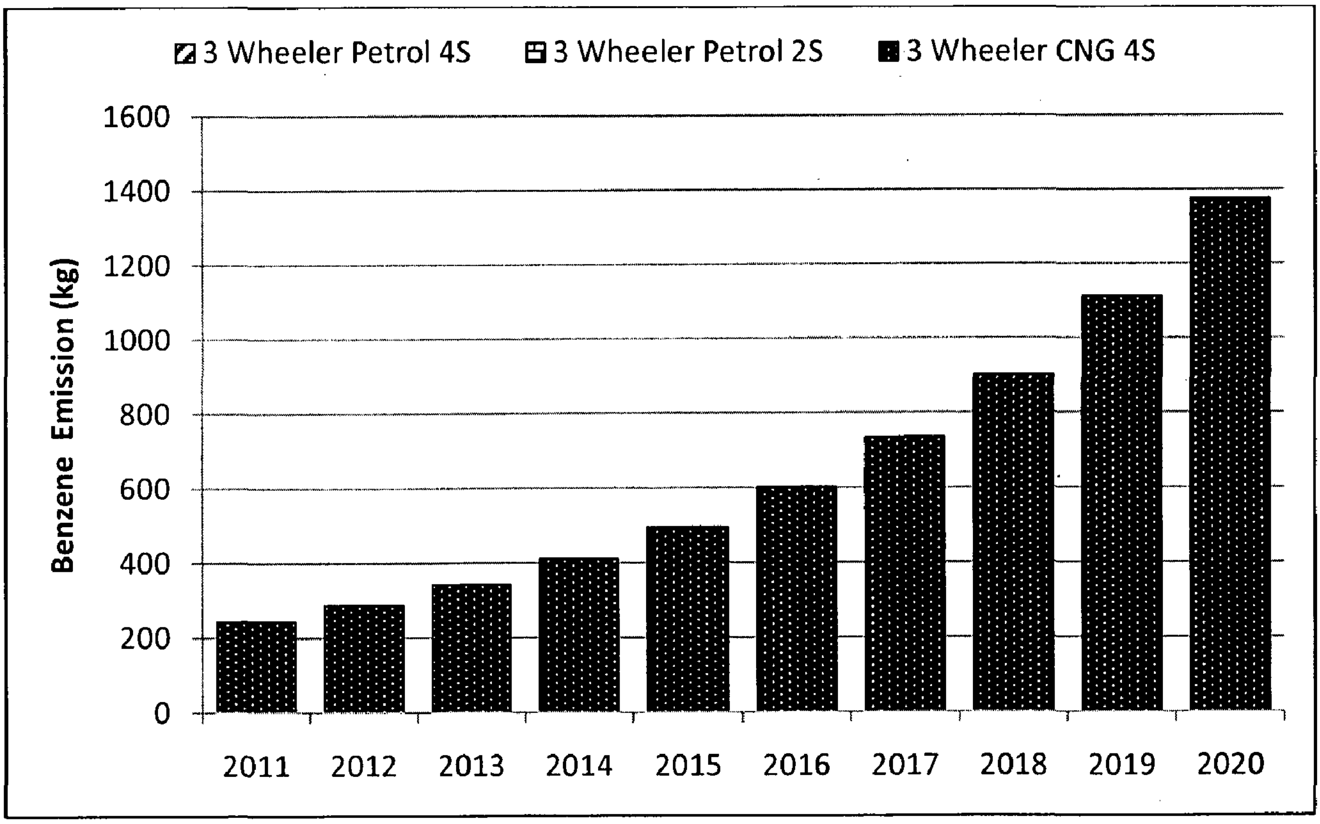


Fig. 6.60a: Benzene emissions as per BAU scenario from three wheelers in megacity Delhi

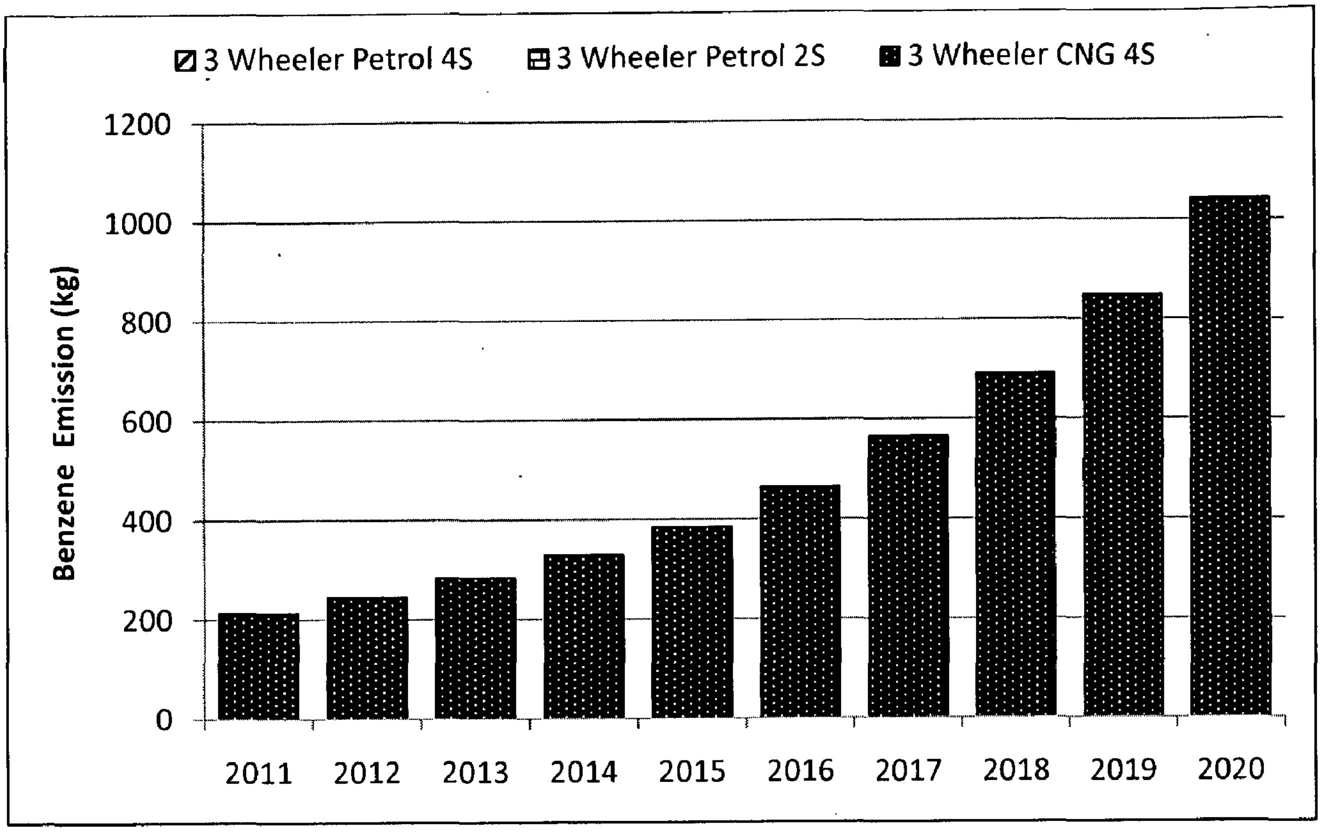


Fig. 6.60b: Benzene emissions as per BES scenario from three wheelers in megacity Delhi

6.2.8.4. Taxis

Emissions of Benzene from taxis in BAU scenario are projected to be 8 kg in 2011 followed by 5 kg in 2015 and 17 kg in 2020. Fig. 6.61a shows the emission of Benzene from petrol, CNG and diesel driven taxis in megacity Delhi. All diesel and petrol driven taxis are coming from outside of Delhi while CNG taxis are registered in Delhi. Decreasing trend is projected from 2011 to 2013 due to phasing out of 1991 model taxis and decreasing emission factors for new model taxis. Fig. 6.61b shows the emission of Benzene from BES scenario. In 2011 emission of Benzene from BES scenario is 7.9 kg while in 2015 it is 4 kg followed by 14 kg in 2020. In comparison to BAU, BES scenario emissions are ~2% less in 2011, 14% in 2015 and 20% less in 2020. Contribution of diesel taxis is much larger (~60-91%,76-92%) than petrol and CNG driven taxis in both the scenarios.

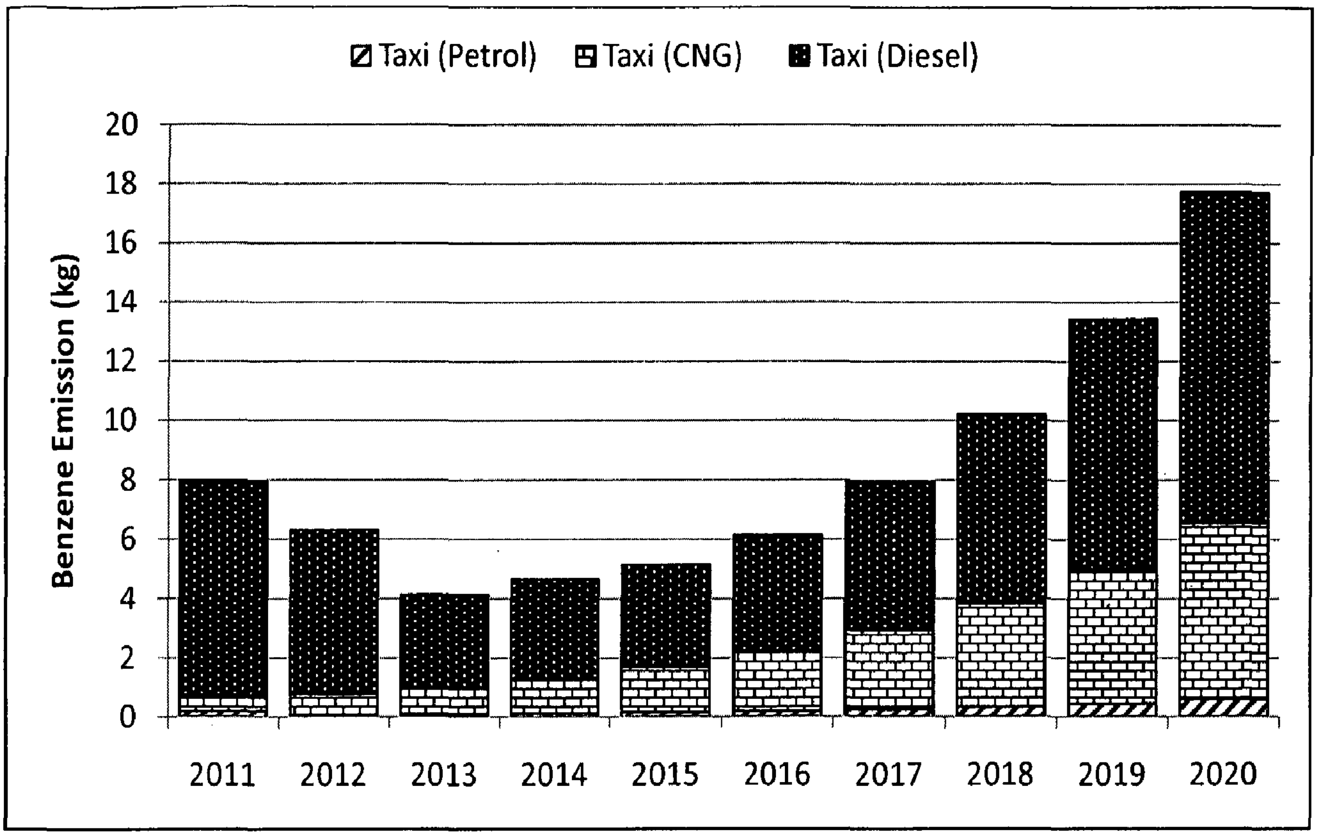


Fig. 6.61a: Benzene emissions as per BAU scenario from taxis in megacity Delhi

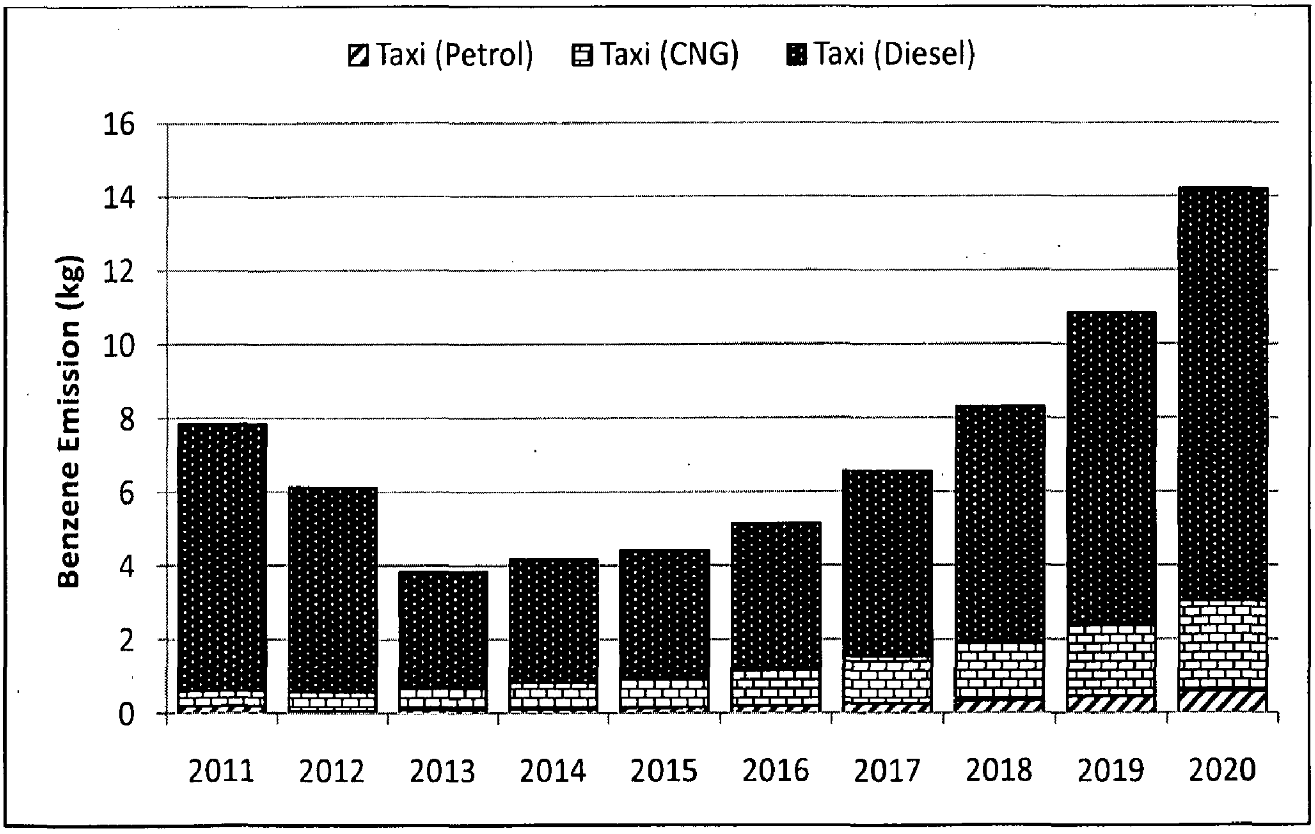


Fig. 6.61b: Benzene emissions as per BES scenario from taxis in megacity Delhi

6.2.8.5. Buses

Emissions of Benzene from buses in BAU and BES scenarios are given in Fig. 6.62 (a and b). Fig. 6.62a indicates that in 2011 emission of Benzene from buses in BAU scenario is 34 kg, followed by 21 kg in 2015 and 47 kg in 2020. Similar to BAU, Benzene emission from buses in BES scenario will be 34 kg in 2011, 20 kg in 2015 and 45 kg in 2020. In both BAU and BES scenarios Benzene emissions are higher from 2011 to 2013, while after 2013 sudden decrease is projected due to higher emission factors for old model buses, and phasing out of old buses in 2014. It is expected that in 2011 BES scenario emissions will be 1% less than BAU, while in 2015 and 2020 it will be 5.13% and 4.51% respectively.

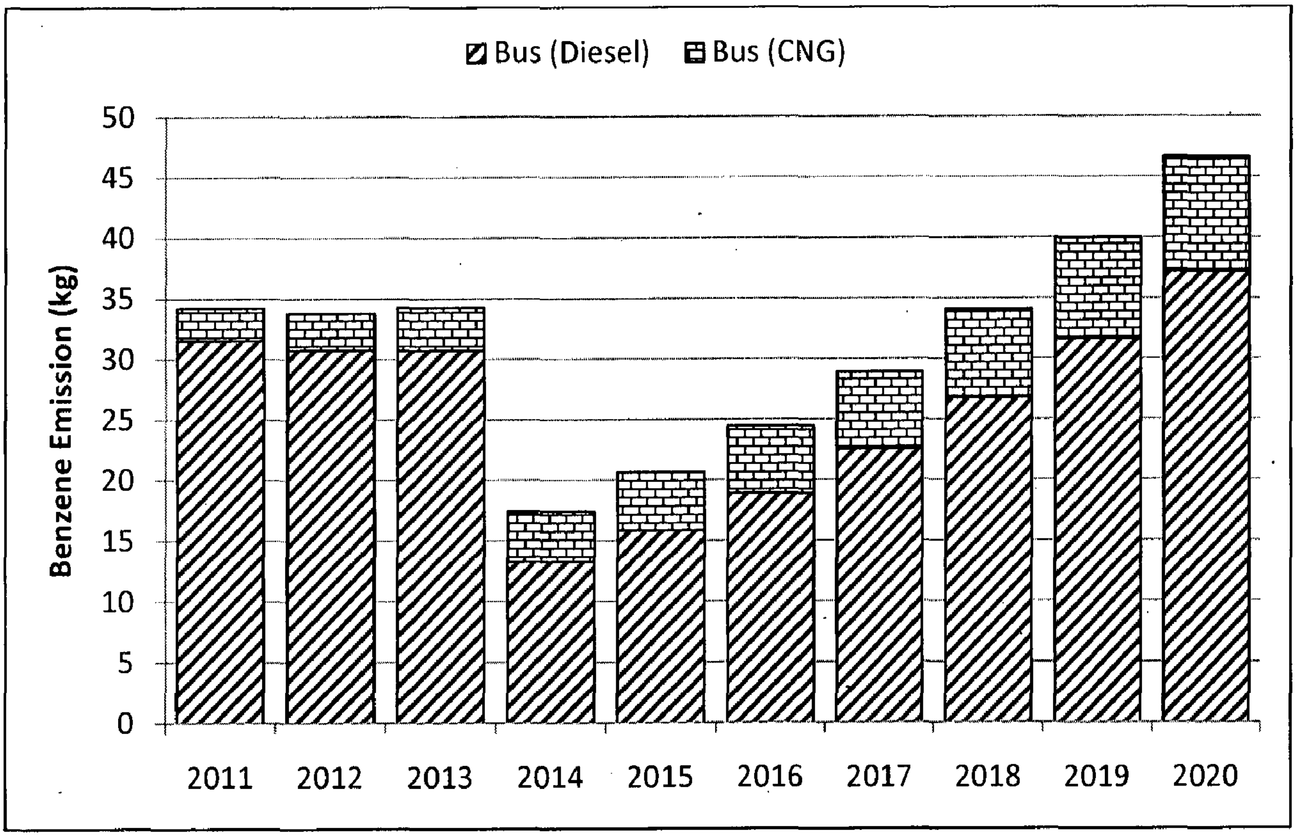


Fig. 6.62a: Benzene emissions as per BAU scenario from buses in megacity Delhi

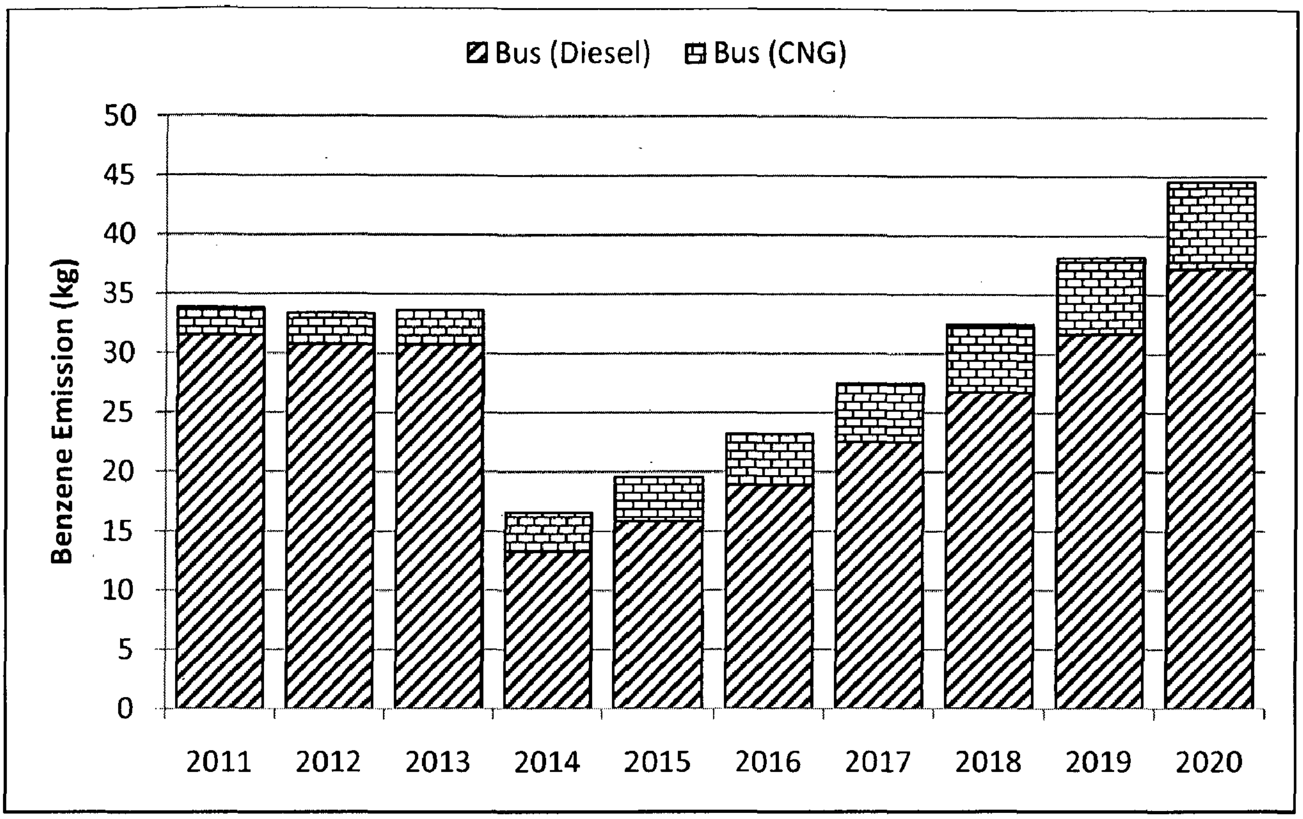


Fig. 6.62b: Benzene emissions as per BES scenario from buses in megacity Delhi

6.2.8.6. LCVs/HCVs

Benzene emissions from CNG equipped LCVs are projected to be very less compared to diesel driven LCVs (Fig. 6.63). In 2011 emission of Benzene from LCVs population will be 318 kg, while 310 kg and 392 kg in 2015 and 2020 respectively. The contribution of diesel driven LCVs during 2011 to 2020 is 98 to 99%. Fig. 6.64 shows the emission of Benzene from HCVs population. In 2011 and 2015 emission of Benzene from HCVs populations are estimated to be 12 kg and ~18 kg in 2020.

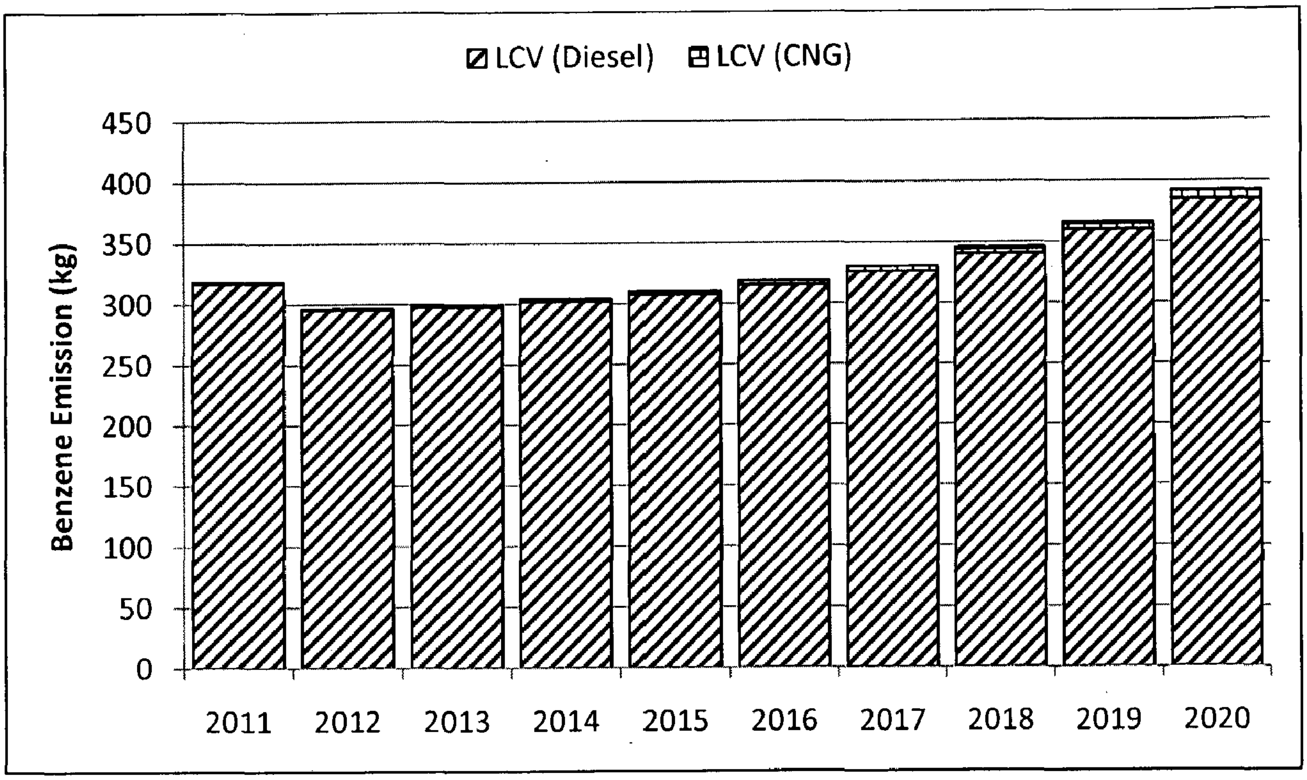


Fig. 6.63: Benzene emissions as per BAU scenario from LCVs in megacity Delhi

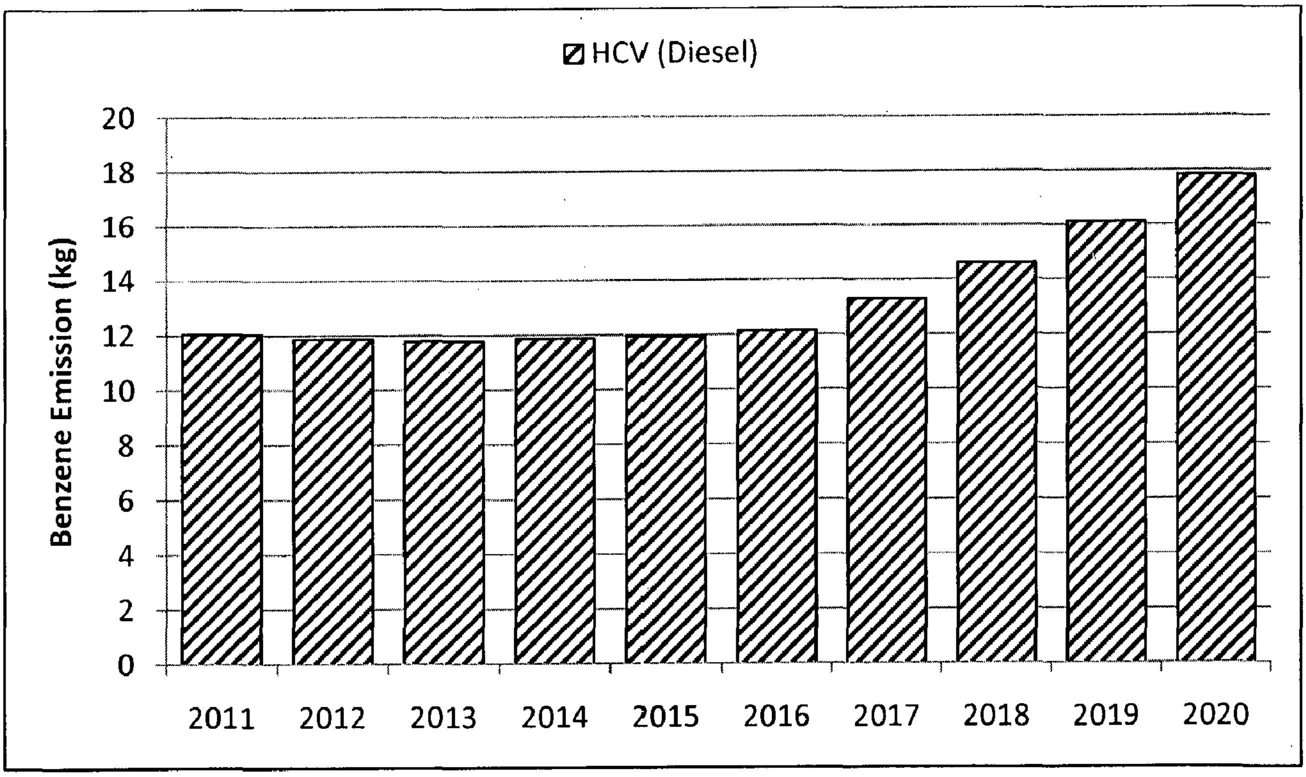


Fig. 6.64: Benzene emissions as per BAU scenario from HCVs in megacity Delhi

6.2.9. Formaldehyde emissions

Emissions of Formaldehyde from various vehicle categories have been given in Fig. 6.65 (a and b) for BAU and BES scenarios. Fig. 6.65a indicates that Formaldehyde emissions from different vehicle categories will be 1252 kg in 2011, followed by 1609 kg in 2015 and 2761 kg in 2020. About 9.3% of average annual growth rate is expected in Formaldehyde emissions in BAU scenario from 2011 to 2020. As compared to BAU scenario Formaldehyde emissions will be 1127 kg in 2011 which is 10% less than BAU emission. Similarly in 2015 emissions will be 1299 kg in 2015 and 2232 kg in 2020 which are ~19% less than BAU emissions. Contribution of two wheelers and cars is expected to be highest among all vehicle categories.

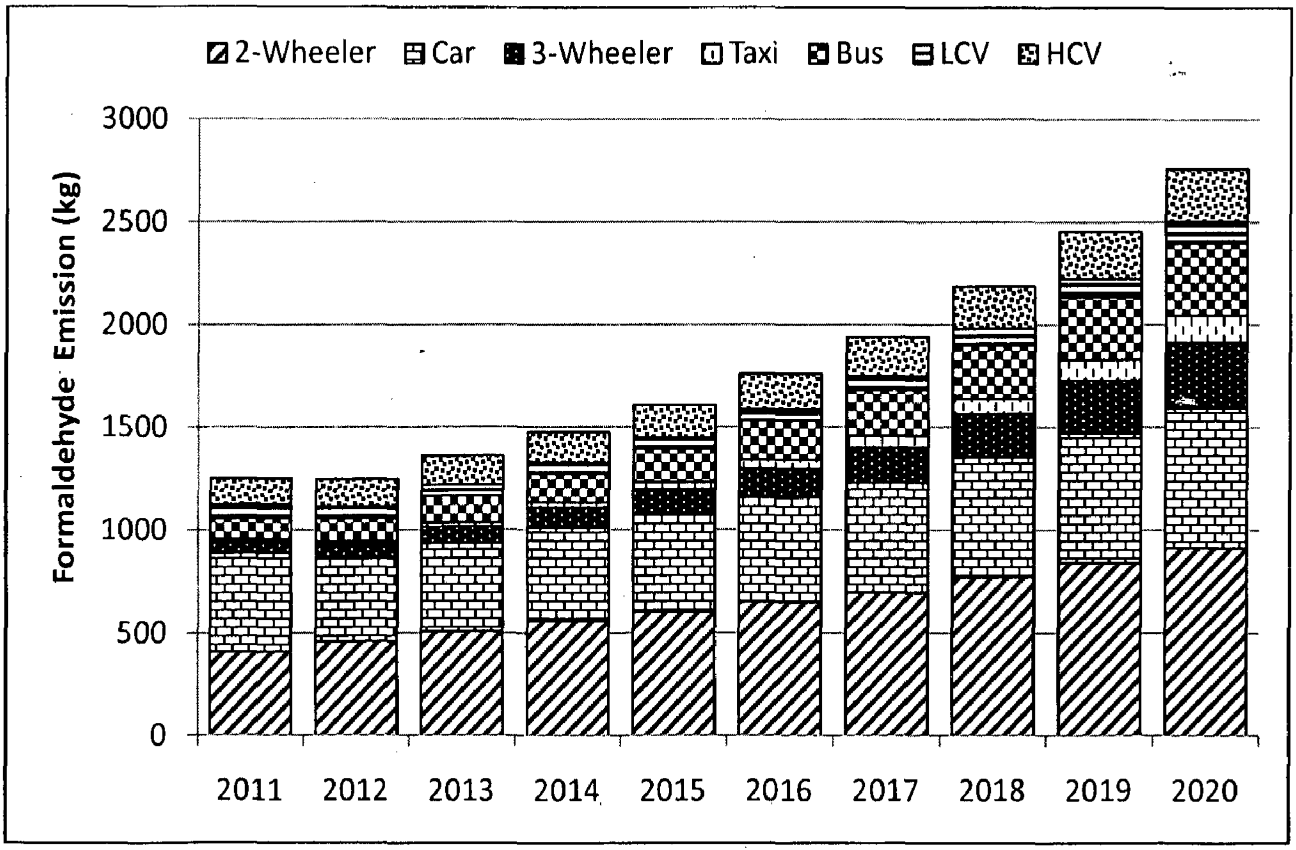


Fig. 6.65a: Formaldehyde emissions as per BAU scenario from vehicles in megacity Delhi

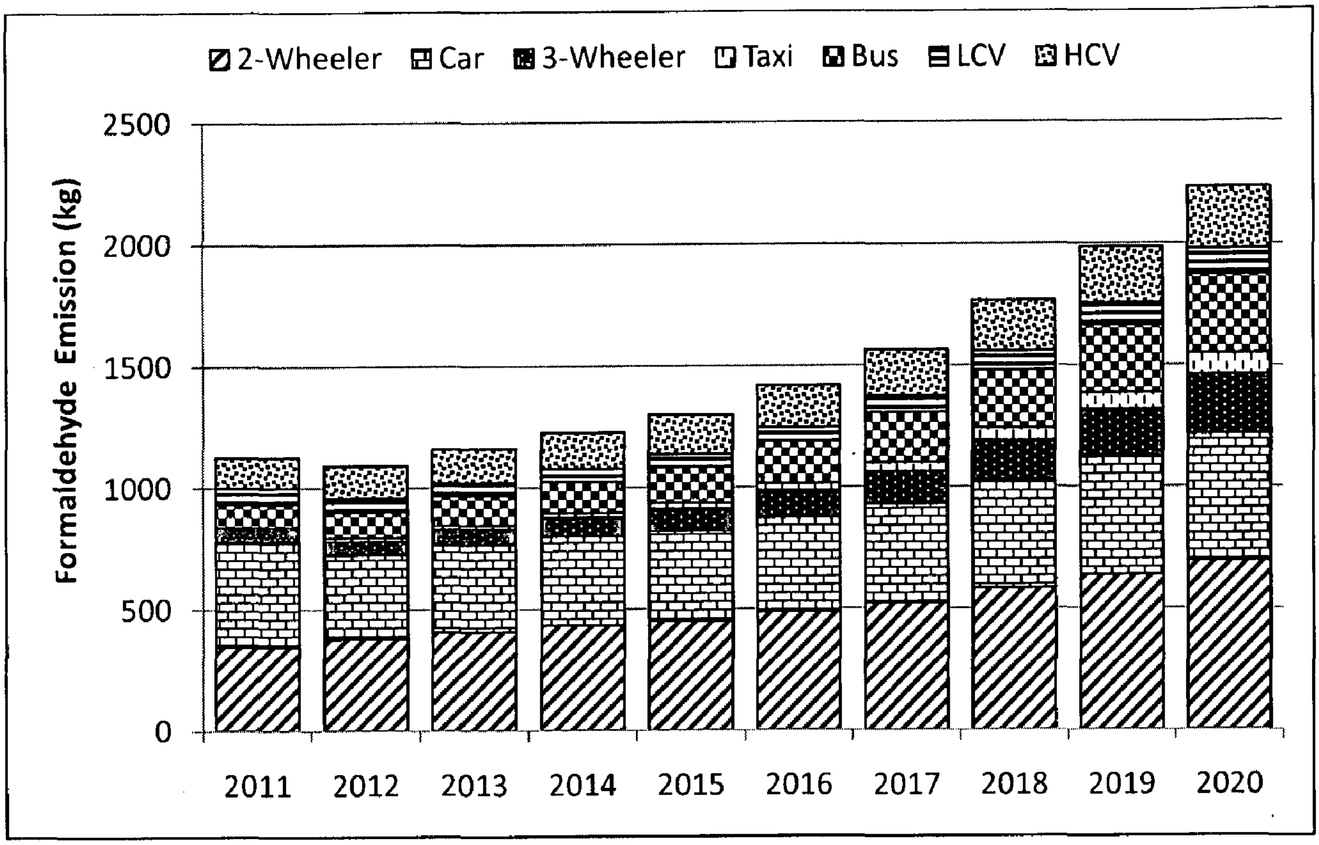


Fig. 6.65b: Formaldehyde emissions as per BES scenario from vehicles in megacity Delhi

6.2.9.1. Two Wheelers

In 2011 emissions of Formaldehyde from two wheelers in BAU scenario will be 411 kg, while in 2015 it is 607 kg, followed by 916 kg in 2020. In BES scenario emissions of Formaldehyde in 2011 are projected to be 349 kg, followed by 455 kg in 2015 and 697 kg in 2020. Among all types of two wheeler categories contribution of four-stroke scooters is highest, followed by two-stroke scooters and mopeds. It is projected that BES scenario emissions in 2011 will be 15% less than BAU, while it will be 24-25% less in 2015 and 2020.

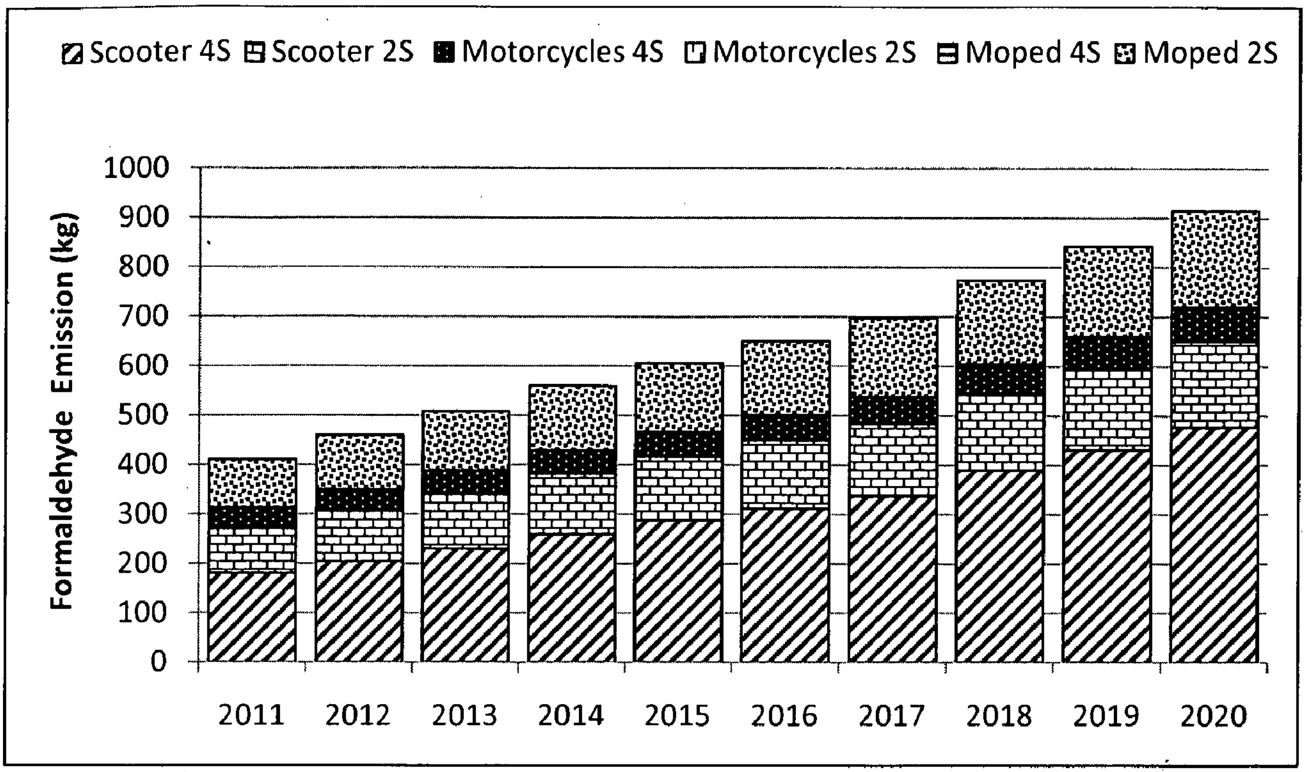


Fig. 6.66a: Formaldehyde emissions as per BAU scenario from two wheelers in megacity Delhi

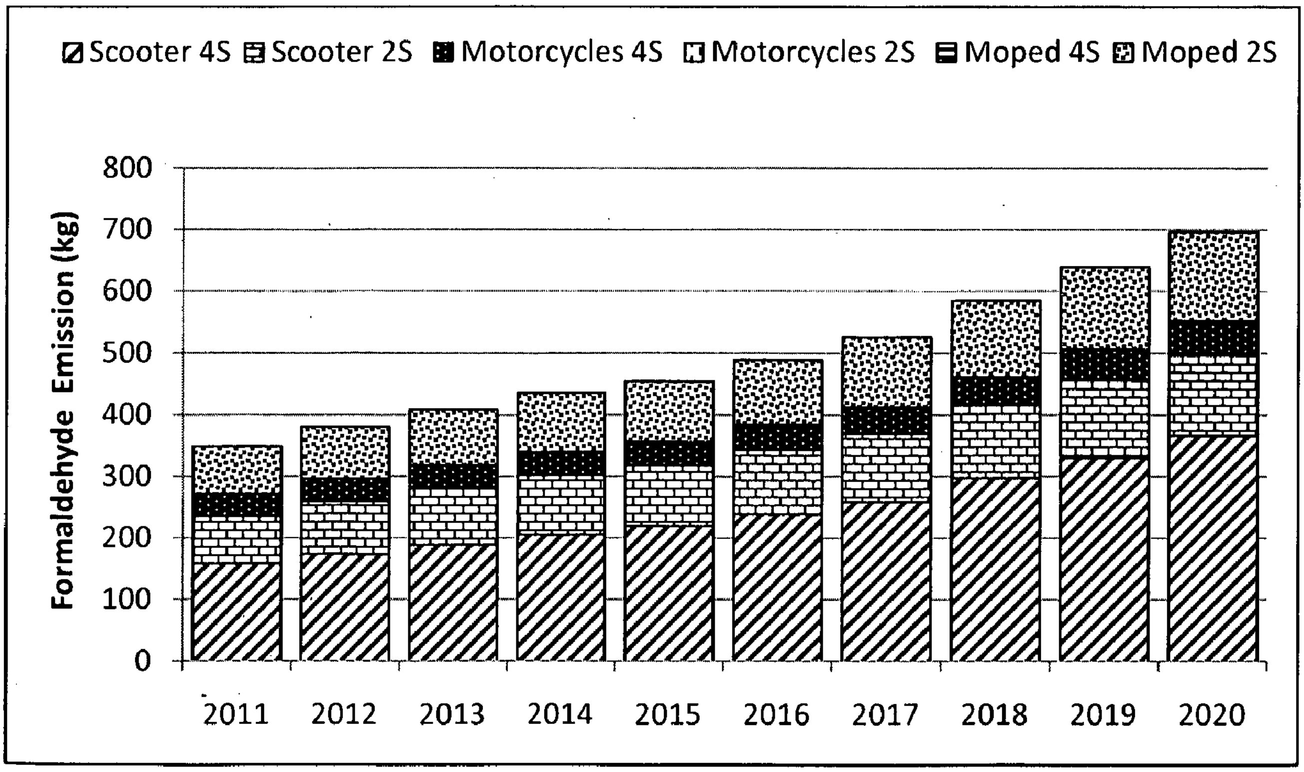


Fig. 6.66b: Formaldehyde emissions as per BES scenario from two wheelers in megacity Delhi

6.2.9.2. Cars

Formaldehyde emissions from cars for BAU and BES scenarios are presented in Fig. 6.67 (a and b). Estimations suggest that in 2011 emission of Formaldehyde from cars in BAU scenario is 481 kg, followed by 479 kg in 2015 and 681 kg in 2020. Similar to BAU, Formaldehyde emissions in BES scenario from cars will be 433 kg in 2011, followed by 372 kg in 2015 and 522 kg in 2020. Emission of Formaldehyde in BES is 10% less than BAU scenario in 2011 and is projected to be 22% in 2015 and 23% in 2020. In both the scenarios emissions from diesel cars are dominant in comparison to CNG and petrol driven cars. Moreover, emissions from diesel and CNG cars are increasing during 2011-2020.

