A

DISSERTATION

ON

Sensitive Analysis of CALINE 4 Highway Dispersion Model Under Mixed Trafic Conditions

SUBMITTED IN THE PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF DEGREE OF

MASTER OF ENGINEERING
(ENVIRONMENTAL ENGINEERING)

SUBMITTED BY:

ANCHAL AGGARWAL

(UNIVERSITY ROLL NO: 9101)

Under the Guidance of
Mr. Rakesh Mehrotra
Associate Professor

Co-Guide
Dr. Niraj Sharma
Scientist, CRRI

Co-Guide
Dr. A.K. Haritash
Asst. Professor

DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING

DELHI COLLEGE OF ENGINEERING

2009-2011

CERTIFICATE

This is certified that the work presented in this thesis entitled **"Sensitive Analysis of CALINE 4 Highway Dispersion Model Under Mixed Traffic Conditions"** by Anchal Aggarwal, University Roll No. 01/ENV/09 in partial fulfillment of the requirement for the award of the Degree of Master of Engineering in Environmental Engineering, Delhi Technological University (Formerly Delhi College of Engineering), Delhi, is an authentic record. The work is being carried out by her under our guidance and supervision in the academic year 2010-2011. This is to our knowledge has reached requisite standards.

The work embodied in this major project has not been submitted for the award of any other degree to the best of our knowledge.

Guide	Co-Guide	Co-Guide
Mr. Rakesh Mehrotra **Associate Professor** D/o Civil & Environmental Engineering Delhi Technological University, Delhi	**Dr. Niraj Sharma** **Scientist** Traffic Planning and Environment Division, Central Road Research Institute, New Delhi	**Dr. A.K. Haritash** **Asst. Professor** D/o Civil & Environmental Engineering Delhi Technological University, Delhi

ACKNOWLEDGEMENTS

It is a matter of great pleasure for me to present my thesis report on **"Sensitive Analysis of CALINE - 4 Highway Dispersion Model Under Mixed Traffic Conditions"**. First and foremost, I am profoundly grateful to my project guides Mr. Rakesh Mehrotra, Associate Professor of Civil and Environment Engineering Department and Dr. A. K. Haritash, Assistant Professor of Civil and Environment Engineering Department for their expert guidance and continuous encouragement during all stages of thesis. Their help in the form of valuable information and research thoughts at proper time has brought life in this thesis. I feel lucky to get an opportunity to work with them. I am thankful to the kindness and generosity shown by them towards me, as it helped me morally to complete the project. I also wish to thanks to the entire faculty of Environmental Engineering, Department of Civil and Environmental Engineering for their constant encouragement.

In particular, I owe my deepest regards and reverence to Dr. Niraj Sharma, Scientist, Transportation Planning and Environment Division, Central Road Research Institute (CRRI) CSIR, New Delhi for his constant guidance and boundless support, right from the development of the concept, setting framework for the approach adopted and to bring the study in its present form. He always provided me the atmosphere of bonhomie, resources, time and motivation during various phases of my project work.

I wish to express my heartfelt gratitude to all the staff of the Department of Civil and Environmental Engineering, Delhi College of Engineering and Central Road Research Institute for their kind help and valuable assistance during various stage of my project work.

I am also thankful to my classmates and Rajni Dhyani, CRRI for their unconditional support and motivation during this work. I am grateful to my parents for their moral support all the time they have been always around to cheer me up, in the odd times of this work.

ANCHAL AGGARWAL

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDIX

LIST OF ABBREVIATIONS

ACF	Autocorrelation Function
ADMS	Air Force Dispersion Assessment Model
ARAI	Automotives Research Association of India
AERMOD	AERMEIC Dispersion Model (USEPA model)
B - J	Box – Jenkins
CALINE3	California Line Source Dispersion Model (Version 3)
CALINE4	California Line Source Dispersion Model (Version 4)
CALPUFF	California Puff Model
CAL3QHC	CALINE3 with Queuing and Hot-spot Calculations
CAL3QHCR	CALINE3 with Queuing and Hot -spot Calculations (Refined)
CAR-FMI	Contaminants in the Air from a Road— Finnish Meteorological Institute, version3 (CAR-FMI)
CERC	Cambridge Environmental Research Consultants
CLAS	Atmospheric Stability Class
CMVR	Central Motor Vehicle Rules
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPCB	Central Pollution Control Board
CRRI	Central Road Research Institute
DMM	Deterministic Mathematical Model
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
GFLSM	General Finite Line Source Model
GM	General Motors
HCV	Heavy Commercial Vehicle
HYROAD	Hybrid Roadway Intersection Model
IDC	Indian Driving Cycle
IOCL	Indian Oil Corporation Limited
IIP	Indian Institute of Petroleum
IIT	Indian Institute of Technology
IITLS	Indian Institute of Technology Line Source (model)

IMD	Indian Meteorological Department
LCV	Light Commercial Vehicle
LSEM	Line Source Emission Model
M	Meter
MIXH	Mixing Height, m
MoEF	Ministry of Environment and Forests, Government of India
MVA	Motor Vehicles Act
NAAQS	National Ambient Air Quality Standards
NCR	National Capital Region
NEERI	National Environmental Engineering Research Institute
NH	National Highway
NO_x	Oxides of Nitrogen
PCAF	Partial Autocorrelation Function
PCU	Passenger Car Unit
PG	Pasquill – Gifford
PM	Particulate Matter
PM_{10}	Particulate Matter with a diameter less than 10 µm
$PM_{2.5}$	Particulate Matter with a diameter less than 2.5 µm
SIAM	Society of Indian Automobile Manufactures
U	Wind Speed, m/s
UN	United Nations
USEPA	United States' Environmental Protection Agency
VRDE	Vehicle Research and Development Establishment
WEF	Weighted Emission Factor
Zo	Aerodynamic Roughness Coefficient, cm

ABSTRACT

Rapid urbanization and industrialization of cities have increased the vehicular traffic leading to increase in air pollution in urban areas. It has been estimated that in India road traffic contributes approximately 70% of air pollution in urban areas. To reduce the impacts of air pollution due to vehicular traffic, it is important to manage and improve the quality of air in such urban areas. Air pollution dispersion models are used to effectively and efficiently plan the management (environment management plan) of vehicular traffic pollution on particular area/ road corridor, along with monitoring of air pollutants. They not only aid in determining the present influenced area/ affected due to vehicular traffic pollution but also help in identifying the future scenarios under different traffic and meteorological conditions made by these models.

Vehicular pollution modeling involves air pollution prediction estimates by simulating impact of emissions from vehicular activities in a given region under specified traffic and meteorological conditions. Throughout the world, including India the prediction of vehicular pollutant concentrations along highways and roads are carried out by using various Gaussian-based highway dispersion models. Based on the Gaussian dispersion model, several prediction models have been developed to predict vehicular pollution levels along the highways. The most popular amongst various highway dispersion models, are the CALINE model (latest being CALINE 4). CALINE 4 developed by Benson (1984) is extensively used throughout the world (including India) for various vehicular pollution estimate/ prediction along the highways. The CALINE 4 Model uses various inputs (viz., Traffic Volume, Emission Factor, Road geometry, Wind Speed, Wind Direction, Background Concentration) to predict the air pollution concentrations at pre-identified receptor locations along the highway.

The present study focuses on sensitivity analysis of CALINE-4 model which is the fourth version simple line source Gaussian plume dispersion model. Ashram Chowk – CRRI highway Corridor of NH-2 was selected as the area of study. Inputs data (viz. traffic volume, traffic compositions, meteorological data etc.) required for CALINE 4 model was collected from field surveys data. Emission factors provided by CPCB (2000) and ARAI (2007) were used to estimate Weighted Emission Factor (WEF) to account for mixed traffic conditions. The CO concentration due to traffic along the

Ashram Chowk – CRRI highway corridor was predicted at the pre-identified receptor locations. The dispersion of CO concentrations was found to be present upto a distance of 150m from the edge of the mixing zone width (road width+3m on each side of the road). The predicted CO concentrations in all the cases (viz., 1-hour Standard Case Run Conditions, 1-hour Worse Case Run Conditions) were within the National Ambient Air Quality Standard, 2009 (NAAQS, 2009) (i.e. 2 mg/m^3 for 8 hours and 4 mg/m^3 for 1 hour for CO). The regression coefficient (r^2) between predicted and observed 1-hour CO concentrations using CPCB emission factors for Standard Case Run Condition was 0.65 and for Worse Case Run Condition was 0.76. Similarly, the regression coefficient (r^2) between predicted and observed 1-hour CO concentrations using ARAI emission factors for Standard Case Run Condition was 0.60 and for Worse Case Run Condition was 0.73.

A sensitivity analysis of the CALINE 4 model had been performed to identify the most influential variables. CALINE 4 model was found to be relatively sensitive to wind angle (s) for small receptor distances. The highest CO concentrations were observed by a wind angle of ~10° as measured from the road centerline. Wind speed had a considerable effect, e.g., predicted CO concentrations were dropped by 75% - 80% as wind speed increased from 0.5 to 5 m/s. From unstable to stable conditions, average increase in CO concentration was 43%. The model consistently predicts lower CO concentrations for greater highway widths. This effect was most apparent for receptors near the roadway edge. Roadway height (from receptor location at ground level) had very less effect for small change in height but has considerable effect for more deeper or elevated roadway height.

Sensitive Analysis of CALINE 4 had also revealed that among various input variable, source strength, wind speed, highway width and median width were most significant input variable and wind direction, roadway height, distance of receptor to roadway and atmospheric stability were the less significant input variables. Surface Roughness and Mixing height had negligible effect on predicted CO concentrations.

CHAPTER 1

INTRODUCTION

1.1 General

Road transport has become a necessary and common part of everyday's life. The transport sector particularly the road transportation plays central role in the overall socio-economic development. Despite its value, flexibility and necessity as part of modern society, road transport is recognised as a major source of various air pollutants and significant contributor to undesirable environmental problems (Park, 2005). With increasing population, increase in vehicular traffic on roads has resulted in increased air and noise pollution levels in the areas along the road corridor. Many times, pollution level exceeds permissible limits specified by various regulatory authorities/ agencies. The air pollutants (CO, SO_2, Hydrocarbons (HC), Pb, NOx, soot and SPM etc.) due to vehicles can effects at – local (e.g., smoke affecting visibility, ambient air, noise etc.), regional (such as smog, acidification) and global (i.e., global warming) (EEA, 2005) levels.

1.2 Vehicular Air Pollution

Environmental concerns have become one of the most important issues in transport policy debates. Significant quantities of CO, HC, NO_x, SPM and other air toxins are emitted from the motor vehicles into the atmosphere causing serious environmental and health impacts. Air pollution from motor vehicles, in many countries, has replaced coal smoke as the major cause for concern. However, continuing growth in vehicle use means that efforts to reduce emissions from individual vehicles are being overtaken by increase in the volume of traffic. Vehicular traffic has become a major source of air pollution in urban areas. Transport sector contributes around 14% towards the global emissions of green house gases (CPCB, 2010). Carbon dioxide represents the largest proportion of basket of greenhouse gas emissions. With rapid urbanization, road transportation related CO_2 emissions from urban areas are likely to increase further in coming years mainly due to inadequate public transportation system, high vehicle density in urban areas and increasing share of private vehicles vis-à-vis public transportation vehicles in developing countries (Sharma et al., 2010). During, the past three decades, CO_2 emissions from transport have increased faster than those from all other sectors and are projected to increase more rapidly in future. From 1990 to 2004, CO_2 emissions from the world's transport sector have increased by 36.5%. Also, for the same period, road transport emissions have increased by 29% in industrialized countries and 61% in the other countries (CPCB, 2010). Worldwide, transport sector is responsible for approx. 23%of energy related CO_2 and 13% of all GHGs emitted from various sources. Further, CO_2 emissions is expected to increase by 1.7% a year from 2004 to 2030 largely attributable increased demand for mobility in developing countries where it is expected to grow with an average of 2.8% a year for the same period.

1.3 Vehicular Air Pollution in India

The problem of air pollution has assumed serious proportions in some of the major metropolitan cities of India. The problem has further been compounded by the concentration of large number of vehicles and comparatively high motor vehicles to population ratios in these cities. In India, the number of motor vehicles has grown from 0.3 million in 1951 to approximately 50 million in 2000, of which, two wheelers (mainly driven by two stroke engines) account for 70% of the total vehicular population. Two wheelers (2W) and cars (four wheelers (4W), excluding taxis) which are mainly constitute personal mode of transportation, account for approximately four-fifths of the total vehicular population. Similarly, human population has also increased from 361 million to more than 1000 million during this period. In India, 25% of the total energy (of which 98% comes from oil) is consumed by road sector only. Although gasoline vehicles dominate (approximately 85%) the vehicular population, the consumption of diesel is six times more than the consumption of gasoline (petrol). A gradual shift in passenger and freight movement from rail to road-based transportation has also lead to marked increase in fuel consumption by the road sector. Vehicles in major metropolitan cities of India are estimated to account for 70% of CO, 50% of HC, 30%-40% of NO_X , 30% of SPM and 10% of SO_2 of the total pollution load of these cities, of which two third is contributed by two wheelers alone.

Increase in urban population, which constitute about 30% of the India's population (from approximately 17% to 28% during 1951-2001) has resulted in larger concentration of vehicles in these urban cities specially in four major metros, namely, Delhi, Mumbai, Chennai and Kolkata accounts for more than 15% of the total vehicular population of the whole country, whereas, more than 40 other metropolitan cities (with human population more than 1 million) accounted for 35% of the vehicular population in the country. Two wheelers account for about 75% of the total vehicular population. Segment wise market shares of vehicles in India in 2010-11 is shown in **Fig. 1.1.**

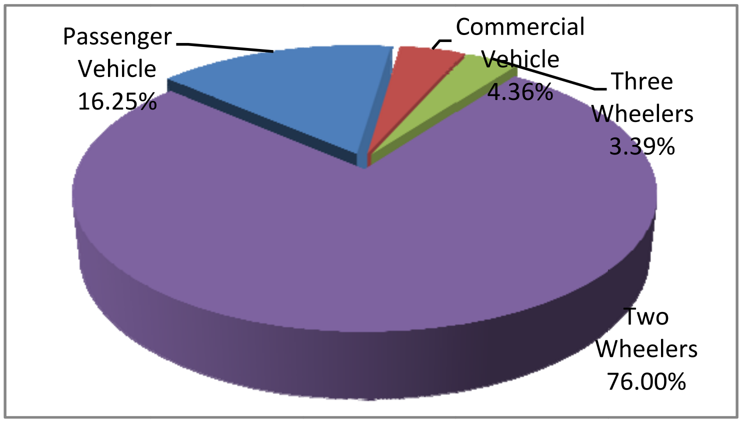


Fig. 1.1: Segment Wise Market Shares of Vehicles in 2010-11 (SIAM, 2011)

With increase in vehicular population, the traffic also increase along the highway annually 3% - 4% and in some cases to the tune of 10%. This indicates the exigency of controlling vehicular pollution (Sharma et al., 2004). As per an estimate, in 2001, air pollution contribution of transport sector was about 72% in Delhi and 48% in Mumbai. Emission analysis of India based on vehicle type is shown in **Fig. 1.2**

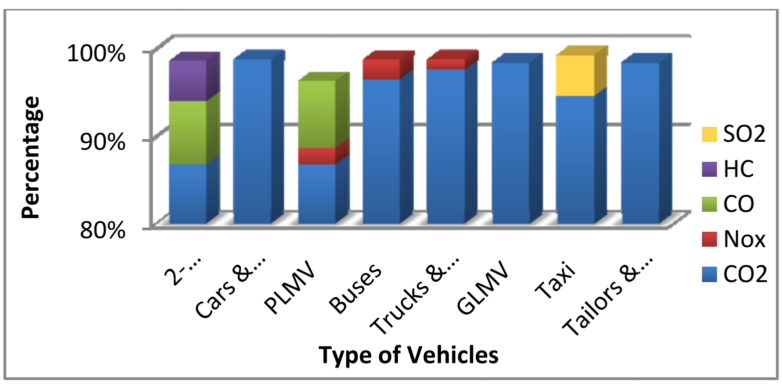


Fig. 1.2: Emission Analysis based on the Vehicle Type (CPCB, 2010)

Amongst all the metro cities in India, the problem is most serious in Delhi, which is often referred to as 'pollution capital' of India due to very high level of air pollutants mainly from vehicles. Against 1.9 million vehicular population in 1990 in Delhi, it rose to nearly 3.6 million in the year 2001 and 5.8 million in the year 2008 has already exceeded 6.8 millions mark (number of vehicles in the Delhi being about sum total of vehicles put together of other three megacities in India namely Mumbai, Chennai and Kolkata). It is quite noteworthy that vehicular population of Delhi alone (8% of the country's total vehicular population) is more than the combined vehicular population of three other major metros, whereas, their combined human population is 3.5 times more than the population of Delhi (more than 10 million at present). High vehicular density, insufficient road space, low traffic speed, bad road conditions and rapid growth in vehicle population have led to a deterioration of the atmospheric conditions over Delhi, a city with one of the highest population densities of India at 11,297 person per square kilometer (City Mayors Statistics, 2011). Percentage contribution of pollutants from various sectors in Delhi and Mumbai is given in **Table 1.1**.

Several laws [viz., Air (Prevention and Control of Pollution) Act 1981, Environmental (Protection) Act 1986, Motor Vehicles Act 1988, Central Motor Vehicle Rules 1989] have been enacted in India to control vehicular pollution, however, their implementation cannot be considered satisfactory. Recently, the central government, various state governments and other regulatory agencies have taken several initiatives to control and reduce the vehicular emissions.

Table 1.1: Percentage Contributions of Pollutants from Various Sectors in Delhi and Mumbai (CPCB, 2010)

S. No.	Parameter	Delhi			Mumbai		
		Transport	Industrial	Domestic & other sources	Transport	Industrial	Domestic & other sources
1	CO	76% to 90%	13% to 37%	10% to 16.3%	92%	8%	Nil
2	NOX	13% to 29%	13% to 29%	1% to 2%	60%	40%	Nil
3	SO2	5% to 12%	84% to 95%	Nil to 4%	2% to 4%	82% to 98%	Nil to 16%
4	PM	3% to 22%	74% to 16%	2% to 4%	Nil to 16%	34% to 96%	53% to 56%

1.4 Vehicular Air Pollution Modelling

In air pollution dispersion studies, the air quality models are used to predict concentrations of one or more species in space and time as related to the dependent variables. They form one of the most important components of an urban air quality management plan (Elsom, 1994, Longhurst et al., 2000). Modelling provides the ability to assess the current and future air quality in order to enable “informed” policy decisions to be made. The air quality models can be classified as point, area or line source models depending upon the source of pollutants, which it models. Line source models are used to simulate the dispersion of vehicular pollutants near highways or roads where vehicles continuously emit pollutants. Vehicular pollution modelling, in general, refers to carrying out air pollution prediction estimates due to vehicular activity in a region. In urban environment it has to be taken into consideration along with other types of sources viz. area and/or point sources whereas, the highway dispersion models are generally used for analyzing the output of existing or proposed highways/roads at a distance of tens to hundreds of meter downwind. The effect of vehicular pollution and vehicular activity is considered to be primary consideration for air quality prediction analysis. Several models have been suggested to predict pollutant concentration near highways or roads treating them as line sources. At present, most of the widely used highway dispersion models are Gaussian based (Sharma et al., 2000; Singh et al., 2006).

In India various Gaussian based line source models like CALINE 4, GFLSM and HIWAY are routinely used to predict the impact of vehicular pollution along the roads/ highways. The present study focuses on the prediction of the CO concentration by CALNE 4 model and sensitivity analysis of the CALINE 4. CALINE-4 is the fourth version simple line source Gaussian plume dispersion model. It employs a mixing zone concept to characterize pollutant dispersion over the roadway. Given source strength, meteorology and site geometry, CALINE-4 can predict the pollutant concentrations for receptors located within 500 meters of the roadway. Its purpose is to assess air quality impacts near transportation facilities and help planners protect public health from the adverse effects of excessive CO exposure. Majumdar et al., (2008) reveals that CALINE 4 with correction factors (0.37) can be applied reasonably well for the prediction of CO in the city of Kolkata. Ganguly et al., (2009) had used two models CALINE 4 and GFLSM and done comparative evolution. Briant et al., (2011) compared the predicted value with observed value and found the percentage errors.

1.5 Sensitive Analysis of CALINE 4 Model

Sensitivity analysis provides a formalized means for checking the behavior of the model under a variety of conditions. A sensitivity analysis of the CALINE 4 model is perform to identify the most influential variables among the different variables: source strength, wind speed, wind direction, distance of receptor to roadway, mixing height, median width, traffic flow, emission factor, highway width and Aerodynamic Roughness coefficient etc. It allows the user to gauge the sensitivity of the model to each input parameter, thereby emphasizing those input parameters which need to be most accurately estimated. It provides benchmark values against which users may check their copies of the model. Because virtually all input parameters act independently within the model, interaction between two or more variables are presumed to be insignificant. Hence, perturbation of one variable at a time is considered sufficient for characterizing the overall sensitivity of the model. Sahlodina et al. (2007) used sensitivity analysis of CALINE 4 model to eliminate the less significant input variable.

1.6 Objective and Scope of the Present Study

CALINE-4 is a line source dispersion models and effective and efficient in predicting the CO concentration at the kerb side of the road. The main objective of the present study is To Analyze the Sensitivity of Caline 4 Model for Various Input Variables (viz., Wind Speed, Wind Direction, Traffic Volume, Mixing Height, Surface Roughness) vis-a vis output in terms of CO concentrations along a pre-identified receptor locations. In the present study, Ashram Chowk – CRRI highway corridors of NH-2 was selected.

1.7 Overview of Project Report

This Project report has been divided into 5 Chapters:

Chapter -1: Introduction - This chapter introduces the topic and presents an insight into the factors that have contributed to deteriorating air quality, along with asserting on the fact that in urban areas, vehicular sources have been identified as the major contributor of the deteriorating air quality.

Chapter -2: **Review of Literature** - It reviews the studies undertaken in the field of vehicular pollution modelling. This chapter stresses the need and objectives of air pollution monitoring and modelling. Various modelling approaches have also been discussed. An overview of some of the models used for air pollution modelling has also been presented. Brief introduction of CALINE-4 model has also been discussed to predict vehicular pollution modelling.

Chapter -3: Methodology- This chapter describes the methodology for estimation of weighted emission factor and various input parameter required for this study. The various input parameters have been discussed, which used in the CALINE-4 model and its sensitive analysis.

Chapter -4: Results & Discussion -This chapter discusses the various results that have been made out of the present study.

Chapter -5: Conclusions and Scope of the Future Studies - This chapter deals with the brief summary of report that has been drawn out of the present study. Recommendations for further work have also been presented in this chapter.

CHAPTER 2

REVIEW OF LITERATURE

2.1 General

A mathematical model is an assembly of concepts or phenomena in the form of one or more mathematical equations, which approximate the behaviour of a natural system or phenomena. They are usually employed to predict the impacts or concentration of parameters under different types of current or future scenarios, using readily available or measured input data. Mathematical models can be used to determine the environmental impacts of the existing or developing transportation projects which combine the effects of source strength and meteorology to describe the resulting ambient air concentrations.

Air pollution dispersion modelling is the mathematical simulation of how air pollutants disperse in the ambient atmosphere. It is performed with computer programs, called dispersion models, that solve the mathematical equations and algorithms which simulate the pollutant dispersion. The dispersion models are used to estimate or to predict the downwind concentration of air pollutants emitted from emission sources such as industrial plants and vehicular traffic. Such models are important to governmental agencies tasked with protecting and managing the ambient air quality. The models also serve to assist in the design of effective control strategies to reduce emissions of harmful air pollutants (Singh et al., 2006).

