MATHEMATICAL MODELLING OF URBAN TRAFFIC AIR POLLUTION IN MINNA METROPOLIS, NIGERIA

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ABSTRACT

Vehicular exhaust emissions are a dominant source of air pollution and contribute significantly to greenhouse gases and human health problems. An improved dispersion model designed to estimate pollutant concentrations near travel ways of urban streets was developed and its performance evaluated. The model has four inbuilt parameters namely; the aerodynamic coefficient, the wind speed offset, the effective release height and the street wind turbulence coefficient. The model was calibrated with field data collected in Mobil-Bosso Road in Minna using a gas analyzer with detector tubes. The model's performance was evaluated and compared with Calder's and OSPM models. The model adequately simulated the concentrations of the pollutants and resulted in a percent error margin less than 10 for all the pollutants considered. The model was validated with data collected in a Copenhagen (Denmark) study for Nitrogen dioxide and was found to over predict the measured concentrations by 4%, which was considered adequate. The model requires less user inputs and modeller expertise and could be used by local authorities or air quality monitoring units in a variety of applications including, but not limited to, air quality and traffic management, urban planning and population exposure studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ABBREVIATIONS, GLOSSARIES AND SYMBOLS

The principal symbols used in this write up are listed below. Others have been explained in the pages where they have been used.

C   Steady state concentration of pollutant at receptor (g/m^3, ppm)

C_o, C_{oi} Measured concentration of pollutant (g/m^3, ppm)

$\overline{C_o}$ Average of measured pollutant concentration (g/m^3, ppm)

C_p, C_{pi} Modelled concentration of pollutant (g/m^3, ppm)

$\overline{C_p}$ Average of modelled pollutant concentration (g/m^3, ppm)

CO_2 Carbon dioxide

CO   Carbon monoxide

e_f Emission factor for a specific pollutant (g/km/veh, g/m/veh)

erf   Error function value

H   Source height with respect to ground level (m)

J, M, N Brigg's stability constants

NO_2 Nitrogen dioxide

NO_x Nitrogen oxides

Q   Source emission rate (g/s)

σ_w Vertical turbulence velocity fluctuation (m/s)

σ_{wo} Traffic created turbulence (m/s)

σ_y Horizontal Gaussian dispersion coefficient (m)

σ_z Vertical Gaussian dispersion coefficient (m)

S^2 Surface area of individual vehicle (m^2)

θ   Angle between wind vector and line source, also angle between wind and perpendicular to line source

T_r	Traffic flow rate (veh/s)
u	Mean ambient wind velocity (m/s)
V	Average vehicle speed (m/s)
W	Width of street (m)
Y	Horizontal distance from plume centre-line
z	Height of receptor with respect to ground level

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Air pollution is the contamination of the atmosphere by the discharge or emissions of undesirable substances and gases, or their formation from the emissions by chemical reactions in the atmosphere. This definition identifies primary and secondary pollutants. The primary pollutants are emitted directly into the atmosphere, while the secondary pollutants are formed by the chemical reactions involving the primary pollutants. Primary pollutants include nitrogen oxides, volatile organic compounds and carbon monoxide. Tropospheric ozone is an example of a secondary pollutant which is photo chemically produced (Aghedo, 2007).

Agriculture is the principal source of employment and income for most poor people in Africa. Despite the slow economy, rapid urbanization occurred in some regions of Africa, for example Nigeria, caused by rural–urban migration due to a combination of factors serving as incentives to migrants, which include social amenities, industry, schools and health-care facilities (Afolayan, 1985). The population of Lagos, Nigeria has increased from 1.7 million in 1975 to about 10.9 million in 2005, and it is projected to become the first and the eleventh most populous city in Africa and the world, respectively by 2015 (UN Urbanization Prospects, 2005), with about 16 million inhabitants. The rapid urbanization has resulted in increasing air pollution emissions, typically arising from transportation, energy production and industrial activities, concentrated in densely populated areas (Gujar *et al.,* 2008) and surpassing the limits of the cities' physically occupied areas, thus contributing significantly to air quality on a global scale through the long range transport of air pollutants (Gujar and Lelieveld, 2005; Butler and Lawrence, 2009). The low economic power implies that

most vehicles in Africa are old or used ones imported from Europe and elsewhere. There have not been corresponding infrastructure development and economic improvements to stem the production of anthropogenic pollutants. It has been reported by Savile (1993) that nearly 50% of global carbon monoxide, hydrocarbon and nitrogen oxides emissions from fossil fuel combustion come from gasoline and diesel powered engines. He further stated that in the city centres, especially on highly congested streets, motor traffic is responsible for as much as 90-95% of ambient carbon monoxide levels, 80-90% of the nitrogen oxides and hydrocarbons and a large portion of particulates, posing significant threats to humans and natural resources. Urban areas are characterized by high population density and economic development. The resulting pollutant emissions place an increasing pressure on the air quality of these areas. Borrego *et al*., (2000) wrote that the major current air pollutants come from road traffic, whereas in the past the major reasons for poor air quality were industrial activity and domestic heating.

Although, African anthropogenic emissions are currently much lower than those in other parts of the world (Aghedo, 2007). This may change in the future, due to industrial advancement, transfer of old technologies from Western world and continued increase in urbanization. Biomass burning and natural sources dominate emissions in Africa, while the emissions of industrialized countries are mainly anthropogenic in origin. This is due to higher energy consumption and industrial activities in industrialized countries than in Africa. For example the total energy consumed by the Organization for Economic Cooperation and Development (OECD) countries in the year 2003 was about 56% of the total energy consumed by the world, despite the fact that these countries are just 18% of the world population (International Energy Outlook, 2006). Natural emissions in Africa are mainly from vegetation and soil,

lightning NO_x emissions. Africa contributes a significant amount to the global emissions from these three sources, while emissions from fossil fuel combustion are important only on the regional scale (Aghedo, 2007).

1.2 Problem Statement

Present day urban environment are mostly dominated by traffic emissions. Economic crisis in most developing countries has led to a fall in the purchasing power of many middle class citizens. This has led to a geometric aging of the vehicular fleet. Even when the populace wishes to buy cars, low income levels have been an incentive to import older used vehicles in recent years, to use cheap two-wheelers and to postpone maintenance (Faiz *et al.*, 1994). In the urban environments and especially in those areas where population and traffic density are relatively high, human exposure to hazardous substances is expected to be significantly increased. This is often the case near busy traffic axis in city centres where urban topography and microclimate may contribute to the creation of poor air dispersion conditions giving rise to contamination hot spots. Traffic density in most city streets is high. The combination of traffic congestion and poor road network can lead to large vehicle emissions and to high levels of pollution within the street. It is at kerbside locations where the general public suffers common exposures to the highest concentration of pollutants (Baumbach *et al*., 1995; Buckland and Middleton, 1997). It is therefore quite expedient that the levels of concentrations of the pollutants from motorized traffic be measured and monitored. A model will be beneficial in its application in situations where no measurements can be obtained. Local authorities through the use of a model, will assess air quality in their areas against targets set by the government and propose proper traffic management policies.

1.3 Aim and Objectives

The aim of this work is to provide modelling tools for the determination of traffic generated air pollution in streets in Minna metropolis in Nigeria.

The specific objectives include:

1. to develop, calibrate and validate an air pollution model for motorized traffic in streets in Minna metropolis.

2. to investigate and determine in volumetric terms, the nature and quantity of some vehicular exhaust pollutants.

3. to measure and obtain emission factors for vehicular traffic in Minna from the analysis of local driving patterns.

1.4 Justification

Transport is contributing more and more significantly to a number of environmental and human health problems, particularly climate change, acidification, ground level ozone formation, local air pollution and noise (Saija and Romano, 2002). Emissions from transport are an often dominant source of air pollution and contribute significantly to greenhouse gases and energy use. Transport has been said to account for 16% of greenhouse gases linked to human activities worldwide (Westmoreland *et al*., 2007). Some of these pollutants contribute to global warming and climate change. Global warming and climate change are two issues that have preoccupied scientists as the Earth is facing a potential danger from natural and manmade sources of pollution. The study of the contribution of the most potent anthropogenic source (motorized traffic) to pollution especially greenhouse gases like Carbon dioxide is quite apt. Carbon dioxide represents more than 95% of the greenhouse gases in the transport sector (Nicolas and David, 2009). At present scientists posit that the increase in the Earth's temperature is due partly to human activities, the chief cause being the burning

of fossil fuels like coal, oil and natural gas which release Greenhouse gases and other substances to the atmosphere. The potential consequences of global warming are so great that many of the world's leading scientists have called for international cooperation and immediate action to counteract the problem. To assess the present and future state of emissions from transport and to evaluate different policies for reducing emissions require the development and application of emission models which are accurate, reliable, consistent and credible.

No locally developed modelling tools exist for environmental protection agencies like the National Environmental Standards and Regulations Enforcement Agency (NESREA) in charge of pollution management and control in Nigeria. There is also no State or Federal regulation as regards traffic air pollution. In more developed climes effective control and efficient reduction of pollutant emissions from automobiles are major focuses of environmental scientists and legislation. Many have argued that the development of air quality regulations and advances in motor vehicle emission reduction technology can curb the environmental pollution. Although these may be true, yet these, in many places are often offset by the increase in the number of automobiles.

Most city roadside traders and dwellers are not aware of the dangers of being exposed to these pollutants. The adverse health effects of roadway-generated pollution have remained major environmental and public concerns. This work would provide awareness for the city dwellers as regards dangers involved in exposing themselves to these pollutants.

1.5 Scope and Limitation of the Work

This work was limited to the development of an improved finite line source model. This is because air pollution dispersion from road traffic has been found to be

Gaussian and treatment of the source had been in the form of a line source. Other pollution sources were not included in the study because the focus of the work was modelling traffic air pollution. Minna was chosen as a case study because it is not home to industries which may constitute a great proportion of background pollution. Minna is a diverse, poorly planned urban sprawl that forces higher rates of motor vehicle use which in turn is expected to increase levels of pollutant emitted. Furthermore the study did not take into consideration roads in the rural areas because of the low population density and economic activity. High population density and economic activities are characteristic of urban areas where the resulting pollutant emissions place an increasing pressure in the air quality of the areas. The work was further limited to the study of gaseous pollutants since most of the vehicles in city streets in Nigeria are cars and motor cycles, whose main pollutants are gaseous as they use premium motor spirit (PMS) or petrol different from the particulate matter discharged from diesel engine vehicles. The work was also limited to measuring concentration of the pollutants and not a study of the chemistry of their formation and deposition since concentrations are influenced primarily by meteorological parameters such as wind speed and direction.

The work also involved a study of the local driving patterns and development of emission factors for the local traffic. This was necessary because the variables used in the calibration and validation of some existing line source models were obtained for local traffic in the United States and Europe where there are enough traffic regulations as regards air pollution.

CHAPTER TWO

LITERATURE REVIEW

2.1 Sources and Types of Air Pollution

Air pollution results from a number of causes, not all of which are within human control. Dust storms in desert areas and smoke from forest fires and grass fires contribute to chemical and particulate pollution of the air. Air pollutants are classified as either directly released or formed by subsequent chemical reactions. A directly released air pollutant is one that is emitted directly from a given source such as Carbon monoxide and Sulphur dioxide which are by-products of combustion; whereas a subsequent air pollutant is formed in the atmosphere through chemical reactions involving direct release pollutants. The formation of ozone in the photochemical smog is the most important example of a subsequent air pollutant (National Safety Council, 2006).

The major classification of pollutants is based on their sources. There are two broad categories namely; anthropogenic and natural sources. Anthropogenic emissions occur as a result of day-to-day human activities connected with industry, transportation, mining, construction and domestic life in the household (such as cooking and heating). Natural sources include volcanic, lighting and all biogenic emissions from living vegetation, soil, termites, and the digestive tracks of animals. Biomass burning is a special category of sources, categorized as savanna, forest and agricultural waste burning. It consists of both human-made and natural fires (Aghedo, 2007).

Aghedo (2007) further stated that the main sources of air pollution in Africa are biomass burning and natural sources while the emissions of industrialized countries are anthropogenic in nature. This can only be true for rural Africa and not urban Africa. Africa is presently responsible for about 40% of biomass burning activities occurring

globally (Crutzen *et al*., 1979; Helas *et al*., 1995). Human activities are the primary source of African biomass burning emissions and they include savanna, forest and agricultural waste burning (Crutzen and Andreae, 1990).

2.2 Major Gaseous Pollutants from Motor traffic

There are a number of pollutants contributed by both natural and anthropogenic sources, but the emphasis here is on gaseous pollutants contributed by the motor car or automobile. The most common pollutants according to Mayer *et al.,* (1999), are the near ground air pollutants like NO, NO_2, CO and others like CO_2, SO_2 and VOCs.

2.2.1 Carbon Monoxide (CO)

This is an odourless and colourless gas. After being inhaled, CO molecules can enter the bloodstream, where they inhibit the delivery of oxygen throughout the body. Low concentrations can cause dizziness, headaches, and fatigue; high concentrations can be fatal. CO is produced by the incomplete burning of carbon-based fuels, including gasoline, oil, and wood. It is also produced from incomplete combustion of natural and synthetic products, such as cigarette smoke. It can build up in high concentrations in enclosed areas such as garages, poorly ventilated tunnels, and along roadsides in heavy traffic (National Safety Council, 2006).

2.2.2 Carbon Dioxide (CO_2)

This is the principal greenhouse gas emitted as a result of human activity (e.g., burning of coal, oil, and natural gas). CO_2 can cause burns, frostbite, and blindness if an area is exposed to it in solid or liquid form. If inhaled, it can be toxic in high concentrations, causing an increase in the breathing rate, unconsciousness, and death.

2.2.3 Nitrogen Oxides (NO_x)

This is formed from reactions between nitrogen oxide (NO) and nitrogen dioxide (NO_2), are major contributors to smog and acid rain. Nitrogen oxides react with

volatile organic compounds to form smog. NO and NO_2 often reach high concentrations in polluted areas. Molecule species that contain nitrogen atoms play an important role in the chemistry of polluted air. NO_x governs the rate of formation and destruction of atmospheric ozone and are principal agents in the formation of photochemical smog. Of total NOx emitted to the atmosphere, some 40% is estimated to be generated by natural sources (lightning, forest fires, manures, etc.). Of the man-made remainder, one third is emitted by the combustion engines of motor vehicles. Lenner (1987) wrote that in the polluted atmospheres of densely populated industrialized areas, 60-75% of the atmospheric NO_x emanates from traffic. NO_2 is more harmful to human health than NO. A large NO_2 proportion leads to a net production of Ozone in the atmosphere.

2.2.4 Sulphur dioxide (SO_2)

This is an odourless gas at low concentrations, but can have a very strong smell at high concentrations. SO_2 is a gas produced by burning fossil fuels and coal, most notably in power plants. Some industrial processes, such as production of paper and smelting of metals, produce Sulphur dioxide. Like nitrogen oxides, SO_2 is a major contributor to smog and acid rain. SO_2 is closely related to sulphuric acid, a strong acid. It can harm vegetation and metals and can cause lung problems, including breathing problems and permanent damage to lungs (National Safety Council, 2006),

2.2.5 Volatile organic compounds (VOCs)

Volatile chemicals produce vapours easily. At room temperature vapours readily escape from volatile liquid chemicals. VOCs include gasoline, industrial chemicals such as benzene, solvents such as toluene and xylene, and perchloroethylene (principal dry cleaning solvent). VOCs are released from burning fuel, such as gasoline, wood, coal, natural gas and from solvents, paints, glues, and other products used at

home or work. Vehicle emissions are an important source of VOCs. Many VOCs are hazardous air pollutants; for example, benzene causes cancer (Mayer *et al.,* (1999), National Safety Council, (2006)).

2.3 Air Pollution and Health

A USEPA report (1994) stated that some chemicals found in polluted air can cause cancer, birth defects, brain and nerve damage, and long term injury to lungs and breathing passages in certain circumstances. Above certain concentrations and durations, certain air pollutants are extremely dangerous and cause severe injury or death. Atmospheric pollutants are responsible for both acute and chronic effects on human health (Vardoulakis *et al*., 2002). It is estimated that three million people indirectly die of respiratory and cardiovascular disease worldwide, many of which cases are linked to air quality and smog. Many of these mortalities are largely attributable to air pollution (USEPA, 1994). Worldwide, more deaths per year are linked to air pollution than the number of deaths caused by automobile accidents. Direct causes of air pollution related deaths include aggravated asthma, bronchitis, emphysema, lung and heart diseases, and other respiratory allergies. The USEPA estimates that a proposed set of changes in diesel engine technology could result in 12,000 less premature mortality, 15,000 fewer heart attacks, 6000 fewer emergency room visits by children with asthma, and 8900 fewer respiratory-related hospital admissions each year in the United States. Greiner, (1995) stated that at concentrations of 2500 to 5000 ppm Carbon dioxide can cause headache. At extremely high levels of 100,000 ppm (10 %), people lose consciousness in ten minutes and at 200,000 ppm (20 %), it causes partial or complete closure of the glottis. He further stated that at 250 ppm, Carbon monoxide causes death to humans. Burnett *et al*., (1998) stated that carbon monoxide is an asphyxiating pollutant that reduces the ability of blood to carry

oxygen to different body organs. Short term exposure to it, might cause acute health impact. Pollutants like benzene have a cumulative effect on human health. Long term exposure to high benzene levels increases the risk for an individual to suffer from cancer (Cicolella, 1997). The health effect of traffic air pollution on traffic policemen was studied in Thailand and Vietnam some years back. De Rosa (2003) reported that young and middle aged men serving as motor toll gates attendants in Italy, subjected to exposure to traffic pollution had their fertility impaired. Health impact of air pollution depends on the pollutant type, its concentration in the air, length of exposure, other pollutants in the air and individual susceptibility. Different people are affected by air pollution in different ways. Poor people, undernourished people, very young and very old, and people with preexisting respiratory disease are more at risk (Finkelstein *et al.*2004). They further stated that the poor tend to live and work in most heavily polluted areas in the cities and in rural areas, the poor are most likely to cook with dirtier fuels. There is increasing evidence that long term exposure to the particulate and gaseous air pollutants common to many metropolitan areas is an important risk factor in mortality. Pope *et al.,* (2002) found that fine particulate- and sulphur dioxide-related pollution was associated with all-cause, lung cancer and cardiopulmonary mortality. Hoek *et al.,* (2002) reported that proximity to major roads produced a larger association with cardiopulmonary mortality than did urban background concentrations of air pollution. The studies demonstrated a relation between air pollution and mortality rates. Air pollution can also damage the environment and property, according to USEPA (1994).

2.4 Air Pollution Dispersion Modelling

A mathematical model is an assembly of concept or phenomena in the form of one or more mathematical equations which approximate behaviour of a natural system

or phenomena (Benarie, 1982). They can be employed to predict the impacts of or concentration of parameters under different types of current or future scenarios using readily available or measured input data.

Atmospheric dispersion modelling is one of the large classes of phenomena, which include a deterministic part and a random element. There are two extreme approaches to atmospheric modelling, the statistical and the analytical approach. Statistical techniques look into pure time series, where as in analytical approach an attempt is made to understand the physical process and to establish cause-effect relationship, which facilitates the final outcome. However, almost none of these ideal approaches are applicable directly in their present form (Benarie, 1987). Modelling provides the ability to assess current and future air quality in order to enable informed policy decisions to be made. These air quality models play an important role in providing information for better and more efficient air quality management planning.

The air quality models can be classified as point, area or line source models depending upon the source of pollutants which they model. Line source models are used to simulate the dispersion of vehicular pollutants near highways or roads where vehicles continuously emit pollutants. Line sources are typically encountered during the atmospheric diffusion modelling of linear transportation corridors and area sources are often treated as assemblages of finite line sources. Esplin (1995) wrote that because an explicit solution to the general finite line source problem is not available, it has to be approximated as a series of point sources.

Vehicular pollution modelling, in general refers to carrying out air pollution estimates by simulating impact of emissions from vehicular activity in a given region. These models are generally used in analyzing the output of an existing or proposed highway / roads at distance of tens to hundreds of meters down wind. The effect of

vehicular pollution and vehicular activity is considered to be the primary consideration for air quality prediction analysis (Benarie, 1987).

Most of the widely used highway dispersion models are Gaussian based (Luhar and Patil, 1989). This is because they are assumed to follow a normal or Gaussian distribution. The most commonly used basis for modelling pollutant dispersion is the Gaussian plume formulation. For this method it is assumed that the emission from a point source of pollution spreads in the atmosphere into a plume whose concentration profile is Gaussian in form in both the horizontal and vertical directions and whose orientation is determined by the wind direction.

Air quality in most developing cities is far from satisfactory. Rapidly increasing vehicular population and urbanization has further aggravated the air pollution problem in developing cities. There is an immediate need to improve the monitoring and emission inventory capabilities in these cities, which are pre-requisite and essential for formulating various air pollution control and management strategies. The values of various input parameters like driving cycles, vehicular type and emission factors, to the models are often adopted from other countries. Besides the basic Gaussian dispersion approach, each dispersion model differs with respect to the treatment of modified wind and turbulence due to vehicular wakes near the roads. The input parameters used in these models are not accurately known leading to incorrect or sometimes even unreliable predictions (Sharma *et al.*, 2005). The greater inaccuracy can be due to improper emission factors used for different categories of vehicles. The emission factors expressed in terms of grams of pollutant per unit travelled (in km) depend on factors like type of fuel, engine type, driving cycle, age of the vehicle, speed of vehicle, driving mode, etc.

Evaluation of traffic pollution in streets requires information on three main factors: traffic emissions, the meteorological conditions and street surroundings. The existing dispersion models with various degrees of sophistication are able to describe dispersion conditions and thus predict the relationships between emissions and the concentration levels in the streets. There is significant uncertainty connected with emission data used (Berkowicz *et al.*, 2006). No effort has been made to accurately determine emission factors and data for different categories of in-use vehicles as a function of vehicle speed, fuel category and age of vehicles. For real-world applications model calculations must be based on "true" emission data whose estimation should not be trivial.

Beychok (2005) asserts that based on the generality that the magnitude of plume diffusion is a function of atmospheric turbulence and time, the actual pattern of diffusion is random. It can then be assumed that the emissions in any crosswind increment of the plume will disperse in vertical and cross wind patterns that are essentially the same as given by the Gaussian distribution.

The generalized Gaussian dispersion equation for a continuous point source plume is:

$$C = \frac{Q}{u\sigma_z\sigma_y 2\pi} e^{-\frac{y^2}{2\sigma_y^2}} \left[e^{-\frac{(z_r-H_e)^2}{2\sigma_z^2}} + e^{-\frac{(z_r+H_e)^2}{2\sigma_z^2}} \right] \tag{2.1}$$

Where C = concentration of emission, g/m^3, at any receptor located at: x metres downwind, y metres crosswind from the center-line and z_r metres above ground

Q = source emission rate, g/sec

u = horizontal wind velocity, m/sec

H_e = plume centerline height above ground, m

σ_z = vertical standard deviation of the emission distribution, m

σ_y = horizontal standard deviation of the emission distribution, m.

According to Beychok (2005), this equation is valid only within the following summarized constraints:

1. Vertical cross wind diffusion occurs according to Gaussian distribution.

2. Downwind diffusion is negligible compared to downwind transport.

3. The emissions rate Q is continuous and constant.

4. The horizontal wind velocity and mean wind direction are constant.

5. All emissions are totally conserved within the plume.

6. There is no upper barrier to vertical diffusion and there is no cross wind diffusion barrier.

7. The emissions reflected upward from the ground are distributed vertically as if released from an imaginary plume within the ground and are additive to the actual plume distribution.

8. The use of σ_z and σ_y as constants at a given downwind distance, implicitly require homogeneous turbulence throughout the x, y and z dimensions of the plume.

The equation thus depends upon the validity of these assumptions. In terms of environmental impact of plume components, such as NO_2, SO_2, and others, the primary concern is usually with their ground level concentrations. The receptor z is at 0 and the ground level centerline and cross wind concentrations are obtained by reducing equation (2.1) to

$$C = \frac{Q}{u\sigma_z\sigma_y\pi}e^{-y^2/2\sigma^2_y}e^{-H^2_e/2\sigma^2_z} \qquad (2.2)$$

The cross wind concentrations are always lower than the centre line concentrations since the Gaussian distribution is symmetrical about its mean interval of maximum

density. The equation for ground level centre line concentrations is obtained by reducing equation (2.1) to equation (2.3) below.

$$C = \frac{Q}{u\sigma_z\sigma_y\pi} e^{-H^2_e/2\sigma^2_z}$$
(2.3)

The receptor is at $z_r = 0$ and $y = 0$.

For ground level centreline concentrations from ground level plumes with receptor at $z_r = 0$, $y=0$ and $H_e = 0$, equation (2.1) reduces to:

$$C = \frac{Q}{u\sigma_z\sigma_y\pi}$$
(2.4)

Equation (2.4) as will be seen later bears a close resemblance to the generalized STREET model for traffic pollution.

2.4.1 Line source models

The passage of the United States National Environmental Policy Act of 1969 initiated modelling of pollution due to vehicles (Rao *et al.,* 1985). During the early 1970's several highway dispersion models (like Hiway I and Caline I and 2) were developed to carry out prediction estimates of vehicular pollutants near roads and highways as part of environment impact analysis process as per the requirements of various regulatory agencies. These early models were suitable primarily for rural, flat terrain under homogeneous traffic conditions. They did not take care of enhanced dispersion due to vehicle wakes and vehicle generated turbulence (Sharma *et al.,* 2005).

In recent years, in most of the developed countries the air pollution from industrial and domestic sources has markedly deceased due to the passage of various acts by different governments (Nagendra and khare, 2002). (Mayer, 1999; Sharma and Khare, 2001) wrote that there has been a substantial increase of air pollution caused by the vehicular exhaust emissions (VEE) due to the addition of more and more vehicles on roadways to meet increase in transportation demand. Line source emission

modelling is an important tool in screening of VEEs and helps in control and management of urban air quality. Most of the line source models are deterministic, while a few are stochastic and some are analytical based on an artificial neural network approach. Our emphasis is on the deterministic line source models.

2.4.1.1 Theoretical approaches to deterministic line source modelling

The deterministic mathematical models (DMM) calculate the pollutant concentrations from emission inventory and meteorological variables according to the solutions of various equations that represent the relevant physical processes. The common Gaussian Line source model is based on the superposition principle, namely that concentration at a receptor is the sum of concentrations from all the infinitesimal point sources making up a line source.

The work of Sutton (1932) may be regarded as the first of its kind in modelling of VEE. One of the early studies on deterministic vehicular pollution modelling was reported in Waller *et al*., (1965). The analytical method for estimating the pollution levels from motor vehicles in the vicinity of highways of common geometric configuration was developed by Chen and March (1971). Dilley and Yen (1971) derived an analytical solution to a 2 – dimensional transport and diffusion equation that described the downwind pollutant concentrates from an infinite cross wind line source. Peters and Klinzing (1971) described two separate equations for ground level and elevated line source and analyzed the effect of diffusion coefficient in line source dispersion. Using the diffusion equation, Lamb and Neiburger (1971) came out with a model for computing pollutant concentrations resulting from both point and line sources.

Csanady (1972) developed a model for a finite line source and it was applicable only when the wind is perpendicular to the roadway. Calder (1973), considered one of

the major classical works in pollution dispersion modelling, showed that the concentration at a roadside receptor increased marginally as wind direction became parallel to the highway. Dabbert *et al*., (1973) presented a practical urban diffusion model for predicting inert vehicular pollutant concentration. Fay and King (1975) formulated a Gaussian model, considering vehicle – induced effects on dispersion of pollutants. This model assumed that near the road, vehicle wake-induced turbulence dominated over atmospheric turbulence. Therefore, dispersion of pollutants was assumed to be independent of atmospheric parameters except wind speed and dependent upon the drag characteristics of passing vehicles.

The US EPA developed a number of air pollution models for highway which included CALINE (Beaton *et al*., 1972), EGAMA (Egan *et al*., 1973) and HIWAY (Zimmerman and Thompson, 1975). The popular HIWAY model was based on the Gaussian equation with the assumption of a series of finite line sources. The CALINE model is also a Gaussian based line source model but has got separate equations for calculating pollutant concentration under crosswind and parallel wind conditions. Chock (1977) and Noll *et al*., (1978) evaluated these models and found that the EPA – HIGHWAY model ever estimated pollutant concentration adjacent to the road way. This model avoids the cumbersome Gaussian integration necessary for the conventional Gaussian model that makes point source assumption; instead it uses an infinite line source approach and specifies one dispersion parameter as a function of wind road orientation from the source. Later there were improved versions of the CALINE model, like CALINE-2, CALINE-3 and CALINE -4 developed by Word et al., (1977) and Benson (1979, 1989).

Data from General Motor (GM) dispersion experiment were utilized by Sedefian and Rao (1981) to assess the characteristics of traffic – generated turbulence

and its effects on the dispersion process near roadways. They found that the dispersion next to the roadway areas was dominated by the traffic and its influence decreased considerably at further downwind distances and at higher elevations. At low winds and perpendicular cases, the traffic contribution was still above 50% at a downwind distance of 30m. Hickman and Colwill (1982) described a simple and effective method of estimating pollutant concentrations around highways, which used the Gaussian dispersion theory with empirical modifications so that it accurately represented the roadside situation.

Beiruti and Al-Omishy (1985) developed a digital computer model simulation of traffic flow. The model was later used to predict Nitrogen dioxide (NO_2) and hydrocarbon concentrations at three busy traffic roads in Baghdad, Iraq. It showed a good agreement with the measured concentration. Gronskei (1988) studied the influence of car speed on dispersion of exhaust emission. He also pointed out that vertical diffusion of exhaust gas tends to be larger from high speed driving cars than low speed driving cars.

Using historical meteorological and vehicular data, Cooper (1989) derived meteorological persistence factor (MPF) and vehicular persistence factor for Florida City. Kono and Ito (1990) later developed a micro-scale dispersion model – the OMG volume source model, which compared favourably with such models as JEA, Tokyo model, and EPA – HIWAY -2 Models.

Benson (1992) studied recent versions of CALINE models namely CALINE-3 and CALINE-4. He found that CALINE-4 performed better than CALINE-3. Alcxopolos *et al*., (1993) came out with a model for spatial and temporal evaluation of traffic emissions in metropolitan cities. The model was found to be useful where raw traffic data, network and number of trip data were difficult to generate. Qin and Kot

(1993) carried out dispersion studies in low wind conditions for three streets in Guangzhou city. Using the observed data a simple operational model was proposed to simulate the dispersion of vehicular emissions in street canyons. Akeredolu *et al*., (1994) used CALINE-4 model for forecasting carbon monoxide at intersections. Chan *et al*., (1995) tested the applicability of model like APRAC, GZE, CALINE-4 and PWILG. These models were evaluated by comparing the predicted CO and NO_x concentrations with measured values at street canyons in Guangzhou. The models were found to be accurate in predicting maximum ground level concentrations. Esplin (1995) presented approximate explicit solution to the general line source problem that could be used down to angles of $15°$ between the line source and the wind vector. For angles below 15^0, he presented a point source approximate solution. Clifford *et al.,* (1995) studied the mechanisms involved in the dispersion of pollutants around slow moving vehicles. Spatial distribution of tracer gas along and across the vehicles showed that a significant level of pollution was received by a commuter in a slow moving vehicle from the automobile immediately in front. Yu *et al*., (1996) developed a mathematical model for predicting trends in CO emissions. The model results were later used for examining long term trends in human exposure to CO. Khare and Sharma (1999) presented a deterministic model for Delhi traffic conditions (heterogeneous in nature) i.e. Delhi finite line source model (DFLSM). Karim and Matsui (1998) developed a computer model consisting of wind distributions, emission dispersion and modified Gaussian equation to identify street canyon and vehicle wake affects on transport of air pollution from urban road micro–environments. Subsequently, the turbulent parameter was integrated in Gaussian equation to estimate CO and NO_x concentration. Later Karim (1999) developed a traffic pollution inventory and modelled dispersion of vehicular pollutant in an urban environment. Buckland and Middleton (1999) presented

monographs for screening of vehicular pollution in congested streets canyons. Sivacoumar and Thanasekaran (2001) evaluated four Gaussian dispersion models, namely: GM, CALINE-3, PAL-2 and ISCST-2 for Indian traffic conditions and found all not to function well in the Indian conditions.

2.4.1.2 Applications and limitations of selected line source models

Nagendra and Khare (2001) summarized the applicability of some line source models to the estimation of roadway traffic air pollution. The principles of operation of most of the models are the same although they differ in their output. The summary is presented in Table 2.1.

Table 2.1: Comparison of line source models

S/No	Model	pollutant	Applicability Receptor location, traffic type	Limitations
1	California line source model (Benton *et al*, 1972)	CO, NO$_x$, SPM	Road side, Homogenous	Tendency to predict high pollutant concentration for parallel wind case no treatment of plume rise due to hot exhaust of vehicles
2	HIWAY -1 (Zimmerman and Thompson, 1975)	CO	Roadside / Homogenous	Predicts poorly for low winds. Over estimation of concentration for stable atmospheric condition and parallel wind case. No treatment for plume rise due to hot exhaust of vehicles
3	CALINE -2 (Ward *et al*, 1977)	CO, NO$_x$, SPM	Roadside / Homogenous	Predicts poorly for unstable and neutral stability Conditions. Over predicts the pollutant concentration for parallel wind cases and under predicts for oblique wind condition.
4	GM model (Chock, 1978)	CO	Roadside / Homogeneous	Tendency to overpredict concentration and or parallel wind conditions. Predicts poorly for low winds.
5	CALINE-3 (Benson,1979)	CO, NO$_x$, SPM	Road side / Homogeneous	Tendency to predict high for parallel wind condition. No proper treatment for mechanical and thermal turbulence created by vehicle exhaust.
6.	HIWAY -2 (Peterson, 1980)	CO	Road side / Homogenous	Inadequate dispersion parameters. No treatment of plume rise due to hot exhaust of vehicles
7	CALINE- 4 (Benson, 1989)	CO, NO$_x$, Aerosol	Road side / Homogeneous	Tendency to predict high for parallel wind condition
8	GFLSM (Luhar and Patil, (1989)	CO, SPM	Road side / Heterogeneous	Predicts poorly for low winds
9	DFLSM (Khare and Sharma, (1999)	CO	Road side / Heterogeneous	Predicts poorly for low winds.