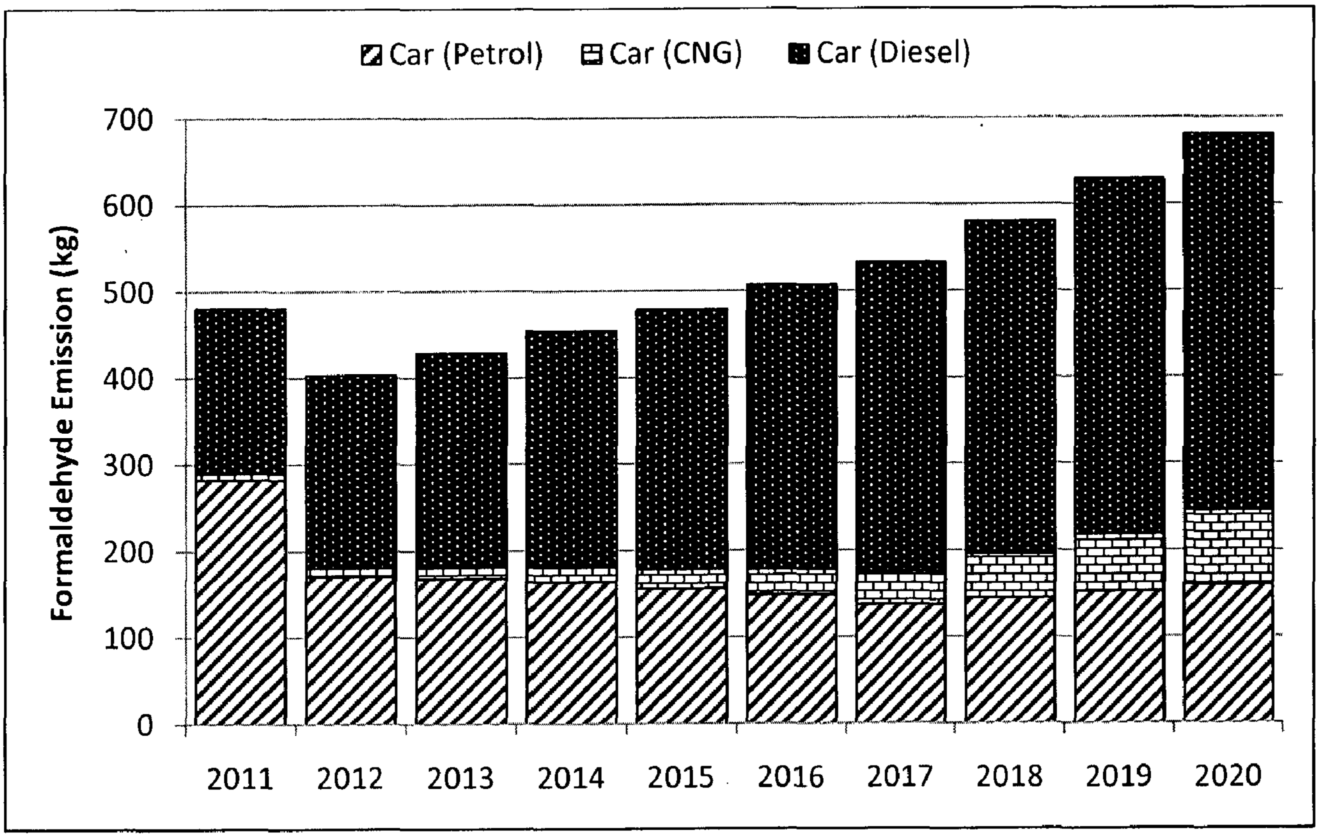


Fig. 6.67a: Formaldehyde emissions as per BAU scenario from cars in megacity Delhi

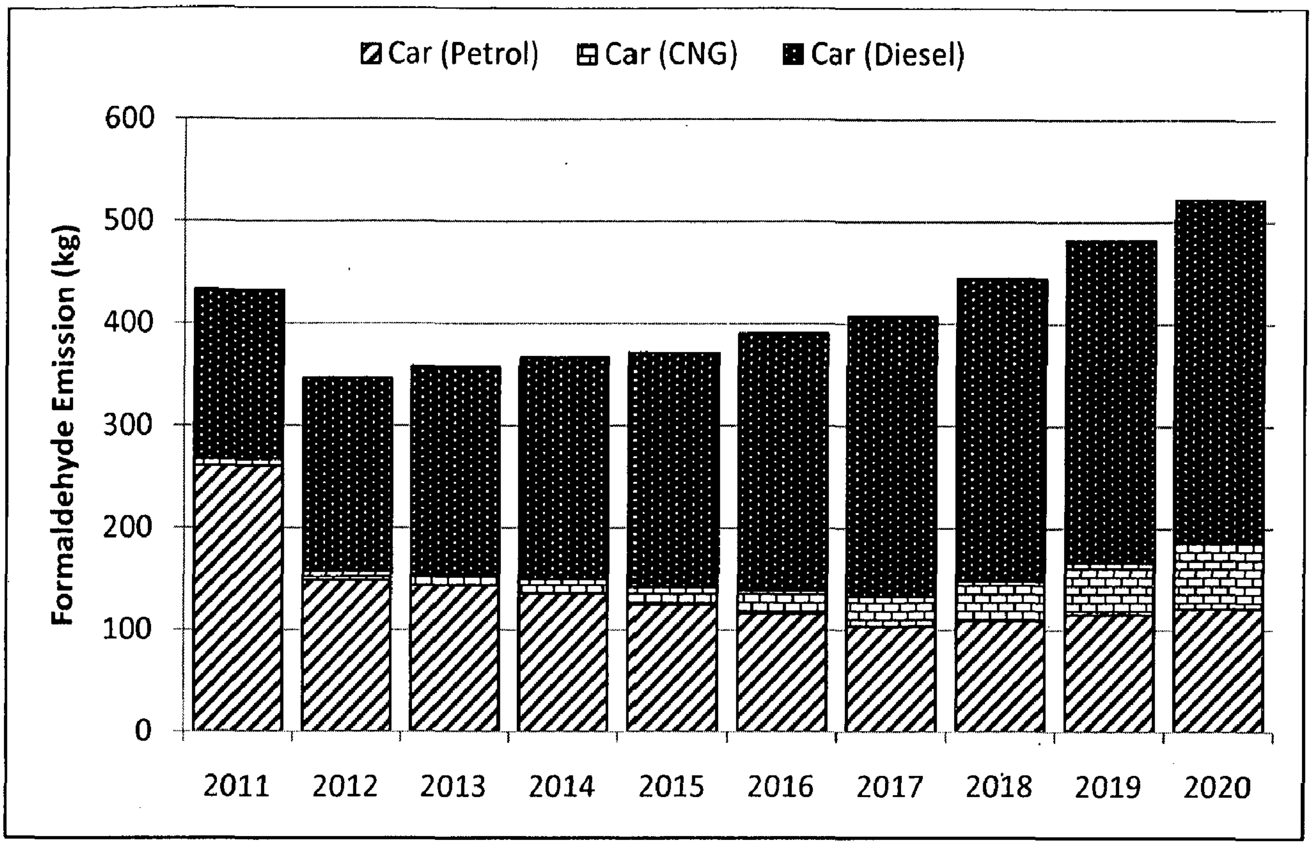


Fig. 6.67b: Formaldehyde emissions as per BES scenario from cars in megacity Delhi

6.2.9.3. Three Wheelers

About 55.5 kg of Formaldehyde is projected to be emitted from three wheelers in 2011 in BAU scenario. The emissions will become 114 kg in 2015 and 319 kg in 2020 (Fig. 6.68a). The annual average growth rate for Formaldehyde emissions from three wheelers during 2011 to 2020 is expected to be 21.5%. Estimated emissions of Formaldehyde from BES scenario in 2011 is 48 kg, followed by 88 kg in 2015 and 242 kg in 2020 (Fig. 6.68b). Emission of Formaldehyde in BES is projected to be 13% less than BAU scenario in 2011 and will be 22% less in 2015 and 24% less in 2020.

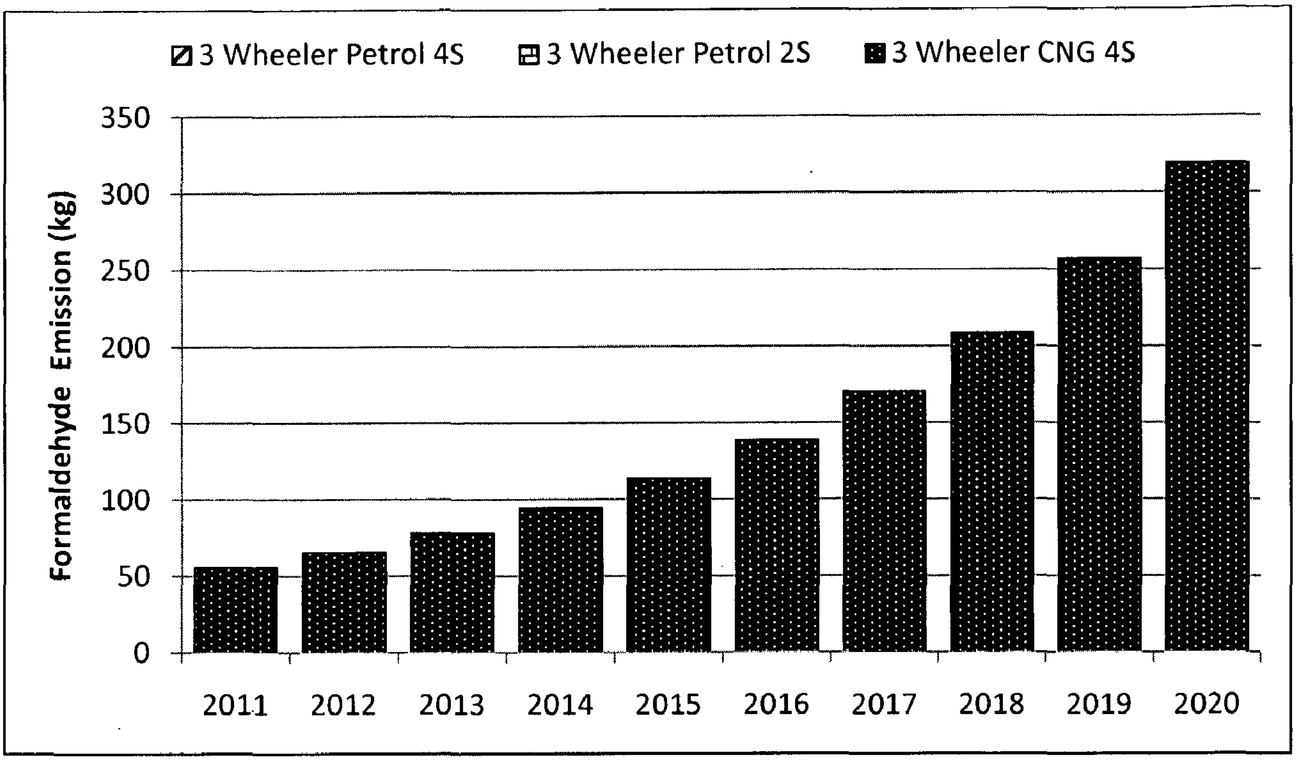


Fig. 6.68a: Formaldehyde emissions as per BAU scenario from three wheelers in megacity Delhi

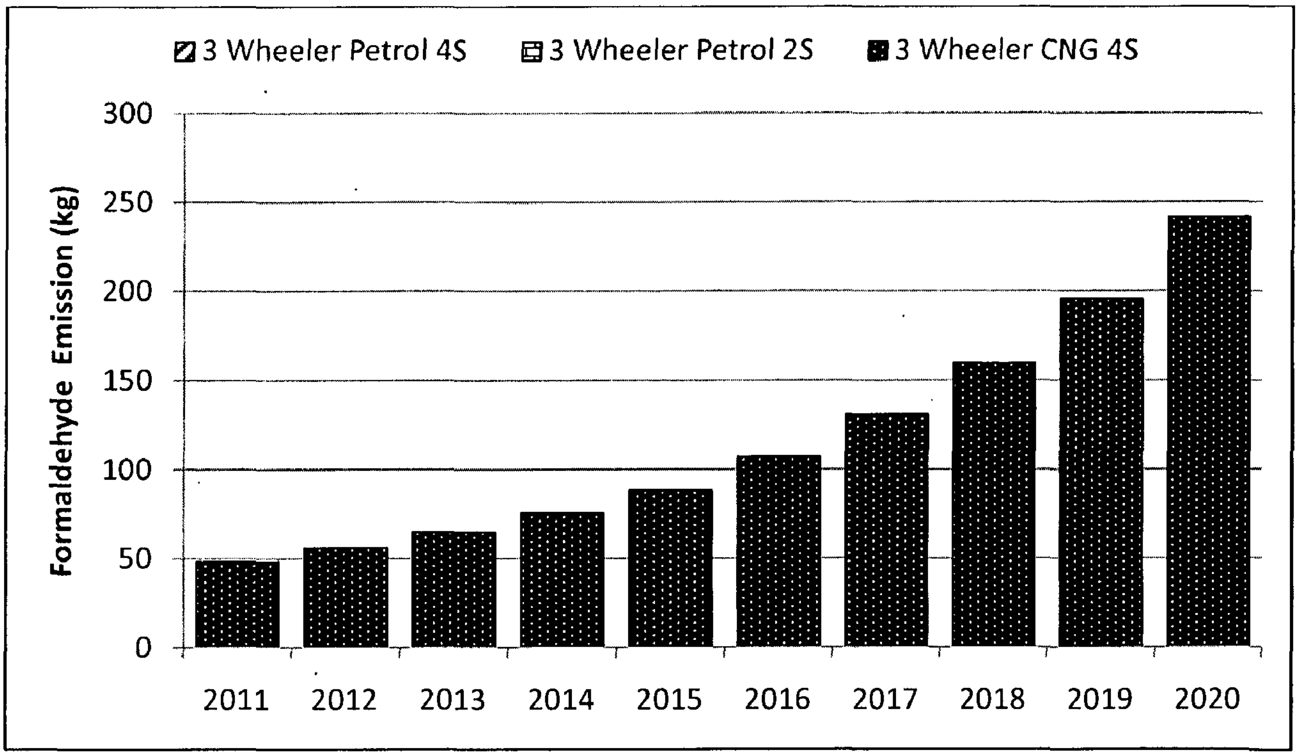


Fig. 6.68b: Formaldehyde emissions as per BES scenario from three wheelers in megacity Delhi

6.2.9.4. Taxis

Fig. 6.69 (a and b) shows the emissions of Formaldehyde from taxis in BAU and BES scenarios for megacity Delhi. Fig. 6.69a indicates that in 2011, Formaldehyde emissions will be 12 kg followed by 34 kg in 2015 and 133 kg in 2020. About 30.6% annual average growth is expected in Formaldehyde emission from 2011 to 2020. Fig. 6.69b suggest that in 2011 emission of Formaldehyde from taxis in BES scenario will be 10 kg, followed by 24 kg in 2015 and 88 kg in 2020. 27% of annual average growth rate is projected in Formaldehyde emissions from 2011 to 2020. Emission of Formaldehyde from BES is 14.5% less than BAU scenario in 2011 and this figure is expected to become 28% in 2015 and 34% in 2020. Nevertheless, emissions from CNG and diesel driven taxis are increasing by about 28-31% and 25-29% annual growth respectively in both the scenarios.

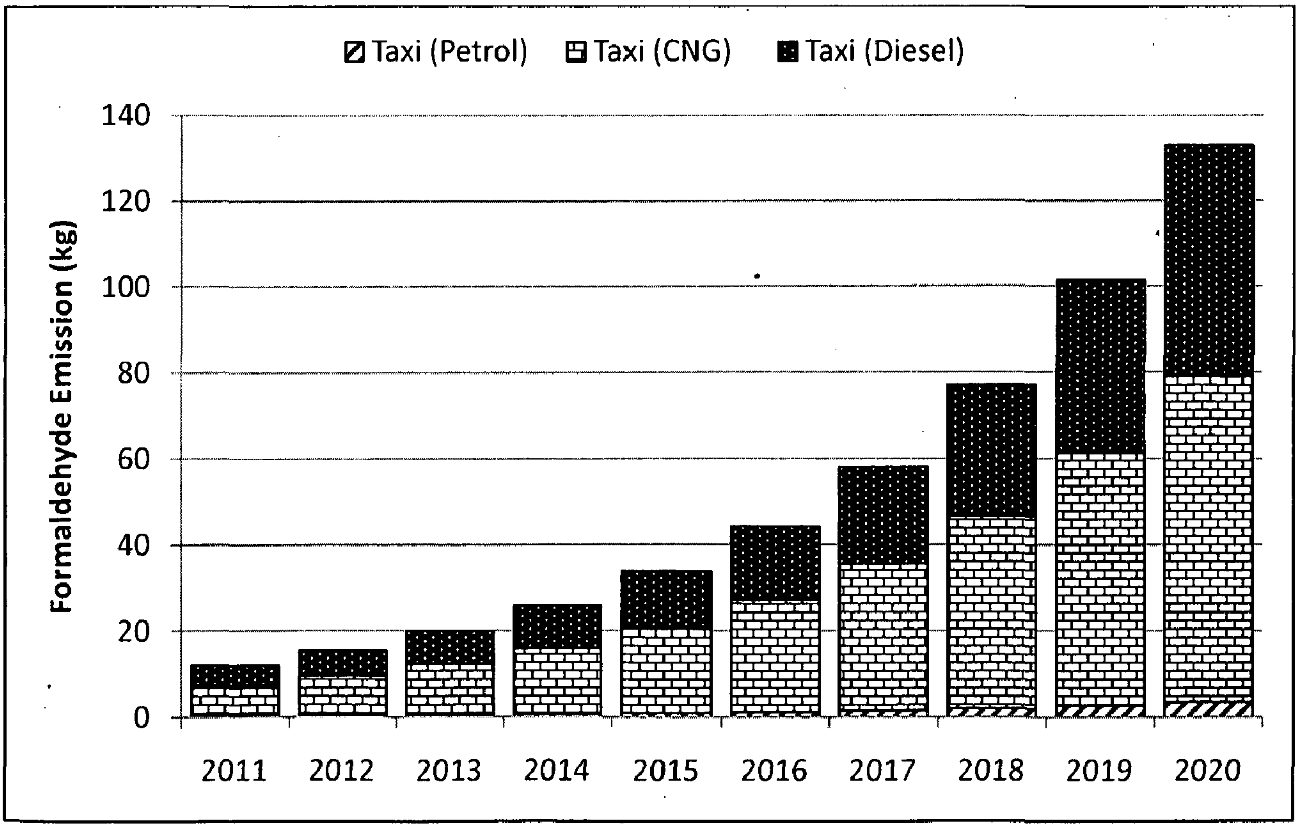


Fig. 6.69a: Formaldehyde emissions as per BAU scenario from taxis in megacity Delhi

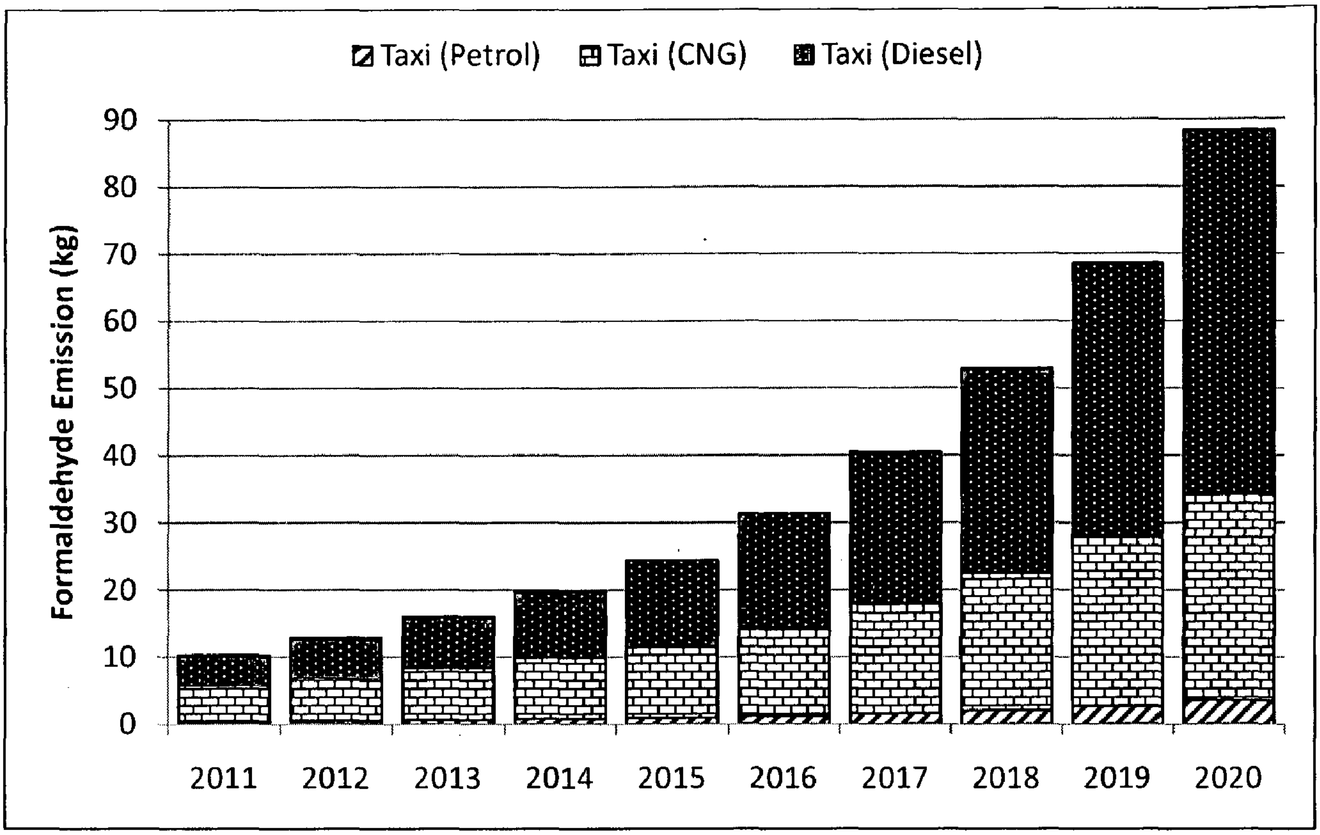


Fig. 6.69b: Formaldehyde emissions as per BES scenario from taxis in megacity Delhi

6.2.9.5. Buses

Emissions of Formaldehyde from buses in megacity Delhi in BAU scenario in 2011 is 102 kg followed by 162 kg in 2015 and 353 kg in 2020 (Fig. 6.70a). About 15% of annual average growth rate is expected in Formaldehyde emissions from buses in BAU scenario during 2011 to 2020. Similar to BAU, Formaldehyde emissions from buses in BES scenario in 2011 is 96 kg, followed by 147 kg in 2015 and 324 kg in 2020 (Fig. 6.70b). About 14.5% of average annual growth rate is estimated in Formaldehyde emissions in BES scenario from 2011 to 2020. Emission of Formaldehyde in BES is found to be 5.3% less than BAU scenario in 2011 and will be 8-9% less in 2015 and 2020. Emissions of Formaldehyde from diesel buses are more than CNG buses.

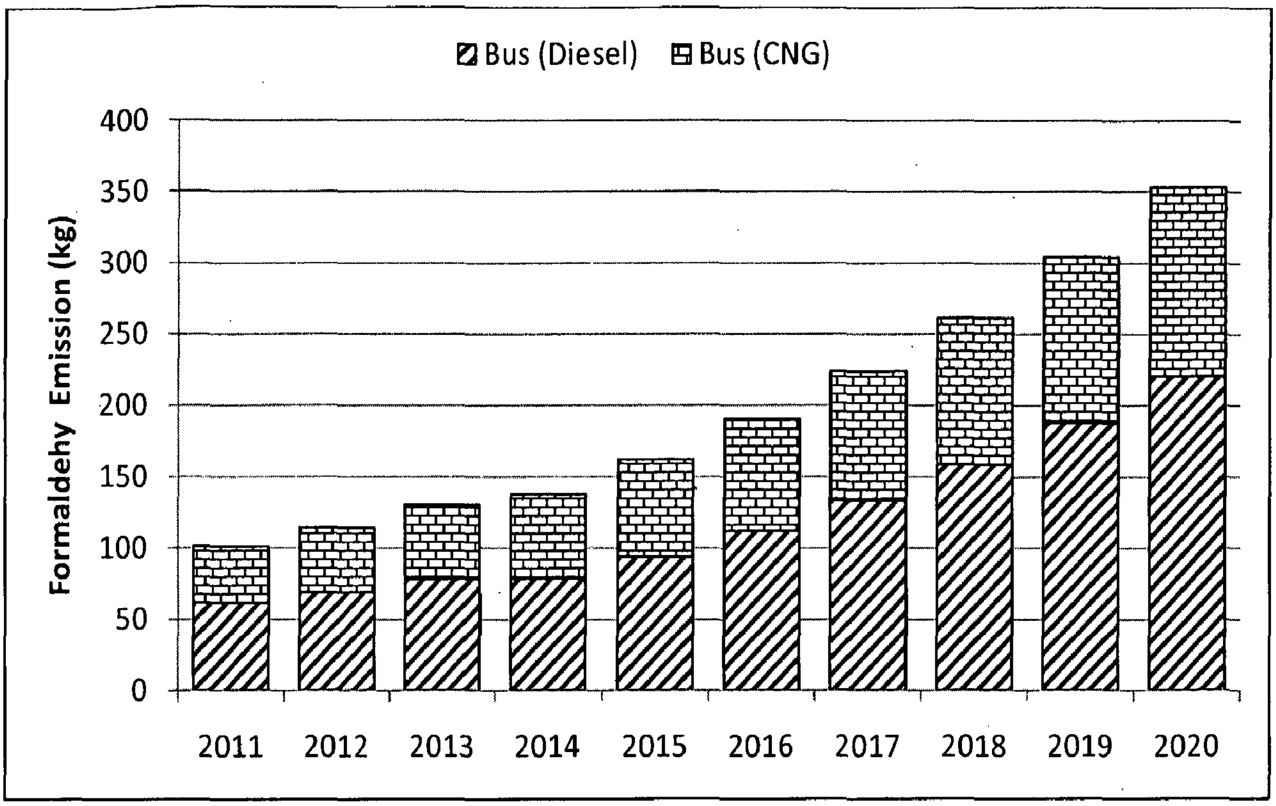


Fig. 6.70a: Formaldehyde emissions as per BAU scenario from buses in megacity Delhi

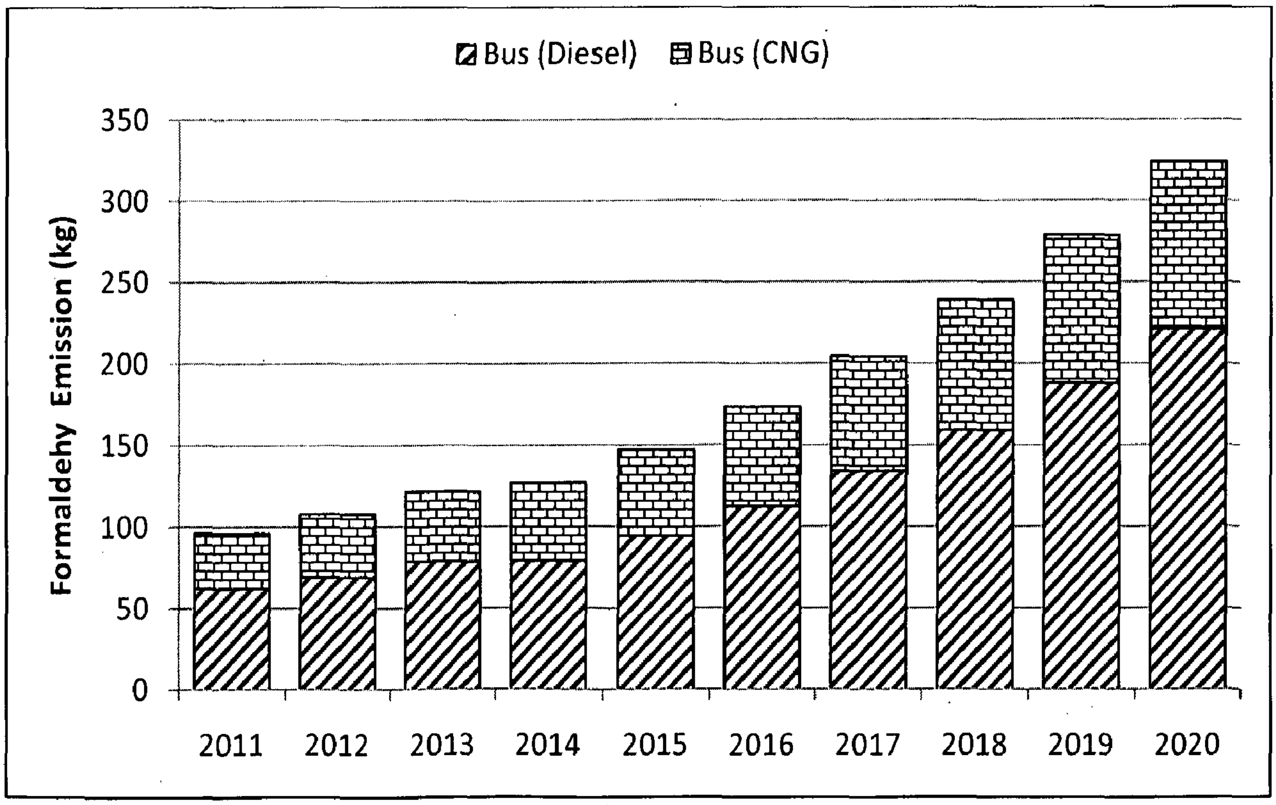


Fig. 6.70b: Formaldehyde emissions as per BES scenario from buses in megacity Delhi

6.2.9.6. LCVs/HCVs

About 65 kg of Formaldehyde is projected to be released by LCVs in the year 2011 followed by 52 kg in 2015 and 105 kg in 2020 (Fig. 6.71). Initially the contribution of diesel driven LCVs is estimated to be highest, while due to CNG conversion the contribution of diesel driven LCVs is decreasing during 2011 to 2015. Formaldehyde emissions from HCVs are given in Fig. 6.72. Initially in 2011 emission of Formaldehyde from HCVs population are projected to be 126 kg, followed by 161 kg in 2015 and 254 kg in 2020. About 8% of average annual growth rate is observed in Formaldehyde emissions from HCVs during 2011 to 2020.

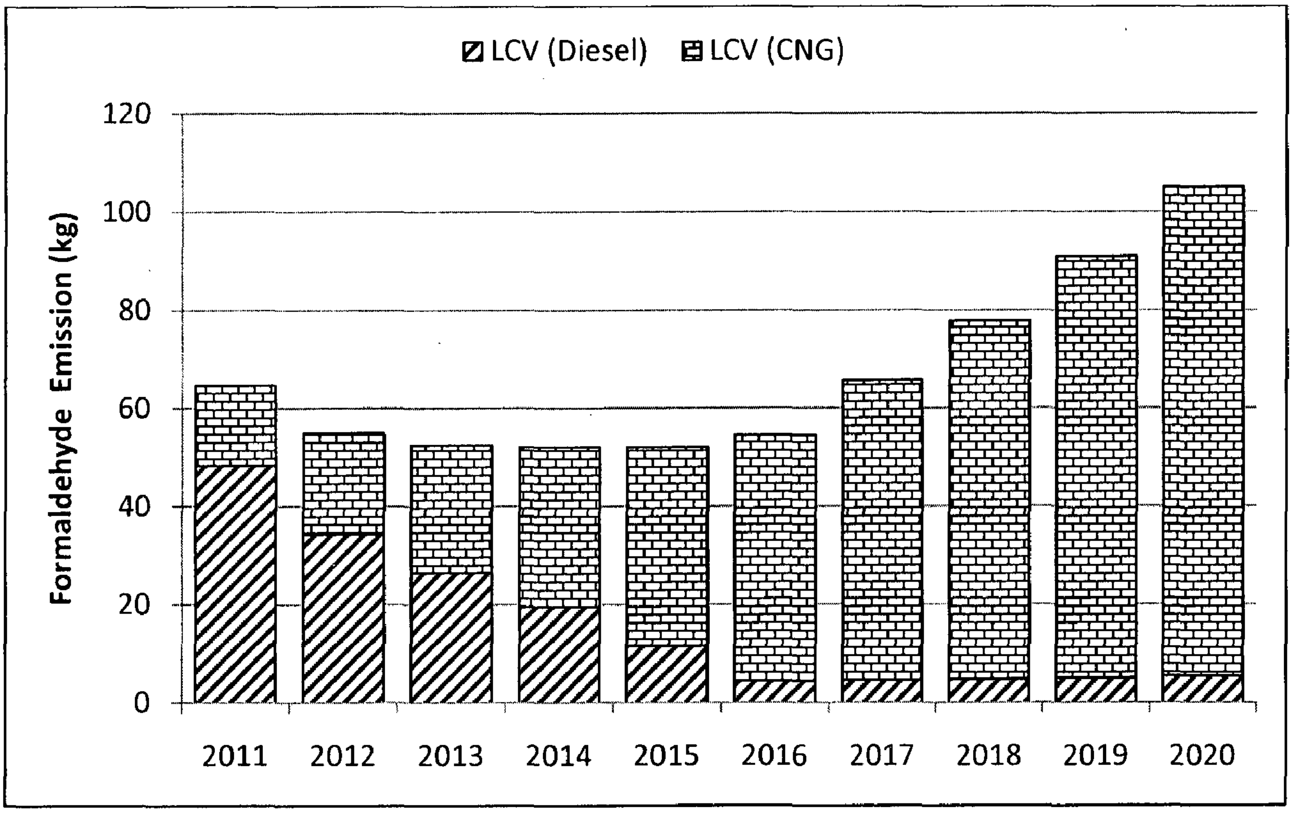


Fig. 6.71: Formaldehyde emissions as per BAU scenario from LCVs in megacity Delhi

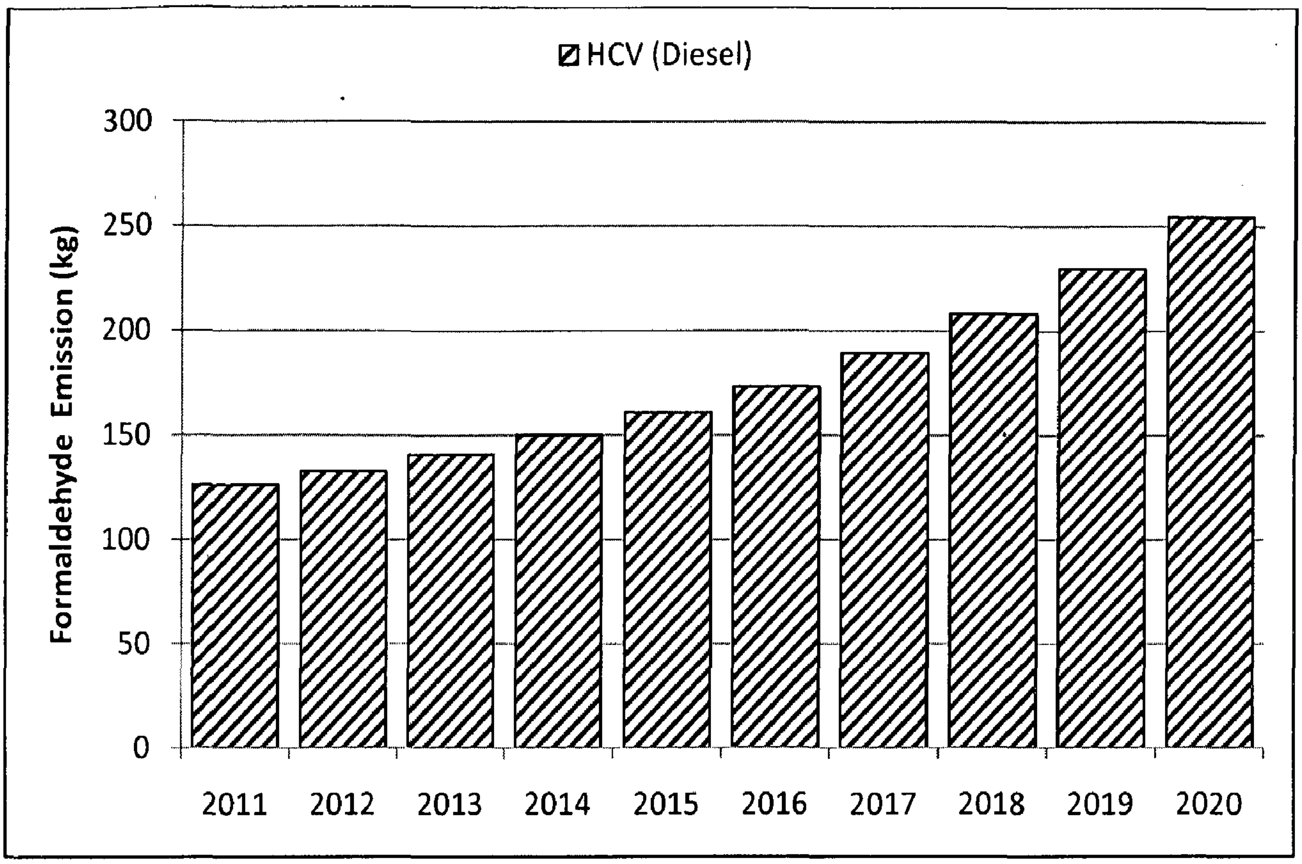


Fig. 6.72: Formaldehyde emissions as per BAU scenario from HCVs in megacity Delhi

6.2.10. Total Aldehyde emissions

Emissions of Total Aldehyde from various vehicle categories in megacity Delhi in BAU and BES scenario are presented in Fig. 6.73 (a and b) respectively. Fig. 6.73a shows that in 2011 Total Aldehyde emissions from various vehicles are 1860 kg. About 7.7% of decrease is projected in Total Aldehyde emissions between 2011 and 2012. Phasing out of 1991 model car population and higher emission factors for old age vehicles is responsible for this negative trend. In 2015 emission of Total Aldehyde from vehicles in BAU scenario is 2079 kg, followed by 3305 kg in 2020. Emissions of Total Aldehyde from vehicles in BES scenario is shown in Fig. 6.73b. It shows that in 2011 emission will be 1699 kg, 1716 kg in 2015, followed by 2723 kg in 2020. Emission in BES is 8.7% less than BAU scenario in 2011, while this difference will be ~18% in 2015 and 2020. Initially cars and two-wheelers release maximum share of total Aldehyde emissions but buses also emerge as large emitters in later years.

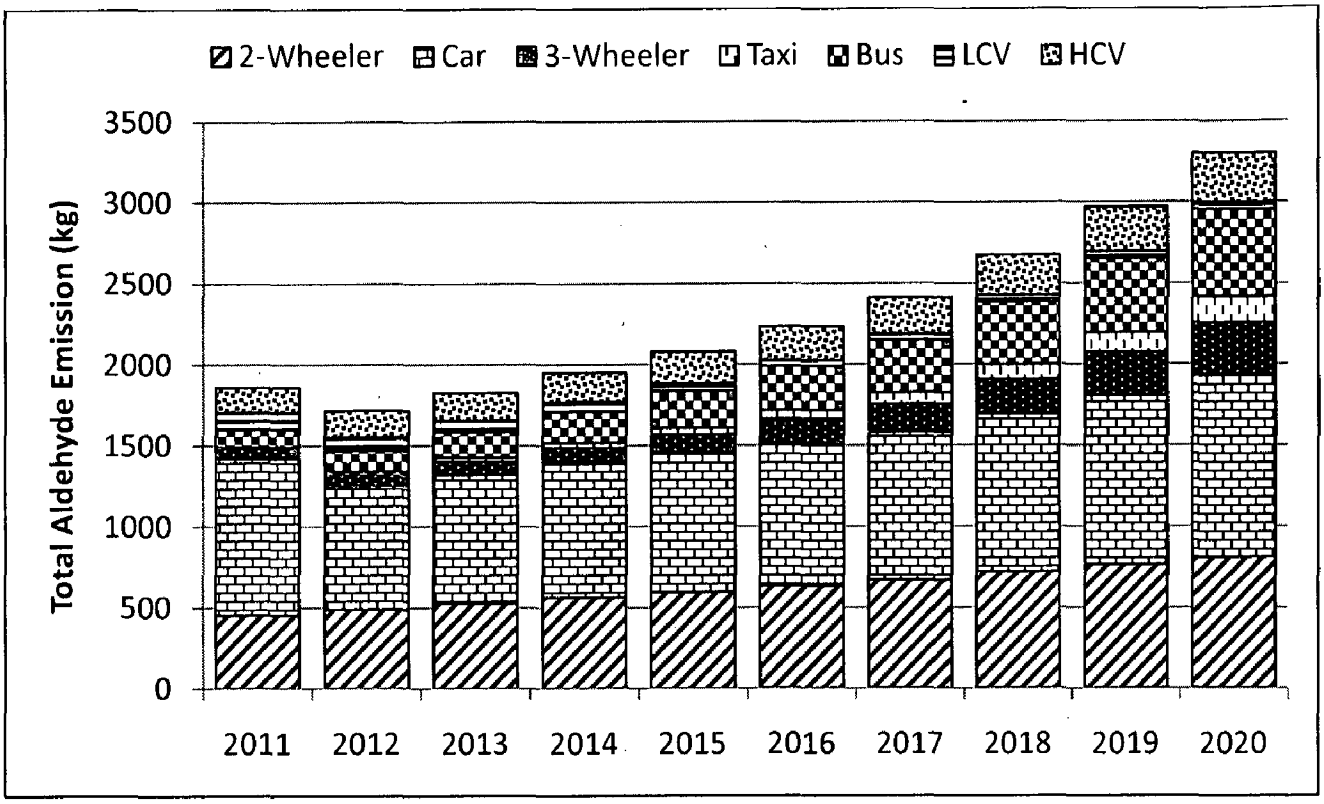


Fig. 6.73a: Total Aldehyde emissions as per BAU scenario from vehicles in megacity Delhi

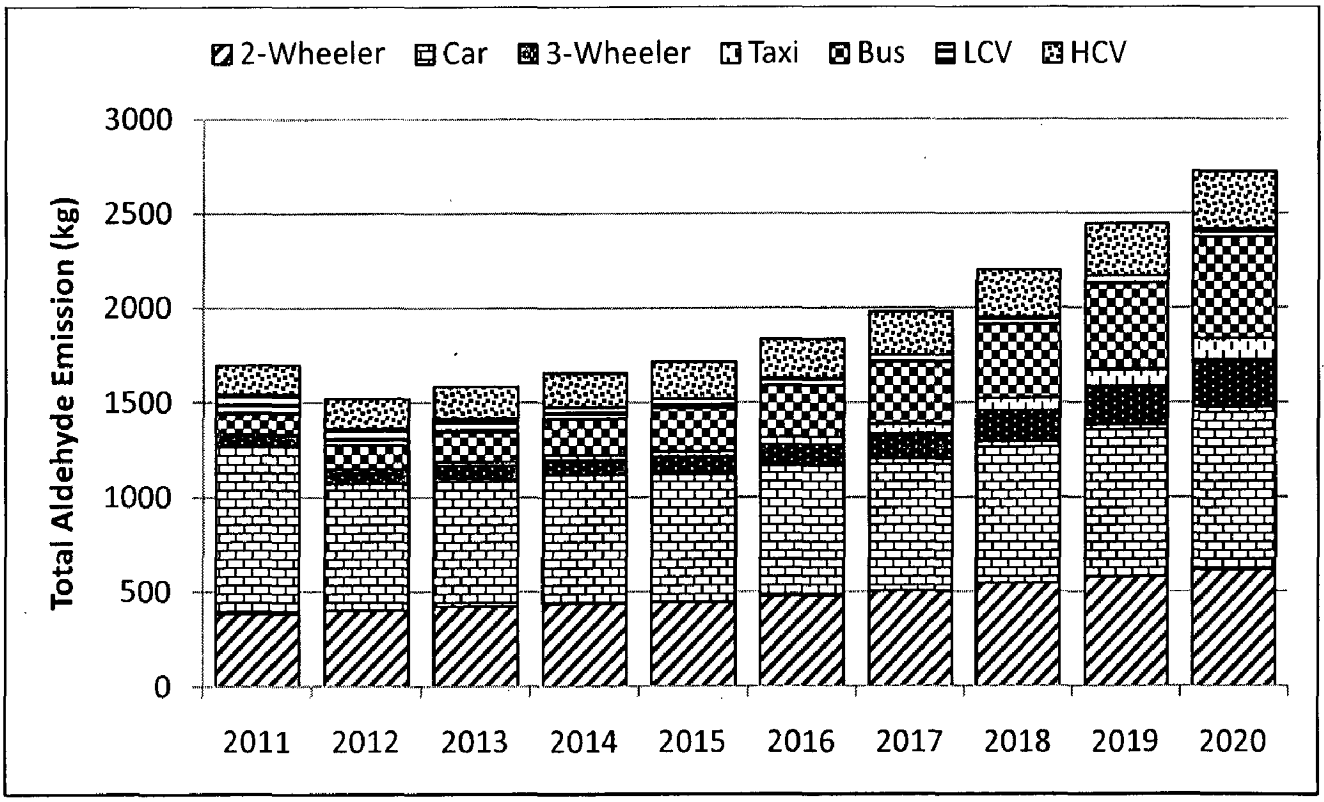


Fig. 6.73b: Total Aldehyde emissions as per BES scenario from vehicles in megacity Delhi

6.2.10.1. Two Wheelers

Fig. 6.74a indicates that in 2011 emissions of Total Aldehyde from two wheelers in BAU scenario will be 457 kg followed by 597 kg in 2015 and 813 kg in 2020. About 6.6% of average annual growth is observed in Total Aldehyde emissions during 2011 to 2020. Fig. 6.74b shows the emission of Total Aldehyde from two wheelers in BES scenario. In 2011 it is 386 kg followed by 449 kg in 2015 and 620 kg in 2020. About 5.4% of annual average growth is estimated in Total Aldehyde emissions from two wheelers during 2011 to 2020. Emission in BES scenario is less than BAU scenario. In 2011 this emission difference between BES and BAU is 15.5%, followed by 24-25% in 2015 and 2020. Two-stroke scooters and two-stroke mopeds are major contributors among all categories of two-wheelers.