The Air pollution models form one of the most important components of an urban air quality management plan and provide the ability to assess the current and future air quality in order to enable "informed" policy decisions to be made

The dispersion models require the input of data which includes:

(i) Meteorological conditions such as wind speed and direction, the amount of atmospheric turbulence (as characterized by what is referred to as the stability class), the ambient air temperature and the height to the bottom of any temperature inversion that may be present aloft.

(ii) Emissions parameters such as vehicle volume, type of vehicle etc.

(iii) Terrain elevations at the source location and at the receptor location. The location, height and width of any obstructions (such as buildings or other structures) in the path of the gaseous emission plume.

There are several ways of classifying the variety of existing models according to their specific attributes (Sharma, 2004). The most important criteria being:

(i) **Source – receptor relationship:** source – oriented (point, area, line, volume) and receptor – oriented (street canyon, intersection model etc.)

(ii) **Basic model structure:** deterministic or non-deterministic, steady state or time dependent

(iii) **Frame of reference:** Eulerian or Lagrangian

(iv) **Dimensionality of computational domain:** one dimensional, two dimensional, three dimensional or multi dimensional

(v) **Scale (space and time):** microscale (1m, sec-min), mesoscale (5-10 km, hour), small synoptic (100 km, hour-day), large synoptic (100 – 1000 km, days) and planetary (>1000 km, weeks)

(vi) **Model structure and the approach:** used for the closure of the turbulent diffusion equation (closed- form, analytical and numerical, statistical and physical)

(vii) **The terrain/area:** to which they are applicable (rural flat terrain, urban flat terrain, complex terrain, coastal areas)

(viii) **Level of sophistication:** level1 (screening models) and level 2 (refined models)

Whatever may be the classification criteria adopted for classifying the models, the characteristics of the system being studied

(i) Size (local, regional, national, global)

(ii) Time horizon (hour, day, month, year)

(iii) Pollutant of concern (SO_2, NOx, CO, SPM, photochemical oxidant etc.)

are equally important. However, the most important and popular way of classifying air pollution models is based on the model structure and the approach used for the closure of the turbulent diffusion equation (Jude, 1989) which is widely used in urban air pollution modelling also (Khare and Sharma, 2002) (**Fig. 2.1**).

The problem fundamental to all modelling studies in air pollution is the identification of the function ‘F’ that would allow the prediction of the concentration of the pollutant C (x, t) at any point in space x, and time t, if the emissions and other meteorological variables are given. Three different approaches have been established to identify ‘F’

(i) Deterministic mathematical modelling (analytical and numerical models)

(ii) Statistical modelling

(iii) Physical modelling

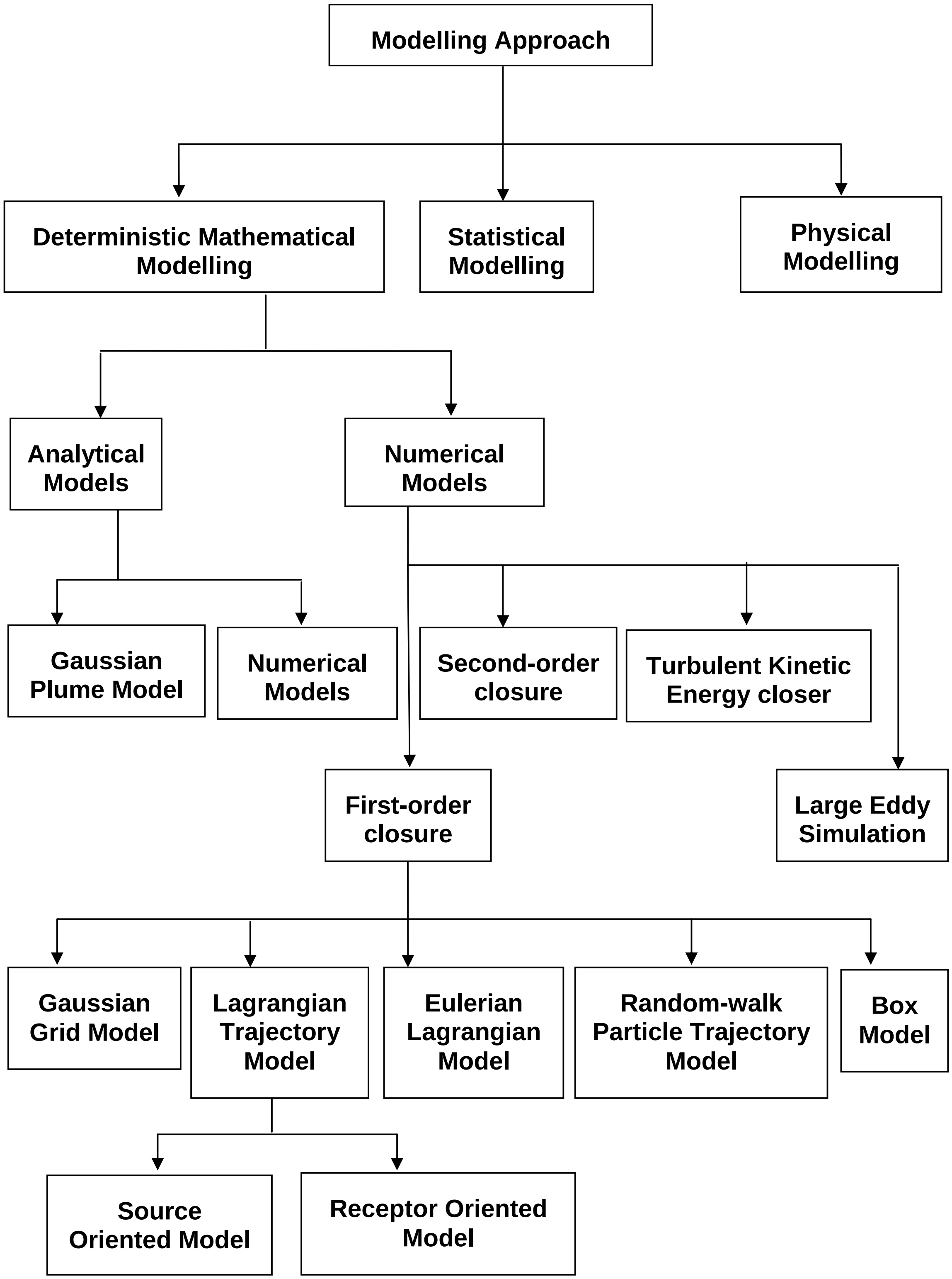


Fig. 2.1: Schematic Presentation of Air Quality Model Classification System

Atmospheric dispersion modelling is one of the large classes of phenomena, which include a deterministic part and a random element. The deterministic component may be modelled with all the precision allowed by the experimental input, whereas the random stochastic part is less precise or unpredictable. There are two extreme approaches to atmospheric modelling, the statistical and the analytical approach. Statistical technique, in its extreme form, looks into pure time series, whereas 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 available/ applicable directly in their present theoretical form. Most statistical models include some explaining variables, whereas most would be 'pure' analytical models requiring some statistical smoothening of input (Sharma, 2004).

2.2 Deterministic Mathematical Models

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. In other words, differential equation is developed by relating the rate of change of pollutant concentration to average wind and turbulent diffusion which, in turn, is derived from the mass conservation principle. The common Gaussian LSM is based on the superposition principle, namely concentration at a receptor, which is the sum of concentrations from all the infinitesimal point sources making up a line source. This mechanism of diffusion from each point source is assumed to be independent of the presence of other point sources. The other assumption considered in DMM is the emission from a point source spreading in the atmosphere in the form of plume, whose concentration profile is generally Gaussian in both horizontal and vertical directions. Deterministic model includes analytical model and numerical model. Both analytical and numerical models are based on mathematical abstraction of fluid dynamics processes.

Limitation of deterministic model:

(i) Inadequate dispersion parameters

(ii) Inadequate treatment of dispersion upwind of the road

(iii) Requires a cumbersome numerical integration especially when the wind forms a small angle with the roadways.

(iv) Gaussian based plume models perform poorly when wind speeds are less than 1m/s.

2.2.1 Analytical Models

Analytical models provide solutions to the basic equations describing the process. In fact, most of the present analytical models for air quality predictions are based on Gaussian equation. These Gaussian models despite several limitations and assumptions have found favour with the scientific community, as they are very simple and include the solution to the simple Gaussian equation (Barratt, 2001). In addition to their user-friendly nature and simplicity, these models are conceptually appealing as they are consistent with the random nature of the turbulence of the atmosphere. Further the development of Gaussian type dispersion equations/ models has reached a level of sophistication such that they are routinely used as assessment tools by various regulatory agencies (USEPA, 2000). These simplified models can be applied with reasonable confidence to pollutant transport within unidirectional flows (e. g., over relatively flat terrains). However they are less reliable for situations where the flows are more complicated. For example, flow over complex terrain or separated flows around obstructions and building wakes where these Gaussian dispersion models cannot be applied (Hanna, 1982; Pasquill and Smith, 1983; Turner, 1994; Seinfield and Pandis, 1998).

The concentration of pollutants (C) at location (x, y, z) from a continuous elevated point source with an effective height of H is given by following Gaussian dispersion equation (Turner, 1970)

$$C(x, y, z, H) = \frac{Q}{2\pi\sigma_y\sigma_z U} \exp-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2 \left[\exp-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2 + \exp-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] \quad \ldots\ldots.(1)$$

Where, σ_y and σ_z are horizontal and vertical dispersion parameters, determined as a function of stability class and distance from the source. U is the mean wind speed, Q is the uniform rate of release of pollutants and H is the effective plume height. For a continuously emitting infinite line source at ground level when wind direction is normal to the line source, the equation (1) reduces to

$$C(x,z) = \frac{Q}{\sqrt{2\pi}U\sigma_z}\left\{\exp-\frac{1}{2}\left(\frac{z+h_0}{\sigma_z}\right)^2 + \exp-\frac{1}{2}\left(\frac{z-h_0}{\sigma_z}\right)^2\right\} \quad \ldots\ldots.(2)$$

For ground level sources H = h_0 (plume rise).

Most of the highway dispersion models used for the preliminary estimation for screening purpose retained the basic Gaussian dispersion approach but used modified vertical and horizontal dispersion curves to account for the effects of surface roughness, averaging time and vehicle induced turbulence (Gilbert, 1997; Sunil, 2008).

2.2.2 Numerical Models

Over the past several years, numerical models have been increasingly used to solve the complicated dispersion problems such as dispersion of heavier – than – air boundary layer flow over complex terrain, studying gas diffusion in thermally stratified flows, dispersion of pollutants around structures/ buildings and in regional and mesoscale dispersion modelling. In addition, various numerical models based upon Lagrangian trajectory and Eulerian grid models are increasingly used for the prediction of various secondary pollutants like ozone. The formation of ozone involves highly complex and nonlinear photochemical reactions between VOC's and NO_x. These models can handle, at least theoretically, non-stationary, non-homogeneous conditions along with complex configurations of spatial domains such as rough terrains. These numerical models require rigorous mathematical computations through computer software and as such cannot be conveniently used for screening purpose by regulatory agencies. Moreover, these models require large input data and larger computational capabilities (Sharma, 2004).

2.3 Statistical Models

In contrast to deterministic modelling, the statistical models calculate concentrations by statistical methods from meteorological and traffic parameters after an appropriate statistical relationship has been obtained empirically from measured concentrations. Regression, multiple regression and time-series technique are some key methods in statistical modelling. The time-series analysis techniques [Box–Jenkins models] have been widely used to describe the dispersion of Vehicular Exhaust Emissions at traffic intersection and at busy roads. Various studies involving statistical techniques have been used to forecast real-time, Short-term as well as long-term pollutant concentrations and for their trend analysis. This has been done by mostly using long-term (some time short also) emission, meteorology and pollution concentration data. This modelling technique has been employed to find concentrations of primary as well as highly complex secondary pollutants like ozone (Sharma, 2004).

Limitation of statistical model:

(i) Require long historical data sets and lack of physical interpretation
(ii) Regression modelling often underperforms when used to model non-linear systems
(iii) Time series modelling requires considerable knowledge in time series statistics i.e. autocorrelation function (ACF) and partial auto correlation function (PACF) to identify an appropriate air quality model
(iv) Statistical models are site specific

2.4 Physical Models

In physical modelling, a real process is simulated on a smaller scale in the laboratory by a physical experiment, which models the important features of the original processes being studied. Typical experimental devices such as wind tunnels or water tunnels are employed, in which the atmospheric flows, for which boundary layer wind tunnels (wind tunnel modelling) are used. This type of physical modelling carried out in the wind tunnel, in which atmospheric flows have been modelled with air as fluid medium, has also been referred to as fluid modelling by various researchers (Sharma, 2004).

Limitation of Physical model:

(i) Major limitations of wind tunnel studies are construction and operational cost
(ii) Simulation of real time air pollution dispersion is expensive
(iii) Real time forecast is not possible

2.5 Summary of Atmospheric Dispersion Models

In the early 1970s, a number of highway air pollution models (mostly Gaussian-based) were developed. These models provided theoretical estimates of air pollution levels as well as temporal and spatial variation under present and proposed conditions as a function of meteorology, highway geometry and downwind receptor locations. However, comparison of experimental results with these model predictions indicated many deficiencies and limitations. These include consideration of inadequate dispersion parameters, the tendency of these models severely to over predict when the winds were parallel to the road, the inapplicability of these models to very low wind speeds (≤1m/s) and the inadequate treatment of dispersion in the upwind direction of the road (Sharma, 2001; Nagendra et al. 2002).

Various researchers used different methodologies and techniques to overcome these limitations that led to a better understanding of the complex dispersion phenomena and thus a more realistic estimation of pollutants near the roads under different traffic and meteorological conditions. Most effort was directed towards incorporating wind speed corrections, modifying dispersion parameters to account for enhanced turbulence due to vehicle wakes, treatment of the line source and the consideration of oblique winds. Attempts were made to validate and evaluate these models with experimental and field data that led to the development of more refined line source models like HIWAY 4, ROADWAY 3, and the California line source (CALINE) 4.

2.5.1 Urban Models

I. AERMEC Dispersion Model (AERMOD)

An AERMOD based on atmospheric boundary layer turbulence structure and scaling concepts, including treatment of multiple ground-level and elevated point, line, area and volume sources. It handles flat or complex, rural or urban terrain and includes algorithms for building effects and plume penetration of inversions aloft. It uses Gaussian dispersion for stable atmospheric conditions and non-Gaussian dispersion for unstable conditions. AERMOD is designed for transport distance of 50 km or less.

II. Contamination in Ai from Road-Finnish Meteorological Institute (CAR-FMI)

This model was developed by the Finnish Meteorological Institute (FMI) for evaluating atmospheric dispersion and chemical transformation of vehicular emissions of inert (CO, NO_x) and reactive (NO, NO_2, O_3) gases from a road network of line sources on a local scale. The CAR-FMI model includes an emission model, a dispersion model and statistical analysis of the computed time series of concentrations. The CAR-FMI model utilizes the meteorological input data evaluated with the meteorological pre-processing model MPP- FMI. Levitina et al. (2005) compared the CAR-FMI with CALINE 4 and found that for the hourly NO_X predicted data, the index of agreement values range from 0.77 to 0.88 and from 0.83 to 0.92 for the evaluations of the CAR-FMI and CALINE4 models respectively.

III. Atmospheric Dispersion Modelling System (ADMS)

ADMS version 3 is an advanced dispersion model (1999) developed by CERC, United Kingdom for calculating concentrations of pollutants emitted continuously from point, line, volume, area sources or discretely from point sources. It characterizes the atmospheric turbulence by two parameters, the boundary layer depth and the Moninobukhov length, rather the single parameter Pasquill-Stability class (CERC, 2000; Sharma et al., 2004; Jungers et al., 2006).

IV. California Puff Model(CALPUFF)

It is a non-steady-state puff dispersion model that simulates the effects of time- and space-varying meteorological conditions on pollution transport, transformation, and removal. CALPUFF is a Lagrangian model that simulates pollutant releases as a series of continuous puffs and is most suitable for releases in the 50 to 200-km range. It has been adopted by EPA as the preferred model for assessing long-range transport of pollutants and their impacts. It can model line sources with constant emissions, as well as point, area, and volume sources (USEPA, 2004).

2.5.2 Line Source Dispersion Models

I. California Line Source Dispersion Model (CALINE)

CALINE model was developed by Benson (1972) for California Department of Transportation (CALTRANS) which was used for predicting CO concentration. In 1975, a revised version of the original model, CALINE 2 was developed. This model could compute concentration for depressed sections and for winds parallel to the roadway. Subsequent studies indicated that CALINE 2 seriously over predicted concentration for stable, parallel wind conditions.

In 1979, a third version, CALINE 3 was developed. CALINE 3 retained the basic Gaussian dispersion methodology but used new horizontal and vertical dispersion curves modified for the effects of surface roughness, averaging time and vehicle induced turbulence. Also, the virtual point source model was replaced by equivalent finite line source model and added multiple link capabilities to the model format. In 1980, Environmental Protection Agency authorized CALINE 3 for use in estimating concentration of non-reactive pollutants near highways. CALINE 4 introduce in 1984 which is the latest version in the CALINE series of models for predicting concentration of CO, NO_2 and aerosols (Robet, 2002). Coe et al. (1998) reformatted CALINE 4 in the form of a CL4 model, a graphical Windows-based user interface designed to ease data entry and increase the online help capabilities of CALINE 4.

II. CAL3QHC and CAL3QHCR

CAL3QHC (CALINE3 with Queuing and Hot-spot Calculations) is a computer program that employs the CALINE3 line source dispersion model and a traffic algorithm for estimating the number of vehicles queued at an intersection (USEPA, 2004). It was certified by both the California Air Resources Board and the EPA for modelling CO or other inert pollutant concentrations from motor vehicles at roadway intersections. The pollutant is dispersed according to CALINE3 for each link, and contributions from each link are added to obtain a CO concentration at a particular receptor location. The CAL3QHC model, therefore, added the capability to model emissions from vehicles queuing at intersections and to permit estimation of total CO concentrations from both moving and idling vehicles.

CAL3QHCR (CALINE3 with Queuing and Hot-spot Calculations Refined) is a refined model that uses observed meteorological data rather than screening meteorology. In addition, calm winds are excluded in multi hour concentration estimates. CAL3QHC/CAL3QHCR only simulates dispersion near intersections for roads that are less than 10 m above grade (Hayes et al., 1985; Wahab, 2004).

III. General Motor Model (GM Model)

GM model is developed by Chock (1978) is a simple line source model. It was developed in attempt to remove the limitations of earlier models by incorporating wind speed correction (U0) and by suggesting modified values for the vertical dispersion parameter, z, to take care of the induced effect of the mechanical turbulence generated by traffic (Nagandra and Khare, 2002).

IV. General Finite Line Source Model (GFLSM)

A simple GFLSM (Luhar and Patil, 1989), based on the Gaussian diffusion equation is formulated so that it could be used for any orientation of wind direction with roadway and also does not have the infinite line source. The GFLSM is modified to predict particulate concentrations by incorporating some simple corrections. It is suitable for heterogeneous traffic conditions and is more suitable for long-term predictions.

V. HIWAY

This US-EPA model is a Gaussian steady-state model for predicting concentrations of non-reactive gases at point receptors downwind of the road in a relatively simple terrain (Turner, 1970). Each lane is modeled as a straight and continuous finite line source with uniform emission rate, simulated by a series of point sources integrated at the receptor. HIWAY-4 is a latest version of HIWAY model developed by incorporating modified dispersion curves and an aerodynamic drag factor to the original HIWAY model (Marmur et al., 2003).

VI. ROADWAY

It is a finite difference model, which predicts pollutant concentration near a roadway. It assumes a surface layer describable by surface layer similarity theory with the superposition of the effect of vehicle wakes. The unique part of the ROADWAY model is the vehicle wake theory, which was originally developed by Eskridge and Hunt, and modified, by Eskridge and Thompson (1982), and Eskridge and Rao (1983, 1986). The model can also be used to predict velocity and turbulence along the roadway. ROADCHEM (Eskridge and Thompson, 1982) is a version of ROADWAY, which incorporates the chemical reactions involving NO, NO2 and O3 as well as advection and dispersion. It uses surface-layer similarity theory to produce vertical angle turbulence profile (Rao et al., 2002).

VII. Hybrid Roadway Intersection Model (HYROAD)

HYROAD is designed to predict the concentrations of carbon monoxide (CO) that occur near intersections. HYROAD addresses the “three key aspects controlling the magnitude of CO concentrations: traffic operations at intersections; vehicle emissions; and atmospheric transport and dispersion”. Each module can be used as a stand-alone program and is not dependent upon the functionality of the other two modules. HYROAD’s dispersion module uses a Gaussian puff approach, with dispersion induced by traffic flow and wind characteristics. HYROAD is intended for use as a roadway intersection model and was designed to account for all of the various aspects of intersection modelling, including queuing, signal timing and other vehicle movement characteristics. Although it is currently considered to be an “alternative” model and is not yet on the USEPA refined model list (USEPA, 2004).

It is important to select a model that most accurately simulates the existing or future emissions source(s), even though it is often difficult to replicate project site characteristics exactly. Some models are Urban models (e.g., AERMOD can model point, area or volume sources), while others are designed for specific applications and use only one approximation method (e.g., CALINE 4, which uses only a line source approximation). The evaluation of models is a matter of great interest and it becomes particularly important in all those fields, in which, modelling is used as a decision- making tool. There is an increasing demand for more objective and formalized procedures in order to evaluate the quality (fitness for purpose) of models. Comparisons of some models which are used for vehicular pollution modelling are discussed in **Table 2.1**. Depending upon availability of input data, geometric condition and output required, suitable model is selected for pollution modelling.

Table 2.1: Comparisons of Other Models with CALINE 4*

S. No.	Model	CALINE 4
1	**CAL3QHC/CAL3QHCR** i) Simulates dispersion near intersections for roads that are less than 10 m above grade ii) Allows for 60 receptor sites iii) Accommodate up to 120 roadway links, each of which can be specified as either a free- flow or queued link	i) Used for vehicles traveling along a segment of roadway can be represented as a "line source" of emissions ii) Allows for 20 receptor sites iii) Accommodate up to 20 roadway links
2	**GFLSM** i) Used for CO and SPM ii) Suitable for heterogeneous traffic conditions and for long-term predictions	i) Used for CO, NO_X and PM ii) Suitable for heterogeneous traffic conditions
3	**HIWAY-4** i) Based on dispersion curves with an aerodynamic drag factor ii) Under predict the concentrations at low wind speed	i) Based on Horizontal and vertical curves ii) Over predict the concentrations at low wind speed
4	**ROADWAY-2** i) Applicable in the near field (within 200m of the highway), where the effects of interactions between the vehicle traffic and the atmospheric surface flow are important ii) Numerical model iii) Simulating simplified chemical reactions involving nitric oxide (NO), nitrogen dioxide (NO2), and ozone (O3)	i) Applicable for longer distances (within 500m of the highway), where, dispersion is dominated by the atmospheric turbulence ii) Gaussian plume dispersion model iii) Does not simulate any chemical reaction
5	**HYROAD** i) Used for CO only ii) Simulate up to 60 receptors and 50 roadway segments	i) Used for CO, NO_X, and PM ii) Simulate up to 20 receptors and 20 roadway segments

S. No.	Model	CALINE 4
6	**ADMS** i) Used for primary pollutants and continuous releases of toxic and hazardous waste products ii) Up to 50 receptors may be specified	i) Used for primary pollutant only ii) Up to 20 receptors may be specified
7	**AERMOD** i) Large program with many features and input requirements ii) Practitioners may be forced to spend a significant amount of time just familiarizing themselves with the program and its various requirements	i) Less input parameters are required ii) User friendly and simple to understand
8	**CALPUFF** i) Non-steady-state Lagrangian model ii) Simulates pollutant releases as a series of continuous puffs iii) Most suitable for releases in the 50 to 200-km range iv) Adopted by EPA for assessing long-range transport of pollutants v) Designed primarily for long-range transport (receptors more than 1 km from a source	i) Steady-state Gaussian based model ii) Simulates pollutant releases as a series of continuous plume iii) Suitable for release in 10km range iv) Used for screening in EIA v) Ideally suited for modelling near-roadway pollution dispersion (500m range)
9	**CAR-FMI** i) Utilizes boundary- layer scaling with a meteorological pre-processing model ii) Used for evaluating atmospheric dispersion and chemical transformation of vehicular emissions of inert (CO, NOx) and reactive (NO, NO_2, O_3) gases	i) Utilizes Pasquill Stability Classification ii) Used for evaluating atmospheric dispersion of vehicular emissions of inert components (CO, NO_2 and Aerosol)

*Various Sources

2.6 Brief Introduction of CALINE 4 Model

CALINE-4 is the fourth version simple line source Gaussian plume dispersion model. It employs a mixing zone concept to characterize pollutant dispersion over the roadway. This version updates CALINE-3, specifically by fine-tuning the Gaussian method and the mixing zone model. Its purpose is to help planners protect public health from the adverse effects of excessive CO exposure.