Source: Nagendra and Khare (2001)

2.4.1.3 Description of some line source models

Below is the description of the features of some commonly used line source models in the United States of America (USA), Canada and most of Europe.

2.4.1.3.1 The CALINE 4 models

This latest version of the CALINE series of pollutant dispersion models is one of the most validated models available for assessing the impact of vehicle traffic on road side air quality. It has been widely used in scientific and engineering applications, mainly concerning highway development and management. Although it is able to handle canyon or intersection situation, it has been used in relatively few urban air quality studies. The model uses Gaussian plume theory to simulate the dispersion of pollutants emitted from a line source. This is divided into a series of elements, which are modelled as equivalent finite line sources located normal to the wind direction. The region directly over the road called mixing zone, is treated as a zone of uniform emission and turbulence (both mechanical and thermal) is taken in to account (Benson, 1992). Each element is modelled as an equivalent finite line source positioned normal to the wind direction and centred at the element mid-point. The dominant dispersive mechanisms are the mechanical turbulence created by moving vehicles and the thermal turbulence created by the hot exhausts. It is also assumed that vehicles emissions are released and rapidly dispersed within the trailing wake of each vehicle. Further initial dispersion occurs through the action of turbulence generated by other passing vehicles. Horizontal wind flow is homogeneous and meteorological conditions are steady state.

The incremental concentrations are then summed up to form a total concentration estimate for a particular location. The receptor distance is measured along a perpendicular from the receptor to the link centre-line. The emission occurring from an element is assumed to be dispersed in a Gaussian manner downwind from the

element. Each element is divided into 3 sub – elements namely: a central sub-element and 2 peripheral sub-elements. Downwind concentrations of the element are modelled using the cross – wind finite line source Gaussian formulation. The total receptor concentration, C from a particular roadway link is computed as follows:

$$C = \frac{1}{u\sqrt{2\pi}} * \sum_{i=1}^{n} \{ \frac{1}{SGZ_i} * \sum_{k=-CNT}^{CNT} [\exp(\frac{-(z-H+2*K*L)^2}{2*SGZ^2_i}) + \exp(\frac{-(z+H+2*K*L)}{2*SGZ^2_i})] *$$
$$* \sum_{j=1}^{e} (WT_j) * QE_i * PD_{ij} \}$$

(2.5)

where n = total number of elements

CNT = number of multiple reflections required for convergence

U = wind speed

L = mixing height

SGZ_i = σ_z as f(x) for i[th] element. Initial vertical dispersion parameter

QE_i = central sub-element lineal source strength for i[th] element

WT_j = source strength weighting factor for j[th] finite line source segment, H = plume centreline height above ground

z = receptor height.

$$PD_{ij} = \frac{1}{\sqrt{2\pi}} \int_{\frac{y_j}{SGY_i}}^{\frac{y_{j+1}}{SGY_i}} \exp(-p/2)dp$$

(2.6)

Where y_j, y_{j+1} = offset distance for j[th] finite line source segment

SGY_i = σ_y as f(x) for i[th] element

The initial vertical dispersion parameter SGZ_i is modelled as a function of pollutant residence time within the mixing zone. A major set back of the CALINE 4 models is its complexity and fact that it is independent of surface roughness and atmospheric stability. Traffic parameters like headways, speed and platooning are not addressed

properly. Individual vehicle emissions represented by emission factors are not addressed, leaving the user to conjecture on how to obtain them.

2.4.1.3.2 The STREET model

This is one of the earliest street pollution models by Johnson *et al*. (1973). The model was empirically derived based on pollution measurements in streets of San Jose and St Louis in the United States. The model assumes that emission from the local street traffic (street contribution C_s) are added to the pollution present in the air that enters from roof level (background contribution C_b).

The street contribution is proportional to the local street emissions and inversely proportional to the roof level wind speed u. for winds blowing at an angle of more than 30º to the street direction two formulae were derived:

For the lee ward side,

$$C_s = \frac{K}{u + u_s} \sum \left[\frac{Q_i}{\left[\left(x_i^2 + z^2 \right)^{1/2} + h_0 \right]} \right]$$ (2.7)

For the wind ward side,

$$C_s = \frac{K}{u + u_s} \frac{H - Z}{H} \sum \frac{Q_i}{W}$$ (2.8)

Where K is an empirically determined constant (k = 7).

u_s accounts for the mechanically induced air movement caused by traffic (u_s = 0.5m/s).

h_0 accounts for initial mixing of pollutants (h_0 = 2m).

x_i and z are the horizontal and the vertical distances from the ith traffic lane to the receptor point.

Q_i is the emission strength of the ith traffic lane.

H and W are the height and the width of canyon respectively.

For wind direction at angles less than 30º to the street direction, the average of (7) and (8) is recommended but actually the model is not designed for this condition. The

formulae are based on the observations that when the roof level wind blows within about ± 60º of the cross – street direction, a helical circulation develops in the street. This causes the pollutants emitted from traffic in the street to be primarily transported towards the leeside while the downwind side is primarily exposed to background pollution and pollution that has recirculated in the street. The model predicts thus that the concentrations on the leeward side of the street are higher than on the wind ward side. These are the most essential features of pollutant dispersion in street canyons and therefore the STREET model with some minor modifications (Benesh, (1978), Gualtieri and Tartaglia, (1997) can be used for engineering applications. Gualtieri and Tartaglia (1997) for example obtained factors for leeward and intermediate sectors of the street with respect to the position of the receptor point. Their model also incorporated variables like air temperature mixing height, solar radiation and relative humidity. Thus their model takes into account, though in a simplified way both physical and photochemical dispersion processes occurring in local sites atmosphere.

Berkowicz (2000) stated that the more detailed features of pollution dispersion in street canyons can, however not be described by such a simplified model as STREET. An essential drawback of the model is the very crude parameterization of wind direction dependence. Furthermore, at reduced ambient wind speeds (calm conditions), a uniform concentration distribution is expected across the street canyon. The STREET model does not describe this feature and actually, it is not recommended for ambient wind speeds less than 1m/s (2knots).

2.4.1.3.3 The Danish Operational Street Pollution Model (OSPM)

The OSPM was developed in 1987 (Hertel and Berkowicz, 1989) at the National Environmental Research Institute (NERI) Denmark, in collaboration with the Norwegian Institute for Air Research (NILU) and the Swedish Meteorological and

Hydrological Institute (SMHI). Concentrations are calculated as a sum of the direct plume contribution and recirculating pollution. The OSPM belongs to a group of parameterized semi-empirical models making use of *a priori* assumptions about the flow and dispersion conditions. Berkowicz (2000) stated that for many practical applications, as e.g. in support of air pollution management the numerical models like CALINE based on solution of the basic flow and dispersion equations are still too complex. He further stated that the quality of input data, such as e.g. emissions is often not sufficient to justify application of the very complex numerical tools.

For the case of wind direction perpendicular to the street axis the expression for the direct contribution is:

$$C_d = \sqrt{\frac{2}{\pi}} \frac{Q}{W\sigma_w} \ln \frac{h_0 + (\sigma_w + u_b)W}{h_0} \qquad (2.9)$$

The expression can be compared with the STREET model formula for leeward concentration, considering ground level concentration at z = 0. If the homogeneous emission distribution (as assumed in the OSPM is replaced by a discrete distribution as assumed in STREET, equation (2.9) becomes

$$C_d = \sqrt{\frac{2}{\pi}} \frac{1}{u_b} \sum_i \frac{Q_i}{[h_0 + (\sigma_w/u_b)x_i]} \qquad (2.10)$$

where C_d is the direct contribution

Q is the homogeneous emission strength

W is the width of the street

U_b is the wind speed at street level

σ_w is the vertical turbulent velocity fluctuation

Q_i is the emission strength of the ith traffic lane

x_i is the corresponding horizontal distance

H_0 is initial mixing height of pollutants (h_0 = 2m)

Expression (2.9) and the continuous emission distribution formula (2.10) represent the direct contribution from a plume travelling with a speed U_b and which at a distance x from the source has the vertical dispersion parameter

$$\sigma_z = h_0 + (\sigma_w / u_b)x \qquad (2.11)$$

The total concentration is made up of the direct and recirculation contributions. The recirculation part is calculated assuming a simple box model; the canyon vortex has the shape of a trapeze with the maximum length of the upper edge being half of the vortex length. The ventilation of the recirculation zone takes place through the edges of the trapeze but the ventilation can be limited by the presence of a downwind building if the building intercepts one of the edges (Berkowicz *et al.,* 1997).

The inflow rate per unit length is given by:

$$Inflow = \frac{Q}{W} L_{rec} \qquad (2.12)$$

where Q and W are as defined earlier and L_{rec} is the width of the recirculation zone. For narrow streets L_{rec} can be determined by the distance between buildings, W. The out flow rate through the top and side edges is calculated with flux velocities given by: σ_{wt} – the top edge, u_t – the upper half of the side edge and u_b – the lower half of the side edge. The outflow rate per unit length is given by:

$$Outflow = C_{rec}(\sigma_{wt} L_t + u_t L_{s1} + u_b l_{s2}) \qquad (2.13)$$

L_t, L_{s1} and L_{s2} are calculated taking into account the canyon geometry and the extension of the recirculation zone.

2.4.1.3.4 Calder's model

Calder (1973) developed a model of the form

$$C_{(\theta, X)} = \frac{\sqrt{\frac{2}{\Pi}} Q \exp\left\{\frac{-H^2}{2\sigma_z^2}\right\}}{U \cos\theta . \sigma_z} \qquad (2.14)$$

where C is the concentration at a receptor placed at an angle θ to the roadway and point x in the horizontal direction; Q is the homogeneous emission strength; H is the height of the source; U is the ambient wind speed; σ_z is the standard deviation function of the plume concentration in the vertical direction and given by GEOMET (1971) as

$$\sigma_z = a(x + c)^b$$

(2.15)

The parameters a and b were determined with c = 0, so as to give a close fit to the Pasquill-Guifford diffusion curves. A value was later selected for c to reflect the non-zero initial size of the pollution cloud produced by the traffic moving on a highway. This gave a σ_z value of 1.5m (Calder, 1973).

2.4.1.4 Line source modelling in Nigeria

Very little reported work has been carried out in African countries on the effects of vehicular traffic on air quality. Work by Baumbach *et al.,* (1995) centered on relationship between traffic density and air pollution in Lagos. Even though they concluded that heavy traffic tends to increase the quantity of pollutants produced, there was no mathematical model depicting the relationships. Only one traffic flow parameter, namely density was considered. Other parameters like volume, composition, speed and age were left out. Lagos is one of Nigeria's most industrialized cities, so it would be misleading to conclude that the pollutants measured came from traffic alone. Ndoke and Jimoh (2005) working in Minna laid more emphasis on the concentrations of pollutants in the air and not the relationship between traffic flow and air quality. Ndoke *et al*., (2006) also looked at the relationship between traffic flow and quantity of Carbon dioxide in the atmosphere of Kaduna and Abuja cities. Mathematical models were also not provided; neither was there any model depicting dispersion of the gas. The work basically looked at the contributions of traffic flow to global warming and the green house effect. Again there are many sources of carbon dioxide, so drawing a

conclusion that traffic alone is responsible for the production of the carbon dioxide can also be misleading. Other works on environmental pollution in Nigeria concentrated on the effect of gas flaring in the Niger Delta of Nigeria (Abdul Kareem, 2005; Jimoh and Alhassan, 2006). Meteorological input variables like wind direction and speed, solar radiation, air temperature, stability class and even humidity were not considered in these studies. A more recent work by Aghedo (2007), centred on development of a global chemistry climate model while looking at impact of air pollution in Africa. The work centred on an appraisal of the contributions of African natural sources of pollution like biomass burning to climate change. This work is therefore coming at the right time when scientists in Africa and other developing countries are becoming more and more aware of the dangers of global warming and climate change. The development of a model that would take into consideration traffic volumes and composition, local meteorological parameters, driver behaviour and road or street topology would be very helpful to local authorities in air quality and traffic management as well as urban planning.

CHAPTER THREE

MATERIALS AND METHODS

This chapter presents the various approaches taken in developing, calibrating and validating the model as well as methods of carrying out field pollutant concentration measurements.

3.1 Model Development

This section involves steps taken in choosing, developing, calibrating and evaluating the model.

3.1.1 Problem definition

To assess the present and future state of emissions from transport and to evaluate different policies for reducing emissions, require the development and application of emission models, which are accurate, reliable, consistent and credible. The model should be relatively non-complex in order to minimize computational time and problem of parameter identification. The model should be conveniently applied for long-term concentration prediction of pollutants where wind direction is of paramount concern. The model should be able to take care of the heterogeneous nature of traffic in the streets.

3.1.2 Model formulation

The model developed consists of two parts: (1) A Gaussian based algorithm part to estimate roadside pollutant concentrations and (2) A vehicle induced turbulence part to estimate the vertical dispersion parameter. The two parts were coupled together to obtain a more realistic estimation of pollutant concentrations with respect to the additional dispersion due to moving vehicles.

3.1.3 Source type

A road segment was chosen as the line source on which were an infinitesimal number of hypothetical point sources represented by the vehicle units, continuously emitting pollutants in the street and into the atmosphere. A length of the road, say L was chosen to be treated as a finite line source. There were buildings of various heights adjoining the road and they were not continuous. The orientation of the street did not matter. In this situation cross wind contribution to the concentration could not be neglected.

3.1.4 Model assumptions

The model was based on the work by Calder (1973) on estimation of pollutants from traffic near a roadway and the postulations of the OSPM (Berkowicz *et al*., 1997), which are all based on the Gaussian diffusion equation and principles. The following assumptions were made in developing the model:

1. The dispersion model is based on the principle of superposition, namely that concentration at a receptor is the sum of all concentrations from all infinitesimal point sources making up the line source (roadway).

2. The emission from the source in the form of a plume has a concentration profile that is Gaussian in both horizontal and vertical directions and all emissions are from hot engines.

3. The horizontal wind speed is assumed uniform within the layer, to allow for uniform dispersion.

4. Horizontal and vertical plume spreads are given by the Briggs' stability equations.

5. In the absence of continuous traffic information, it is assumed that traffic flow rates are the same for a given time of the day for weekdays.

6. Dispersion of pollutants is only dependent on wind speed and drag characteristics of passing vehicles.

3.1.5 The Gaussian based algorithm

The line source (roadway) was regarded as a series of hypothetical point sources along the road representing a certain interval over the road. The Gaussian plume equation for point source was applied to evaluate the contribution of each point source on a certain receptor. The generalized Gaussian plume equation for a continuous point source concentration according to Wark *et al.,* (1998) is given by:

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\frac{y^2}{\sigma^2_y}\right]\left[\exp\left[-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^{\,2}}\right] + \exp\left[-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^{\,2}}\right]\right] \qquad (3.1)$$

where C (g/m^3) is the steady state concentration at a receptor; Q (g/s) is emission rate; u (m/s) is mean ambient wind speed; y (m) and z (m) are the horizontal distance from the plume centre-line and height of receptor with respect to ground respectively; H (m) is height of source with respect to ground (road elevation); σ_y and σ_z (m) are the horizontal and vertical Gaussian dispersion parameters respectively. The first exponential term in Equation (3.1) is the crosswind contribution in the y-direction. The second exponential term is the actual emission distribution and the third exponential term is the upward reflected emissions from the ground. The model could be used for calculating concentration of pollutant at jam concentration moments in the streets, when the individual point sources are taken into account.

3.1.6 Mathematical analyses

The basic approach to develop the model was the coordinates transformation between the wind coordinate and line source coordinate systems. Two axes OXY and Oxy with the line source aligning with the Y-coordinate axis, horizontally across wind were considered. The X-coordinate was taken to be in the surface wind direction as

shown in Fig. 3.1. The wind was assumed to make an angle θ with the perpendicular (represented by the X-axis) to the line source. (This angle is a complimentary wind angle, different from the angle between the wind vector and the line source). An upwind point source of concentration strength Q was assumed to release emissions in the form of a plume. Let the point source form the origin of a new coordinate system x-y, with x-axis chosen to be parallel to the wind vector. A receptor R was assumed to be located at X_r, Y_r. Two lines AA and BB passing through an axial point P_o at a distance OP downwind from O and respectively parallel to the axes Oy and OY were drawn.
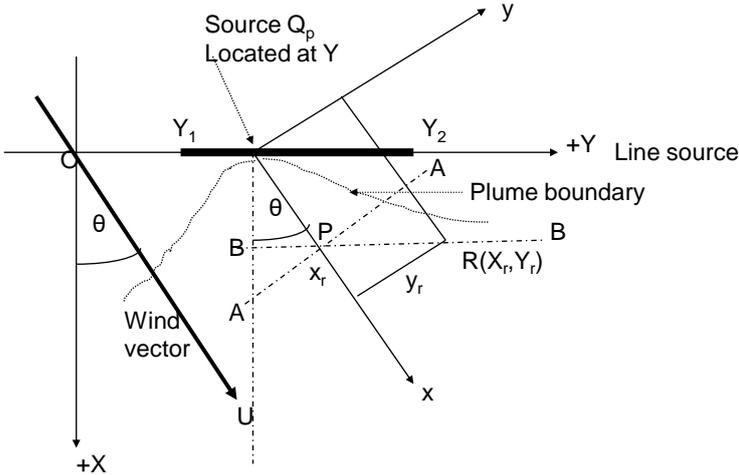
Fig. 3.1 Orientation of coordinate axis and point-source plume

The x-axis is rotated by an angle θ relative to the fixed X-axis. Let PB be the distance from P_o to any point on the line BB parallel to OY as shown in Fig. 3.2. If we draw a line from BB to x, cutting Ox at right angles at a point C, we can find the coordinates of R (X_r, Y_r).
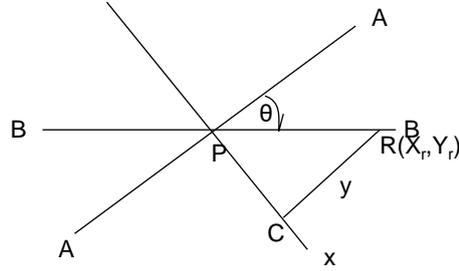
Fig. 2: Geometric arrangement of lines
at axial point P

From Fig. 3.2,

$$\sin\theta = \frac{PC}{PR} \text{ and } \cos\theta = \frac{CB}{PR} \qquad (3.2)$$

But $PR = Y_r - Y_o$ (3.3)

The perpendicular distance of location $X_r = OP \cos\theta$ (3.4)

Therefore, $OP = \dfrac{X_r}{\cos\theta}$ (3.5)

The distance from origin of point source (O,Y) to any point, say C on the x-axis is given by $OC = OP + PC$

Substituting equations 3.3 and 3.5 into equation 3.2, we obtain equation 3.6.

$$x = OP + (Y_r - Y_o)\sin\theta \text{ , implying } x = \frac{X_r}{\cos\theta} + (Y_r - Y_o)\sin\theta$$

and $y = (Y_r - Y_o)\cos\theta$ (3.6)

$Y_r = X_r \tan\theta$ From geometry and from similar triangles this implies

$Y_o = Y + X_r \tan\theta$ (3.7)

and $PR = Y_r - Y - X_r \tan\theta$ (3.8)

$y = ((Y_r - Y) - X_r \tan\theta)\cos\theta$ (3.9)

Simplifying we have $y = (Y_r - Y)\cos\theta - X_r \sin\theta$ and

$$x = \frac{X_r}{\cos\theta} + \left[(Y_r - Y) - X_r \tan\theta \right]\sin\theta \tag{3.10}$$

The total line source contribution to a downwind point will be only from those parts of the line source Y_1Y_2 that lie within half a plume width of Y. The concentration gradient normal to the wind direction (along the y-axis) will be normally much greater than concentration gradient parallel to the wind direction (along the x-axis) according to Calder (1973). Thus over the limited width of the plume, the concentration variation for an oblique traverse along BB will arise primarily from the variation of the perpendicular distance from the plume axis rather than through variation of distance parallel to the axis.

According to Calder (1973) the concentration C_p from the imaginary point source of constant strength Q_p at the origin O is written as

$$C_p = Q_P \phi(x, y) \tag{3.11}$$

where $\Phi(x, y)$ is some form of dispersion equation, in this case the generalized Gaussian point source dispersion formula (Equation 3.1). Assuming that the section of the line source being analyzed is of uniform strength and from Fig. 2, dPR = -dY. The concentration at R (X_r, Y_r) can be given by

$$C(X_r, Y_r) = -Q_P \int_{Y_1}^{Y_2} \phi(OP, PR\cos\theta) dPR \tag{3.12}$$

Since $y = PR \cos\theta$

$$C(X_r, Y_r) = -Q_P \int_{Y_1}^{Y_2} \phi(\frac{X_r}{\cos\theta}, y) \frac{dy}{\cos\theta} \tag{3.13}$$

The diffusion equation is the generalized Gaussian plume source equation for a continuous point source and can be substituted for Φ.

Substituting into equation 3.1, we obtain equation 3.14

$$C_p = \frac{Q_P}{2\pi\sigma_y\sigma_z u\cos\theta}\left[\exp\left\{ -\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2 \right\} + \exp\left\{ -\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2 \right\} \right]$$

$$x\int_{Y_1}^{Y_2} \exp\left(\frac{-y}{\sigma_y\sqrt{2}}\right)^2 dy \tag{3.14}$$

The integral can be solved by setting

$$q = \frac{y}{\sigma_y \sqrt{2}}$$ (3.15)

$$\frac{dq}{dy} = \frac{1}{\sigma_y \sqrt{2}}$$ (3.16)

This implies that

$$dy = \sigma_y \sqrt{2} dq$$ (3.17)

Equation 3.14 can now be written as

$$C_p = \frac{Q_P}{2\pi\sigma_y\sigma_z u \cos\theta} \left[\exp\left\{ -\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2 \right\} + \exp\left\{ -\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2 \right\} \right]^2$$

$$x \frac{\sqrt{\pi}}{2} \sigma_y \sqrt{2} \int_{q_1}^{q_2} \frac{2}{\sqrt{\pi}} \exp(-q)^2 dq$$ (3.18)

From the definition of the error function (one sided normal cumulative distribution function), the solution to the integral of the cross wind term is

$$\int_{q_1}^{q_2} \exp(-q^2)dq = \frac{\sqrt{\pi}}{2} \left[erf(q_1) - erf(q_2) \right]$$ (3.19)

The limits of integration are

$$q_1 = \left(\frac{(Y_r - Y_1)\cos\theta - X_r \sin\theta}{\sigma_y \sqrt{2}} \right) \quad \text{and}$$

$$q_2 = \left(\frac{(Y_r - Y_2)\cos\theta - X_r \sin\theta}{\sigma_y \sqrt{2}} \right)$$ (3.20)

where Y_1 and Y_2 are the beginning and end of the finite line source.

Substituting equations 3.20 into equation 3.18, we obtain

$$C_p = \frac{Q_P}{2\sqrt{2\pi}\sigma_z u \cos\theta} \left[\exp\left\{ -\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2 \right\} + \exp\left\{ -\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2 \right\} \right]$$

$$x \left[erf\left(\frac{\cos\theta(Y_r - Y_1) - X_r \sin\theta}{\sqrt{2}\sigma_y} \right) - erf\left(\frac{\cos\theta(Y_r - Y_2) - X_r \sin\theta}{\sqrt{2}\sigma_y} \right) \right]$$ (3.21)

3.1.7 Dispersion parameters, turbulence and traffic flow

The vertical dispersion parameter σ_z, was modelled assuming that the dispersion of the plume is solely governed by mechanical turbulence which is generated by two

mechanisms, namely wind and traffic in the street. From Berkowicz *et al*., (1997), the vertical turbulent velocity fluctuation is given by

$$\sigma_w = ((\alpha u)^2 + \sigma^2_{wo})^{1/2} \qquad (3.22)$$

where α is the wind turbulent parameter, σ_w is the vertical turbulent velocity fluctuation and σ_{wo} is the traffic created turbulence. The equation for the traffic created turbulence according to Berkowicz *et al*., (1997) is given by

$$\sigma_{wo} = b \left(\frac{TrVS^2}{W} \right)^{1/2} \qquad (3.23)$$

where b is the aerodynamic drag coefficient, T_r is the traffic flow rate; S^2 is the horizontal area occupied by a vehicle; V is the average vehicle speed and W is the width of street.

The traffic flow rate T_r, was modelled considering the numbers of a particular vehicle type that could be found at any instant in the line source. The line source for convenience had lengths ranging from 100m to 400m between intersections. The origin of the line source however still remained point 0m. This meant for every line source, the point was taken as (0, 100), (0, 200), (0, 300) and (0, 400). The number of lanes in the line source as well as traffic flow type (i. e. whether homogeneous or heterogeneous) were also considered. Traffic on most roads is heterogeneous. In this study traffic was categorized into motorcars and jeeps, heavy duty vehicles and motorcycles and tricycles according to the Highway capacity manual (Transportation Research Board, 2000).

Let the length of line source be L_l and let the length of vehicles be L_c, L_m and L_h respectively for cars, motorcycles and heavies. Assuming the vehicles were following each other at a constant spacing d, the length of lane occupied by vehicles

$$L = (L_c + L_m + L_h) + 3d \qquad (3.24)$$

Therefore total number of vehicles expected on a single lane of line source

$$D = \left(\frac{L_l}{L} \right) \qquad (3.25)$$

If the number of lanes is N, then the total number of vehicles is given by

$$D = \left(\frac{L_l N}{L_c + L_m + L_h + 3d} \right) \tag{3.26}$$

Assuming a homogeneous traffic flow and calculating separately for the different types

of vehicles then the density can also be expressed as $\quad D = \left(\frac{L_l N}{L_i + d} \right) \tag{3.27}$

From the fundamental traffic flow equation $\quad T_r = VD \tag{3.28}$

$$T_r = \left(\frac{L_l NV}{L_i + d} \right) \tag{3.29}$$

Substituting Equation 3.23 into Equation 3.22, we obtain

$$\sigma_w = \left((\alpha u)^2 + \frac{b^2 T_r V S^2}{W} \right)^{\frac{1}{2}} \tag{3.30}$$

Substituting Equation 3.29 into Equation 3.30, we obtain

$$\sigma_w = \left((\alpha u)^2 + \frac{b^2 L_l N V^2 S^2}{W(L_i + d)} \right)^{\frac{1}{2}} \tag{3.31}$$

The vertical dispersion parameter can be calculated from

$$\sigma_z = \sigma_w \frac{X_r}{u} + h_0 \tag{3.32}$$

As given by Berkowicz *et al.*, (1997).

where X_r is the perpendicular distance to the receptor and u is the mean ambient wind speed, h_0 is the effective release height and accounts for initial dispersion of pollutants from the vehicles. It also represents the height of the simulated roadside receptor.

Substituting Equation 3.30 into Equation 3.32 we obtain Equation 3.33 following Berkowicz *et al.,* (1997)

$$\sigma_z = \left((\alpha u)^2 + \frac{b^2 T_r V S^2}{W} \right)^{1/2} \frac{X_r}{u} + h_0 \tag{3.33}$$

However, since the wind is in an oblique situation, Equation 3.33 becomes

$$\sigma_z = \left((\alpha u \cos\theta)^2 + \frac{b^2 T_r V S^2}{W} \right)^{1/2} \frac{X_r}{u \cos\theta} + h_0 \tag{3.34}$$

The parameters are as earlier defined. Equation 3.31 can be used to obtain the vertical dispersion parameter when the traffic flow rate is not known, while Equation 3.34 can be used when the flow rate is known or can easily be obtained.

The horizontal dispersion parameter which is wind dependent was obtained for urban areas from Briggs (1973) stability equations of the form below:

$$\sigma_y = JX_r(1 + MX_r)^N \tag{3.35}$$

where X_r is downwind distance in m; J, M and N are constants obtained for respective stability conditions which can be read from tables.

The emission rate per unit length can be modelled from the emission factors of the vehicles, i. e.

$$Q_P = T_r e_f \tag{3.36}$$

where T_r (vehicles/s) is the traffic flow rate, e_f (g/m) is emission factor per vehicle.

Substituting Equations 3.34, 3.35, and 3.36 into Equation 3.21 we obtain Equation 3.37 which is the developed simple parameterized mathematical line source model for the direct estimation of pollutant concentration from traffic at a receptor placed at a point R (X_r, Y_r) from the source in a city street.

$$
C = \frac{T_r e_f}{2\sqrt{2\pi} u_C \left((\alpha u_C)^2 + \frac{b^2 T_r VS^2}{W}\right)^{1/2} \frac{X_r}{u_C} + h_0}
\left[
\begin{array}{l}
\exp\left\{-\frac{1}{2}\left(\frac{z - H}{\left((\alpha u_C)^2 + \frac{b^2 T_r VS^2}{W}\right)^{1/2} \frac{X_r}{u_C} + h_0}\right)^2\right\} \\[2em]
+ \exp\left\{-\frac{1}{2}\left(\frac{z + H}{\left((\alpha u_C)^2 + \frac{b^2 T_r VS^2}{W}\right)^{1/2} \frac{X_r}{u_C} + h_0}\right)^2\right\}
\end{array}
\right]
$$

$$
* \left[erf\left(\frac{\cos\theta(Y_r - Y_1) - X_r \sin\theta}{\sqrt{2}(JX_r(1 + MX_r)^{-\frac{1}{2}})}\right) - erf\left(\frac{\cos\theta(Y_r - Y_2) - X_r \sin\theta}{\sqrt{2}(JX_r(1 + MX_r)^{-\frac{1}{2}})}\right) \right]
$$

$$\tag{3.37}$$

where C (g/m^3) is the steady state concentration at a receptor; T_r is traffic flow rate (veh/s); $u_{c\ =}$ ucosθ (m/s) is mean ambient wind speed in the direction relative to the normal to the road surface; e_f is specific emission factor, z (m) is height of receptor

53

with respect to ground respectively; H (m) is height of source with respect to ground (road elevation); V(m/s) is average vehicle speed, S^2 is surface area occupied by a particular vehicle, W (m) is width of the street, X_r (m) is the perpendicular distance of the receptor from the source and Y_r is the horizontal distance along the direction of the source, Y_1 and Y_2 are the beginning and end of the line source, J and M are constants for the Briggs stability classes.

The model allows for the estimation of the concentration of a particular pollutant from a particular vehicle type. If the vehicle types are three say, then estimates are made for the concentration of a particular pollutant generated by the vehicles by summing the contributions of the individual vehicle types. These concentrations to be estimated were taken as total values including the background concentrations. The background concentrations would be obtained from measurements of pollutants when the sources were not present, especially at hours in the night when there was no motor traffic.

This model is an improvement on the work by Calder (1973) on estimating pollutant concentrations from line sources and the OSPM (Berkowicz *et al*., 1997). A major improvement is the incorporation of turbulence, which was largely neglected by Calder. Another improvement is the consideration of the heterogeneity of motor traffic in streets which had been neglected even by a more recent model like the OSPM. Individual vehicle type contributions to the quantity of pollutant can now be easily estimated with this model. Separate aerodynamic drag coefficients were also established for the different types of vehicle.

The height of source with respect to the ground, that is, the road elevation was also adjusted in this model to be the exhaust pipe height from the ground. This was not considered in previous models like the OSPM and the CALINE 4. Calder did not make any mention of this fact. It is just logical that the apparent elevation (the ground level taken as 0m) be adjusted.

A singularity problem exists at 0° wind direction, that is, when winds are perpendicular to the line source. In this regard, Csanady's model for perpendicular winds (Csanady, 1972) could be used to calculate the concentrations at this wind direction.

3.1.8 Model flow chart

A flow chart to assist in the development of the computer programme is presented below. The flow chart is simple. The user will be required to input data on vehicle and pollutant type, the programme will read the emission factors then the user will again input traffic flow rate, source length, wind and vehicle speeds. The atmospheric stability class will then be read by the programme and linear emissions calculated, from which the pollutant concentration is calculated for the specific vehicle type. This is repeated for the other vehicle types and final concentrations obtained for the particular pollutant.

```
                    ╭─────────────────╮
                    │      START       │
                    ╰─────────────────╯
                             │
  ┌──────────────────────────┤
  │            ╱─────────────────────╱
  │           ╱   INPUT VEHICLE      ╱
  │          ╱    AND POLUTANT      ╱
  │         ╱                      ╱
  │          ─────────────────────
  │                    │
  │           ╱─────────────────────────╱
  │          ╱  READ EMISSION FACTOR,   ╱
  │         ╱   SURFACE AREA AND EXHAUST╱
  │        ╱    HEIGHT                 ╱
  │          ────────────────────────
  │                    │
  │        ╱─────────────────────────────────╱
  │       ╱ INPUT TRAFFIC FLOW RATE, LENGTH  ╱
  │      ╱  AND WIDTH OF LINE SOURCE WIND    ╱
  │     ╱   AND VEHICLE SPEED              ╱
  │       ──────────────────────────────
  │                    │
  │         ╱─────────────────────────╱
  │        ╱  READ STABILITY CLASS AND ╱
  │       ╱   BRIGGS CONSTANTS        ╱
  │         ────────────────────────
  │                    │
  │           ╱─────────────────────╱
  │          ╱   CALCULATE LINEAR    ╱
  │         ╱    EMISSION           ╱
  │           ────────────────────
  │                    │
  │        ╱─────────────────────────────╱
  │       ╱  CALCULATE DISPERSION AND     ╱
  │      ╱   POLLUTANT CONC. FOR VEHICLE  ╱
  │     ╱    TYPE i, Ci                 ╱
  │       ────────────────────────────
  │                    │
  │           ╱─────────────────────╱
  │          ╱      PRINT Ci         ╱
  │           ────────────────────
  └────────────────────┤
             ╱─────────────────────────────╱
            ╱  CALCULATE TOTAL POL.         ╱
           ╱   CONCENTRATION C, FOR ALL     ╱
          ╱    VEHICLE TYPES              ╱
            ────────────────────────────
                       │
              ╱─────────────────────╱
             ╱      PRINT C          ╱
              ────────────────────
                       │
                    ╭─────────────────╮
                    │      STOP        │
                    ╰─────────────────╯
```

3.2 Parameter Estimation and Sensitivity analysis

The model has four inbuilt empirical parameters namely the street wind coefficient α, the aerodynamic drag coefficient b, the wind speed offset Us and the effective release height ho. There are five input variables or external parameters namely traffic flow rate, emission factor, ambient wind speed, wind direction and average vehicle travelling speed.