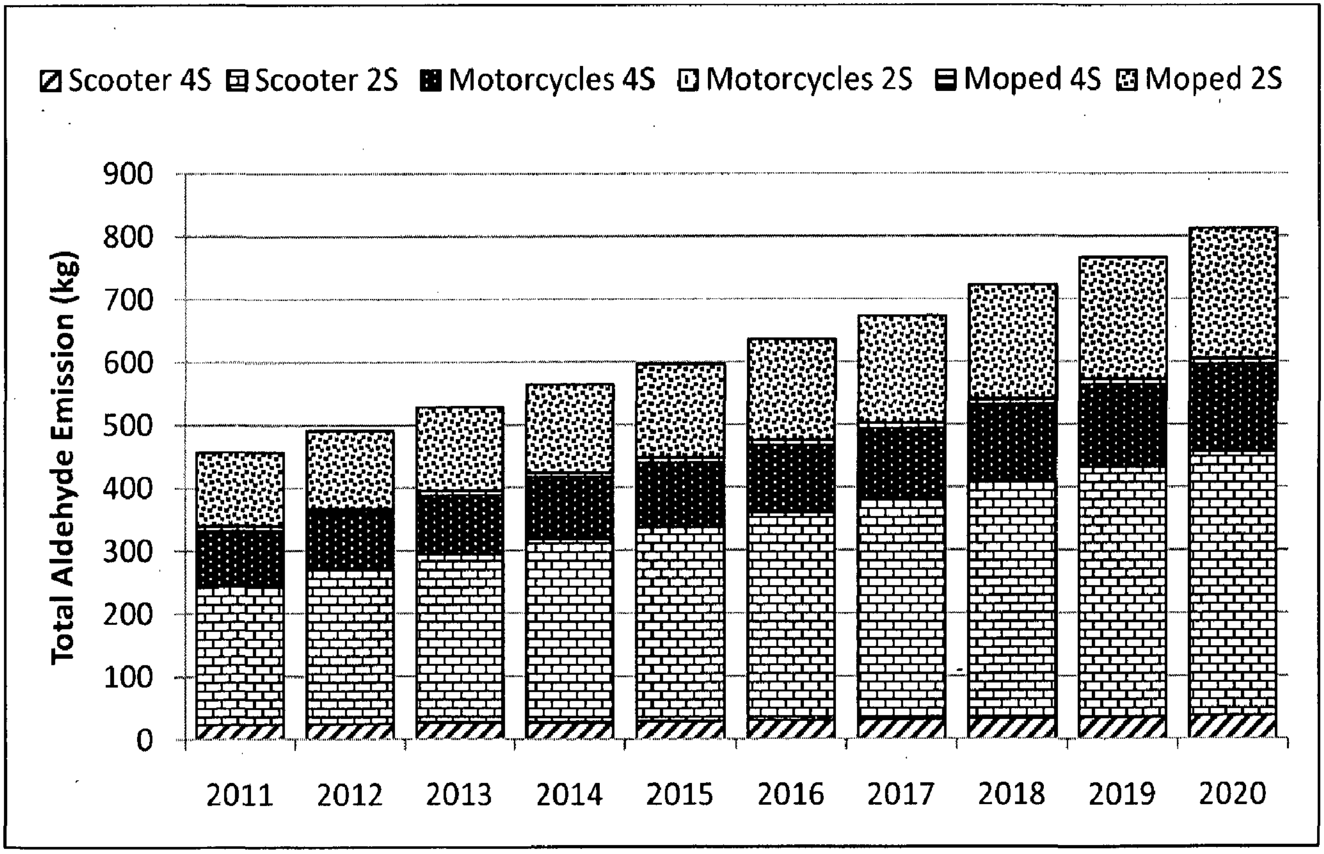


Fig. 6.74a: Total Aldehyde emissions as per BAU scenario from two wheelers in megacity Delhi

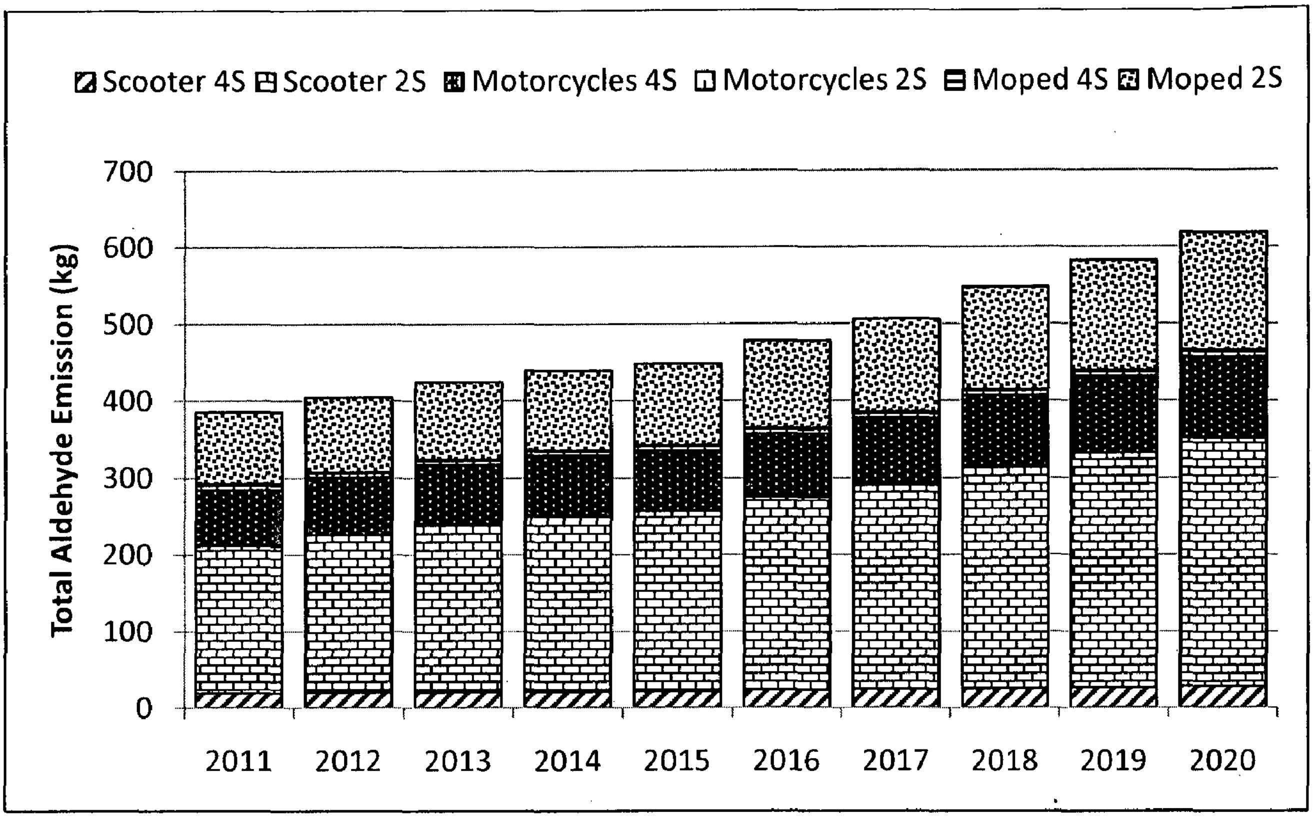


Fig. 6.74b: Total Aldehyde emissions as per BES scenario from two wheelers in megacity Delhi

6.2.10.2. Cars

Emissions of total Aldehyde from cars in BAU and BES scenario are presented in Fig. 6.75 (a and b). Fig. 6.75a indicates that in 2011 Total Aldehyde emissions from cars are 964 kg followed by 854 kg in 2015 and 1117 kg in 2020. About 21% of decline is observed in the year between 2011 and 2012 because of phasing out of 1991 model cars in 2012. Fig. 6.75b indicates that in 2011 Total Aldehyde emissions from cars is 883 kg, while in 2015 it is 676 kg followed by 860 kg in 2020. Similar to BAU decline is projected in BES during 2011 and 2012 because of same reason. Total Aldehyde emission in BES is 8.4% less than BAU during the year 2011 and will be 21-23% in 2015 and 2020. However, emission contributions from diesel and petrol driven cars is much more than CNG driven cars in both the scenarios.

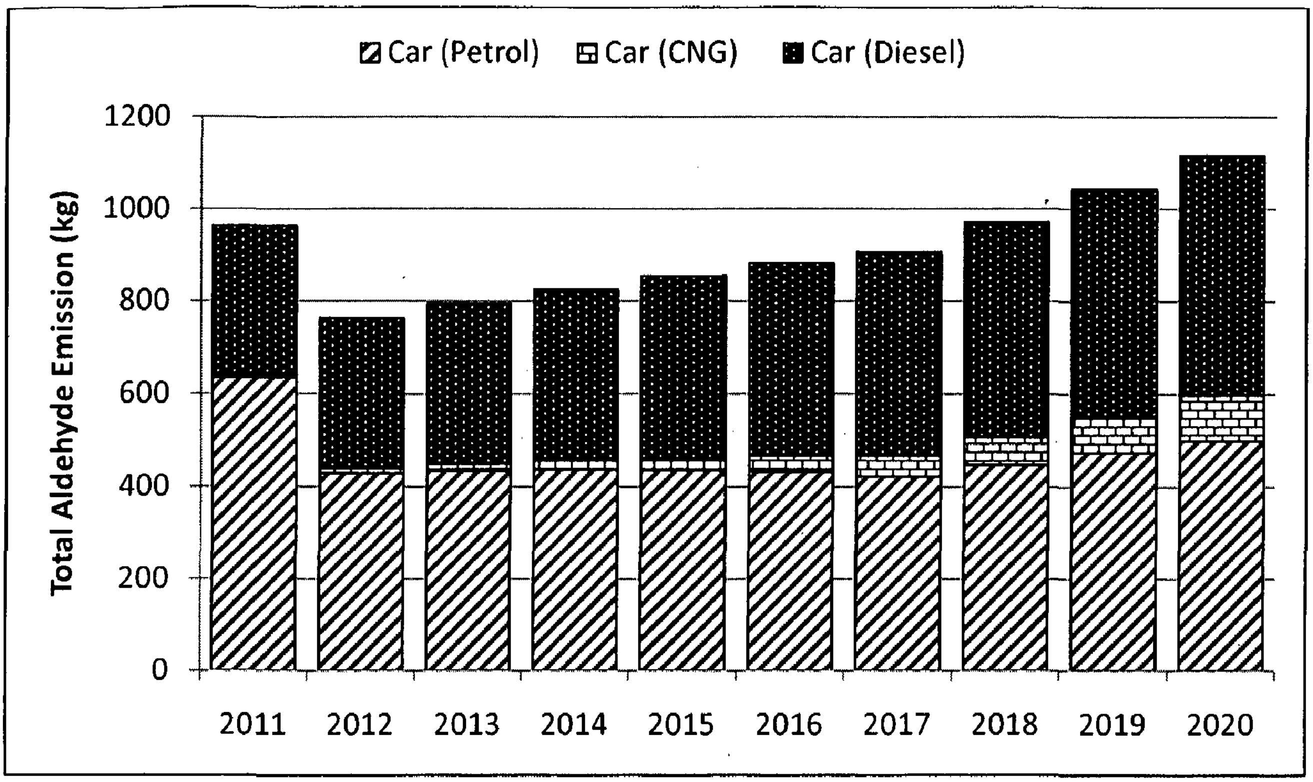


Fig. 6.75a: Total Aldehyde emissions as per BAU scenario from cars in megacity Delhi

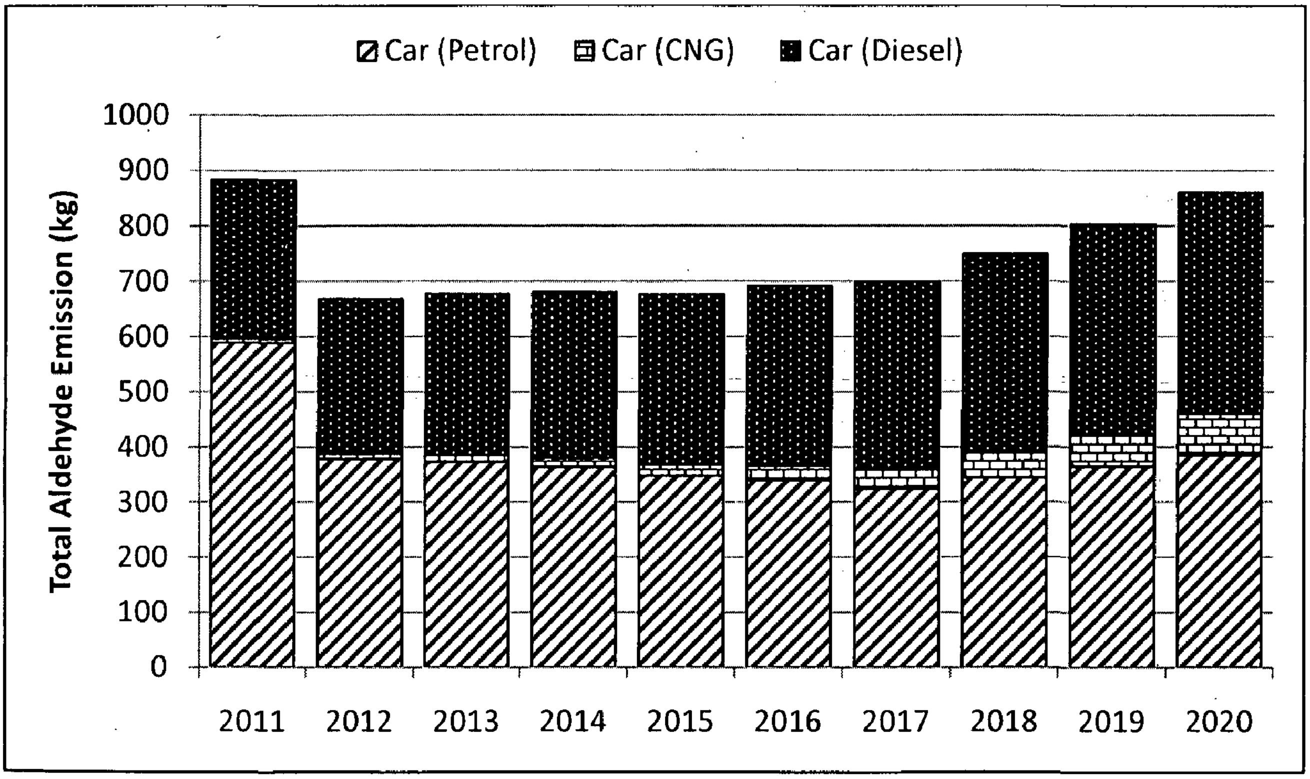


Fig. 6.75b: Total Aldehyde emissions as per BES scenario from cars in megacity Delhi

6.2.10.3. Three Wheelers

Total Aldehyde emissions from three wheelers (predominantly from CNG driven four-stroke category) in BAU and BES scenario are given in Fig. 6.76 (a and b). During the year 2011, Total Aldehyde emissions from three wheelers in BAU scenario are estimated to be 58 kg, 117 kg in 2015 and 326 kg in 2020. About 21% average annual growth is projected in Total Aldehyde emissions from 2011 to 2020 in BAU scenario. Fig. 6.76b indicates that in 2011 emissions will be 50 kg, followed by 91 kg in 2015 and 246 kg in 2020. Emission in BAU scenario is higher than BES throughout the study period. Approximately 13% of difference is observed in Total Aldehyde emission in BAU and BES scenario in 2011, followed by 22% in 2015 and 24% in 2020.

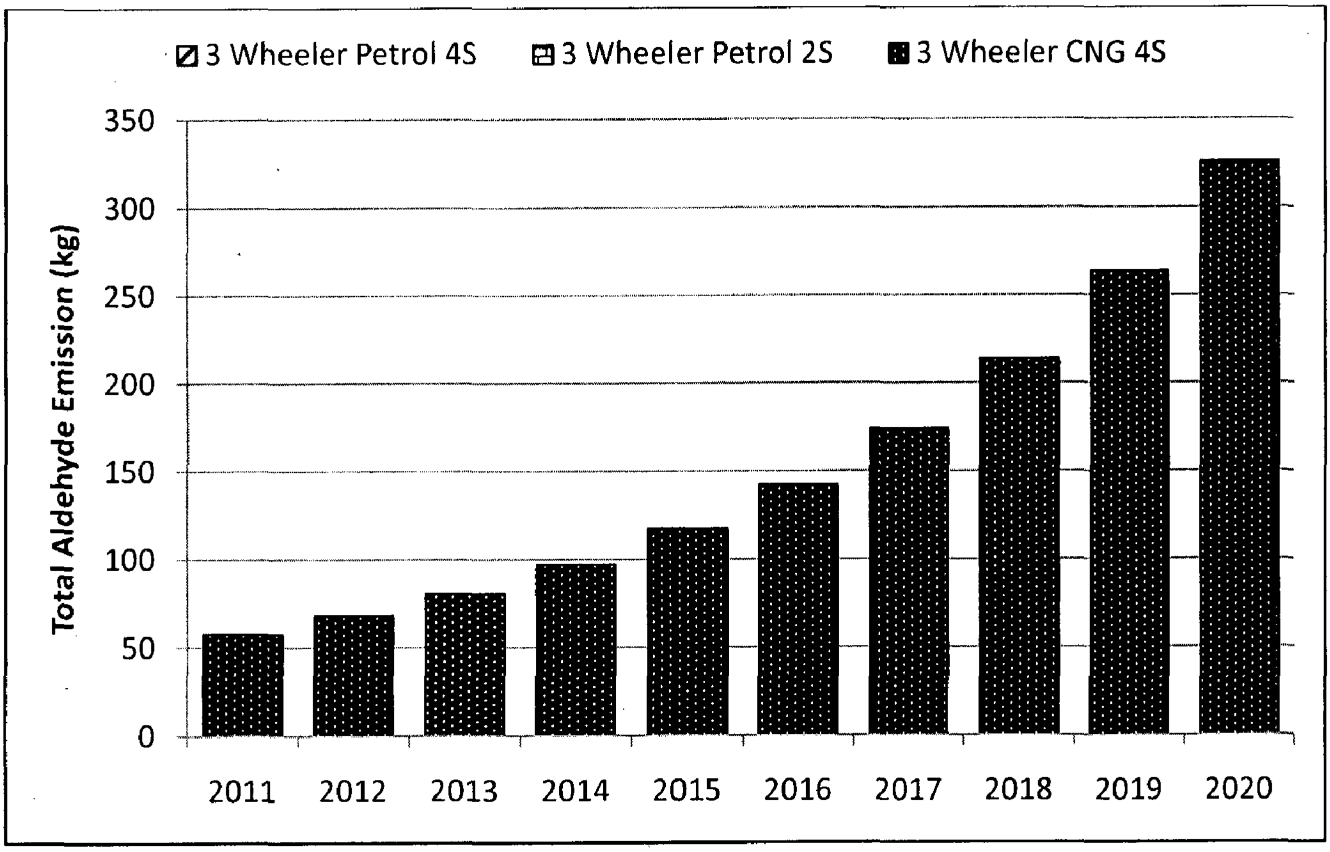


Fig. 6.76a: Total Aldehyde emissions as per BAU scenario from three wheelers in megacity Delhi

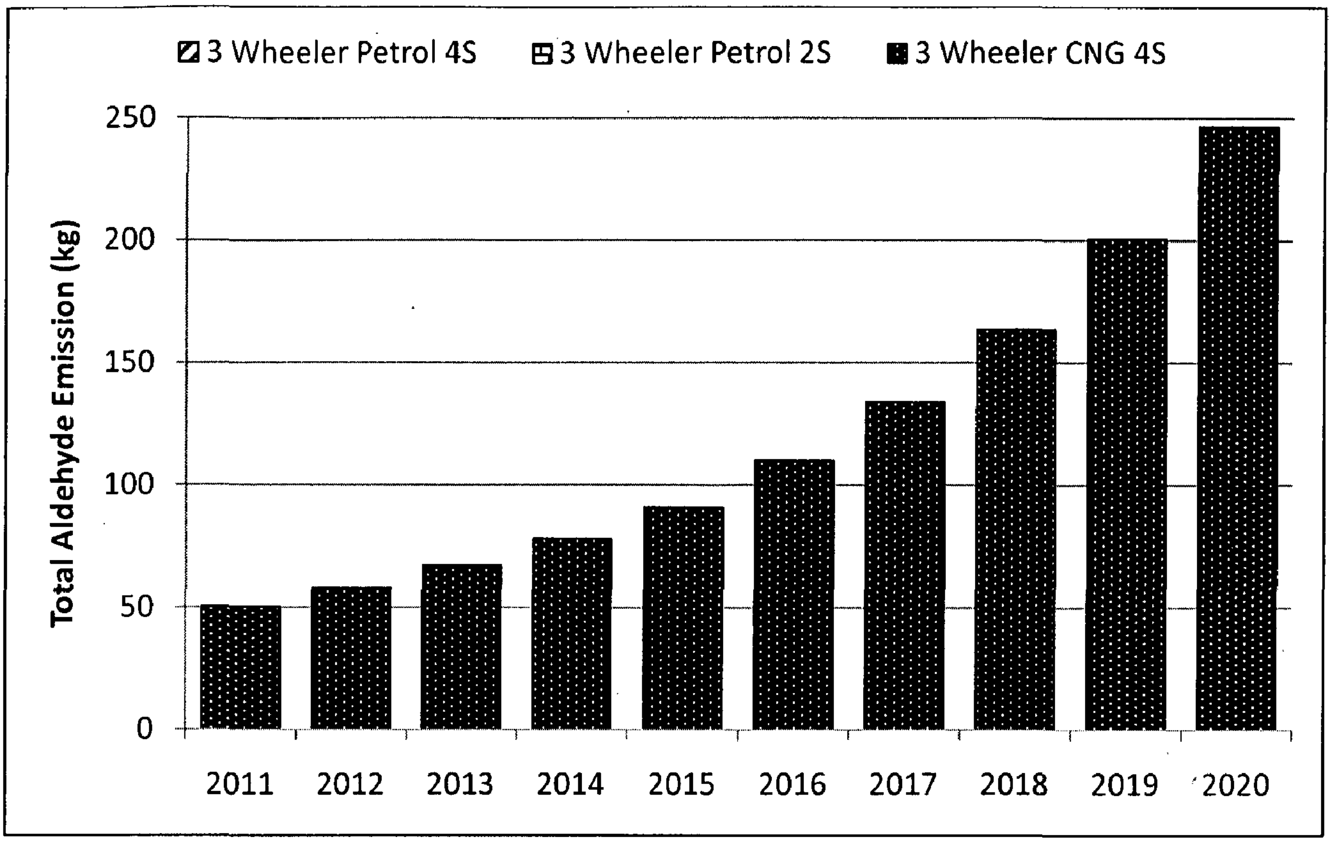


Fig. 6.76b: Total Aldehyde emissions as per BES scenario from three wheelers in megacity Delhi

6.2.10.4. Taxis

In BAU scenario Total Aldehyde emissions from taxis is estimated to be 15 kg in 2011, followed by 42 kg in 2015 and 163 kg in 2020 (Fig. 6.77a). About 30% of annual average growth is projected in Total Aldehyde emissions from 2011 to 2020. Fig. 6.77b shows the emission of Total Aldehyde in BES scenario from 2011 to 2020. In 2011 emission of Total Aldehyde in BES scenario are 14 kg, and are projected to be 31 kg in 2015 and 114 kg in 2020. About 26.4% of annual average growth is projected in Total Aldehyde emission in BES scenario from 2011 to 2020. Emission of Total Aldehyde in BES scenario is ~13% less than BAU scenario in 2011, followed by 26% in 2015 and 32% in 2020. In both the scenarios diesel and CNG driven taxis are the major contributors of Total Aldehyde emissions.

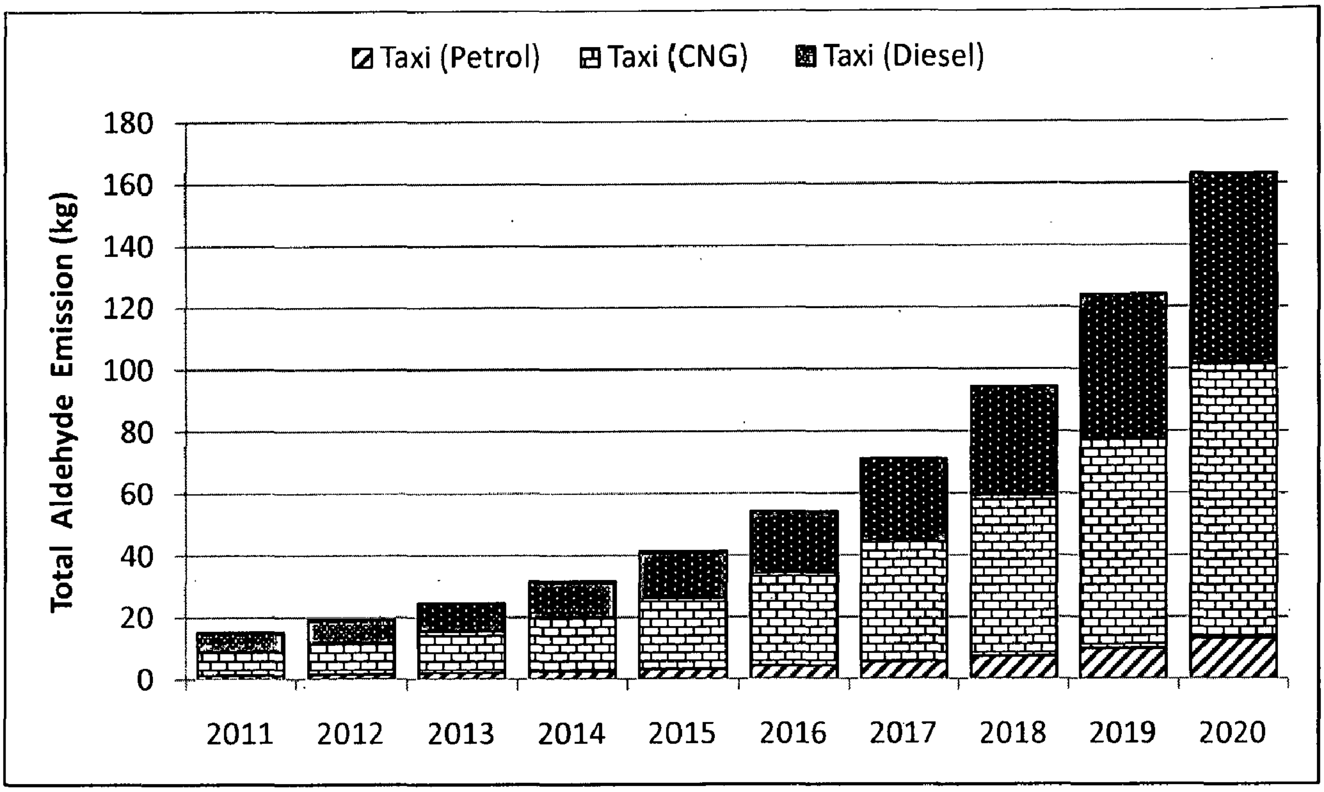


Fig. 6.77a: Total Aldehyde emissions as per BAU scenario from taxis in megacity Delhi

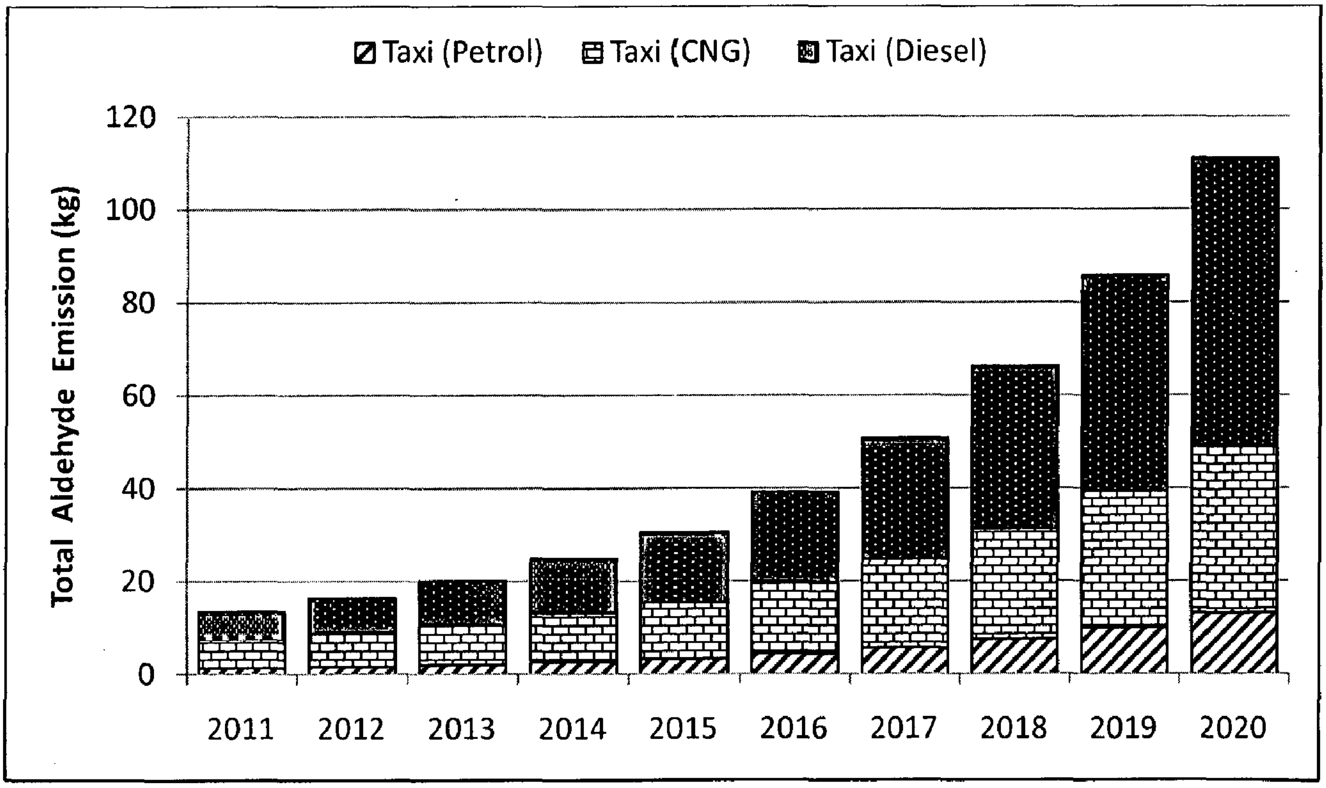


Fig. 6.77b: Total Aldehyde emissions as per BES scenario from taxis in megacity Delhi

6.2.10.5. Buses/LCVs/HCVs

Due to unavailability of emission factors of CNG driven buses and LCVs, emissions are calculated only for diesel driven buses and LCVs during 2011 to 2020. Total Aldehyde emissions from buses are projected to be 108 kg in 2011 followed by 229 kg in 2015 and 537 kg in 2020 (Fig. 6.78). About 19.5% of average growth rate is projected annually in Total Aldehyde emissions from buses during 2011 to 2020. Estimated emissions of Total Aldehyde from diesel driven LCVs are decreasing along with their population and estimated to be 104 kg in 2011 followed by 47 kg in 2015 and 43.6 kg in 2020 (Fig. 6.79). Further, as visible from Fig. 6.80 Total Aldehyde emissions from HCVs will be 154 kg in 2011, followed by 193 kg in 2015 and 305 kg in 2020.

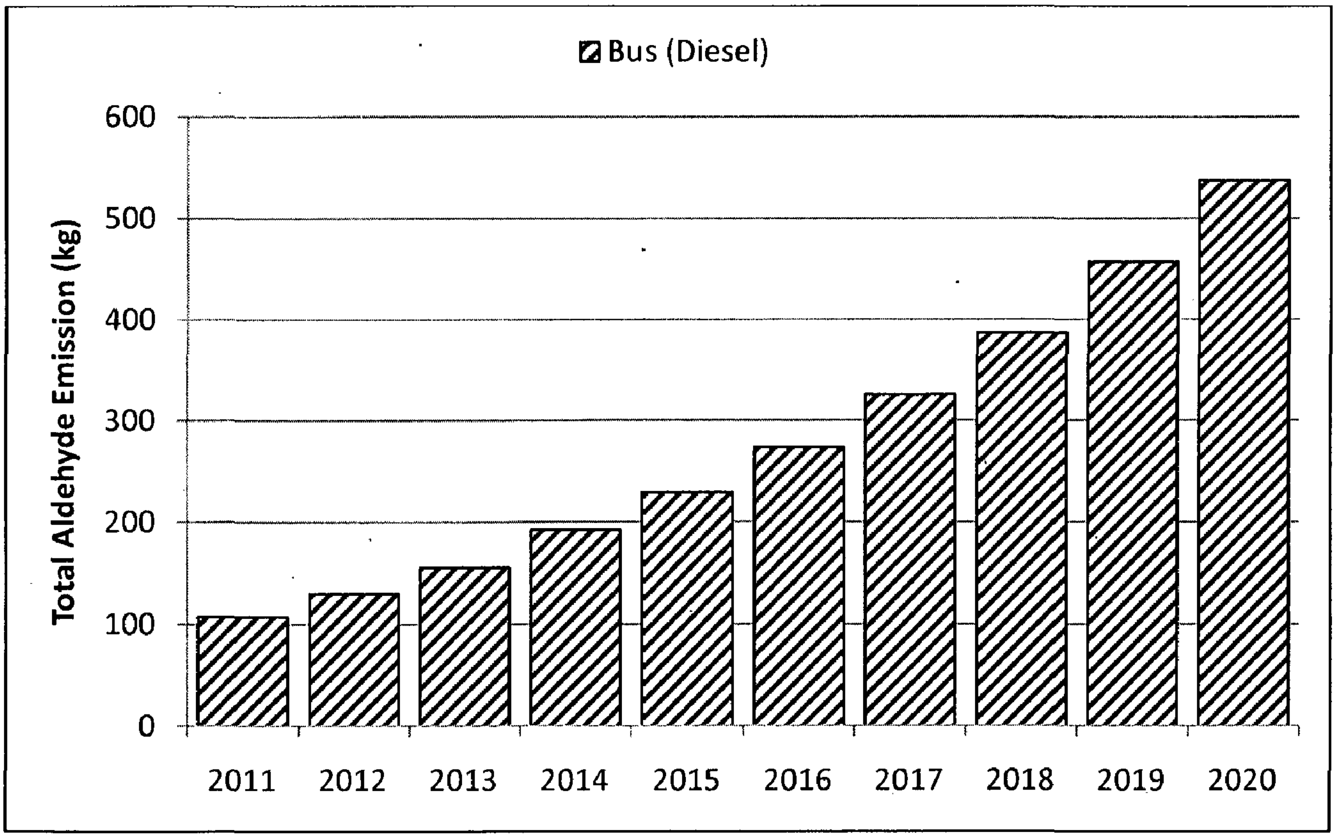


Fig. 6.78: Total Aldehyde emissions as per BAU scenario from buses in megacity Delhi

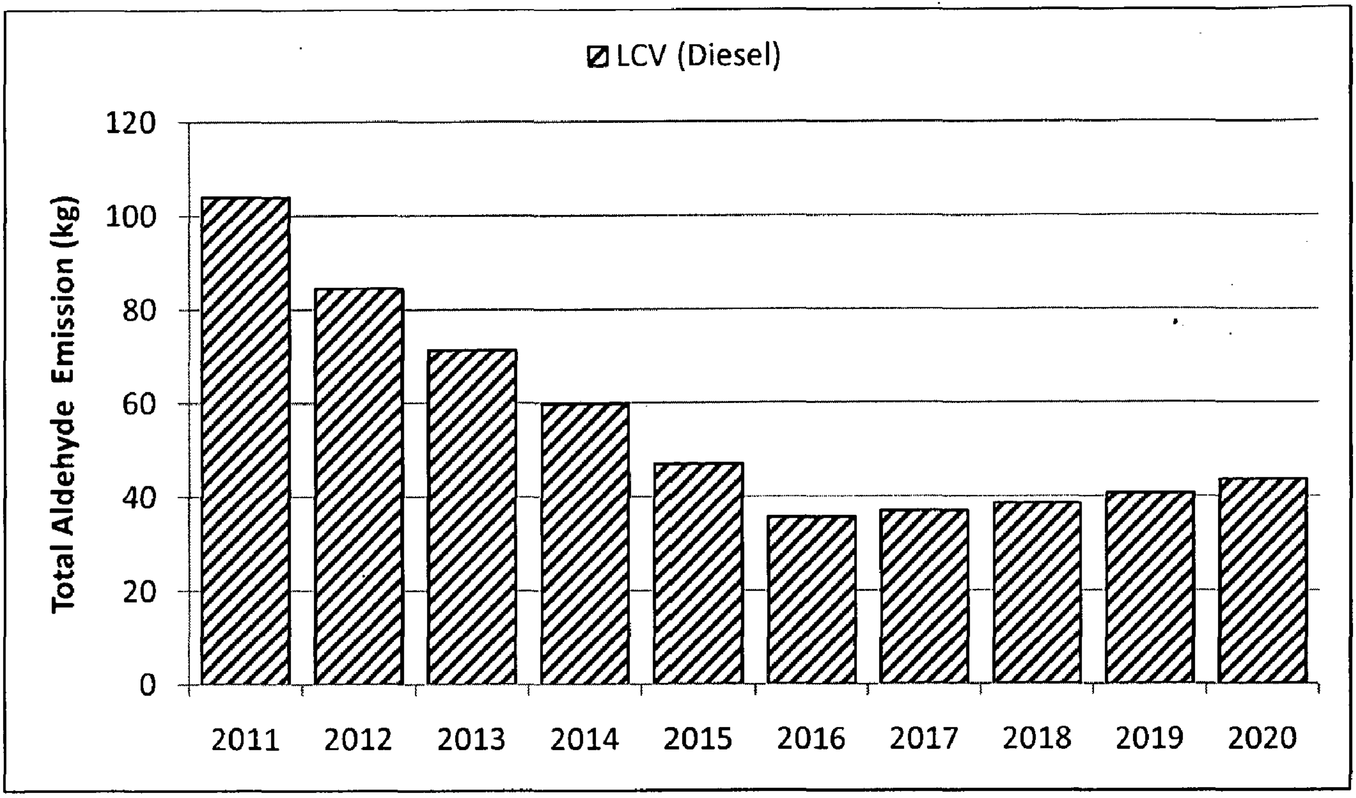


Fig. 6.79: Total Aldehyde emissions as per BAU scenario from LCVs in megacity Delhi

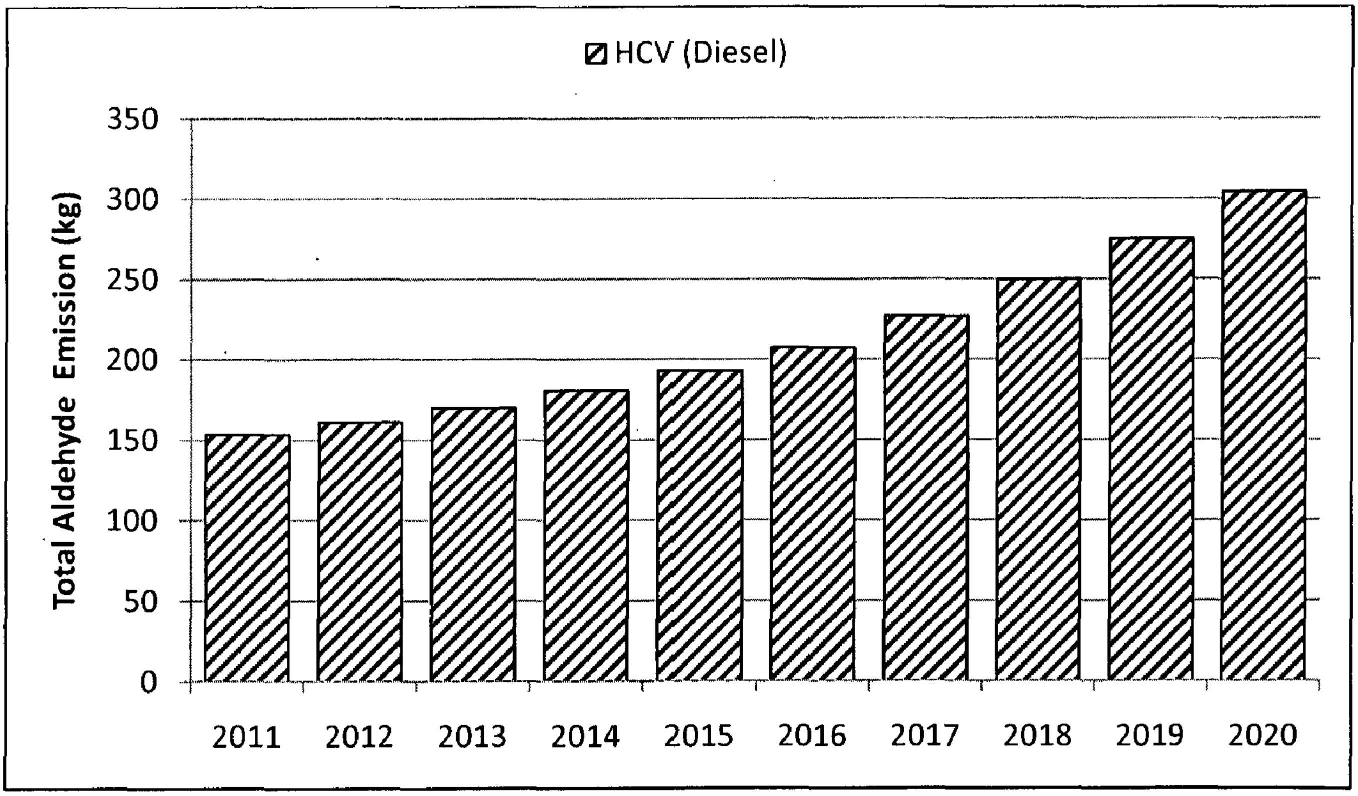


Fig. 6.80: Total Aldehyde emissions as per BAU scenario from HCVs in megacity Delhi

6.2.11. Total PAH emissions

Emissions of Total PAH from various vehicle categories in BAU and BES scenarios are shown in Fig. 6.81 (a and b). Total PAH emissions from various vehicles will be 41 Mg in 2011 followed by 53 Mg in 2015 and 82 Mg in 2020. The annual average growth rate between 2011 and 2020 in BAU scenario is expected to be 8%. In BES scenario Total PAH emissions in 2011 will be 37 Mg, 45 Mg in 2015 and 70 Mg in 2020. The annual average growth in Total PAH emissions from 2011 to 2020 is 7.2%. In both scenarios two wheelers are expected to dominate for Total PAH emissions from 2011 to 2020. LCVs are the second major contributor throughout the study period. However, CNG driven three-wheelers also emerge as the high emitters of total PAH. Emissions of Total PAH from BES scenario is 8.7% lower than BAU scenario in 2011 followed by 14.2% in 2015 and 14.4% in 2020.