The main purpose of the model is to assess air quality impacts near transportation facilities. Given source strength, meteorology and site geometry, CALINE-4 can predict the pollutant concentrations for receptors located within 500 meters of the roadway. It predicts the air concentrations of carbon monoxide (CO), nitrogen dioxide (NO_2), and suspended particles near roadways. It also has special options for modelling air quality near intersections, street canyons and parking facilities. The greatest advantage of CALINE-4 in comparison of earlier versions is that it is more user-friendly which has a graphical windows-based user interface, designed to ease data entry and increase the on-line help capabilities of CALINE-4.

CALINE-4 can model roadways at-grade, depressed, and filled (elevated); bridges (flow under roadway); parking lots; and intersections. Bluffs and canyons (topographical or street) also can be simulated. CALINE-4 accepts weighted vehicle emission factors (expressed in grams per vehicle) developed and input by the user for each roadway link. The user inputs composite emission factors by link. Users also enter hourly information on traffic/sources by link. Additional inputs include wind direction bearing, wind speed, atmospheric stability class, mixing height, wind direction standard deviation, and temperature. CALINE-4 is a Gaussian model whose formulations are based on steady-state horizontally homogenous conditions. The region directly over the highway is treated as a zone of uniform emissions and turbulence. An area equal to the travelled roadway plus 3 m on each side is referred to as the mixing zone. Mechanical turbulence (from moving vehicles) and thermal turbulence (from vehicle exhausts) are the dominant dispersive mechanisms.

A modified version of the Pasquill-Smith curves is used for the vertical dispersion coefficient, σ_z. The vertical dispersion parameter is assumed constant over the mixing zone from the centre of the roadway link to a computed distance from the link centre and then follows a power curve outside this distance. Dispersion is adjusted for vehicular heat flux (Emission factor) and surface roughness, which is assumed to be fairly uniform over the study area. The horizontal dispersion is a function of the horizontal standard deviation of the wind direction, downwind distance, diffusion time, and Lagrangian time scale. CALINE-4 divides highway links into a series of smaller elements. Each element is modelled as an equivalent finite line source (FLS) positioned perpendicular to the wind direction. Each element is subdivided into three sub elements to distribute the emissions. The downwind concentrations from an element are modelled using the crosswind FLS Gaussian formulation. The concentration at individual receptors is a series of incremental contributions from each element FLS. The number of receptors that can be modelled by CALINE-4 is limited to 20, making it difficult to compare results to other models that can handle many more receptor locations. CALINE-4 is an older model with 1980s science. It is a plume model with steady state, homogeneous conditions. The roadway links cannot be more than 10 km above or below local topography (Sunil, 2008).

CALINE 4 divides individual highway links into a series of elements from which incremental concentrations are computed and then summed to form a total concentrations estimate for a particular receptor location. The receptor distance is measured along a perpendicular from the receptor to the link centreline. The first element, $€_o$, is formed as a square with sides equal to the highway width. Its location is determined by the roadway wind angle PHI. Each element is modelled as an equivalent finite line source (FLS) positioned normal to the wind direction and cantered at the element midpoint. A local x−y coordinate system aligned with the wind direction and originating at the element mid point is defined for each element. The emissions occurring within an element areas summed to be released along the FLS representing the element. The emissions are then assumed to disperse in a Gaussian manner downwind from the element (**Fig. 2.2**). The length and orientation of the FLS are functions of the element size and roadway wind angle. CALINE4 computes receptor concentrations as a series of incremental contributions from each element FLS (Benson, 1979).

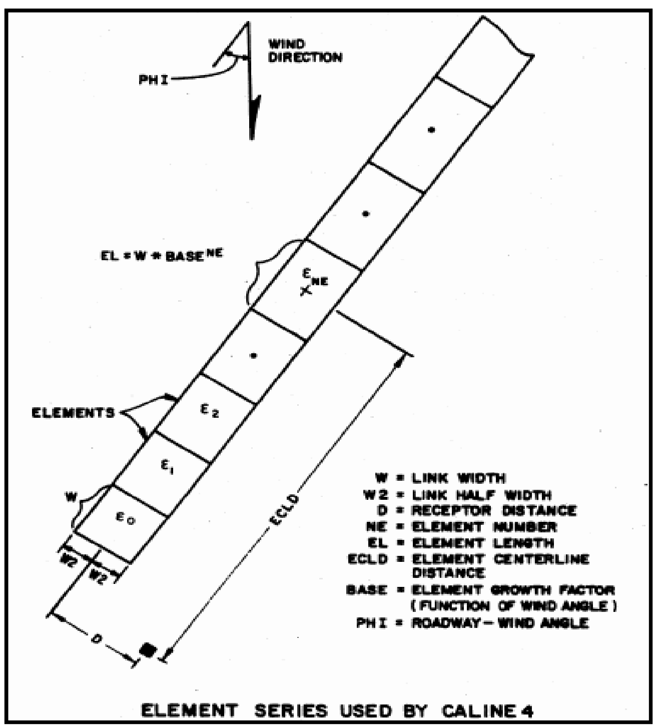


Fig. 2.2: Element Series Represented by Series of Equivalent FLS

Benson et al. (1986) also evaluated the performance of the CALINE 4 line source model for complex terrain applications based on a controlled field tracer study. They found the performance of the CALINE 4 model to be unsatisfactory and not as good as that for similar modelling situations in flat terrain. Coe et al. (1998) reformatted CALINE 4 in the form of a CL4 model, a graphical Windows-based user interface designed to ease data entry and increase the online help capabilities of CALINE 4. The CL4 setup program is self-contained with both programs (the CL4 interface and the CALINE-4 dispersion model), so the user only needs to complete a single installation step. The original CALINE-4 executable files are copied to the CL4 program directory.

In California, CALINE4 has been widely accepted for many years as the standard modelling tool to evaluate project-level CO impacts (Jungers et al., 2006). In India, various Gaussian based line source models like CALINE 4, GM and HIWAY 4 are routinely used to predict the impact of vehicular pollution along the roads/highways. Few studies using CALINE-4 model have also been reported in literature (Sharma et al., 2005). Although most of the studies involving CALINE-4 models have been to predict CO concentrations along roads and highways, however some recent studies have also been carried to predict concentrations of fine particles and NO/NO_x concentrations. Sivacoumar and Thanasekaran (1998) used the GFLSM to predict the CO concentrations near major highway in Chennai. Khare and Sharma (1999) used GFLSM model to predict CO concentrations at three traffic intersections in Delhi. The predicted values were compared with the actual field data and found that the GFLSM model over predicted the CO concentrations by considerable amount. However, after removing the error function, the model performance improved significantly. A study carried out by CRRI (CRRI, 2001) reported the use of CALINE-4 to assess the impact of vehicular pollution on NH-2 between Delhi and Agra. Goyal et al., (1999) have developed a line source model called IITLS for the city of Delhi at IIT, Delhi. This model was proposed to describe the downwind dispersion of pollutants near roadways and its performances were comparable with that of CALINE-3 model and also with observed values.

Nirjar et al., (2002) had used CALINE-4 to predict the concentration of CO along the urban and semi-urban roads in Delhi and found the predicted concentrations to be less than the observed values and found the moderate r^2 correlation between them. On the basis of the above, a linear model was also developed which when validated on a highway gave fairly accurate results within ± 20%. Gramotnev et al., (2003) used CALINE4 for the analysis of aerosols of fine and ultra-fine particles, generated by vehicles on a busy road. Levitin et al., (2005) found that the performance of CALINE 4 was better at a distance of 34m, compared with that at a distance of 17m. It was also analyzed the difference between the model predictions and measured data in terms of the wind speed and direction. The performance of CALINE 4 in most cases deteriorated as the wind speed decreased and also as the wind direction approached a direction parallel to the road. Lin and Ge (2006) used the cell-transmission approach for air quality modelling of CO by CALINE 4 model. The cell based approach defines micro-homogeneous traffic conditions and produces better emission estimation than the link-average approach in current dispersion models. The cell- based approach is also more advantageous than microscopic (i. e., individual vehicle) traffic simulation models in terms of emission estimation as information about individual vehicles (model, year, etc.) in traffic is generally unavailable. The cell-based approach can reduce computational requirement and enables fine spatial, temporal scale prediction of on-road traffic and roadside pollution concentrations. Anjaneyulu et al., (2006) studied the CO concentrations of Calicut city in the state of Kerala, India using CALINE 4 and IITLS and Linear regression models. It was revealed that linear regression model performs better than the CALINE4 and IITLS models.

CALINE 4 offers several advantages over other models and is chosen as the base model for the purpose of developing a modified line source model. Carbon monoxide is chosen for the model predictions because it is principally emitted from vehicular sources and considered as a guide to the levels of other vehicular pollutants, gaseous as well as particulate matter that is small enough to have long term suspension in air. CO has several advantages as a reference material for the estimation of traffic-produced pollutants. As CO is produced both by the petrol and diesel driven vehicles and it is also possible to measure CO atmospheric concentration continuously. Thus these information data can be used effectively for testing the model for short periods when there are fluctuations in the traffic flows and meteorological conditions (Anjaneyulu et al., 2006).

Most of these predictions or estimations are carried out as part of Environmental Impact Assessment (EIA) studies (Sharma et al., 2007). According to EIA notification, it had made mandatory for all new and existing highway/road projects to carry out EIA studies. Further, as a part of EIA requirements, prediction estimates of vehicular pollutants along the highways/roads are routinely carried out (CRRI, 2005). Based on the modelling exercise, Environmental Management Plan is suggested so that the predicted air pollution level does not exceed the National Ambient Air Quality Standards (NAAQS) **(Annexure I)**. Central Pollution Control Board (CPCB), Delhi had issued necessary guidelines for air quality modelling, but unfortunately they do not contain any reference/guidelines, with respect to line source models, resulting in use of different types of line source models. The experience so far has shown that the values of various input parameters to these models are often adopted from other countries without understanding their applicability in Indian context, resulting in inaccurate and unreliable predictions (Sharma et al. 2007). Kenty et al., (2007) used the CALINE-4 to find out the concentrations of NO_x and NO_2 in Florida (USA). Further, Yura et al., (2007) have reported that the CALINE-4 does not perform well in densely populated areas and differences in topography may be a decisive factor in determining when the model was used to predict concentrations of $PM_{2.5}$. Majumdar et al., (2008) reveals that CALINE 4 with correction factors (0.37) can be applied reasonably well for the prediction of CO in the city of Kolkata. It was also found that Authorities embarking on development projects should follow up the predictive analysis done with CALINE 4 with a cost benefit analysis, as this would paint a true picture of the effects of the project. However, in order to make it more useful, refinements need to be carried out so as to make it more complete tool for prediction.

Every model's accuracy for predicting concentration of pollutant depend on the inputs data, similarly CALINE 4 model efficiency also depends on various input variables. Thus, sensitivity of CALINE 4 model is required to identify the most influential input variables. A sensitivity analysis of the CALINE4 model was performed to identify the most influential variables. Sripraparkon et al. (2003) found the Major factors that affected to model calculation (wind direction, vehicle volume, height of receptor and composite emission factor) and Minor parameters (wind speed, distance of receptor and ambient pollutant concentration) by sensitive analysis of CALINE 4. Sahlodina et al. (2007) used sensitivity analysis of CALINE 4 model to eliminate the less significant input variable. Ganguly et al. (2009) had used two models CALINE 4 and GFLSM and done comparative evolution. Briant et al. (2011) compared the predicted value with observed value and found the percentage errors. They also found sensitivity of CALINE 4 for three variable stability class, emission height and distance from road.

2.7 Inadequacies of Vehicular Pollution Modelling

A number of studies that have been carried out to examine the reliability of predicted concentrations from these models. Models are more reliable for estimating longer time-averaged concentrations than for estimating short-term concentrations at specific locations. These models are reasonably reliable in estimating the magnitude of highest concentrations sometimes occurring within the area (e.g. air pollution episodes). The concentration estimates that occur at a specific time and site are poorly correlated with actually observed concentrations and are less reliable (Barratt, 2001).

The Various Gaussian based line source models are routinely used in India for carrying out vehicular pollution predictions along the highways and roads generally require various input parameters pertaining to meteorology, traffic, road geometry, land use pattern, besides receptor locations. Besides the basic Gaussian dispersion approach, each dispersion model differs with respect to the treatment of modified wind and turbulence due to vehicle wakes near the roads. Adequacies, limitations, reliability and associated uncertainties of these dispersion models have already been discussed by various researchers. Various Gaussian based dispersion models are extensively used in India without properly calibrating them for Indian climatic and traffic conditions. Moreover, various input parameters used in these models are not accurately known leading to incorrect or sometimes even unreliable predictions. Greatest inaccuracy in vehicular pollution modelling exercise in India is due to the improper emission factors used for different categories of vehicles. Uncertainties and unreliability associated with the emission factors have already been discussed in detail and reported by various researchers.

Unfortunately in India, no serious efforts have been made to accurately determine the emission factors for different categories of in-use vehicles as a function of vehicle speed, engine technology, fuel quality and age of the vehicles. Various researchers had used emission factors that were obtained from limited experimental data on chassis dynamometer under laboratory conditions or directly adopting emission factors which are applicable to European vehicles. The problem is further compounded, as vehicles with a wide range of engine technologies with different quality fuels are being used in these vehicles (CPCB; 2000a, b). Thus, with different combinations of vehicles (age wise and technology wise) and fuels of wide ranging quality, finding reliable emission factors for different categories of vehicles under Indian driving and road conditions with limited emission testing facilities is a task which needs to be addressed immediately. Another source of inaccuracy in these models pertain to non- availability of on-site meteorological data. Most often modellers in India rely on nearest Indian Meteorological Department (IMD) data which does not reflect actual field conditions and adds to inaccurate prediction estimates. Thus, there is a need to upgrade and modernize the facilities so that these IMD stations can better serve in understanding and explaining the dispersion phenomena in urban/city conditions (USEPA, 2000).

Unfortunately in India, no serious efforts have been made to accurately determine the emission factors for different categories of in-use vehicles as a function of vehicle speed, engine technology, fuel quality and age of the vehicles. Various researchers had used emission factors which were obtained from limited experimental data on chassis dynamometer under laboratory conditions or directly adopting emission factors which are applicable to European vehicles. While the use of emission factors obtained from old generation vehicles grossly over predict the emissions from the new generation Euro I, Euro II compliance vehicles presently plying on Indian roads, the use of emission factors developed for European vehicles to Indian vehicles results in gross under prediction of the emissions from these Indian vehicles (CRRI, 2007). The problem is further compounded, as vehicles with a wide range of engine technologies with different quality fuels are being used in these vehicles (CPCB; 2000a, 2000b). In India, vehicles as old as belonging to 1970s and as new as Euro III and Euro IV compliant vehicles can be found to be playing on the roads. The quality of fuel supplied in the whole country is also not same. While, better quality fuel comparable to Europe and other developed countries is being supplied in Delhi and few other major metros, the quality of fuel being supplied in other parts of the country is still far from satisfactory. Thus, with different combinations of vehicles (age wise and technology wise) and fuels of wide ranging quality, finding reliable emission factors for different categories of vehicles under Indian driving and road conditions with limited emission testing facilities is a task which needs to be addressed immediately.

Further, with the recent emphasis on replacing old technology vehicles with the latest ones and improvement of fuel quality, the existing facilities need to be upgraded keeping in tune with the latest developments that are taking place in the other parts of the world. Although, recently serious efforts are being made by various research and regulatory agencies including Central Pollution Control Board (CPCB), Society of Indian Automobile Manufacturers (SIAM), Automotive Research Association of India (ARAI), VRDE (Vehicle Research and Development Establishment), Indian Institute of Petroleum (IIP), National Environmental Engineering Research Institute (NEERI) and various academic institutions like Indian Institute of Technology (IIT's) to estimate emission factors for different categories of in-use vehicles under field conditions as a function of vehicle speed, age and related variables. Recently, CPCB (CPCB, 2000a) has suggested a set of emission factors for different categories of vehicles on the basis of year of manufacture and engine technology. However, it is still a long way before more reliable emission factors that reflect Indian traffic conditions are worked out. Majumdar et al. (2010) use the CALINE 4 with correction factor and determine the lessening of CO in the atmosphere as a result of the project of construction of flyover.

Automotive Research Association of India (ARAI), under the auspices of IOCL/MOEF sponsored project related to source apportionment studies for various cities, determination of emission factories for different categories of in-use vehicles is under progress. A draft report on the same has also been published (ARAI, 2007). It is expected that with the development of reliable emission factors for various categories of in -use vehicle using modified Indian Driving Cycle (IDC) representative of present day traffic conditions, various uncertainties related to use of emission factor will be removed to a great extent in India.

2.8 Vehicular Emission Related Legislations in India

India is the one of the few countries of the world, which has provided for constitutional safe guards for the protection and conservation of the environment. Various laws have been enacted in India having direct or indirect bearing on various aspects related to the transport and environment (Sarin et al., 2001). Important amongst them are Air (Prevention and Control of Pollution) Act, (1981) the Environment (Protection) Act (EPA, 1986) and the Motor Vehicles Act (MVA, 1988) including the Central Motor Vehicle Rules (CMVR, 1989) (CPCB, 2006). These laws cover a wide range of rules, regulations and/or provisions related to ambient air quality standards, vehicle emission norms for different categories of vehicles : in-use as well as for vehicles at conformity of production (COP) stage, specification of fuels, guidelines for EIA for highway and road projects.

Apart from the legislative Acts, Constitution also empowers the parliament to enact legislations in conformity with various international agreements. India is already a signatory to international agreements pertaining to controlling the ozone depleting substances in the atmosphere (Montreal Protocol, 1986) and controlling the GHG's emissions (Rio Declaration, 1992; Kyoto Protocol, 1997) and contributing to various global environmental conservation and management programmers under the auspices of United Nations (UN).

2.8.1 Vehicular Emission Standards

The mass emission norms for vehicles at manufacturing stage as well as for in-use vehicles have been notified during 1990-91 but these did not require the manufactures any modification. The emission norms along with fuel specifications laid down in 1996 required the automobile manufacturers to make modifications in engine design particularly with regard to crankcase emissions and evaporative emission control. New standards have been laid time to time. Some of these are mentioned below:

- April 1995: New passenger cars were registered only if fitted with catalytic converters in Delhi, Mumbai, Calcutta and Chennai.
- April 1998: The testing method for passenger cars norms was changed to cold start, which is stricter procedure than the previous one.
- June 1999: Private vehicles had been required to meet EURO-I or EURO-II and only those vehicles, which conformed to these rules, were registered.
- Year 2000: The norms required major modification in the engine design especially with regard to the fuel injection system in passenger cars and fitment of catalytic converters in the two-stroke engines. These standards are akin to Euro-I norms adopted in the European countries in 1992.
- 1st April 2000: Only such private vehicles, which meet EURO-II norms, were registered in National Capital Region (NCR).

- On October 6, 2003, the National Auto Fuel policy has been announced which envisages a phased program for introducing Euro II-IV emission and fuel regulations by 2010.
- In the year 2005 Bharat stage-III emission norms have been implemented in 11 megacities for all the new vehicles except 2 & 3 wheelers while Bharat stage-II norms have been implemented all over the country.
- On April 1, 2010 Bharat stage-IV emission norms have been implemented in 11 megacities for all the new vehicles except 2 & 3 wheelers while Bharat Stage-III norms have been implemented for 2 & 3 wheelers all over the country.

CHAPTER 3

METHODOLOGY

The present study aims to carry out sensitivity analysis of CALINE 4 Model which includes estimation of Weighted Emission Factor (WEF) of vehicles plying along Ashram Chowk – CRRI highway corridor at NH – 2 (**Fig. 3.1**) and prediction of the Carbon Monoxide concentration along the highway corridor using CALINE 4 air quality dispersion model.

Fig. 3.1: Base Map of Ashram Chowk - CRRI Highway Corridor of NH- 2

3.1 Field Survey

Following field surveys/ parameters were required for the CALINE 4 model:

(i) Traffic Survey (hourly traffic volume, composition: 2W, Auto, Cars, LCV, HCV, Buses)

(ii) Fuel Station Survey: (Fuel used in vehicle & Age of vehicle)

(iii) Information for Road Geometry (road width, median width, length and orientation of the road)

(iv) Collection of Meteorological Data (wind speed, direction, stability class, ambient temperature and mixing height)

(v) Land Use Survey: (Surface roughness: Rural, Sub-Urban, Urban; distance of receptor from the intersection)

3.1.1 Traffic Survey

Traffic survey was carried out at New Friends Colony petrol pump (Secondary data from CRRI) for the estimation of weighted emission factor which is the input requirement of the CALINE 4 model. Traffic volume along Ashram Chowk – CRRI highway corridor of NH-2 is shown in **Table 3.1** and **Fig. 3.2, 3.3 & 3.4**. Further, the traffic survey has been done by manual counting of vehicles on the corridor and found out the number of different categories of vehicles (2W, 3W, Cars, LCV, HCV and Buses etc.) for 24 hour duration**.** Further, it was evident from **Table 3.1** that the major portion of total traffic is being contributed by cars (42%) and two wheelers (33%).