The Brute force method also called blind hill climbing method was used for the sensitivity analysis (Chinneck, 2000). Helton *et al.*, (2006) also favoured this method for simple and quicker models like the one just developed. This involved changing a selected range of values for a parameter over reasonably constant values of the other parameters. At every change in value of the parameter, the concentrations were calculated. This was done for all the inbuilt parameters. Although the model was calibrated using the brute force method, an objective function was chosen to obtain optimal parameter values. The index of agreement (Rao *et al.,* 1985) was chosen as the objective function. It is given by the formula below.

$$d = \left[1 - \frac{\sum_{i=1}^{n}(C_{pi} - C_{oi})^2}{\sum_{i=1}^{n}(|C_{pi} - \overline{C_{oi}}| + |C_{oi} - \overline{C_{oi}}|)^2} \right]$$

(3.38)

Where C_o is the measured concentration of the pollutant, C_p is the modelled concentration, d is the index of agreement and n is the number of samples. The over bar represents average values of the measured and modelled concentrations.

In the trial runs to calibrate the model, the calculated values of pollutant concentrations from the chosen parameter values were then compared with the measured concentration values. Parameter combinations that gave calculated

concentration values close to or equal to the measured values were then chosen as the optimal values.

These were then fitted in the model to get the final model with values of the parameters for streets in Minna. Negative values were not used as they would give negative concentrations and in the cases where their squares were to be used in the calculations it was noticed that the concentrations were the same like those for positive values of the parameters. In this case logical reasoning prevailed in the choice between positive and negative values. The change in the dependent variable, that is, the concentration of pollutant at a particular location with respect to independent variables like traffic flow and speed, wind speed and directions was also obtained.

3.3 Model Performance Evaluation and Validation

The performance of the model was determined firstly by applying some statistical measures like the fractional bias, index of agreement, sum of squared residuals and percentage error to the measured and modelled concentration data of three pollutants namely CO, CO_2 and NO_2. The fractional bias is a measure of the agreement of the mean values of the concentrations. It shows the tendency of the model to over predict if the value is positive and under predict if the value is negative. The index of agreement determines the extent to which magnitudes and signs of the measured values about the measured mean are related to the modelled deviations about the measured mean and allows for sensitivity towards differences in the measured and modelled values as well as proportionality changes and it is always positive. The squared residual is the squared difference between a single modelled and observed data point. Error for a group of data points is the simple arithmetic sum of the error associated with each single data point.

The equations for the fractional bias, index of agreement and squared residuals are given respectively as:

$$FB = \frac{\overline{C_p} - \overline{C_o}}{0.5\left(\overline{C_p} + \overline{C_o}\right)} \tag{3.39}$$

$$d = \left[1 - \frac{\sum\limits_{i=1}^{n}\left(C_{pi} - C_{oi}\right)^2}{\sum\limits_{i=1}^{n}\left(\left|C_{pi} - \overline{C_{oi}}\right| + \left|C_{oi} - \overline{C_{oi}}\right|\right)^2}\right] \tag{3.40}$$

$$E = \sum\limits_{i=1}^{n}\left(C_o - C_p\right)^2 \tag{3.41}$$

where FB is the fractional bias, C_o is the measured concentration of the pollutant, C_p is the modelled concentration of the pollutant, σ_o is the standard deviation of the observed concentration values and σ_p is the standard deviation of the modelled concentration values, d is the index of agreement, E is the error between a measured and modelled concentration and n is the number of samples. The over bar represents average values of the measured and modelled concentrations.

Oscillations were taken care of by applying the perturbed error method. The perturbed error is the sum of the squared residual between a measured data set and a data set arrived at by increasing or decreasing each measurement by a percentage α. The perturbed error index provides a method to relate naturally expected error with the error in dispersion model estimates thereby taking care of oscillations and is given by.

$$PE = \sum\limits_{i=1}^{n}\left\{\left(1 \pm \frac{\alpha}{100}\right) \times C_o - C_o\right\}^2 \tag{3.42}$$

where PE is the perturbed error, α is the percentage by which the measured data C_o is either increased or decreased.

The results obtained for the model were later compared with the results obtained using Calder's model and the OSPM model. The developed model was validated using data collected for Jagtvej Street in Copenhagen, Denmark for NO_2 as presented by

Berkowicz *et al*., (2006). These data were used to calibrate and validate the OSPM model too. A traffic volume of 2700vph was used. The emission factor was calculated from the total NO_2 emissions recorded for traffic within the street.

3.4 Experimental Methods

Measurements were carried out for traffic flow, emission factors, meteorological conditions and background concentrations to validate and evaluate the model for different seasonal and environmental conditions and for different traffic flows and speeds.

3.4.1 Description of project area

Mobil roundabout to Unity Bank segment of the Paiko-Bosso road in Minna was used for this study (Fig. 3.3). The segment is 280 m long with a 40 m wide street and has buildings lining both sides of the road. The road is orientated at approximately 30 degrees west of North and links the two main entrance and exit gates in Minna. This portion of the road was considered the most congested by virtue of its heavy and slow moving traffic during all periods of the day compared to other roads. The Minna central market is also located along this road. The average height of the buildings is 6 m with the tallest building being 12 m high. The road is a dual carriageway with a 5 m wide median. The street was considered an avenue canyon since it has an aspect ratio (height of building to width of street) of less than 0.5. The significant differences in building heights make it an asymmetric canyon also. The buildings are well spaced and act essentially as isolated roughness elements which means the air travels a significant distance downwind of the first building before encountering the next obstacle. There is therefore little room for wake interferences and formation of vortices hence recirculation effect of pollutants is minimized. These facts are presented in Plates I and II.

Plate I: Project site with tallest buildings and vehicles emitting pollutants

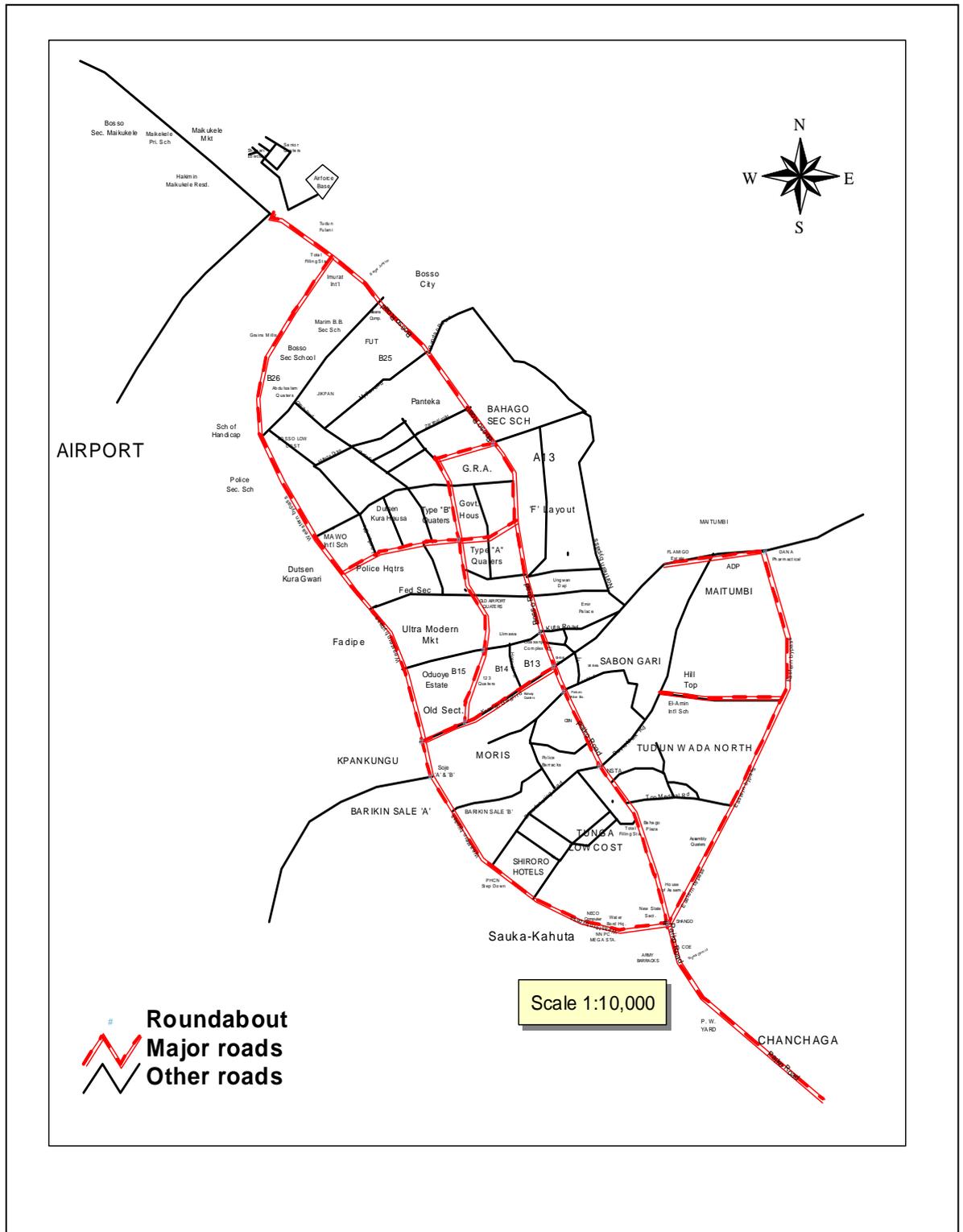**Plate II:** Travel way and road median of project site

Fig. 3.3: Minna road map

3.4.2 Traffic studies

Traffic was monitored for three months in 2008, namely March, July and October. These months were randomly chosen to represent dry season months, rainy season months and windy months respectively. Traffic volumes, fleet composition and average vehicle speeds were all manually measured. This was done to ensure accuracy and minimization of data losses.

Traffic flow at the census point was first conducted to determine the peak periods. The counts were done manually between 7:00 am and 7:00pm from Monday to Thursday. The average travelling speed on the segment which is the total distance travelled divided by time taken to traverse the distance was also measured by placing two attendants one at each end of the segment, with synchronized electronic wrist watches to record the plate number and time the vehicle passed his marked point on the road. The time to traverse the distance was the difference between the time the vehicle left the segment and when it entered the segment. Three 6 m distances were also chosen at the beginning, middle and end of the segment from where spot speed studies were carried out. This was done to determine congestion periods and positions within the peak hours. This was also necessary so as to have an idea of effects of speed to pollutant concentration.

Physical dimensions of the vehicles were measured using a tape rule. The physical dimensions included lengths, widths and exhaust pipe heights of the vehicles. Average values were then calculated, from which the surface areas were obtained. Data was also collected for vehicle ages as well as year of registration in Nigeria. These would assist in making a clear distinction between the ages of vehicles plying the streets in Africa and those plying streets in Europe.

3.4.3 Vehicle emission factors

The developed model required separate emission factors for small and large vehicles to be specified. Automotive emissions occur at ground level and are expressed in terms of emission factors (mass of pollutant per distance travelled which depends on driving conditions). A measuring car with an engine capacity of 2.0, and using petrol as fuel as used to follow some randomly selected vehicles within the town. The velocities of the selected vehicles as well as the engine revolutions were measured at 5 seconds interval. The total distance travelled for each driving cycle was also noted. Four driving conditions namely acceleration, deceleration, cruising and idling were identified for cars and heavy vehicles. This method of measurement is in accordance with Beiruti and Al-Omishy (1985). Drivers of the some of the randomly selected vehicles were then told to keep their engines running at 900rev/min for idling, 2500rev/min for decelerating 2800rev/min for cruising and 3500rev/min for accelerating at a stationary position. At each engine revolution, the RAE LP-2000 hand gas pump was used to measure the quantity of pollutants emitted. The quantity emitted for a whole driving cycle was got by adding all four concentrations. The specific emission factors for particular pollutants were obtained by dividing the total emissions per cycle per minute by the average travelling speed in km/min. The units were in g/km per vehicle. This approach is in line with that suggested by Jensen (1995), where he concluded that travel speed rather than length of road is crucial to the level of emissions. The values obtained were then compared with values proposed by Gujar *et al*., (2004) for the Indian vehicle fleet. The stationary method was the only one used for motorcycles since most of them do not have engine revolution meters and the dangers inherent in mobile measurements for motorcycles were enormous and practically insurmountable.

3.4.4 Meteorological data

Data on average wind speed, direction, ambient temperature and relative humidity were obtained from the Nigeria Meteorological (NIMET) station located at the Minna Airport in Niger state. The atmospheric stability was also specified based on the average wind speed. The most important meteorological parameters are wind speed and direction. The values of the wind speeds at street level were taken to be 0.37 times the value of wind speed at roof level following the power relationship conversion between roof and street winds according to Berkowicz *et al.*, (1997).

3.4.5 Field measurements of pollutant concentrations

A standard gas analyzer, a RAE LP-2000 hand gas pump with detector tubes was used for measuring the concentrations of the gaseous pollutants. The choice of this type of monitor was determined by response time. Response time, which is the time over which the sample is taken was the major factor considered for the suitability of the monitoring technique. Standard gas analyzers are sufficiently sensitive and fast to give real time measurements of the pollutants. The results were then averaged over short time periods. Measurements were carried out at midpoints between junctions. This was adjudged to provide representative measurements for the street as traffic flow is known to be less affected at these points by traffic control, and turbulence will be at its maximum. It was hoped also that the vehicles will neither be accelerating nor decelerating.

A detector tube specific for each gas was slotted into the pump and air dragged into it. Measurements were carried out for the peak periods of the day. Background measurements were carried out at very early hours of the day between 3.30 A.M. and 4.30 A.M. when there was no motorized traffic, and on some less trafficked roads in the city outskirts during peak periods on the selected segment to form the baseline or

background concentrations. One of the locations was the vicinity of the project site while the others were two roads namely Western and Eastern by-passes a few kilometers away from the project site. The average values were then obtained from these three readings. This was done for a week in each of the months of March, July and October. Plates III and IV show the researcher measuring pollutants at the kerbside and the typical vehicle mix at the project site.

Plate III: Roadside measurement of pollutants at project site

Plate IV: Typical vehicle mix at project site

RESULTS

This chapter presents the data collected from field studies. The model required inputs on street geometry, traffic flow and composition, emission factors and meteorological parameters.

4.1 Traffic Data

The results of the average hourly and daily traffic are shown in Figs. 4.1 to 4.3 for March, July and October respectively. The average total daily traffic is given in Fig. 4.4. Meanwhile average daily traffic volumes for the selected days of the three months are presented in the appendix.
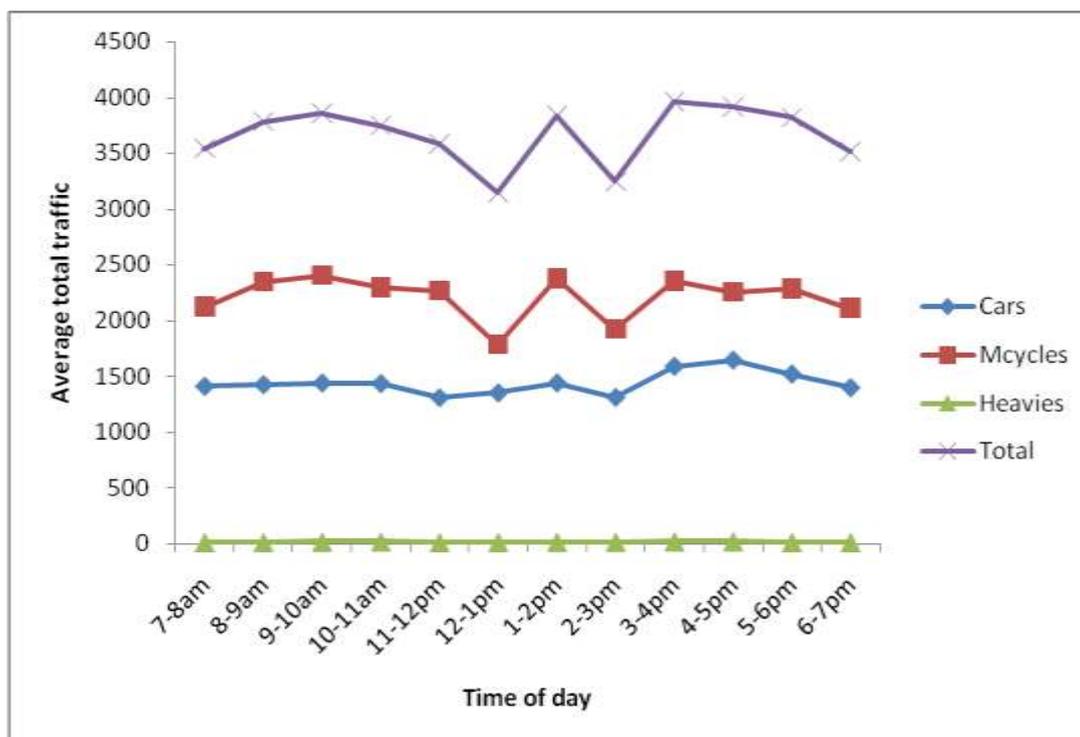

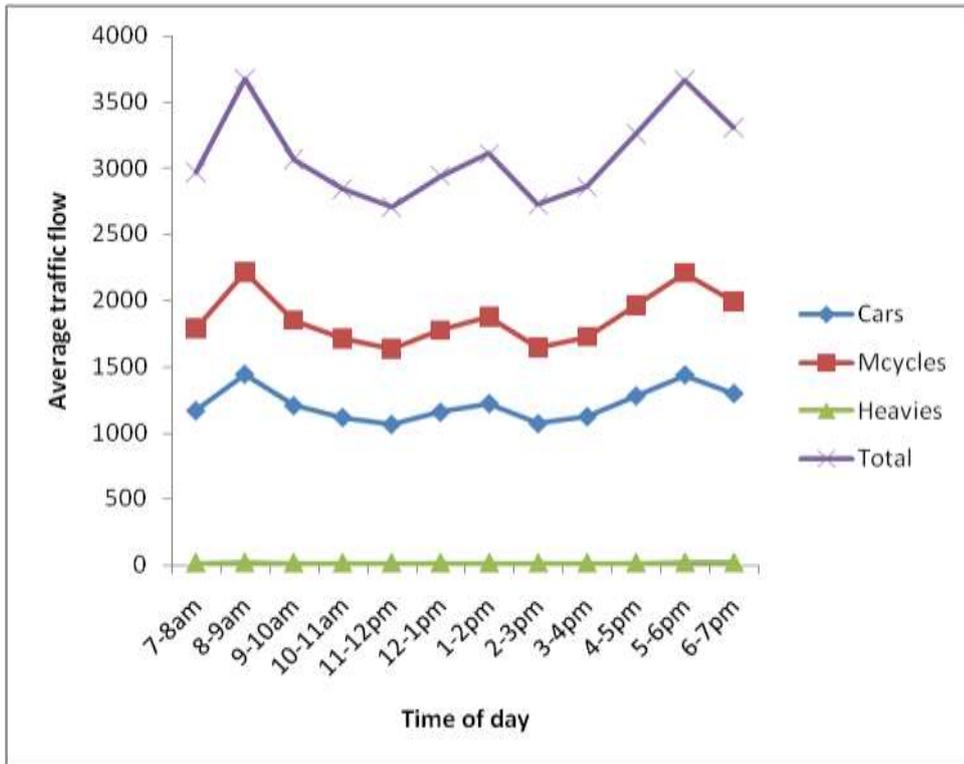**Fig. 4.1:** Average hourly and total daily traffic for March 2008

Fig. 4.2: Average hourly and total daily traffic for July 2008
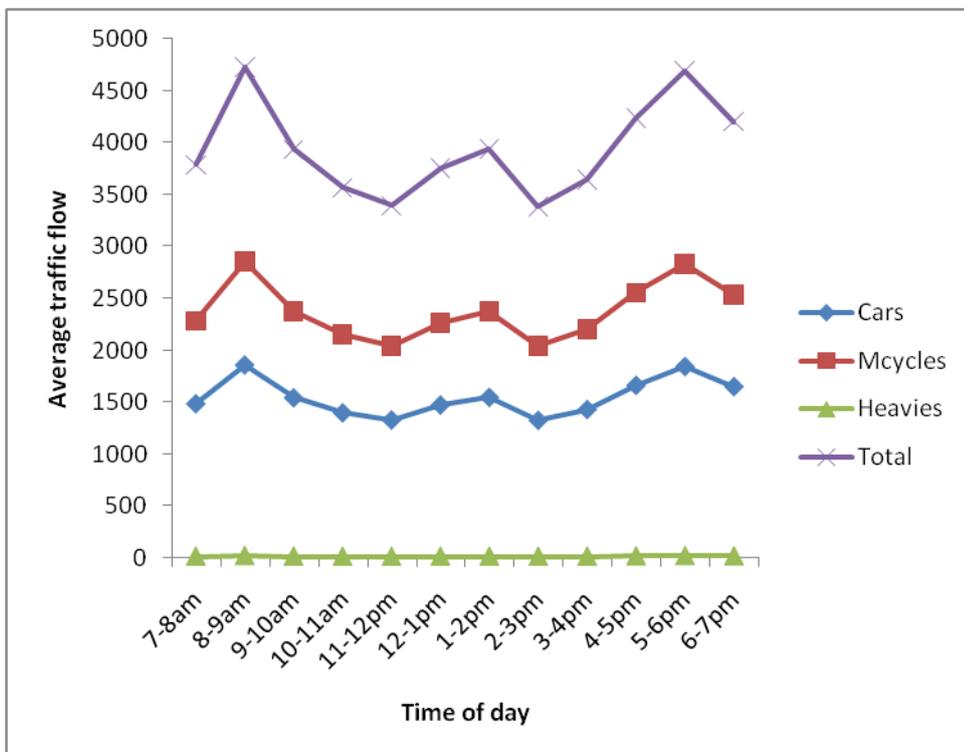

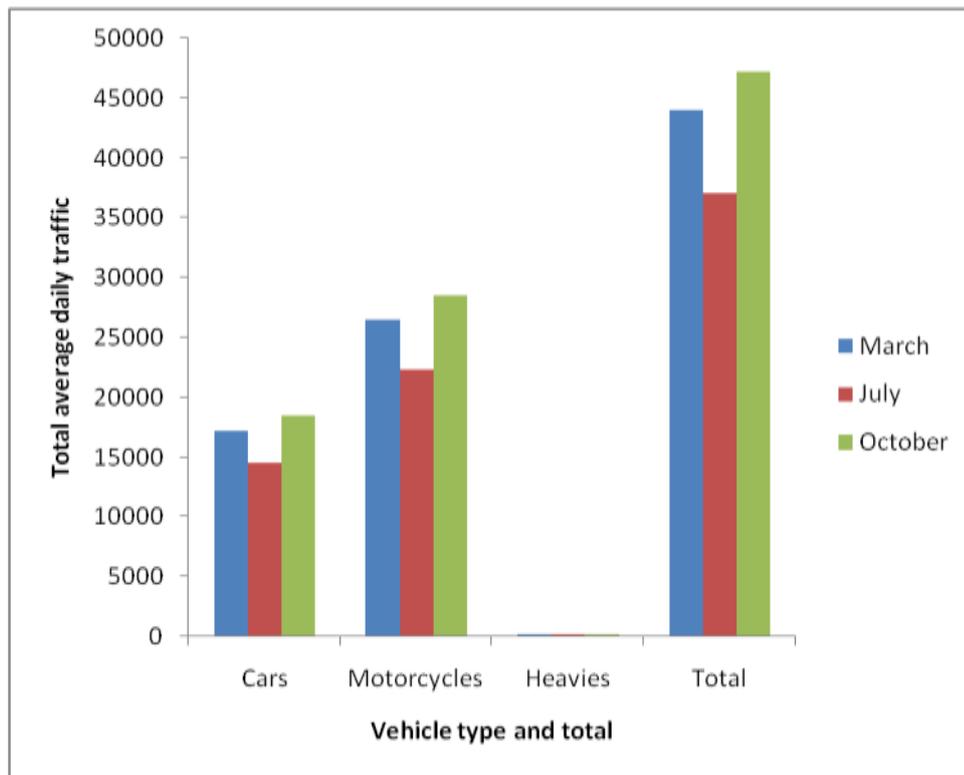**Fig. 4.3:** Average hourly and total daily traffic for October 2008

Fig. 4.4: Average total daily traffic for the three months

The traffic proportions for the three months are shown in Table 4.1. The values in the brackets are the proportions of the vehicles vis-à-vis total daily traffic mix.

Table 4.1: Average total traffic volumes and proportions

Month	Cars	Motorcycles	Heavies	Total
March	17239	26548	184	43971
	(0.392)	(0.604)	(0.004)	
July	14539	22362	185	37086
	(0.392)	(0.603)	(0.005)	
October	18525	28499	237	47261
	(0.392)	(0.600)	(0.008)	

The average values of the lengths, widths, surface areas and exhaust pipe heights are presented below.

Table 4.2: Representative physical dimensions of vehicles

Vehicle type	Length (m)	Width (m)	Area (m^2)	Exhaust pipe height
Car /jeep	4.38	1.5	6.57	0.3
Heavies	11.8	2.40	28.32	0.68
Motorcycles	1.70	0.70	1.19	0.24

The age distribution of some randomly selected vehicles is shown in Table below while a bar chart of the total number of vehicles (cars and buses) in each age range is presented in Fig. 4.5.

Table 4.3: Age distribution of some vehicles in Minna

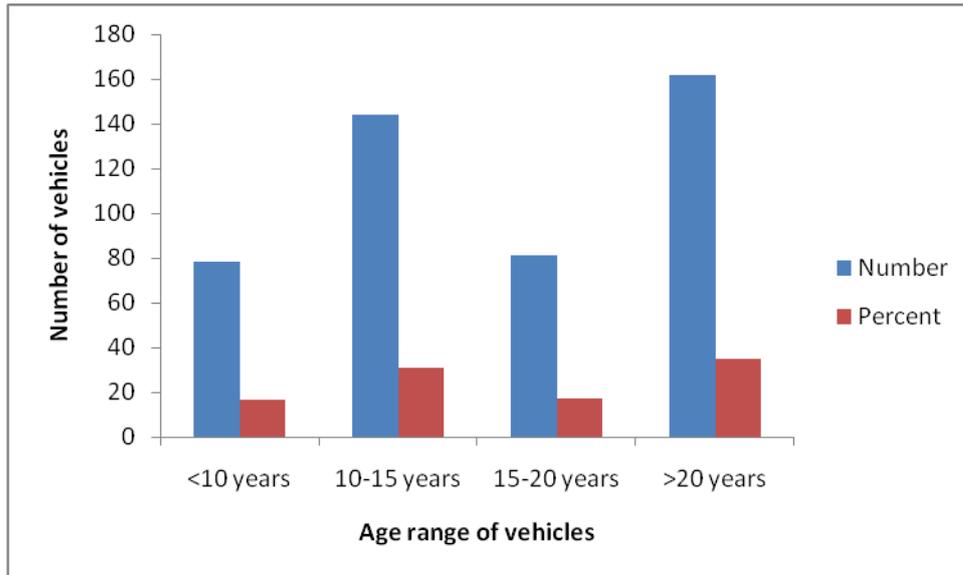| Vehicle type	<10 years	10-15 years	15-20 years	>20 years	Total
Audi (car)	2	12	15	0	29
Mercedes Benz	5	37	19	15	76
BMW	5	13	5	3	26
Datsun	0	0	3	12	15
Honda	17	33	21	24	95
Kia	2	1		0	3
Opel	4	5	3		12
Peugeot	12	7	6	20	45
Toyota	20	26	32	60	138
Volkswagen	6	7	6	8	27
Toyota (bus)	5	3	5	20	33
Motorcycles	85	15	0	0	100
Total (Cars and Buses)	78	144	81	162	

Fig. 4.5: Age range of sampled vehicles in Minna

4.2 Emission factors

Average values of the calculated emission factors for three pollutants namely carbon monoxide, carbon dioxide and nitrogen dioxide are presented in Table 4.4. The emission factors from the Indian study Gujar *et al.,* (2004) are also presented for the three pollutants for comparison.

Table 4.4 Average emission factors for different pollutants and vehicle type

Vehicle type	Motorcycle (g/m)		Cars (g/m)		Heavy vehicles (g/m)	
Pollutant	This study	Gujar *et al.*	This study	Gujar *et al.*	This study	Gujar *et al.*
Carbon monoxide	0.022	0.007	0.036	0.014	0.0210	0.007
Carbon dioxide	0.384	0.125	3.84	1.30	6.840	2.30
Nitrogen dioxide	0.00001	0.000003	0.0001	0.00003	0.0062	0.0025

4.3 Meteorological data

Data for wind speeds and relative humidity are presented in Table 4.5, while the Brigg's stability constants and class are presented in Table 4.6.

Table 4.5: Monthly relevant local meteorological parameters for Minna in 2008

Month (1)	Relative humidity (%)	Roof level wind speed in m/s (3)	Street level wind speed m/s (0.37 * (3)	Occurrences (5)
January	45	23	8.5	Once
February	46	13	4.8	Once
March	44	mild	mild	
April	48	18	6.5	Thrice
May	56	20	7.5	seven times
June	70	21.5	8	six times
July	82	14.5	5.5	twice
August	80	17	6	thrice
September	80	17	6.3	six times
October	78	17	6.3	fourteen times
November	76	17	6.3	twice
December	54	15	5.6	once

Adapted from NIMET, Minna National Airport

Table 4.6: Briggs' stability constants

Stability class	Wind (m/s)	J	M	N
A-B	0 to 3	0.320	0.0004	-0.5
C	3 to 5	0.220	0.0004	-0.5
D	5 to 6	0.160	0.0004	-0.5
E-F	greater than 6	0.110	0.0004	-0.5

Source: Beychok (2005)

4.4 Parameter Estimation and Sensitivity analyses

The internal parameters so considered were the aerodynamic drag coefficient b, the street wind turbulence factor or atmospheric turbulence factor α, the wind speed offset u_s, and the effective release height h_0. The concentrations of CO obtained at 60º, which is representative of the typical wind direction for the road at different combinations of the parameters are shown in Table 4.7.

Table 4.7: CO concentrations (p p m) at different values of parameter estimates

Trial no.	b, u_s, h	α=0.05	0.1	0.15	0.2
1	0.1, 0.1, 1.0	10.56	10.52	10.49	10.45
2	0.2, 0.2, 1.5	7.32	7.29	7.26	7.20
3	0.3, 0.3, 2.0	5.84	5.81	5.77	5.71
4	0.4, 0.4, 2.5	4.94	4.96	4.86	4.50

The relationship between concentrations of CO and the other internal parameters are shown in the figures below.
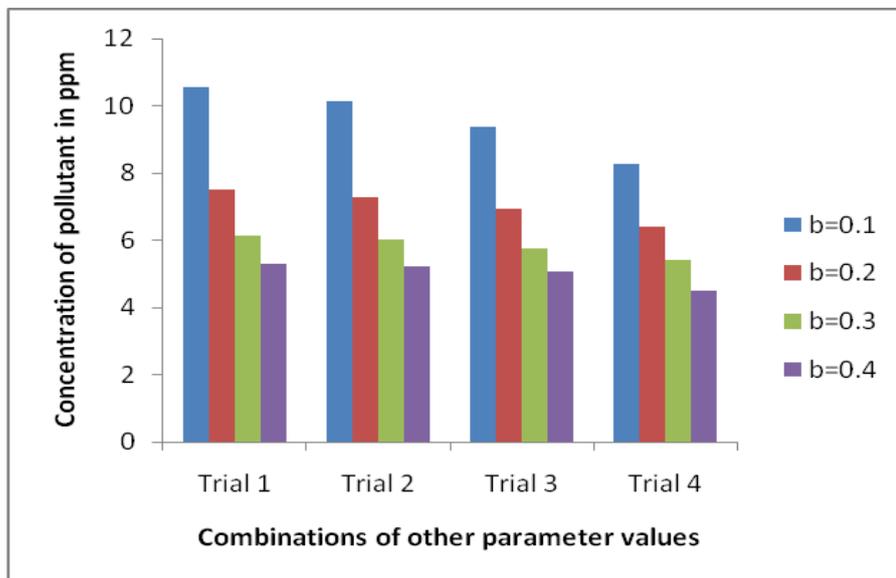

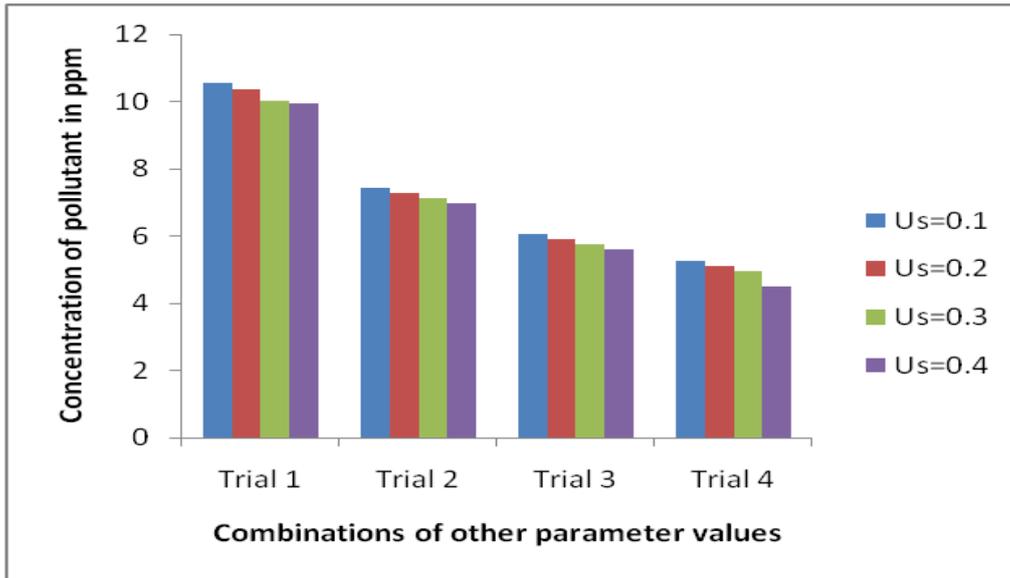**Fig. 4.6:** Relationship between concentration of CO and aerodynamic drag coefficient

Fig. 4.7: Relationship between concentration of CO and wind speed offset
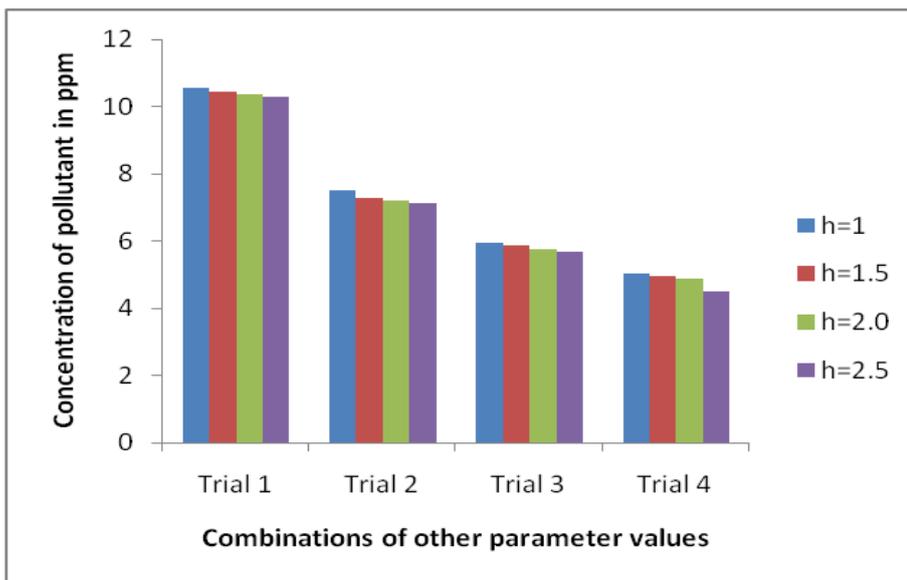

Fig. 4.8: Relationship between concentration of CO and effective
  release height

Considering the optimum values obtained for the internal parameters, a final

form for Equation 3.37 for the calculation of concentrations of gaseous pollutants in

streets in Minna metropolis can be written as shown in Equation 4.1.

$$C = \frac{T_r e_f}{2\sqrt{2\pi}u_a\left((0.15u_a)^2 + \frac{b^2 T_r VS^2}{W}\right)^{1/2}\frac{X_r}{u_a}+1.5} \left[\exp\left\{-\frac{1}{2}\left(\frac{z-H}{\left((0.15u_a)^2 + \frac{b^2 T_r VS^2}{W}\right)^{1/2}\frac{X_r}{u_a}+1.5}\right)^2\right\} + \exp\left\{-\frac{1}{2}\left(\frac{z+H}{\left((0.15u_a)^2 + \frac{b^2 T_r VS^2}{W}\right)^{1/2}\frac{X_r}{u_a}+1.5}\right)^2\right\}\right]$$

$$*\left[erf\left(\frac{\cos\theta(Y_r - Y_1) - X_r\sin\theta}{\sqrt{2}(JX_r(1+MX_r)^{-\frac{1}{2}})}\right) - erf\left(\frac{\cos\theta(Y_r - Y_2) - X_r\sin\theta}{\sqrt{2}(JX_r(1+MX_r)^{-\frac{1}{2}})}\right)\right]$$

(4.1)

Where $u_a = u\cos\theta + 0.2$m/s is the adjusted street wind considering the wind offset value of 0.2m/s, 1.5m is the optimum effective release height, which is representative of the height at which receptor is held and 0.15 is the street wind turbulence coefficient. No value was placed for b, the aerodynamic drag coefficient since different values were obtained for the different vehicles considered. All other parameters are as defined for Equation 3.37.