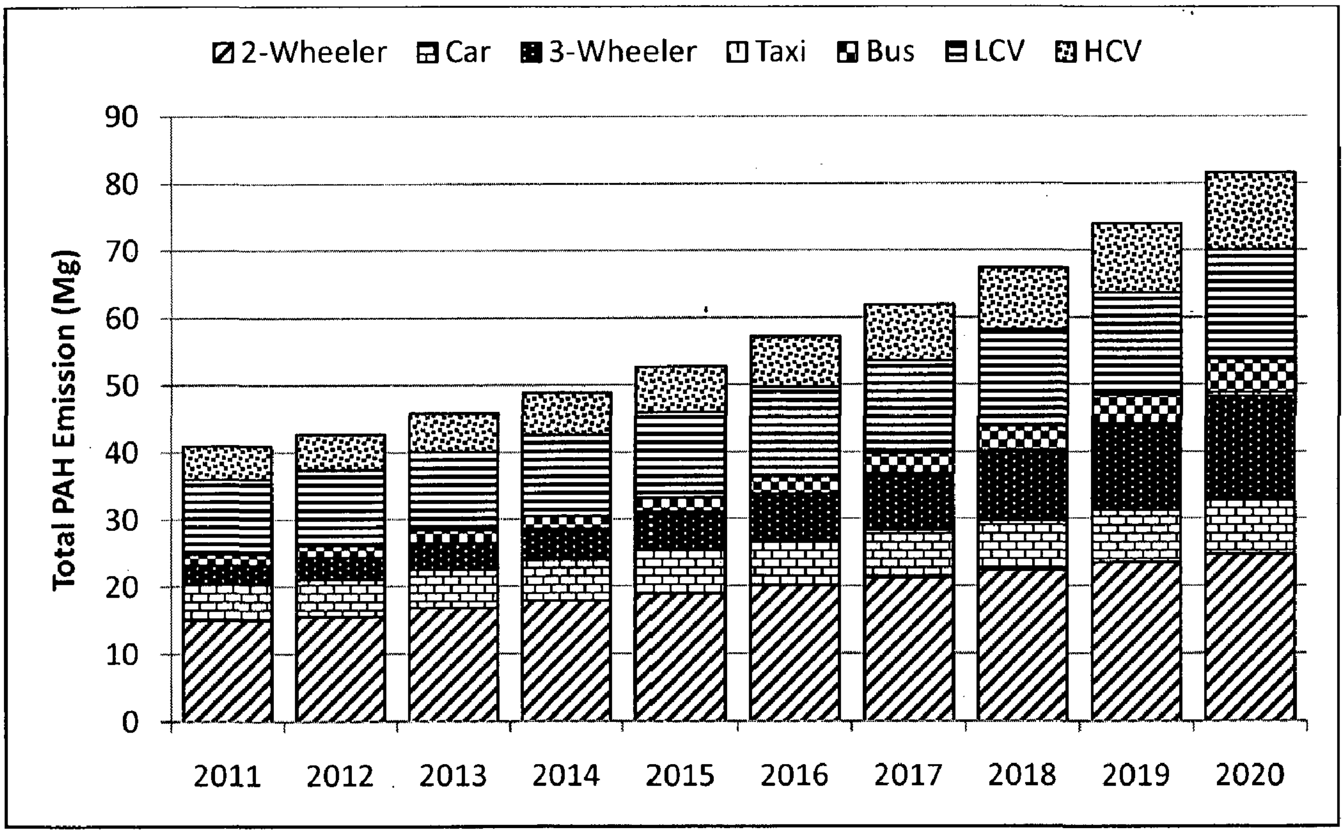


Fig. 6.81a: Total PAH emissions as per BAU scenario from vehicles in megacity Delhi

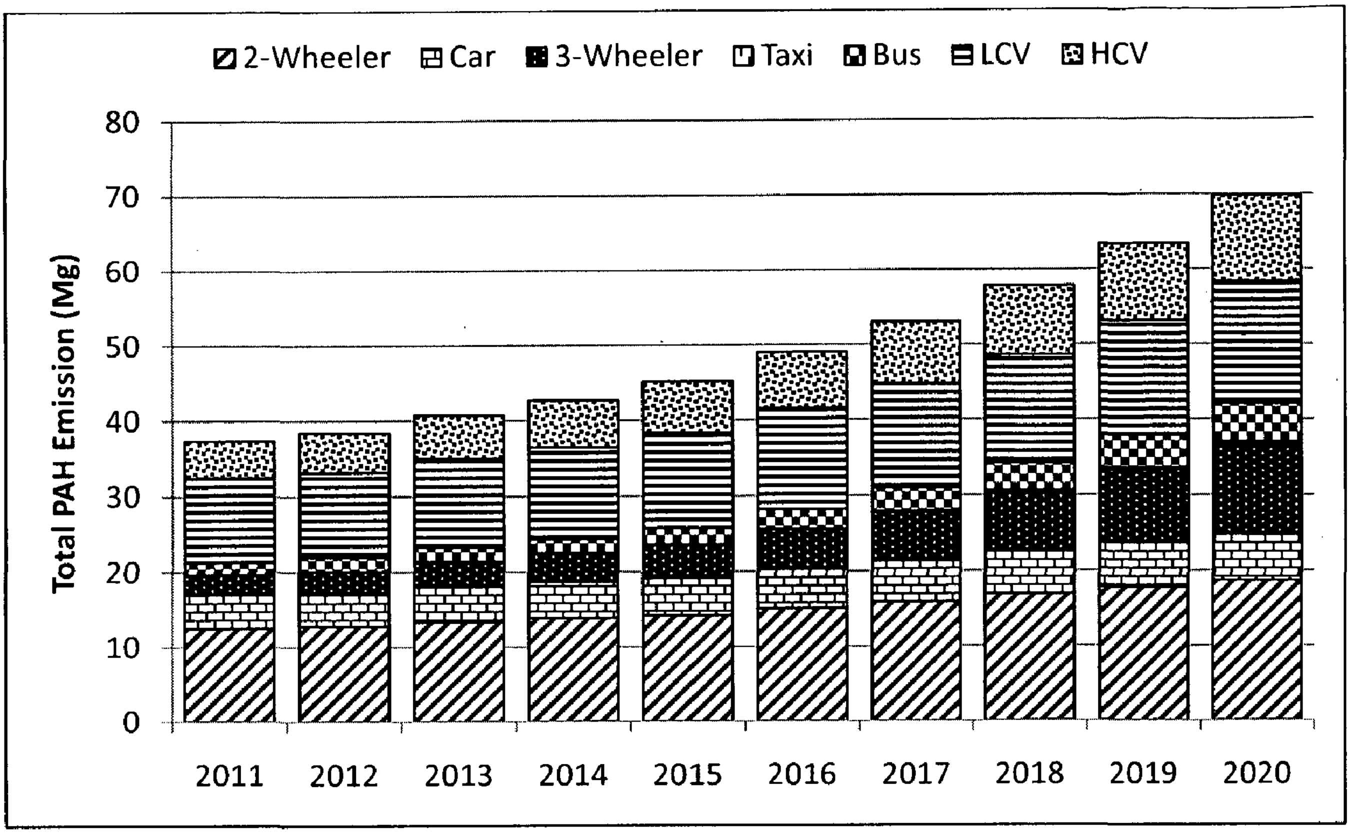


Fig. 6.81b: Total PAH emissions as per BES scenario from vehicles in megacity Delhi

6.2.11.1. Two Wheelers

Emissions of Total PAH from two wheelers during 2011 to 2020 in BAU and BES scenario are shown in Fig. 6.82 (a and b). Emission of Total PAH from two wheelers in BAU scenario will be 15 Mg in 2011, followed by 19 Mg in 2015 and 25 Mg in 2020. About 5.8% of annual average growth is projected in Total PAH emissions from two wheelers in BAU scenario during 2011 to 2020. Total PAH emissions from BES scenario from two wheelers in 2011 will be 13 Mg, 14 Mg in 2015 and 19 Mg in 2020. About 4.6% of annual average growth is observed in Total PAH emission from two wheelers in BES scenario. Emission of Total PAH in BES is 16% lower than BAU scenario in 2011 and is estimated to be 25% in 2015 and 24% in 2020. Four-stroke motorcycles are the largest contributors followed by two-stroke mopeds and two-stroke scooters.

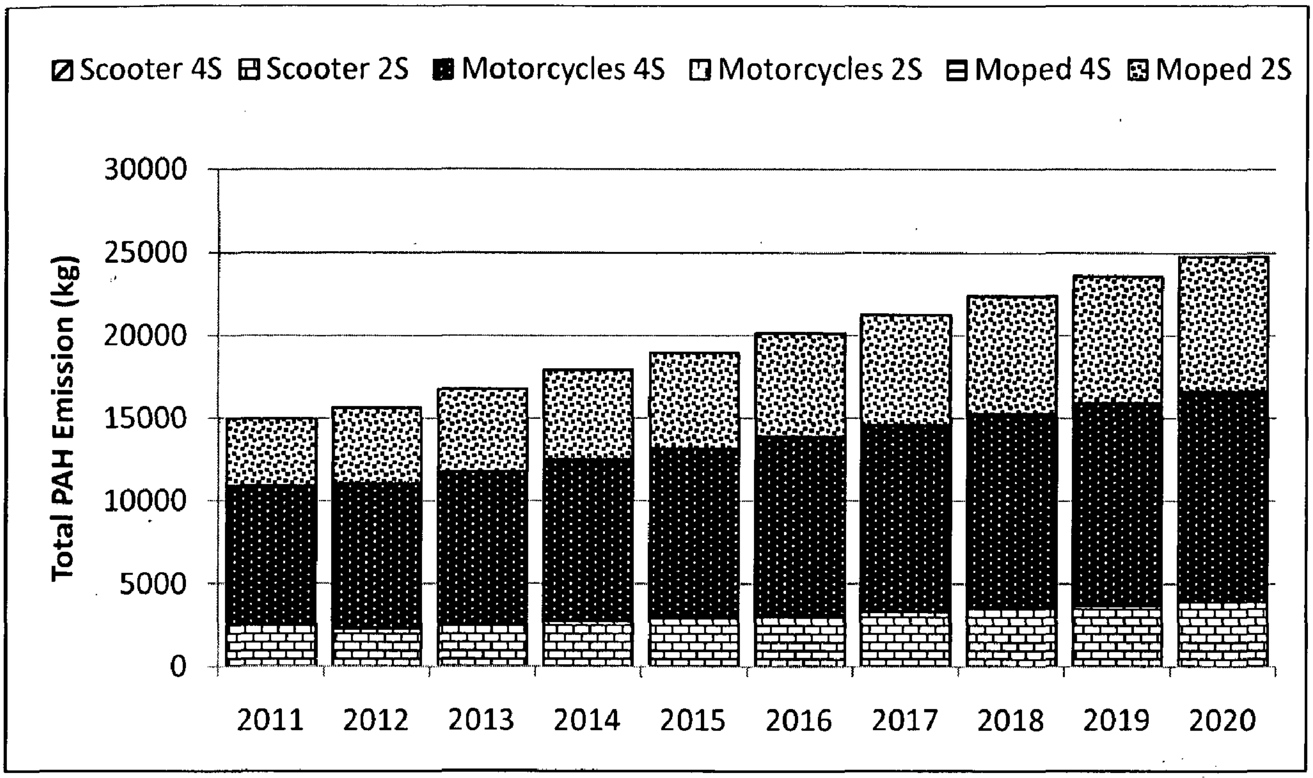


Fig. 6.82a: Total PAH emissions as per BAU scenario from two wheelers in megacity Delhi

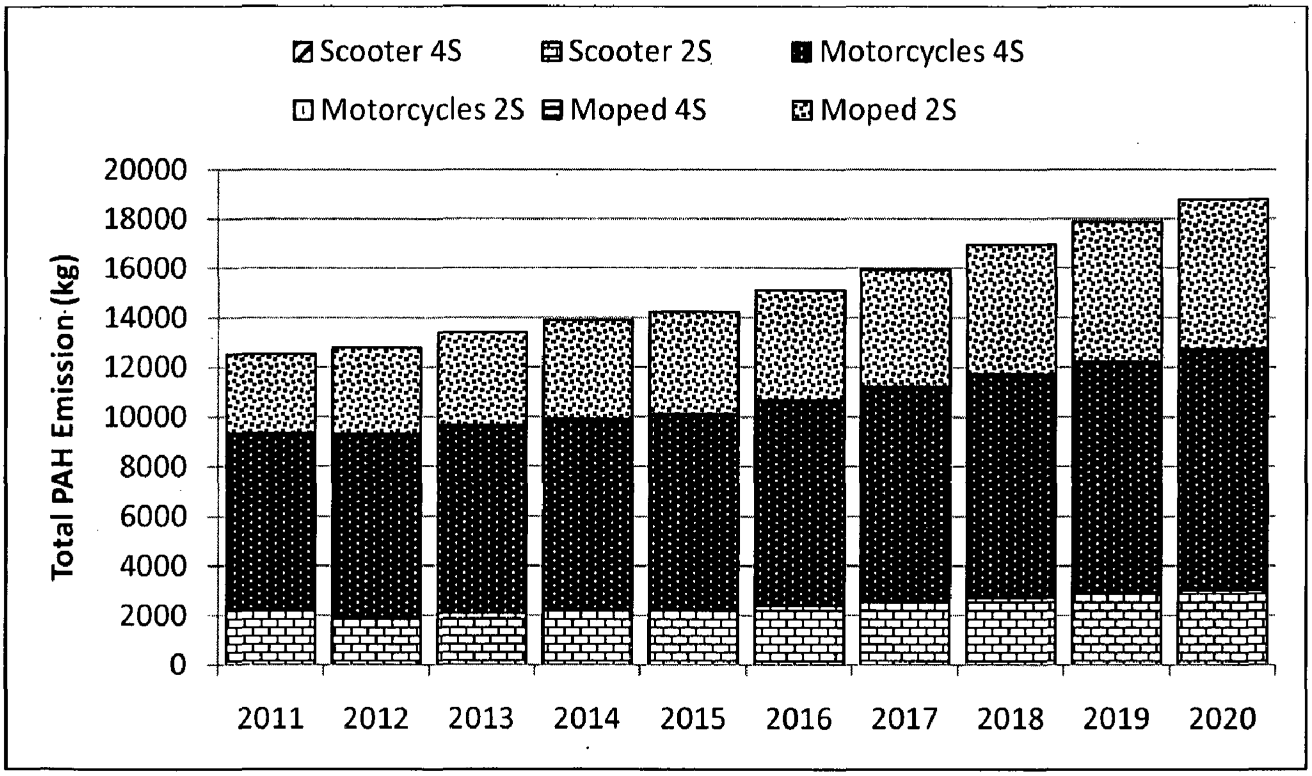


Fig. 6.82b: Total PAH emissions as per BES scenario from two wheelers in megacity Delhi

6.2.11.2. Cars

Emissions of Total PAH from cars in megacity Delhi in both BAU and BES scenarios are given in Fig. 6.83 (a and b). Fig. 6.83a suggests that in 2011 emission of Total PAH from cars will be 5524 kg, followed by 6417 kg in 2015 and 8051 kg in 2020. It is projected that in 2011 Total PAH emissions from cars in BES scenario will be 4714 kg, followed by 4958 kg in 2015 and 6155 kg in 2020. Estimated emission of Total PAHs from two wheelers in BES scenario in year 2011 will be 14.7% lower than BAU scenario, while in 2015 it will be 22.7% lower in 2015 and 23.6% lower in 2020. Diesel and petrol driven cars are the major contributors.

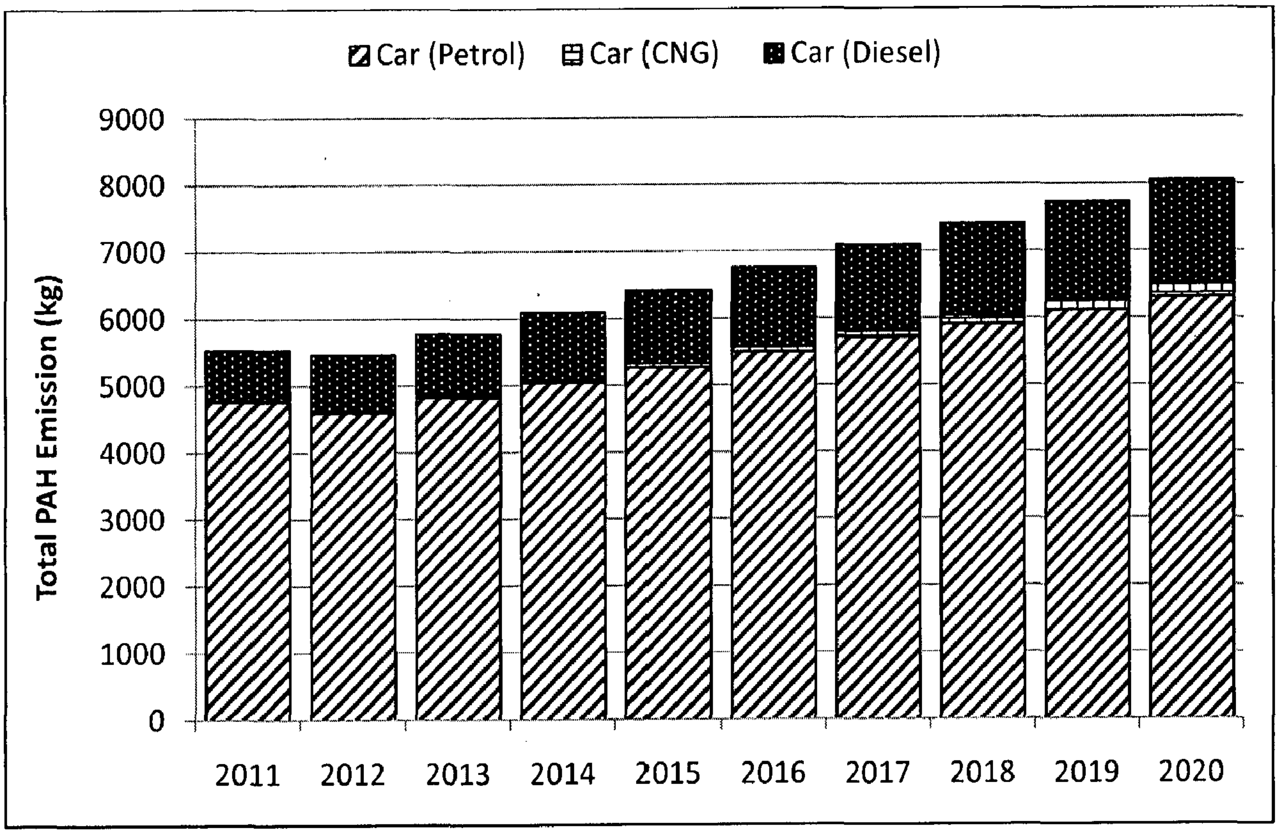


Fig. 6.83a: Total PAH emissions as per BAU scenario from cars in megacity Delhi

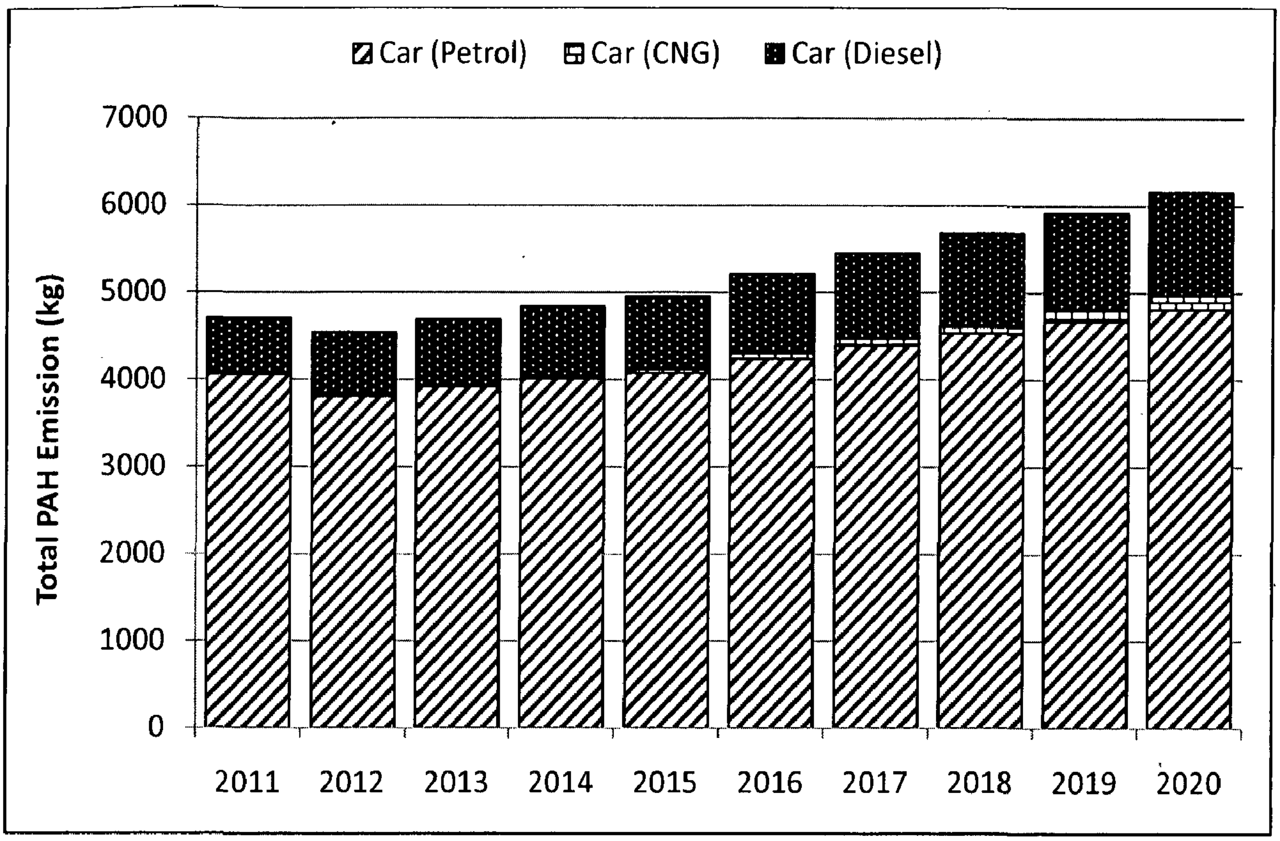


Fig. 6.83b: Total PAH emissions as per BES scenario from cars in megacity Delhi

6.2.11.3. Three Wheelers

Estimated emissions of Total PAH from three wheelers (CNG driven) in BAU scenario will be 2743 kg in 2011, (Fig. 6.84a) followed by 5564 kg in 2015 and 15456 kg in 2020. About 21% of annual average growth rate is projected in Total PAH emissions from 2011 to 2020 in BAU scenario. Fig. 6.84b shows Total PAH emissions from three wheelers in BES scenario. It indicates that in 2011 emissions will be 2393 kg, followed by 4321 kg in 2015 and 11707 kg in 2020. About 19.33% of annual average growth is estimated in Total PAH emissions from BES scenario during 2011 to 2020. Emission of Total PAH in BES is supposed to be 12.8% lower than BAU scenario during 2011, followed by 22.3% in 2015 and 24.3% in 2020.

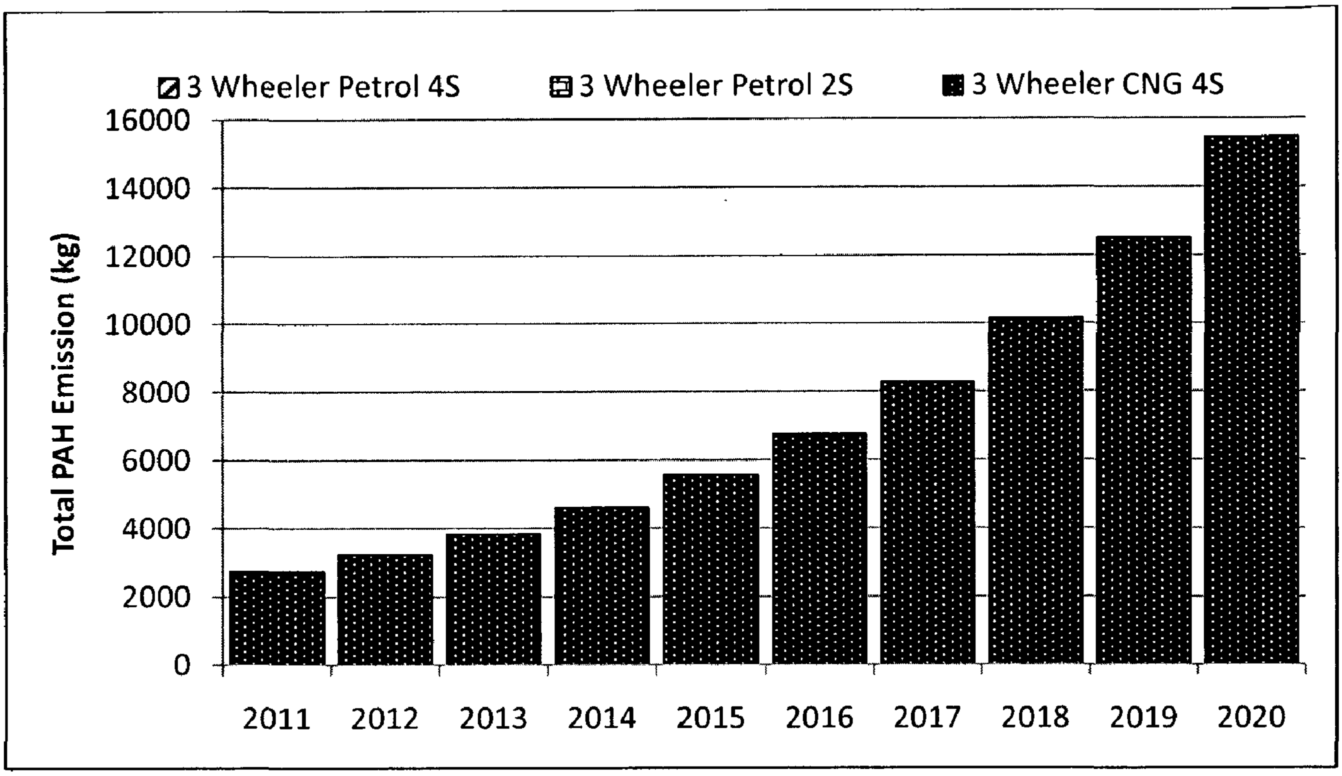


Fig. 6.84a: Total PAH emissions as per BAU scenario from three wheelers in megacity Delhi

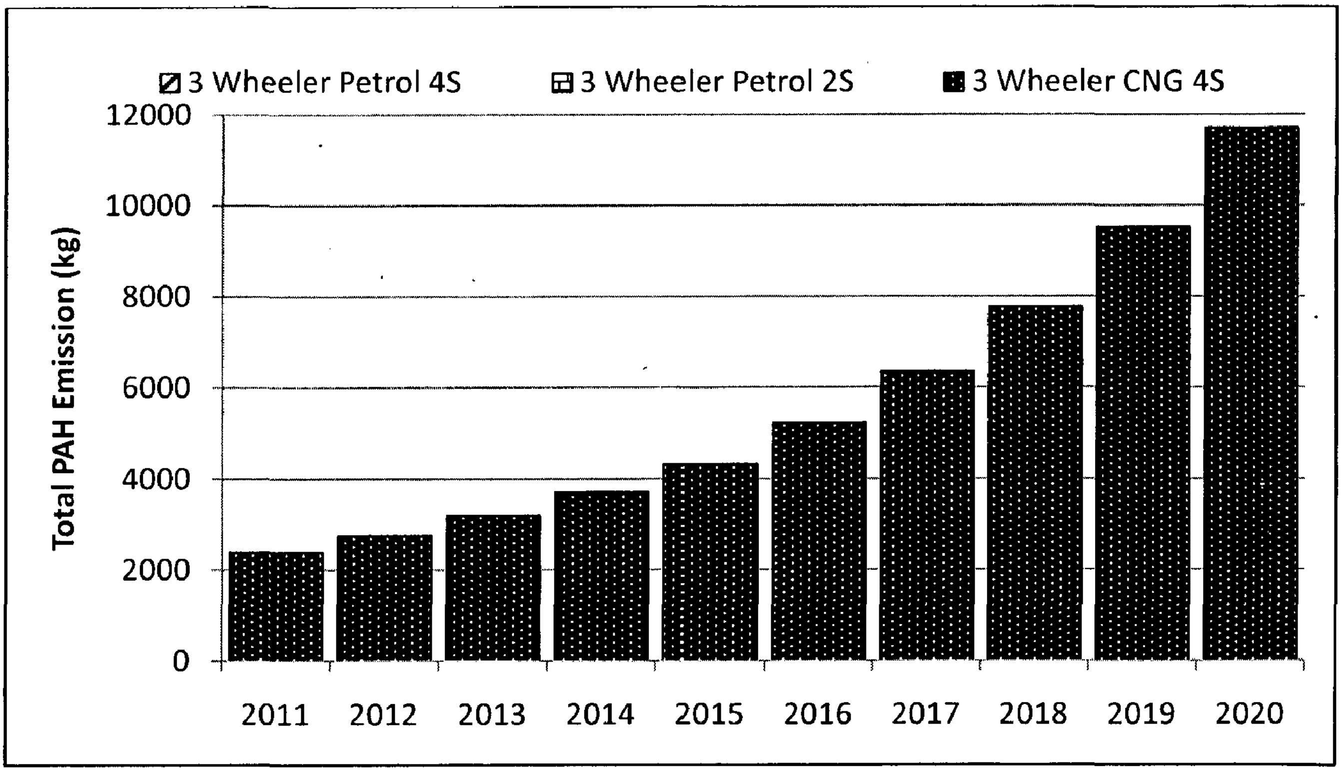


Fig. 6.84b: Total PAH emissions as per BES scenario from three wheelers in megacity Delhi

6.2.11.4. Taxis

Total PAH emissions from taxis in megacity Delhi during 2011 to 2020 for BAU and BES scenario are presented in Fig. 6.85 (a and b). Total PAH emissions (Fig. 6.85a) from taxis will be 53 kg in 2011, followed by 134 kg in 2015 and 507 kg in 2020. About 28.5% of annual average growth is projected in Total PAH emissions in BAU scenario during 2011 to 2015. Fig. 6.85b indicates that in 2011 Total PAH emission from taxis in BES scenario will be 49 kg, followed by 111 kg in 2015 and 395 kg in 2020. About 26% of annual average growth is expected in Total PAH emissions from 2011 to 2020 in BES scenario. Emission of Total PAH in BES scenario is 8% lower than BAU scenario in 2011, followed by 17.46% in 2015 and 22.13% in 2020.

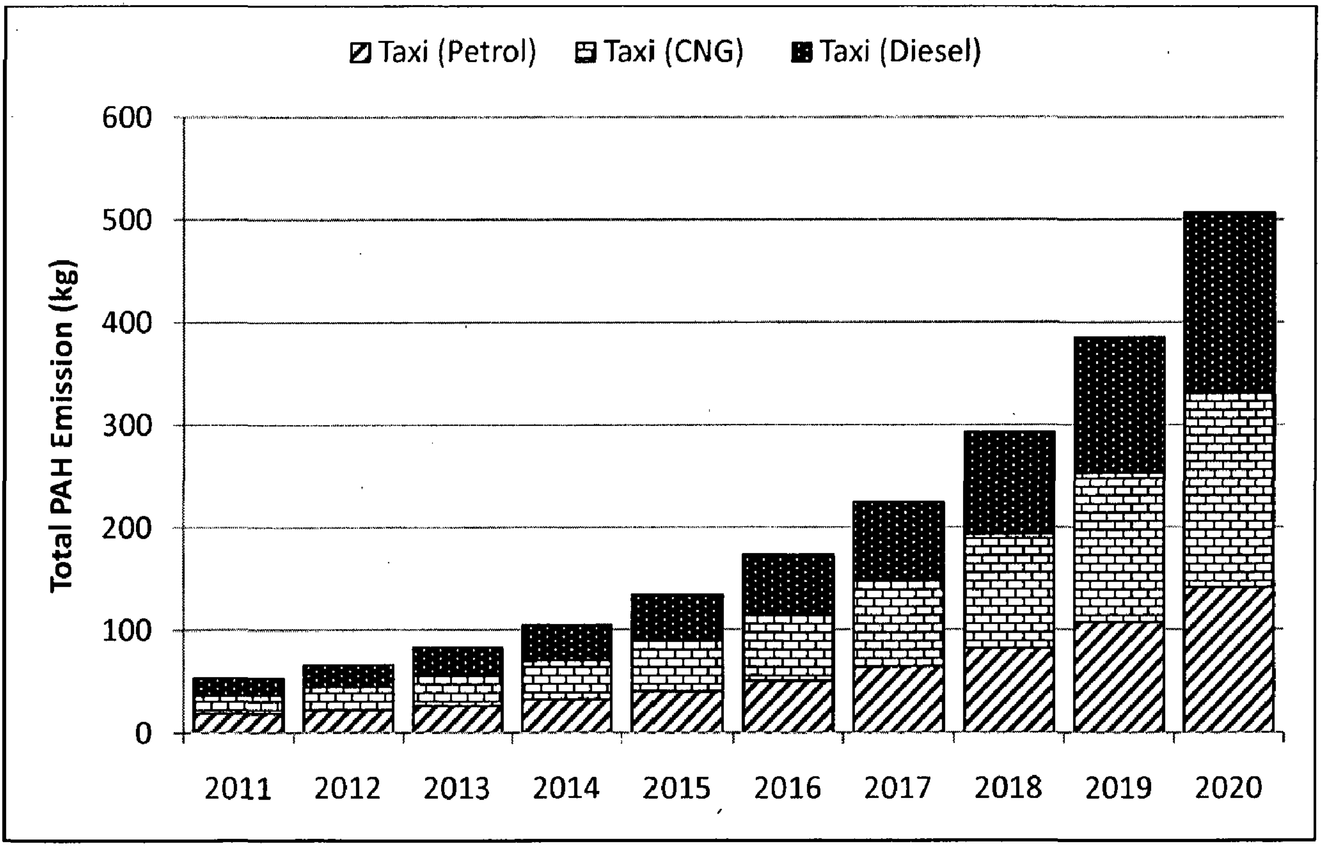


Fig. 6.85a: Total PAH emissions as per BAU scenario from taxis in megacity Delhi

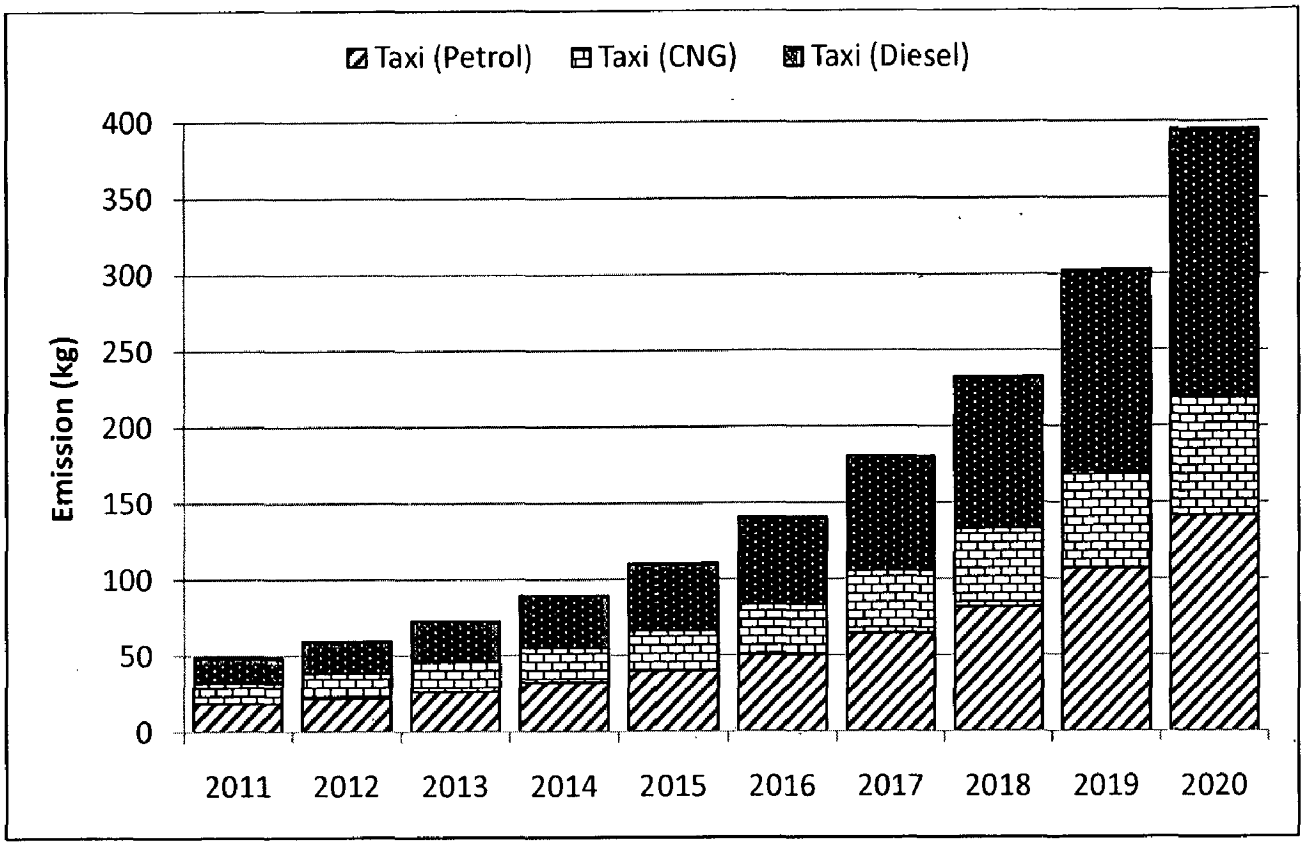


Fig. 6.85b: Total PAH emissions as per BES scenario from taxis in megacity Delhi

6.2.11.5. Bus/LCVs/HCVs

Fig. 6.86 shows the emission of Total PAH from diesel driven buses during 2011 to 2020. Estimated emissions of Total PAH from diesel driven buses will be 1675 kg in 2011, followed by 2157 kg in 2015 and 5054 kg in 2020. About 13.5% of annual average growth is found in Total PAH emissions from diesel driven buses between 2011 to 2020. Fig. 6.87 shows the emission of Total PAH from diesel driven LCVs during 2011 to 2020. In 2011 emission of Total PAH from diesel driven LCVs will be 11090 kg, followed by 12685 kg in 2015 and 16251 kg in 2020. About 4.4% of annual average growth is found in Total PAH emissions from diesel driven LCVs during 2011 to 2020. Emissions of Total PAH from HCVs are shown in Fig. 6.88. It indicates that in 2011 emissions of Total PAH will be 4924 kg, followed by 6819 kg in 2015 and 11507 kg in 2020. About 9.9% of annual average growth is found in Total PAH emissions from HCVs during 2011 to 2020.

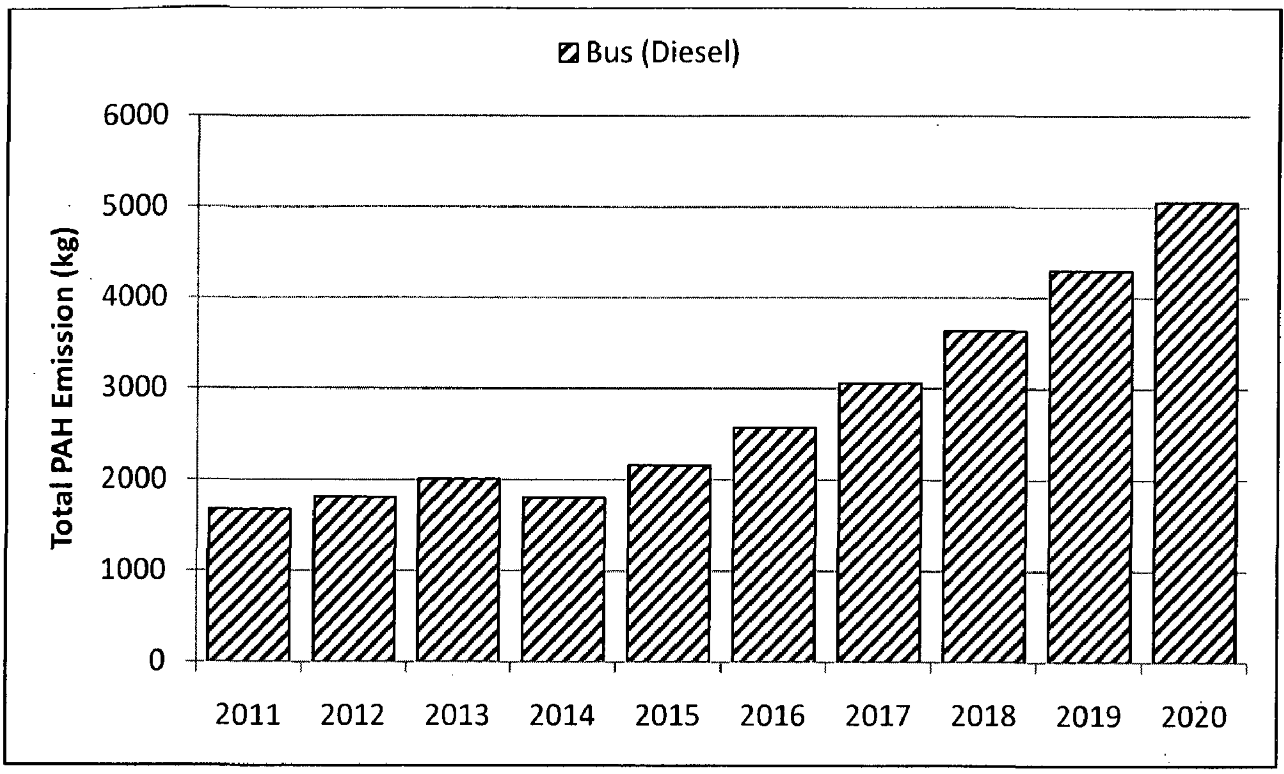


Fig. 6.86: Total PAH emissions as per BAU scenario from buses in megacity Delhi

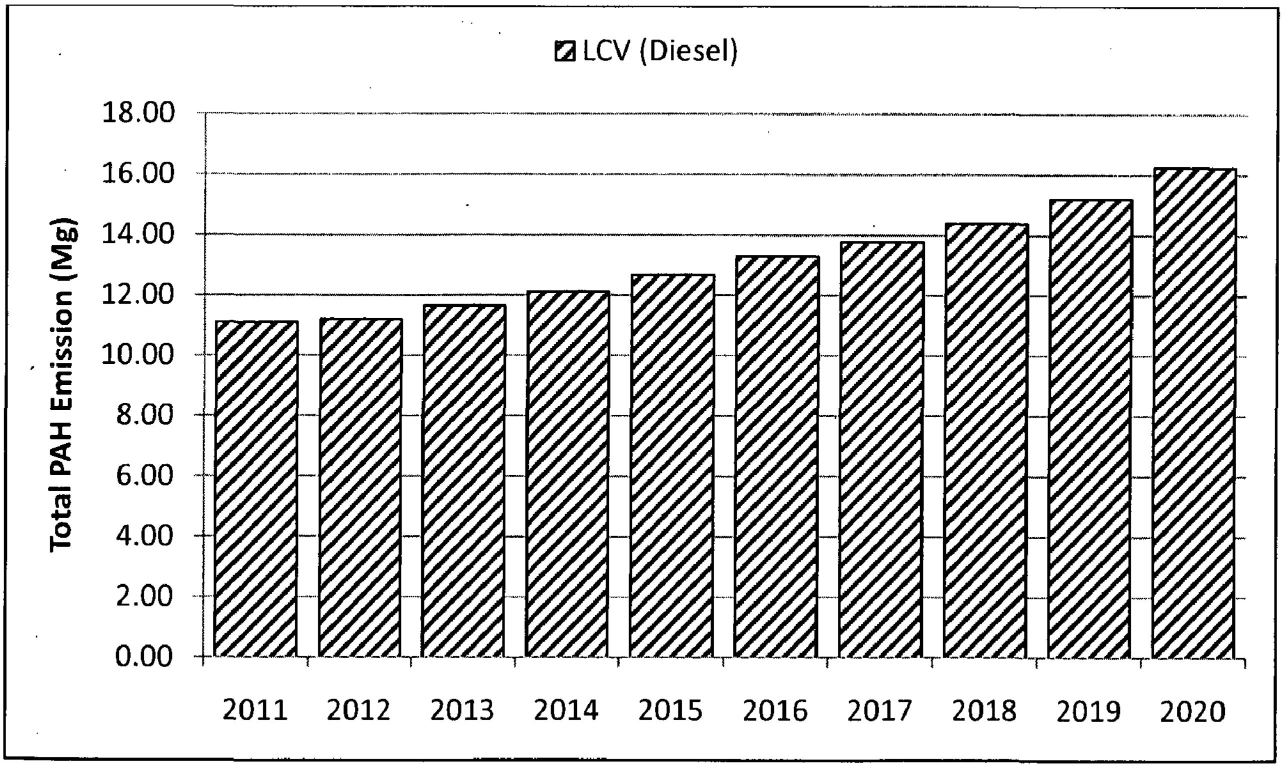


Fig. 6.87: Total PAH emissions as per BAU scenario from LCVs in megacity Delhi

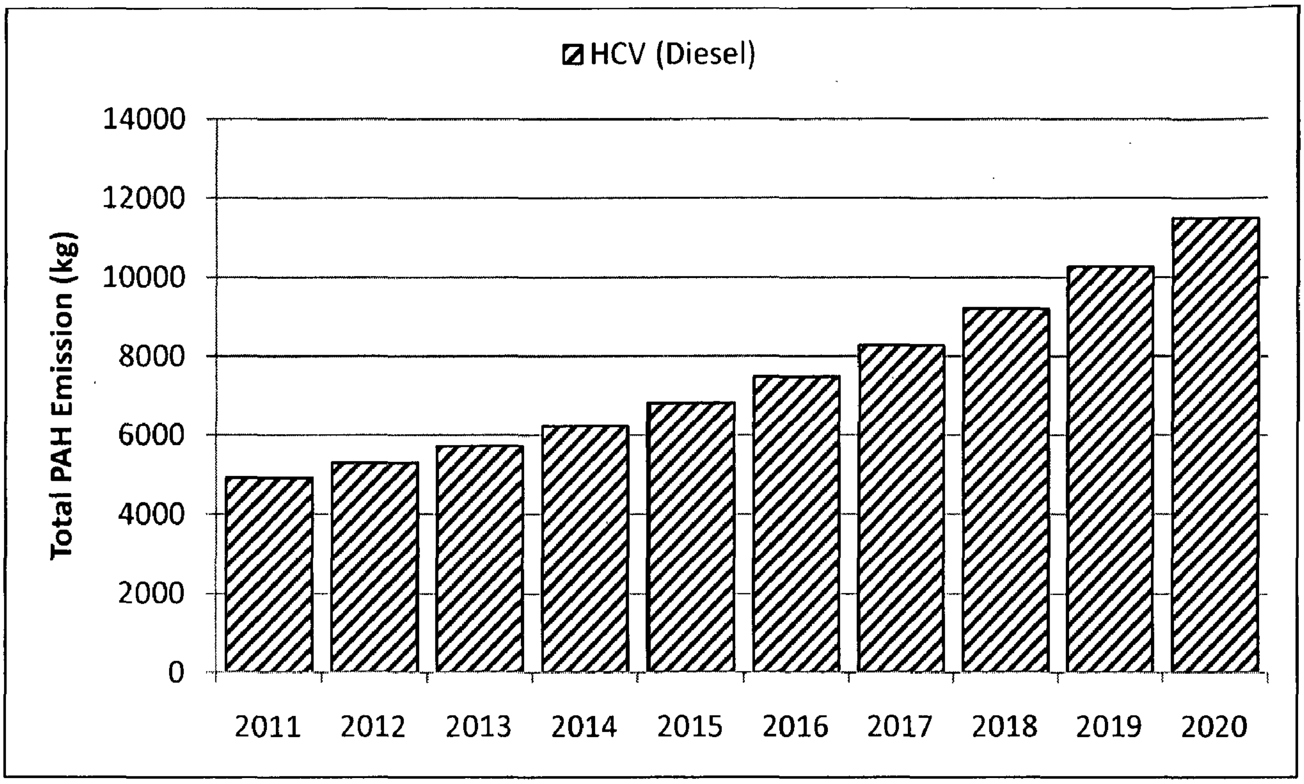


Fig. 6.88: Total PAH emissions as per BAU scenario from HCVs's in megacity Delhi

6.3. CONCLUSION

Emissions of eleven types of pollutants from various vehicle categories in BAU and BES scenarios have been estimated for future years (2011-2020). This has been observed that emission estimations for BAU scenario for all pollutants are higher than the corresponding estimates for BES scenario. For example, CO emissions in BAU scenario are 10-18% higher than BES scenario during 2011-2020. About 10-16% of difference is observed between BAU and BES scenario estimates for CO_2 emissions. This difference is ~7-13% for NO_x emissions and 11-18% in case of HC emissions. Highest difference has been found in taxis during 2011-2020. For PM in BAU emission is 5242 Mg in 2011 and in 2020 it is 9497 Mg, while in BES scenario it is 5018 Mg in 2011 and 8818 Mg in 2020. Emission of 1-3 Butadiene from BES scenarios is 3% less than BAU scenario in 2011, while in 2020 it is 11%. Acetaldehyde emission in BAU scenario is 10-20% higher than BES scenario during 2011 to 2020. In case of Benzene, emission in BAU scenario is 3990 kg in 2011 and 2252 kg in 2020 while in BES scenario these emissions are 3877 kg and 1836 kg, respectively. 10-19% of difference is observed between BAU and BES scenario for Formaldehyde emissions. Emission of Total Aldehyde from BAU scenario is 9-18% higher than BES scenario, while in case for total PAH this difference is 9-14%.