Table 3.1: Traffic Volume along Ashram Chowk - CRRI Highway Corridor of NH-2

Time (hrs.)	2W	Auto	Cars	LCV	HCV	Buses	Total
0—1	302	240	1029	314	666	31	2581
1—2	162	120	662	351	698	18	2011
2—3	45	86	373	164	1171	29	1866
3—4	49	93	411	117	1018	37	1725
4—5	86	183	498	140	911	114	1931
5—6	373	372	993	162	619	171	2689
6—7	849	452	1749	253	462	177	3941
7—8	1424	647	2076	307	652	255	5361
8—9	3168	1205	4320	197	69	215	9174
9—10	4003	1134	4788	177	70	233	10406
10—11	3630	1265	4162	162	65	244	9528
11—12	3650	1280	4269	301	111	225	9837
12—13	3373	1451	4205	309	189	224	9752
13—14	3073	1225	3643	228	186	183	8539
14—15	3122	1274	3573	345	198	233	8744
15—16	3155	1325	3756	475	229	280	9220
16—17	3323	1336	4028	592	206	329	9815
17—18	3551	1374	4387	450	156	368	10288
18—19	3938	1052	4531	301	68	354	10244
19—20	**3989**	**1154**	**4888**	**242**	**92**	**358**	**10724**
20—21	3334	932	3705	350	266	169	8755
21—22	2582	827	2931	460	557	142	7499
22—23	1298	605	2345	297	642	134	5321
23—24	723	450	1738	321	745	38	4016
Total	53202	20083	69061	7014	10046	4560	163967
Percentage	32.4%	12.2%	42.1%	4.3%	6.1%	2.8%	100.0%

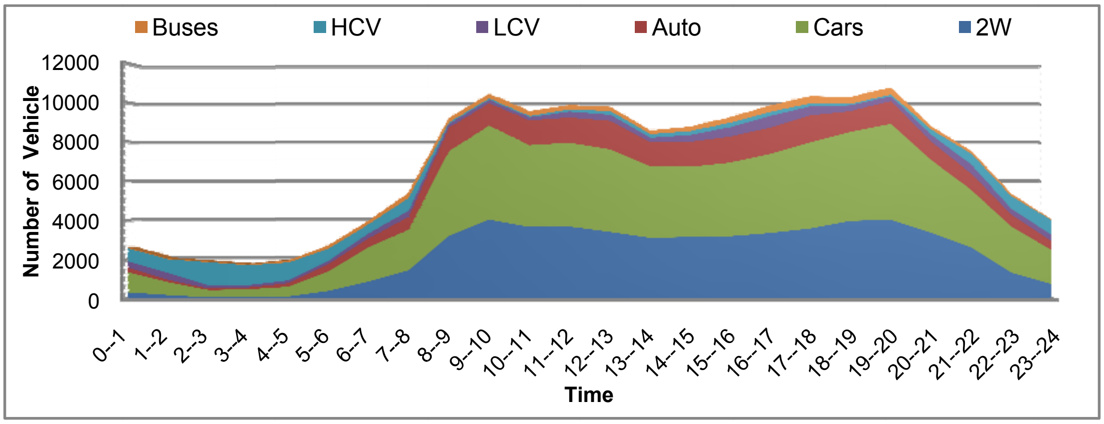


Fig. 3.2: Total Traffic Volumes along Ashram Chowk - CRRI Highway Corridor of NH-2

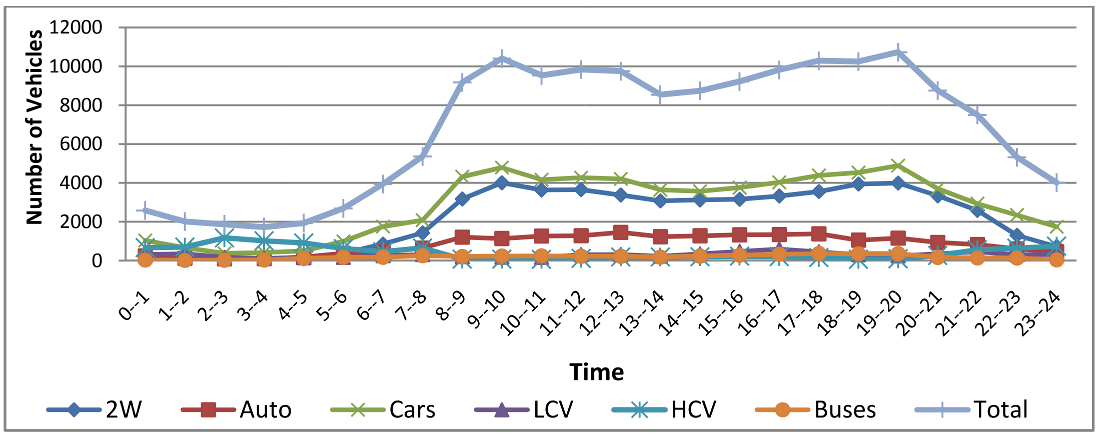


Fig. 3.3: Hourly Traffic Variations along Ashram Chowk - CRRI Highway Corridor of NH-2

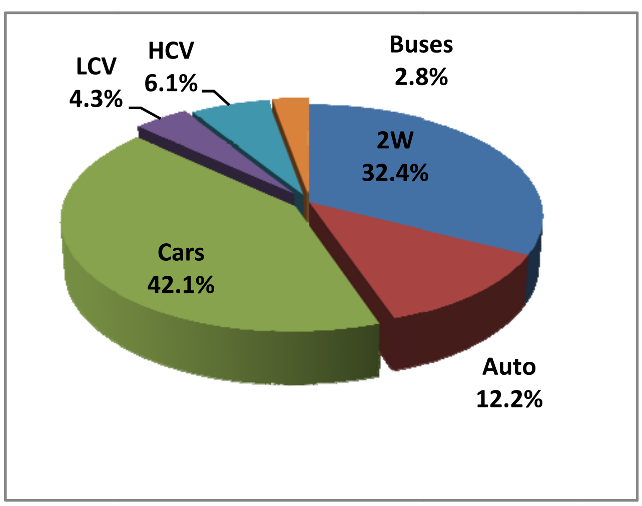


Fig. 3.4: Percentage Distributions of Vehicle Types along Ashram Chowk – CRRI of NH-2

The total number of passenger car unit (PCU) along Ashram Chowk – CRRI Highway Corridor is 164656 shown in **Table 3.2**. The PCU is estimated on the basis of **Table 3.1** and **Appendix II A & Appendix II B** as shown in **Figure 3.5 & 3.6.** Maximum average hourly traffic volume was found during 05:00-08:00 pm **(Table 3.2)**. Traffic survey was carried out with the help of trained enumerators and recorded in a prepared format. Proper checks and countercheck measures were taken to ensure the accuracy and authenticity of the traffic data.

Table 3.2: Total Numbers of Passenger Car Unit along Ashram Chowk - CRRI Highway Corridor of NH - 2

Time	PCU						
	2W	**Auto**	**Cars**	**LCV**	**HCV**	**Buses**	**Total**
0—1	121	120	1029	690	2329	93	4382
1—2	65	60	662	772	2442	53	4054
2—3	18	43	373	360	4097	87	4977
3—4	19	47	411	257	3565	112	4411
4—5	34	92	498	307	3188	342	4461
5—6	149	186	993	357	2166	512	4363
6—7	339	226	1749	556	1616	531	5017
7—8	570	323	2076	676	2282	764	6692
8—9	1267	602	4320	433	243	646	7511
9—10	1601	567	4788	389	246	699	8291
10—11	1452	632	4162	357	228	733	7565
11—12	1460	640	4269	663	388	674	8094
12—13	1349	726	4205	681	663	671	8294
13—14	1229	613	3643	501	652	550	7188
14—15	1249	637	3573	758	692	699	7607
15—16	1262	662	3756	1045	801	841	8367
16—17	1329	668	4028	1302	721	987	9036
17—18	**1420**	**687**	**4387**	**990**	**547**	**1105**	**9138**
18—19	1575	526	4531	663	239	1062	8596
19—20	1596	577	4888	533	322	1074	8990
20—21	1333	466	3705	770	931	506	7711
21—22	1033	413	2931	1011	1949	425	7763
22—23	519	303	2345	653	2246	401	6467
23—24	289	225	1738	706	2608	115	5681
Total	21281	10042	69061	15431	35160	13681	164656
Percentage	13%	6%	42%	9%	21%	8%	100%

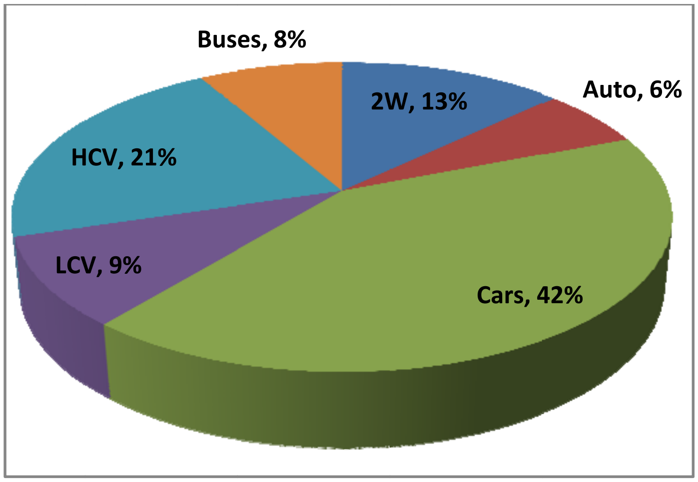


Fig. 3.5: Percentage of Passenger Car Unit along Ashram Chowk –CRRI of NH-2

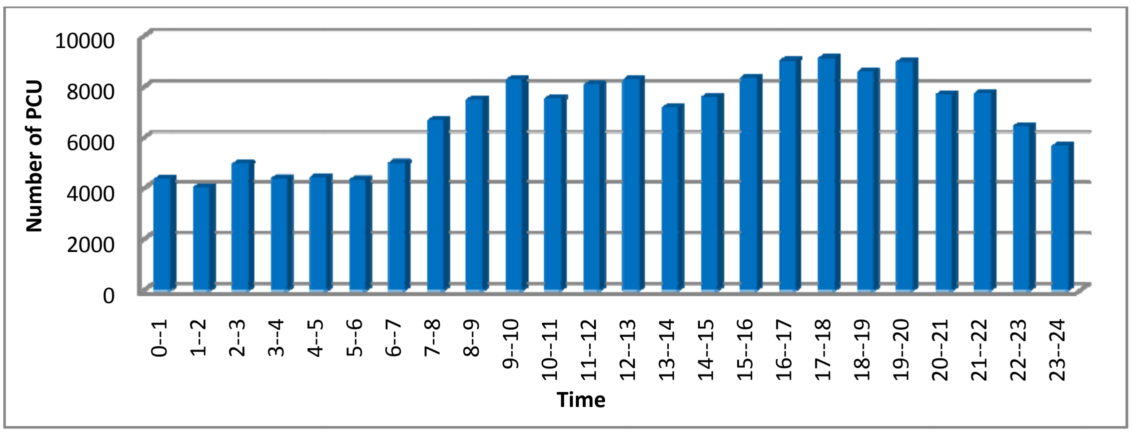


Fig. 3.6: Hourly Passenger Car Units along Ashram Chowk – CRRI Highway Corridor of NH – 2

3.1.2 Fuel Station Survey

It is not possible to ascertain the percentage of two and four stroke vehicles in two wheeler category and to know the type of the fuel used in the four wheelers during manual traffic count. Further, it is not possible to know the vintage (i.e., year of manufacture) of each vehicle counted in the traffic survey. To take care of all the above, a fuel station survey at different petrol pumps (2 in numbers) and gas filling stations (2 in numbers) along the corridors have been carried out. The results of the fuel station survey has been extended to the traffic survey, assuming that the vehicles plying on the road can be represented by vehicles coming to the fuel stations for filling up of the fuel. The fuel stations were carried out at different fuel stations to know the vintage of the vehicles plying on the road as well as the percentage of two stroke and four stroke vehicles in two wheeler category and also to know the percentage of petrol, diesel and CNG driven vehicles in four wheelers (i.e., passenger car) category. It was assumed that the vehicles coming to the fuel stations are truly reflective of the vehicles plying on the road. The summary of the fuel station survey along the Ashram Chowk - CRRI corridor at NH-2 is given in **Table3.3**. The observed distribution of two and four stroke vehicles (in two wheeler category) and petrol, diesel and CNG vehicles (in passenger car category) have been shown in **Fig. 3.7 (a) – (b)** and **Fig. 3.8.**

Table 3.3: Numbers of Vehicle According to Fuel Type along Ashram Chowk – CRRI Highway Corridor of NH - 2

Time	2W		Auto (CNG)	Cars			LCV		HCV		Buses (CNG)	Total
	2W-2S	2W-4S		Petrol	Diesel	CNG	Diesel	CNG	Diesel	CNG		
8—9	1267	1901	1205	2592	1642	86	10	187	3	66	215	9174
9—10	1601	2402	1134	2873	1819	96	9	168	4	67	233	10406
10—11	1452	2178	1265	2497	1581	83	17	154	3	62	244	9537
11—12	1460	2190	1280	2562	1622	85	15	286	6	105	225	9837
12—13	1349	2024	1451	2523	1598	84	15	294	9	180	224	9752
13—14	1229	1844	1225	2186	1384	73	11	216	9	177	183	8539
14—15	1249	1873	1274	2144	1358	71	17	327	10	188	233	8744
15—16	1262	1893	1325	2254	1427	75	24	451	11	217	280	9220
16—17	1329	1994	1336	2417	1531	81	30	562	10	196	329	9815
17—18	1420	2131	1374	2632	1667	88	23	428	8	148	368	10288
18—19	1575	2363	1052	2719	1722	91	15	286	3	65	354	10244
19—20	1596	2393	1154	2933	1858	98	12	230	5	88	358	10724
20—21	1333	2000	932	2223	1408	74	17	332	13	253	169	8755
21—22	1033	1549	827	1759	1114	59	23	437	28	529	142	7499
22—23	519	779	605	1407	891	47	282	15	610	32	134	5321
23—24	289	434	450	1043	660	35	305	16	708	37	38	4016
0—1	121	181	240	617	391	21	298	16	632	33	31	2581
1—2	65	97	120	397	252	13	333	18	663	35	18	2011
2—3	18	27	86	224	142	7	155	8	1112	59	29	1866
3—4	19	29	93	247	156	8	111	6	968	51	37	1725
4—5	34	52	183	299	189	10	133	7	865	46	114	1931
5—6	149	224	372	596	377	20	154	8	588	31	171	2689
6—7	339	509	452	1049	665	35	240	13	439	23	177	3941
7—8	570	854	647	1246	789	42	292	15	619	33	255	5361
Total	21281	31921	20083	41437	26243	1381	2542	4481	7326	2719	4560	16397 6
Percentage	**13.0%**	**19.5%**	**12.2%**	**25.3%**	**16.0%**	**0.8%**	**1.6%**	**2.7%**	**4.5%**	**1.7%**	**2.8%**	**100%**

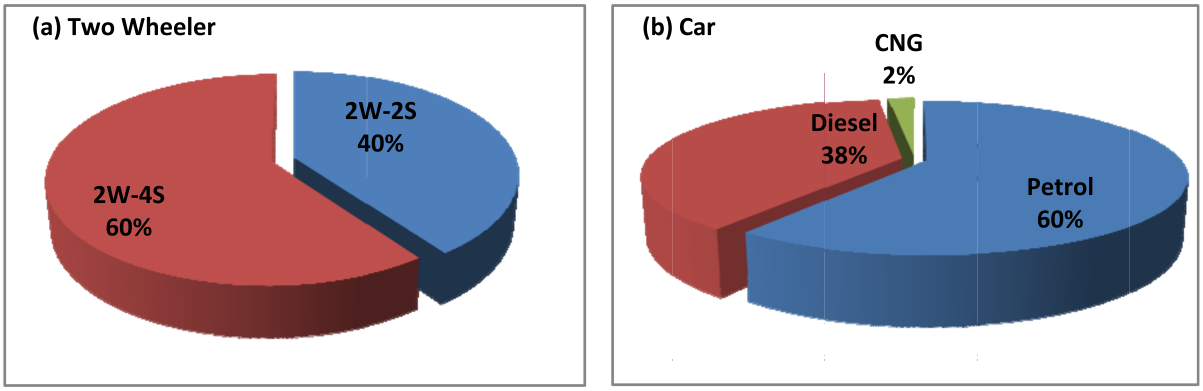


Fig. 3.7 (a) - (b): Summary of Fuel Station Survey along Ashram Chowk - CRRI Highway Corridor of NH-2

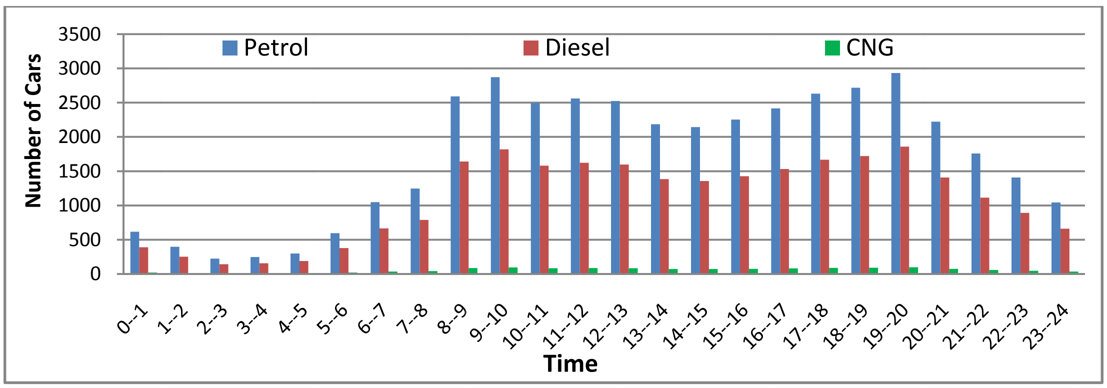
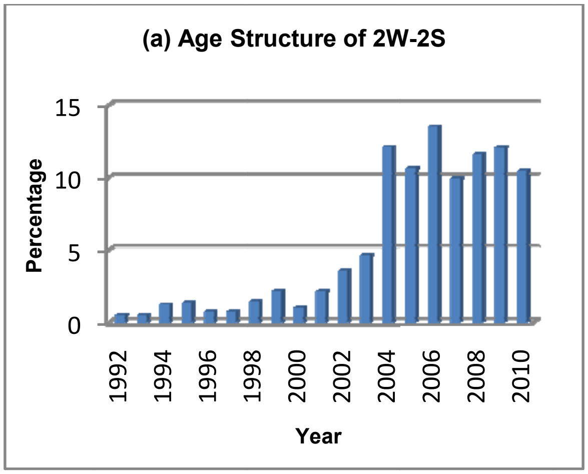
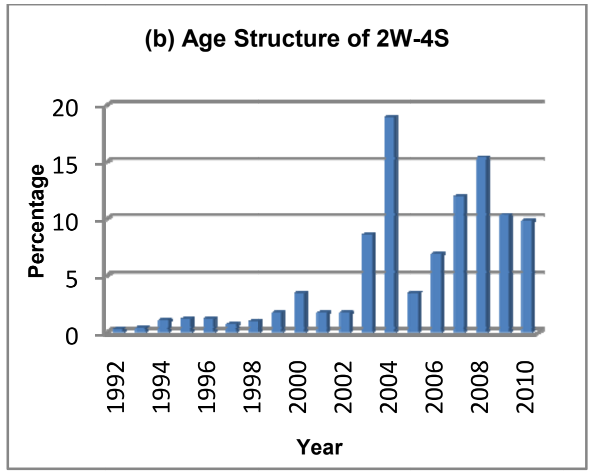
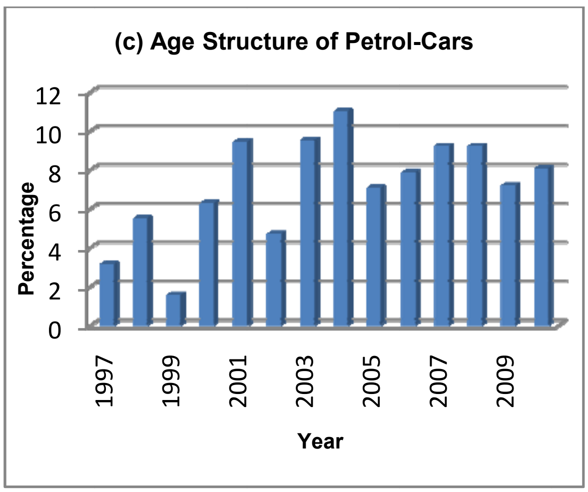


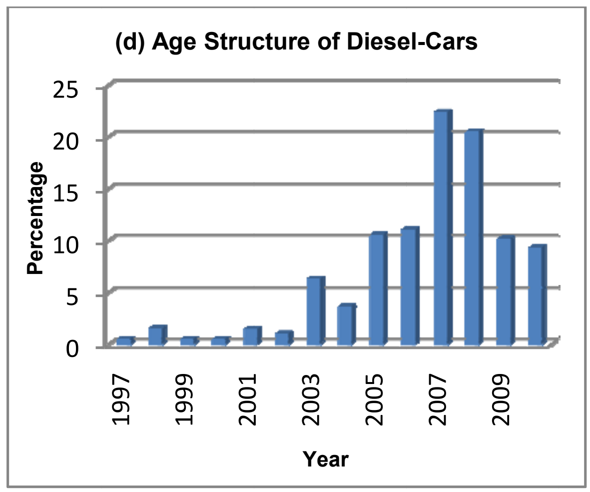
Fig. 3.8: Compositions of Cars According to Fuel Type along Ashram Chowk - CRRI Highway Corridor at NH-2

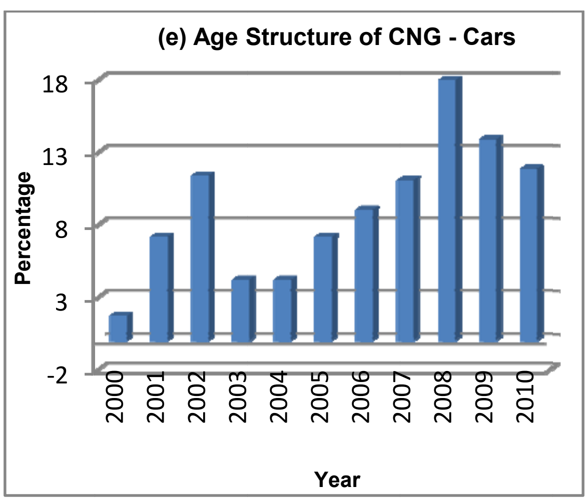
In Delhi, CNG driven LCVs and HCVs were introduced in 2009. Therefore, CNG driven LCVs and HCVs were assumed 95% of total LCVs and HCVs during day time (8:00 am – 10:00 pm) and 5% of total LCVs and HCVs during night time (10:00 pm – 8:00 am) because entry of outside Delhi registered commercial vehicles are allowed only in night time and their entry is restricted during day time (**Table 3.3**). Further, the Age - wise distribution of vehicles as obtained from fuel station survey has been given in **Appendix III**. Since CNG driven LCV and HCV were introduce in 2009 so, it was assumed that 50% of CNG driven LCV and HCV belong to year 2009 and 50 % to year 2010. From the distribution **Table 3.3** and **Fig. 3.9 (a) – (h)**, it was clear that the most of the vehicles belong to year 2004-2009 and were comparatively new, which was against the normal perception that the most of the vehicles plying on the Delhi and in neighbouring satellite belong to old model (i.e., vintage) vehicles.