The sensitivity of the model to such external parameters as traffic speeds and flows, emission factors, wind speed and direction was also determined by changing values of each of these parameters while holding the others constant. The relationships obtained between concentrations of CO and the external parameters are shown in the following figures.
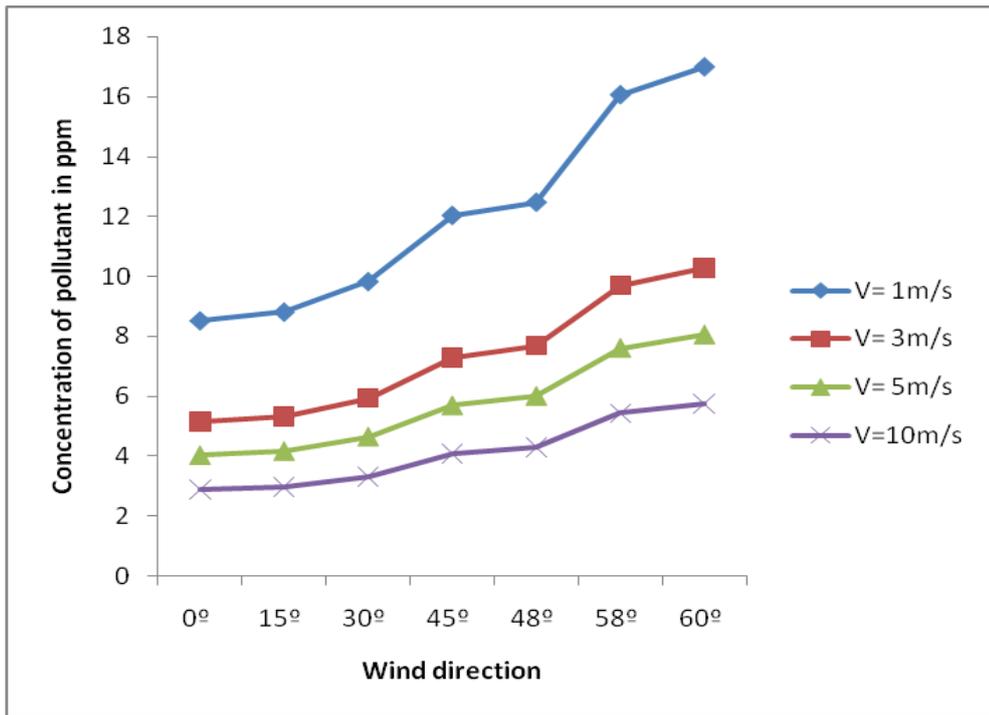
Fig. 4.9: Relationship between concentration of CO and average traffic Speed
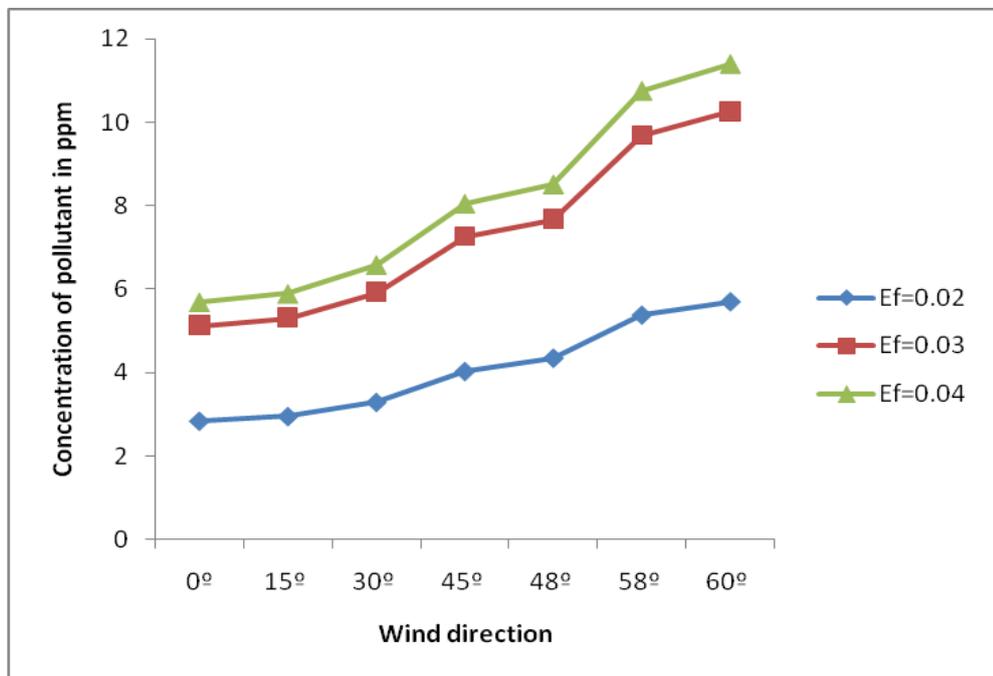

Fig. 4.10: Relationship between concentration of CO and emission factors
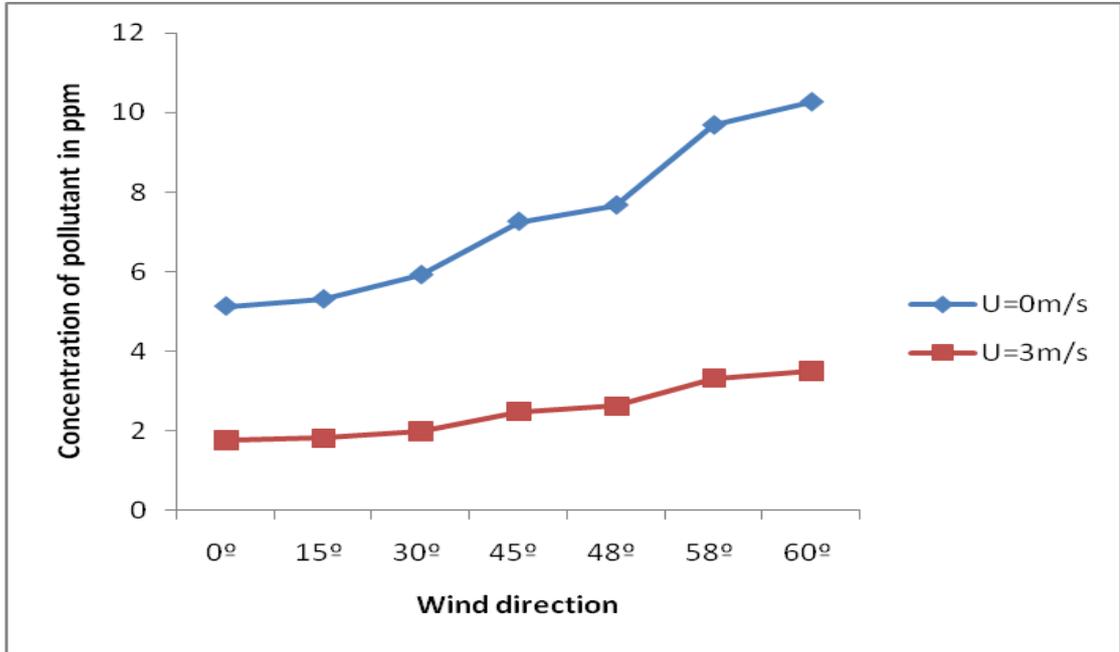
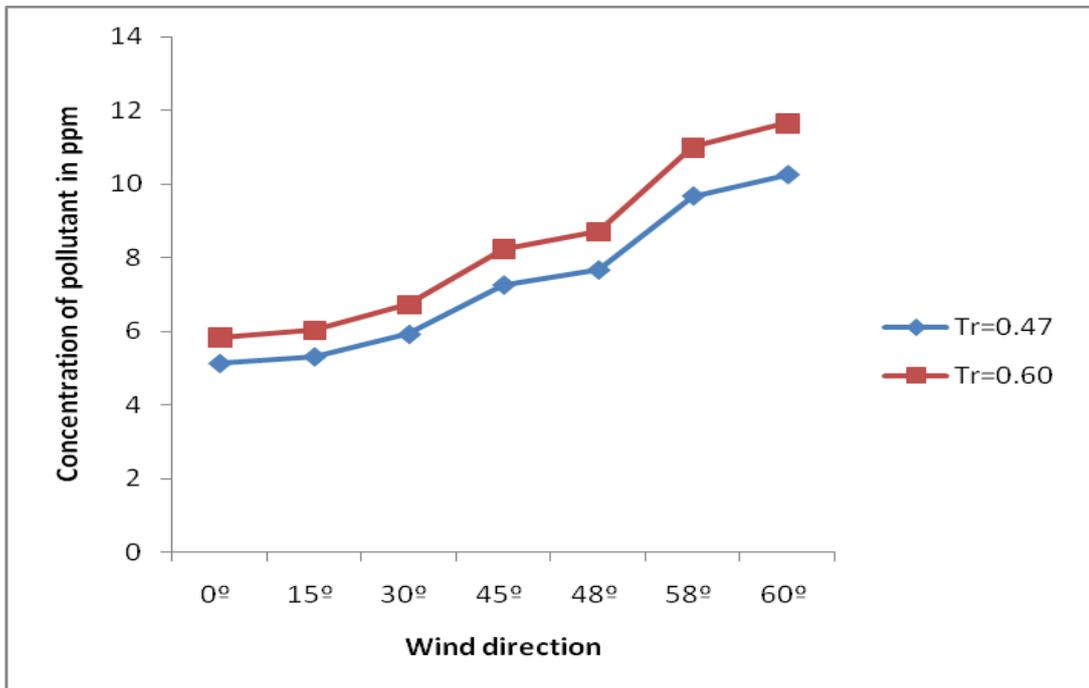**Fig. 4.11:** Relationship between concentration of CO and ambient wind speed

Fig. 4.12: Relationship between concentration of CO and traffic flow rate

4.5 Comparison of Modelled and Measured Concentrations

The model was used to calculate concentrations of the pollutants and the results compared with values obtained from measurements. The figures below show a time series comparison of the measured and modelled concentrations of the pollutants.

4.5.1 Carbon monoxide concentrations

Figs 4.13 to 4.21 show a comparison of the measured and modelled concentrations for carbon monoxide for the months of March, July and October.
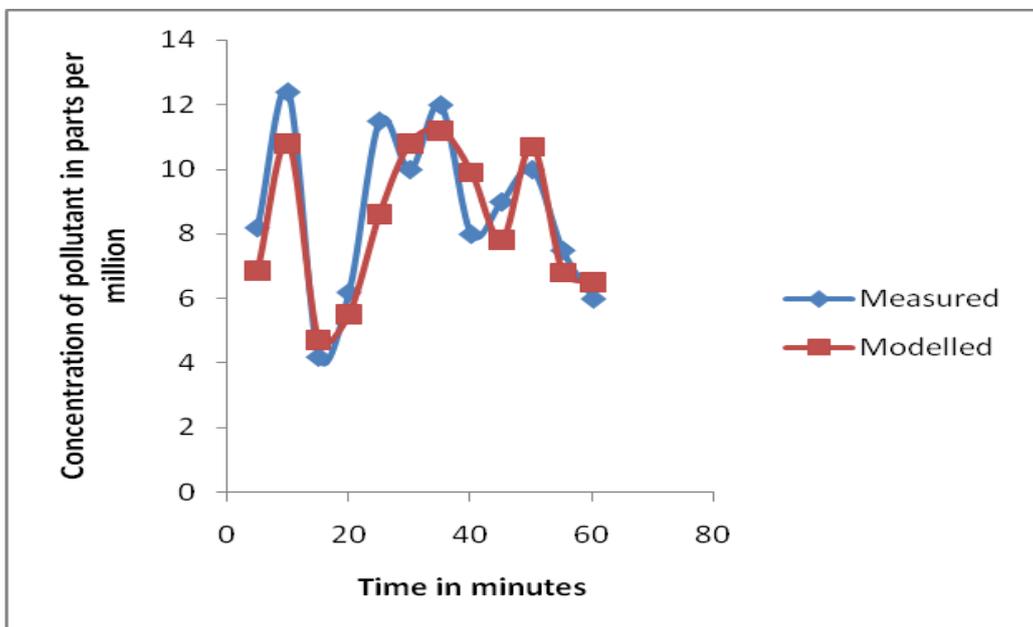
Fig. 4.13: Carbon monoxide concentrations for March 3
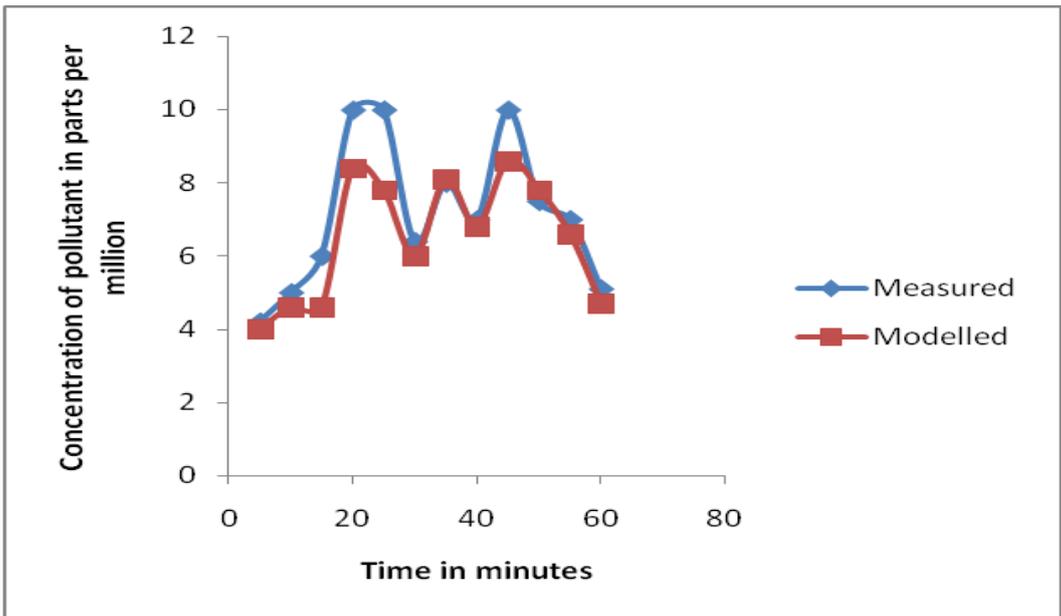
Fig. 4.14: Carbon monoxide concentrations for March 4
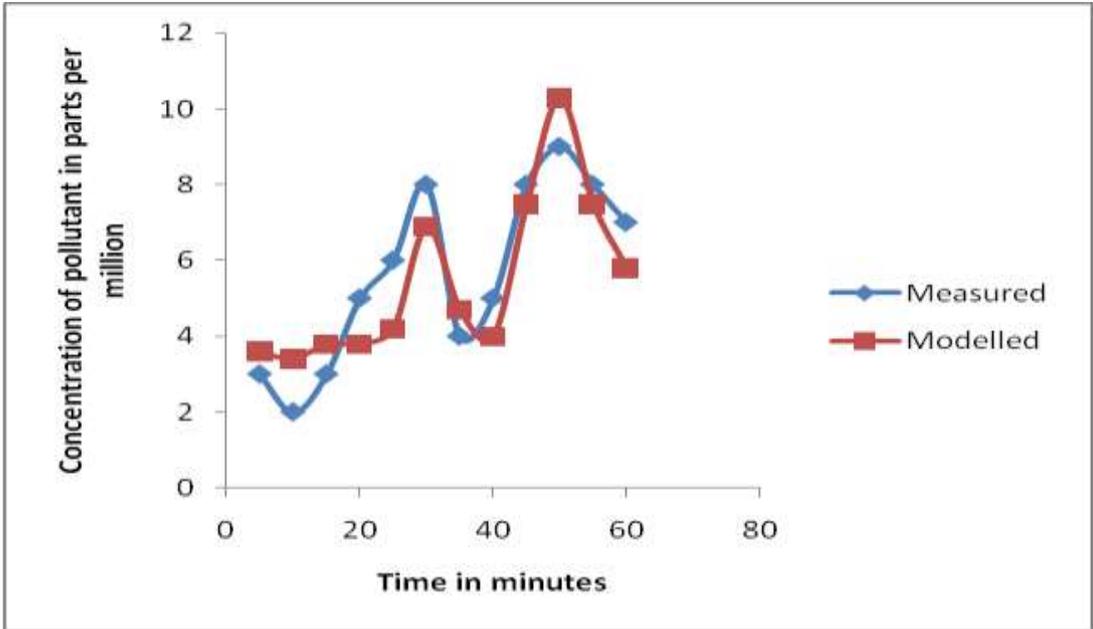
Fig. 4.15: Carbon monoxide concentrations for March 5

Fig. 4.16: Carbon monoxide concentrations for July 1
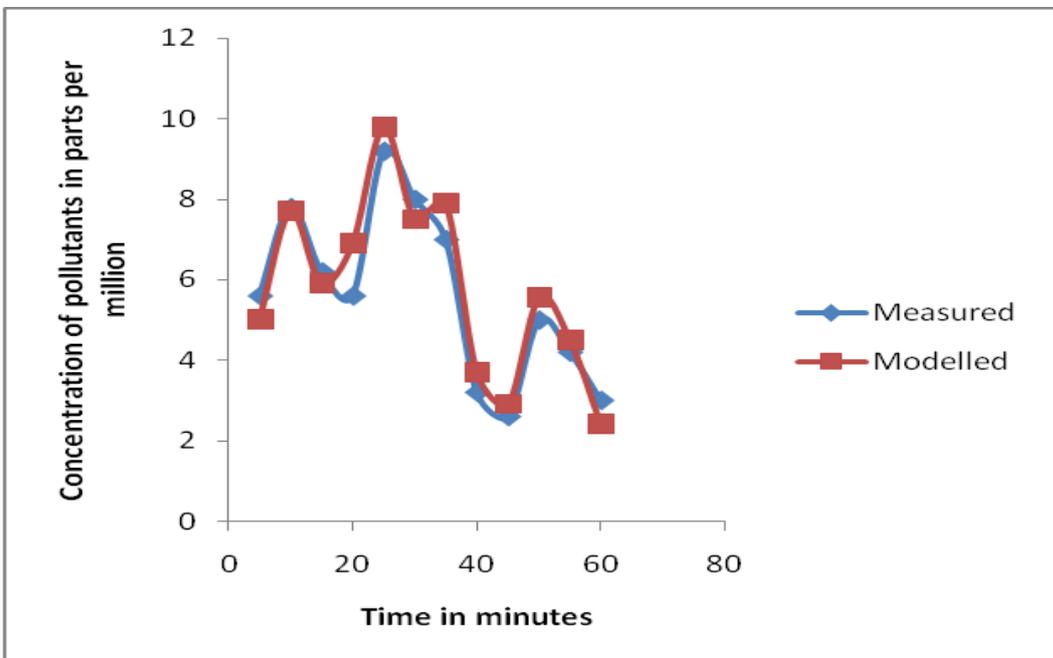
Fig. 4.17: Carbon monoxide concentrations for July 2
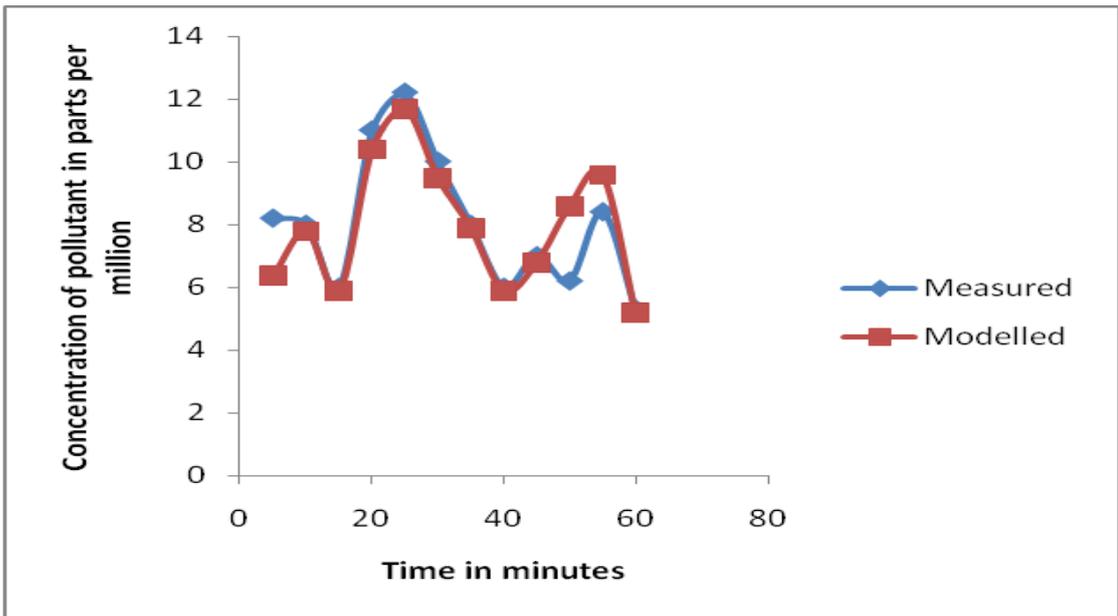
Fig. 4.18: Carbon monoxide concentrations for July 3
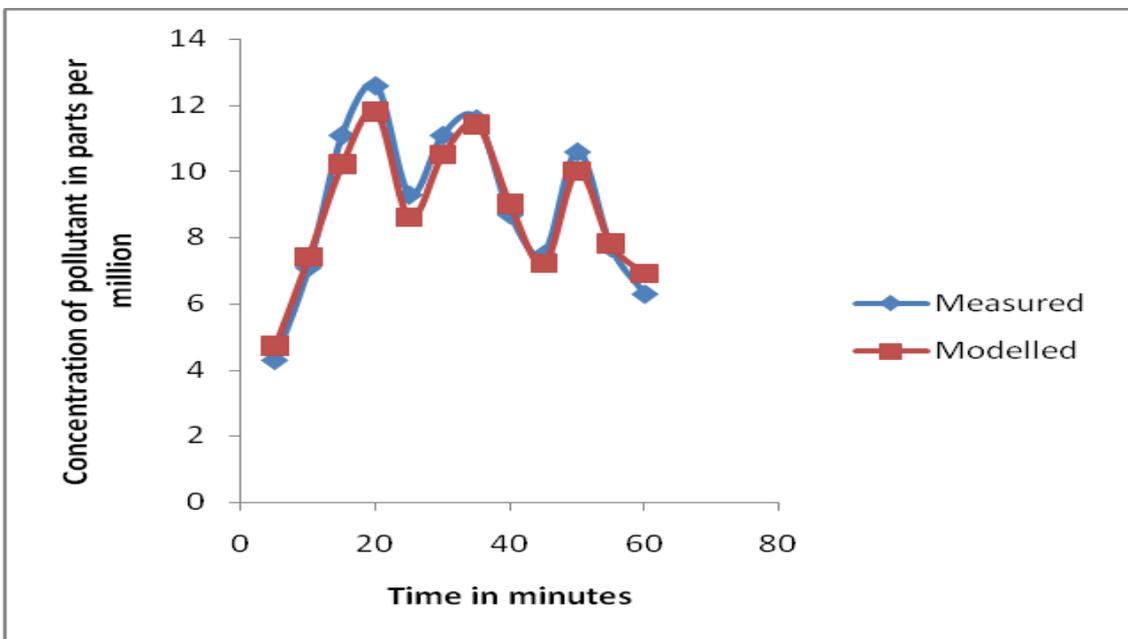
Fig. 4.19: Carbon monoxide concentrations for October 1
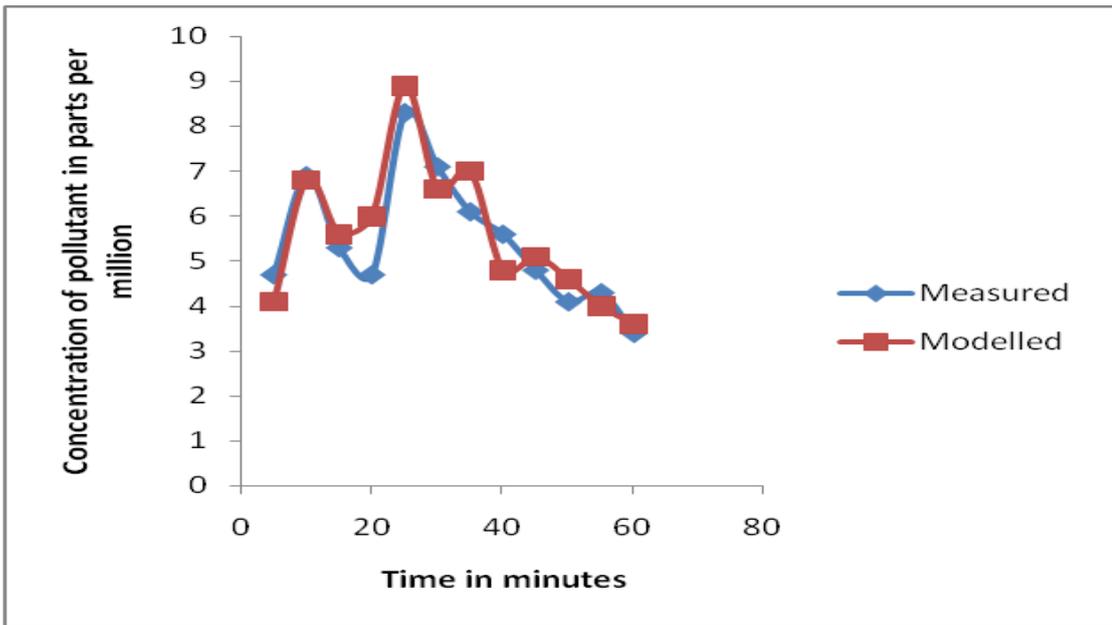
Fig. 4.20: Carbon monoxide concentrations for October 2
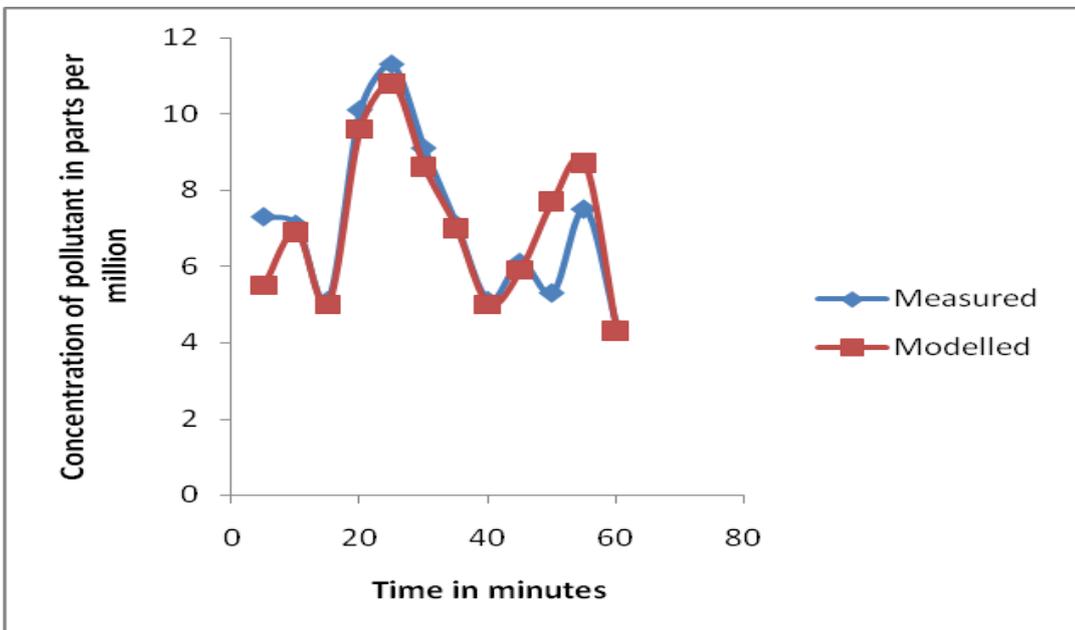
Fig. 4.21: Carbon monoxide concentrations for October 3