CHAPTER 7

Non-Exhaust Emissions from Vehicles in Megacity Delhi (1991-2010)

7.1. INTRODUCTION

Emissions from motor vehicles are divided into three categories: exhaust (tailpipe) emissions, non-exhaust (tier, break wear) emissions and evaporative (vapor) emissions. Exhaust emissions have been estimated and discussed in detail in Chapter 5 and Chapter 6. In the present chapter non-exhaust and evaporative emissions have been estimated for the period of 1991-2010 by using VAPI model for various vehicle categories in megacity Delhi. Due to possibility of similar future trend (because of same emission factors) non-exhaust emissions have been calculated for the year 1991 to 2010 only.

7.2. EVAPORATIVE EMISSION VOLATILE ORGANIC COMPOUNDS (VOCs)

Evaporative emissions are the result of gasoline vapors escaping from the vehicle's fuel system. These emissions are generally grouped into three categories namely: diurnal emissions, hot-soak emissions and running losses. Running losses are evaporative emissions that occur while a vehicle operates; this is caused by the generation of vapors from the fuel tank as the fuel is heated during driving (Westhuisen et al., 2004).

Fig.7.1 shows the evaporative emissions of VOCs from various vehicle categories in megacity Delhi. It indicates an increasing trend of VOCs from vehicles. In 1991 emissions of VOCs from vehicles are 516 Mg followed by 712 Mg in 1995 and 915 Mg in 2000. Throughout the study period VOC emissions from vehicles show a positive trend. Noticeable changes were observed in VOC emissions during 2002 (~47%) and 2005 (22%). In 2002 government of Delhi implemented CNG emission norms for all types of commercial vehicles, while in 2005 about 19000 new buses were included in megacity Delhi. Except during the years 2002 and 2005, VOC emissions from vehicles showed almost similar growth rate. Initially from 1991 to 2000 contribution of two wheelers was highest (50-55%), followed by cars (39-45%) and three wheelers (4-6%). During 2001 to 2004 cars emerged as the major contributors followed by two wheelers and buses, while after 2004 contribution of buses overtook cars and two wheelers.

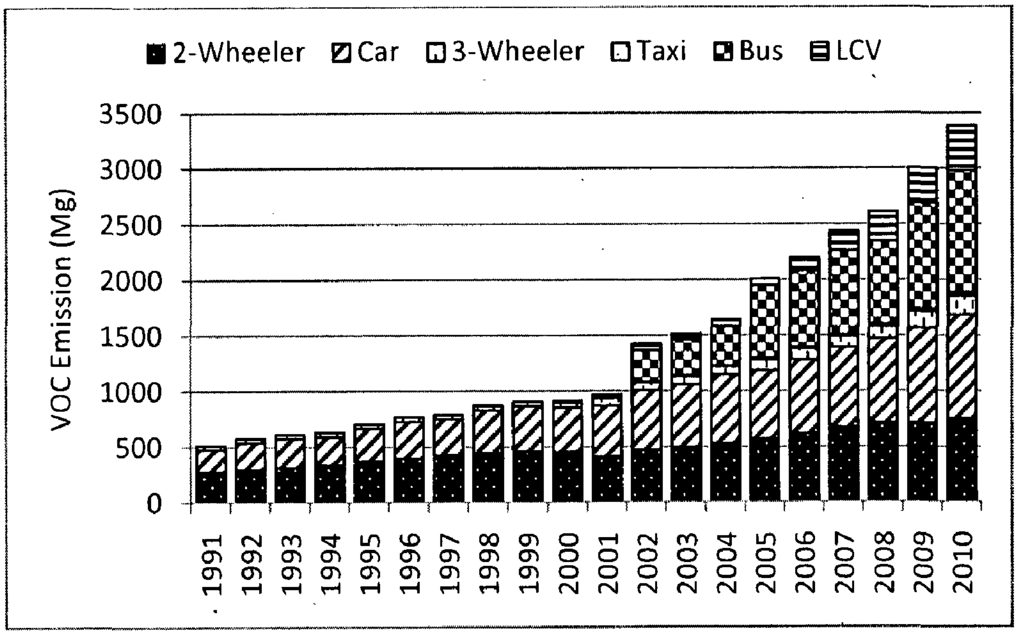


Fig.7.1: Evaporative emission from various vehicles in megacity Delhi

7.2.1. Two Wheelers

Evaporative emissions of VOCs from two wheelers in megacity Delhi have been shown in Fig. 7.2. About 282 Mg of VOCs were emitted by two wheelers in 1991 which became 373 Mg in 1995 in megacity Delhi. Initialy from 1991 to 1999 annual emission growth of VOCs evaporation ranged between 2.5 to 9%. In between 1999 and 2001 a declining trend has been observed, with 0.30% during 1999-2000, while 9.40% during 2000-2001. The decline observed during these years is due to decrease in on road vehicle population. After 2001 evaporative emissions of VOCs have been increasing continuously. In 2000 evaporative emissions of VOCs are 458 Mg, which became 571 Mg in 2005 and 753 Mg in 2010. With concern to contribution, share of two-stroke scooters was highest during 1991 to 2007, while after 2007 four-stroke motercycles emerged as the highest contributor. Two-stroke mopeds were the second largest contributor during 1991 to 1996, which were overtaken by two-stroke motorcycles during 1997 to 2006.

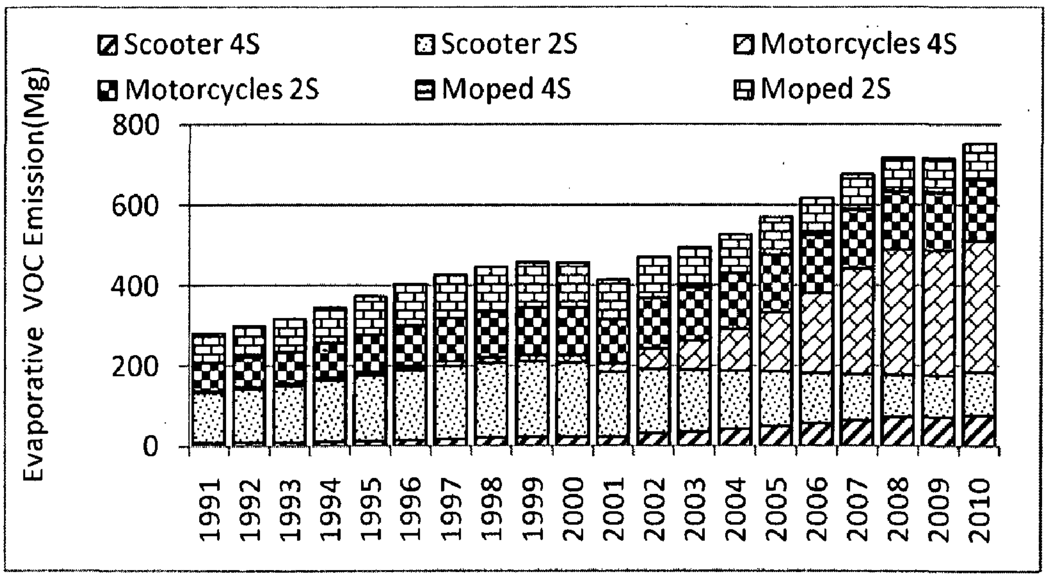


Fig. 7.2: Evaporative emissions from two wheeler population in megacity Delhi

7.2.2. Cars

Evaporative emissions from cars have been shown in Fig. 7.3, which are predominantly from petrol driven cars due to their large population. It indicates growing trend from 1991 to 2010 with 9% average annual growth rate. In 1991 evaporative emissions of VOCs from cars was ~200 Mg, followed by 297 Mg in 1995 and 398 Mg in 2000. Decrease in evaporative emissions of VOCs is observed during 1994, 1997, 2000 and 2005, which might be due to the reduction in on road population of cars during the respective years. In 2005 evaporative emissions of VOCs from car population was 614 Mg, followed by 932 Mg in 2010. Because of less population of CNG driven cars the contribution of CNG driven cars is lower.

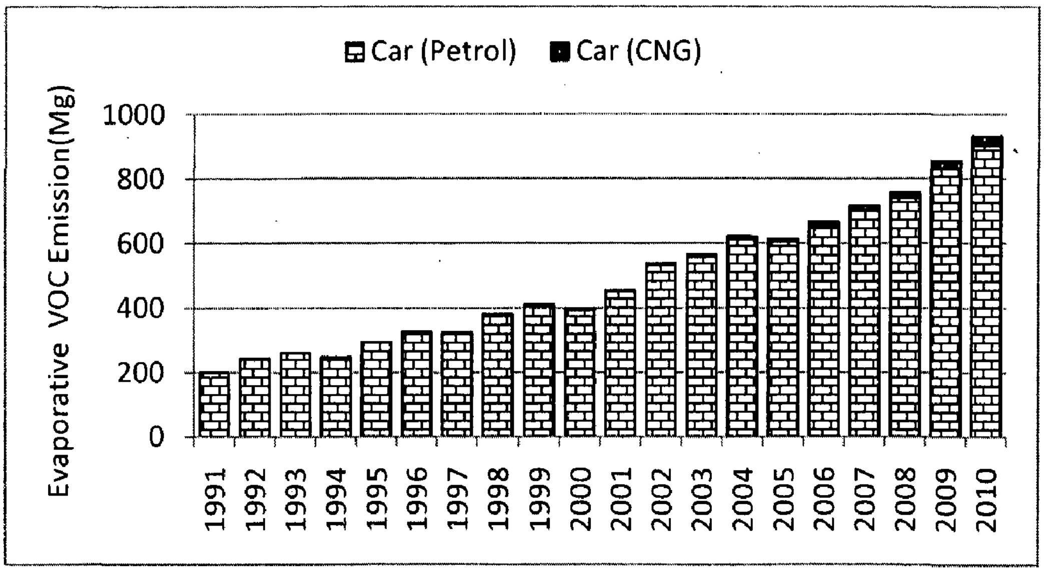


Fig. 7.3: Evaporative emissions from car population in megacity Delhi

7.2.3. Three Wheelers

Emissions of evaporative VOCs from three wheelers are shown in Fig. 7.4. Two different kinds of trends are observed in three-wheeler emissions from 1991 to 2000 and 2001 to 2010. From 1991 to 2000 emissions of evaporative VOCs show a stable trend because of constant population of on-road petrol driven three wheelers. Emissions are growing gradually because of increasing CNG driven three wheelers during 2001 to 2010. In 1991 evaporative emission of VOCs from three wheelers was ~33 Mg and in 1995 it became ~40 Mg, followed by ~46 Mg in 2000. From 1991 to 1999 almost all VOC evaporative emissions are released by petrol driven three-stroke and four-stroke three wheelers, while after 2000 most of the evaporative VOCs are emitted by four-stroke CNG driven three wheelers because of their dominancy in total population. In 2005, emission of VOCs from three-wheeler population is 100 Mg followed by 173 Mg in 2010.

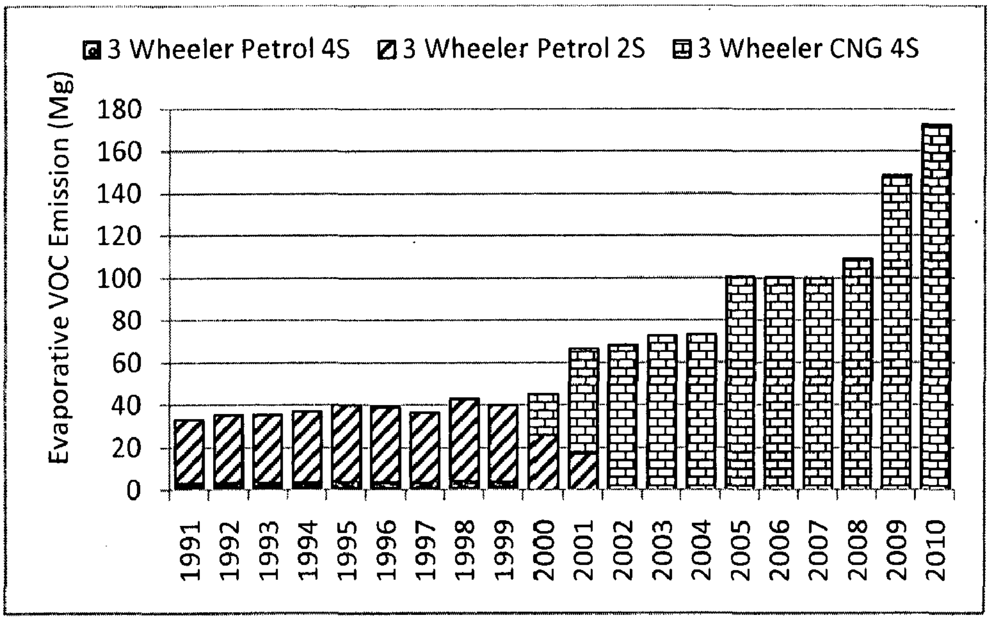


Fig.7.4: Evaporative emission from three wheelers in megacity Delhi

7.2.4. Taxis

Fig. 7.5 shows the emissions of evaporative VOCs from taxis in megacity Delhi during 1991 to 2010. During most of the study period, VOC emissions from taxis follow a positive trend with a sharp increase (30%) from 2002-2010. Initially VOC emissions were 1.2 Mg in 1991 and with 21% growth rate it became 1.4 Mg in 1992. In 1995 emissions of VOC from taxis was 1.6 Mg, followed by about 2 Mg in 2000, 10 Mg in 2005 and 30 Mg in 2010. Highest growth in VOC emissions from taxis is found in the year 2002 because of CNG implementation.

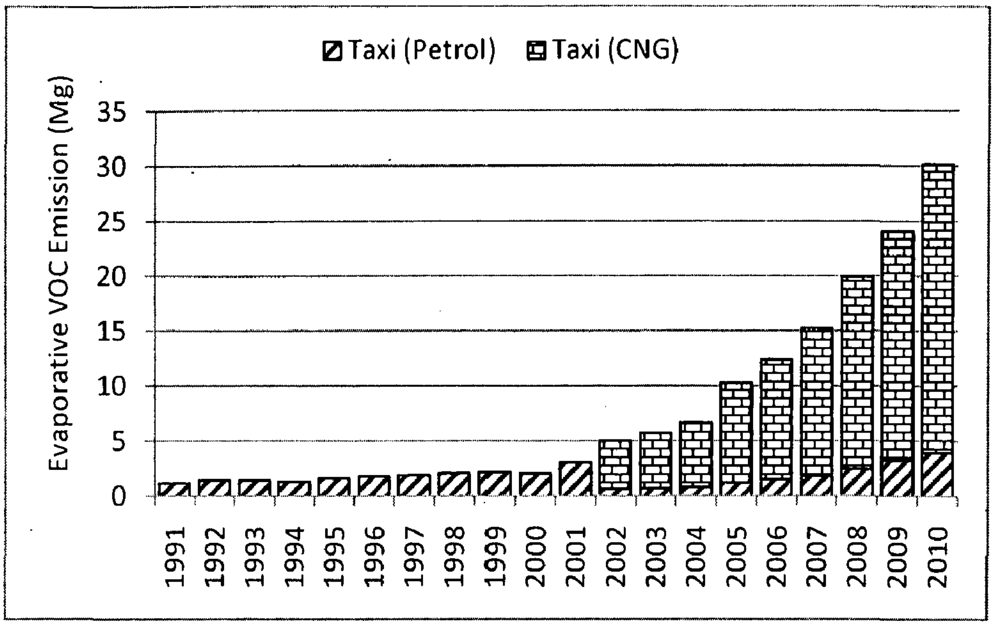


Fig.7.5: Evaporative emissions from taxi population in megacity Delhi

7.2.5. Buses

No evaporative emissions of VOC are observed until 2000 because of diesel driven buses. This is because hot soak emissions only applies to gasoline-fueled and CNG engines; diesel engines are assumed to have no significant evaporative emissions due to the very low volatility of diesel fuel compared to gasoline and CNG (USEPA, 1998) . From 2001 government of Delhi implemented CNG norms for commercial vehicles including buses. In 2002 emissions of VOCs from buses were about 287 Mg, while in 2004 it was 356 Mg. Between 2004 and 2005 higher increment was observed because in 2005 about 19000 new buses were added in public bus fleet in New Delhi. Similar increment was observed between 2008 and 2009 because of increased vehicle population in 2009. In 2005 evaporative emissions of VOCs from buses was 653 Mg followed by 1094 Mg in 2010. Overall growth of about 20% was in VOC evaporative emissions during 2002-2010.

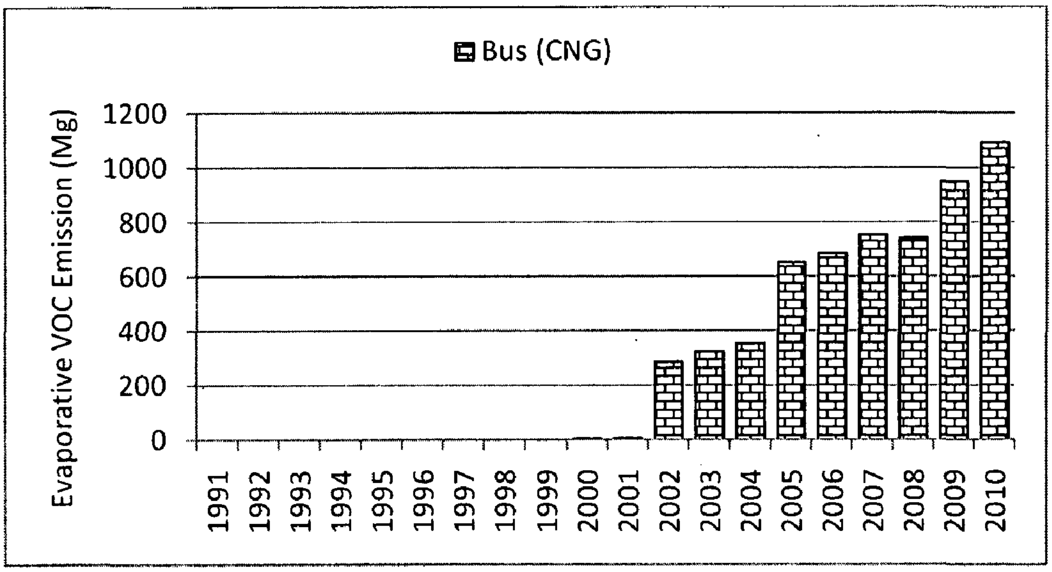


Fig. 7.6: Evaporative emissions from bus population in megacity Delhi

7.2.6. LCVs

Initially there were no mandatory CNG norms for LCVs in megacity Delhi, while in 2006 government implemented CNG norms for newly registered LCVs (IGL, 2009b). In 2000 emissions of VOCs from LCVs through evaporation was about 8 Mg and in 2005 it was 62 Mg (Fig. 7.7). In 2006, emission of VOC sharply increased to 112 Mg because of compulsory CNG implementation for LCVs in 2006. In 2010 emissions became 404 Mg. After 2005 until 2010 an average growth of ~40% in evaporative emissions from LCVs is observed because of continuous increase in CNG driven LCVs population in megacity Delhi.

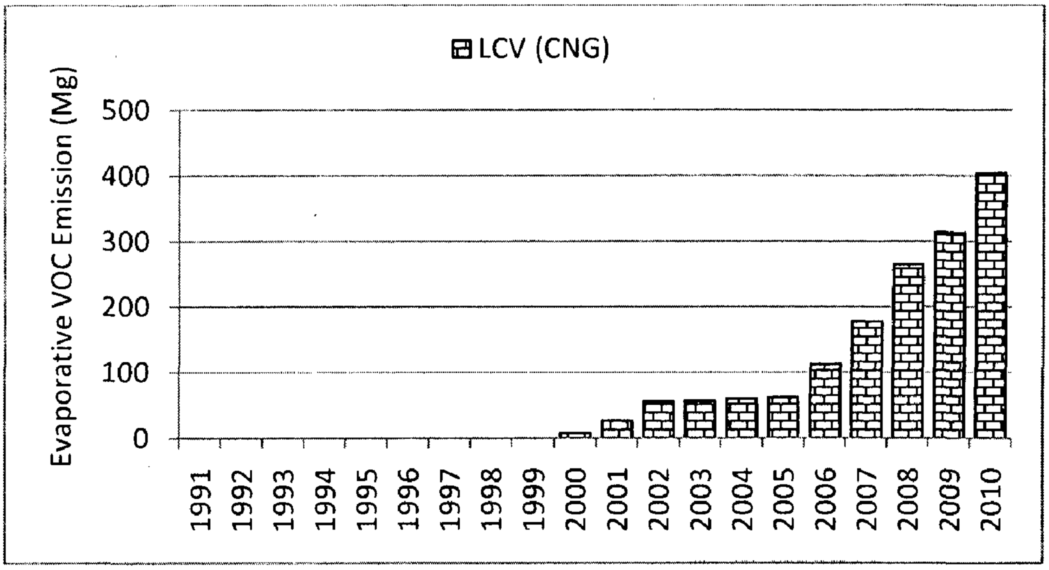


Fig. 7.7: Evaporative emissions from LCVs population in megacity Delhi

7.3. EMISSIONS FROM ROAD DUST SUSPENSION (PM10/PM2.5)

Similar trend is observed in emissions of PM10 and PM2.5 from road dust suspension by various categories of vehicles in megacity Delhi. In 1991 emission of PM10 from road dust suspension was 4403 Mg, while in 1995 it was 5877 Mg, followed by 7479 Mg in 2000, 10458 Mg in 2005 and 16645 Mg in 2010 (Fig. 7.8a). In case of PM2.5, in 1991 emission was 170 Mg, followed by 227 Mg in 1995, 289 Mg in 2000, 404 Mg in 2005 and 642 Mg in 2010 (Fig. 7.8b). Emissions of PM10 and PM2.5 from road dust suspension is increasing annually from 1991 to 2010 with an average growth rate of 7.36% except a slight decrease during 2001 and 2002 due to phasing out old age vehicle population.

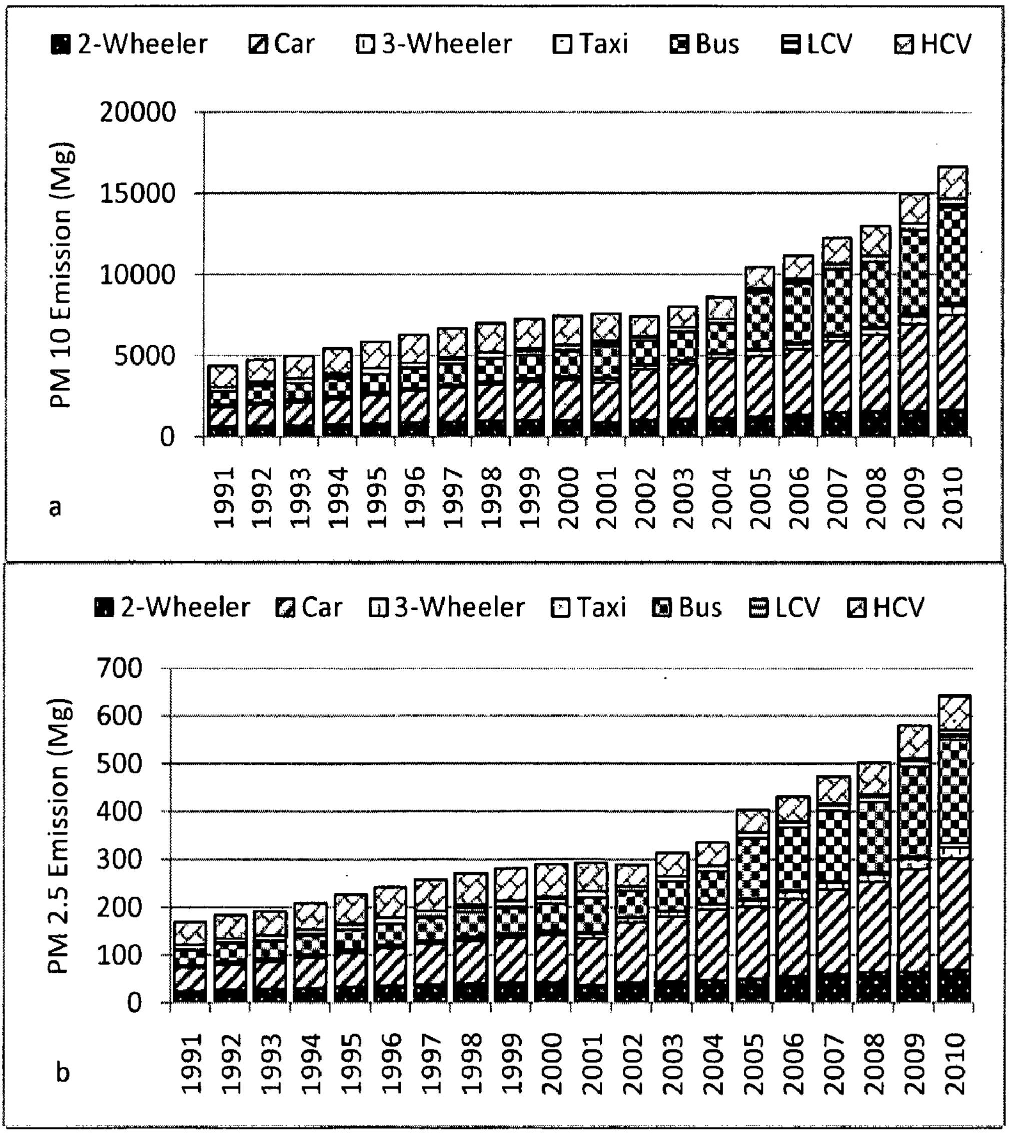


Fig.7.8: Emission of (a) PM10 and (b) PM2.5 from road dust suspension by various vehicles in megacity Delhi

7.3.1. Two Wheelers

Emissions of PM10 and PM2.5 from road dust suspension due to two wheelers is given in Fig. 7.9 (a and b). Fig. 7.9(a) indicates that in 1991 emission of PM10 from road dust suspension by two wheelers was about 635 Mg, followed by 842 Mg in 1995, 1030 Mg in 2000, 1285 Mg in 2005 and 1696 Mg in 2010. In case of PM2.5 emission in 1991 was 26 Mg, while in 1995 it was 34 Mg, followed by 52 Mg in 2000 and 2005, and 68 Mg in 2010. Initially contribution of two-stroke scooters was highest for PM10 and PM2.5 emissions, while from 2005 four-stroke motorcycles emerged as the highest contributor.

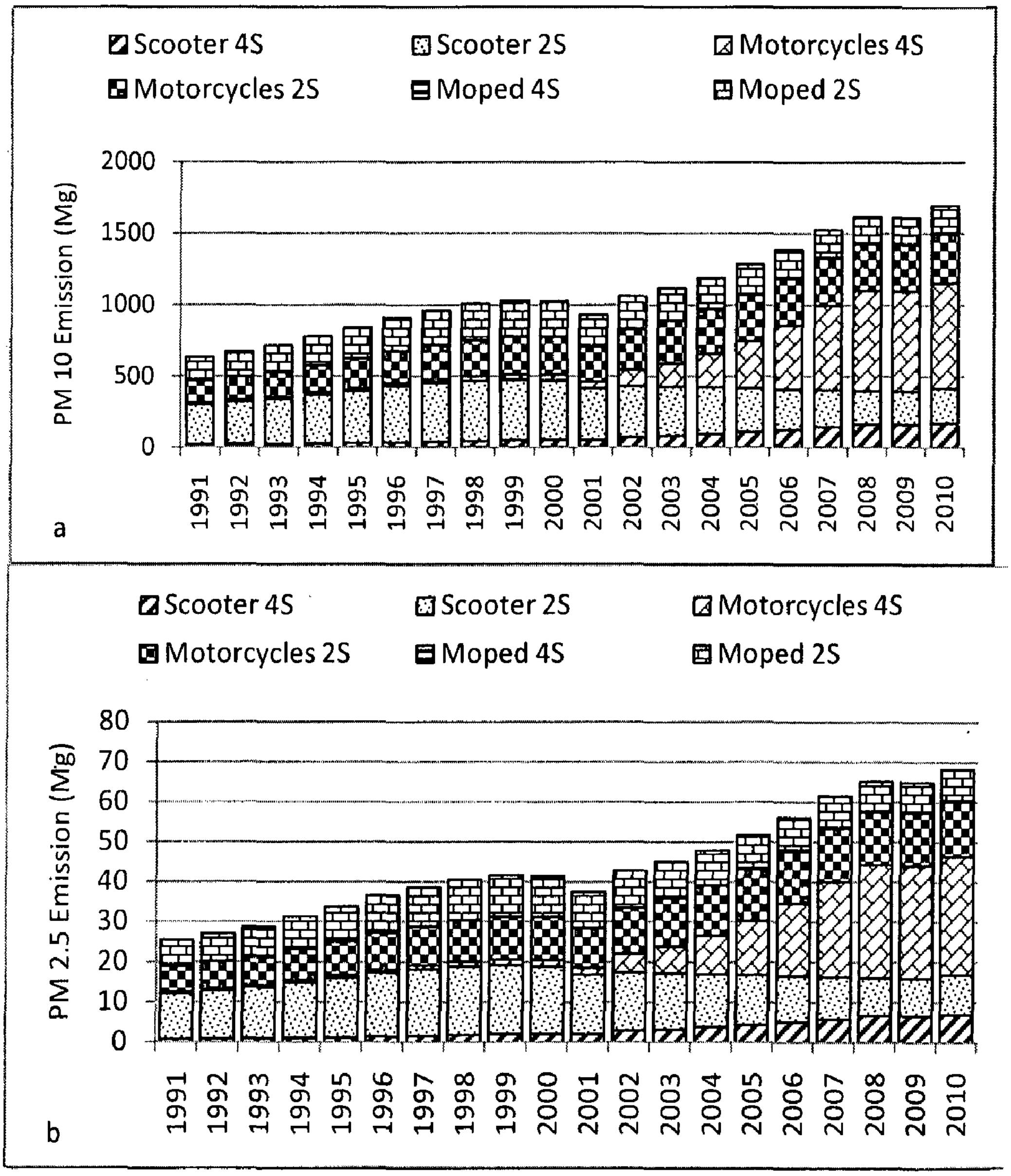


Fig.7.9: Emission of (a) PM10 and (b) PM2.5 from road dust suspension by two wheelers in megacity Delhi

7.3.2. Cars

Emissions of road dust suspension by cars population during 1991 to 2010 in megacity Delhi are shown in Fig. 7.10 (a and b). In 1991 emission of PM10 from road dust suspension by cars was 1203 Mg, followed by 1737 Mg in 1995, 2498 Mg in 2000, 3709 Mg in 2005 and 5804 Mg in 2010. Following similar trends, emissions of PM2.5 from road dust suspension by cars were 49 Mg, while in 1995 it was 70 Mg, 101 Mg in 2000, 150 Mg in 2005 and 235 Mg in 2010.

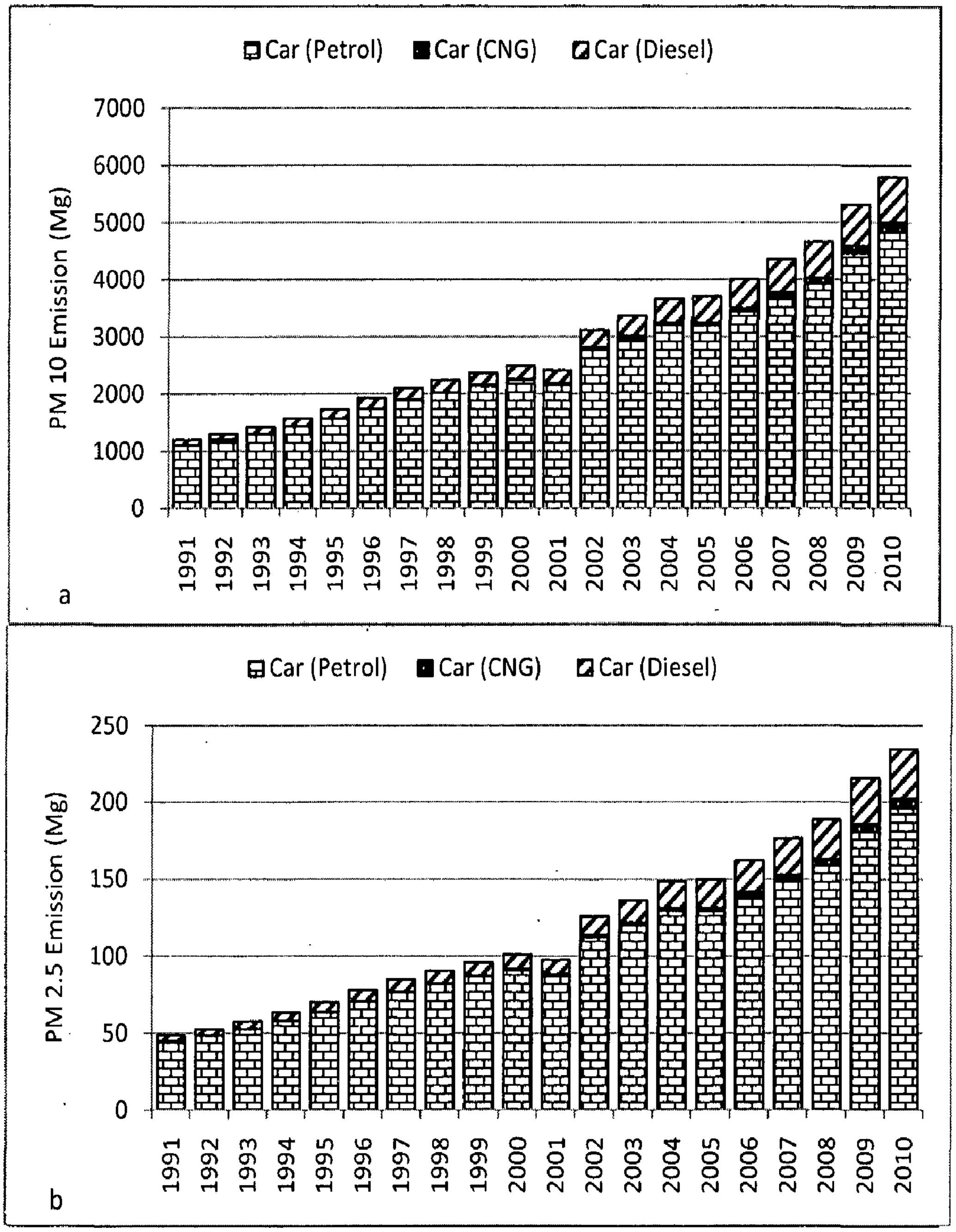


Fig.7.10: Emission of (a) PM10 and (b) PM2.5 from road dust suspension by car population in megacity Delhi

7.3.3. Three Wheelers

Fig. 7.11 (a and b) shows the emission of PM10 and PM2.5 from road dust suspension by three wheelers in megacity Delhi. A sudden growth in emission was observed in year 2001, 2005 and 2009 because of the entry of new three wheelers in respective years. In 1991 PM10 emission from road dust suspension by three wheelers was 112 Mg, followed by 135 Mg in 1995, 153 Mg in 2000, 338 Mg in 2005 and 581 Mg in 2010. Similarly emission of PM2.5 was 4.6 Mg in 1991, followed by 5.5 Mg in 1995, 6.3 Mg in 2000, 13.8 Mg in 2005 and 23.8 Mg in 2010. During initial half of the total period two-stroke petrol driven three wheelers had the dominant share in emissions whereas in later half these were almost entirely from four-stroke CNG driven three wheelers.

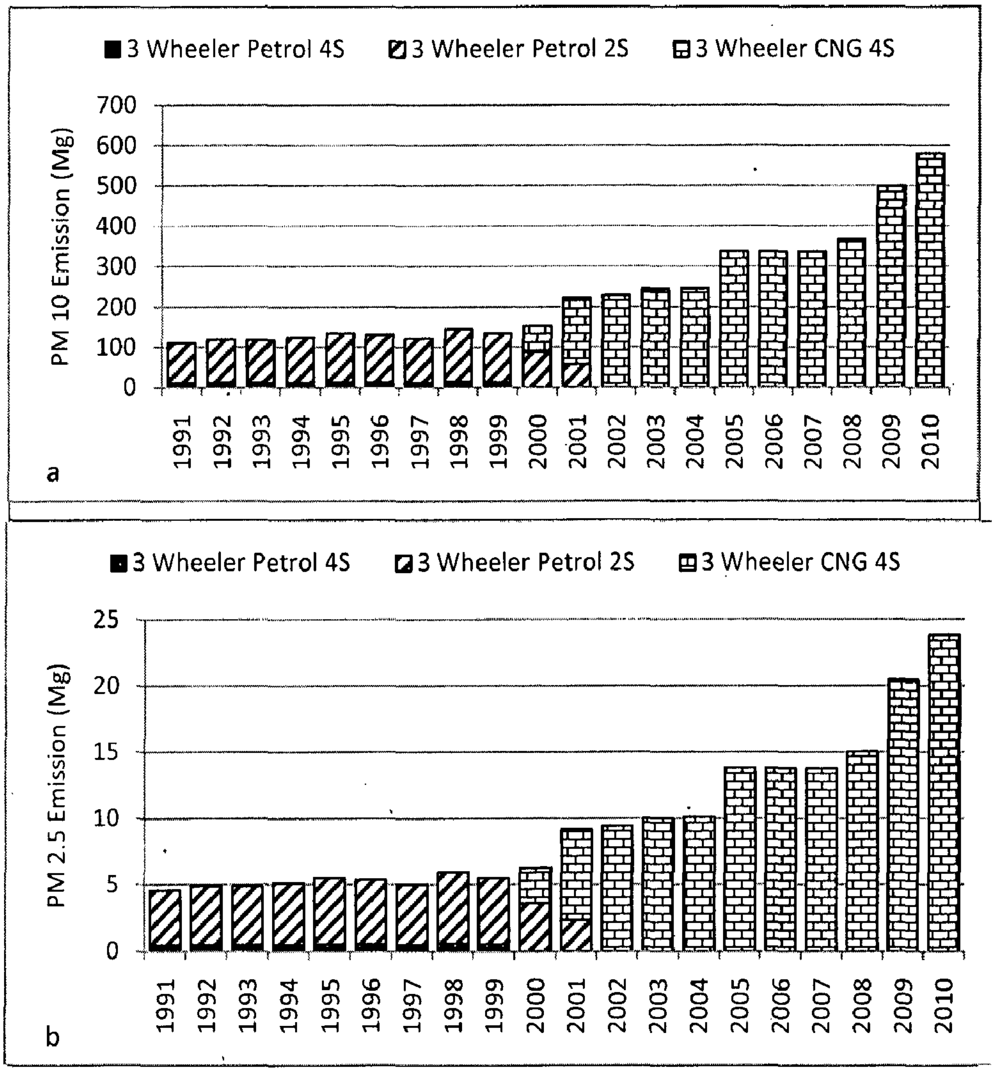


Fig.7.11: Emission of (a) PM10 and (b) PM2.5 from road dust suspension by three wheelers in megacity Delhi

7.3.4. Taxis

Emissions of PM10 and PM2.5 from road dust suspension by taxis in megacity Delhi is given in Fig. 7.12 (a and b). From 1991 to 2001 emission of PM10 and PM2.5 showed almost similar positive trend, while between 2001 and 2002 sudden decrease in emission was observed because of phasing out of old age commercial vehicles in 2002. In 1991 emission of PM10 from road dust suspension by taxis was 33 Mg, followed by 44 Mg in 1995, 59 Mg in 2000, 66 Mg in 2005 and 183 Mg in 2010. Emission of PM2.5 from road dust suspension by taxis in 1991 was 1.3 Mg, followed by 1.8 Mg in 1995, 2.4 Mg in 2000, 2.7 Mg in 2005, 7.4 Mg in 2010. Since 1991 to 2001 the emissions of PM10 and PM2.5 from road dust suspension by taxis in megacity Delhi increased steadily but after a sharp decline between 2001-2002 the emissions increased rapidly from 2002-2010 following the fast annual average growth rate (23%) in population of taxis.

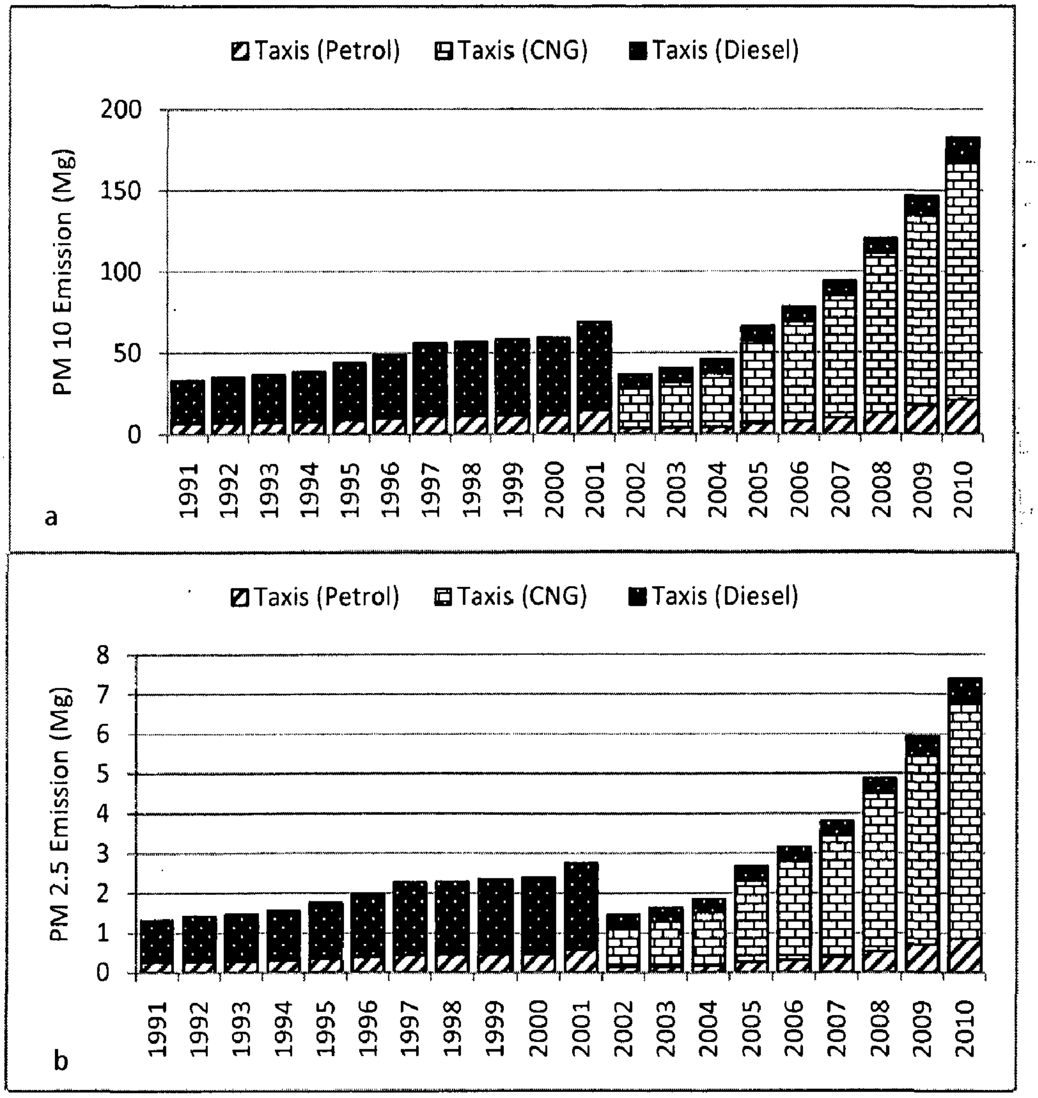


Fig.7.12: Emission of (a) PM10 and (b) PM2.5 from road dust suspension by taxis in megacity Delhi

7.3.5. Buses

Emissions of PM10 and PM2.5 from road dust suspension by buses in megacity Delhi are shown in Fig. 7.13 (a-b). It indicates that from 1991 to 2001 emission was going with positive growth rate while it suddenly decreased in year 2002 because of phasing out program for commercial vehicles in 2001 and 2002. Sudden growth between 2004 and 2005, 2008 and 2009 was observed because of increased entry of new buses in megacity Delhi. In 1991 emission of PM10 from road dust suspension by bus population was 849 Mg, followed by 1140 Mg in 1995, 1541 Mg in 2000, 3486 Mg in 2005 and 5914 Mg in 2010. Similarly emission of PM2.5 was 31 Mg in 1991, 42 Mg in 1995, 56 Mg in 2000, 127 Mg in 2005 and 216 Mg in 2010.