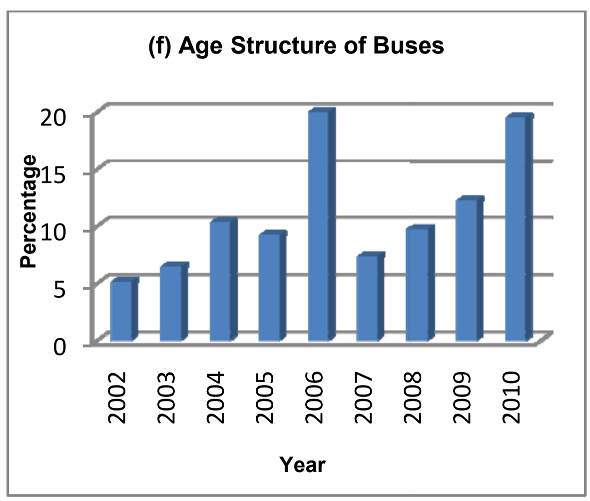

(a) Age Structure of 2W-2S
Percentage
15
10
5
0
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year


(b) Age Structure of 2W-4S
Percentage
20
15
10
5
0
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year


(c) Age Structure of Petrol-Cars
Percentage
12
10
8
6
4
2
0
1997
1999
2001
2003
2005
2007
2009
Year


(d) Age Structure of Diesel-Cars
Percentage
25
20
15
10
5
0
1997
1999
2001
2003
2005
2007
2009
Year


(e) Age Structure of CNG - Cars
Percentage
18
13
8
3
-2
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Year


(f) Age Structure of Buses
Percentage
20
15
10
5
0
2002
2003
2004
2005
2006
2007
2008
2009
2010
Year

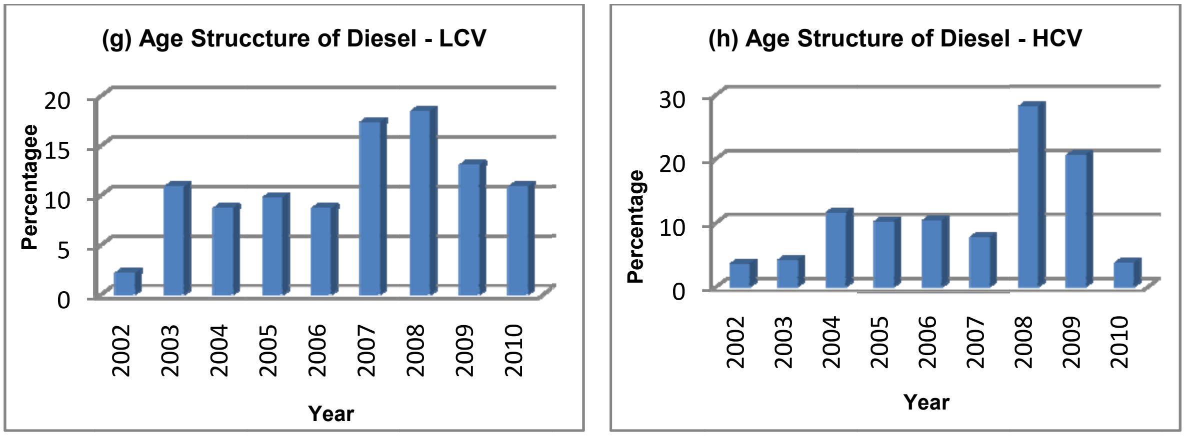


Fig. 3.9(a) - (h): Age –Wise Variations of Sampled Vehicular Volume along Ashram Chowk - CRRI Highway Corridor of NH-2

3.1.3 Information of Road Geometry

Ashram Chowk and CRRI are geographically located at 28°34’16”N, 77°15’37”E and 28°33’2”N, 77°16’30”E respectively at 216 meters above mean sea level (MSL). Ashram Chowk – CRRI, 2.7 km long highway corridor of NH-2 (**Fig. 3.1 & Appendix IV**) provided for both urban and regional traffic from/to Faridabad and beyond. Ashram Chowk – CRRI highway corridor cater heavy traffic throughout the day as it located at the junction of Ring Road and Mathura Road (**Fig. 3.10 & 3.11** respectively).

Fig. 3.10: Land Use and Traffic Scenario at Ashram Chowk

Fig. 3.11: Land Use and Traffic Scenario at CRRI

The average median width of the road is 3.03m and carrigeway width is 24.53m, so mixing zone width determined is 30.03m (Carrigeway + Median Width + 3m on either side i. e., 6m). Further, 18 receptor points (9 points on each side of the highway corridor) have been selected at pre-identified receptor locations with a specified distance (meter) from the edge of the mixing zone width i.e. -1.0m, -2m, -5m, -10m, -15m, -25m, -50m, -100m, -150m in South-West direction and 1.0m, 2m, 5m, 10m, 15m, 25m, 50m, 100m, 150m in North-East direction.

3.1.4 Meteorology

The meteorological parameters (at the sampling sites along the Ashram Chowk - CRRI corridors) viz., winds speed, wind direction, temperature; relative humidity and mixing height during the sampling duration (winter months, secondary data from CRRI) have been shown in **Table 3.4.** The wind speed and wind direction were monitored at the sampling site itself by using meteorological sensors fitted with Grimm dust monitors. The mixing height data (for winter month) averaged over ten years, were obtained from the Indian Meteorological Department (IMD) and were used in the present study.

Table 3.4: Summary of the On-Site Meteorological Parameters in the Vicinity of CRRI (March, 2010)

Time (hrs)	Temp.	Humidity	Wind Speed (m/s) (at 10m distance above GL)*	Wind Direction	Stability Class (P-G)	Mixing Height (m)	Ventilation Coefficient (m^2/s)
00-01	23.0 °C	73%	0.21	S	F	410	86.1
01-02	22.0 °C	83%	0.23	S	F	390	89.7
02-03	22.0 °C	78%	0.25	S	F	356	89.0
03-04	22.0 °C	73%	0.25	SSW	F	362	90.5
04-05	21.0 °C	78%	0.23	SSW	F	358	82.3
05-06	20.0 °C	83%	0.21	SSW	F	318	66.7
06-07	20.0 °C	83%	0.21	SSW	F	282	76.1
07-08	19.0 °C	88%	0.22	SSW	B	370	81.4
08-09	19.0 °C	88%	0.45	WSW	B	606	272.7
09-10	23.0 °C	65%	0.51	SW	B	1040	530.4
10-11	26.0 °C	51%	0.54	SW	B	1598	862.9
11-12	29.0 °C	40%	0.67	WSW	A	1908	1278.3
12-13	29.0 °C	29%	1.00	WSW	A	2144	2144.0
13-14	29.0 °C	29%	1.05	WSW	A	2356	2437.8
14-15	29.0 °C	35%	1.02	W	B	2460	2509.2
15-16	27.0 °C	45%	1.01	W	B	2324	2347.2
16-17	26.0 °C	51%	0.45	W	B	2060	927.0
17-18	22.0 °C	78%	0.11	S	B	1352	148.7
18-19	21.0 °C	83%	0.12	S	D	816	97.9
19-20	21.0 °C	83%	0.21	S	D	656	137.7
20-21	20.0 °C	88%	0.23	S	F	530	121.9
21-22	20.0 °C	88%	0.21	S	F	488	102.3
22-23	20.0 °C	88%	0.22	S	F	438	96.3
23-24	20.0 °C	88%	0.21	S	F	420	88.2

*The wind speed at 10m above GL has been found out by using velocity power law equation given below:

$$\frac{U_1}{U_2} = \left(\frac{Z_1}{Z_2} \right)^{0.33}$$

The value of corresponding to urban terrain conditions have been taken as 0.33 (Counihan, 1975)

Since, in any air basin, observed mixing heights do not change much during particular season/months. The wind data collected at approximately 3m above ground level (GL) was extrapolated to find the wind speed at 10m height above GL by using the velocity power law with the power law exponent ' α' =0.33, corresponding to the urban / semi urban area, corresponding to outskirt area of large cities(like Delhi) **(Table 3.5)** . The wind speed (at 10m) and mixing height were used to calculate the hourly ventilation coefficient (ventilation coefficient = mixing height x average wind speed).

Table 3.5: Values of 'α' and 'δ' for different Types of Terrain (Counihan, 1975)

Type of terrain	α	δ (m)
Rural terrain	0.143 – 0.167	
Suburban terrain	0.21 – 0.23	
Urban terrain	0.28	600
Grassland, Prairie, Desert	0.133	275
Farmland with scattered trees and buildings	0.154	305
Open fields with walls and hedges, scattered trees and buildings	0.1818	335
Scattered two- storey buildings, scattered wind brakes of trees	0.222	366
Forest, Scrubs, Parkland	0.266	412
Towns, Suburbs, Outskirts of large cites	0.333	457
Centre of large cities	0.40-0.66	550

The hourly stability classes viz., A–F (Pasquill and Gifford; P- G; **Table 3.6**) were obtained by the Turner Scheme (Turner, 1964) by using solar insolation and net radiation index (NR) data **(Table 3.7 & Table 3.8)**. Sun's altitude was calculated during daytime at hourly intervals after evaluating the local apparent time (L.A.T.). Insolation class numbers (IN) were obtained by using **Table 3.7**.

Table 3.6: Pasquill Stability Categories

Surface wind speed (m/s) (at 10m height)	Day – time insolation			Night- time conditions	
	Strong	Moderate	Slight	Thin overcast or≥ 4/8 cloudiness	≤ 3/8 cloudiness
< 2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
> 6	C	D	D	D	D

A – Extremely unstable; B-Moderately unstable; C-Slightly unstable; D-Neutral; E-Slightly stable; F-Moderately stable

Table 3.7: Insolation as a Function of Solar Altitude (Turner, 1964)

Solar altitude	Insolation	Insolation Class Number (IN)
$60^0 < \alpha$	Strong	4
$35^0 < \alpha < 60^0$	Moderate	3
$15^0 < \alpha < 35^0$	Slight	2
$\alpha < 60^0$	Weak	1

Table 3.8: Pasquill Stability Categories as a Function of Net Radiation Index (NR) and Wind Speed

Wind speed (knots)**	Net radiation Index (NR)*						
	4	3	2	1	0	-1	-2
0,1	1	1	2	3	4	6	7
2,3	1	2	2	3	4	6	7
4,5	1	2	3	4	4	5	6
6	2	2	3	4	4	5	6
7	2	2	3	4	4	4	5
8,9	2	3	3	4	4	4	5
10	3	3	4	4	4	4	5
11	3	3	4	4	4	4	4
>12	3	3	4	4	4	4	4

*The stability categories 1, 2…3. 6 corresponds to A, B…F, a seventh class - Extremely stable 'G' has also been added. ** 1 knot =0.515 m/s

Visual observations were made for the cloud cover during the study period and corrections were applied to IN based on the same data to obtain NRI **(Table 3.9)**. The hourly atmospheric stabilities (A-F) were derived from average wind speed and NR data for a particular hour using the relationship given in **Table 3.8**. The stability classes (P-G) along with the ventilation coefficient are the indicators of the atmospheric conditions. The stable atmospheric conditions (E and F) along with low ventilation coefficients are indicative of the atmospheric conditions where pollution dispersion is restrictive in nature, where as unstable atmospheric conditions (A-C) along with high ventilation coefficient facilitates the pollution dispersion in the atmosphere. In the present study, atmospheric conditions during the daytime (07:00 hrs to 18:00 hrs) were represented by unstable atmospheric conditions.

Table 3.9: Determining the Stability Conditions of the Atmosphere (Turner Scheme, 1964)

S. No.	Method of Calculating the Stability Conditions
1	**For day or night:** If total cloud cover (TC)=10/10 and ceiling <7000ft (2134m) NR=0 in **Table 3.7**
2	**For night time** (defined as period from one hour before sunset to one hour after sunrise): (a) If TC ≤ 4/10, use NR = -2 in **Table 3.7** (b) If TC > 4/10, use NR = -1 in **Table 3.7**
3	**For Daytime:** Determine Insolation Class Number (IN) from **Table 3.7.** (a) If TC≤ 5/10, use NR = IN in Table 3.7 (b) If TC > 5/10, modify IN by the sum of the following applicable number (i) If ceiling < 7000ft (2134m) modification = -2 (ii) If ceiling < 7000ft (2134m) but < 16000ft (4877m) modification = -1 (iii) If TC =10/10 and ceiling ≥ 7000ft, modification = -1 And let modified value of IN = NR in Table 3.7 except for day time NR cannot be <+1

Wind rose for Ashram Chowk – CRRI highway corridor of NH-2 is shown in **Fig. 3.12**. During this the ventilation coefficient facilitates the dispersion of pollutants (maximum being in the afternoon) **(Fig. 3.13 to Fig. 3.14**), whereas during the night times (1800 - 0700hrs), the conditions are not conducive for efficient pollution dispersion, as indicated by stable atmospheric conditions and lower ventilation coefficient values during these hours.

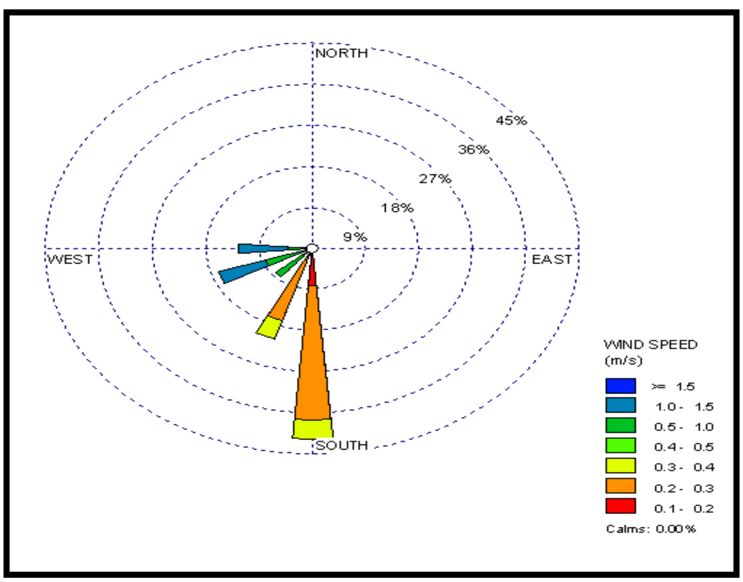


Fig. 3.12: Wind Rose for Ashram Chowk – CRRI Highway Corridor of NH-2

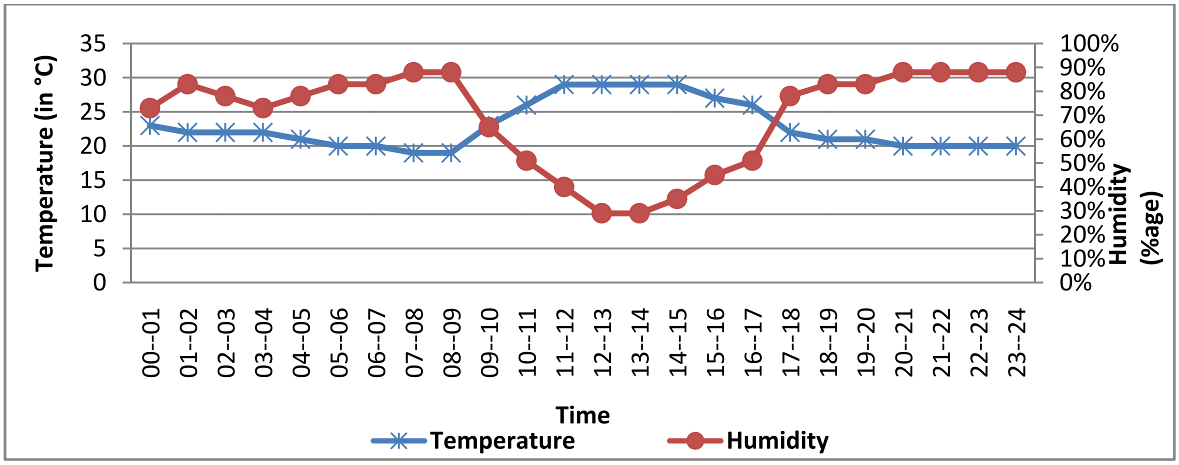


Fig. 3.13: Hourly Distributions of Temperature and Humidity

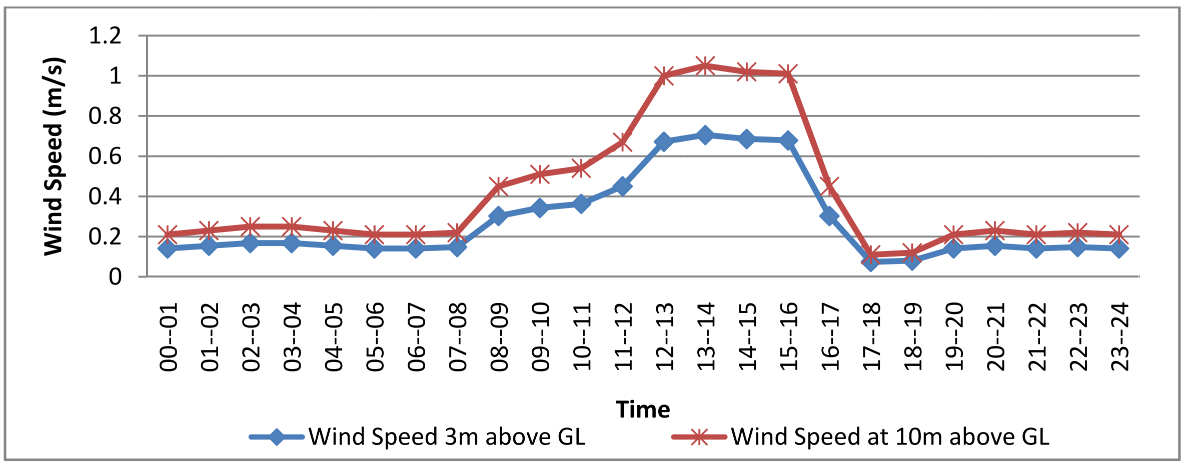


Fig. 3.14: Hourly Distribution Patterns of Wind Speed (m/s) at 3m and 10m above Ground Level (GL)

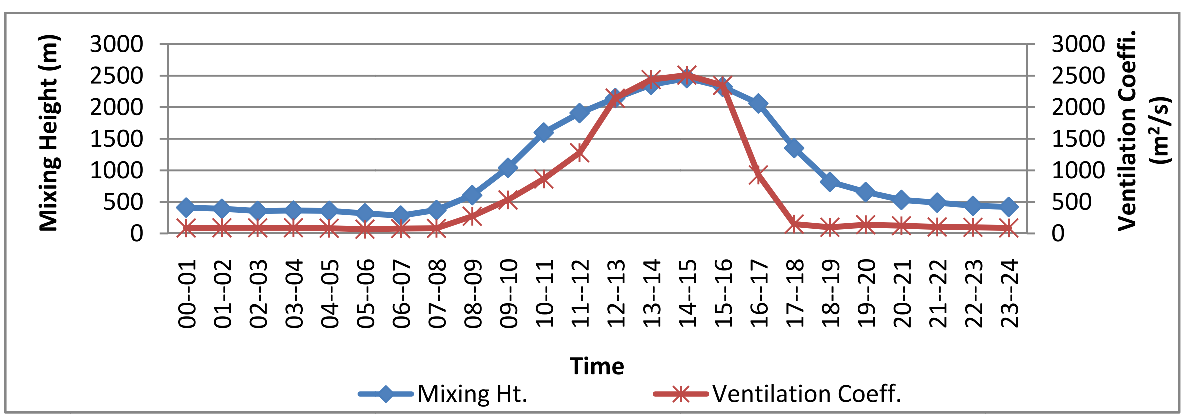


Fig. 3.15: Hourly Distribution of Mixing Height and Ventilation Coefficient

3.2 Methodology for Weighted Emission Factor (WEF)

One of the important requirements for Caline-4 modelling is the input for emission factor for vehicles. In the present study, the emission factors specified by the Automotives Research Association of India (ARAI) and Central Pollution Control Board (CPCB) have been used for calculation of weighted emission factors (ARAI, 2007 **Appendix V A** and CPCB, 2000 **Appendix V B** respectively). These emission factors have been expressed for various pollutants in terms vintage of the year (i.e., year of manufacture), type of fuel used (for petrol and diesel driven passenger cars) and type of engine (two stroke or four stroke in the case of two wheelers). The improvement in engine technology, resulting in reduced emission factors are reflected in these emission factors specified by CPCB. Since, there is only one input requirement for total no. of vehicles in the CALINE 4 model, whereas, there are different categories of vehicles (viz., 2W, 3W, Cars, Bus and trucks) with different year of manufacture and fuel used, it is essential that a single value representing the equivalent or weighted emission factors for all the vehicles is input into the model. Thus, WEF expressed in g/mile (converted from gm/km) has been used in the present modelling exercise.

(i) Collection of data on number and type of vehicles plying on that particular road/highway corridor through field (i.e. traffic) studies (vehicle count/classification data from field survey (Primary data) which includes carrying out traffic survey (24 hour) at selected location(s) to know the hourly traffic (i.e., total no. of vehicles/ hour) and its composition (% of 2W, Auto, Cars, LCV, HCV, Buses etc.).

(ii) Both the opposite direction traffic were summed up to find out the total vehicular traffic corresponding to different category of vehicles for calculating WEF.

(iii) Age structure (i.e. model year) was determined for the different categories of vehicles plying on that highway corridor through fuel station survey.

(iv) Percentage of 2 stroke (2S) and 4 stroke(4S) vehicles (in two wheeler category) and petrol(P), diesel(D) and CNG vehicles (in four wheeler category) through the fuel station survey (step (iii)) was determined. The age structure and distribution of 2S and 4S; petrol, diesel and CNG driven cars; diesel and CNG driven LCV and HCV are determined assuming that the vehicles at the fuel station(s) along the highway/road corridor have the similar age structure and distribution of vehicles as that of vehicle fleet plying on the highway corridor. Further, step (iii) and (iv) are required to make the traffic (vehicle count) data compatible with emission factor data for different category of vehicles provided by the Central Pollution Control Board (CPCB, 2000) and Automotives Research Association of India (ARAI, 2007).

(v) The total no. of vehicles (particular category i.e., 2W, Auto etc.) for that hour is distributed according to the percentage found in fuel station survey.

(vi) The vehicles are grouped in different age groups (i.e. 1992-95, 1996-2005 and 2006-2010) to make them compatible with CPCB emission factors. The emission factors are given for Carbon Monoxide for different categories of vehicles (i.e., 2W-2S, 2W-4S, Auto, Petrol, Diesel and CNG cars, Diesel and CNG LCV, Diesel and CNG HCV, Buses) for different age groups as mentioned above. Further, they are combined/grouped according to their Deterioration Factors (DF) given by CPCB for various categories of - petrol and diesel vehicles (CPCB, 2000) as per their vehicle-age profiling (**Appendix VI A & VI B**).

(vii) All the WEFs corresponding to different categories of vehicle were then summed up to find out WEF expressed in g/mile to conform to Caline-4 requirements. Weighted Emission Factor is estimated by:

$$\textbf{WEF} = [\sum(j)\ \sum(ky)\ N(j, ky) \cdot EF(i, j, ky)] / \text{Total No. Vehicles}$$

Where,

WEF	=	Weighted emission factor(g/km)
N (j, ky)	=	Number of vehicles of a particular type j and age ky in year y (average daily traffic)
EF(i,j, Ky)	=	"Emission Factor" for Component i in the vehicle type j and age ky in Year y (g/km)
I	=	Pollutant component (viz., CO)
J	=	Type of vehicle (i.e. 2W, 3W, Cars, Bus, Truck etc.)
Ky	=	Age of vehicle in year y

3.2.1 Estimation of Weighted Emission Factor

As discussed above, weighted emission factor estimation has been carried using traffic survey data collected at New Friends Colony Petrol Pump along the Ashram Chowk - CRRI highway corridor of NH-2. The WEF have been estimated for both emission factor specified by the Central Pollution Control Board (CPCB, 2000) and Automotives Research Association of India (ARAI, 2007). The estimation of weighted emission factor has been done by developing spreadsheets **(Appendix VII).**

The weighted emission factor for CO using ARAI's and CPCB's emission factor along Ashram Chowk – CRRI highway corridor of NH-2 is shown in **Table 3.10** and **Table 3.11** respectively. For demonstration purposes the methods of calculation of CO Weighted Emission Factor (gm/km) for all traffic volume has been shown using ARAI's emission factor in **Appendix VIII**. The WEF along the Ashram chowk- CRRI highway Corridor of NH-2 using ARAI's emission factor is 2.96 gm/km per vehicle and using CPCB's emission factor is 2.67 gm/km per vehicle.