4.5.2 Carbon dioxide concentrations

Measured and modelled concentrations of carbon dioxide for March, July and October are presented in Figs. 4.22 to 4.30.
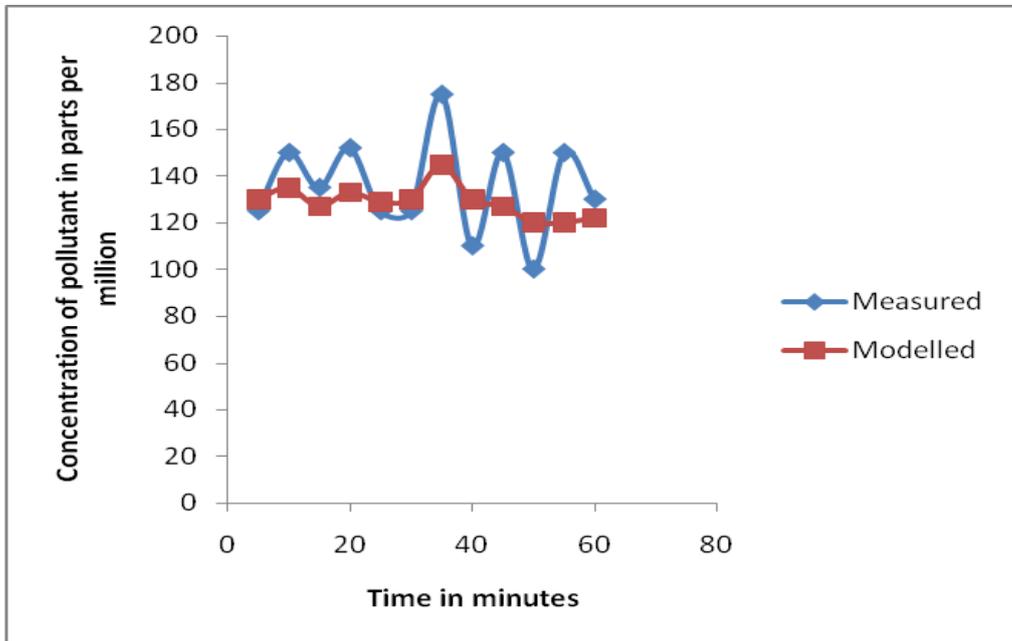
Fig. 4.22: Carbon dioxide concentration for March 24
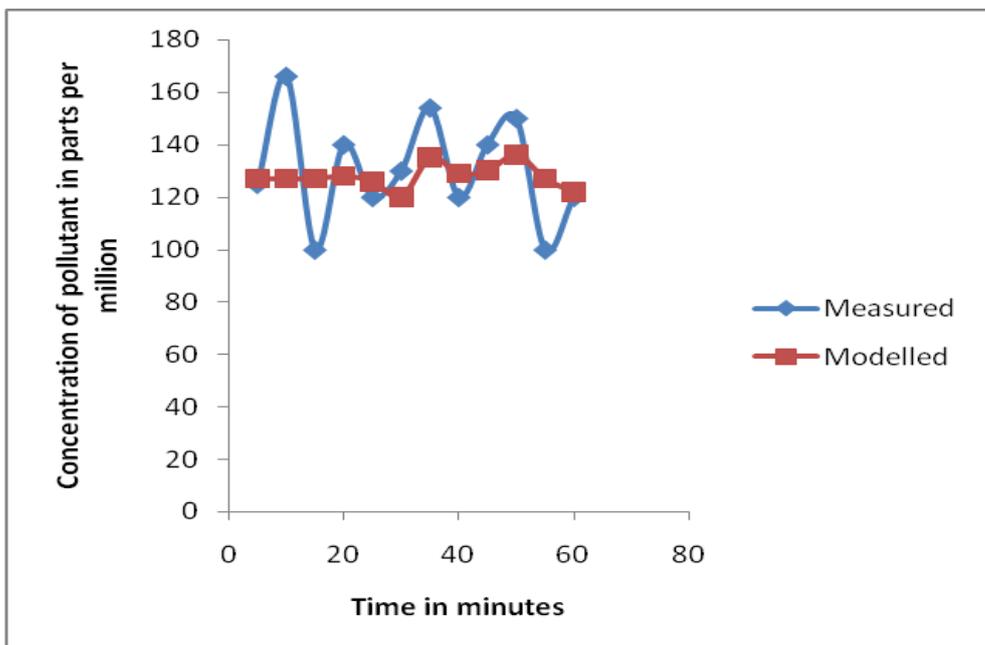
Fig. 4.23: Carbon dioxide concentration for March 25
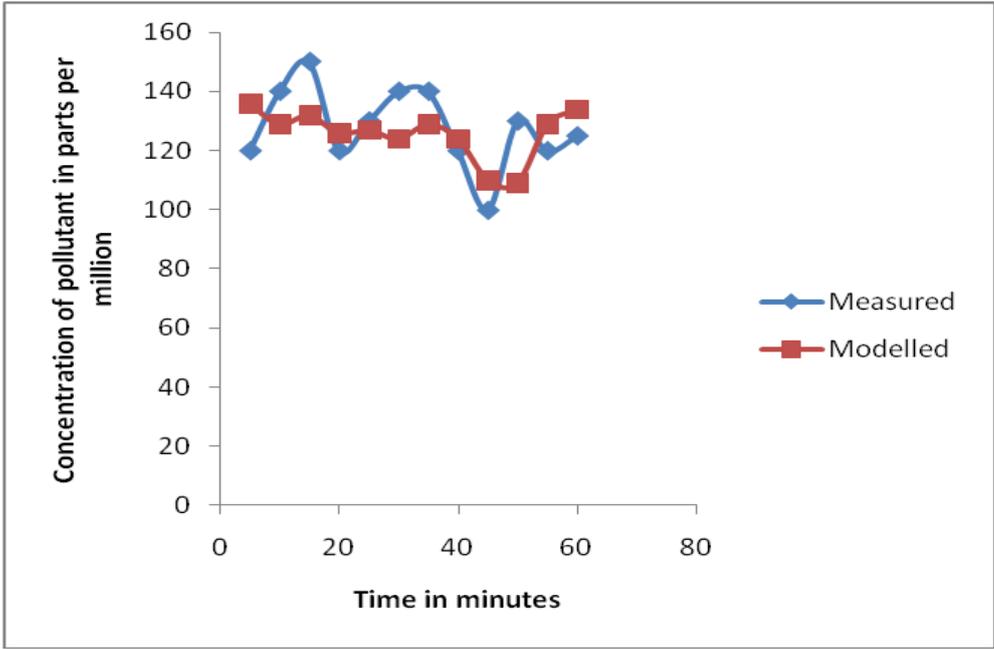
Fig. 4.24: Carbon dioxide concentration for March 26
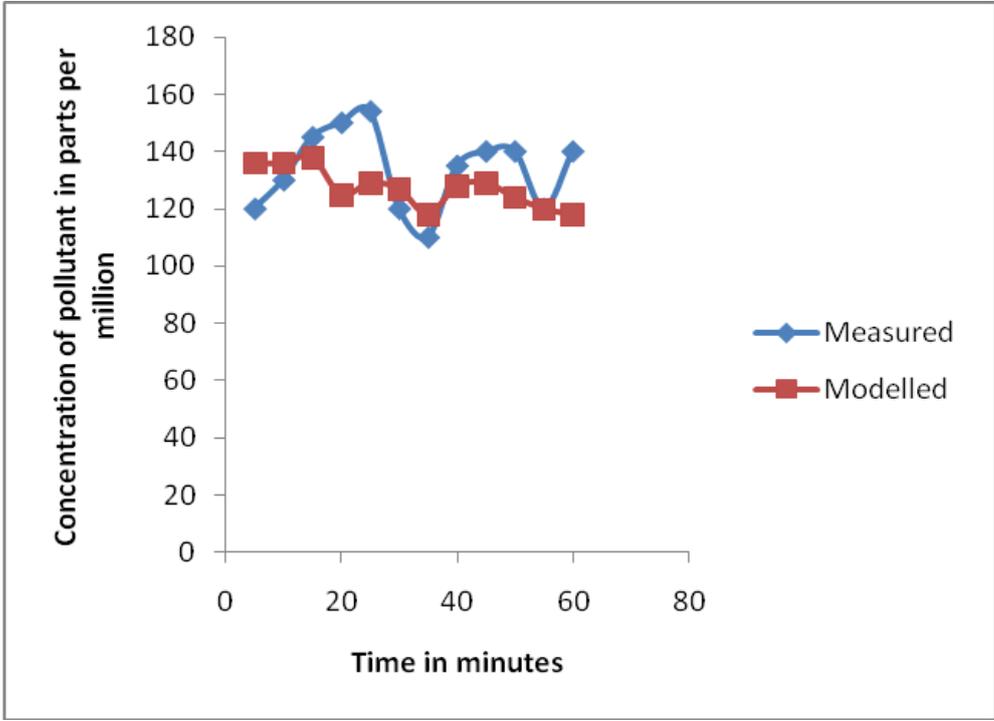
Fig. 4.25: Carbon dioxide concentration for July 9
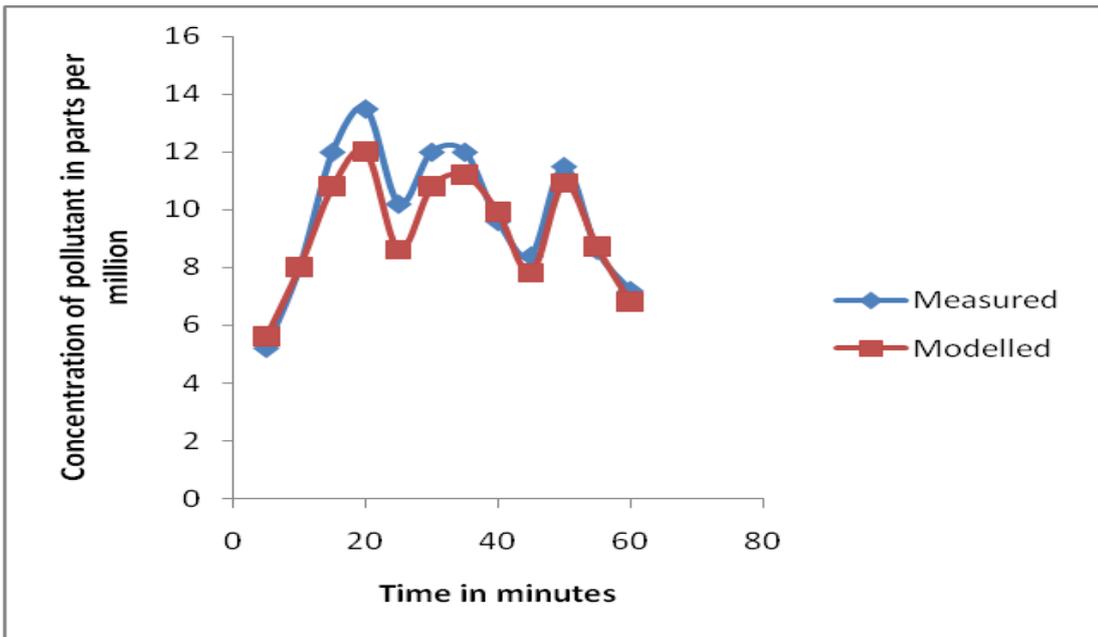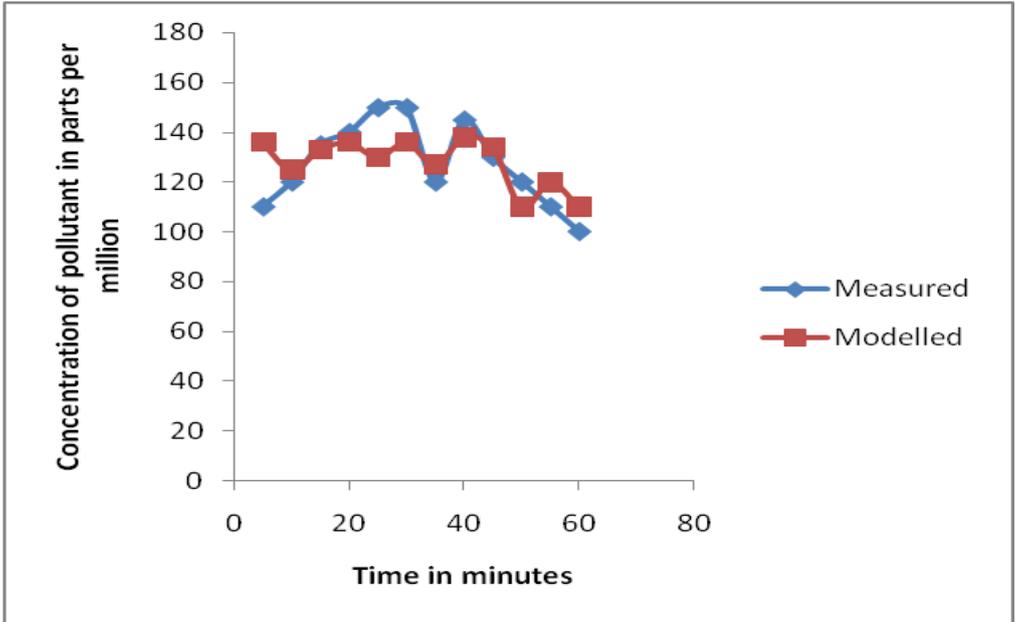
Fig. 4.26: Carbon dioxide concentration for July 10
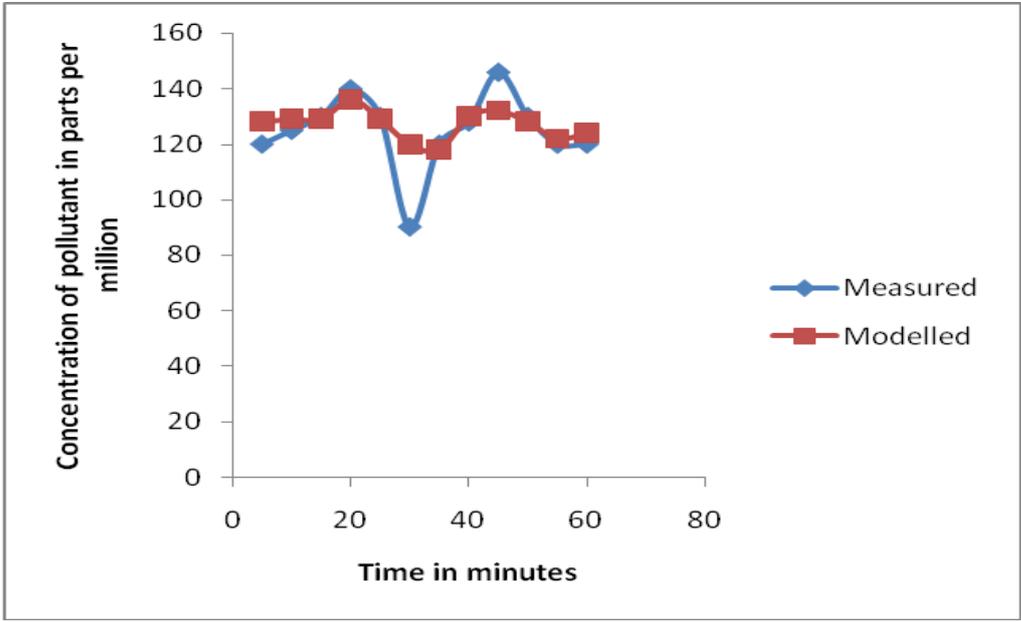
Fig. 4.27: Carbon dioxide concentration for July 11
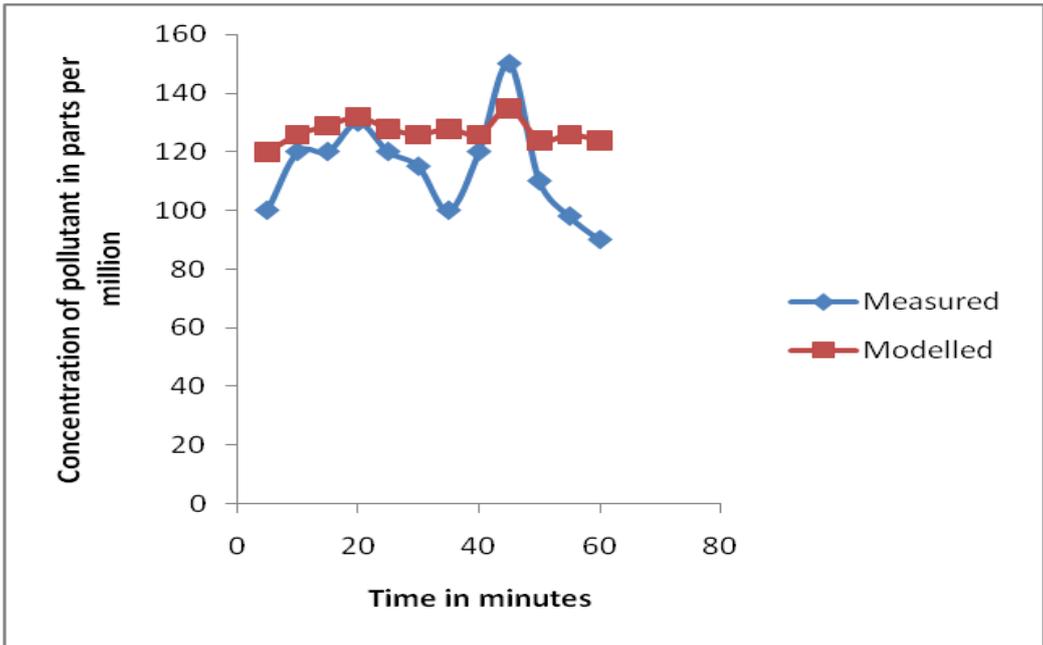
Fig. 4.28: Carbon dioxide concentration for October 20
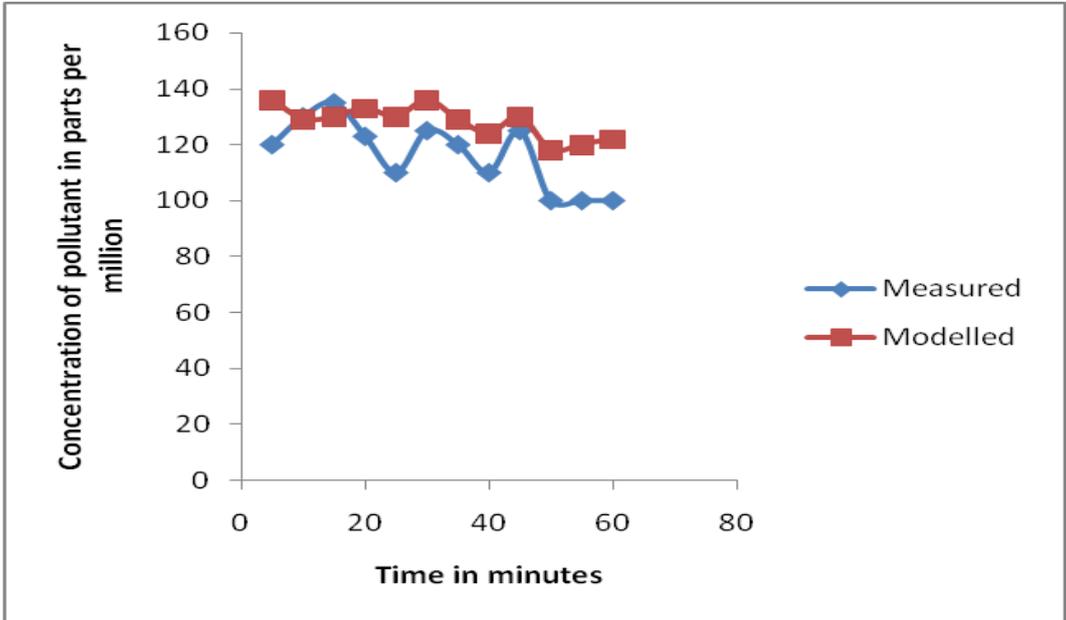
Fig. 4.29: Carbon dioxide concentration for October 21
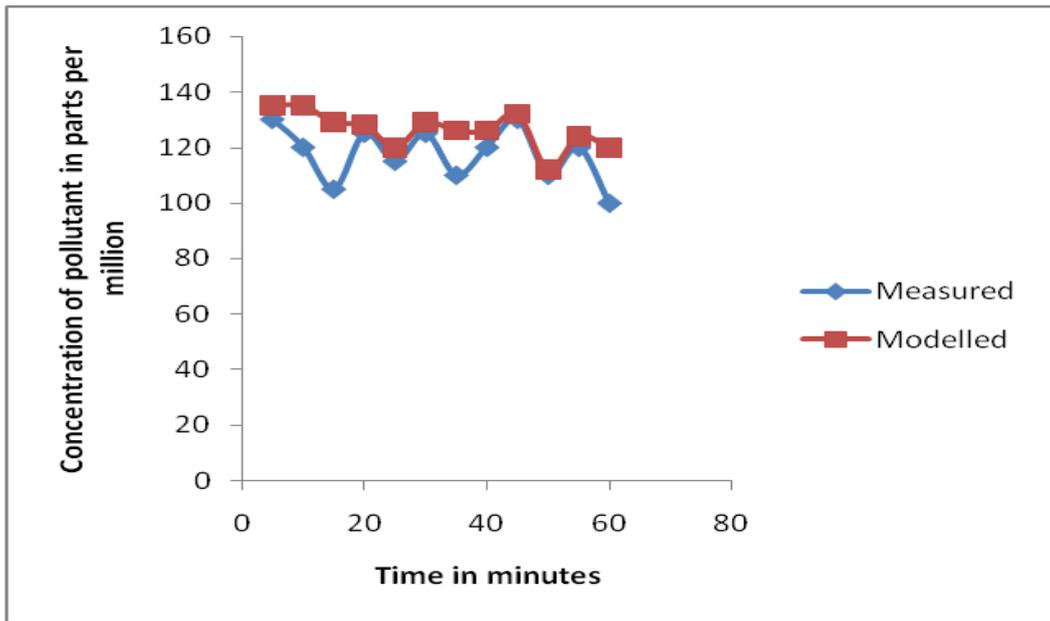
Fig. 30: Carbon dioxide concentration for October 22

4.5.3 Nitrogen dioxide concentrations

Measured and modelled concentrations of Nitrogen dioxide are presented in Figs 4.31 to 4.39.
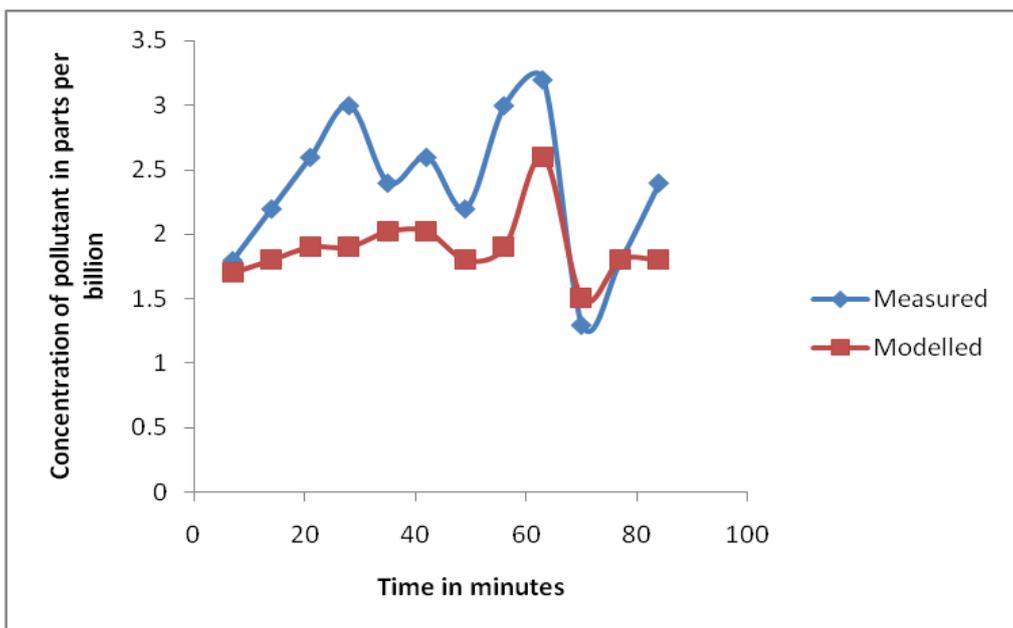
Fig. 4.31: Nitrogen dioxide concentration 10 March
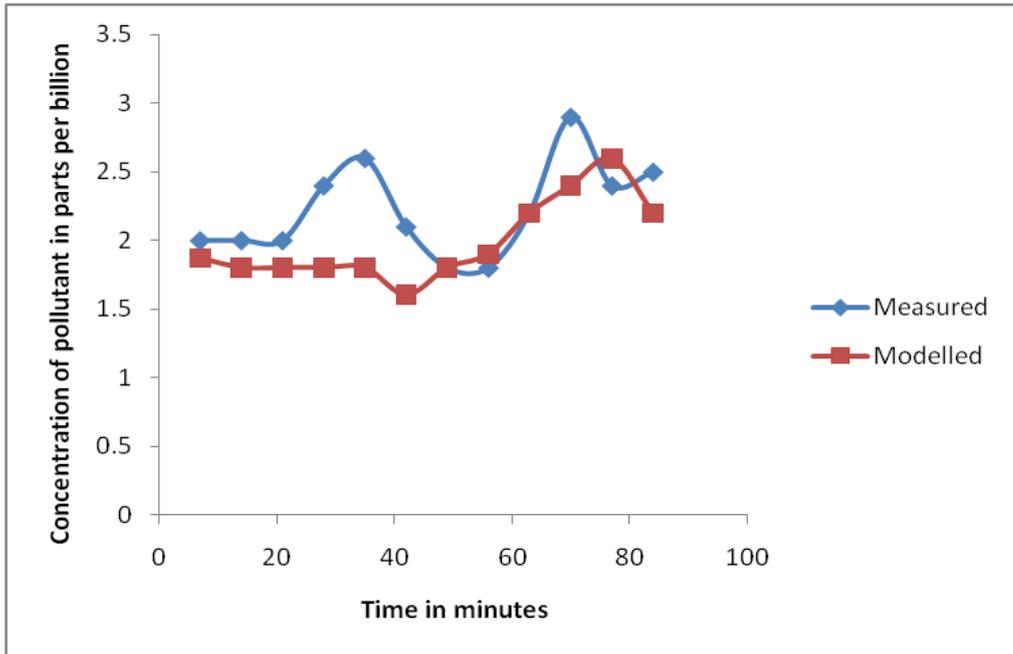
Fig. 4.32: Nitrogen dioxide concentration 11 March
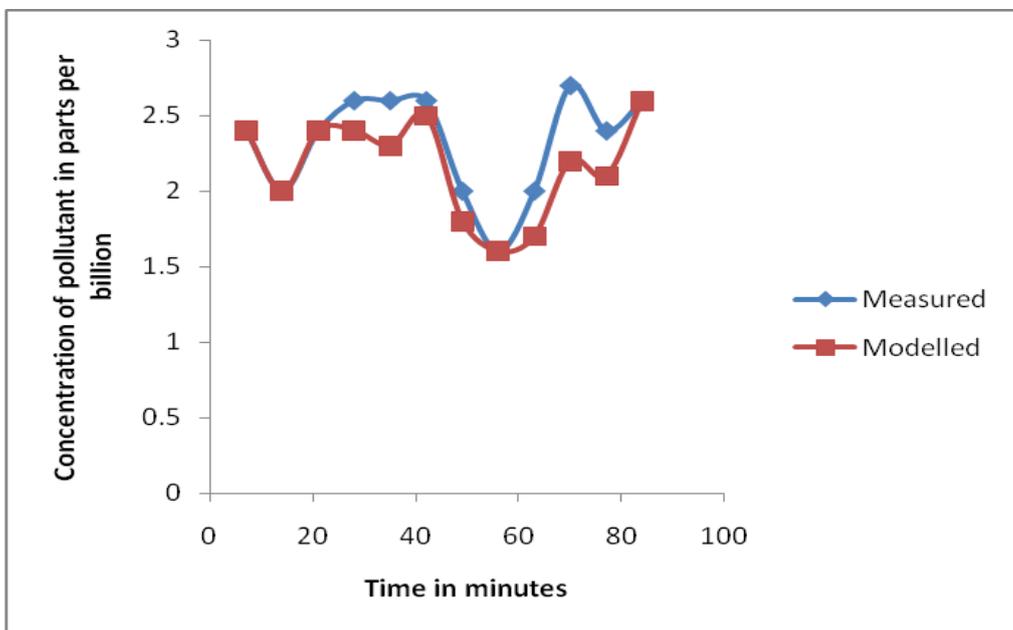
Fig. 4.33: Nitrogen dioxide concentration 12 March
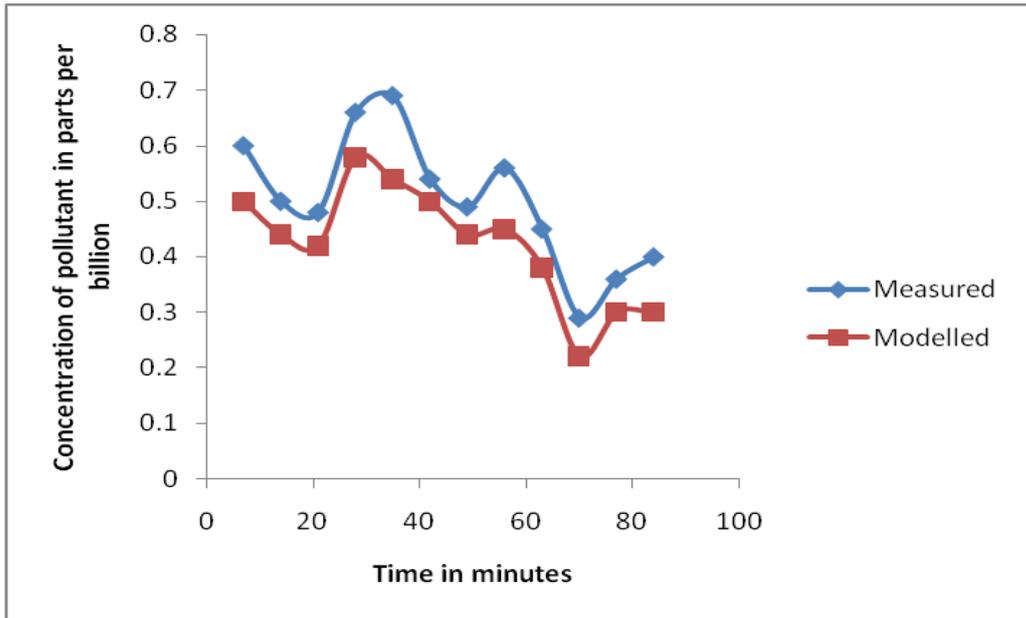
Fig. 4.34: Nitrogen dioxide concentration 14 July
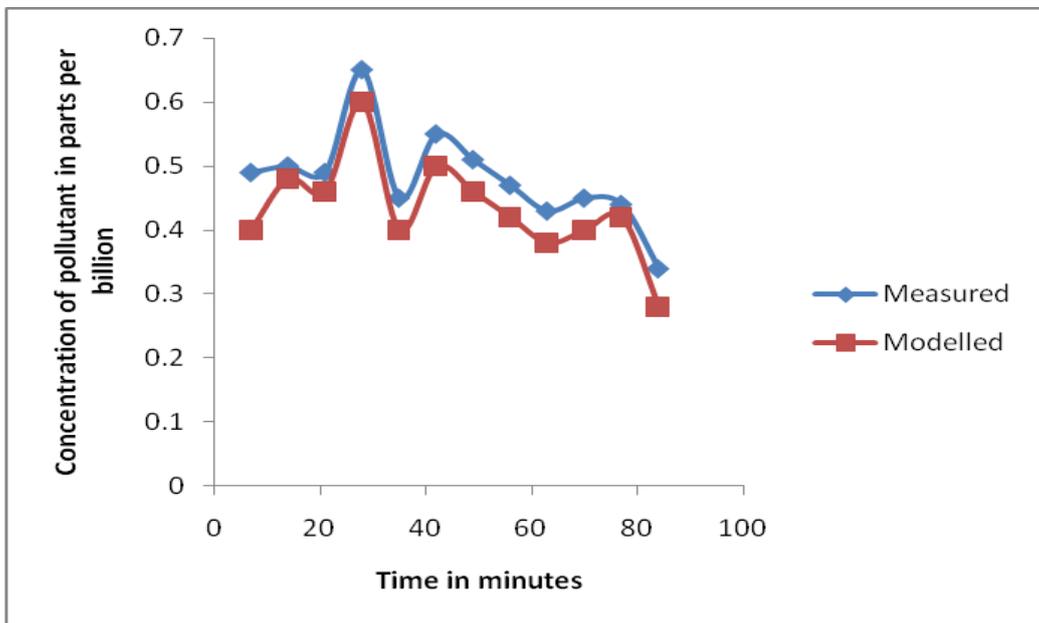
Fig. 4.35: Nitrogen dioxide concentration 15 July
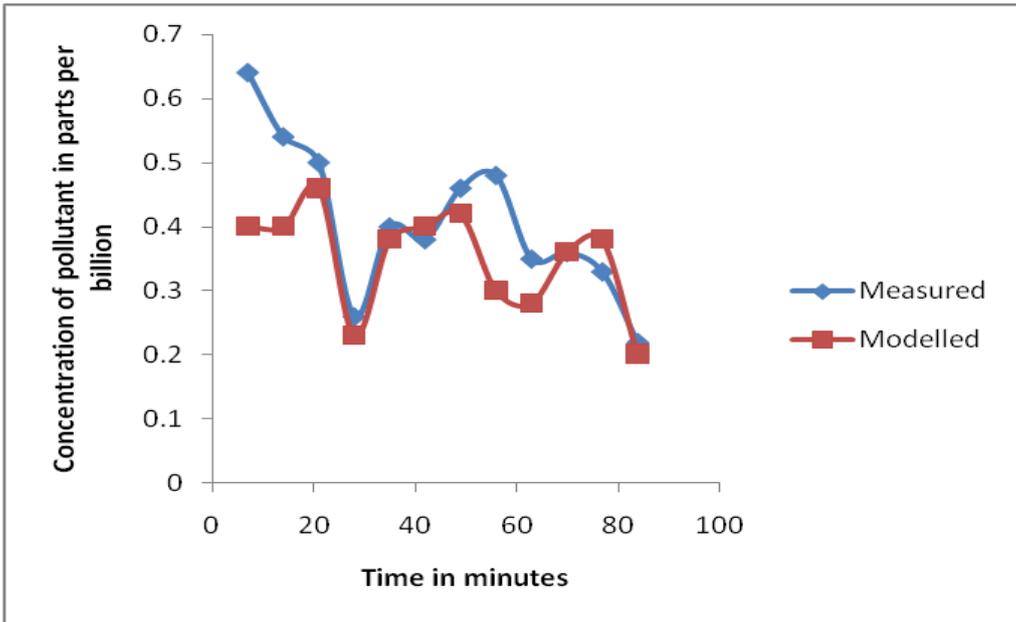
Fig. 4.36: Nitrogen dioxide concentration 16 July
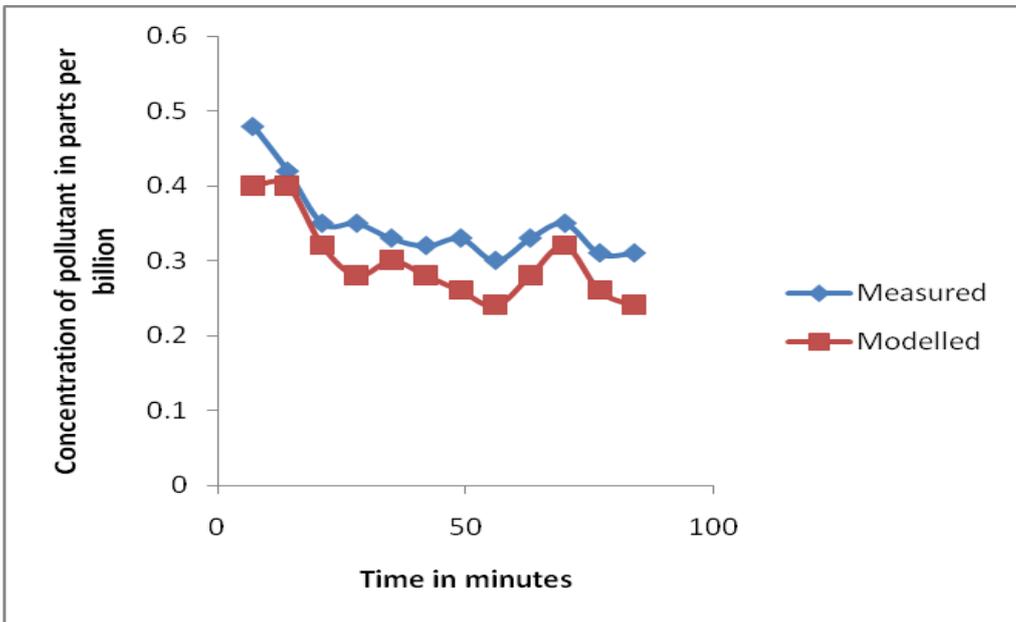
Fig. 4.37: Nitrogen dioxide concentration 6 October
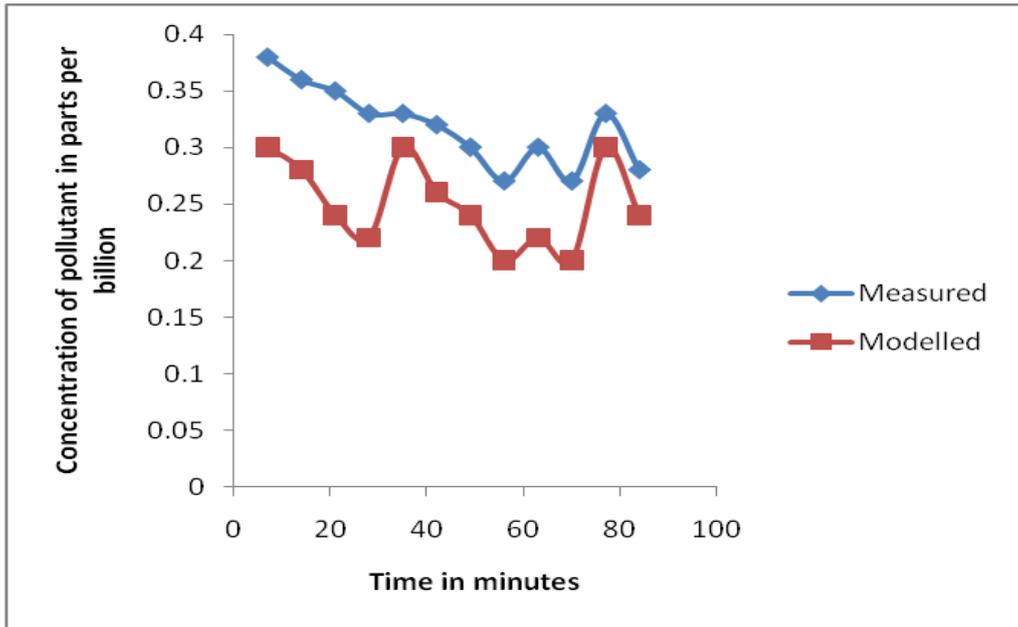
Fig. 4.38: Nitrogen dioxide concentration 7 October
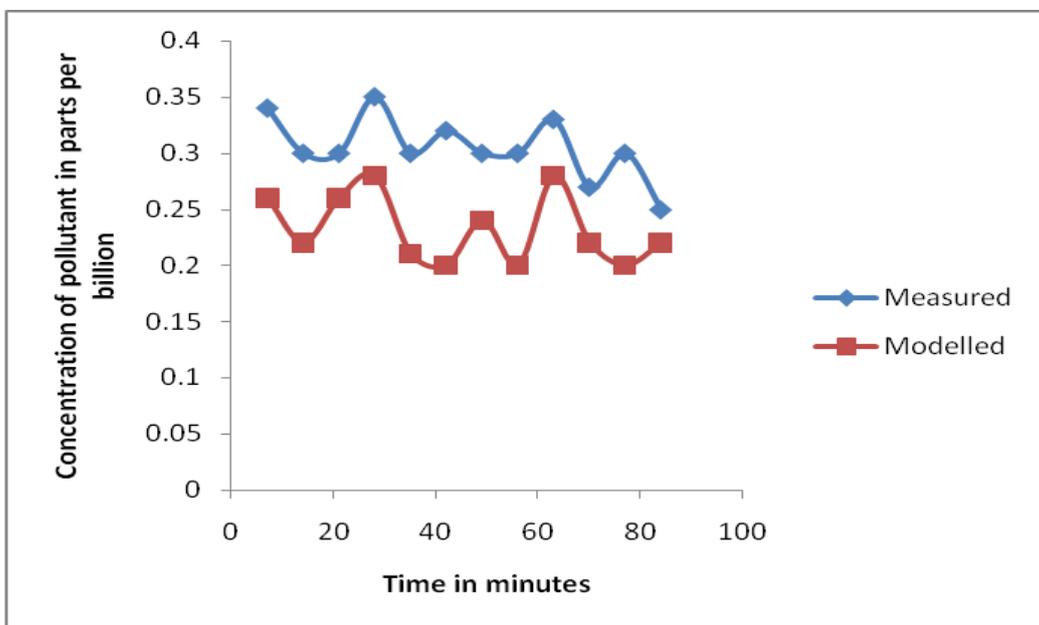
Fig. 4.39: Nitrogen dioxide concentration 8 October