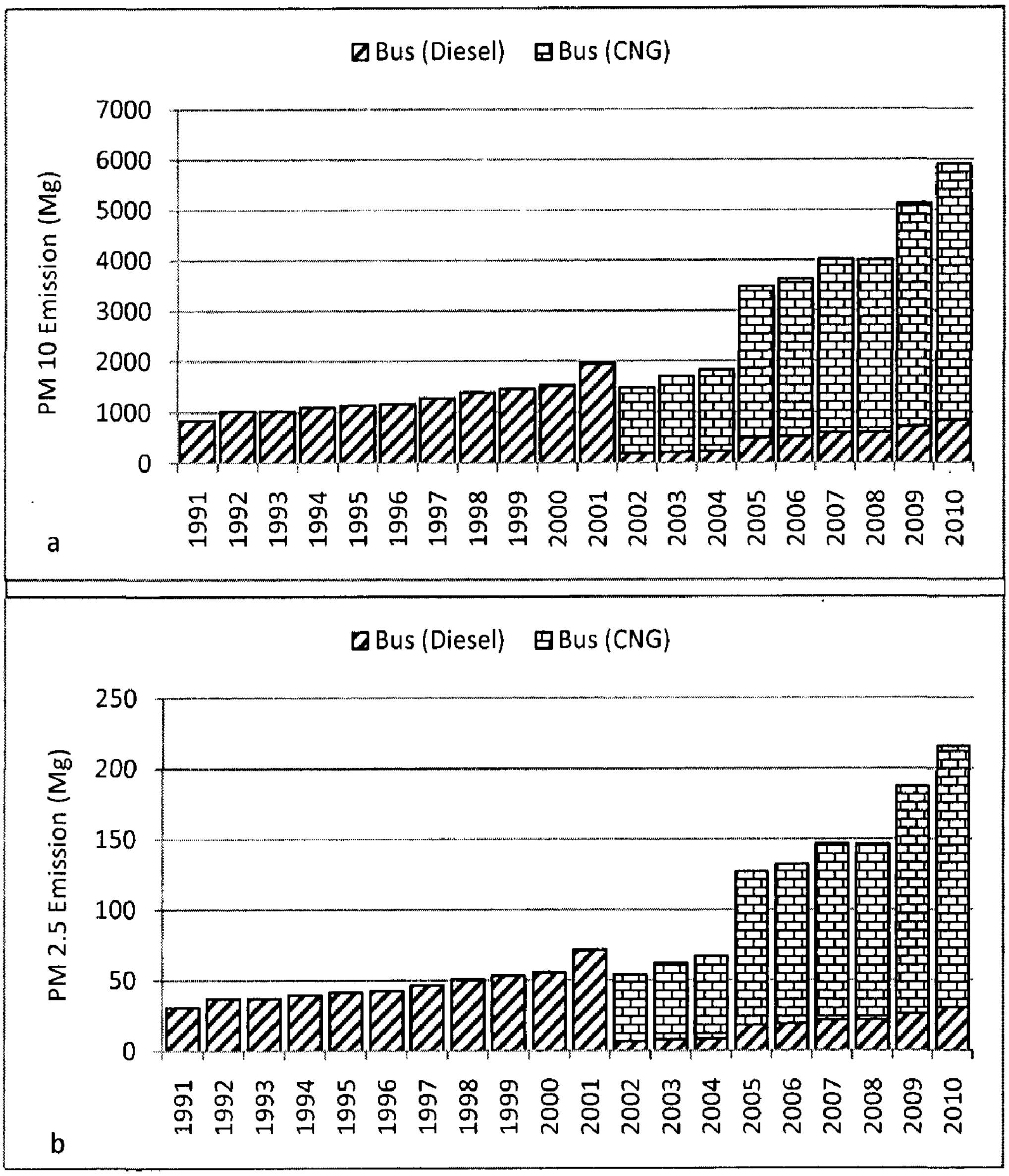


Fig.7.13: Emission of (a) PM10 and (b) PM2.5 from road dust suspension by bus population in megacity Delhi

7.3.6. LCVs

PM10 and PM2.5 emissions from LCVs due to road dust suspension are given in Fig. 7.14 (a and b). Similar to other vehicles emission of PM10 and PM2.5 it also shows increasing growth rate from 1991 to 1999. After 1999 emission of PM10 and PM2.5 started to decrease till 2001 because of phasing out program by Delhi government. In 1991, emission of PM10 from road dust suspension of LCVs was 270 Mg in 1991, followed by 340 Mg in 1995, 377 Mg in 2000, 273 Mg in 2005 and 497 Mg in 2010. Emission of PM2.5 from road dust suspension by LCVs was 11 Mg in 1991, followed by 14 Mg in 1995, 15 Mg in 2000, 11 Mg in 2005 and 20 Mg in 2010.

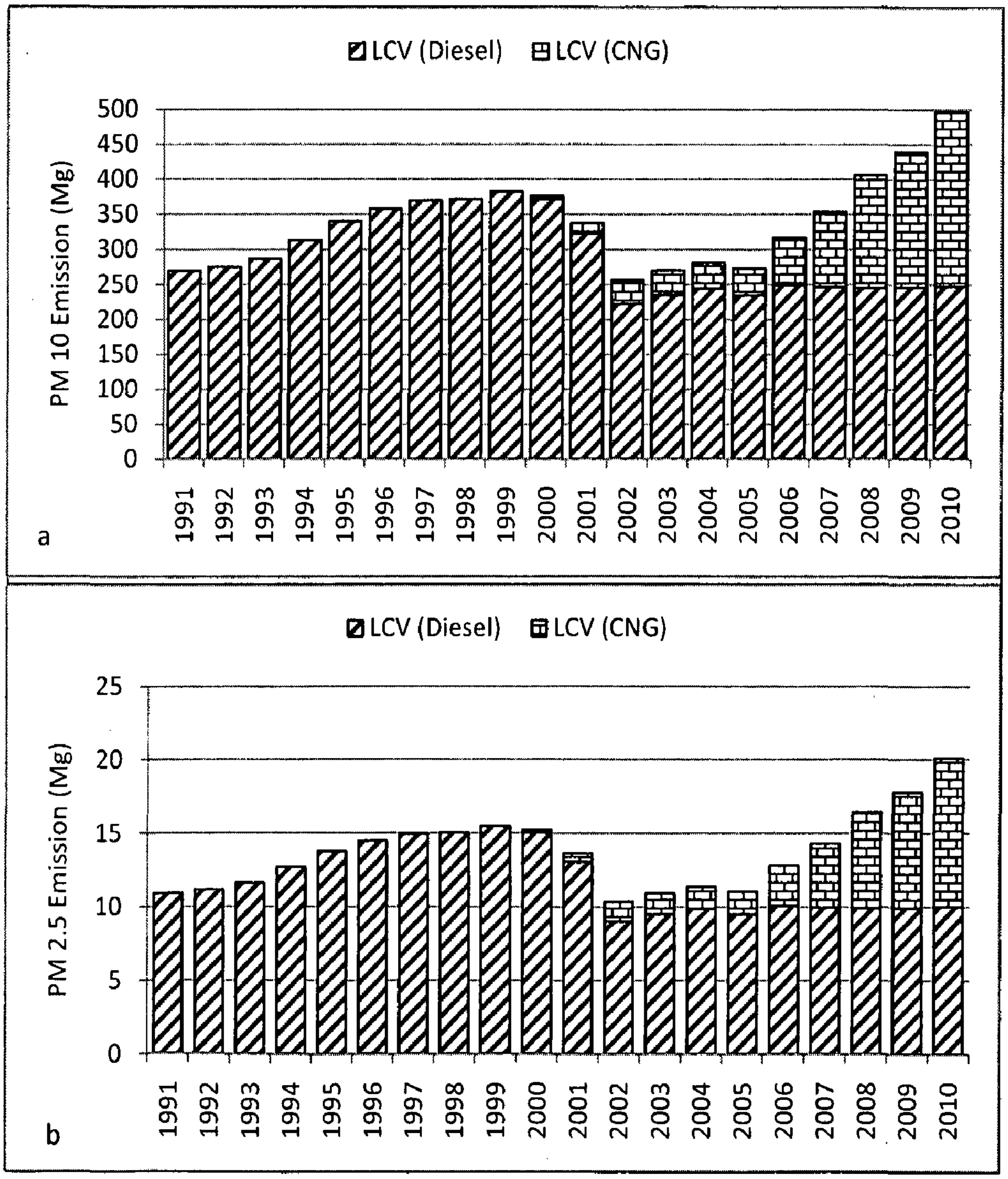


Fig.7.14: Emission of (a) PM10 and (b) PM2.5 from road dust suspension by LCVs population in megacity Delhi

7.3.7. HCVs

Road dust suspension emissions of HCVs are given in Fig. 7.15 (a and b). Figures indicate that from 1991 to 1999 emissions showed a gradual growth, while after 1999 decrease was observed till 2002, thereafter emissions had increasing trend till 2010. In 1991, emission of PM10 from road dust suspension by HCVs was 1301 Mg, followed by 1640 Mg in 1995, 1821 Mg in 2000, 1300 Mg in 2005 and 1971 Mg in 2010. Emission of PM2.5 from road dust suspension by HCVs was 47 Mg in 1991, 60 Mg in 1995, followed by 66 Mg in 2000, 47 Mg in 2005 and 72 Mg in 2010.

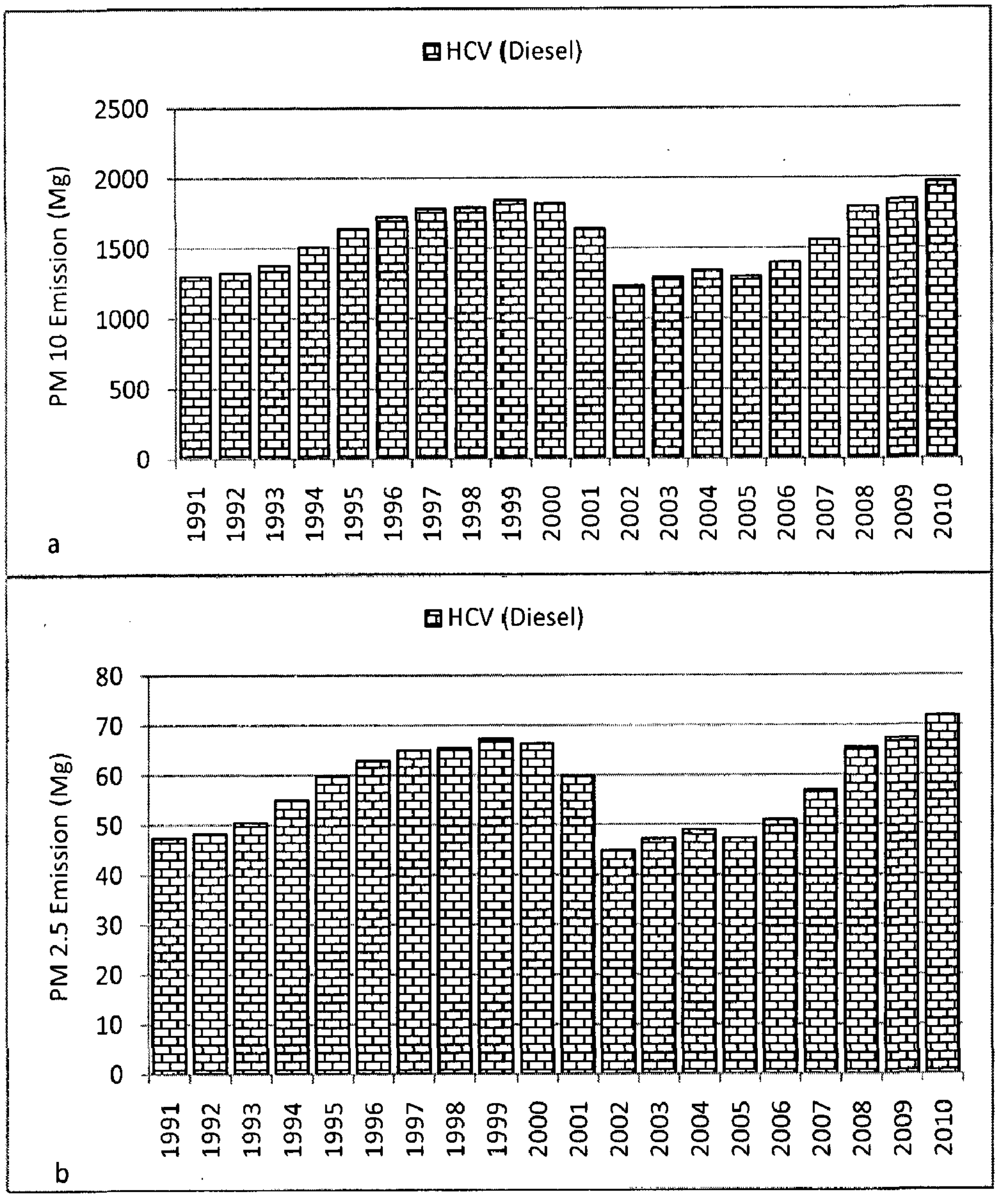


Fig.7.15: Emission of (a) PM10 and (b) PM2.5 from road dust suspension by HCVs population in megacity Delhi

7.4. PM10 AND PM2.5 EMISSIONS FROM TYRE WEARS

Emissions of PM10 and PM2.5 from tyre wear of various vehicles during 1991 to 2010 has been given in Fig. 7.16 (a and b). The trend of emissions in both figures show positive growth rate from 1991 to 2010. Minute change in emission was observed in 2001 because of phasing out program by government of Delhi. In 1991 emission of PM10 from tires of various vehicles was 90 Mg, followed by 122 Mg in 1995, 161 Mg in 2000, 222 Mg in 2005 and 346 Mg in 2010. Similarly, emission of PM2.5 was 23 Mg in 1991, 31 Mg in 1995, 41 Mg in 2000, 56 Mg in 2005 and 88 Mg in 2010.

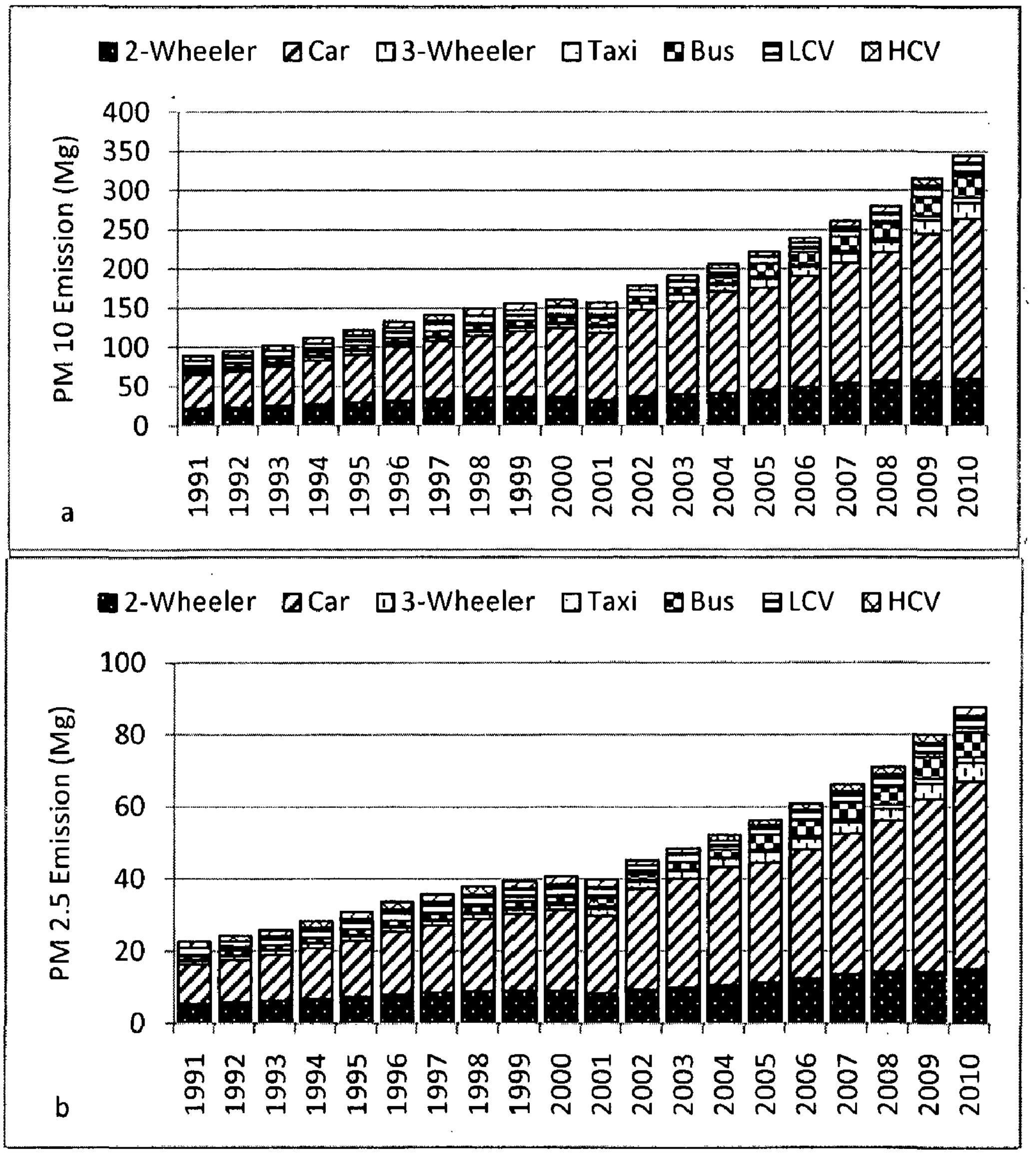


Fig.7.16: Emission of (a) PM10 and (b) PM2.5 from various vehicles tyre wears in megacity Delhi

7.4.1. Two Wheelers

In 1991 emissions of PM10 from tire wears of two wheelers were about 23 Mg, followed by 30 Mg in 1995, 37 Mg in 2000, 46 Mg in 2005 and 61 Mg in 2010 (Fig. 7.17a) . Similarly emissions of PM2.5 from tire wears of two wheelers were 6 Mg in 1991, followed by 8 Mg in 1995, 9 Mg in 2000, 12 Mg in 2005 and 15 Mg in 2010 (Fig. 7.17b). The reason of quite similar trend in PM10 and PM2.5 is increasing population of two wheelers with similar growth rate. Following their share in population, there is a gradual shift from two-stroke scooters to four-stroke motorcycles to cause these emissions.

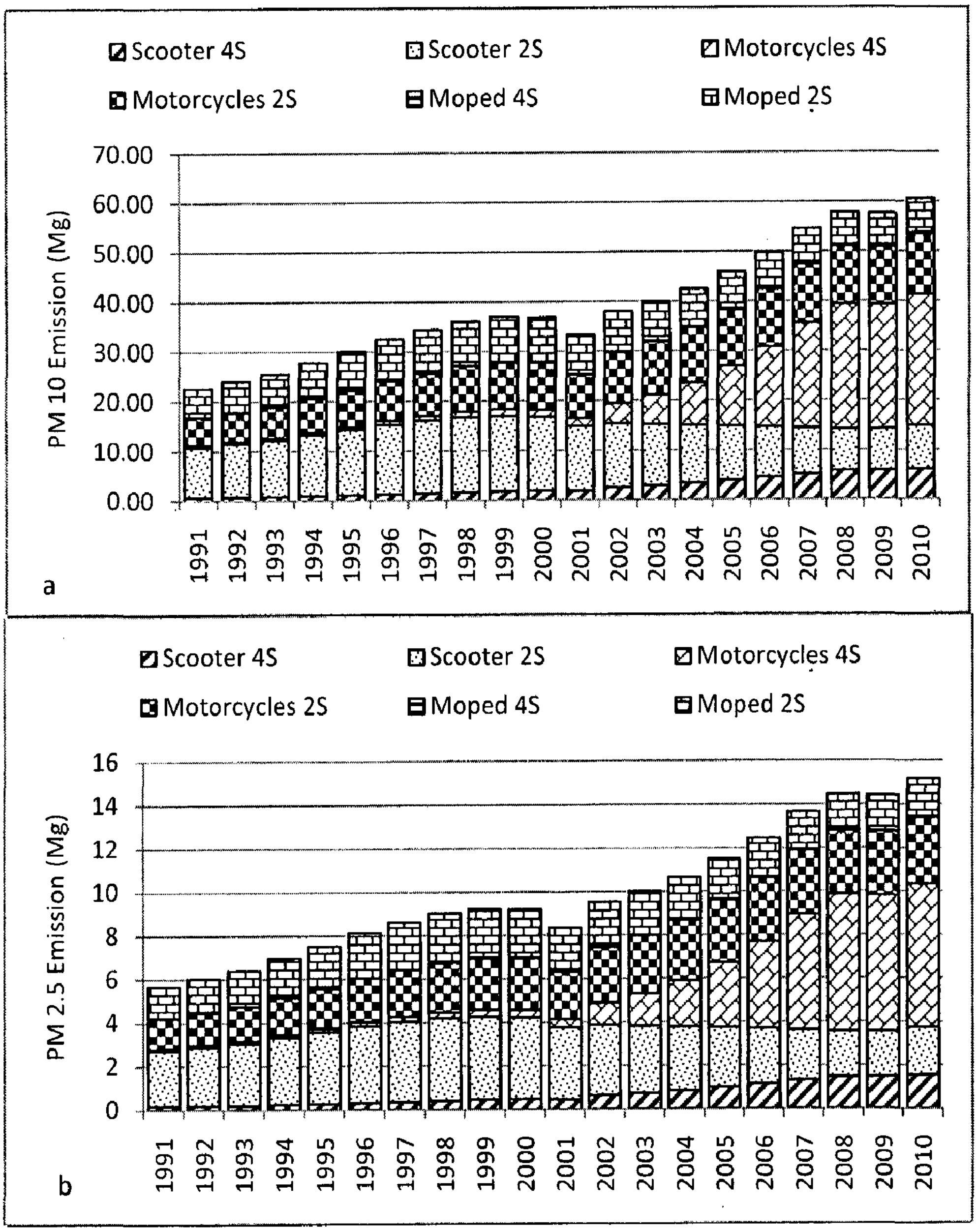


Fig.7.17: Emission of (a) PM10 and (b) PM2.5 from two wheelers tyre wears in megacity Delhi

7.4.2. Cars

Emissions of PM10 and PM2.5 from cars tyre wear are given in Fig. 7.18 (a and b). Emissions show an overall positive trend from 1991 to 2010 with petrol driven cars being the predominant cause. In 2010 emission of PM10 from cars tyre wear was 42 Mg followed by 71 Mg in 1995, 88 Mg in 2000, 130 Mg in 2005 and 204 Mg in 2010. Further, emission of PM2.5 from cars tyre wear was 11 Mg in 1991, followed by 16 Mg in 1995, 22 Mg in 2000, 33 Mg in 2005 and 51 Mg in 2010.

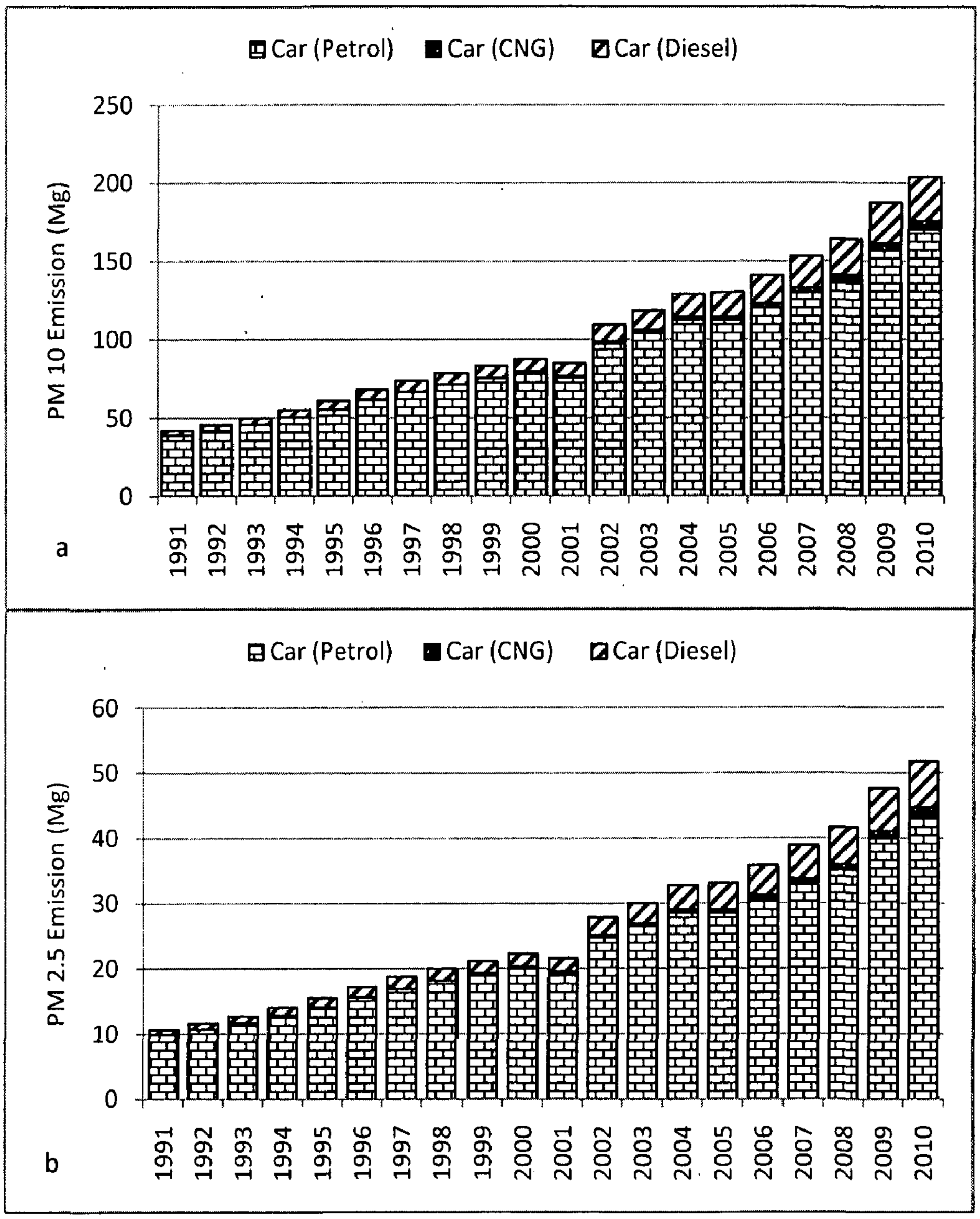


Fig.7.18: Emission of (a) PM10 and (b) PM2.5 from cars tyre wears in megacity Delhi

7.4.3. Three Wheelers

Fig. 7.19 (a and b) shows the emissions of PM10 and PM2.5 from three wheelers tyre wear in megacity Delhi from 1991 to 2010. As per their population, a sharp shift of share in emissions due to two-stroke petrol driven to four-stroke CNG driven three wheelers is also visible, In 1991 emission of PM10 from three wheelers tyre wear was about 4 Mg, followed by 5 Mg in 1995, 5 Mg in 2000, 12 Mg in 2005 and 20 Mg in 2010. Emission of PM2.5 from the tyre wear of three wheelers in Delhi was 1 Mg in 1991, 1.2 Mg in 1995, 1.4 Mg in 2000, 3 Mg in 2005 and 5 Mg in 2010.

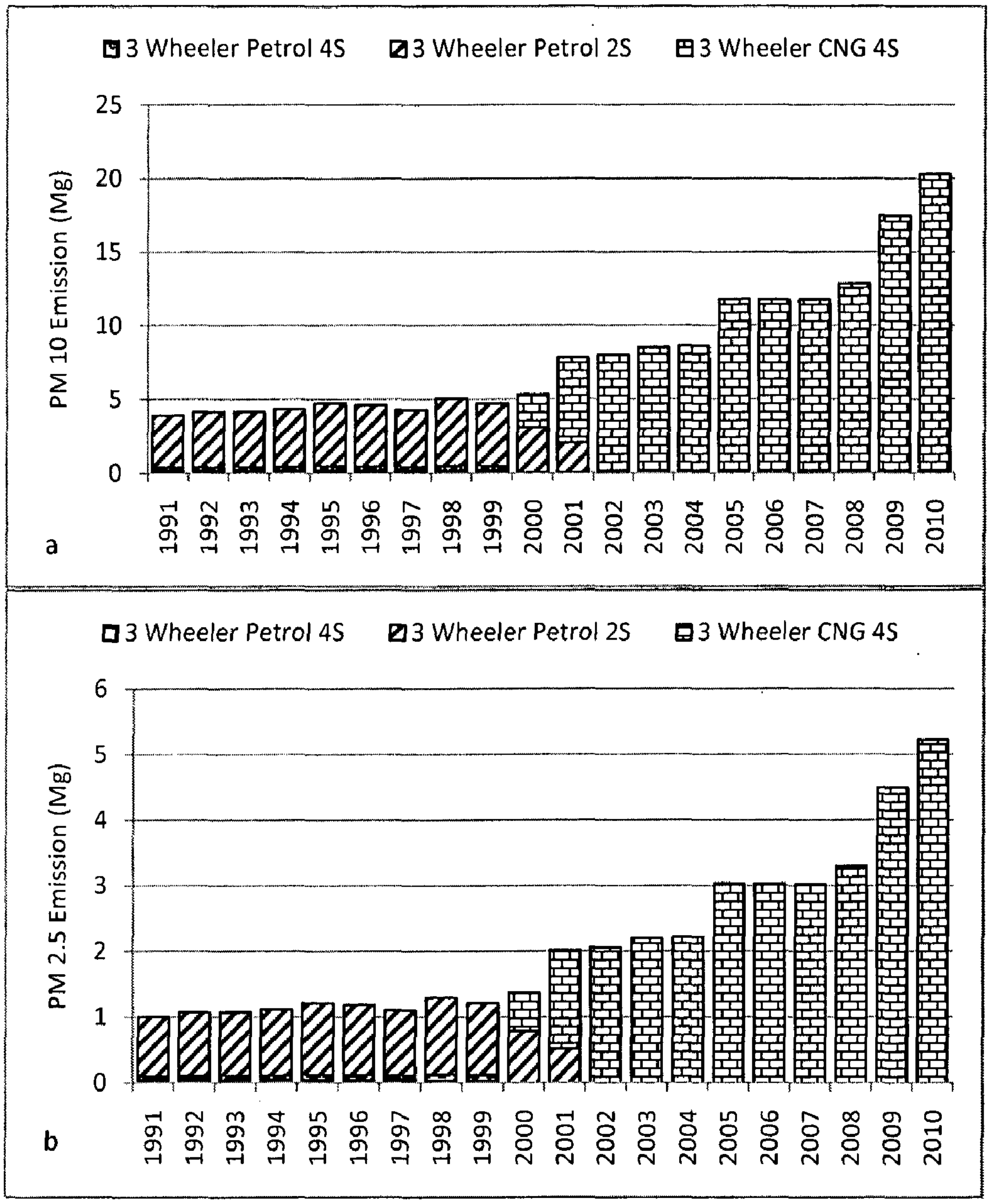


Fig.7.19: Emission of (a) PM10 and (b) PM2.5 from three wheeler tyre wears in megacity Delhi

7.4.4. Taxis

Emission of PM10 from taxi population tyre wear in 1991 was 1.2 Mg, followed by 1.5 Mg in 1995, 2.1 Mg in 2000, 2.3 Mg in 2005 and 6.4 Mg in 2010 (Fig. 7.20a). Similarly emission of PM2.5 from the tyre wear of taxis was 0.3 Mg in 1991, 0.4 Mg in 1995, 0.5 Mg in 2000, 0.6 Mg in 2005 and 1.6 Mg in 2010 (Fig. 7.20b). As per their population proportion, tyre wear emissions are dominated by diesel driven taxis in first half whereas by CNG driven taxis in later half.

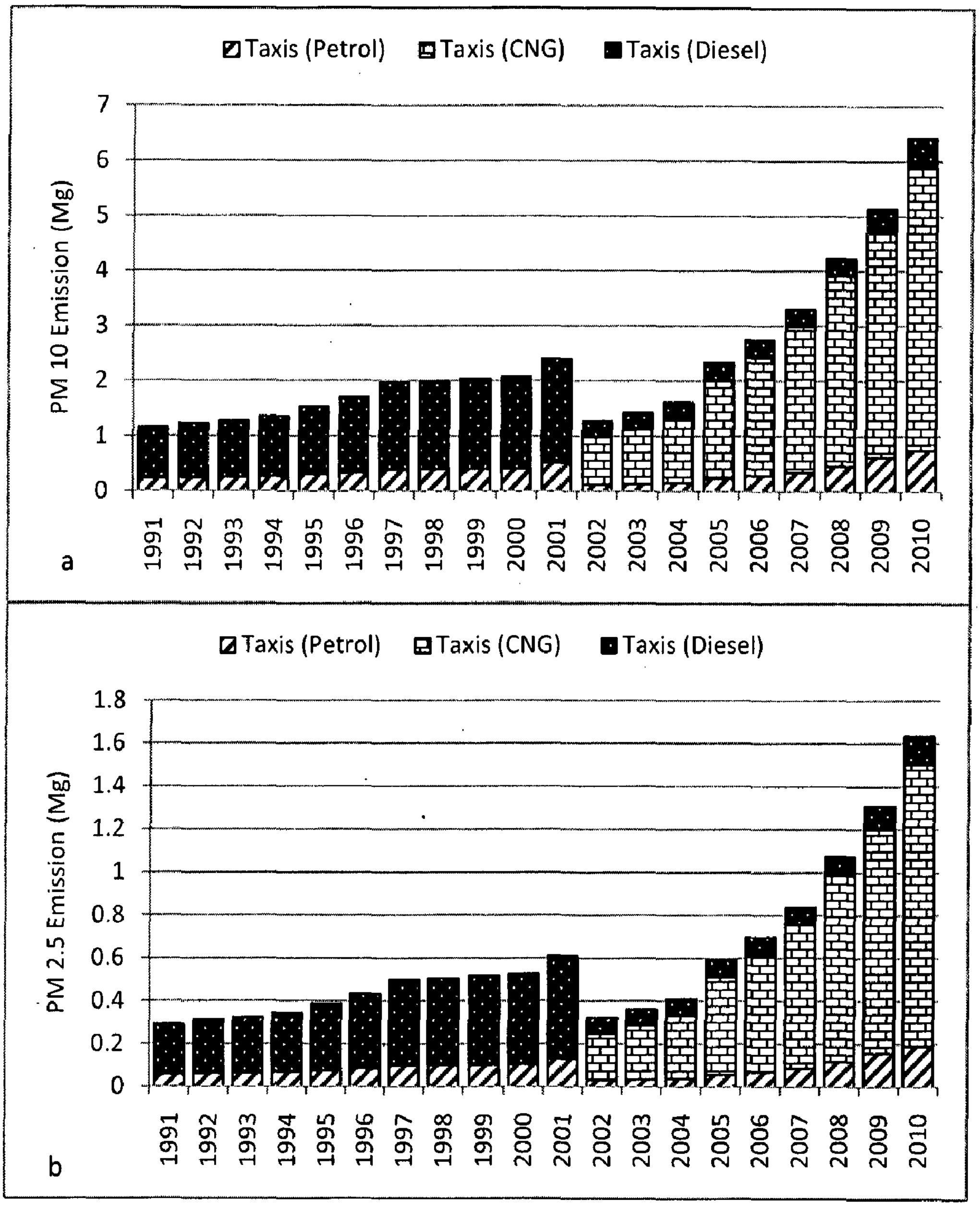


Fig.7.20: Emission of (a) PM10 and (b) PM2.5 from taxis tyre wears in megacity Delhi

7.4.5. Buses

PM10 and PM2.5 emission from tyres of buses in megacity Delhi is available in Fig. 7.21 (a and b). Our estimations suggest that emissions of PM10 from tyre of buses in 1991 were about 4 Mg followed by 5.3 Mg in 1995, 7.2 Mg in 2000, 16 Mg in 2005 and 28 Mg in 2010. Similarly, emission of PM2.5 from tyre of buses was 1 Mg in 1991, 1.4 Mg in 1995, 1.8 Mg in 2000, 4.1 Mg in 2005 and 7 Mg in 2010.

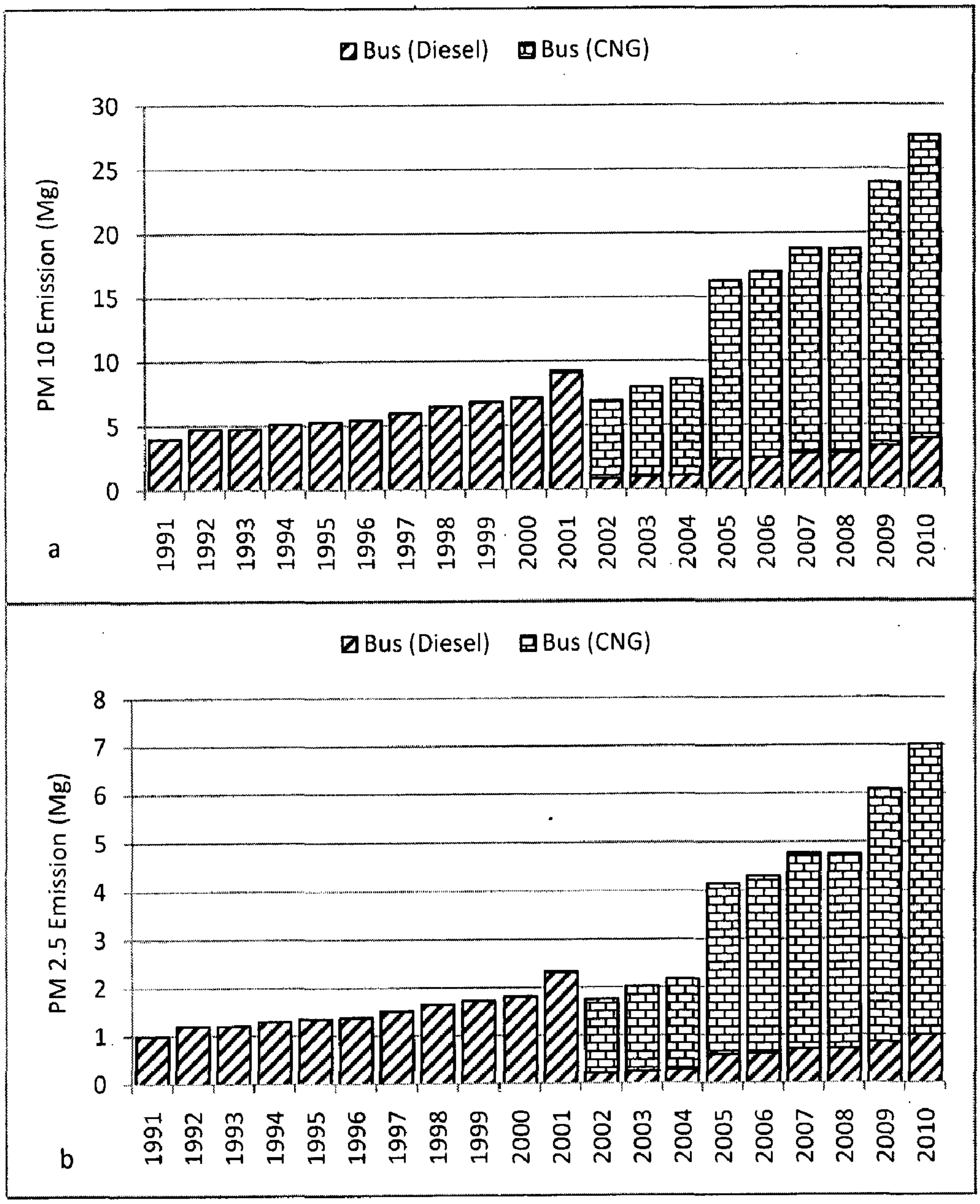


Fig.7.21: Emission of (a) PM10 and (b) PM2.5 from buses tyre wears in megacity Delhi

7.4.6. LCVs

Emission of PM10 from tyre wear of the LCVs population is given in Fig. 7.22(a). Figure indicates that in 1991 emission of PM10 was 9.5 Mg, followed by 12 Mg in 1995, 13 Mg in 2000, 9.6 Mg in 2005 and 17.5 Mg in 2010. Similarly emission of PM2.5 from tyre wear of LCVs population is given in Fig. 7.22(b). It indicates that in 1991 emission of PM2.5 was 2.4 Mg, followed by 3 Mg in 1995, 3.4 Mg in 2000, 2.4 Mg in 2005 and 4.4 Mg in 2010. Decline in emissions are visible during 2000-2002 when old buses were phased out and/or were off the road due to strict implementation of CNG in public road transport system in Delhi.

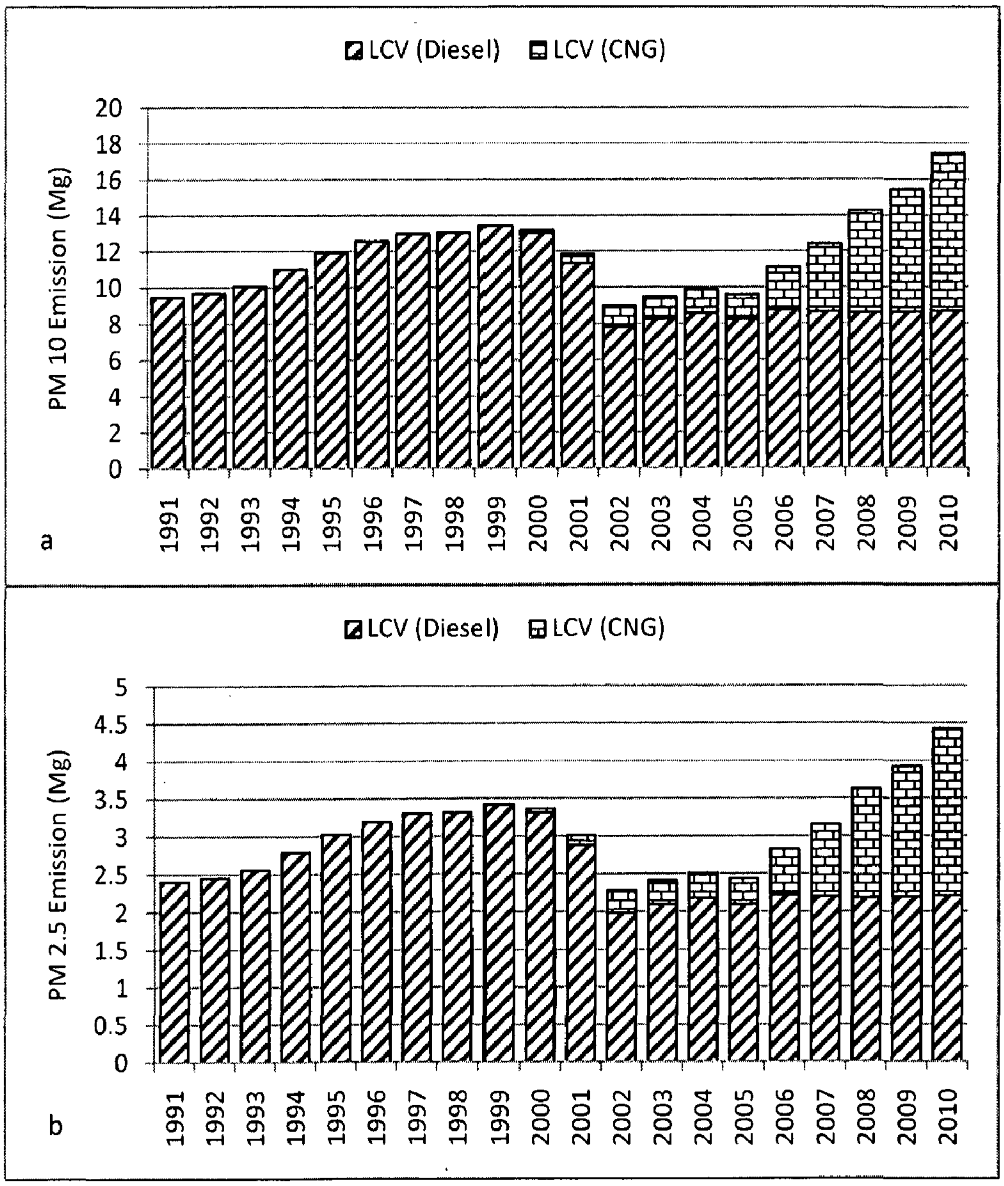


Fig.7.22: Emission of (a) PM10 and (b) PM2.5 from LCVs tyre wears in megacity Delhi

7.4.7. HCVs

Emission of PM10 from tyre wear of HCVs in 1991 was about 6 Mg, followed by 8 Mg in 1995, 9 Mg in 2000, 6 Mg in 2005 and 9 Mg in 2010 (Fig. 7.23a). Similarly emission of PM2.5 from tyre wear of HCVs was 1.5 in 1991, while it was ~2 Mg in 1995 and 2000, 1.5 Mg in 2005 and 2.3 Mg in 2010 (Fig. 7.23b). Because of phasing out program for old age vehicles of government of Delhi there is decline trend observed during 2000 to 2002.

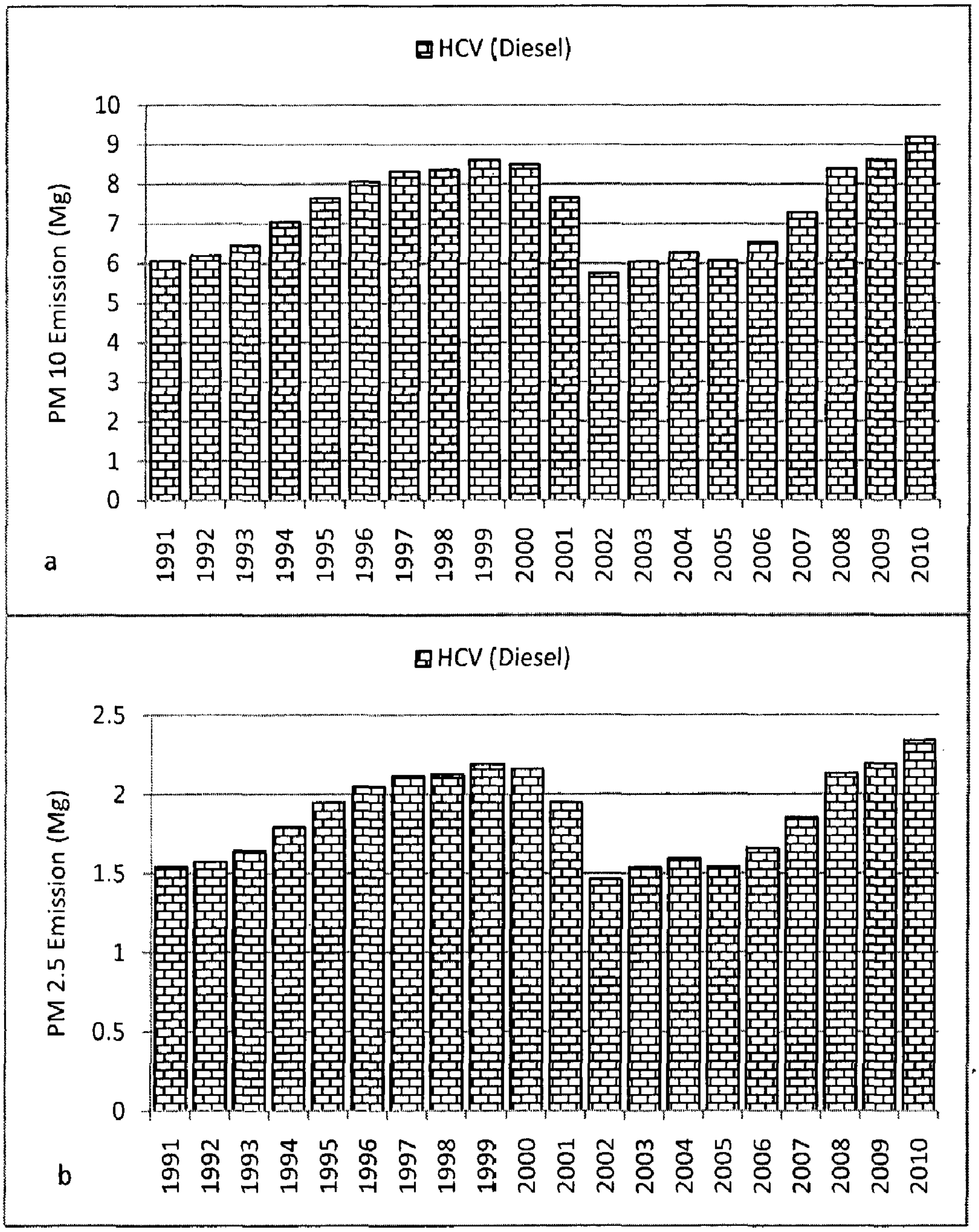


Fig.7.23: Emission of (a) PM10 and (b) PM2.5 from HCVs tyre wears in megacity Delhi

7.5. PM10 AND PM2.5 EMISSIONS FROM BRAKE WEARS

Emissions of PM10 and PM2.5 from various vehicles brake wears are given in Fig. 7.24 (a and b) for 1991-2010. PM10 emissions are increasingly dominated by cars and buses particularly in later years, whereas PM2.5 are associated with cars during entire period. In 1991 emission of PM10 from vehicles brake wears was 319 Mg, followed by 426 Mg in 1995, 542 Mg in 2000, 758 Mg in 2005 and 1207 Mg in 2010. Similarly, emission of PM2.5 from brake wears of different vehicles was 16 Mg in 1991, 22 Mg in 1995, 29 Mg in 2000, 39 Mg in 2005 and 62 Mg in 2010 (Fig. 7.24b). The average annual growth in these emissions from brake wears is about 7.4%.