Table 3.10 Weighted Emission Factor for CO using ARAI Emission Factors along Ashram Chowk – CRRI Highway Corridor of NH-2

Type of Vehicle	No. of Vehicle	CO concentration (gm/km)	Weighted Emission Factor for CO (gm/km)/ vehicle
2W-2S	21281	49587.3	2.33
2W-4S	31921	46348.9	1.45
Auto (CNG)	20083	20425.4	1.02
Car-Petrol	41437	162423.8	3.92
Car-Diesel	26243	7000.0	0.27
Car-CNG	1381	64.6	0.65
LCV-Diesel	2542	29606.6	4.04
LCV-CNG	4481	14339.1	3.20
HCV-Diesel	7326	58682.3	8.01
HCV-CNG	2719	10115.6	3.72
Buses	4560	18089.2	3.97
Average			**2.96**

Table 3.11 Weighted Emission Factor for CO using CPCB Emission Factors along Ashram Chowk – CRRI highway corridor of NH-2

Type of Vehicle	No. of Vehicle	CO Concentration (gm/km)	Weighted Emission Factor for CO (gm/km) (gm/km)/ vehicle
2W-2S	21281	55105.8	2.59
2W-4S	31921	73991.5	2.32
Auto (CNG)	20083	75126.9	3.74
Car-Petrol	41437	101492.2	2.45
Car-Diesel	26243	19097.8	0.73
Car-CNG	1381	64.6	0.65
LCV-Diesel	2542	16512.0	2.35
LCV-CNG	4481	14339.1	3.20
HCV-Diesel	7326	29700.5	4.05
HCV-CNG	2719	10115.6	3.72
Buses	4560	16230.9	3.56
Average			**2.67**

3.3 Air Quality Predictions Using CALINE 4 Model

In the present study, CALINE-4 model has been used to predict the CO concentration along Ashram Chowk - CRRI highway corridor of NH-2 **Fig. 3.1**. A brief introduction of CALINE 4 model has been given in Review of Literature.

3.3.1 Data Entry Screens

CL4 contains five data entry screen, listed below, and must be complete in order to run CALINE4:

I. Job Parameters
II. Link Geometry
III. Link Activity
IV. Run Conditions
V. Receptor Conditions

I. Job Parameters Screen

The Job Parameters Screen **(Fig. 3.16)** contains general information that identifies the job, defines general modelling parameters, and sets the units (feet or meters) that will be used to input data on the Link Geometry and Receptor Positions Screens.

File Name: Display only, not editable. Displays the name of the file where the current job is stored.

Job Title: Optional, Provides a space for the user to enter a brief job description, up to 40 characters in length.

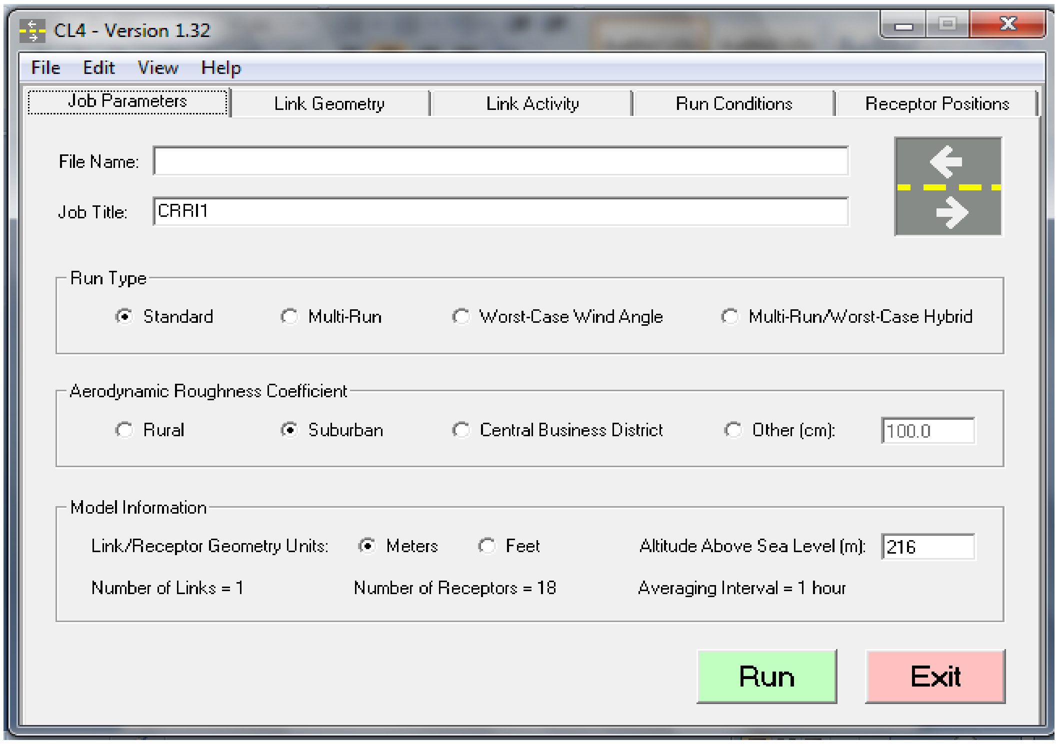


Fig. 3.16: Job Parameters Input Screen

Run Type: Different choices determine averaging times (for CO concentrations) and how the hourly average wind angle(s) will be determined. (Wind angle is the angle between the roadway link and the wind direction. CALINE4 calculates the angles based on data in the Link Geometry and Run Conditions Screens). Most users should invoke the "worst-case wind angle" run type and apply a persistence factor of 0.6 to 0.7 in order to estimate an 8-hours average CO concentration.

i. **Standard** – Calculates 1-hour average CO concentrations at the receptors. The user must input a wind direction on the Run Conditions Screen.
ii. **Multi-Run** – Calculates 8-hours average CO concentrations at the receptors. The user must input wind angles for each hour.
iii. **Worst-case wind angle** – Calculates 1-hour average CO concentrations at the receptors. The model selects the wind angles that produce the highest CO concentrations at each of the receptors. This is the most appropriate choice for most users.

iv. **Multi-Run/Worst-Case hybrid** – Calculates 8-hours average CO concentrations at the receptors. The model selects the wind angles that produce the highest CO concentrations at each of the receptors.

Aerodynamic Roughness Coefficient: Also known as the Davenport - Wieringa roughness- length. These choices determine the amount of local air turbulence that affects plume spreading. This subject is usually discussed in elementary meteorology books. CL4 offers the following 4 choices for aerodynamic roughness coefficient: ·

Rural: Roughness Coefficient = 10 cm

Suburban: Roughness Coefficient = 100 cm

Central Business District: Roughness Coefficient = 400 cm

Other: Use **Table 3.12** as guidance to select an appropriate value.

Model Information: Provides summary information for convenience and quality assurance.

Link/Receptor Geometry Units: Select whether meters or feet will be used to define the geometry of the roadway links and receptor positions. This choice only affects the Altitude input choice, and the data shown on the Link Geometry and Receptor Positions pages. Meteorological inputs always require inputs with metric units. Emission factors are always defined in terms of grams per mile. (Note that CALINE4 reports data in metric units, with the exception of the Altitude.)

Table 3.12: Aerodynamic Roughness Coefficient Defined for Various Types of Landscapes (Source: User's guide for CL4, Coe et al., 1998)

Roughness Coefficient (cm)	Landscape Type
0.002	Sea, paved areas, snow-covered flat plain, tide flat, smooth desert
0.5	Beaches, pack ice, morass, snow-covered fields
3	Grass prairie or farm fields, tundra, airports, heather
10	Cultivated areas with low crops and occasional obstacles (such as bushes)
25	High crops, crops with varied height, scattered obstacles (such as trees or hedgerows), vineyards
50	Mixed far fields and forest clumps, orchards, scattered buildings
100	Regular coverage with large obstacles, open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests
≥ 200	Centers of large towns or cities, irregular forests with scattered clearings

Altitude above Sea Level: Define the altitude above mean sea level. This input is used to determine the rate of plume spreading. It does not affect the Link Geometry or Receptor Positions.

Number of Links: The sum total number of links that the user has defined on the Link Geometry Page.

Number of Receptors: The sum total number of receptors that the user has defined on the Receptor Positions page. Averaging Interval: Indicates whether the user has opted to calculate 1-hour or 8-hour average CO concentrations at the receptors.

"Run" – Click this button to run the job as specified. First, be sure that the information on all five pages of CL4 is complete: Job Parameters, Link Geometry, Link Activity, Run Conditions, and Receptor Conditions.

"Exit" – Click this button to exit the CL4 program. CL4 issues a warning if changes or new user inputs might be lost.

II. Link Geometry Screen

Fill in the matrix to define the roadway network to be modelled **(See Figure 3.17)**.

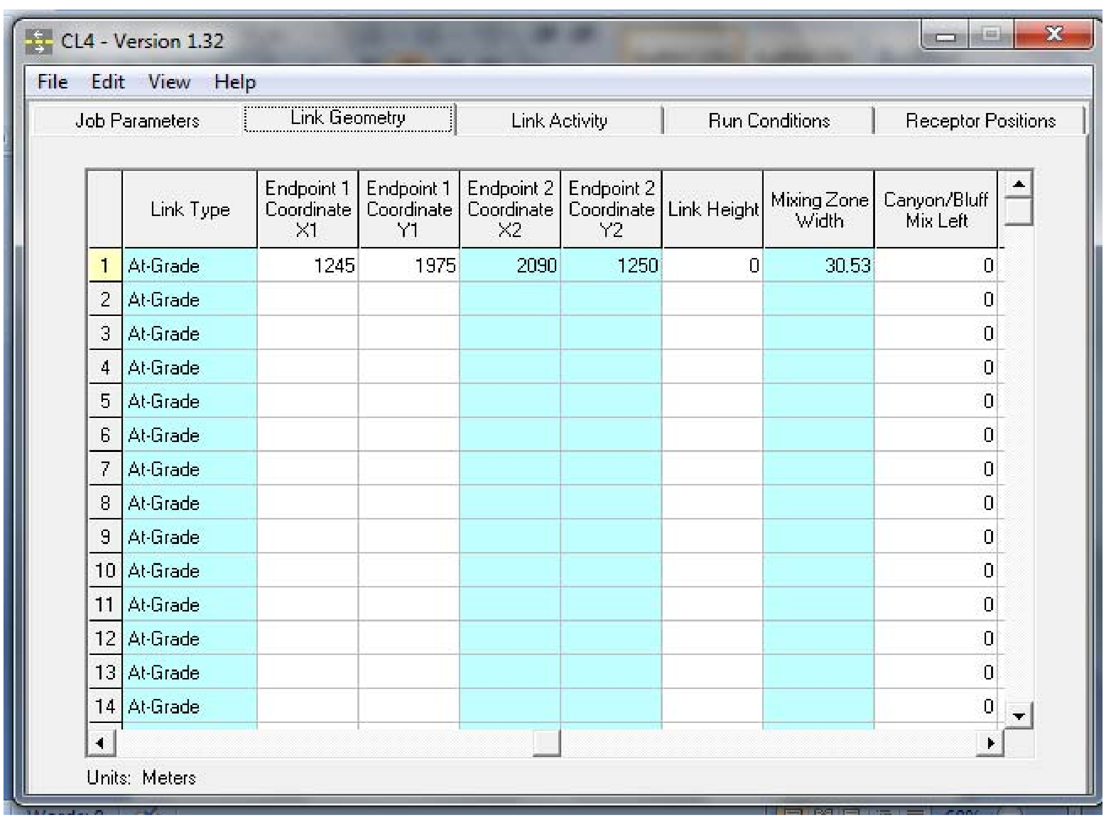


Fig. 3.17: Link Geometry Data Entry Screen

Each row in the matrix defines a single link. Up to 20 links may be entered. Links are defined as straight-line segments. The distance between the centreline of the curved roadway, and the straight-line link should be no greater than 3 meters.

Link Type: The user must select one of the following 5 choices to define the type of roadway that each link represents. (Click a cell in this column to view a drop list and select from the following 5 options.)

- **At-Grade** – For at-grade sections, CALINE does not permit the plume to mix below ground level, which is assumed to be at a height of zero. The height of the link above the ground is defined in the Link Height cell.
- **Fill** – For fill sections, CALINE4 automatically resets the link height to zero, and assumes that air flow follows the surface terrain, undisturbed. This choice is functionally no different than the At-Grade choice with a link height defined as zero. If you wish to model a link that is slightly elevated above ground, the At-Grade choice is more appropriate.
- **Depressed** – For depressed sections, CALINE4 increases the residence time of an air parcel in the mixing zone. The residence time increases in relation to the depth of the roadway depression. (Mixing zone = width of traffic lane(s) plus 3 meters on each side.) In such a case, CO concentrations adjacent to the mixing zone are higher than those for an equivalent at-grade or fill section. CO concentration drops more rapidly downwind of a depressed link because vertical mixing increases with residence time.
- **Bridge** – For bridge sections, CALINE4 allows air to flow above and below the link. The plume is permitted to mix downward from the link, until it reaches the distance defined in the Link Height cell.
- **Parking Lot** – Parking lot links should be defined to be coincident with the parking lot access ways. The CALINE4 algorithms adjust to account for the reduced mechanical and thermal turbulence anticipated from slow-moving, cold-start vehicles.

Endpoint Coordinates: Links are defined as straight-line segments. The entire length of each link should deviate no further than 3 meters from the centreline of the actual roadway. The endpoint coordinates, (x1, y1) and (x2, y2), define the positions of link endpoints.

- The units of measure (feet or meters) are user-specified on the Job Parameters Page.
- The user must define the link geometry and receptor positions with a consistent Cartesian coordinate system. The position of the coordinate system origin is arbitrary and at the user's discretion. The y-axis should be oriented north-south, with values increasing in the northward direction. The x-axis should be oriented east-west, with values increasing in the eastward direction. The choice of magnetic north, true north, or some other approximation is at the user's discretion. However, the wind direction must be defined on the Run Conditions page according to the same definition of north.
- A map of the link geometry is shown on the Receptor Positions Page.

Link Height: For all link types except bridges, Link Height represents the height of the link above the surrounding terrain. Ground level is defined at 0 meters or feet (z=0). The units of measure (feet or meters) are user-specified on the Job Parameters Page. For at-grade links, the link height may be defined as 0 or a positive value. For fill links, CALINE4 always treats the link as though its height was zero. For depressed links, the depth of the depression should be indicated as a negative value. For parking lots, the link height should be defined as zero. For bridges, Link Height defines the height of the bridge above the surface beneath it (a positive value), while the link itself is considered to be at z=0 (**Fig. 3.18**).

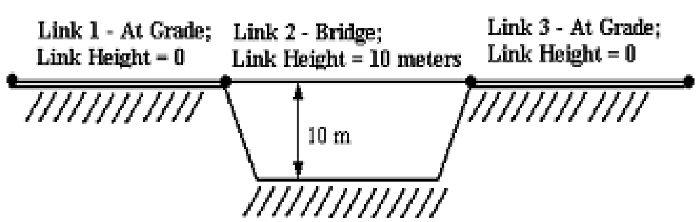


Fig. 3.18: Illustrations of Link Heights

Mixing Zone Width: Mixing zone is defined as the width of the roadway, plus 3 meters on either side. The minimum allowable value is 10 meters, or 32.81 feet.

Canyon/Bluff Mix: CALINE4 is based on two somewhat restrictive assumptions:

1) Horizontally homogeneous wind flow, and
2) Steady-state meteorological conditions.

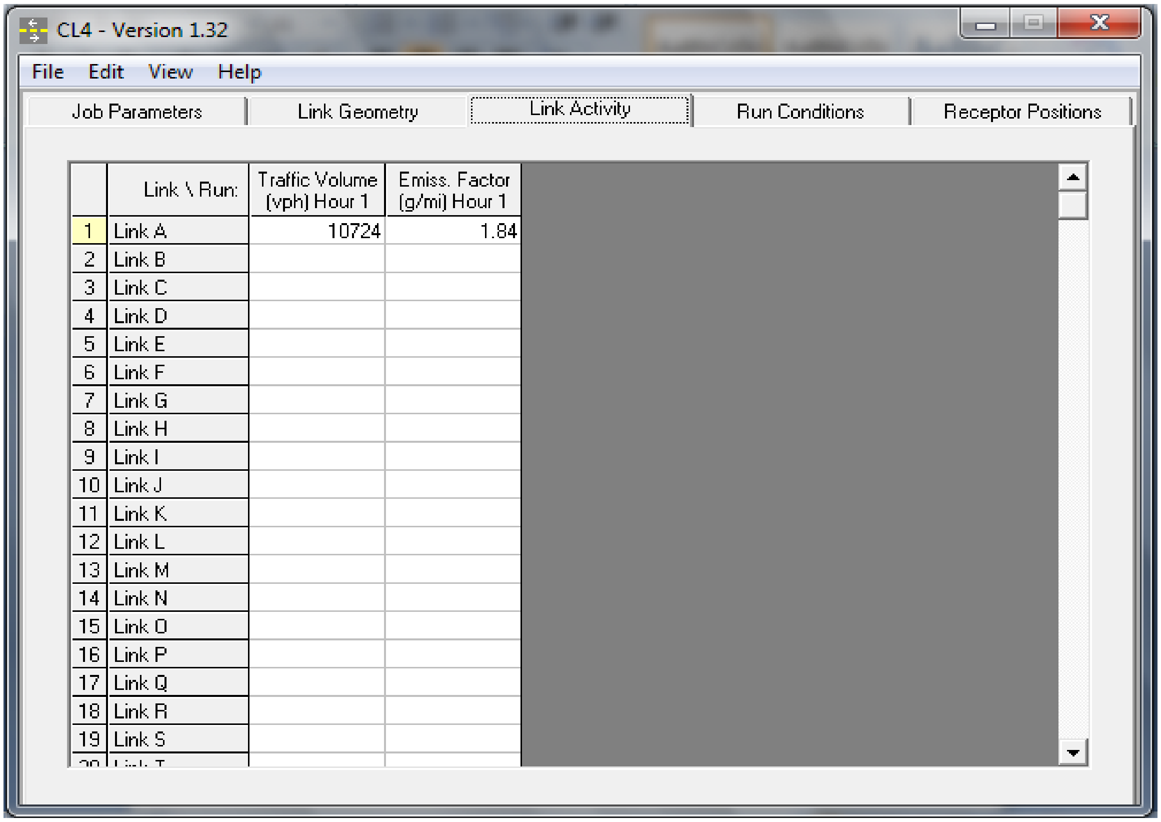
Complex topography can invalidate each of these assumptions. Land features such as canyons can channel winds. Hills and valleys are likely to cause frequent shifts in wind direction. For these reasons, use of CALINE4 in complex terrain should be approached with care. CALINE4 handles certain bluff and canyon situations by reflecting the plume at the distances specified on one or both sides of the mixing zone (Turner, 1970). CALINE4 assumes that the topographic barrier and wind direction are parallel to the roadway. CALINE4 also alters the vertical dispersion curve to account for vehicle-related heat flux distributed over the width of the canyon. This is especially important in the case of a narrow urban street canyon. The Canyon/Bluff Mix feature has not been validated with field measurements. Only very rare circumstances warrant its use. Use extreme caution with this feature. Users of the Canyon Bluff Mix feature should be thoroughly familiar with dispersion modelling, with the key reference (Turner, 1970), and with the CALINE4 source code. All other users should leave the Canyon/Bluff input values set to zero, which disables the feature.

III. **Link Activity Screen**

The Link Activity screen **(Fig. 3.19)** defines the level of traffic and auto emission rate observed at each link.

Traffic Volume: The hourly traffic volume anticipated to travel on each link, in units of vehicles per hour. If a multi-run scenario is selected, traffic volume must be defined for 8 hours.

Emission Factor: The weighted average emission rate of the local vehicle fleet, expressed in terms of grams per mile per vehicle. Emission factors should be modelled using the CT-EMFAC computer model 3. Emission rates vary by time of day. Therefore, if a multi-run scenario is selected, emission factors must be defined for 8 hours.



(Note: If a multi-run scenario is selected on the Job Parameters page, additional data columns appear to contain data for 8 hours)

Fig. 3.19: Link Activity Data Entry Screen

IV. Run Conditions Screen

The Run Conditions screen **(Fig. 3.20)** contains the meteorological parameters needed to run CALINE4. Users should employ the worst-case meteorological conditions that can be anticipated at the project location. The selection of worst-case conditions should be made in consultation with the local air district.

Wind Speed – Expressed in meters per second. The minimum choice of wind speed available for CALINE4 is 0.5 m/s. Alternatively, EPA (1992) recommends a value of 1 m/s as the worst-case wind speed. The local air district should be consulted to make a decision that is appropriate for the project location.

Wind Direction – The direction the wind is blowing from, measured clockwise in degrees from the north (0 = north, 90 = east, 180 = south, 270 = west). Most users should opt for the “Worst-Case Wind Angle” choice on the Job Parameters screen. If “Worst-Case” is selected, CALINE4 does not use this input.

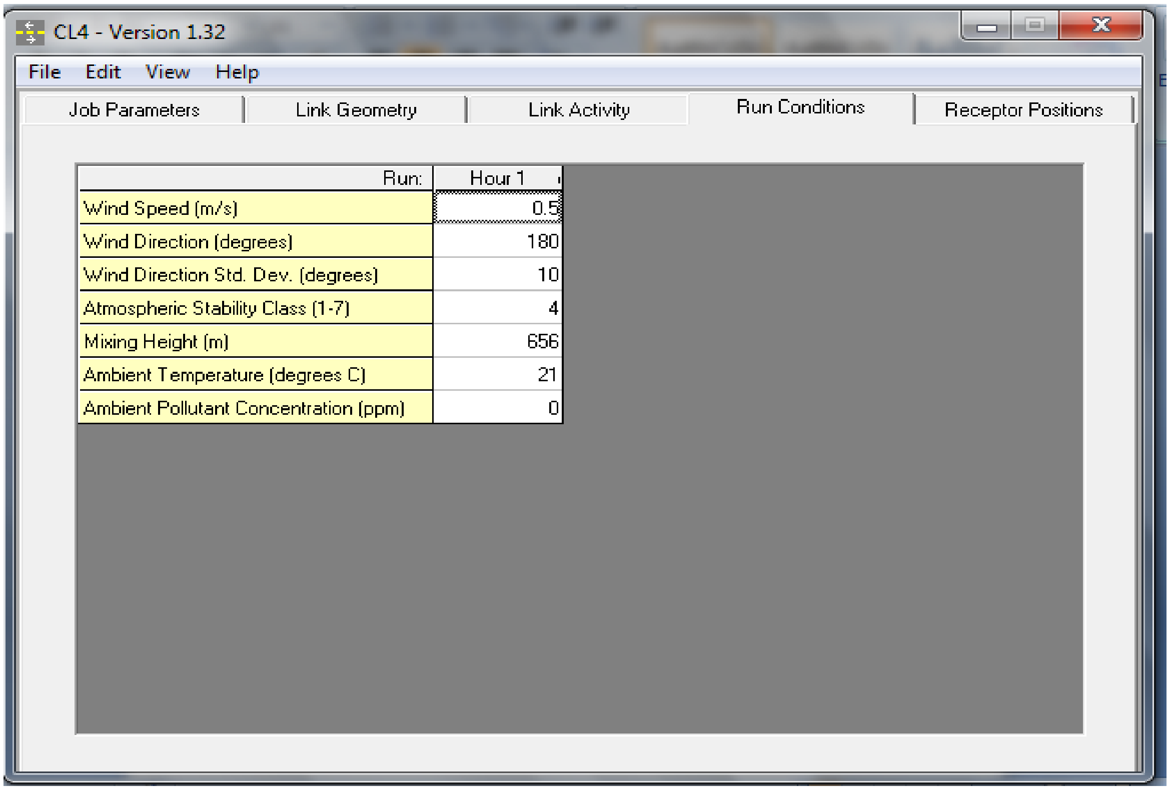


Fig. 3.20: Run Conditions Data Entry Screen

Wind Direction Standard Deviation – The statistical standard deviation of the Wind Direction, sometimes termed "sigma theta". **Table 3.13** provides guidance for this choice.

Atmospheric Stability Class – It is a measure of the turbulence of the atmosphere. This concept is discussed further in elementary meteorological textbooks. Values 1 through 7 correspond to the standard definitions for stability class A through E. **Table 3.6** provides guidance for this choice. Stability class E (or 7) represents the most stable conditions.