4.6 Model Performance Evaluation

The agreement between the measured and modelled concentration data for the three selected gaseous pollutants was evaluated using the fractional bias and index of agreement as well as the squared residual error and results presented in the following tables.

Table 4.8: Fractional bias and Index of agreement for CO data sets

Date in 2008	Average measured concentrations (ppm)	Average modelled concentrations (ppm)	Fractional bias	Index of agreement
March 3	8.75	8.35	-0.05	0.92
March 4	7.20	6.50	-0.10	0.92
March 5	5.67	5.46	-0.04	0.93
July 1	9.85	9.26	-0.06	0.96
July 2	5.62	5.81	0.03	0.98
July 3	8.02	7.98	-0.01	0.94
October 1	8.99	8.79	-0.02	0.98
October 2	5.44	5.59	0.03	0.95
October 3	7.13	7.10	-0.01	0.94

Table 4.9: Fractional bias and Index of agreement for CO_2 data sets

Date in 2008	Average measured concentrations (ppm)	Average modelled concentrations (ppm)	Fractional bias	Index of agreement
March 24	135.60	129.00	-0.05	0.58
March 25	130.40	127.80	-0.02	0.37
March 26	127.90	125.75	-0.02	0.59
July 9	133.67	127.33	-0.05	0.52
July 10	127.50	127.92	0.01	0.76
July 11	124.92	127.08	0.01	0.67
Oct. 20	114.42	127.00	0.10	0.57
Oct. 21	116.50	128.00	0.09	0.60
Oct. 22	117.50	126.33	0.07	0.61

Table 4.10: Fractional bias and Index of agreement for NO$_2$ data sets

Date in 2008	Average measured concentrations (ppb)	Average modelled concentrations (ppb)	Fractional bias	Index of agreement
March 10	2.37	1.90	-0.22	0.73
March 11	2.22	1.98	-0.11	0.69
March 12	2.30	2.17	-0.06	0.88
July 14	0.50	0.42	-0.17	0.86
July 15	0.48	0.43	-0.11	0.87
July 16	0.41	0.35	-0.16	0.74
Oct. 6	0.35	0.30	-0.15	0.81
Oct. 7	0.32	0.25	-0.25	0.73
Oct. 8	0.31	0.24	-0.25	0.73

4.6.1 Model error and Perturbation metrics

The squared difference (squared residual) between a single modelled and measured data was calculated for each data set for the three pollutants. The perturbed error was also calculated and some of the results presented in Tables below.

Table 4.11: Sums of Squared Residual and Perturbed errors for CO data

Date in 2008	Squared residual error	Percent error	Perturbed error	α (%)
March 3	21	2.1	2.5	5
March 4	12	1.8	6.2	10
March 5	14	3.1	0.6	4
July 1	9	0.8	4	6
July 2	5	1.1	0.4	3
July 3	11	1.4	0.02	1
October 1	4	0.3	0.5	2
October 2	5	1.2	0.4	3
October 3	11	1.7	0.01	1

Table 4.12: Sums of Squared Residual and Perturbed errors for CO_2 data

Date in 2008	Squared residual error	Percent error	Perturbed error	α (%)
March 24	3909	1.7	361	4
March 25	4005	1.9	84	2
March 26	1842	0.9	79	2
July 9	2614	1.2	541	5
July 10	1731	0.9	87	1
July 11	1226	0.7	76	2
October 20	3887	2.4	1600	10
October 21	2706	1.4	1570	9
October 22	1592	1.0	1067	8

Table 4.13: Sums of Squared Residual and Perturbed errors for NO$_2$ data

Date in 2008	Squared residual error	Percent error	Perturbed error	α (%)
March 10	4.5	6.3	2.6	19
March 11	1.7	2.9	0.6	10
March 12	0.6	1.0	0.2	6
July 14	0.1	2.7	0.1	16
July 15	0.03	1.1	0.03	10
July 16	0.12	5.6	0.1	22
October 6	0.03	2.3	0.03	14
October 7	0.06	5.2	0.06	22
October 8	0.07	6.3	0.05	22

4.6.2 Comparison of model performance with OSPM and Calder's model

The modelled concentrations of the pollutants using the optimum parameter values have been compared with measured concentrations, as well as values obtained using the OSPM and Calder's model and results presented in Figs 4.40-4.48, while others are presented in the appendix.
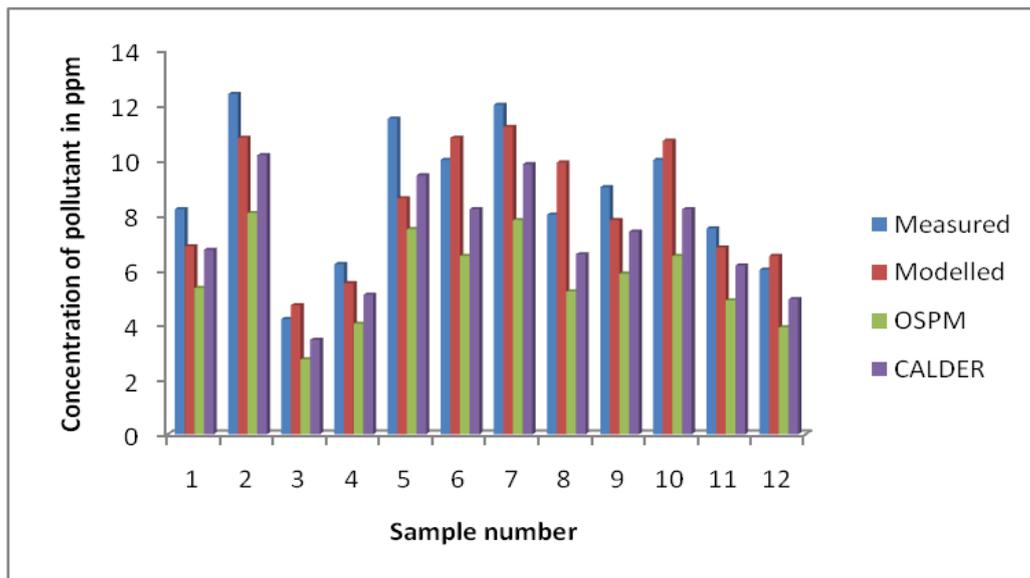
Fig. 4.40: Compared concentrations of CO from the three models for March 3
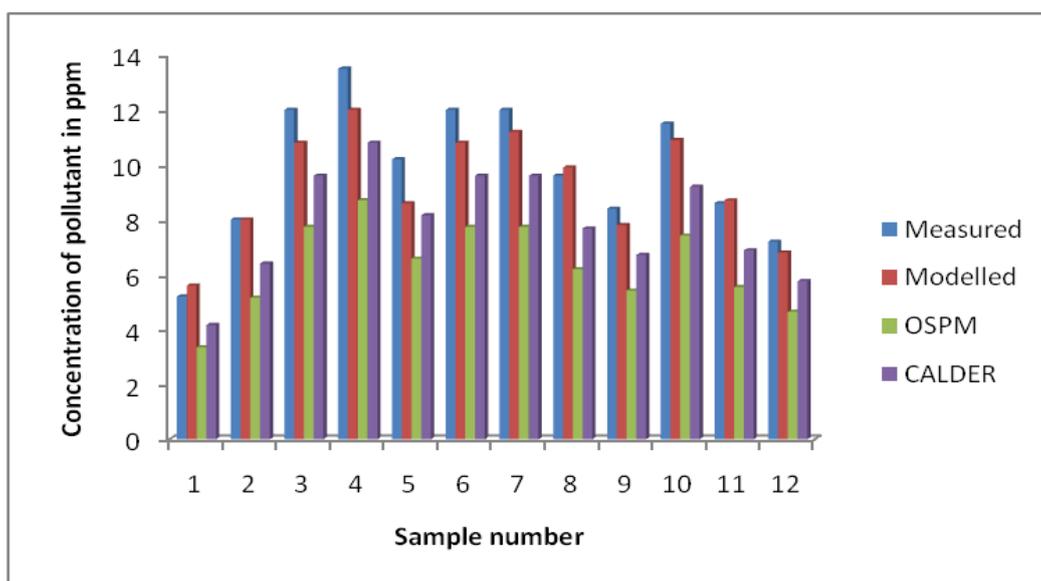
Fig. 4.41: Compared concentrations of CO from the three models for July 1
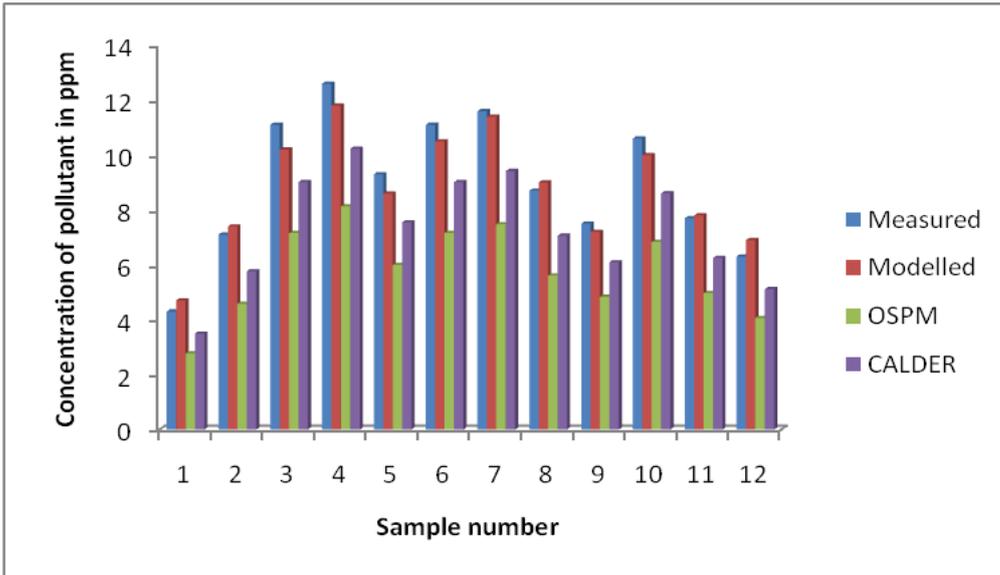
Fig. 4.42: Compared concentrations of CO from the three models for Oct 1
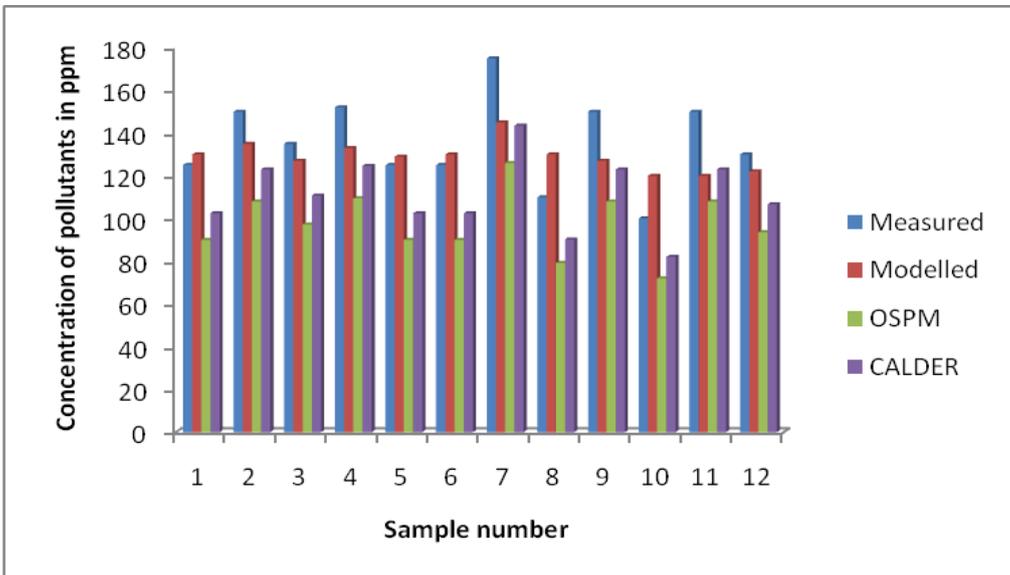
Fig. 4.43: Compared concentrations of CO_2 from the three models for March 24
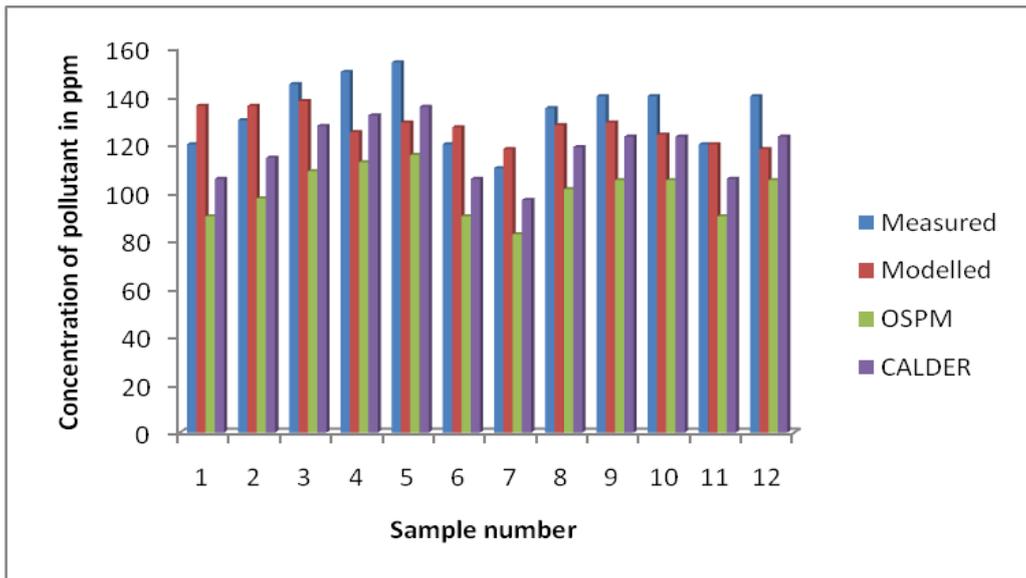
Fig. 4.44: Compared concentrations of CO_2 from the three models for July 9
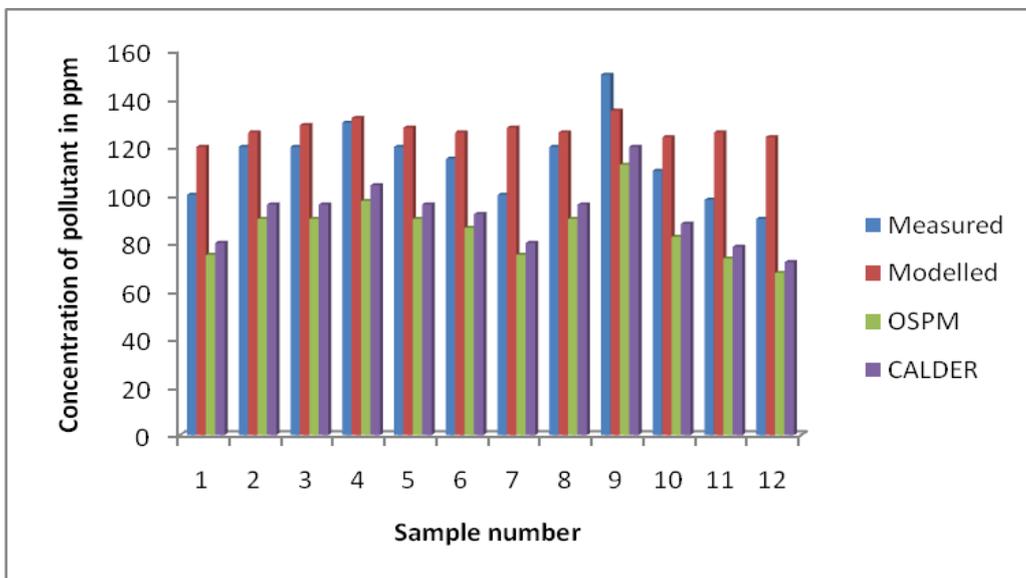
Fig. 4.45: Compared concentrations of CO_2 from the three models for Oct 20
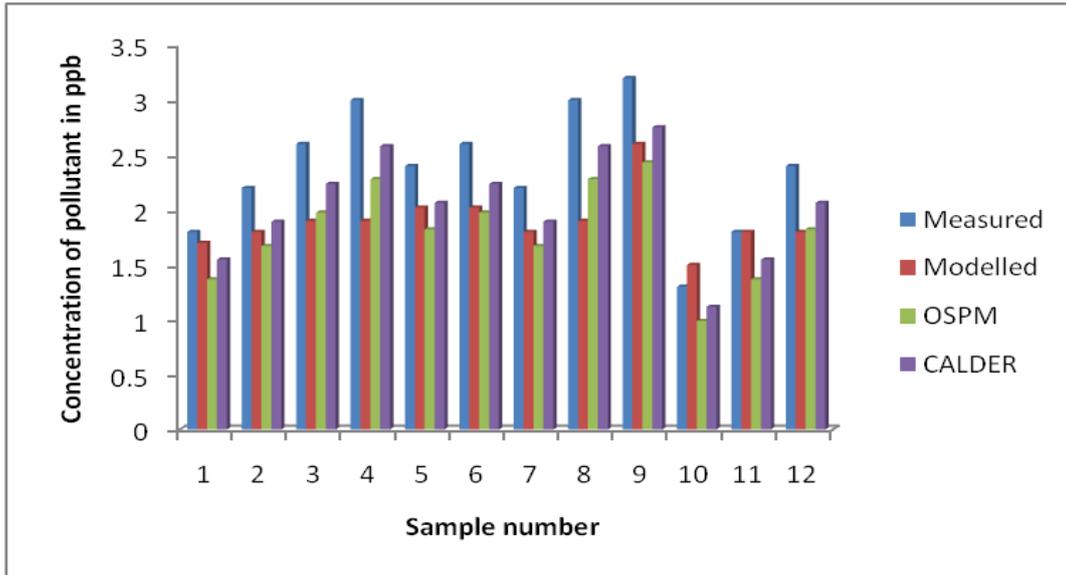
Fig. 4.46: Compared concentrations of NO$_2$ from the three models for March 10
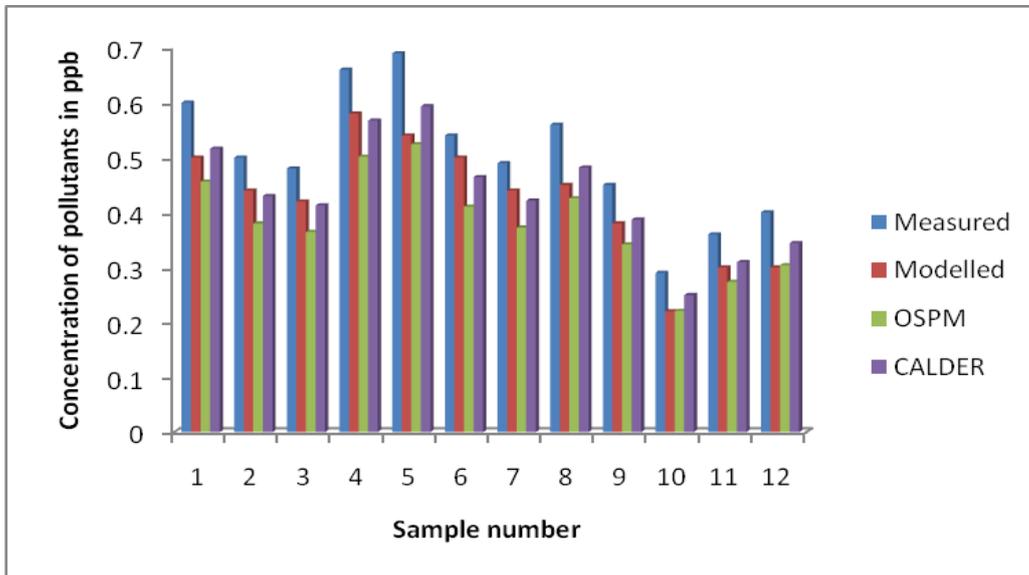
Fig. 4.47: Compared concentrations of NO$_2$ from the three models for July 14
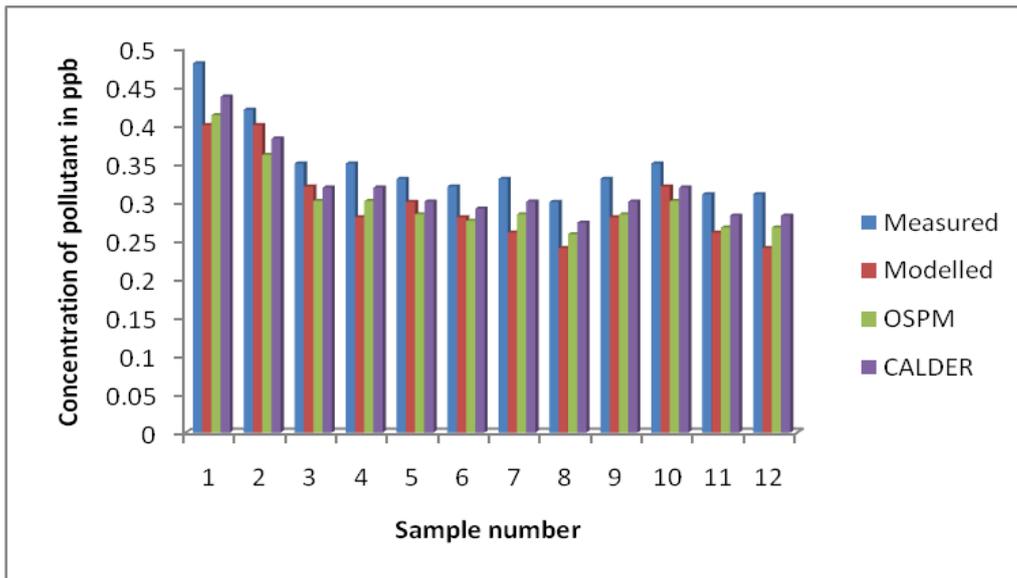
Fig. 4.48: Compared concentrations of NO$_2$ from the three models for Oct 6

4.6.3 Model Validation

The concentrations of NO$_2$ obtained by applying the developed model and the OSPM to data in Jagtvej Street in Copenhagen are presented in Figure below.
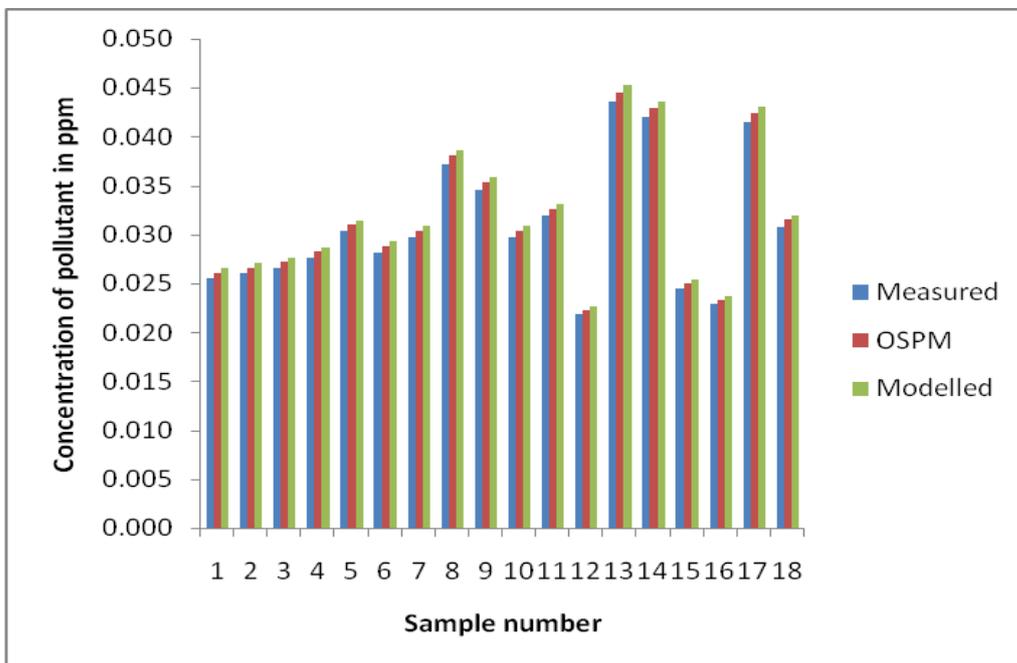
Fig. 4.49: Developed model validated with NO$_2$ concentration data in Jagtvej Street

CHAPTER FIVE
DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussion

The results obtained and presented in Chapter Four are hereby discussed.

5.1.1 Traffic studies

It can be seen from Figs 4.1 to 4.4 that the morning and evening peak period for the three months are identical, that is, morning peak hour starts from 8.00 AM and ends at around 10.30 AM. There is a general lull in traffic around the afternoon hours of 12.00 PM to 2.00 PM. The evening peak periods are between 3.00 PM and 5.30 PM. These periods represent when people go to work and school in the morning, when they are in the offices or schools and when they return home. The average daily total traffic for the months were 43971 vehicles per day, 37086 vehicles per day and 47261 vehicles per day respectively for March, July and October. The low traffic volumes for July could be as a result of the rainy season. The season limits the movements of most commuters. Another reason for the low traffic could be the fact that schools were on holidays, thereby reducing the number of commuters. October and March traffic were high as a result of the fact that schools were in session and there were no rains to greatly limit journeys. October traffic being highest could be attributed to the more conducive October weather and resumption of schools. Table 4.1 presents identical proportions for the three months namely 60% motorcycles, 39% cars and other small vehicles and less than 1% heavy vehicles, clearly showing that there were no traffic regulatory laws as regards management of traffic congestions. It was quite evident that the same types of vehicles always plied the roads. The average peak hour travel speed was found to be 3.5 m/s or 12.6 km/h. This travel speed favoured congestion on the road during the peak periods. From Table 4.2, it can be seen that the heavy vehicles are about four times the size of cars and other smaller vehicles and close to twenty four

times the size of the motorcycles. From this study the passenger car equivalent factor for heavy vehicles was found to be 4 and 0.2 for motorcycles. This could assist traffic analysts in the nearest future if they wished to convert all traffic to passenger cars based on occupied surface areas of the respective vehicles.

The age distribution of a sampled population of vehicles is presented in Table 4.3 and in Fig. 4.5. It can be seen that of the 465 vehicles, aside motorcycles sampled, 83% of these are over ten years old, 52.2% of the vehicles are over 15 years old and 34.2% are over 20 years old. This shows that a greater proportion of the vehicles are without catalytic converters.

5.1.2 Emission factors

It can be seen from Table 4.4 that the emission factors for this study were almost three times higher than those for the Indian study with similar vehicle fleets. The higher emission factors might have come from the contributions by the larger number of old vehicles. Eighty percent of the cars and buses sampled are ten years and above. Most of these vehicles were in poor shape and do not have catalytic converters. A vast majority of fleet emissions comes from a small number of poorly maintained vehicles according to Singh and Huber (2000). The three vehicle types emit more carbon dioxide than they emit the other pollutants. This implies that a large number of these vehicles can have a marked effect on the ozone layer as more carbon dioxide implies more depletion of the ozone layer. Nitrogen dioxide is emitted in very small quantities from the exhaust emissions. It is emitted alongside other oxides of Nitrogen like Nitric oxide.

5.1.3 Meteorological data

From Table 4.5 it could be seen that there were practically very calm periods in March, giving a stability class of A. In July and October, the average winds were 5.5

and 6.3m/s respectively giving stability class D which corresponded to neutral stability conditions. The average wind speeds obtained for Minna showed that the winds were not up to typhoon levels, hence there was still a high probability of having some level of pollution in the streets throughout the year.

5.1.4 Parameter estimation and sensitivity analysis

It was noticed that the change in concentration of the pollutant as regards the street wind turbulence parameter, the effective release height and the wind speed offset was marginal, while the aerodynamic drag coefficient had a more noticeable effect on the concentration of the pollutant. The aerodynamic constant influences concentrations due to the role of cruising vehicles in the calculation of mechanical turbulence in the street. Since the value is squared in the calculations, a smaller decimal will invariably give a higher concentration value. This is also indicative of the fact that the engine is made to work at a higher revolution, producing more pollutants than when the coefficient is high.

From calculations using the objective function optimum values were obtained for the inbuilt parameters for given wind speeds, direction, traffic flow and speed. Results are shown in Table 4.8. The modelled values of the CO concentrations were very close to the measured values, hence these parameter values were taken as the optimum values, which were fitted in to the model for validation studies. The OSPM model by Berkowicz *et al*., (1997) validated by Vardoulakis *et al*., (2002), did not consider the wind speed offset, which means at mild wind conditions their model would perform poorly. It also did not consider the heterogeneous nature of traffic in the typical African city street.