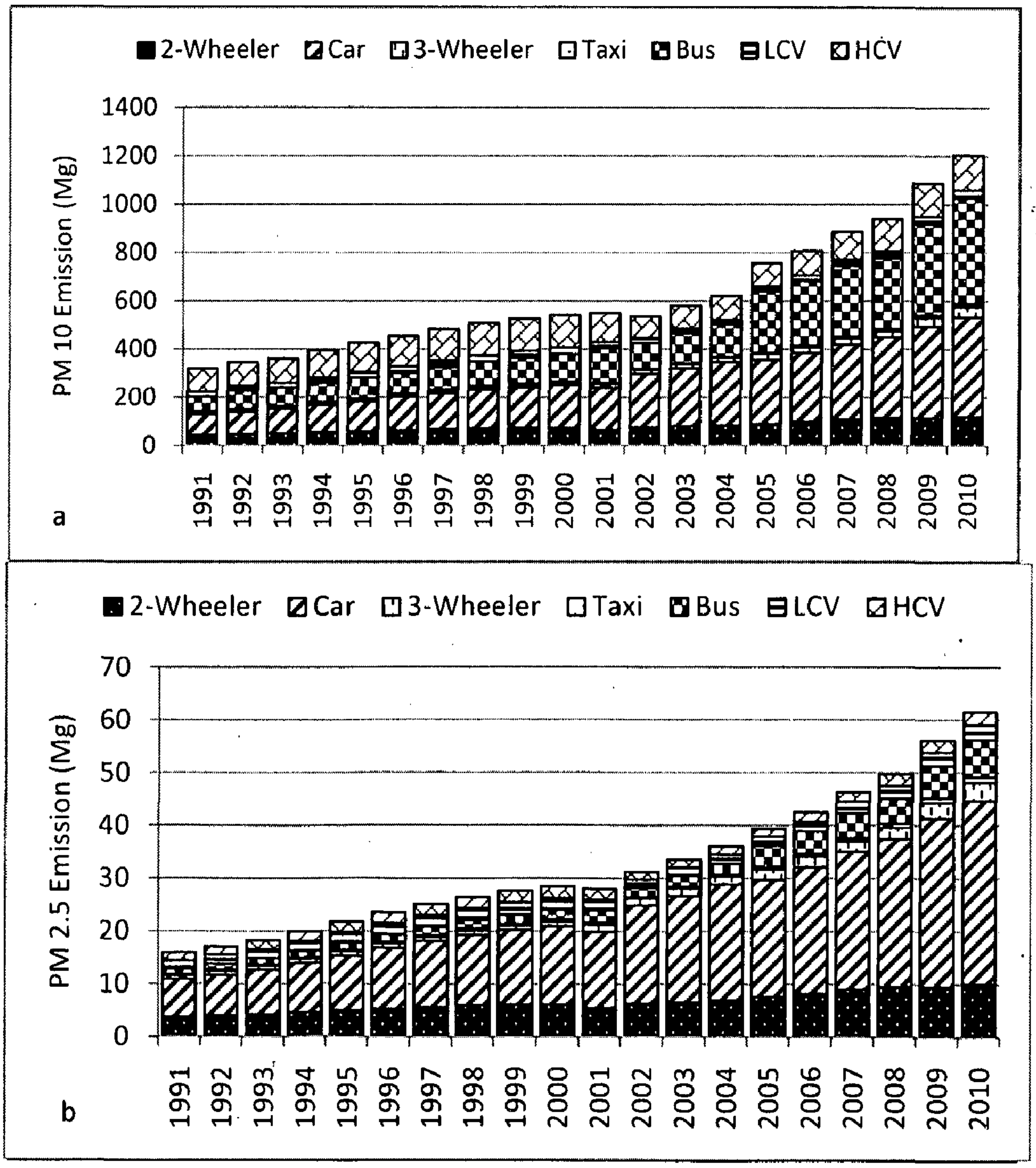


Fig.7.24: Emission of (a) PM10 and (b) PM2.5 from various vehicles brake wears in megacity Delhi

7.5.1. Two Wheelers

Fig. 7.25a shows that in 1991 emission of PM10 from brake wears of the two wheelers was 45 Mg, while in 1995 it was 60 Mg, followed by 74 Mg in 2000, 92 Mg in 2005 and 121 Mg in 2010. Fig. 7.25b shows the emission of PM2.5 from brake wear of two wheelers. In 1991 emission of PM2.5 from brake wears of two wheelers was 3.8 Mg, followed by 5 Mg in 1995, 6.2 Mg in 2000, 7.7 Mg in 2005 and 10 Mg in 2010. The average annual growth in these emissions associated with two wheelers is 5.42% for both PM10 and PM2.5.

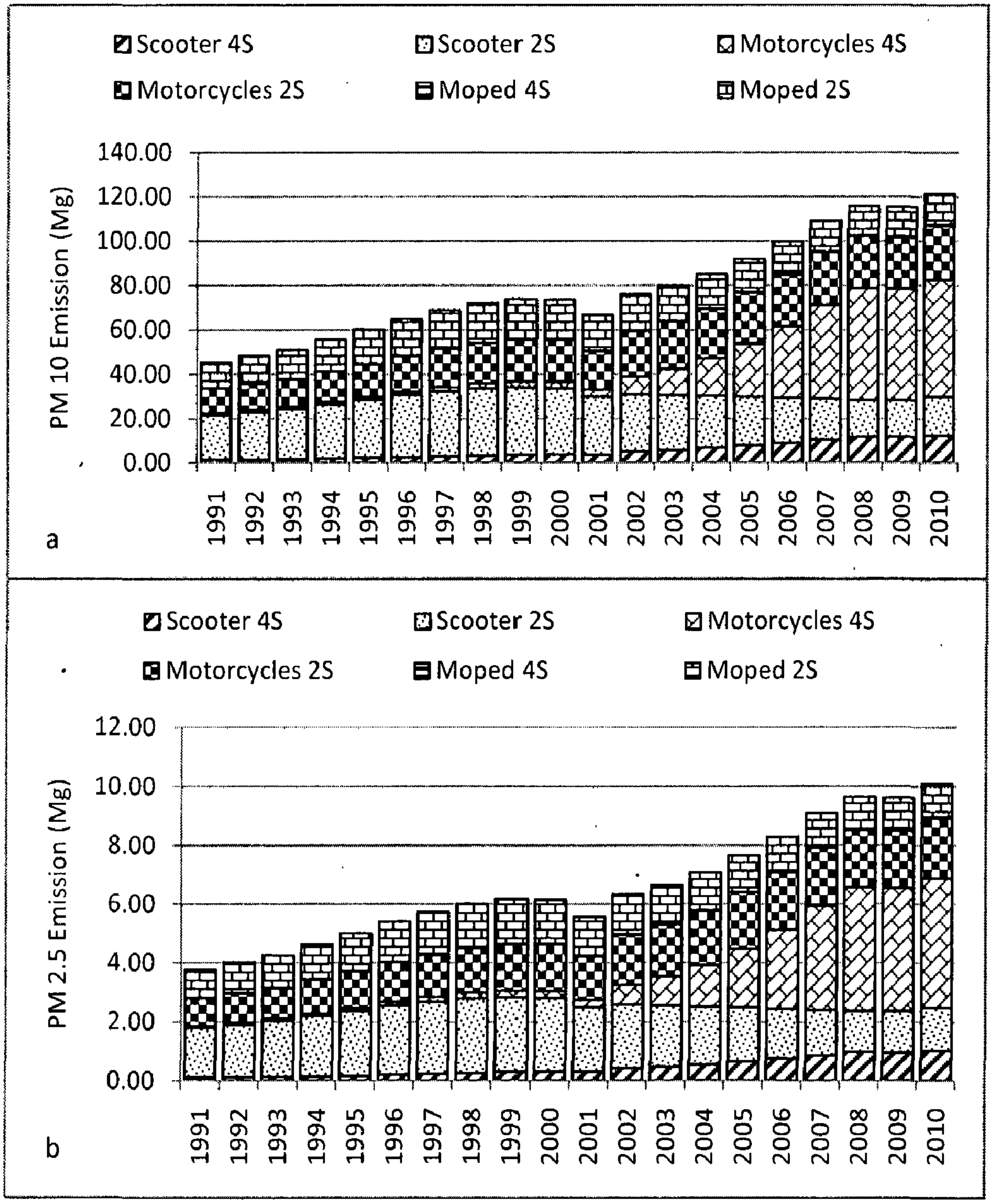


Fig.7.25: Emission of (a) PM10 and (b) PM2.5 from two wheelers brake wears in megacity Delhi

7.5.2. Cars

Emissions of PM10 from brake wears of the cars in 1991 was 86 Mg, followed by 124 Mg in 1995, 178 Mg in 2000, 265 Mg in 2005 and 415 Mg in 2010 (Fig. 7.26a). Similarly emission of PM2.5 from brake wear of cars was 7.16 Mg in 1991, followed by 10.33 Mg in 1995, 14.87 Mg in 2000, 22 Mg in 2005 and 34.54 Mg in 2010 (Fig. 7.26b). Brake wear emissions of PM10 and PM2.5 from cars constantly increase with 9% annual growth rate except between 2000-2001 when it decreases by 3% due to phasing out of old age cars.

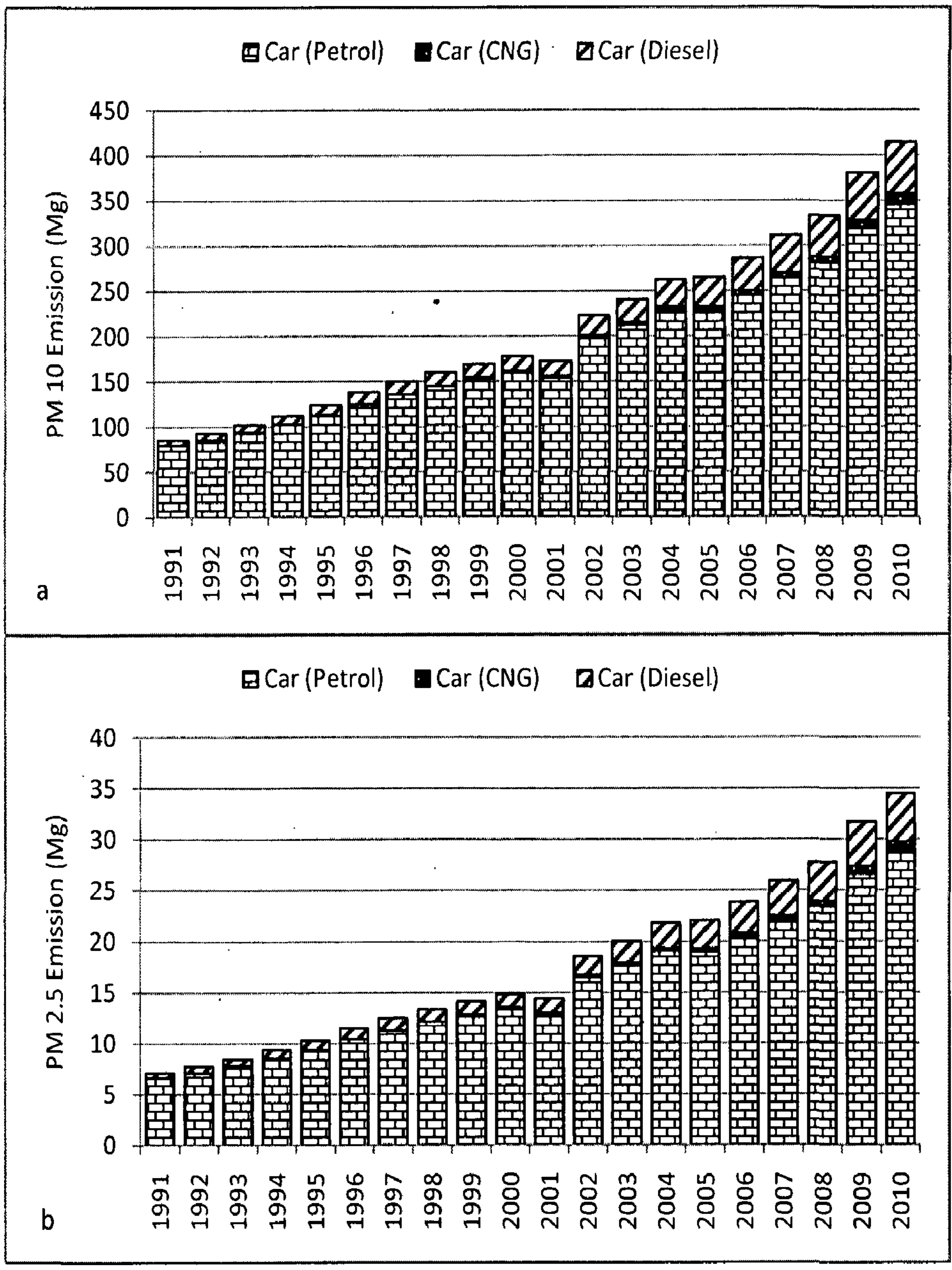


Fig.7.26: Emission of (a) PM10 and (b) PM2.5 from cars brake wears in megacity Delhi

7.5.3. Three Wheelers

Emission of PM10 from three wheelers in 1991 was 8 Mg, followed by 10 Mg in 1995, 11 Mg in 2000, 24 Mg in 2005 and 42 Mg in 2010 (Fig. 7.27a). Similarly for PM2.5 emission was 0.7 Mg in 1991, followed by 0.8 Mg in 1995, 0.9 Mg in 2000, 2 Mg in 2005 and 3.5 Mg in 2010 (Fig. 7.27b). Unlike cars, brake wear emissions of PM10 and PM2.5 from three wheelers were more or less constant during 1991-2000 but it rapidly increased afterwards until 2010. This is because of increasing population of three wheelers.

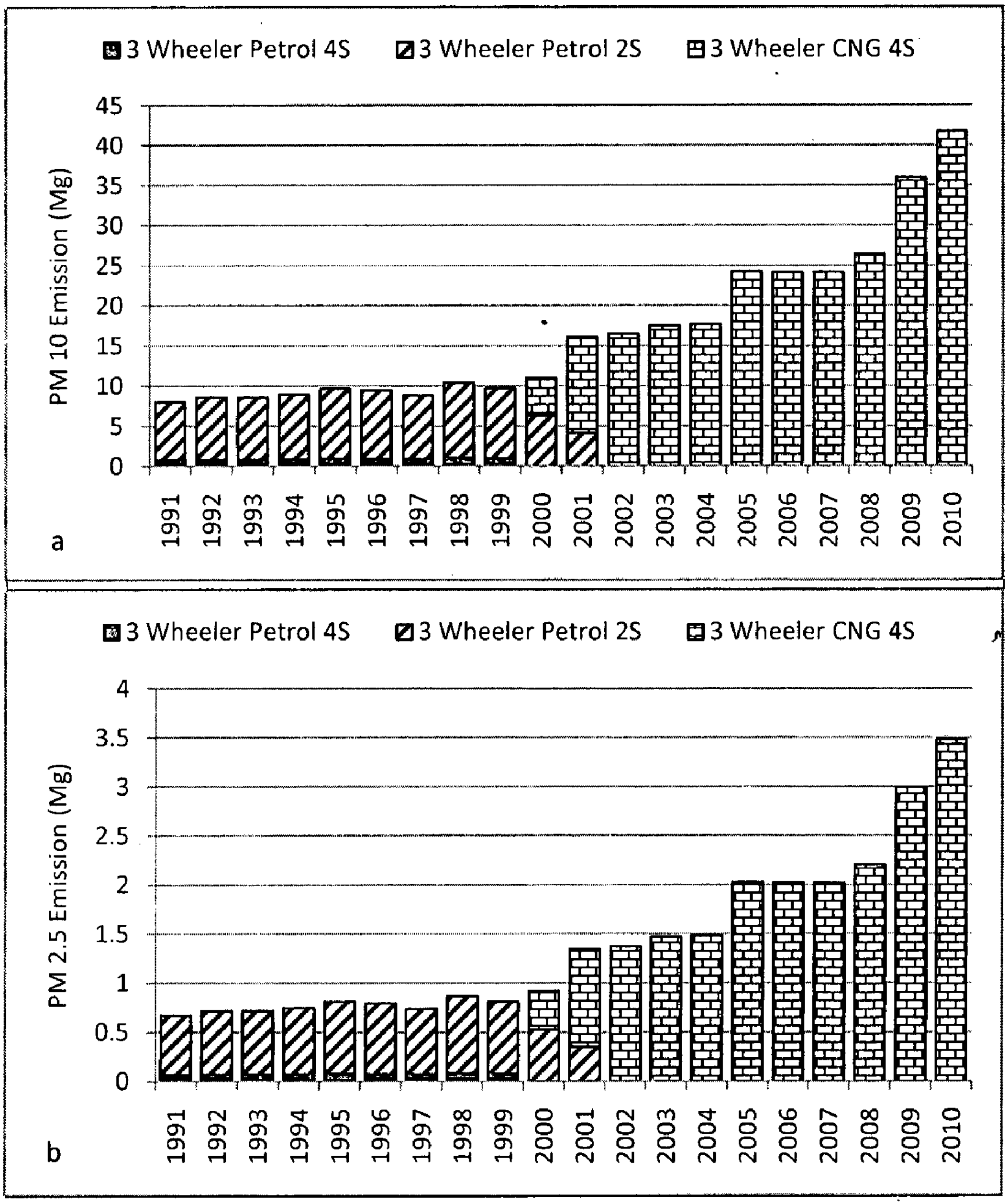


Fig.7.27: Emission of (a) PM10 and (b) PM2.5 from three wheelers brake wears in megacity Delhi

7.5.4. Taxis

Emissions of PM10 from taxi population brake wear were 2.4 Mg in 1991, followed by 3.1 Mg in 1995, 4.2 Mg in 2000, 4.8 Mg in 2005 and 13.1 Mg in 2010 (Fig. 7.28a). In case of PM2.5, emission from brake wear was 0.2 Mg in 1991, while in 0.3 Mg in 1995, followed by 0.4 Mg in 2000 and 2005 and 1.1 Mg in 2010 (Fig. 7.28b). Similar to three wheelers, brake wear emissions from taxis have increased rapidly during 2002-2010.

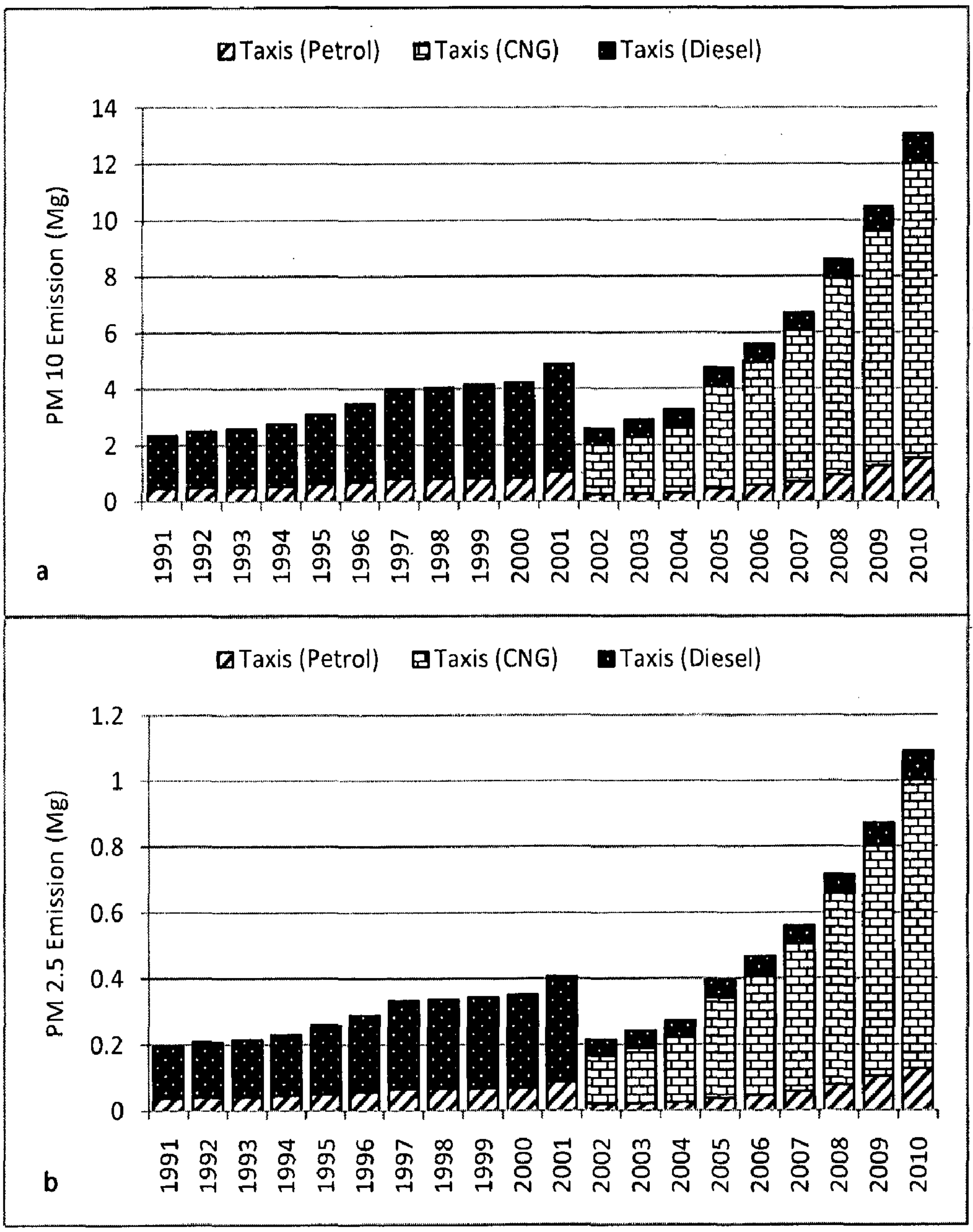


Fig.7.28: Emission of (a) PM10 and (b) PM2.5 from taxis brake wears in megacity Delhi

7.5.5. Buses

Emissions of PM10 and PM2.5 from brake wear of bus population are given in Fig. 7.29 (a and b). According to Fig. 7.29a emission of PM10 from brake wear of buses was 63 Mg in 1991, followed by 84 Mg in 1995, 113 Mg in 2000, 257 Mg in 2005 and 436 Mg in 2010. Emission of PM2.5 from brake wear of buses is given in Fig. 7.29b. It indicates that in 1991 emission was 1 Mg, followed by 1.4 Mg in 1995, 1.8 Mg in 2000, 4.1 Mg in 2005 and 7 Mg in 2010. Emission of PM10 and PM2.5 is increased with the annual average growth rate of 12% from 1991 to 2010. However, a decline of about 25% is observed between 2001 and 2002 because of phasing out program of buses in 2002.

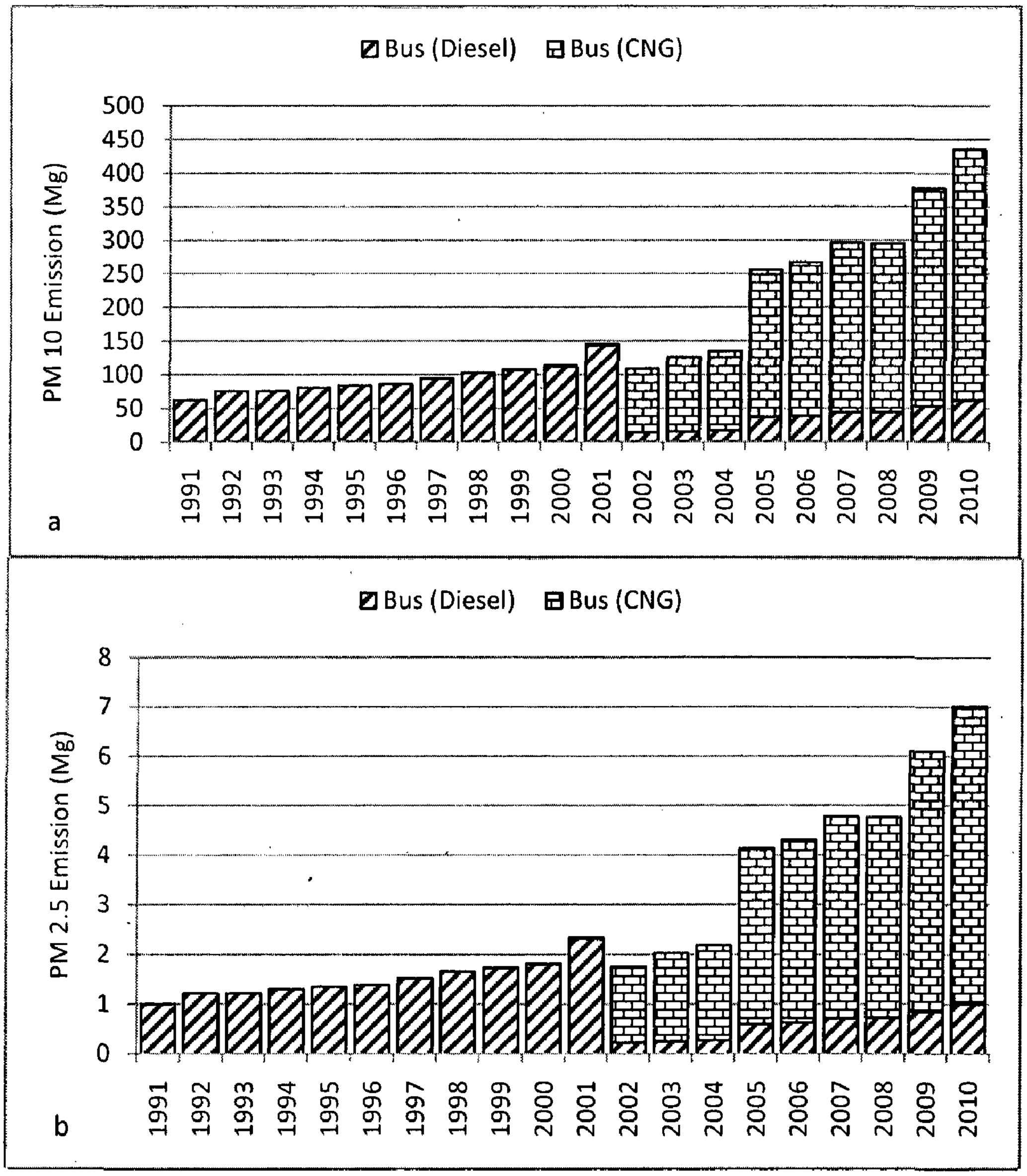


Fig.7.29: Emission of (a) PM10 and (b) PM2.5 from buses brake wears in megacity Delhi

7.5.6. LCVs

Emissions of PM10 from LCVs brake wear were 19.3 Mg in 1991, followed by 24.3 Mg in 1995, 26.6 Mg in 2000, 19.5 Mg in 2005 and 35.5 Mg in 2010 (Fig. 7.30a). Emission of PM2.5 from brake wear of LCVs in 1991 was 1.6 Mg, followed by 2 Mg in 1995, 2.2 Mg in 2000, 1.6 Mg in 2005 and 2.9 Mg in 2010 (Fig. 7.30b). Emissions of PM10 and PM2.5 are increasing with annual average growth rate of 4% while negative trend is observed between 2000 and 2002 because of phasing out program of government of Delhi.

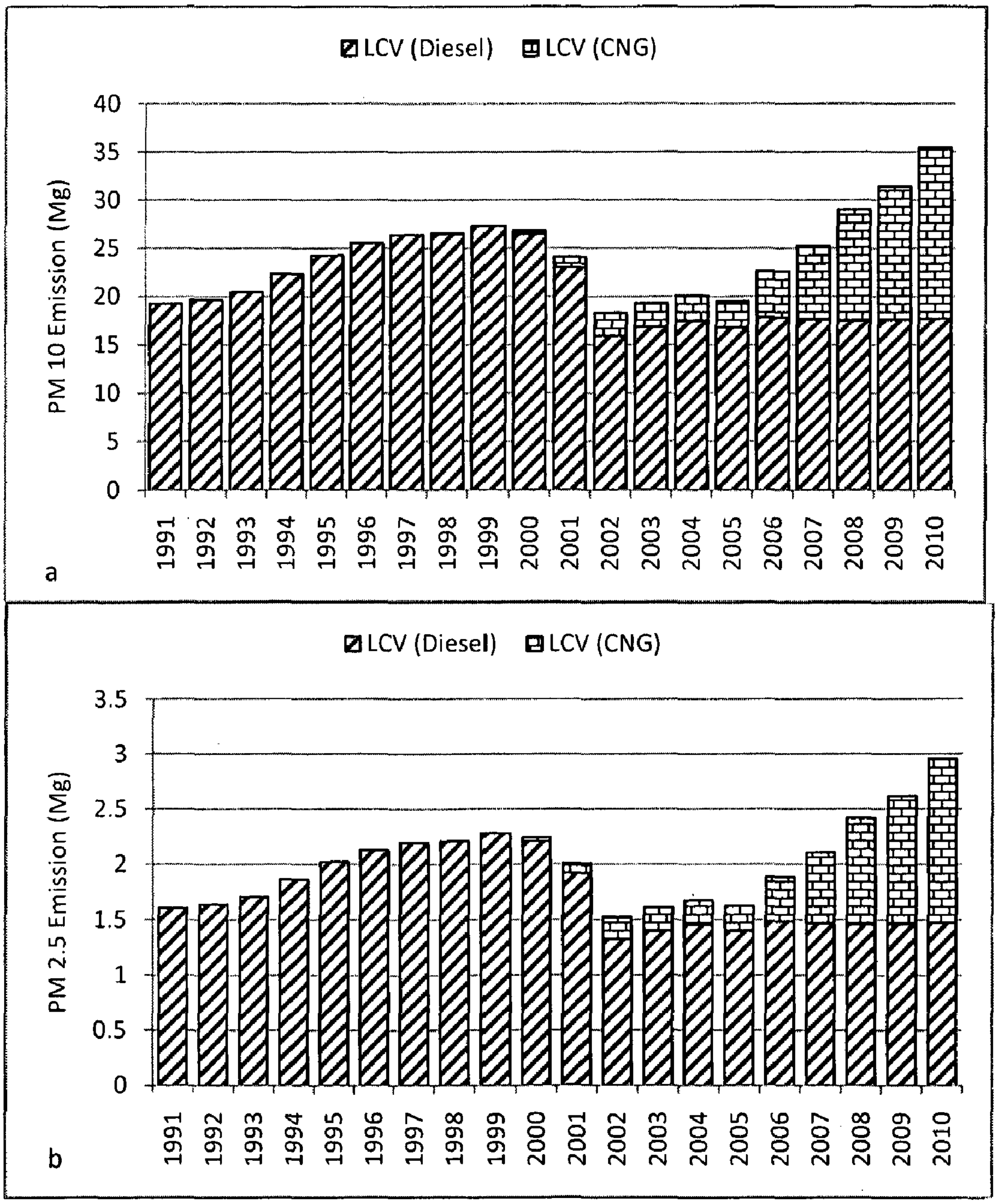


Fig.7.30: Emission of (a) PM10 and (b) PM2.5 from LCVs brake wears in megacity Delhi

7.5.7. HCVs

Fig. 7.31(a-b) shows the emissions of PM10 and PM2.5 from HCVs brake wear. In 1991 emission of PM10 from HCVs brake wear was 96 Mg, followed by 121 Mg in 1995, 134 Mg in 2000, 96 Mg in 2005 and 145 Mg in 2010. Similarly emission of PM2.5 from brake wear of HCVs was 1.54 Mg in 1991, followed by 1.9 Mg in 1995, 2.2 Mg in 2000, 1.5 Mg in 2005 and 2.3 Mg in 2010. Emissions of PM10 and PM2.5 increasing with 3% annual average growth rate from 1991 to 2010 while some negative trend in emission is observed between 1999-2002 (12%) and 2004-2005 (3%) because of phasing out of vehicle population.

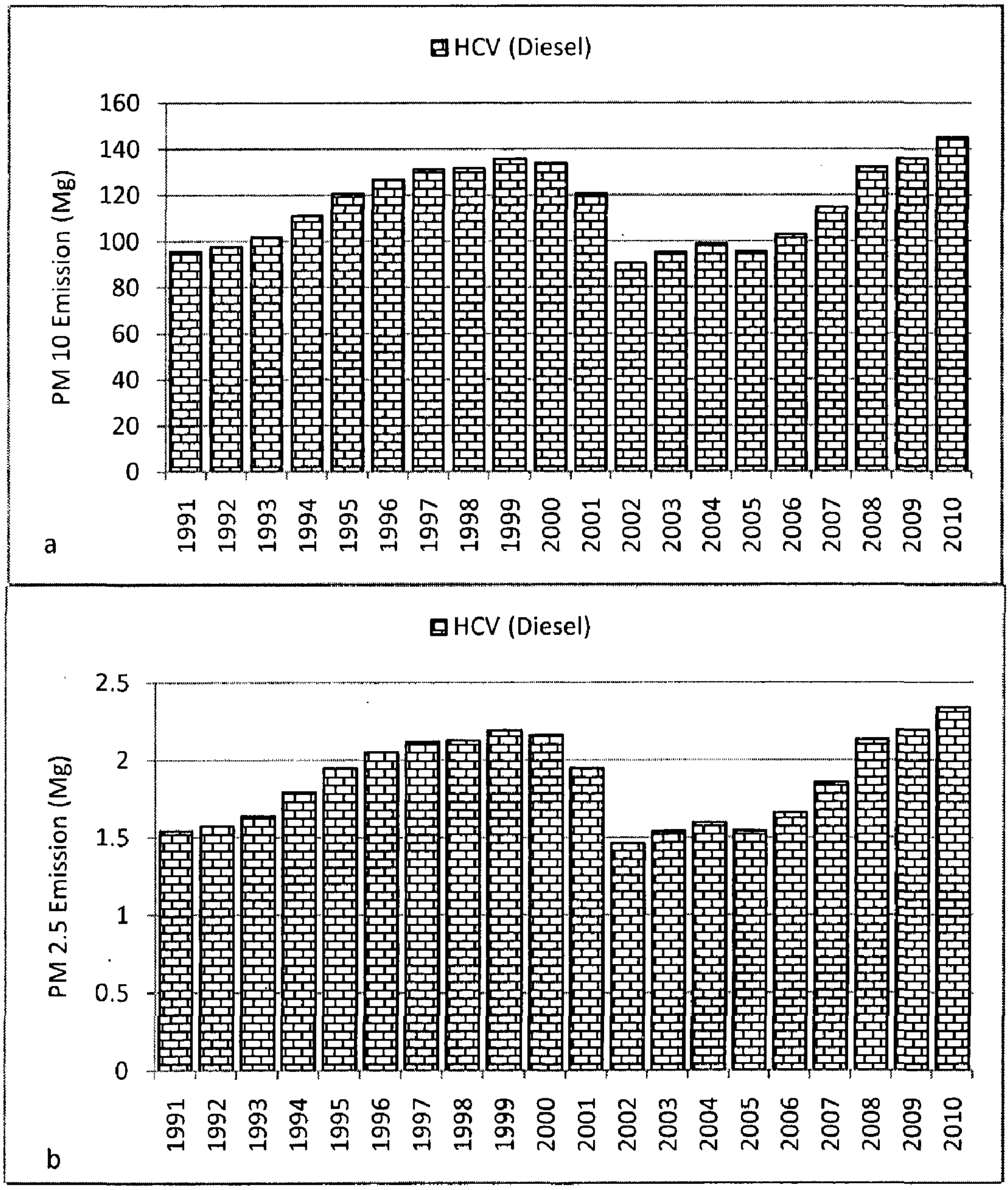


Fig.7.31: Emission of (a) PM10 and (b) PM2.5 from HCVs brake wears in megacity Delhi

7.6. CONCLUSION

Non-exhaust emissions from various vehicle categories in megacity Delhi have been presented in this chapter. It is observed that evaporative emissions of VOCs from vehicles follow an increasing trend along with growth vehicle population in megacity Delhi. No emissions are estimated for diesel driven vehicles. This is because diesel engines are assumed to have no significant evaporative emissions due to very low volatility of diesel fuels compared to gasoline and CNG (USEPA, 1998). Sudden increase (15%) in VOCs from various vehicles is observed from 2002. This is due to introduction of CNG norms in year 2002. Initially from 1991 to 2001 cars and two wheelers were the largest contributors of VOCs, while 2002 onwards CNG buses and petrol driven cars emerged as highest contributors. In case of PM10 and PM2.5 emissions from road dust suspension, the share of HCVs and buses is highest (34-35%) during the entire study period (1991-2010) due their high dust spreading capacity. Emissions of PM10 and PM2.5 from road dust suspension have increased with the growth rate of 6% from 1991 to 2001, while about 2% decline is observed between 2001 and 2002 because of phasing out of old age vehicles. After 2002, emissions increase with high growth rate (11%) due to rising population of vehicles. With respect to tyre wear, the share of cars is highest (47-62%) throughout the study period. In case of PM10 emissions from brake wear the contribution of cars, HCVs and buses is highest.

CHAPTER 8

Uncertainty & Sensitivity Analysis of Exhaust Emissions from Vehicles

8.1. INTRODUCTION

Emission factors and emission inventories have inherent uncertainty due their dependency on several variables. Quantification of uncertainty in emission factors and emission inventories is, therefore, increasingly being recognized as a necessary requirement and there are a growing number of examples of such efforts. The Intergovernmental Panel on Climate Change (IPCC) has developed good practice guidelines for quantification of uncertainty in greenhouse gas (GHG) emission estimates (IPCC, 2000). Uncertainties have been assessed quantitatively for emission factors, including source categories such as power plants, industries, and vehicles (Frey and Rhodes 1998, Zhao and Frey, 2003). High quality uncertainty estimates give important information on research priorities for the future improvement of emission inventories. As suggested by IPCC, to assess uncertainties of variables in the vehicular emissions the Tier 2 methodology has been used. This methodology employs Monte Carlo Stochastic Simulation technique, which is also referred to as the Monte Carlo method (IPCC, 2001). The core of Monte Carlo analysis is to vary the input parameters (e.g., population, per capita consumption, emission factors) in accordance with probability distribution function (PDF) (Kumar et al., 2004).

Monte Carlo analysis is a common name for a group of iterative statistical techniques (Int Panis, 2004). This essentially involves replacing each estimated parameter in the calculation by a probability distribution which describes the range of values that a parameter can take as well as the probability that a certain value will actually occur. This procedure is then repeated a large number of times (e.g., 20000 trials in this study) so that a number of combinations of different input parameters are available. All calculations for this study were performed with the commercially available Oracle Crystal Ball 11.1.1.0.00 software (Oracle, 2010) on a desktop computer.

8.2. METHODOLOGY

As each trial requires a large amount of data generation that need a great deal of computational time and resources, only one year of study period was considered for uncertainty analysis. Since most of the activity data are available for years between 1991 and 2008, so year 2007 was selected to perform uncertainty analysis.

According to IPCC (2000), in case of emission factors the probability density functions are assumed to be normal unless clear evidence to the contrary is available. IPCC proposes lognormal distributions for values with high uncertainties (more than or equal to 30% standard deviation of the mean) and normal distribution for low uncertainty (IPCC, 2000). Tinus et al. (2006) noticed that normal and lognormal probability distribution functions at lower uncertainties are quite similar. And at higher uncertainties both functions start deviating from each other. Based on the observations of Tinus et al. (2006) and also based on Fig. 8.1, we applied lognormal distributions for all variables for our analysis. In order to obtain large number of combinations of different input variables, about 20000 trial numbers were selected for uncertainty analysis through Monte Carlo method.

Because of unavailability of control range of input parameters (e.g., vehicle population, temperature, humidity, emission factor) most of the variables were either borrowed from secondary literature or assumed based on expert judgment. In either case, they are considered uncertain and analyzed using Oracle Crystal Ball 11.1.1.0.00 software. Standard deviation for emission factors were taken from their respective sources or from IPCC (2000) for those which were unavailable or assumed as per expert judgment. As on-road vehicle population data were calculated according to the prescribed retirement age but not on the basis of data obtained through actual field survey, there are greater chances of uncertainty in such input parameters. Moreover, due to scarcity of actual data it is very difficult to exactly estimate the number of vehicles with their subtypes and/or categories (e.g., two-stroke, four-stroke two wheelers, mopeds, motorcycles, scooters; fuel-wise cars, LCVs, HCVs, etc.). Hence, maximum standard deviations (30%) are taken for vehicle population due to unavailability of supporting data and uncertainty in GDP/PCI, human population, per 1000 vehicle population etc. In case of VKT, temperature and humidity, standard deviations are taken from their respective sources and probability distribution functions are chosen as per the data.

A simplified example of a Monte Carlo simulation using the commercial software "Crystal Ball 11.1.1.0.00" is presented below. To perform uncertainty analysis with the Crystal Ball 11.1.1.0.00 the following steps are followed:

1. Develop the model on an Excel spreadsheet,
2. Identify probability distributions for the input parameters, also called assumptions,
3. Identify the output parameter(s) that need to be analyzed, also termed as forecast(s),
4. Run the Monte Carlo simulation in Crystal Ball,
5. Stop the simulation when frequency distribution displayed on-screen for the forecast is stabilized,
6. Review the forecast statistics contained in the report generated by Crystal Ball
7. Modify model and/or input assumptions and rerun until satisfactory results (best probability distribution function) are reached

8.3. RESULTS AND DISCUSSION

8.3.1. Uncertainty in Emissions from Various Vehicle Categories

Summarized results of uncertainty analysis of forecasted CO, CO_2, NO_x , HC, PM, 1-3 Butadiene, Acetaldehyde, Benzene, Formaldehyde, Total Aldehyde and Total PAH emissions from various vehicle categories in megacity Delhi are shown in Table 8.1. It is observed that there is highest uncertainty in emission estimations of various pollutants from three wheelers (43-45%), cars (42-44%), buses (31-44%) and taxies (25-41%) while the least uncertainty (26-36%) is observed from LCVs. Because the Crystal Ball 11.1.1.0.00 software has been used to estimate uncertainty for emission of each pollutant from each vehicle category separately (with different probability distribution function for different variables), it is not easy to understand the variation in uncertainty for dissimilar vehicle types and pollutants. Furthermore, it might be possible that variability in technology of vehicles, fuel categories, vehicle population, emission factors etc. are the parameters that are responsible for the variation in the uncertainty of emissions of pollutants from various vehicles. With concern to percentage variation of standard deviation, 95% upper and lower limits from the mean value for most the pollutants emission from separate vehicle values are almost same because of same dominating variables (e.g., vehicle population, VKT etc.; discussed in section 8.3.2) used for calculating emissions of various pollutants from each vehicle category. While changes in emission factors are responsible for slight variation in standard deviation and 95% upper / lower limits. For emissions of most of the pollutants, the standard deviation is ranged between 34-36% of mean values for two-wheelers and for three wheelers it is 43-45%. In case of cars, the standard deviation is 42-44% of mean value in most of the cases. For emissions of different pollutants from buses the standard deviation is 31-44% of mean value while for HCVs it is 33-36%. Similar to standard deviation, the 95% upper and lower limits of uncertainty for most of the pollutants from seperate vehicle categories are almost same. In case of two wheelers the 95% lower limit from the mean value is 60-62% while upper limit is 71-81% for emissions of most of the pollutants. For three wheelers lower limit is 59-61% of mean and upper is 106-113% of mean. In case of cars 95% lower limit is 58-60% of the mean and upper value is 102-109%.

Fig. 8.1 shows the forecasted probability distribution function (spread of emissions from the mean values) of CO, CO_2, NO_x , HC, PM , 1-3 Butadiene, Acetaldehyde emissions from two wheelers, three wheelers, cars, taxies, buses, LCVs and HCVs. In most of the cases, the probability distribution functions are lognormal.