Table 3.13: Lateral Turbulence Criteria for Initial Estimate of Standard Deviation of Wind Angle

Initial estimate of P-G stability category	Standard deviation of wind azimuth angle σ_{θ} (degrees)
A	$22.5 \leq \sigma_{\theta}$
B	$17.5 \leq \sigma_{\theta} < 22.5$
C	$12.5 \leq \sigma_{\theta}$ 17.5
D	$7.5 \leq \sigma_{\theta} < 12.5$
E	$3.8 \leq \sigma_{\theta} < 7.5$
F	$\sigma_{\theta} < 3.5$

Mixing Height – The altitude to which thermal turbulence occurs due to solar heating of the ground. This concept is discussed further in elementary meteorological textbooks. Reasonable values for the worst-case mixing height rarely have a significant impact on CALINE4 model results. If an extreme condition could be anticipated at the project location (mixing height £ 10 meters), the local air district should be consulted for guidance.

Ambient Temperature – The ambient air temperature significantly affects vehicle CO emissions. A temperature that reflects wintertime conditions should be selected, expressed in degrees Celsius.

Ambient Pollutant Concentration – This measure reflects the pre-existing background level of carbon monoxide, expressed in parts per million. CALINE4 adds the pre-existing and modelled CO concentrations together to determine the total impact at each receptor. Consult the CO Protocol and the local Air District for guidance.

V. **Receptor Positions Screen**

The Receptor Positions Screen **(Fig. 3.21)** contains the data inputs for all receptor positions, and also displays a diagram of the link geometry and receptor positions.

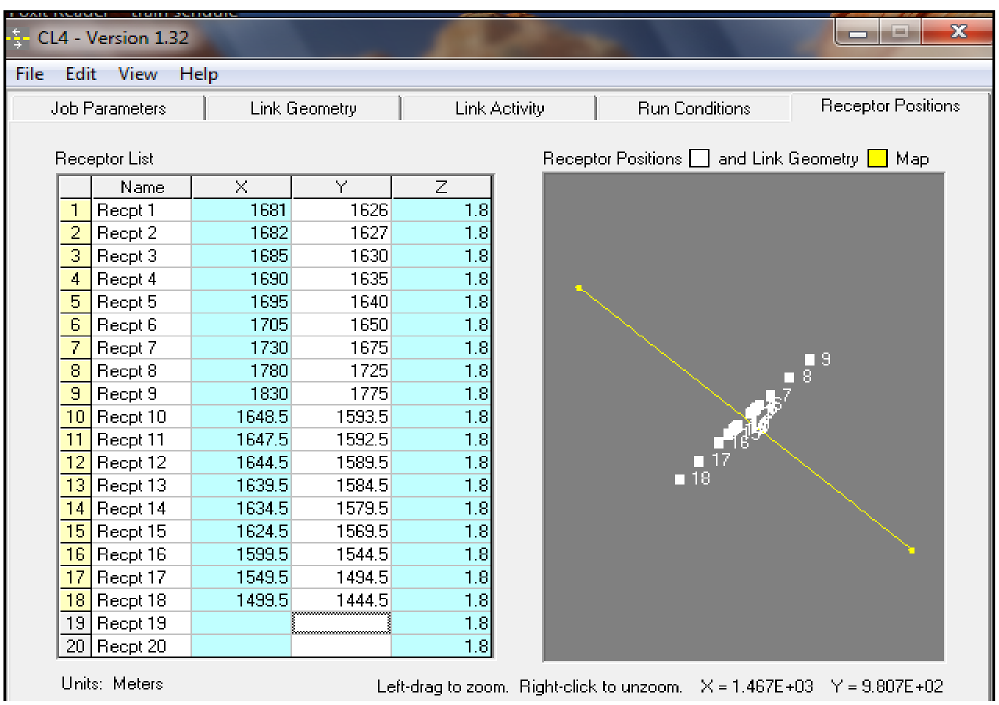


Fig. 3.21: Receptor Positions Data Entry Screen

Receptors should be defined with the same Cartesian coordinate system and units of measure as the link geometry. For each receptor (maximum no. of receptors = 20), space is provided for an 8-character description, the X-coordinate, the Y-coordinate, and the height (Z).

3.3.2 CALINE 4 Output File

The CALINE 4 output file is divided into four sections, Header, (I) Site Variables, (II) Link Variables, and (III) Receptor Locations and Model Results. **Appendix IXA** and **Appendix IXB** are examples of output file. The variables named in CALINE4 output files are defined below:

U = wind speed

Z0 = aerodynamic roughness coefficient

ALT = altitude above sea level

BRG = wind angle

VD = deposition velocity

CLAS = atmospheric stability class

VS = settling velocity

MIXH = atmospheric mixing height

AMB = ambient CO concentration

SIGTH= standard deviation of wind direction

TEMP= ambient temperature

Type = Link type (AG = at-grade, etc., DP = depressed, FL = fill, PK = parking lot)

VPH = Vehicles per hour

EF = Emission Factor

H = Link Height

W = Mixing Zone Width

Pred Conc = Predicted CO concentration at the receptor, including AMB

Conc/Link = The incremental CO concentration contributed by each link at a receptor position

AVG = Average 8-hour CO concentration predicted at the receptor

3.4 Brief Introduction to Sensitive Analysis of CALINE 4 Model

A sensitivity analysis for CALINE 4 is included in this report for the following reasons:

1. It provides a formalized means for checking the behavior of the model under a variety of conditions.
2. It allows the user to gauge the sensitivity of the model to each input parameter, thereby emphasizing those input parameters which need to be most accurately estimated.
3. It provides benchmark values against which users may check their copies of the model.

Because virtually all input parameters act independently within the model, interaction between two or more variables were presumed to be insignificant. Hence, for sensitivity analysis effect of each input variable was seen by changing one input variable at a time keeping other variable constant. The main series of sensitivity runs consist of CO concentration-wind angle (PHI) graphs. Here, wind angle was taken with respect to roadway i.e., 0˚ means parallel to the roadway and 90˚ means perpendicular to roadway. Sensitivity analysis was run for a single highway links at four distances from the mixing zone width: 1, 5, 10 and 15 m. In parallel wind condition, CO concentrations were dispersed both side of roadway and in oblique wind condition, the CO concentrations were dispersed towards one side of roadway i.e., towards north-east direction so, CO concentrations at northeast side of roadway were less in parallel wind condition than oblique wind condition. The sensitivity was run for 19:00 - 20:00 hour (peak hour) under Standard Run Condition. Following are the inputs used for the sensitivity analysis:

I. Site Variables

Wind Speed:	U = 0.5	(m/s)
Wind Direction:	BRG = Variable	(deg)
Atmospheric Stability:	CLAS = 4	(D)
Mixing Height:	MIXH = 656	(m)
Surface Roughness:	ZO = 100	(cm)
Ambient Concentration:	AMB=0	

II. Link Variables

Traffic Volume:	VPH=10724	(vehicles/hr)
Emission Factor:	EF=1.84	(gm/mile-vehicles)
Height:	H=0	(m)
Width:	W= 30.5	(m)
Link Coordinates:	X1= 1245, Y1 = 1975	
	X2= 2090, Y2= 1250	

III. Receptor Locations

XR = 1, 5, 10, 15 (m)

YR = 0

ZR = 0

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results of objective i.e. to analyze the sensitivity of CALINE 4 Model for various input variables along the Ashram Chowk – CRRI highway corridors of NH-2 have been discussed. Sensitivity analysis provides a formalized means for checking the behavior of the model under a variety of conditions. A sensitivity analysis of the CALINE 4 model was performed to identify the most influential variables among the different variables: Source Strength, Wind Speed, Wind Direction, Mixing Height, Median Width, Highway Width and Surface Roughness etc. CALINE 4 model allows the user to gauge the sensitivity of the model to each input parameter, thereby emphasizing those input parameters which need to be most accurately estimated. The CALINE 4, highway dispersion model, as already discussed earlier, has been used to predict the CO concentrations along Ashram Chowk – CRRI highway corridor of NH-2.

4.1 Prediction of CO Concentrations (Without Background Concentration)

The predictions of CO concentrations were carried out to find out 1-hour (Standard and Worst- Case run) and 8-hours (Multi Run and Multi-Run /Worst-Case Hybrid Scenario) average CO concentrations. Averages CO concentrations were predicted on both sides of the highway corridor (NH-2) along Ashram Chowk - CRRI at pre-identified 18 receptor points (9 points on each side of the highway corridor). CO concentrations were predicted using WEF calculated based on the emission factors provided by the Central Pollution Control Board (CPCB, 2000) and Automotive Research Association of India (ARAI, 2007) for Indian vehicles. The on-site meteorological parameters at receptor locations were taken (CRRI, 2010) **Table 3.4**. The prediction of CO concentrations (x) estimated were due to vehicular traffic and hence background CO concentrations (ΔX) were assumed as zero (i.e., $\Delta X = 0$), hence predicted CO concentrations thus only reflect the incremental increase in CO concentrations due to vehicular activities.

$$X = x + \Delta X \qquad \text{........... (1)}$$

Where, X = Estimated CO Concentration ($\mu g/m^3$)

Predicted 1-hour CO concentrations for Standard and Worst-Case Run at receptor locations using ARAI (2007) emission factors have been shown in **Table 4.1** and **Table 4.2** respectively. Similarly predicted 1-hour CO concentrations obtained by using CPCB (2000) emission factors have been shown in **Table 4.3** and **Table 4.4** respectively. Predicted 8-hour CO concentrations for Multi-Run and Multi-Run/ Worst-Case Hybrid at receptor locations using ARAI emission factors have been shown in **Table 4.5** and **Table 4.6** respectively. Similarly predicted 8-hour CO concentrations for Multi-Run and Multi-Run/ Worst- Case Hybrid at receptor locations using CPCB emission factors have been shown in **Table 4.7** and **Table 4.8** respectively. A sample output screen of CALINE 4 model for Standard Case Run Conditions is shown in **Appendix IXA** and for Worse Case Run Conditions is shown in **Appendix IXB**. Contour Map of CO concentrations along the Ashram Chowk-CRRI highway corridor of NH-2 is shown in **Fig. 4.1** which reflects the incremental increase in CO concentrations due to vehicular activities only at pre-identified receptor locations. The predicted CO concentrations for ARAI and CPCB emission factors have been shown in **Fig. 4.2** and **Fig. 4.3** for 1-hour CO concentrations (Standard-Case run) and 8-hours CO concentrations (Multi-Run/Worst-Case Hybrid) respectively.

The brief summary of results of modelling exercise is as follows:

(i) The maximum predicted 1-hour CO concentrations at receptor locations using ARAI emission factors was found to be 1025.6 μg/m^3 (1ppm= 1139.6 μg/m^3) in Standard and 1595 μg/m^3 in Worst Case Run conditions.

(ii) The maximum predicted 1-hour CO concentrations at receptor locations using CPCB emission factors was found to be 911.7 μg/m^3 in Standard and 1481 μg/m^3 in Worst Case Run conditions.

(iii) Predicted CO concentration was greater for Worse Case Run Conditions as compare to Standard Case Run Conditions because for Worse Case the model selects the wind angles that produce the highest CO concentrations at each of the receptors locations.

(iv) Dispersion of CO concentrations at receptor locations for both emission factors were found to be maximum in the North-East direction for Standard Run conditions as average wind direction was from South-West direction which disperse the CO concentrations at receptor locations in downwind direction (i.e., in North-East direction).

(v) Predicted CO concentrations were found to be maximum in evening hours (05:00-08:00 pm) due to maximum traffic volume in these hours.

(vi) The dispersion of CO concentrations was found to be present up to a distance of 150 m from the edge of the mixing zone width (road width + 3 m on each side of the road).

(vii) The maximum predicted 8-hour CO concentration at receptor locations was found to be 797.7 $\mu g/m^3$ using both ARAI emission factors and CPCB emission factors in Multi Run conditions.

(viii) The maximum predicted 8-hour CO concentrations at receptor locations was found to be 1254 $\mu g/m^3$ using ARAI emission factors and 1140 $\mu g/m^3$ using CPCB emission factors in Multi Run /Worst Case Hybrid conditions. Predicted CO concentration was greater for ARAI emission factors (2.96 gm/km/vehicle) as compare to CPCB emission factors because WEF using ARAI emission factors was greater as compare to WEF using CPCB emission factors (gm/km/vehicle). This was because emission factor is directly proportional to the predicted CO concentration. WEF for ARAI was more because ARAI emission factor are more accurate.

Table 4.1: Predicted (1-hour) CO Concentrations Using ARAI's Emission Factors Under Standard Run

Duration (Hours)	Distance (m) from the Edge of the Mixing Zone Width																		
	South-West (CO Concentrations, µg/m^3)										North-East (CO Concentrations, µg/m^3)								
	150	**100**	**50**	**25**	**15**	**10**	**5**	**2**	**1**	**0**	**1**	**2**	**5**	**10**	**15**	**25**	**50**	**100**	**150**
00—1	0	0	0	0	0	0	0	0	0		227.9	227.9	227.9	227.9	114.0	114.0	0.0	0.0	0.0
1—2	0	0	0	0	0	0	0	0	0		227.9	227.9	114.0	114.0	114.0	0.0	0.0	0.0	0.0
2—3	0	0	0	0	0	0	0	0	0		227.9	227.9	114.0	114.0	114.0	0.0	0.0	0.0	0.0
3—4	0	0	0	0	0	0	0	0	0		114.0	114.0	114.0	114.0	0.0	0.0	0.0	0.0	0.0
4—5	0	0	0	0	0	0	0	0	0		227.9	114.0	114.0	114.0	0.0	0.0	0.0	0.0	0.0
5—6	0	0	0	0	0	0	0	0	0		227.9	227.9	227.9	227.9	114.0	114.0	0.0	0.0	0.0
6—7	0	0	0	0	0	0	0	0	0		341.9	341.9	341.9	227.9	227.9	227.9	114.0	0.0	0.0
7—8	0	0	0	0	0	0	0	0	0		455.8	455.8	341.9	341.9	227.9	227.9	114.0	0.0	0.0
8--9	0	0	0	0	0	0	0	0	0		797.7	797.7	683.8	569.8	455.8	341.9	227.9	114.0	0.0
9--10	0	0	0	0	0	0	0	0	0		911.7	797.7	683.8	569.8	455.8	341.9	227.9	114.0	114.0
10--11	0	0	0	0	0	0	0	0	0		797.7	797.7	683.8	569.8	455.8	341.9	227.9	114.0	0.0
11--12	0	0	0	0	0	0	0	0	0		797.7	683.8	569.8	455.8	455.8	341.9	227.9	114.0	0.0
12--13	0	0	0	0	0	0	0	0	0		683.8	569.8	455.8	455.8	341.9	227.9	114.0	0.0	0.0
13--14	0	0	0	0	0	0	0	0	0		569.8	455.8	455.8	341.9	227.9	227.9	114.0	0.0	0.0
14--15	0	0	0	0	0	0	0	0	0		683.8	569.8	455.8	455.8	341.9	227.9	114.0	0.0	0.0
15--16	0	0	0	0	0	0	0	0	0		683.8	683.8	569.8	455.8	341.9	227.9	227.9	0.0	0.0
16--17	0	0	0	0	0	0	0	0	0		911.7	911.7	797.7	683.8	569.8	455.8	227.9	227.9	114.0
17--18	0	0	0	0	0	0	0	0	0		911.7	911.7	797.7	569.8	569.8	455.8	227.9	227.9	114.0
18--19	0	0	0	0	0	0	0	0	0		911.7	911.7	797.7	683.8	569.8	455.8	341.9	227.9	114.0
19--20	0	0	0	0	0	0	0	0	0		**1025.6**	**911.7**	**797.7**	**683.8**	**569.8**	**455.8**	**341.9**	**227.9**	**114.0**
20--21	0	0	0	0	0	0	0	0	0		797.7	797.7	683.8	569.8	455.8	341.9	227.9	227.9	114.0
21--22	0	0	0	0	0	0	0	0	0		683.8	683.8	569.8	455.8	455.8	341.9	227.9	114.0	114.0
22--23	0	0	0	0	0	0	0	0	0		455.8	455.8	455.8	341.9	341.9	227.9	227.9	114.0	0.0
23--24	0	0	0	0	0	0	0	0	0		341.9	341.9	341.9	227.9	227.9	227.9	114.0	0.0	0.0

Table 4.2: Predicted (1-hour) CO Concentrations Using ARAI's Emission Factors Under Worse Case Run

Duration (Hours)	Distance (m) from the Edge of the Mixing Zone Width																		
	South-West (CO Concentrations, µg/m^3)										North-East (CO Concentrations, µg/m^3)								
	150	**100**	**50**	**25**	**15**	**10**	**5**	**2**	**1**	**0**	**1**	**2**	**5**	**10**	**15**	**25**	**50**	**100**	**150**
00—1	0	0	114	228	228	228	342	342	342		570	456	342	342	228	228	114	0	0
1—2	0	0	0	114	228	228	228	228	342		456	342	342	228	228	114	114	0	0
2—3	0	0	0	114	228	228	228	228	228		342	342	342	228	228	114	0	0	0
3—4	0	0	0	114	114	228	228	228	228		342	342	228	228	228	114	0	0	0
4—5	0	0	0	114	228	228	228	228	228		456	342	342	228	228	114	0	0	0
5—6	0	0	114	228	228	228	342	342	342		570	456	456	342	228	228	114	0	0
6—7	0	114	228	228	342	342	456	456	456		798	684	570	456	342	342	228	114	0
7—8	0	0	114	228	228	342	342	456	456		684	570	456	342	342	228	114	0	0
8—9	114	114	228	342	456	570	684	798	798		1140	1026	912	684	570	456	228	114	114
9—10	114	228	342	456	570	570	798	798	912		1368	1254	1026	798	684	456	342	228	114
10—11	114	114	228	342	456	570	684	798	798		1254	1140	912	684	570	456	342	228	114
11—12	0	114	228	342	456	456	570	684	684		1026	912	798	570	456	342	228	114	0
12—13	0	0	114	228	342	342	456	570	570		798	684	570	456	342	342	228	0	0
13—14	0	0	114	228	228	342	342	456	456		684	570	456	342	342	228	114	0	0
14—15	0	0	114	228	342	342	456	456	570		798	684	570	456	342	228	228	0	0
15—16	0	0	114	228	342	342	456	570	570		798	798	570	456	342	228	228	0	0
16—17	114	228	228	456	456	570	684	798	912		1254	1140	912	684	570	456	342	228	114
17—18	114	228	342	456	570	570	684	798	912		1254	1254	1026	798	570	456	342	228	114
18—19	114	228	342	456	570	684	798	912	1026		1481	1368	1026	798	684	570	342	228	114
19—20	**114**	**228**	**342**	**456**	**570**	**684**	**798**	**912**	**1026**		**1595**	**1368**	**1140**	**912**	**684**	**570**	**342**	**228**	**228**
20—21	228	228	342	456	570	570	798	798	912		1368	1254	1026	798	684	456	342	228	228
21—22	114	228	228	342	456	570	684	798	798		1254	1026	912	684	570	456	342	228	114
22—23	114	114	228	342	342	456	570	570	570		912	798	684	570	456	342	228	114	114
23—24	0	114	228	228	342	342	456	456	570		798	684	570	456	342	342	228	114	0

Table 4.3: Predicted (1-hour) CO Concentrations Using CPCB's Emission Factors Under Standard Run

Distance (m) from the Edge of the Mixing Zone Width																			
Duration (Hours)	**South-West (CO Concentrations, µg/m^3)**										**North-East (CO Concentrations, µg/m^3)**								
	150	**100**	**50**	**25**	**15**	**10**	**5**	**2**	**1**	**0**	**1**	**2**	**5**	**10**	**15**	**25**	**50**	**100**	**150**
00—1	0	0	0	0	0	0	0	0	0		227.9	227.9	227.9	227.9	114.0	114.0	0.0	0.0	0.0
1—2	0	0	0	0	0	0	0	0	0		227.9	227.9	114.0	114.0	114.0	0.0	0.0	0.0	0.0
2—3	0	0	0	0	0	0	0	0	0		227.9	114.0	114.0	114.0	0.0	0.0	0.0	0.0	0.0
3—4	0	0	0	0	0	0	0	0	0		114.0	114.0	114.0	0.0	0.0	0.0	0.0	0.0	0.0
4—5	0	0	0	0	0	0	0	0	0		114.0	114.0	114.0	114.0	0.0	0.0	0.0	0.0	0.0
5—6	0	0	0	0	0	0	0	0	0		227.9	227.9	227.9	114.0	114.0	114.0	0.0	0.0	0.0
6—7	0	0	0	0	0	0	0	0	0		341.9	341.9	227.9	227.9	227.9	227.9	114.0	0.0	0.0
7—8	0	0	0	0	0	0	0	0	0		455.8	455.8	341.9	341.9	227.9	227.9	114.0	0.0	0.0
8—9	0	0	0	0	0	0	0	0	0		797.7	683.8	569.8	455.8	455.8	341.9	227.9	114.0	0.0
9—10	0	0	0	0	0	0	0	0	0		797.7	797.7	683.8	569.8	455.8	341.9	227.9	114.0	114.0
10—11	0	0	0	0	0	0	0	0	0		797.7	797.7	683.8	569.8	455.8	341.9	227.9	114.0	0.0
11—12	0	0	0	0	0	0	0	0	0		683.8	683.8	569.8	455.8	341.9	341.9	227.9	114.0	0.0
12—13	0	0	0	0	0	0	0	0	0		569.8	569.8	455.8	341.9	341.9	227.9	114.0	0.0	0.0
13—14	0	0	0	0	0	0	0	0	0		455.8	455.8	341.9	341.9	227.9	227.9	114.0	0.0	0.0
14—15	0	0	0	0	0	0	0	0	0		569.8	569.8	455.8	341.9	341.9	227.9	114.0	0.0	0.0
15—16	0	0	0	0	0	0	0	0	0		683.8	569.8	455.8	455.8	341.9	227.9	114.0	0.0	0.0
16—17	0	0	0	0	0	0	0	0	0		911.7	797.7	683.8	569.8	455.8	341.9	227.9	114.0	114.0
17—18	0	0	0	0	0	0	0	0	0		911.7	797.7	683.8	569.8	455.8	341.9	227.9	114.0	114.0
18—19	0	0	0	0	0	0	0	0	0		911.7	911.7	683.8	569.8	569.8	455.8	227.9	227.9	114.0
19—20	0	0	0	0	0	0	0	0	0		**911.7**	**911.7**	**797.7**	**683.8**	**569.8**	**455.8**	**341.9**	**227.9**	**114.0**
20—21	0	0	0	0	0	0	0	0	0		797.7	683.8	683.8	569.8	455.8	341.9	227.9	227.9	114.0
21—22	0	0	0	0	0	0	0	0	0		683.8	683.8	569.8	455.8	341.9	341.9	227.9	114.0	114.0
22—23	0	0	0	0	0	0	0	0	0		455.8	455.8	341.9	341.9	341.9	227.9	227.9	114.0	0.0
23—24	0	0	0	0	0	0	0	0	0		341.9	341.9	341.9	227.9	227.9	227.9	114.0	0.0	0.0

Table 4.4: Predicted (1-hour) CO Concentration Using CPCB's Emission Factors Under Worse Case Run