5.1.4.1 Model sensitivity to external parameters

Concentration of pollutants measured at a point is a function of traffic volume, composition and speed; emission strength; wind speed and direction. It could be seen from Fig. 4.10 that at lower traffic speeds, the concentration was higher and as the speed increased concentration drastically reduced. This could be attributed mainly to the effects of traffic generated turbulence which disperses the pollutant as the speed increases. Pollutant diffusion could be said to be dictated primarily by the locally generated turbulence with some contributions from the atmospheric stability. Concentration of pollutant was noticed to increase with increasing wind directions. At $0°$ wind direction, (that is the wind is perpendicular to the roadway) pollutants from other parts of the roadway were not transported to the receptor. But as the wind became more oblique, pollutants were carried from other parts of the roadway to the receptor, hence the increase in concentration as the wind direction increased. From the model, it was noticed that an increase in emission factor would invariably lead to an increase in the concentration of the pollutant, other factors being held constant. From the results presented in Fig. 4.10, it could be seen that a higher emission factor led to a higher pollutant concentration. This is in line with findings by Elminir (2005). The emission factor and number of vehicles contributed greatly to the concentration of the pollutant. The relationship depicted in Fig. 4.15 showed that concentration of the pollutant is directly proportional to the volume of traffic or traffic flow. The higher the traffic the more the concentration and vice-versa. A high emission factor is indicative of a troubled engine.

From Fig. 4.11, the two wind speeds considered showed that the concentration reduced with increased wind speeds. This could be attributed to the increase in atmospheric turbulence created by the wind that enhanced the diffusion of the

pollutants (Elminir, 2005). When winds are mild, the resident time of the pollutants in the street increases leading to more of it being measured at the receptor. New concentrations seemed to be added to the already existing concentrations and a total higher concentration was obtained at these mild wind conditions.

5.1.5 Effects of atmospheric conditions on the concentrations of pollutants

Background measurements of the concentration of carbon monoxide gave values ranging from 0.8ppm to 1.2ppm, giving an average of 1ppm or $1145\mu g/m^3$. The background measurements were assumed to have come from such sources as firewood, cooking stoves, refuse burning and generating sets. Highest concentrations occurred in July during the rainy season compared to March in the dry season and October in the windy periods. Wind effects and vehicular turbulence might have played a major part in the dispersion of the pollutant in the month of October. The rainy season concentrations taken mostly after rains had fallen and traffic had become regular again, are higher than the dry season concentrations mostly due to more stable atmospheric conditions in the former. In the dry season thermal turbulence, cloud cover, higher temperatures and low relative humidity may cause a drop in the quantity of the pollutant because fast mixing is encouraged. The pollutant concentrations varied directly with the relative humidity values. The low humidity and low concentrations of pollutant could be attributed to the influence of clear free Tropospheric air masses. An increase in relative humidity reflects an updraft of the boundary layer air masses to the 3km level leading to higher levels of concentration of such pollutants as carbon monoxide (Elminir, 2005).

Maximum concentration of carbon dioxide of up to 175ppm was measured in March and a minimum value of 109ppm was measured in October. The average daily concentrations were seen to decrease with increasing relative humidity. The main

reason for this might have been the change in the background concentrations brought about by enhanced sources like bush burning, refuse burning, generating sets and even animal respiration in the dry season. The background concentrations were 1250ppm, 1100ppm and 900ppm respectively for March, July and October. Low concentration values in October were attributed to wind effects.

For Nitrogen dioxide a maximum concentration of 3.2ppb was observed in March while lowest concentration of 0.2ppb was recorded in October. Nitrogen dioxide concentrations decrease with increasing values of relative humidity. This was attributed mainly to the enhanced oxidation of hydrocarbons in the atmosphere which supports ozone formation. The higher values in March were also attributed to the formation of a secondary Nitrogen dioxide from ozone and other gases like Nitric oxide. The concentration of Nitrogen dioxide would fluctuate depending on the rate at which Nitric oxide is converted to it. High humidity in July and October are indications of precipitation events accompanied by in-cloud scavenging which results in lower concentrations of the pollutant (Elminir, 2005). Wind effects again were responsible for the lower concentrations in the windy months. The average background concentration was 0.1ppb.

5.1.6 Model performance evaluation and validation

Applying the developed model to pollutant concentration data collected in Minna, showed that the model had maximum percent errors of 3, 2.4 and 6.3 respectively for CO, CO_2 and NO_2. The wider error margin for NO_2 which can be seen in Fig. 4.39 was attributed mainly to the unstable nature of the environment and precursors of NO_2 like Ozone and Nitric oxide. From Tables 4.8 to 4.10, the index of agreement ranged from .92 to 0.98, 0.37 to 0.76, and 0.69 to 0.88 respectively for CO, CO_2 and NO_2. This shows a closer agreement of CO measured and modelled data than

for the other pollutants. Figs 4.40-4.48 showed that the OSPM and Calder's models, under predicted the Minna data by up to 30%, even though Calder's model performed better compared to the OSPM. The developed model predicts 98% of the data on the average for CO and CO_2 and 94% of the NO_2 data. The oscillations noticed in the data arrangements and expressed in terms of fractional bias were removed through the use of the perturbed error indices.

The developed model was validated with NO_2 data collected in Copenhagen Denmark, which were also used to validate the OSPM (Berkowicz *et al*., 2006). The comparisons are shown in Fig. 4.49. It was noticed from calculations that under the same atmospheric and traffic conditions, the OSPM over predicted the Copenhagen data by 2%, while the developed model over predicted same data by 4%. This could be attributed mainly to the treatment of the traffic and emission factors. The model could be used to estimate concentration of pollutants in other cities since the range of over prediction is just 4%. Rao *et al.,* (1986) had written that model predictions that are within 30% of measured concentrations should be considered perfect for dispersion modelling purposes given the natural variability of atmospheric transport.

5.2 Conclusions

The results of this thesis could be summarized as follows:

1. An urban street air pollution model was developed, based on the Gaussian diffusion principles, Calder's model and the OSPM model, both of which are based on the Gaussian diffusion principles. The model is a hybrid between a typical model for a rural roadway setting as given by Calder (1973) and a typical urban street canyon model as given by the OSPM. The model was validated as sufficient to predict the average concentrations of the pollutants so considered.

2. The model can calculate concentrations of pollutants at all stability classes, turbulence and wind direction and various wind speeds, a fact not clearly shown in the other models. The model also considers the heterogeneous nature of traffic in a typical Nigeria street which was not considered in the other models like the OSPM which only considered cars. The model recognizes the fact that pollutant diffusion is dictated in the street by locally generated turbulence and wind, a fact not explicitly accounted for by Calder. The vertical dispersion parameter in Calder's work was made dependent on ambient wind and stability conditions alone and the horizontal dispersion parameter was neglected by the OSPM, depending more on the contributions of the street canyon effects to the pollutant concentrations. This parameter could not be neglected in the developed model because of the irregular nature of the buildings in the street and side roads which allowed for cross wind effects.

3. One of the objectives that the model should be simple in calculation has been retained and the number of parameters maintained at a manageable level to avoid the problem of parameter identification and increase in computer time. The model has four inbuilt parameters namely the aerodynamic drag coefficient, the wind speed offset, the street wind coefficient and the effective release height.

4. Sensitivity analyses showed that the aerodynamic drag coefficient had more effects on the pollutant concentration than the other parameters whose effects were just marginal. Different values of the aerodynamic drag coefficient were empirically obtained for the different types of vehicles.

5. The index of agreement was used as a suitable objective function from which optimal values of the parameters were determined. From this, three different aerodynamic drag coefficients 0.1 for motorcycle, 0.2 for car and 0.3 for heavies were obtained. A new value for the wind speed offset, 0.2m/s was also obtained. New values

for the effective release height (1.5m) and street wind coefficient (0.15) were also obtained marking a clear difference and departure from values proposed by Chock (1978) and Berkowicz *et al.*, (1997).

6. Results from traffic studies in Minna showed higher traffic volumes in March and October and lower volumes in July. This fluctuation was attributed to the seasons. The dry season months would naturally encourage more movements of people than the rainy season months. The traffic mix was similar for all the months and days of measurement with motorcycles having an average of 60%, motorcars 39% and heavy vehicles 1%.

7. Emission factors were obtained for the most common vehicles plying roads in Minna and were found to be close to three times higher than the average values obtained from a similar study in India. This was attributed to the age and poor maintenance of the vehicles.

8. The performance of the model was assessed by comparing it with other models like the OSPM and Calder's. The model predicted 98% of the concentration data for CO, while the OSPM predicted 70% and Calder's model predicted 80%. The model was validated with data collected in Copenhagen and was found to perform reasonably well.

9. The concentrations of the gases measured are still within the limits stipulated by WHO and NESREA. This implies that traffic emission in Minna, with a population of 300,000 people and 3000 vehicles is still within the safe limits. The NESREA ambient limits for one hour average exposure are respectively 10 ppm and 0.04 ppb for Carbon monoxide and Nitrogen dioxide. No limits are specified for carbon dioxide but inferences could be drawn from Greiner (1995) who fixed 2500 ppm as the limits beyond which people begin to experience headaches and dizziness.

5.3 Recommendations

The following have been given as recommendations from this work.

1. The use of non diesel vehicles in the streets was recommended. Diesel vehicles are the major producers of nitrogen oxides, which contribute to the depletion of the ozone layer, hence accelerating climate change and global warming.

2. Although it was found that the pollutant concentration levels within the city streets were still within the specified limits, the use of vehicles with catalytic converters was recommended. These would reduce the pollutant concentrations to the barest minimum, still buying African countries some time and giving them a voice in the war against climate change and global warming. Eighty percent of the vehicles sampled in streets in Minna are above ten years of age and they were found to have higher emission factors. The Federal Government is here by advised to place a ban on the importation of vehicles above ten years of age.

3. Government agencies like the Vehicle Inspection Organization (VIO), Federal Road Safety Commission (FRSC) should be empowered to enforce some traffic control measures in the streets which could reduce the production of the pollutants. These measures should include a 3-month bill of health for every vehicle to be issued by the organizations showing the level of compliance with recommended maintenance schedules for each vehicle.

4. The phasing out of the motorcycle as a mode of transport in the cities was recommended. The government has jettisoned the mass transit schemes in many Nigerian cities and with attendant congestion; the motorcycle has become a very welcome mode of transportation. From this work, the government is advised to pay more attention to the mass transit system. This would cut down the production of

pollutants in cities and reduce effect of vehicular traffic on greenhouse gas production and climate change.

5. This model is recommended for use in urban environments which no measurements can be obtained. All the user need have is the traffic volumes and compositions, speed, wind speed and directions as well as emission factors for pollutant concentrations to be calculated.

6. The model parameters should be calibrated for other cities in Nigeria, to obtain values for the model parameters in those cities for a wider usage.

7. Further studies should be carried out on modelling non gaseous pollutants like particulate matter which may have a propensity to be harmful to humans and the environment.

5.4 Contributions to knowledge

The following are the contributions of this work to knowledge.

1. An improved dispersion model designed to estimate concentrations of pollutants in a regular urban street was developed, which is a hybrid between a roadway model and an urban street canyon model.

2. Emission factors peculiar to the Nigeria vehicular fleet resident in Minna were also developed, which showed the effects of having old unmaintained vehicles in the streets.

3. It was also shown that the pollutant concentration levels within Minna metropolis are still within the limits stipulated by NESREA, hence no cause for alarm.

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APPENDIX A: TRAFFIC VOLUME COUNTS

1. March 2008

Table A1: Average traffic volume for Mondays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1416	2112	18	3546
8-9am	1756	1890	17	3663
9-10am	1546	2064	16	3626
10-11am	1514	2472	17	4003
11-12pm	1245	2037	16	3298
12-1pm	1324	1980	14	3318
1-2pm	1400	2360	17	3777
2-3pm	1300	1900	19	3219
3-4pm	1669	2325	20	4014
4-5pm	1718	2790	26	4534
5-6pm	1730	2619	17	4366
6-7pm	1450	2463	12	3925
Total	18068	27012	209	45289

Table A2: Average traffic volume for Tuesdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1228	1871	8	3107
8-9am	1012	2961	15	3988
9-10am	1431	2633	15	4079
10-11am	1435	2491	20	3946
11-12pm	1200	2722	7	3929
12-1pm	1286	1890	15	3191
1-2pm	1609	2789	9	4407
2-3pm	1306	1933	17	3256
3-4pm	1806	2652	18	4476
4-5pm	1724	2025	13	3762
5-6pm	1370	2655	12	4037
6-7pm	1400	2304	9	3713
Total	16807	28926	158	45891

Table A3: Average traffic volume for Wednesdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1531	2053	14	3598
8-9am	1519	2034	8	3561
9-10am	1309	2799	15	4123
10-11am	1401	2184	18	3603
11-12pm	1445	2272	12	3729
12-1pm	1420	2043	12	3475
1-2pm	1340	2163	12	3515
2-3pm	1350	1861	11	3222
3-4pm	1500	2436	15	3951
4-5pm	1542	2257	23	3822
5-6pm	1505	1980	11	3496
6-7pm	1430	2002	8	3440
Total	17292	26084	159	43535

Table A4: Average traffic volume for Thursdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1457	2456	9	3922
8-9am	1400	2512	13	3925
9-10am	1460	2128	19	3607
10-11am	1379	2050	12	3441
11-12pm	1332	2038	12	3382
12-1pm	1365	1230	14	2609
1-2pm	1400	2204	13	3617
2-3pm	1281	2000	11	3292
3-4pm	1368	2020	19	3407
4-5pm	1581	1951	18	3550
5-6pm	1463	1900	16	3379
6-7pm	1300	1678	15	2993
Total	16786	24167	171	41124

Table A5: Average daily traffic for March

Time	Cars	Motorcycles	Heavies	Total
7-8am	1408	2123	12	3543
8-9am	1422	2349	14	3785
9-10am	1437	2406	17	3860
10-11am	1432	2299	18	3749
11-12pm	1306	2267	12	3585
12-1pm	1349	1786	14	3149
1-2pm	1437	2379	16	3832
2-3pm	1309	1924	16	3249
3-4pm	1586	2358	19	3963
4-5pm	1641	2256	20	3917
5-6pm	1517	2289	14	3820
6-7pm	1395	2112	12	3519
Total	17239	26548	184	43971

2. July 2008
Table A6: Average traffic volume for Mondays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1116	1717	14	2847
8-9am	1593	2450	20	4063
9-10am	1028	1581	13	2622
10-11am	1134	1745	14	2893
11-12pm	1105	1700	14	2819
12-1pm	1179	1814	15	3008
1-2pm	1218	1874	15	3107
2-3pm	1016	1562	13	2591
3-4pm	1087	1673	14	2774
4-5pm	1394	2145	18	3557
5-6pm	1579	2429	20	4028
6-7pm	1341	2062	17	3420
Total	14790	22752	187	37729

Table A7: Average traffic volumes for Tuesdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1180	1816	15	3011
8-9am	1326	2039	17	3382
9-10am	1150	1768	15	2933
10-11am	1072	1649	14	2735
11-12pm	1047	1611	13	2671
12-1pm	1125	1730	14	2869
1-2pm	1089	1674	14	2777
2-3pm	1039	1599	13	2651
3-4pm	1087	1672	14	2773
4-5pm	1192	1834	15	3041
5-6pm	1361	2093	17	3471
6-7pm	1217	1872	16	3105
Total	13885	21357	177	35419

Table A8: Average traffic volume for Wednesdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1151	1770	15	2936
8-9am	1443	2219	18	3680
9-10am	1352	2079	17	3448
10-11am	1192	1833	15	3040
11-12pm	1098	1688	14	2800
12-1pm	1254	1929	16	3199
1-2pm	1355	2084	17	3456
2-3pm	1160	1785	15	2960
3-4pm	1129	1737	14	2880
4-5pm	1213	1865	15	3093
5-6pm	1348	2074	17	3439
6-7pm	1286	1978	16	3280
Total	14981	23041	189	38211

Table A9: Average traffic volumes for Thursdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1208	1858	15	3081
8-9am	1394	2144	18	3556
9-10am	1277	1964	16	3257
10-11am	1053	1620	13	2686
11-12pm	991	1524	13	2528
12-1pm	1053	1620	13	2686
1-2pm	1208	1858	15	3081
2-3pm	1053	1620	13	2686
3-4pm	1177	1810	15	3002
4-5pm	1301	2001	17	3319
5-6pm	1449	2229	18	3696
6-7pm	1332	2048	17	3397
Total	14496	22296	183	36975

Table A10: Average daily traffic for July

Time	Cars	Motorcycles	Heavies	Total
7-8am	1164	1790	15	2969
8-9am	1439	2213	18	3670
9-10am	1202	1848	15	3065
10-11am	1113	1712	14	2839
11-12pm	1060	1631	14	2705
12-1pm	1153	1773	15	2941
1-2pm	1218	1873	15	3106
2-3pm	1067	1642	14	2723
3-4pm	1120	1723	14	2857
4-5pm	1275	1961	16	3252
5-6pm	1434	2206	18	3658
6-7pm	1294	1990	17	3301
Total	14539	22362	185	37086

3. October 2008
Table A11: Average traffic volumes for Thursdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1469	2259	19	3747
8-9am	2026	3117	26	5169
9-10am	1543	2374	20	3937
10-11am	1493	2296	19	3808
11-12pm	1454	2237	19	3710
12-1pm	1550	2384	20	3954
1-2pm	1597	2457	20	4074
2-3pm	1327	2041	17	3385
3-4pm	1392	2141	18	3551
4-5pm	1866	2870	24	4760
5-6pm	2002	3079	26	5107
6-7pm	1705	2623	22	4350
Total	19424	29878	250	49552

Table A12: Average traffic volumes for Thursdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1501	2309	19	3829
8-9am	1827	2810	23	4660
9-10am	1436	2209	18	3663
10-11am	1316	2025	17	3358
11-12pm	1308	2012	17	3337
12-1pm	1506	2317	19	3842
1-2pm	1423	2189	18	3630
2-3pm	1265	1946	16	3227
3-4pm	1445	2223	18	3686
4-5pm	1533	2358	20	3911
5-6pm	1758	2704	22	4484
6-7pm	1559	2398	20	3977
Total	17877	27500	227	45604

Table A13: Average traffic volumes for Thursdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1439	2213	18	3670
8-9am	1804	2774	23	4601
9-10am	1606	2471	20	4097
10-11am	1481	2279	19	3779
11-12pm	1368	2104	17	3489
12-1pm	1543	2373	20	3936
1-2pm	1630	2507	21	4158
2-3pm	1435	2208	18	3661
3-4pm	1392	2141	18	3551
4-5pm	1509	2321	19	3849
5-6pm	1691	2601	22	4314
6-7pm	1616	2486	21	4123
Total	18514	28478	236	47228

Table A14: Average traffic volumes for Thursdays

Time	Cars	Motorcycles	Heavies	Total
7-8am	1527	2349	19	3895
8-9am	1764	2714	23	4501
9-10am	1581	2432	20	4033
10-11am	1299	1998	17	3314
11-12pm	1186	1825	15	3026
12-1pm	1287	1980	16	3283
1-2pm	1529	2352	19	3900
2-3pm	1274	1960	16	3250
3-4pm	1487	2287	19	3793
4-5pm	1731	2663	22	4416
5-6pm	1908	2935	24	4867
6-7pm	1710	2631	22	4363
Total	18283	28126	232	46641

Table A15: Average daily traffic for October

Time	Cars	Motorcycles	Heavies	Total
7-8am	1484	2283	19	3786
8-9am	1855	2854	24	4733
9-10am	1541	2372	20	3933
10-11am	1397	2150	18	3565
11-12pm	1329	2045	17	3391
12-1pm	1472	2264	19	3755
1-2pm	1545	2376	18	3939
2-3pm	1325	2039	17	3381
3-4pm	1429	2198	18	3645
4-5pm	1660	2553	21	4234
5-6pm	1840	2830	24	4694
6-7pm	1648	2535	21	4204
Total	18525	28499	236	47260

APPENDIX B: POLLUTION CONCENTRATIONS

Table B1: Carbon monoxide measured and modelled concentrations in March 2008

sample no	3-Mar Measured	3-Mar Modelled	4-Mar Measured	4-Mar Modelled	5-Mar Measured	5-Mar Modelled
1	8.20	6.85	4.20	4.00	3.00	3.60
2	12.4	10.80	5.00	4.60	2.00	3.40
3	4.20	4.70	6.00	4.60	3.00	3.80
4	6.20	5.50	10.00	8.40	5.00	3.80
5	11.50	8.60	10.00	7.80	6.00	4.20
6	10.00	10.80	6.40	6.00	8.00	6.90
7	12.00	11.20	8.00	8.10	4.00	4.70
8	8.00	9.90	7.00	6.80	5.00	4.00
9	9.00	7.80	10.00	8.60	8.00	7.50
10	10.00	10.70	7.50	7.80	9.00	10.30
11	7.50	6.80	7.00	6.60	8.00	7.50
12	6.00	6.50	5.10	4.70	7.00	5.80

Table B2: Carbon monoxide measured and modelled concentrations in July 2008

sample no	1-Jul Measured	1-Jul Modelled	2-Jul Measured	2-Jul Modelled	3-Jul Measured	3-Jul Modelled
1	5.2	5.6	5.6	5.0	8.2	6.4
2	8.0	8.0	7.8	7.7	8.0	7.8
3	12.0	10.8	6.2	5.9	6.0	5.9
4	13.5	12.0	5.6	6.9	11.0	10.4
5	10.2	8.6	9.2	9.8	12.2	11.7
6	12.0	10.8	8.0	7.5	10.0	9.5
7	12.0	11.2	7.0	7.9	8.0	7.9
8	9.6	9.9	3.2	3.7	6.0	5.9
9	8.4	7.8	2.6	2.9	7.0	6.8
10	11.5	10.9	5.0	5.56	6.2	8.6
11	8.6	8.7	4.2	4.5	8.4	9.6
12	7.2	6.8	3.0	2.4	5.3	5.2

Table B3: Carbon monoxide measured and modelled concentrations in October 2008

Sample No.	1-Oct Measured	1-Oct Modelled	2-Oct Measured	2-Oct Modelled	3-Oct Measured	3-Oct Modelled
1	4.3	4.7	4.7	4.1	7.3	5.5
2	7.1	7.4	6.9	6.8	7.1	6.9
3	11.1	10.2	5.3	5.6	5.1	5.0
4	12.6	11.8	4.7	6.0	10.1	9.6
5	9.3	8.6	8.3	8.9	11.3	10.8
6	11.1	10.5	7.1	6.6	9.1	8.6
7	11.6	11.4	6.1	7.0	7.1	7.0
8	8.7	9.0	5.6	4.8	5.1	5.0
9	7.5	7.2	4.8	5.1	6.1	5.9
10	10.6	10.0	4.1	4.6	5.3	7.7
11	7.7	7.8	4.3	4	7.5	8.7
12	6.3	6.9	3.4	3.6	4.4	4.3

Table B4: Carbon dioxide measured and modelled concentrations for March 2008

Sample no.	Measured (ppm) Day 1	Modelled (ppm) Day 1	Measured (ppm) Day 2	Modelled (ppm) Day 2	Measured (ppm) Day 3	Modelled (ppm) Day 3
1	125	130	125	127	120	136
2	150	135	166	127	140	129
3	135	127	100	127	150	132
4	152	133	140	128	120	126
5	125	129	120	126	130	127
6	125	130	130	120	140	124
7	175	145	154	135	140	129
8	110	130	120	129	120	124
9	150	127	140	130	100	110
10	100	120	150	136	130	109
11	150	120	100	127	120	129
12	130	122	120	122	125	134

Table B5: Carbon dioxide measured and modelled concentrations July 2008

Sample no.	Measured (ppm) Day 1	Modelled (ppm) Day 1	Measured (ppm) Day 2	Modelled (ppm) Day 2	Measured (ppm) Day 3	Modelled (ppm) Day 3
1	120	136	110	136	120	128
2	130	136	120	125	125	129
3	145	138	135	133	130	129
4	150	125	140	136	140	136
5	154	129	150	130	130	129
6	120	127	150	136	90	120
7	110	118	120	127	120	118
8	135	128	145	138	128	130
9	140	129	130	134	146	132
10	140	124	120	110	130	128
11	120	120	110	120	120	122
12	140	118	100	110	120	124

Table B6: Carbon dioxide measured and modelled concentrations for Oct. 2008

Sample no.	Measured (ppm) Day 1	Modelled (ppm) Day 1	Measured (ppm) Day 2	Modelled (ppm) Day 2	Measured (ppm) Day 3	Modelled (ppm) Day 3
1	100	120	120	136	130	135
2	120	126	130	129	120	135
3	120	129	135	130	105	129
4	130	132	123	133	125	128
5	120	128	110	130	115	120
6	115	126	125	136	125	129
7	100	128	120	129	110	126
8	120	126	110	124	120	126
9	150	135	125	130	130	132
10	110	124	100	118	110	112
11	98	126	100	120	120	124
12	90	124	100	122	100	120

Table B7: Nitrogen dioxide measured and modelled concentrations (ppb) for March 2008

Sample No.	10-Mar		11-Mar		12-Mar	
	Measured	modelled	Measured	Modelled	Measured	Modelled
1	1.80	1.70	2.00	1.87	2.40	2.40
2	2.20	1.80	2.00	1.80	2.00	2.00
3	2.60	1.90	2.00	1.80	2.40	2.40
4	3.00	1.90	2.40	1.80	2.60	2.40
5	2.40	2.02	2.60	1.80	2.60	2.30
6	2.60	2.02	2.10	1.60	2.60	2.50
7	2.20	1.80	1.80	1.80	2.00	1.80
8	3.00	1.90	1.80	1.90	1.60	1.60
9	3.20	2.60	2.20	2.20	2.00	1.70
10	1.30	1.50	2.90	2.40	2.70	2.20
11	1.80	1.80	2.40	2.60	2.40	2.10
12	2.40	1.80	2.50	2.20	2.60	2.60

Table B8: Nitrogen dioxide measured and modelled concentrations (ppb) for July 2008

	14-Jul		15-Jul		16-Jul	
Sample No.	Measured	Modelled	Measured	Modelled	Measured	Modelled
1	0.60	0.50	0.49	0.40	0.64	0.40
2	0.50	0.44	0.50	0.48	0.54	0.40
3	0.48	0.42	0.49	0.46	0.50	0.46
4	0.66	0.58	0.65	0.60	0.26	0.23
5	0.69	0.54	0.45	0.40	0.40	0.38
6	0.54	0.50	0.55	0.50	0.38	0.40
7	0.49	0.44	0.51	0.46	0.46	0.42
8	0.56	0.45	0.47	0.42	0.48	0.30
9	0.45	0.38	0.43	0.38	0.35	0.28
10	0.29	0.22	0.45	0.40	0.36	0.36
11	0.36	0.30	0.44	0.42	0.33	0.38
12	0.40	0.30	0.34	0.28	0.22	0.20

Table B9: Nitrogen dioxide measured and modelled concentrations (ppb) for October 2008

Sample No.	6-Oct Measured	6-Oct Modelled	7-Oct Measured	7-Oct Modelled	8-Oct Measured	8-Oct Modelled
1	0.48	0.40	0.38	0.30	0.34	0.26
2	0.42	0.40	0.36	0.28	0.30	0.22
3	0.35	0.32	0.35	0.24	0.30	0.26
4	0.35	0.28	0.33	0.22	0.35	0.28
5	0.33	0.30	0.33	0.30	0.30	0.21
6	0.32	0.28	0.32	0.26	0.32	0.20
7	0.33	0.26	0.30	0.24	0.30	0.24
8	0.30	0.24	0.27	0.20	0.30	0.20
9	0.33	0.28	0.30	0.22	0.33	0.28
10	0.35	0.32	0.27	0.20	0.27	0.22
11	0.31	0.26	0.33	0.30	0.30	0.20
12	0.31	0.24	0.28	0.24	0.25	0.22

APPENDIX C: COMPUTER PROGRAMME

```
PROGRAM   POLLUTIONMODEL
* Mathematical Modelling of Urban Traffic Air Pollution in Minna Metropolis
*      By NDOKE, P. N.
*       Ph.D DISSERTATION
*     PRINT'*********************************************************'
*     PRINT'*********************************************************'
*     PRINT'*********************************************************'
      DIMENSION CERF1(100),CERF2(100),CERF(100)
      PRINT*,   'THIS PROGRAM IS FOR MODELLING URBAN TRAFFIC AIR'
      PRINT*,    'POLLUTION IN MINNA METROPOLIS, MODEL DESIGNED BY'
      PRINT*, 'NDOKE, PETER NDOKE (B.Eng. (Hons), M.Eng. (Civil Engg)'
      PRINT*,        '(Reg. No. Ph.D/SEET/05/144)'
      PRINT*,            'SUPERVISOR:'
      PRINT*,       ' Engr.Prof. O. D. Jimoh'
      PRINT*,         ' CO-SUPERVISORS:'
      PRINT*,        ' Engr.Prof. J.O.Odigure'
      PRINT*,          'Engr. Prof. S. Sadiku'
      PRINT*,       'DEPARTMENT OF CIVIL ENGINEERING'
      PRINT*, 'SCHOOL OF ENGINEERING AND ENGINEERING TECHNOLOGY'
      PRINT*,     'FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA'
      PRINT*,           'NIGER STATE, NIGERIA'
*********************************************************************
**
*********************************************************************
**
*********************************************************************
**
open(unit=7, file='answer1.prn',status='new')
 Write(7,11)'Theta, u, z, Yr, CERF, C3'
  Write(*,*)'Enter IVT:'
 Write(*,*)'Enter 1 for car:'
 Write(*,*)'Enter 2 for Motorcycle:'
 Write(*,*)'Enter 3 for Heavies:'
 Read(*,*)IVT
 Write(*,*)IVT
    Write(*,*)'Enter IPT:'
Write(*,*)'Enter 4 for carbonmonoxide:'
Write(*,*)'Enter 5 for carbondioxide:'
Write(*,*)'Enter 6 for Nitrogenoxides:'
Write(*,*)'Enter 7 for Sulphurdioxide:'
Read(*,*)IPT
Write(*,*)IPT
 IF (IVT.EQ.1.AND.IPT.EQ.4) THEN
      ef=0.036
      S2=6.5
      H=0.3
    ELSEIF (IVT.EQ.2.AND.IPT.EQ.4) THEN
```

```
      ef=0.022
      S2=1.19
      H=0.24
        ELSEIF (IVT.EQ.3.AND.IPT.EQ.4) THEN
      ef=0.021
      S2=28.3
      H=0.68
ENDIF
        IF (IVT.EQ.1.AND.IPT.EQ.5) THEN
      ef=3.84
      S2=6.5
      H=0.3
        ELSEIF (IVT.EQ.2.AND.IPT.EQ.5) THEN
      ef=0.384
      S2=1.19
      H=0.24
        ELSEIF (IVT.EQ.3.AND.IPT.EQ.5) THEN
      ef=6.84
      S2=28.3
      H=0.68
ENDIF
 IF (IVT.EQ.1.AND.IPT.EQ.6) THEN
   ef=0.0001
   S2=6.5
   H=0.3
 ELSEIF (IVT.EQ.2.AND.IPT.EQ.6) THEN
   ef=0.00001
   S2=1.19
   H=0.24
ELSEIF (IVT.EQ.3.AND.IPT.EQ.6) THEN
   ef=0.0062
   S2=28.3
   H=0.68
ENDIF
IF (IVT.EQ.1.AND.IPT.EQ.7) THEN
   ef=0.00026
   S2=6.5
   H=0.3
ELSEIF (IVT.EQ.2.AND.IPT.EQ.7) THEN
   ef=0.00008
   S2=1.19
   H=0.24
ELSEIF (IVT.EQ.3.AND.IPT.EQ.7) THEN
   ef=0.0055
   S2=28.3
   H=0.68
ENDIF
Write(*,*)'Enter Traffic flow Rate Tr(Number/secs):'
Read(*,*)Tr
Write(*,*)'Enter beginning of line source(m):'
```

```fortran
Read(*,*),Y1
Write(*,*)'Enter end of line source(m):'
Read(*,*),Y2
Write(*,*)'Enter average Vehicle Speed, V(m/s):'
Read(*,*)V
Q=Tr*ef
Write(*,*)'Enter width of street, W(m):'
Read(*,*)W
Write(*,*)'Enter aerodynamic coefficient, b:'
Read(*,*)be
BB1=(be*Tr*V*S2)/W
Write(*,*)'Enter ambient wind speed, U:'
Read(*,*)U
IF(0.0.LT.U.AND.U.LE.3.0)THEN
bJe=0.320
ELSE IF(3.0.LT.U.AND.U.LE.5.0) THEN
bJe=0.220
ELSE IF(5.0.LT.U.AND.U.LT.6) THEN
bJe=0.110
ELSE IF (U.GE.6) THEN
bJe=0.110
END IF
Write(*,*)'Enter downwind distance:'
Read(*,*)xr
Write(*,*)'Enter effective release height, h:'
Read(*,*)he
Write(*,*)'Enter wind turbulence coefficient, a:'
Read(*,*)ai
Write(*,*)'Enter wind speed offset, Us:'
Read(*,*)Us
BB2=(SQRT((ai*((U*AAC)+Us)))**2+BB1))*(xr/((U*AAC))+Us))+he
DO 100 J=1,91
Theta=(J-1)*1
Pi=22.0/7.0
Zeta=(pi/180.00)*Theta
AAS=SIN(Zeta)
AAC=COS(Zeta)
BB3=2*(SQRT(2*pi))*(U*AAC)+Us
   DO 200 K=1,10
   Z=(K-1)*1
 RF=exp((-1./2.)*((z-H)/BB2)**2)+exp((-1./2.)*((z+H)/BB2)**2)
 C1=Q/(BB2*BB3)
 C2=RF*C1
   DO 300 MF=1,7
 Yr=FLOAT((MF-1)*50)
     RT=SQRT(2.)
   CC1=ABS(AAC*(Yr-Y1)-xr*AAS/(RT*bJe*xr/(SQRT(1.+(0.0004*xr)))))
 CC2=ABS(AAC*(Yr-Y2)-xr*AAS/(RT*bJe*xr/(SQRT(1.+(0.0004*xr)))))
   a1=1.0/(1.0+0.33*CC1)
a2=1.0/(1.0+0.33*CC2)
```

```
      A1S3=a1**2
      A1S4=a1**3
      A1S5=a1**4
      A1S6=a1**5
      A2S3=a2**2
      A2S4=a2**3
      A2S5=a2**4
      A2S6=a2**5
      b1=0.25*a1-(0.28*A1S3)+(1.42*A1S4)-(1.45*A1S5)+(1.06*A1S6)
      b2=0.25*a2-(0.28*A2S3)+(1.42*A2S4)-(1.45*A2S5)+(1.06*A2S6)
        DF1=CC1**2
        DF2=CC2**2
        CERF1(MF)=1.0-(b1*exp(-1.0*DF1))
        CERF2(MF)=1.0-(b2*exp(-1.0*DF2))
        CERF(MF)=CERF1(MF)+CERF2(MF)
        C3=C2*CERF(MF)
        WRITE(7,11)Theta,u,z,Yr,CERF(MF),C3
11      FORMAT(F6.1,F5.1,F5.1,F7.1,F7.4,F7.6)
300  CONTINUE
200  CONTINUE
100  CONTINUE
      !11 FORMAT(
        STOP
      END
```