Table 8.1: Uncertainty estimation results for forecasted CO, CO_2, NO_x , HC, PM , 1-3 Butadiene, Acetaldehyde, Benzene, Formaldehyde, Total Aldehyde and Total PAH emissions from various vehicle categories obtained after 20000 trials for year 2007

Statistics	**2Ws**	**3Ws**	**Cars**	**Taxis**	**Buses**	**LCVs**	**HCVs**
			CO				
Mean	81.28 (Gg)	4.87 (Gg)	105.92 (Gg)	0.80 (Gg)	19.22 (Gg)	8.89 (Gg)	16.60 (Gg)
95% Lower	32.34	1.92	42.73	0.45	8.93	5.24	8.32
95% Upper	139.27	10.37	221.54	1.34	37.23	14.16	30.37
Standard Deviation	27.37	2.17	46.45	0.23	7.31	2.31	5.74

Statistics	**2Ws**	**3Ws**	**Cars**	**Taxis**	**Buses**	**LCVs**	**HCVs**
			CO_2				
Mean	638.43	261.19	2553.18	140.90	2602.89	1060.32	977.20
	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)
95% Lower	249.86	105.58	1064.02	65.66	1231.65	622.02	500.37
95% Upper	1099.34	544.28	5238.32	273.02	4983.22	1722.73	1771.60
Standard Deviation	216.55	114.46	1080.24	54.82	985.52	284.09	326.92
			NO_x				
Mean	3652.29	1.72	13.88	0.42	17.33	7.57	13.58
	(Mg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)
95% Lower	1318.25	0.69	5.69	0.18	6.93	4.37	6.94
95% Upper	7135.75	3.58	29.07	0.84	36.20	12.47	24.95
Standard Deviation	1481.10	0.76	6.08	0.17	7.61	2.09	4.63
			HC				
Mean	36.57	0.87	11.93	0.46	10.71	4.68	1482.00
	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Gg)	(Mg)
95% Lower	14.41	0.36	5.00	0.20	4.61	2.73	729.20
95% Upper	63.13	1.79	24.44	0.92	21.71	7.69	2761.89
Standard Deviation	12.39	0.37	5.11	0.19	4.42	1.27	529.44
			PM				
Mean	744.73	50.33	179.88	3.72	496.57	926.49	1.86
	(Mg)	(Mg)	(Mg)	(Mg)	(Mg)	(Mg)	(Gg)
95% Lower	284.60	20.22	73.25	1.84	199.57	481.26	0.94
95% Upper	1296.71	104.62	368.10	7.07	1042.42	1651.41	3.35
Standard Deviation	257.34	22.06	76.81	1.36	220.71	305.18	0.62
			1-3 Butadiene				
Mean	163.67	16.37	1556.35	1.14	5.16	416.14	15.82
	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)	(Kg)
95% Lower	65.49	6.62	627.56	0.68	2.12	219.97	7.99
95% Upper	283.60	33.74	3239.87	1.82	10.54	725.26	28.95
Standard Deviation	55.38	7.08	681.14	0.29	2.22	129.25	5.44

Statistics	2Ws	3Ws	Cars	Taxis	Buses	LCVs	HCVs
			Acetaldehyde				
Mean	203.64 (Kg)	4.66 (Kg)	137.46 (Kg)	1.81 (Kg)	4.68 (Kg)	13.34 (Kg)	28.04 (Kg)
95% Lower	77.23	1.88	55.69	0.83	2.47	7.26	14.45
95% Upper	360.08	9.75	286.00	3.62	8.04	23.06	50.92
Standard Deviation	71.96	2.04	59.39	0.72	1.44	4.06	9.43
			Benzene				
Mean	115.58 (Kg)	120.69 (Kg)	2076.68 (Kg)	1.33 (Kg)	41.37 (Kg)	408.91 (Kg)	12.90 (Kg)
95% Lower	44.31	49.03	830.95	0.80	17.36	213.38	6.38
95% Upper	208.94	249.82	4342.17	2.09	84.88	726.23	23.86
Standard Deviation	41.83	52.77	914.57	0.33	17.49	132.71	4.51
			Formaldehyde				
Mean	276.58 (Kg)	27.99 (Kg)	262.18 (Kg)	6.29 (Kg)	73.67 (Kg)	107.19 (Kg)	103.15 (Kg)
95% Lower	105.99	11.42	109.55	2.87	38.51	54.42	52.82
95% Upper	484.93	58.08	543.21	12.46	131.24	198.32	187.76
Standard Deviation	96.01	12.17	113.23	2.51	23.84	37.07	34.55
			Total Aldehyde				
Mean	381.29 (Kg)	28.57 (Kg)	552.01 (Kg)	7.83 (Kg)	59.48 (Kg)	178.90 (Kg)	128.10 (Kg)
95% Lower	143.66	11.57	226.93	3.82	24.08	87.49	65.18
95% Upper	680.93	59.22	1128.04	15.03	124.13	333.76	236.19
Standard Deviation	136.82	12.44	236.67	2.93	26.21	63.95	43.90
			Total PAH				
Mean	13189.27 (Kg)	1.36 (Mg)	3788.22 (Kg)	34.61 (Kg)	1.52 (Mg)	9.58 (Mg)	5.23 (Mg)
95% Lower	5047.40	0.55	1519.45	20.69	0.62	3.04	2.68
95% Upper	23505.63	2.80	7635.97	54.63	3.15	15.79	9.47
Standard Deviation	4716.67	0.59	1586.97	8.78	0.66	3.12	1.76

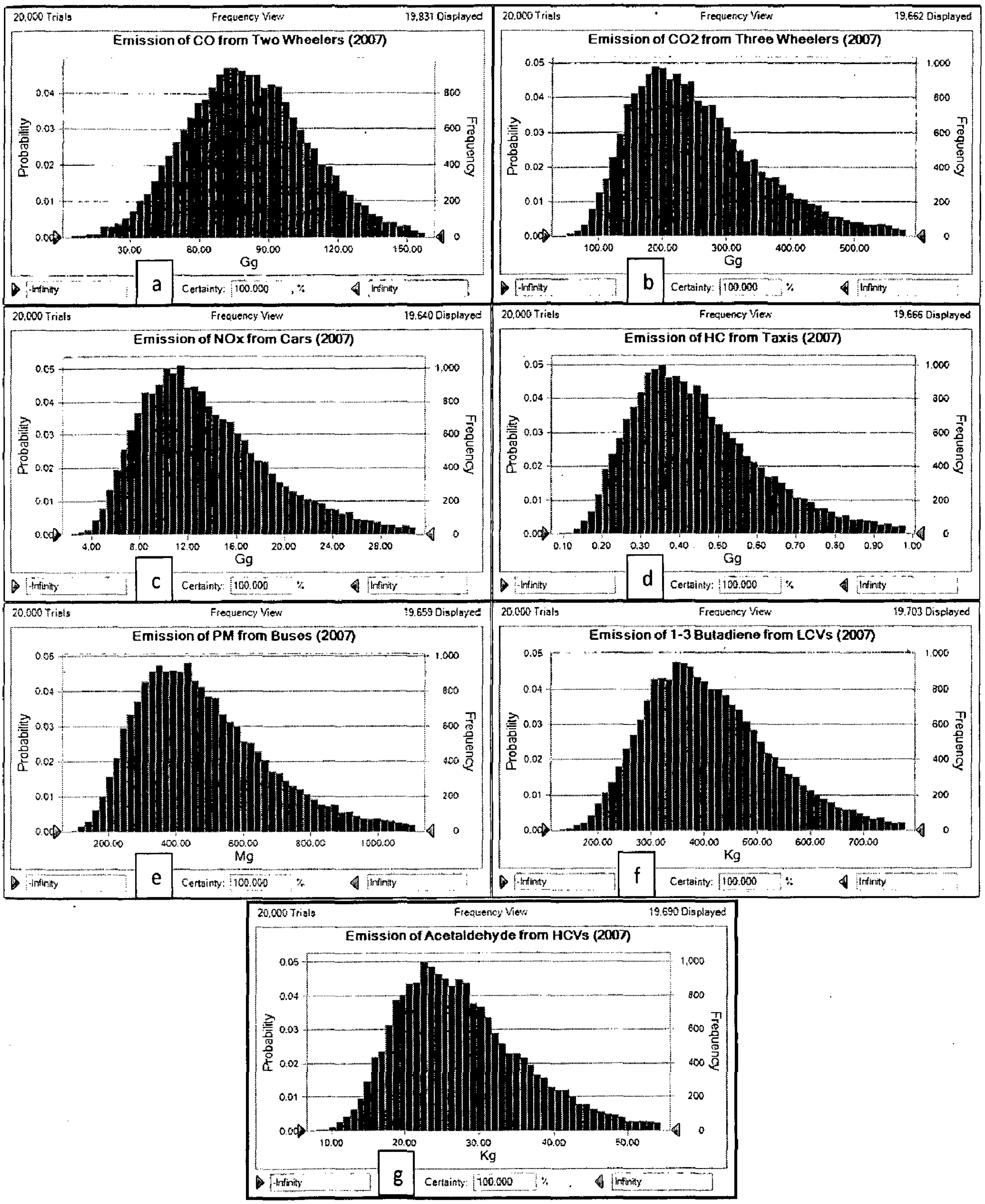


Fig.8.1: Probability distribution Function of (a) CO emission from two wheelers, (b) CO_2 emission from three wheelers, (c) NO_x emission from cars, (d) HC emission from taxis, (e) PM emission from buses, (f) 1-3 Butadiene emission from LCVs and (g) Acetaldehyde emission from HCVs in year 2007

8.3.2. Sensitivity Analysis

Sensitivity analysis, i.e. analysis of relative importance of input parameters used in the emission estimations of various pollutants released from different vehicle categories has also been carried out as described below.

8.3.2.1. CO emissions

Sensitivity analysis of important input parameters for CO emissions from various vehicle categories are given in Table 8.2. Based on % values of sensitivity estimations, this can be inferred that in case of two wheelers, vehicle kilometer travelled (VKT) has emerged as the most important parameter for CO emission estimates. While for three wheelers, cars, taxies, buses, LCV and HCVs, both population and VKT have emerged as important input parameters for CO emission estimations.

Table 8.2: Sensitivity analysis results of CO emissions from various vehicles categories.

Pollutants	Important sensitive input variable and their contribution in %
2Ws	VKT of all types of two wheelers (+81.6%), Population of two stroke scooter (+6.2%), Population of two stroke motorcycle (+5.7%), Population of four stroke motorcycle (+3.5%), Population of two stroke moped (+1.8%)
3Ws	Population of Three Wheeler (+48%), VKT of three wheeler (+47%), Temperature (+3.6%)
Cars	VKT diesel and petrol driven cars (+48.5%), Population of petrol driven car (+48.1%), Temperature (+1.9%)
Taxis	VKT CNG driven taxi (+38.6%), Population of CNG driven Taxi (+37.7%), Population of Petrol driven Taxi (+20.7%), Temperature (-1%)
Buses	Population of internal CNG buses (+48.6%), VKT of Internal CNG buses (+47.7%), VKT external buses (+1.6%), population external buses (+1.3%)
LCVs	VKT internal CNG LCV (+26.4%), Population internal CNG LCVs (+26.2%), Population internal diesel LCVs (+16.6%), VKT internal diesel LCVs (+16.1%), VKT diesel External LCVs (+6.7%), Population external LCVs (+6.5%)
HCVs	Population HCVs internal (+44.8%), VKT HCVs internal (+44.2%), Population External HCVs (+5.3%), VKT HCVs External (+4.9%)

8.3.2.2. CO_2 Emissions

Sensitivity analysis results for CO_2 emission from various vehicle categories are shown in Table 8.3. For CO_2 emissions from all two wheelers, VKT of all categories of two wheelers appears to play most important role. In case of three wheelers, however, their population and VKT are most dominating input parameters. For cars, VKT of diesel and petrol driven cars are the most important parameters followed by population of petrol driven cars. VKT of internal CNG driven buses is the most influencing input variable for CO_2 emissions, followed by population of CNG driven buses and external diesel buses. VKT of internal CNG driven LCVs is the most sensitive variable for CO_2 emissions from LCVs, followed by population of internal CNG driven LCVs, VKT and population of internal diesel driven LCVs. For HCVs, population of internal HCVs and their VKT are most sensitive variables.

Table 8.3: Sensitivity analysis results of CO_2 emissions from various vehicles categories.

Pollutants	**Important sensitive input variable and their contribution in %**
2Ws	VKT of all types of two wheelers (+81.7%), Population motorcycle four stroke (+10.7%), Population motorcycle two stroke (+2.6%), Population scooter two stroke (+1.6%), Population moped two stroke (+1.4%)
3Ws	Population of three wheelers (+49.8%), VKT of three wheeler (+49.0%)
Cars	VKT diesel and petrol driven cars (+50%), Population petrol driven car (+49%)
Taxis	Population CNG driven Taxi (+49.3%), VKT CNG taxi (+48.9%), Population taxi petrol (+0.9%), CO_2 emission factor CNG taxi year 2005 (+0.3%)
Buses	VKT internal CNG buses (+47.4%), Population of CNG buses (+46.9%), Population of external diesel buses (+2%), VKT external diesel buses (+1.8%),
LCVs	VKT internal CNG LCVs (+30.2%), Population internal CNG LCVs (30.2%), VKT internal diesel LCVs (+13.9%), Population internal diesel LCVs (+13.3%), Population external LCVs (+5.8%), VKT external diesel LCVs (+5.2%)
HCVs	Population internal HCVs (+47.7%), VKT internal HCVs (41.2%), VKT external HCVs (8.1%), Population external HCVs (+7.4%)

8.3.2.3. NO_x Emissions

Sensitivity analysis results for NO_x emissions from various vehicle categories are given in Table 8.4 in terms of % values. It shows that VKT of all two wheeler categories and population of two-stroke motorcycles are highly sensitive variables for NO_x emissions from two wheelers. Temperature and humidity are also sensitive variables, affecting NO_x emissions negatively. For three wheelers, VKT and population of three wheelers are the sensitive variable, affecting the NO_x emissions positively, while humidity is affecting it negatively. In case of cars, VKT of diesel and petrol driven cars and population of petrol driven cars affect NO_x emissions effectively. For taxies and buses their VKT and population are affecting significantly (positively). In case of LCVs, VKT of LCVs driven by CNG, population of internal CNG LCVs, population of internal diesel LCVs, VKT of internal diesel LCVs, VKT of external diesel LCVs, and population of external diesel LCVs affect considerably. Population of HCVs and their VKT are the major influencing input variables in case of NO_x emissions from HCVs.

Table 8.4: Sensitivity analysis results of NOx emissions from various vehicles categories.

Pollutants	Important sensitive input variable and their contribution in %
2Ws	VKT of all two wheeler categories (+60.8%), Population two stroke motorcycle (28.7%), Temperature (-5.4%), Humidity (-2.4%), Population four stroke scooter (+1.6%)
3Ws	VKT three wheeler (+48.9%), Population three wheeler (+48.8%), Humidity (-1.3%),
Cars	VKT diesel and petrol driven cars(+48.6%), Population petrol car (+47.9%), Emission factor NOx 1991 (+1.5%), Humidity (-0.9%)
Taxis	Population CNG Taxi (+49%), VKT Taxi CNG (+48.5%), Humidity (-1.2%)
Buses	Population internal CNG buses (+49.6%), VKT internal CNG buses (+48.8%), Emission Factor 2005 (+1.3%)
LCVs	VKT LCVs CNG internal (+34.3%), Population internal CNG LCVs (+33.7%), Population internal diesel LCVs (+11.4%), VKT internal diesel LCVs (+11.4%), VKT external diesel LCVs (+3.9%), Population external diesel LCVs (+3.8%)
HCVs	Population HCVs internal (+43.2%), VKT internal HCVs (+42.2%), Population external HCVs (+7.1%), VKT external HCVs (+6.6%)

8.3.2.4. HC Emissions

Table 8.5 shows the sensitivity analysis results of HC emission from various vehicle categories. It shows that VKT of all two wheelers, population of two stroke motorcycle, scooter and moped are prime variables which affect HC emissions from two wheelers. For three wheelers, cars, taxies and buses their VKT and population are highly sensitive parameters. In case of LCVs, VKT of CNG driven LCVs, population internal CNG driven LCVs, population internal diesel LCVs, VKT internal diesel LCVs, Population external diesel LCVs, and VKT external diesel LCVs are the most sensitive parameters. While in case of HCVs population internal HCVs, VKT of internal HCVs, VKT external HCVs and population external HCVs are the most sensitive parameter which affects the emission of HC from HCVs.

Table 8.5: Sensitivity analysis results of HC emissions from various vehicles categories

Pollutants	**Important sensitive input variable and their contribution in %**
2Ws	VKT for all two wheelers (+82.5%), Population of two stroke motorcycle (+7.2%), Population of two stroke scooter (+5.3%), Population of two stroke moped (+3.2%), Population of two four stroke motorcycle (+1.2%)
3Ws	VKT of three wheeler (+50.1%), Population of three wheeler (+49.1%)
Cars	VKT of diesel and petrol driven car (+49.4%), Population of petrol driven car (+48.9%)
Taxis	VKT of CNG taxi (+50.1%), Population CNG taxi (+49%)
Buses	VKT of internal CNG buses (+49.4%), Population of internal CNG buses (+48.9%)
LCVs	VKT CNG LCVs internal (+32.9%), Population internal CNG LCVs (+31.8%), Population internal diesel LCVs (+13%), VKT internal diesel LCVs (+12.9%), Population external diesel LCVs (+4.2%), VKT external diesel LCVs (+3.8%)
HCVs	Population internal HCVs (+46.1%), VKT internal HCVs (+45.1%), VKT external HCVs (+4.2%), Population external HCVs (+4.0%)

8.3.2.5. PM Emissions

Sensitivity analysis results for PM emissions from various vehicle categories have been shown in Table 8.6. For PM emission from two wheelers VKT of all two-wheelers is the most influencing variable followed by population of four-stroke motorcycles and two-stroke scooters. In case of three wheelers and cars their population and also VKT are most sensitive parameters. For taxies, VKT of CNG driven internal taxies and their population are most sensitive parameters. For PM emission from buses, VKT of external diesel buses and their population are highly sensitive variables. In case of PM emissions from LCVs, population of internal diesel LCVs, VKT of internal diesel LCVs, Population of external diesel LCVs and VKT of external diesel LCVs are most important parameters. For PM emission from HCVs, VKT of internal HCVs, population of internal HCVs, VKT of external HCVs and population external HCVs are most sensitive variables.

Table 8.6: Sensitivity analysis results of PM emissions from various vehicles categories

Pollutants	Important sensitive input variable and their contribution in %
2Ws	VKT of all two wheelers (+81.2%), Four stroke motorcycle (+8.1%), Two stroke scooter (+6.7%), Two stroke motorcycle (+1.6%), Two stroke moped (+1.5%)
3Ws	Population of Three wheeler (+50.4%), VKT of three wheeler (+48.7%),
Cars	Population petrol driven car (+50.1%), VKT diesel and petrol driven car (+48.9%)
Taxis	VKT CNG taxi (+48.5%), Population CNG taxi (+47.8%), Population petrol taxi (+2.5%)
Buses	VKT External buses (+49.5%), Population external diesel buses (+48.6%), Emission factor external diesel buses 2005 (+1.6%)
LCVs	Population internal diesel LCVs (+40.3%), VKT internal diesel LCVs (+38.5%), Population external diesel LCVs (+10.4%), VKT external diesel LCVs (+9.9%)
HCVs	VKT internal HCVs (+43.8%), Population internal HCVs (+41.5%), VKT external HCVs (+7.2%), Population external HCVs (+6.5%)

8.3.2.6. 1-3 Butadiene Emissions

Table 8.7 shows the sensitivity analysis results for 1-3 Butadiene emission from various vehicle categories. It is observed that VKT of two wheelers is highly sensitive variable, followed by population of four-stroke motorcycles, two-stroke motorcycles, four-stroke scooters and two-stroke scooter. VKT of three wheelers and their population are sensitive variables for 1-3 Butadiene emissions from three wheelers. For cars, population of petrol driven cars and their VKT are sensitive variables. In case of taxi, population of petrol driven taxi are major sensitive variable, followed by VKT and population of CNG taxies. For buses, population of external diesel buses and their VKT are major influencing parameters. In case of LCVs, VKT and population of internal and external diesel LCVs are prime parameters, which affect the emissions of 1-3 Butadiene from LCVs. For HCVs, VKT and population of internal and external HCVs are major parameters affecting the emission of 1-3 Butadiene.

Table 8.7: Sensitivity analysis results of 1-3 Butadiene emissions from various vehicles categories

Pollutants	**Important sensitive input variable and their contribution in %**
2Ws	VKT by all two wheelers (+80.7%), Population of fours stroke motorcycle (+6.7%), Population two stroke motorcycle (+5.1%), Population four stroke scooter (+4.2%), Population two stroke scooter (+1.9%)
3Ws	VKT three wheelers (+50.1%), Population three wheelers (+48.4%),
Cars	Population petrol driven car (+48.9%), VKT diesel and petrol driven car (+48.9%),
Taxis	Population of petrol driven taxi (+86.1%), VKT of CNG Taxi (+6.2%), Population of CNG taxi (+6.0)
Buses	Population of External diesel buses (+49.5%), VKT of external diesel buses (+48.9%),
LCVs	VKT internal diesel LCVs (+28.1%), Population of internal diesel LCVs (+27.4%), VKT of external diesel LCVs (+21.8%), Population external diesel LCVs (+21.3%)
HCVs	VKT internal HCVs (+43.8%), Population internal HCVs (+43.8%), Population of external HCVs (6.0%), VKT external HCVs (+5.6%)

8.3.2.7. Acetaldehyde Emissions

Sensitivity analysis results for Acetaldehyde emission from various vehicle categories have been given in Table 8.8. VKT of two wheelers and population of two-stroke scooters are major variables affecting Acetaldehyde emission from two wheelers. Similar to other pollutants, population of CNG driven three wheelers and their VKT are prime variables which affect emission of Acetaldehyde from this category. In case of cars, on the other hand, population of petrol driven cars and their VKT are more important factors. In case of taxies, population of CNG driven taxies and their VKT are parameters affecting Acetaldehyde emissions positively, while temperature affecting negatively. Population of internal CNG buses, VKT of internal CNG buses, VKT of external diesel buses and their population are most sensitive parameters which affect emission of Acetaldehyde significantly. For LCVs and HCVs their internal and external population and their VKT are more sensitive parameters.

Table 8.8: Sensitivity analysis results of Acetaldehyde emissions from various vehicles categories

Pollutants	**Important sensitive input variable and their contribution in %**
2Ws	VKT of two wheelers (+77%), Population two stroke scooter (+13.5%), Population four stroke scooter (+4.8%), Population two stroke moped (+1.9%)
3Ws	Population three wheelers (+49.6%), VKT three wheelers (+49.2%)
Cars	Population petrol driven car (+49.1%), VKT petrol and diesel driven car (+48.5%),
Taxis	Population of CNG taxi (+48.5%), VKT of taxi CNG (+48.3%), Temperature (-1.6%)
Buses	Population internal CNG buses (+27.7%), VKT internal CNG buses (+27.5%), VKT external diesel buses (+21.7%), Population external diesel buses (+20.8%), Temperature (-0.9%)
LCVs	Population internal diesel LCVs (+35.8%), VKT internal diesel LCVs (+35.5%), VKT external diesel LCVs (+13.8%), Population external diesel LCVs (+13.4%),
HCVs	Population internal HCVs (+41.9%), VKT internal HCVs (+40.6%), VKT external HCVs (+8.2%), Population external HCVs (+8.2%)

8.3.2.8. Benzene Emissions

Table 8.9 shows the sensitivity analysis results for Benzene emissions from various vehicle categories. VKT of two wheelers and population of four-stroke motorcycles are more sensitive parameters in case of Benzene emissions from two wheelers. Similar to other pollutants, VKT of three wheelers and their population are more sensitive parameters for Benzene emission from three wheelers. Population of petrol driven car, VKT of petrol and diesel driven cars are most sensitive variables in case of cars. Population of petrol taxis, VKT of CNG taxis, and their population are sensitive parameters for Benzene emission from taxies. For buses, population of external diesel buses and their VKT are more sensitive variables. Population and VKT of internal and external diesel LCVs and HCVs are sensitive parameters for LCVs and HCVs population.

Table 8.9: Sensitivity analysis results of Benzene emissions from various vehicles categories

Pollutants	Important sensitive input variable and their contribution in %
2Ws	VKT of two wheelers (+72.2%), Population four stroke motorcycle (+22.8%), Population two stroke scooter (+2.5%)
3Ws	VKT three wheelers (+49.6%), Population three wheelers (+49.5%)
Cars	Population petrol driven car (+49.1%), VKT petrol and diesel driven car (+47.9%), Emission factor 1991 (+2.4%)
Taxis	Population petrol taxi (+65.9%), VKT taxi CNG (+16.4%), Population CNG taxi (+15.5%)
Buses	Population external diesel buses (49.0%) ,VKT external diesel buses (+48.7%)
LCVs	Population internal diesel LCVs (+40.2%), VKT internal diesel LCVs (+39.5%), VKT external diesel LCVs (+10%), Population external diesel LCVs (+9.4%),
HCVs	Population internal HCVs (+45.2%), VKT internal HCVs (+44.9%), VKT external HCVs (+4.9%), Population external HCVs (+8.2%)

8.3.2.9. Formaldehyde Emissions

Table 8.10 shows the sensitivity analysis results of Formaldehyde emission from various vehicle categories. For two wheelers most sensitive input variable is the VKT of two wheelers. Also, populations of four-stroke scooters and two-stroke scooters and of two-stroke mopeds are the variables that have minor influence on Formaldehyde emissions. Three wheeler population and their VKT are parameters which affect Formaldehyde emissions significantly. VKT of petrol and diesel driven cars and population of petrol driven cars are the parameters which significantly influence the emission of Formaldehyde from cars. In taxies, their population and VKT are the parameters which affect Formaldehyde emissions positively, while temperature is the parameter which affects the emissions negatively. In case of buses, population and VKT of external diesel buses, VKT and population of internal CNG buses are the most important parameters affecting Formaldehyde emissions. For LCVs, population and VKT of internal and external diesel LCVs are more important parameters as par their contribution in Formaldehyde emission from LCVs. In case of HCVs, population internal HCVs their VKT, VKT of external HCVs and their population are important input parameters.

Table 8.10: Sensitivity analysis results of Formaldehyde emissions from various vehicles categories

Pollutants	Important sensitive input variable and their contribution in %
2Ws	VKT of two wheelers (+78.6%), Population four stroke scooter (+9.3%), Population two stroke scooter (+4.6%), Population of two stroke moped (+4.2%)
3Ws	Population three wheelers (+49.7%), VKT three wheelers (+49.2%)
Cars	VKT petrol and diesel driven car (+49.3%), Population petrol driven car (+49.0%), Emission factor 1991 (+1.1%)
Taxis	Population CNG taxi (+49.0%), VKT taxi CNG (+47.6%), Temperature (-1.7%)
Buses	Population external diesel buses (39.3%) ,VKT external diesel buses (+39.0%), VKT internal CNG buses (+9.8%), Population internal CNG buses (+9.7%)
LCVs	Population internal diesel LCVs (+47.5%), VKT internal diesel LCVs (+46.3%), Population external diesel LCVs (+2.7%),VKT external diesel LCVs (+2.2%),
HCVs	Population internal HCVs (+42.7%), VKT internal HCVs (+42.2%), VKT external HCVs (+7.1%), Population external HCVs (+7.1%)

8.3.2.10. Total Aldehyde Emissions

Sensitivity analysis results of total Aldehyde emission are given in Table 8.11. Similar to other pollutants, VKT of two wheelers is most sensitive input parameter which affects total Aldehyde emissions significantly. While other parameters are population of two stroke scooters and moped and four-stroke motorcycle that have minor effect. Population of three wheelers and their VKT are most sensitive parameter for total Aldehyde emission from three wheelers. VKT of petrol and diesel driven car and population of petrol driven car are sensitive parameters for total Aldehyde emission from cars. Similar to cars, VKT of taxi fueled by CNG and their population are sensitive parameters for total Aldehyde emissions from taxies. In case of buses VKT of external diesel buses and their population are more responsible parameters for total Aldehyde emission. For LCVs and HCVs, VKT and population of internal and external diesel LCVs and HCVs, are more sensitive parameters.

Table 8.11: Sensitivity analysis results of total Aldehyde emissions from various vehicles categories

Pollutants	Important sensitive input variable and their contribution in %
2Ws	VKT of two wheelers (+74.7%), Population two stroke scooter (+16.8%), Population two stroke moped (+3.7%), Population of four stroke motorcycle (+1.9%)
3Ws	Population three wheelers (+49.8%), VKT three wheelers (+49.3%)
Cars	VKT petrol and diesel driven car (+49.5%), Population petrol driven car (+48.7%)
Taxis	VKT taxi CNG (+48.8%), Population CNG taxi (+48.4%), Population petrol taxi (+1.9%)
Buses	VKT external diesel buses (+49.4%), Population external diesel buses (49.2%)
LCVs	VKT internal diesel LCVs (+46.8%), Population internal diesel LCVs (+46.3%), VKT external diesel LCVs (+3.4%), Population external diesel LCVs (+2.8%)
HCVs	Population internal HCVs (+43.4%), VKT internal HCVs (+42.9%), VKT external HCVs (+7.0%), Population external HCVs (+5.8%)

8.3.2.11. Total PAH Emissions

Table 8.12 shows the sensitivity analysis results for total PAH emission from various vehicle categories in year 2007. VKT of two wheelers is the most important parameter for total PAH emission from two wheelers, while population of four stroke motorcycle, two stroke scooter, and moped are other important input variables. Similar to other pollutants, VKT and population of three wheelers are the most sensitive parameters for total PAH emission from three wheelers. VKT of petrol and diesel cars and population of petrol car are important parameters for total PAH emission from cars. Population of petrol driven taxies, CNG taxi and its VKT are more sensitive parameters for total PAH emission from taxies. For buses, VKT of external diesel buses and their population are more sensitive variables. In case of LCVs, population of external diesel LCVs its VKT and population of internal diesel LCVs and its VKT are more sensitive variables. Population of internal HCVs their VKT and VKT external HCVs and their population are sensitive parameters in case of total PAH emission from HCVs.

Table 8.12: Sensitivity analysis results of total PAH emissions from various vehicles categories

Pollutants	Important sensitive input variable and their contribution in %
2Ws	VKT of two wheelers (+75.2%), Population four stroke motorcycle (+15.3%), Population two stroke scooter (+5.0%), Population of two stroke moped (+3.4%)
3Ws	VKT three wheelers (+50%), Population three wheelers (+49.2%),
Cars	VKT petrol and diesel driven car (+49.6%), Population petrol driven car (+49.4%)
Taxis	Population petrol taxi (+50.4%), Population CNG taxi (+24.6%), VKT taxi CNG (+23.1%),
Buses	VKT external diesel buses (+49.6%), Population external diesel buses (48.9%)
LCVs	Population external diesel LCVs (+41.7%), VKT external diesel LCVs (+41.5%), Population internal diesel LCVs (+8.0%), VKT internal diesel LCVs (+7.2%),
HCVs	Population internal HCVs (+42.0%), VKT internal HCVs (+41.9%), VKT external HCVs (+7.7%), Population external HCVs (+7.3%)

8.3. CONCLUSION

Uncertainty and sensitivity analysis for emissions of various pollutants from different vehicle categories have been carried out for the year 2007. On the basis of above, it can be concluded that available uncertainty of each vehicle categories for various pollutants are almost same because of similar dominating variables like vehicle population and VKT. For two wheelers the uncertainty ranged from 60-95% for various pollutants. For cars, the lower level of uncertainty of all pollutants from its mean value is 58% while upper level is 109%. For taxis, uncertainty range in emissions of various pollutants is 40-100%. For buses minimum uncertainty level of various pollutants is 47% while maximum is 110%. About 41-86% of uncertainty is observed in emissions of various pollutants from LCVs population, while for HCVs this range lies between 48-86%. Sensitivity analysis performed for various pollutants from different vehicle categories show that VKT of most of the vehicles and their population are the most sensitive parameters that affect the emission estimates positively. Whereas, in some cases temperature and humidity are the parameters which influence the output negatively but the contribution of these parameters is relatively less.

CHAPTER 9

Conclusions and Recommendations

9.1. ACHIEVEMENTS

The level of air pollution in urban areas, which is largely affected by road traffic, is an issue of high importance due to its environmental and human health implications. This study focuses on modeling of vehicular emissions in megacity Delhi along with assessment of their health impacts and uncertainty/sensitivity analysis. Chapter 1 gives the general introduction of study and presents extensive literature review. To understand the health risk potential of ambient air pollution in megacity Delhi, human health risks have been estimated using Ri-Map model in Chapter 2. Furthermore, given the fact that emission inventory is the basic building block of any air pollution management program, formulation and development of an emission inventory model; namely Vehicular Air Pollution Inventory (VAPI) model has been carried out in Chapter 3.

Chapter 4 presents the impact of altitude, temperature and humidity on emission of various pollutants (e.g., CO, HC, 1-3 Butadiene, Formaldehyde and Acetaldehyde) from different vehicles. With concern to impact of altitude, temperature and humidity, the following conclusions were drawn from this study:

- With respect to CO, NO_x, 1-3 Butadiene, Formaldehyde and Acetaldehyde emissions in all three cities (Delhi, Dehradun and Mussoorie), emissions of certain air pollutants (e.g., CO, 1-3 Butadiene, Formaldehyde and Acetaldehyde) are increasing with altitude from two wheelers while emissions of NO_x are decreasing with increasing altitude. With respect to contributions among all two wheeler categories, the four-stroke scooters emit least amount of CO in all three cities while it is highest from two-stroke scooters. Among all the two-wheeler categories, emission rate of two-stroke moped is least with respect to NO_x and 1-3 Butadiene emissions in all three cities, whereas for Formaldehyde and Acetaldehyde, two-stroke motorcycles are the least emitters.

- CO emissions decrease with increasing altitude from petrol driven cars while for CNG and LPG it is increasing with altitude. In case of NO_x, emissions from petrol driven cars decrease with increasing altitude while in case of CNG it is increasing. Nevertheless, there is no significant effect of altitude observed on LPG driven car. Further, 1-3 Butadienes, Formaldehyde and Acetaldehyde emissions are decreasing with increasing altitude for petrol driven cars, while for LPG and CNG they are increasing. There is no effect of altitude on diesel driven cars for emissions of any pollutant. Emission rate of CO from diesel driven cars is least among all types of car categories in all the three cities. For NO_x and Acetaldehyde, however, emission rate of petrol driven car is least among all categories, while 1-3 Butadiene and Formaldehyde are emitted in least amount from CNG and LPG fueled cars, respectively.
- With respect to increasing altitude, emissions of CO, 1-3 Butadienes, Formaldehyde and Acetaldehyde from petrol driven four-stroke and two-stroke three wheeler are increasing while for NO_x it is decreasing. For CNG and LPG driven two-stroke and four-stroke three wheeler emissions of NO_x and CO are decreasing with increasing altitude while no effects of altitude is observed on emission of 1-3 Butadienes, Formaldehyde and Acetaldehyde from CNG and LPG driven two-stroke and four-stroke three wheeler. In case of three wheelers, the diesel driven ones emit least CO, while NO_x emission from four-stroke LPG driven three wheelers is least. Emission rate of 1-3 Butadiene from four-stroke petrol driven three wheelers is least among all categories of three wheelers. For Formaldehyde and Acetaldehyde, emission rate of two- and four-stroke CNG three wheelers is least, respectively.
- Emissions of CO, NO_x, 1-3 Butadienes, Formaldehyde and Acetaldehyde from diesel driven buses are increasing with altitude. Emissions of 1-3 Butadienes, Formaldehyde and Acetaldehyde from CNG buses also increase with altitude while in case of NO_x the trend is reversed (i.e. decreasing with altitude). Emission rate of CO is least from diesel driven buses, while for NO_x, 1-3 Butadiene, Formaldehyde and Acetaldehyde CNG buses have least emission rate.
- There are no effects of altitude on emissions of CO, NO_x, 1-3 Butadienes, Formaldehyde and Acetaldehyde from diesel driven LCVs. In case of CNG driven LCVs, emissions of

CO, 1-3 Butadienes, Formaldehyde and Acetaldehyde are increasing with altitude while for NO_x it is decreasing. Emission rate of CO, NO_x, Formaldehyde and Acetaldehyde is least from diesel driven LCVs, while for 1-3 Butadiene the CNG driven LCVs have least emission rate.

- Emissions of CO, NO_x, 1-3 Butadienes and Formaldehyde from diesel driven HCVs is increasing with increasing altitude. In case of CNG driven HCVs, emissions of CO, 1-3 Butadienes, Formaldehyde and Acetaldehyde are increasing with increasing altitude while for NO_x it is decreasing. In case of HCVs, contribution of CNG driven HCVs is least for almost all the pollutants.

Chapter 5 describes the emission inventory of eleven types of pollutants (CO, NO_x, PM, HC, CO_2, Benzene, 1-3 Butadiene, Formaldehyde, Acetaldehyde, Total Aldehyde and Total PAH) from various vehicle categories for the period of 1991 to 2010. Validation of NO_x and CO emissions have also been carried out by comparing their trend with ambient air quality concentrations. The overall conclusions of this chapter are given below:

- Emissions of most of the pollutants from two wheelers are increasing from 1991 to 2000, while sudden decrease is observed in 2001 because of phasing out of the two wheelers. Emissions of CO, HC, Acetaldehyde and total Aldehyde from two wheelers during 2002 to 2006 show quite similar trends (decreasing or stable) with each other, while other pollutants show increasing trend. Emissions of CO, HC, PM, Benzene and total PAH decreased between 2006 and 2007 because of change in emission factors for newly modeled two-wheelers, while emissions of other pollutants are increasing from 2006 to 2010.
- Emissions of CO, CO_2, NO_x, HC, PM, Formaldehyde, Total PAH, Total Aldehyde from car population show continuous increasing trend from 1991 to 2010 with slight fall in emissions in 2001 because of phasing out of car population in that year. Emissions of 1-3 Butadiene, Acetaldehyde and Benzene show quite stagnant or modest increase during 1996 to 2010, the reason being lower emission factor for new model cars.

- Emissions of CO, HC, PM, Acetaldehyde, Formaldehyde, Total Aldehyde and Total PAH from three-wheelers show similar trend from 1991 to 2010. Initially from 1991 to 1999 emissions of these pollutants show fluctuating trend because of little change in on-road three wheeler population and emission factors for three wheelers. From 1999 to 2002 emissions of these pollutants are decreasing because of phasing out of old vehicles and CNG conversion program by the Delhi government. Large decrease is observed between 2001 and 2002 because of CNG norms strictly implemented in this year. After 2002, however, emissions of these pollutants started increasing, whereas sudden increase is observed in the year 2005 and 2009 because of change in emission factor and three wheelers population (more emission factor for new model three wheelers). Emissions of other pollutants increase from 1991 to 2010 because of lower emission factors for previous year models (1991-2001) and higher emission factors for latest year models (2002-2010). Initially from 1991 to 2001 the contribution of petrol driven cars is higher, while 2002 onwards the share of CNG driven three wheelers increases because of their higher population.
- Emissions of most of the pollutants from taxies are increasing from 1991 to 2001. Except HC and CO_2, emissions of all other pollutants have decreased between 2001 and 2002 because of CNG conversion and phasing out of old vehicles. The reason behind increment of HC and CO_2 in year 2002 is higher emission factor of CNG driven taxies. From 1991 to 2001 the contribution of petrol and diesel driven taxies is higher for most of the pollutants because of their higher populations, while 2002 onwards the contribution of CNG driven taxies increased for most of the pollutants (e.g. CO, CO_2, NO_x, HC, Acetaldehyde, Formaldehyde, Total Aldehyde and Total PAH) due to their rising population. Contribution of CNG driven taxies for some pollutants (PM, 1-3 Butadiene, Benzene) is very less from 2002 onwards because of their very less emission factors.
- From 1991 to 1999 most of the pollutants show increasing emission trend from buses, while after 2000 onwards different pollutants show different trends. Emissions of CO, HC, PM, 1-3 Butadiene and Acetaldehyde show decreasing trend during 2000 and 2001 due to less emission factors for recent model buses, while other pollutants show

increasing trend due to higher emission factors for recent model buses. Except HC all pollutant emissions declined between 2001 and 2002 because of phasing out of old buses and CNG conversion program for buses. HC did not show decrement due to high emission factor of CNG buses introduced in 2002. After 2002 emissions of most of the pollutants are increasing, while in 2005 sudden increase in emissions is observed due to introduction of additional 19000 buses by the Government of Delhi. Initially from 1991 to 2001 the contribution of diesel buses for emission of various pollutants is higher, while 2002 onwards contribution of CNG driven buses is higher for most of the pollutants except PM, 1-3 Butadiene and Benzene.

- Emissions of CO, CO_2, NO_x, HC from LCVs population show quite similar trends. Initially from 1991 to 2000, emissions of these pollutants are increasing, while decline is observed in 2001 and 2002 because of phasing out program by the Government of Delhi. After 2002, emissions of these pollutants increase gradually till 2010. Emissions of PM, Acetaldehyde, Benzene, Formaldehyde and Total Aldehyde from LCVs show similar trend. Initially from 1991 to 1999 emissions show an increasing trend, while 2000 onwards emissions are gradually decreasing.
- From 1991 to 2000, emissions of CO, HC and Benzene from HCVs are increasing, while 2001 onwards decline in emissions is observed which continued till 2010. Emissions of other pollutants show increasing trend from 1991 to 1999, and after a decline from 2000 to 2002, emissions follow again an increasing trend.
- This is observed that emissions of NO_x and CO estimated by using VAPI model follow similar trends and statistically show close proximity to that of their ambient air concentrations near traffic junctions, which indirectly validate the VAPI model.

Emissions of various pollutants from different vehicle categories in BAU and BES scenarios are described in Chapter 6. As compared to BAU scenario, emissions of CO from BES scenario are estimated 10-18% less in future years (2011-2020) from all vehicle categories. In case of CO_2, about 10-16% difference is observed between BAU and BES scenarios from 2011-2020. NO_x emissions from all vehicle categories in BES scenario are also less in comparison to BAU scenario. In 2011, NO_x emissions in BES are 7% lower than BAU scenario, followed by 12% in 2015 and 13% in 2020. Similar to above mentioned pollutants, emission of other pollutants from all vehicle categories are also higher in BAU scenario than in BES scenario. On the basis of scenario based studies it can be inferred that shifting of passengers from personal vehicles to public transport (e.g., metro rail) and conversion of two-stroke two wheelers to four-stroke will reduce emissions of several pollutants in megacity Delhi. Government should provide better facility in public transport for shifting of passengers from cars to public transport as the car population has highest percentage share among most of the emissions.

As discussed in Chapter 7, evaporative emissions of VOCs from different vehicle categories are increasing with about 11% annual average growth rate from 1991 to 2010. Initially the share of two wheelers in VOC emissions was higher while after 1999 it started to decrease because of increasing share of petrol car population and implementation of CNG for buses, three wheelers and taxis. In case of road dust suspension emissions (PM10 and PM2.5), the share of HCVs and buses population is higher. On the other hand, for emissions of PM10 and PM2.5 from tyre wear, cars share highest percentage because of their higher population. For emissions ofPM 10 and PM2.5 from brake wear the contributions of HCVs, buses and cars population are higher than other vehicles.

Chapter 8 gives idea about the uncertainty introduced in emission estimates of various pollutants from different vehicle categories due to uncertain input parameters. Highest uncertainty is observed in the emissions of various pollutants from three wheelers, cars, buses and taxies while least is from LCVs. With concern to percentage variation of standard deviation, 95% upper and lower limits for most of the pollutants from separate vehicle categories are almost same because of same variables (e.g., vehicle population, VKT) used for calculating the emissions. It also describes the sensitivity of various input parameters used in emission estimations. Sensitivity analysis results of various pollutants from different vehicle categories show that VKT of most of the vehicles and their population are more sensitive parameters, which affect the output positively. While in some cases temperature and humidity are the parameters which affect the output negatively but the net contribution of these parameters is less. This is inferred that it is very important to ensure accuracy of VKT related data. They must be obtained based on wide field surveys to ensure that the values of VKT used in model are authentic enough to give reliable results.

9.2. RECOMMENDATIONS

- It is observed from the health risk study that North-West Delhi district of megacity Delhi has highest value for excess number of cases of total mortality, respiratory mortality, cardiovascular mortality, hospital admissions COPD disease from 2002 onwards. Thus, the Delhi Government can think of enforcing suitable norms (to reduce particularly SPM and NO_x emissions (e.g., to discourage vehicles entering into the core zone of the district by introducing an entry fee or extra tax).
- At present, emission factors are available only for few vehicle categories and less number of vehicle models. Research efforts are required to generateemission factors for more vehicle categories and models so that more reliable estimations of emissions can be accomplished.
- No data are available at present related to inspection and maintenance of vehicles in India. Strict enforcement of emission regulations is required so that people can be motivated to make their vehicles regularly inspected and maintained for less tailpipe emissions.
- For many vehicle types (especially personal vehicles like car) emissions of various pollutants like CO, 1-3 Butadiene, Formaldehyde and Acetaldehyde are increasing with high altitudinal city like Mussoorie where tourist flotation is high. Some policy mechanism can be developed to restrict use of such vehicle categories in high altitude tourist places.
- Emission estimates based on VAPI model show that for most of pollutants (CO, CO_2, HC, 1-3 Butadienes, Acetaldehyde, Benzene, Formaldehyde, total aldehyde, total PAH) the share of personal vehicles such as cars and motorcycles are higher in megacity Delhi. Therefore, appropriate policy measures are required to promote more use of public transport in Delhi. Moreover, suitable technological interventions are required to reduce tailpipe emissions from personal vehicles (e.g., cars and two-wheelers).
- It is observed from the uncertainty and sensitivity analysis that VKT and vehicle population are most uncertain parameters and significantly influence the emission estimations for different vehicle categories. This is, therefore, an urgent need to improve the accuracy of these input parameters to construct less uncertain emission inventories for vehicles.

9.3. FUTURE SCOPE

- The relative risk values used in Ri-MAP model to calculate both mortality and morbidity are associated with cohort studies primarily conducted in the United States. Thus, there is inherent uncertainty in such results when we use them to assess health risks in cities of other countries like India. There is an urgent need and scope to conduct such type of studies to evaluate relative risk for mortality and morbidity in Indian conditions.
- We have calculated health risk based on the annual average values of pollutant concentration, which might be giving erroneous results because ambient air concentration and daily exposure vary quite significantly. There is scope to estimate health risk based on daily average concentration data, which might give more accurate results.
- For calculating health risks, effects of the separate pollutants are only considered in the study while there is possibility of synergistic affects of mixture of pollutants on human health. Hence, there is scope for future researchers to develop such health risk models that consider synergistic effects of mixture of pollutants.
- VAPI model considers only average VKT for emission estimations. There is scope to improve the model by incorporating driving cycle related calculations. However, the requisite for this is to conduct driving cycle related studies in various cities of India so that real-world field data for Indian conditions are available to get them used in the model.
- VAPI model is calculating emissions of 11 types of pollutants from 23 vehicle categories. Moreover, it considers only three geographic and climatic correction factors for Indian conditions. Therefore, there is opportunity for future researchers to modify and improve the model in such a way so that it can consider more pollutants, vehicle categories and other parameters (e.g., inspection and maintenance, road conditions, driving patterns, etc.) to widen the scope and usability of the model.

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3. Gurjar, B. R., **Nagpure, A. S.**, Kumar, Prashant, Sahni, Nalin, 2010. Pollutant Emissions from Road Vehicles in Mega-City Kolkata, India: Past and Present Trends. Indian Journal of Air Pollution Control, Vol.X No.2 September 2010 pp 18 to 30, mypages.surrey.ac.uk/m01455/Gurjar-Kumar-Kolkata(2011).pdf.
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