APPENDIX D: CONVERSION FACTORS

Table D1: Converting from ppm to $\mu g/m^3$

Pollutant	Molecular weight	Converting to ppm (Divide by)	Converting to $\mu g/m^3$ (multiply by)
Carbon monoxide	28.01	1145	1145
Carbon dioxide	44.01	1799.26	1799.26
Nitrogen dioxide	46.01	1881	1881
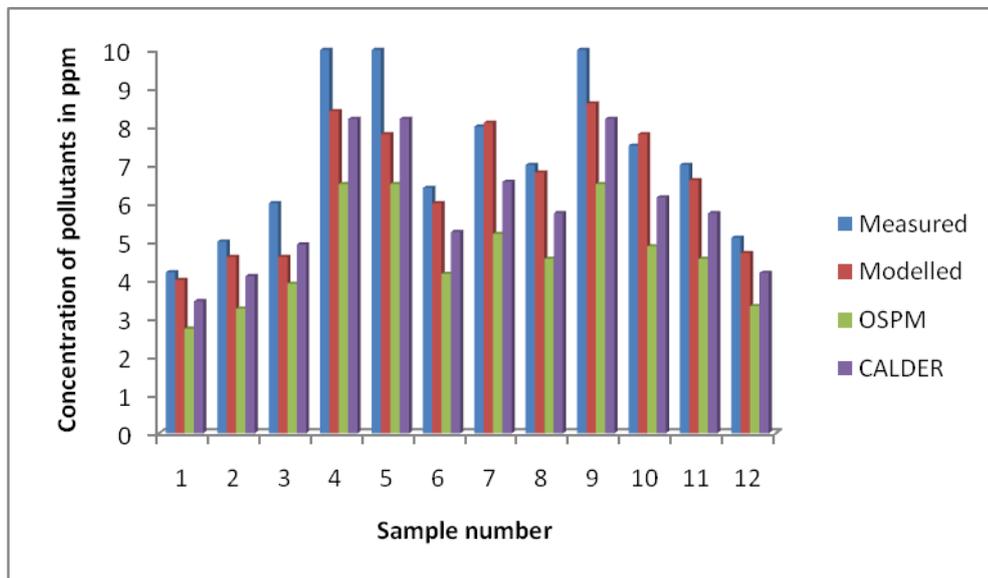
Fig. E1: Compared concentrations of CO for March 4
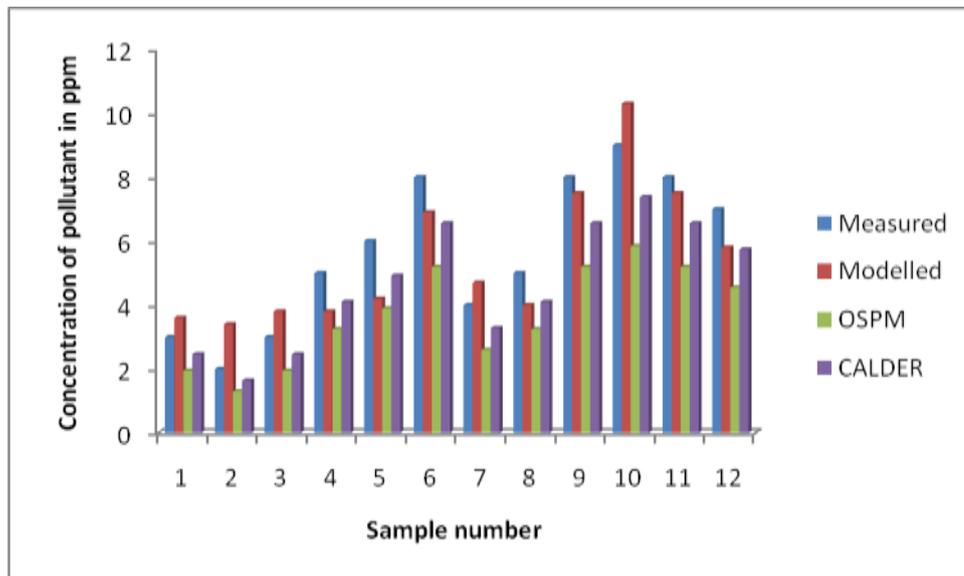
Fig. E2: Compared concentrations of CO for March 5
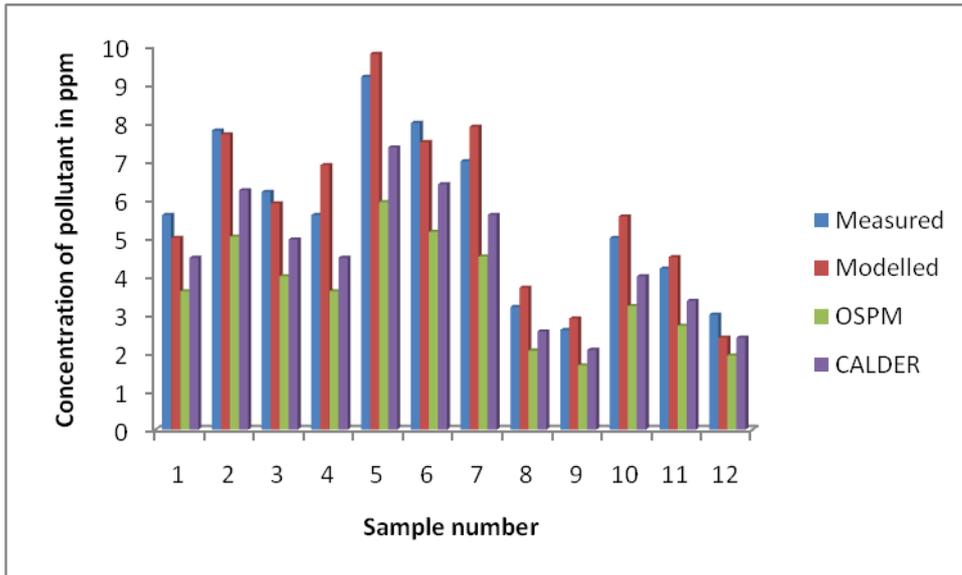
Fig. E3: Compared concentrations of CO for July 2
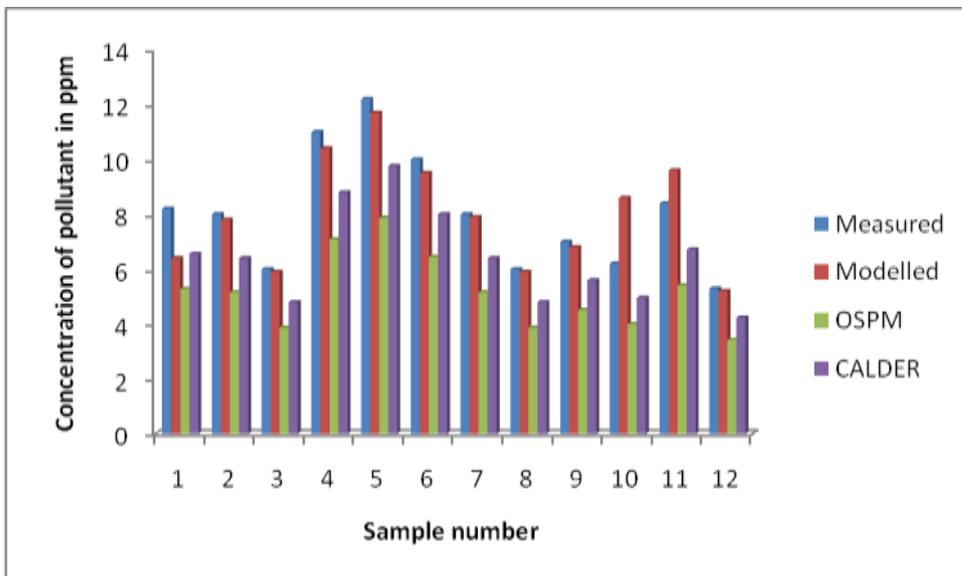
Fig. E4: Compared concentrations of CO for July 3
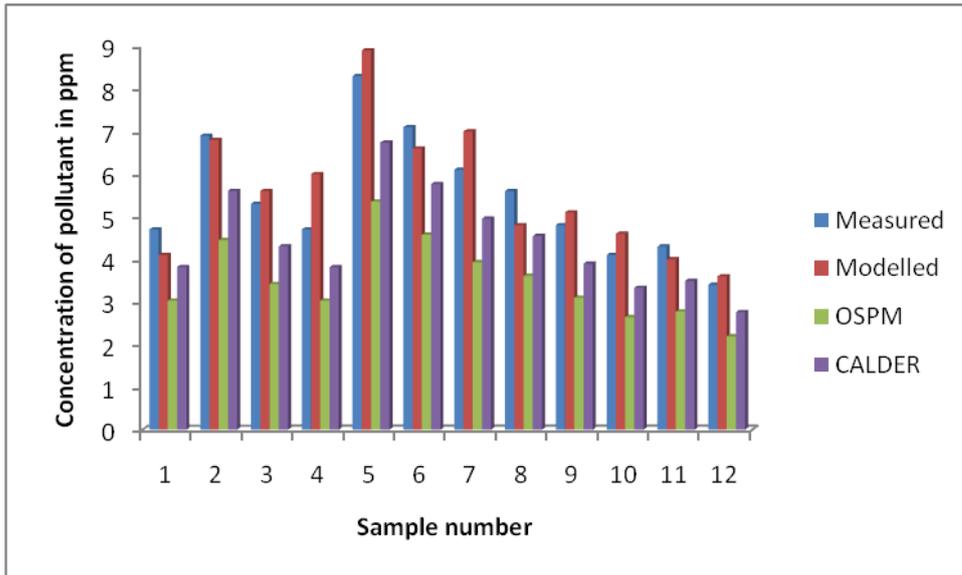
Fig. E5: Compared concentrations of CO for Oct 2
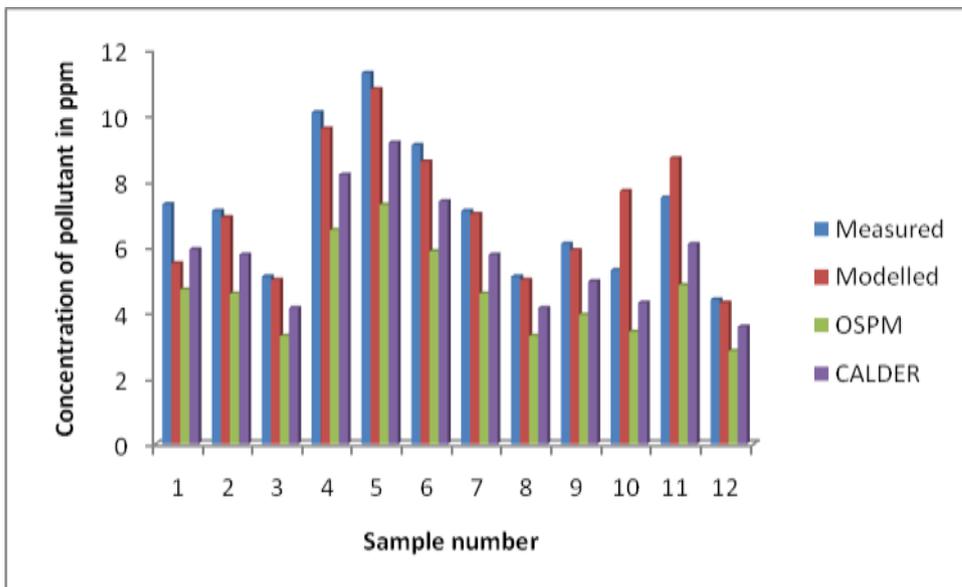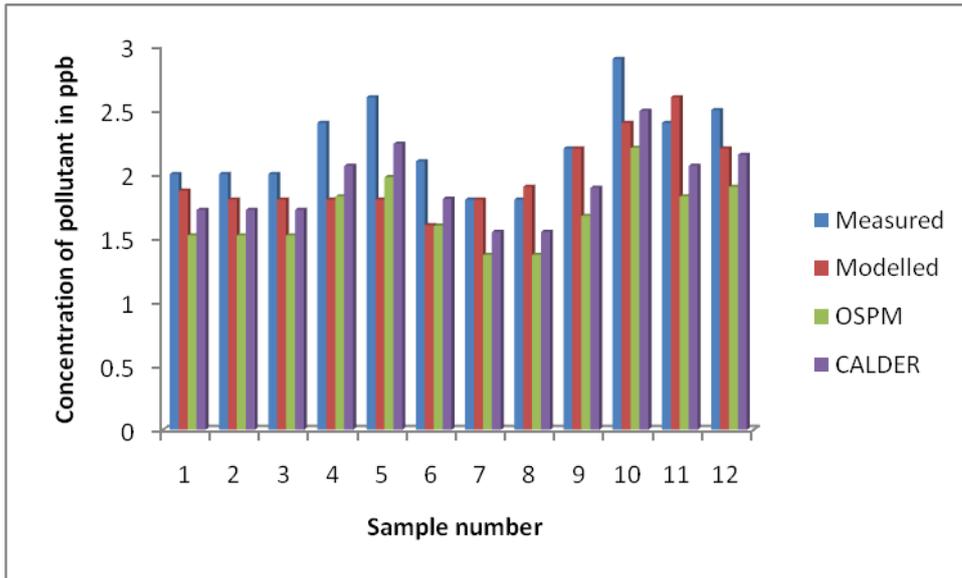

Fig. E6: Compared concentrations of CO for Oct 3
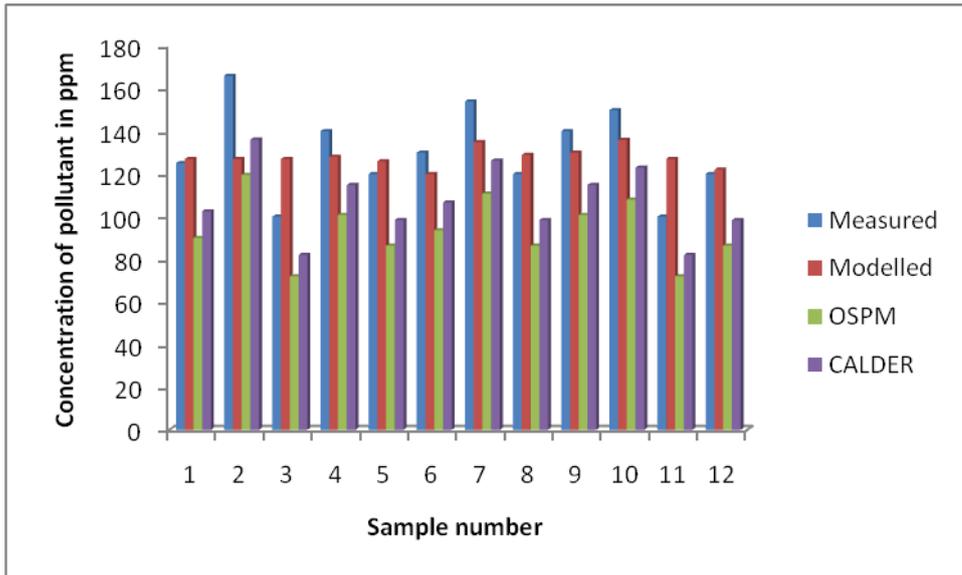
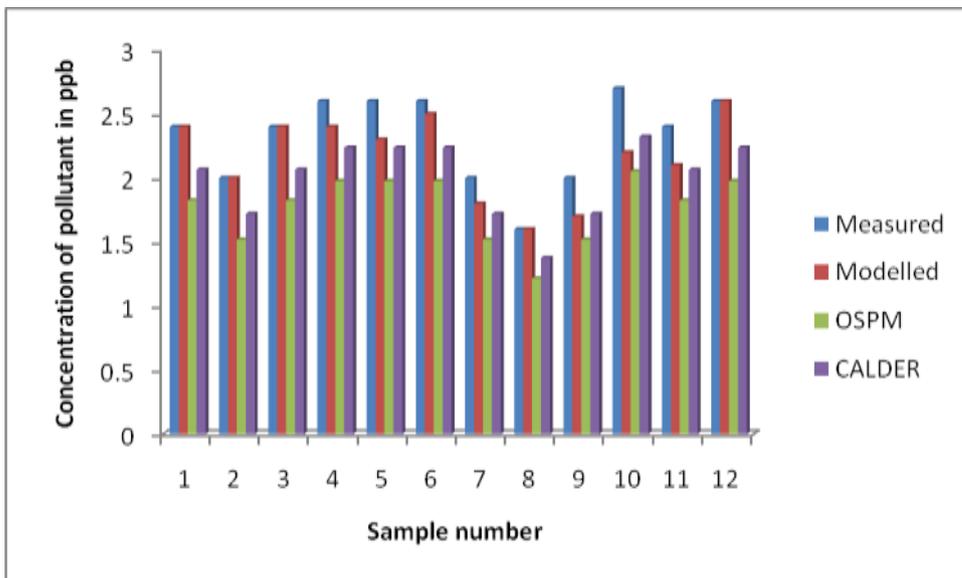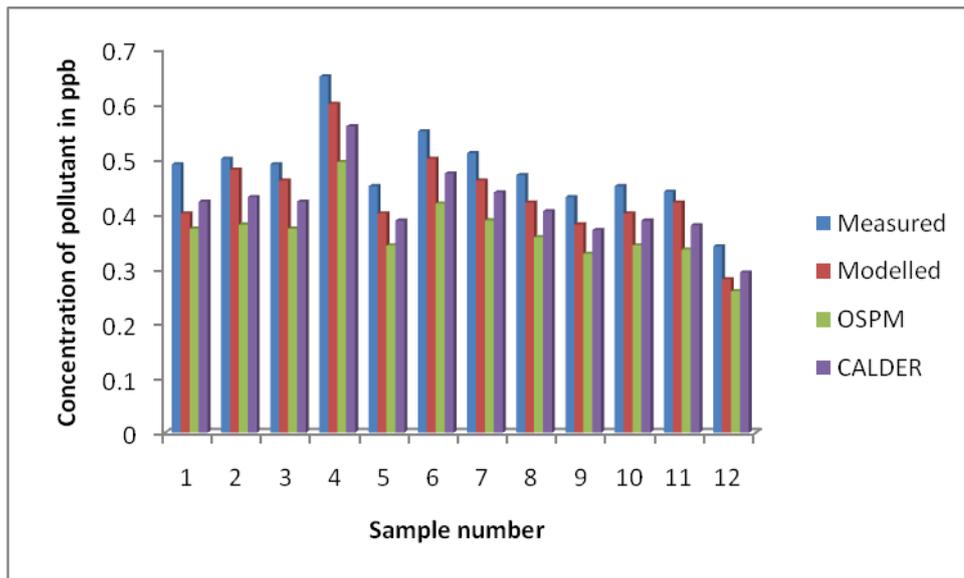**Fig. E7**: Compared concentrations of CO_2 for March 25
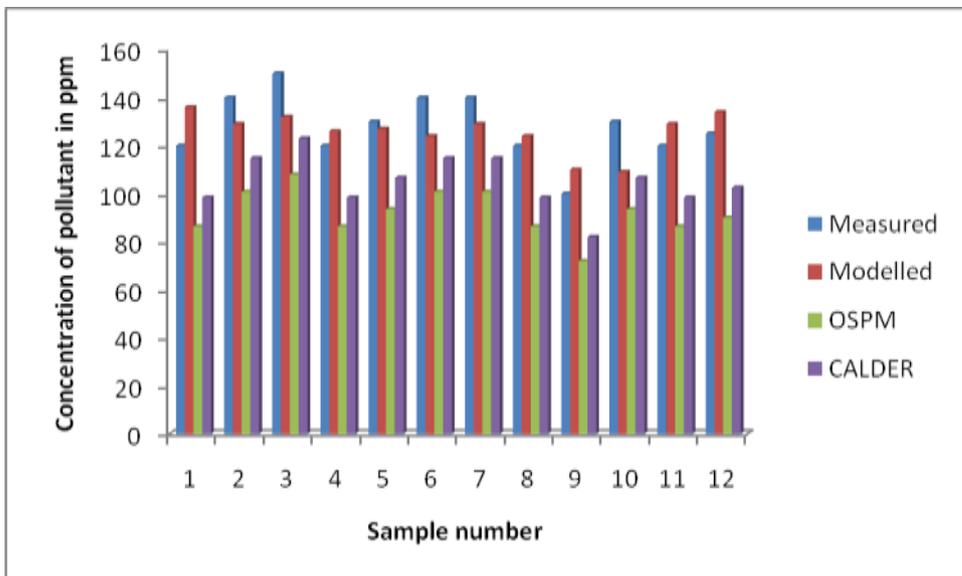
Fig. E8: Compared concentrations of CO_2 for March 26

146
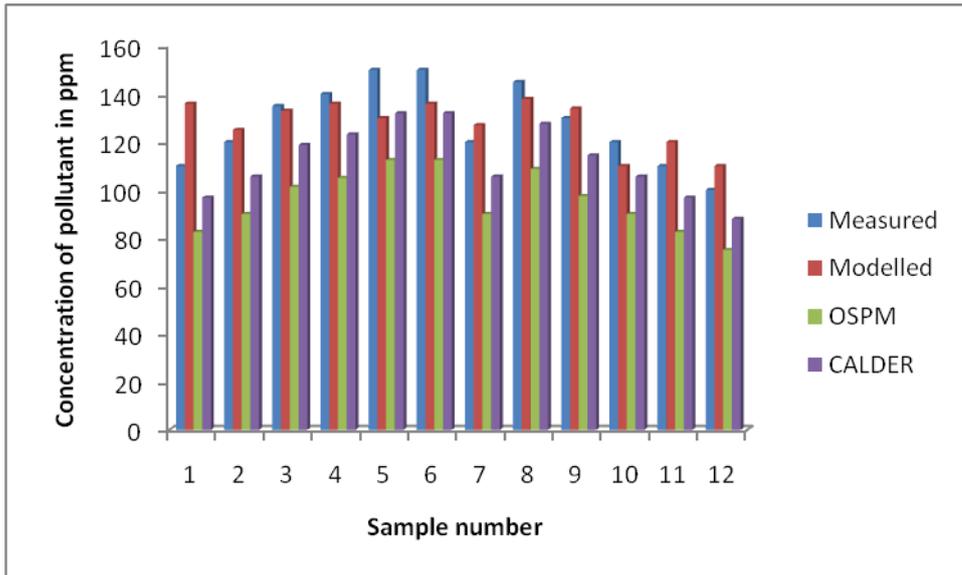
Fig. E9: Compared concentrations of CO_2 for July 10
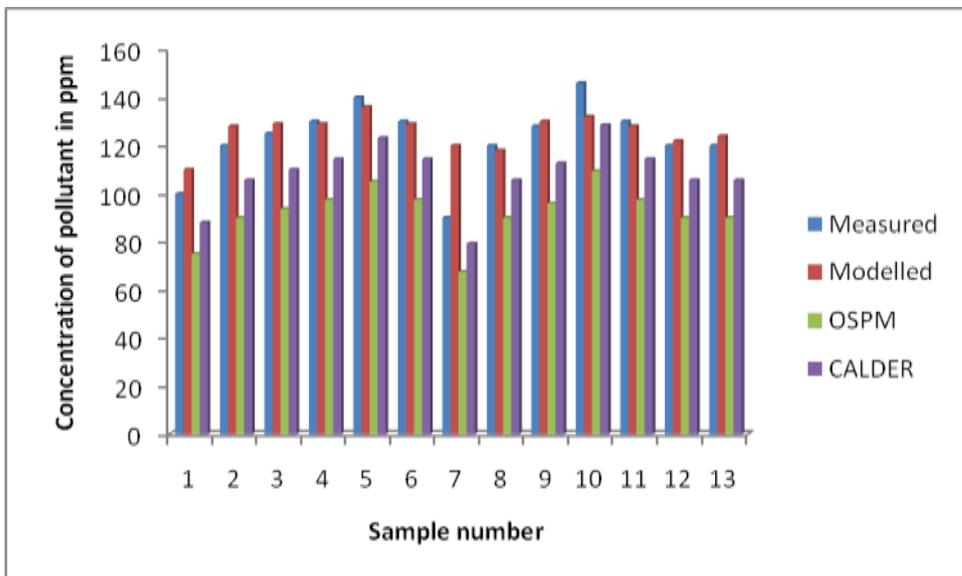
Fig. E10: Compared concentrations of CO_2 for July 11
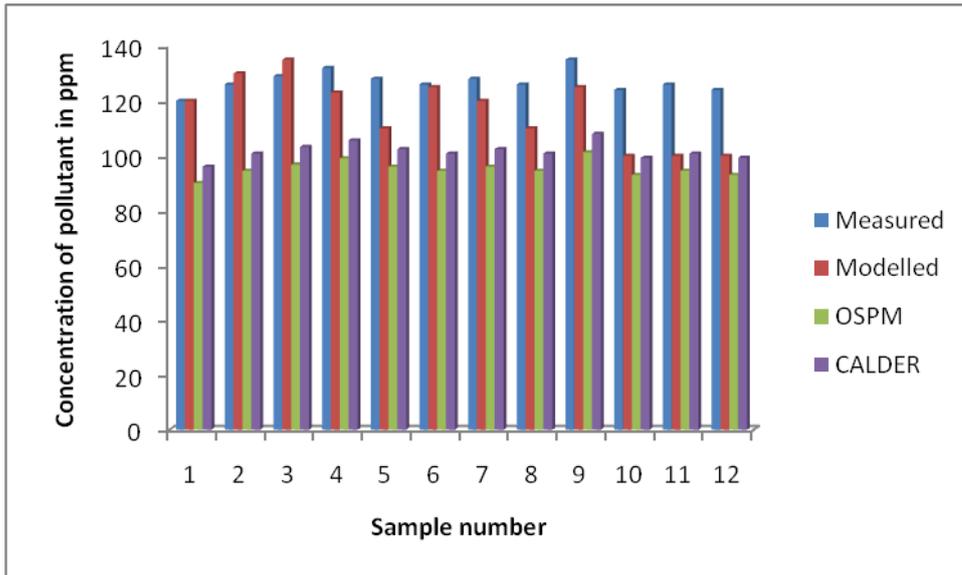
Fig.E11: Compared concentrations of CO_2 for Oct 21
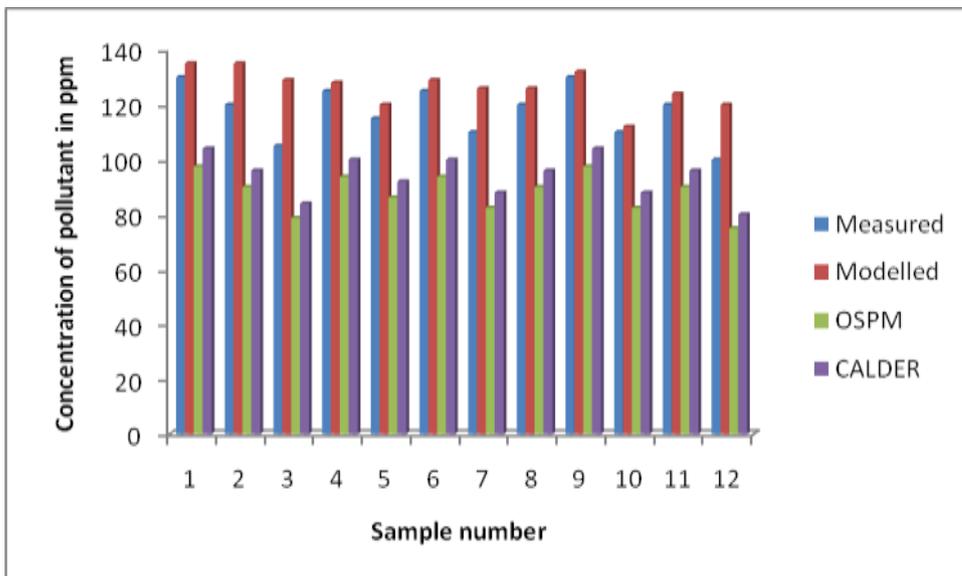
Fig. E12: Compared concentrations of CO_2 for Oct 22

Fig. E13: Compared concentrations of NO_2 for March 11

Fig. E14: Compared concentrations of NO_2 for March 12

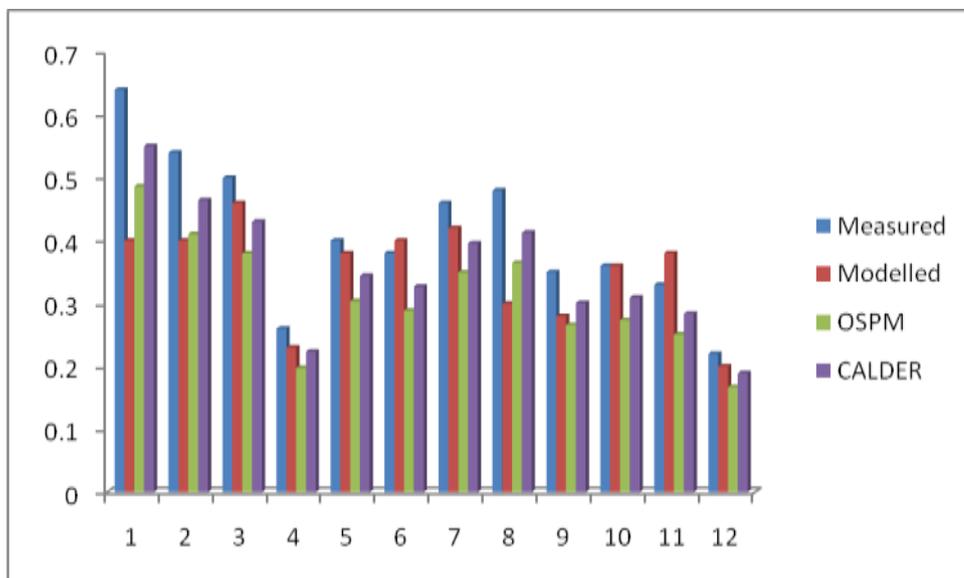**Fig. E15**: Compared concentrations of NO_2 for July 15

Fig. E16: Compared concentrations of NO_2 for July 16
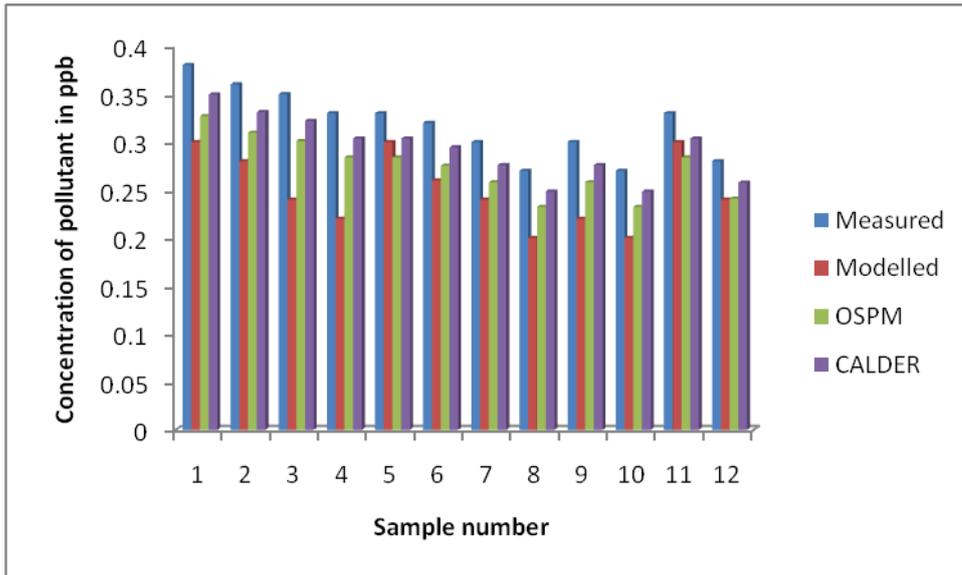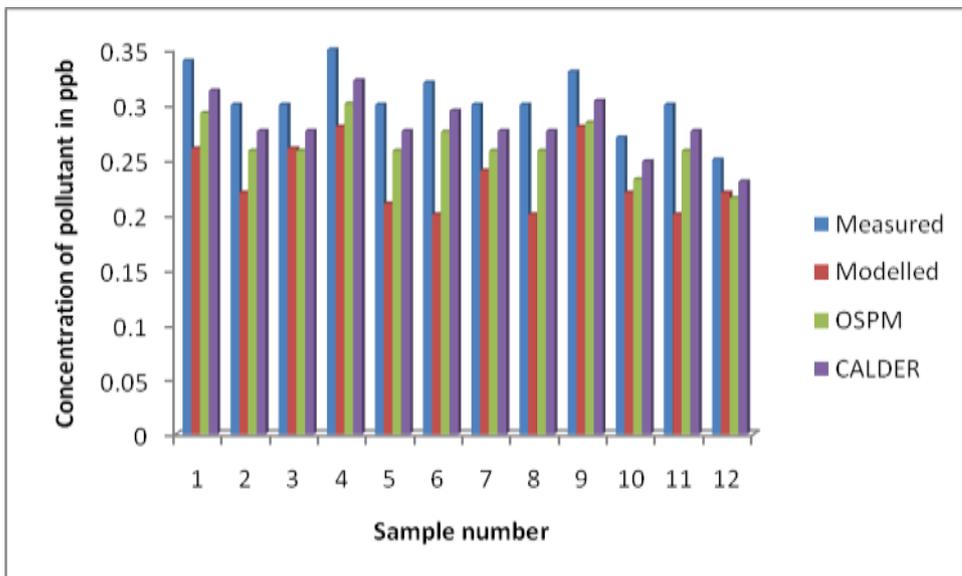
150

Fig. E17: Compared concentrations of NO_2 for Oct 7

Fig. E18: Compared concentrations of NO_2 for Oct 8