Duration (Hours)	Distance (m) from the Edge of the Mixing Zone Width																		
	South-West (CO Concentrations, µg/m^3)										North-East (CO Concentrations, µg/m^3)								
	150	**100**	**50**	**25**	**15**	**10**	**5**	**2**	**1**	**0**	**1**	**2**	**5**	**10**	**15**	**25**	**50**	**100**	**150**
00—1	0	0	114	228	228	228	342	342	342		456	456	342	342	228	228	114	0	0
1—2	0	0	114	228	228	228	342	342	342		456	342	342	228	228	114	0	0	0
2—3	0	0	0	114	228	228	228	228	228		342	342	228	228	228	114	0	0	0
3—4	0	0	0	114	114	228	228	228	228		342	342	228	228	228	114	0	0	0
4—5	0	0	0	114	228	228	228	228	228		342	342	228	228	228	114	0	0	0
5—6	0	0	0	114	114	228	228	228	228		456	456	342	342	228	228	114	0	0
6—7	0	0	114	228	228	228	342	342	342		684	684	570	456	342	228	228	114	0
7—8	0	114	228	228	342	342	456	456	456		684	570	456	342	342	228	114	0	0
8—9	0	0	114	228	228	342	342	456	456		1140	1026	798	570	570	342	228	114	0
9—10	0	114	228	342	456	456	570	684	684		1254	1140	912	684	570	456	342	228	114
10—11	114	228	228	456	456	570	684	798	798		1140	1026	912	684	570	456	228	114	114
11—12	114	114	228	342	456	570	684	798	798		912	798	684	570	456	342	228	114	0
12—13	0	114	228	342	342	456	570	570	684		798	684	570	456	342	228	114	0	0
13—14	0	0	114	228	342	342	456	456	570		570	570	456	342	342	228	114	0	0
14—15	0	0	114	228	228	342	342	456	456		684	684	570	456	342	228	114	0	0
15—16	0	0	114	228	342	342	456	456	456		798	684	570	456	342	228	114	0	0
16—17	0	0	114	228	342	342	456	456	570		1140	1140	912	684	570	456	228	114	114
17—18	114	114	228	342	456	570	684	798	798		1254	1140	912	684	570	456	342	228	114
18—19	114	114	228	342	456	570	684	798	798		1368	1254	1026	798	684	456	342	228	114
19—20	**114**	**228**	**342**	**456**	**570**	**684**	**798**	**912**	**912**		**1481**	**1368**	**1026**	**798**	**684**	**570**	**342**	**228**	**114**
20—21	114	228	342	456	570	684	798	912	912		1254	1140	912	684	570	456	342	228	114
21—22	114	228	342	456	570	570	684	798	798		1140	1026	798	684	570	456	228	228	114
22—23	114	228	228	342	456	570	570	684	798		912	798	684	456	456	342	228	114	114
23—24	114	114	228	342	342	456	456	570	570		684	684	570	456	342	228	228	114	0

Table 4.5: Predicted (8-hours) CO Concentrations Using ARAI's Emission Factors Under Multi Run

Distance (m) (from the Edge of the Mixing Zone Width)																			
Duration (hrs.)	South-West (CO Concentrations, µg/m^3)										North-East (CO Concentrations, µg/m^3)								
	150	100	50	25	15	10	5	2	1	0	1	2	5	10	15	25	50	100	150
0-8	0	0	0	0	0	0	0	0	0		227.9	227.9	227.9	227.9	114.0	114.0	0.0	0.0	0.0
8—16	0	0	0	0	0	0	0	0	0		683.8	683.8	569.8	455.8	341.9	341.9	227.9	114.0	0.0
16-24	0	0	0	0	0	0	0	0	0		**797.7**	**797.7**	**683.8**	**569.8**	**455.8**	**341.9**	**227.9**	**114.0**	**114.0**

Table 4.6: Predicted (8-hours) CO Concentrations Using ARAI's Emission Factors Under Multi Run/Worst -Case Hybrid

Distance (m) (from the Edge of the Mixing Zone Width)																			
Duration (hrs.)	South-West (CO Concentrations, µg/m^3)										North-East (CO Concentrations, µg/m^3)								
	150	100	50	25	15	10	5	2	1	0	1	2	5	10	15	25	50	100	150
0-8	0	0	114	228	228	228	342	342	342		456	456	342	342	228	228	114	0	0
8—16	0	114	228	342	342	456	570	684	684		912	912	684	570	456	342	228	114	0
16-24	**114**	**228**	**228**	**456**	**456**	**570**	**684**	**798**	**798**		**1254**	**1140**	**912**	**684**	**570**	**456**	**342**	**228**	**114**

Table 4.7: Predicted (8-hours) CO Concentrations Using CPCB's Emission Factors Under Multi Run

Distance (m) (from the Edge of the Mixing Zone Width)																			
Duration (hrs.)	South-West (CO Concentrations, µg/m^3)										North-East (CO Concentrations, µg/m^3)								
	150	100	50	25	15	10	5	2	1	0	1	2	5	10	15	25	50	100	150
0-8	0	0	0	0	0	0	0	0	0		227.9	227.9	227.9	114.0	114.0	114.0	0.0	0.0	0.0
8—16	0	0	0	0	0	0	0	0	0		683.8	683.8	569.8	455.8	341.9	341.9	227.9	0.0	0.0
16-24	0	0	0	0	0	0	0	0	0		**797.7**	**683.8**	**569.8**	**455.8**	**455.8**	**341.9**	**227.9**	**114.0**	**114.0**

Table 4.8: Predicted (8-hours) CO Concentrations Using CPCB's Emission Factors under Multi Run/Worst -Case Hybrid

Distance (m) (from the Edge of the Mixing Zone Width)																			
Duration (hrs.)	South-West (CO Concentrations, µg/m^3)										North-East (CO Concentrations, µg/m^3)								
	150	100	50	25	15	10	5	2	1	0	1	2	5	10	15	25	50	100	150
0-8	0	0	114	228	228	228	228	342	342		456	456	342	228	228	228	114	0	0
8—16	0	114	228	342	342	456	570	570	570		912	798	684	570	456	342	228	114	0
16-24	**114**	**228**	**228**	**342**	**456**	**570**	**684**	**684**	**798**		**1140**	**1026**	**798**	**684**	**570**	**456**	**228**	**228**	**114**

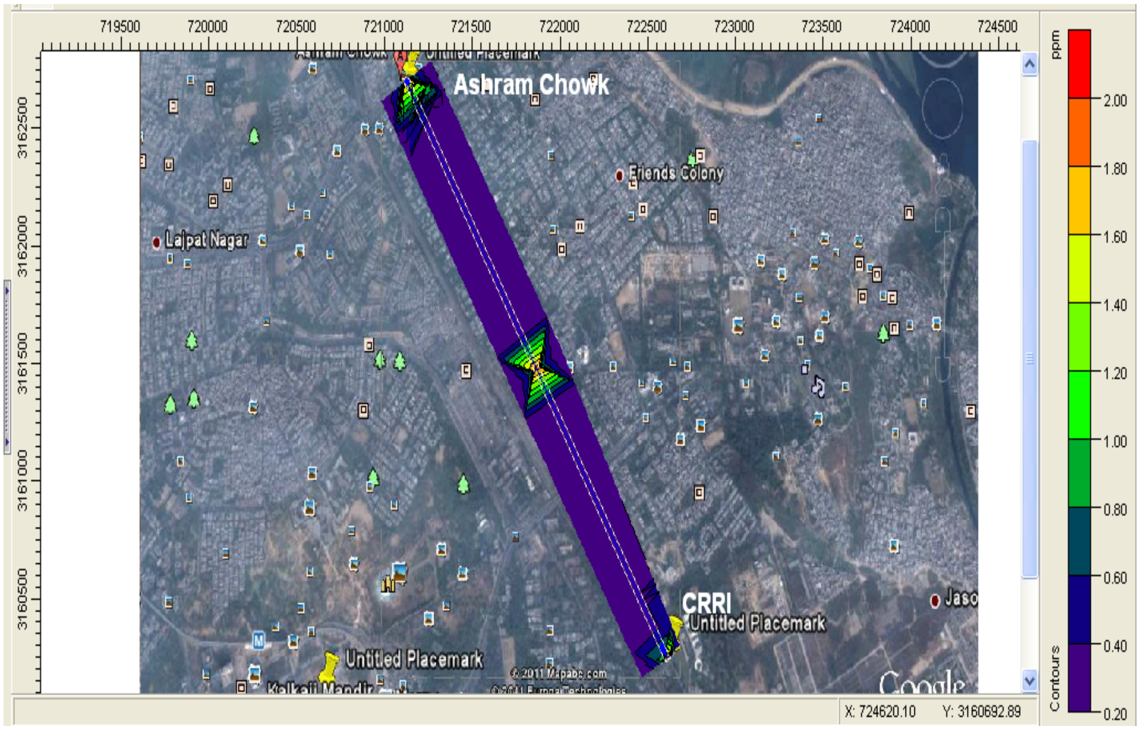


Fig. 4.1: Contour Map of CO Concentration along the Ashram Chowk-CRRI Highway Corridor of NH-2

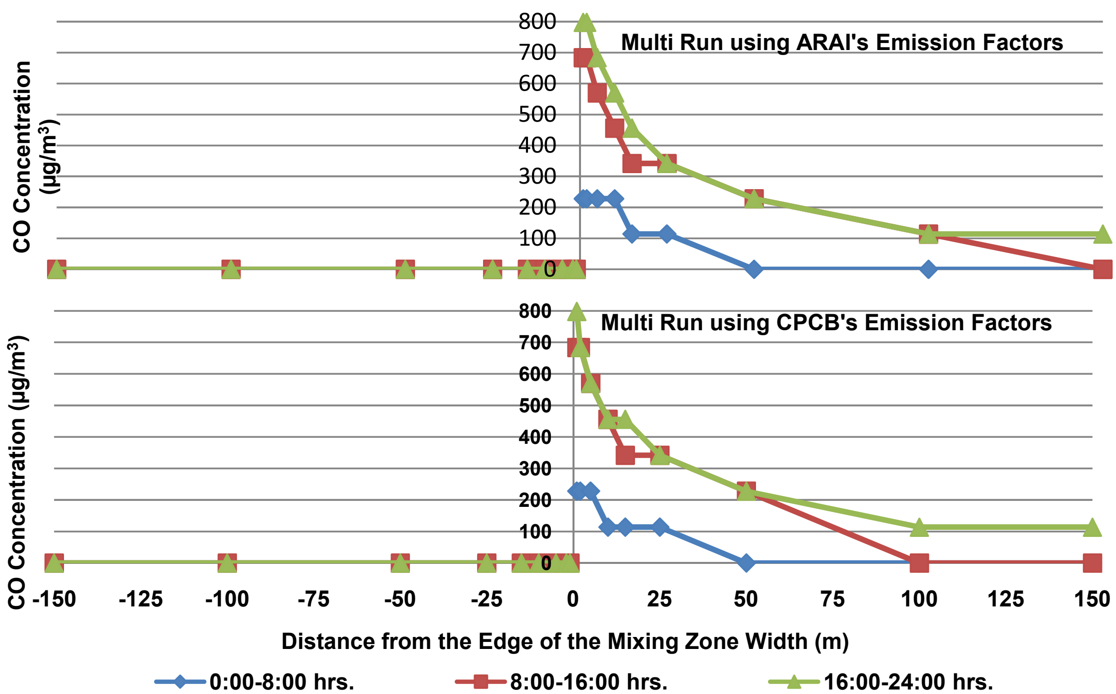


Fig. 4.2: Prediction of CO Concentrations (8 hrs.) along Ashram Chowk – CRRI Highway Corridor of NH-2 (Multi Run Conditions)

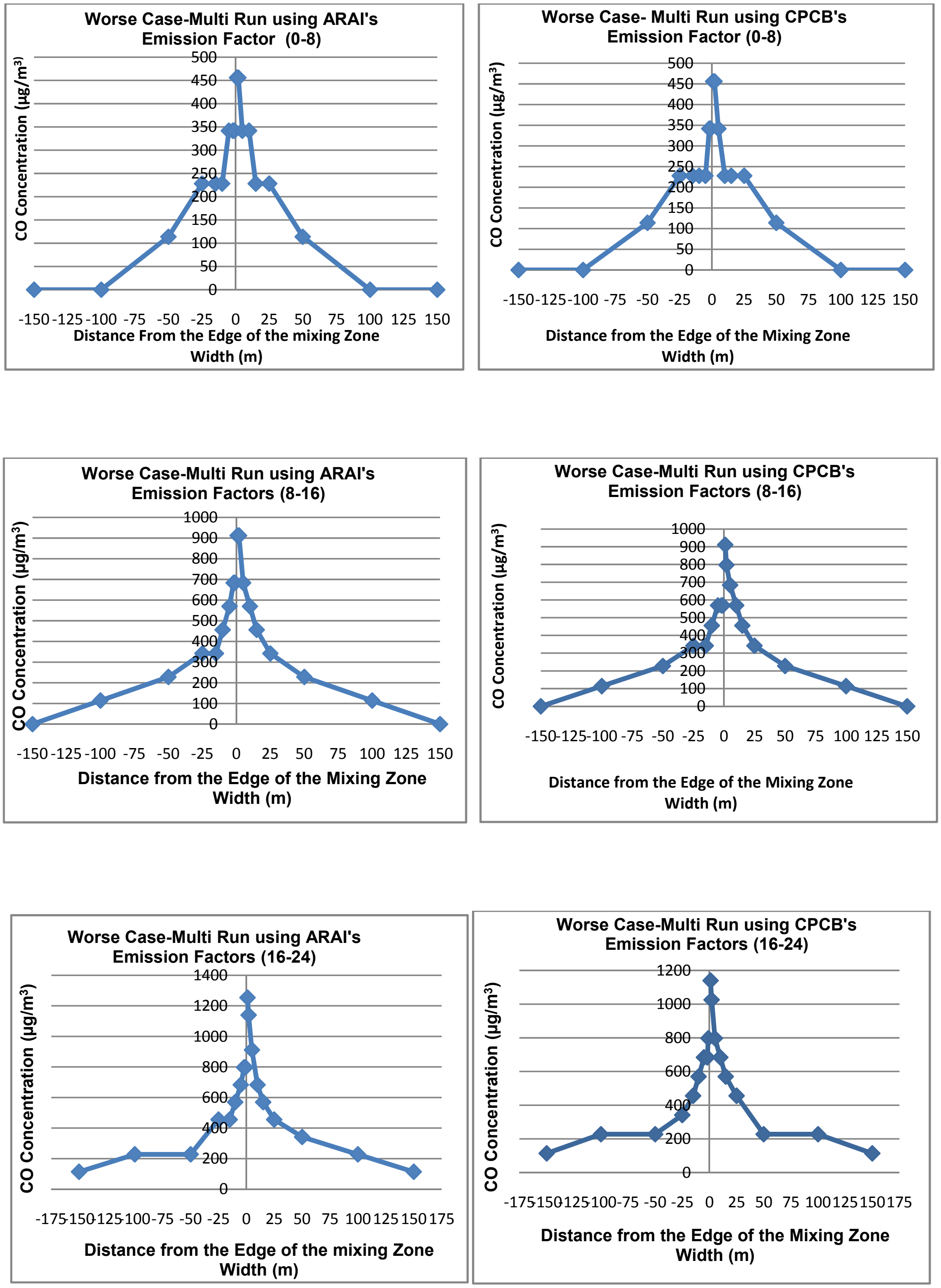


Fig. 4.3: Prediction of CO Concentrations (8 hrs.) along Ashram Chowk – CRRI Highway Corridor of NH-2 (Multi Run/Worse Case Conditions)

4.2 Prediction of CO Concentrations (With Background Concentration)

Predicted CO concentrations (x) at receptor location 1m distance from Mixing Zone width is added to hourly background CO concentrations (CRRI, 2002) hence, estimated CO concentrations (X) along Ashram Chowk – CRRI highway corridor of NH-2 was obtained.

$$X = x + \Delta X$$

Where, X = Estimated CO Concentration (µg/m^3)

The estimated CO concentrations and observed CO concentrations (CRRI) were shown in **Table 4.9**. A diurnal variation of observed CO concentrations at pre-identified receptor location along Ashram Chowk – CRRI highway corridor of NH-2 is shown in **Fig. 4.4**. Correlation between the estimated/predicted (using CALINE 4) and the observed (monitored) CO concentrations were developed and shown in **Fig. 4.5** to **Fig. 4.8**.

Table 4.9: Estimated CO Concentrations at 1m from Mixing Zone width (Background + Predicted)

Duration (Hours)	Background CO (µg/m^3)	Predicted CO (Standard Case) (µg/m^3)		Predicted CO (Worse Case) (µg/m^3)		Estimated CO Concentrations (Standard Case) (µg/m^3)		Estimated CO Concentrations (Worse Case) (µg/m^3)		Observed CO (µg/m^3)
	(x)	(ΔX)		(ΔY)		(x+ΔX)		(x+ΔY)		
		CPCB	ARAI	CPCB	ARAI	CPCB	ARAI	CPCB	ARAI	
00—1	1254	228	228	456	570	1481	1481	1709	1823	1623
1—2	1128	228	228	456	456	1356	1356	1584	1584	1465
2—3	1083	228	228	342	342	1311	1311	1425	1425	1394
3—4	1140	114	114	342	342	1254	1254	1481	1481	1386
4—5	1094	114	228	342	456	1208	1322	1436	1550	1452
5—6	1402	228	228	456	570	1630	1630	1858	1972	1481
6—7	1322	342	342	684	798	1664	1664	2006	2120	1546
7—8	1003	456	456	684	684	1459	1459	1687	1687	1709
8—9	1242	798	798	1140	1140	2040	2040	2382	2382	1945
9—10	1094	798	912	1254	1368	1892	2006	2348	2462	1754
10—11	1197	798	798	1140	1254	1994	1994	2336	2450	1834
11—12	1265	684	798	912	1026	1949	2063	2177	2291	1764
12—13	1128	570	684	798	798	1698	1812	1926	1926	1723
13—14	809	456	570	570	684	1265	1379	1379	1493	1356
14—15	934	570	684	684	798	1504	1618	1618	1732	1465
15—16	1165	684	684	798	798	1849	1849	1963	1963	1843
16—17	1105	912	912	1140	1254	**2017**	2017	2245	2359	2137
17—18	1105	912	912	1254	1254	**2017**	2017	2359	2359	2198
18—19	1026	912	912	1368	1481	1937	1937	2393	2507	2393
19—20	1014	912	1026	1481	1595	**1926**	**2040**	**2496**	**2610**	2346
20—21	1105	798	798	1254	1368	1903	1903	2359	2473	2284
21—22	1105	684	684	1140	1254	1789	1789	2245	2359	2054
22—23	1299	456	456	912	912	1755	1755	2211	2211	1965
23—24	1254	342	342	684	798	1595	1595	1937	2051	1864

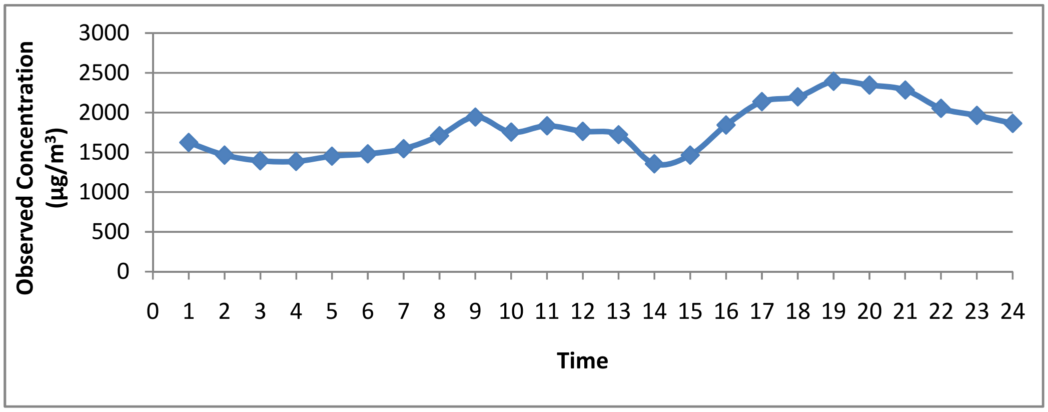


Fig. 4.4 Diurnal Variation of Observed CO Concentrations at Pre-identified Receptor Location along Ashram Chowk – CRRI Highway Corridor of NH-2

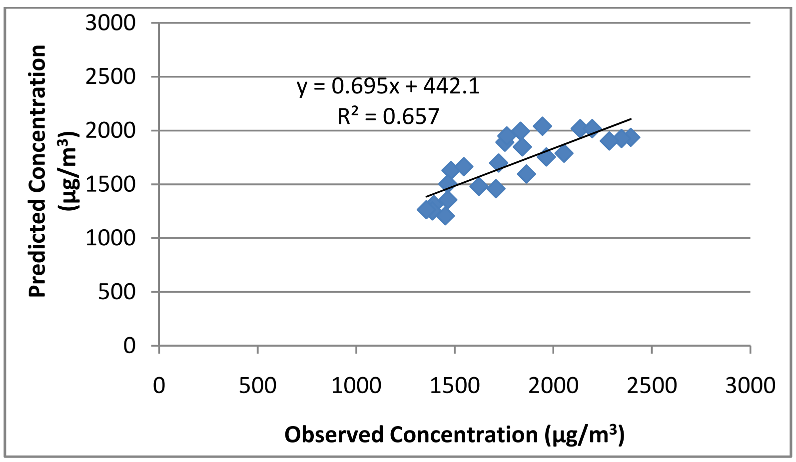


Fig. 4.5: Correlation between Predicted (using CALINE 4) and Observed 1-hour CO Concentrations using CPCB Emission Factors (Standard Case)

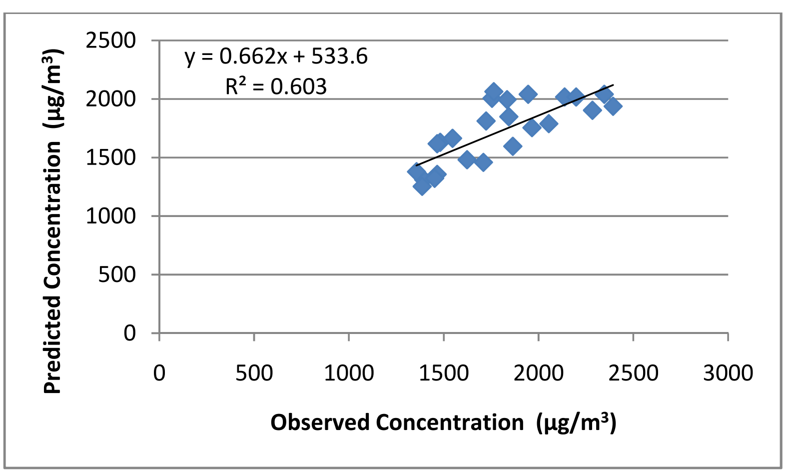


Fig. 4.6: Correlation between Predicted (using CALINE 4) and Observed 1-hour CO Concentrations using ARAI Emission Factors (Standard Case)

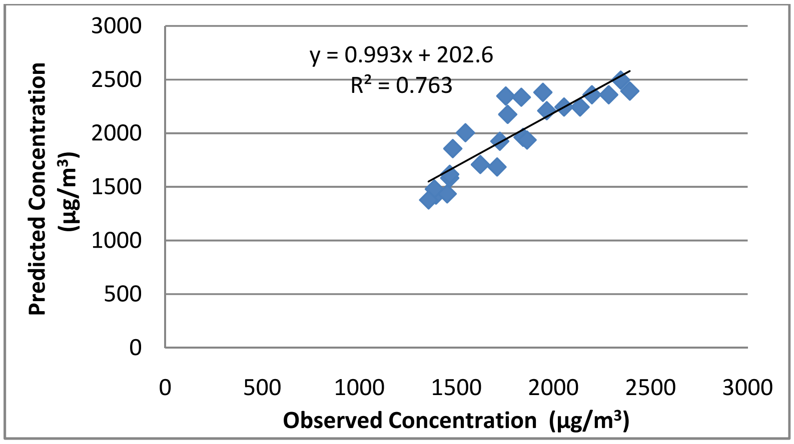


Fig. 4.7: Correlation between Predicted (using CALINE 4) and Observed 1-hour CO Concentrations using CPCB Emission Factors (Worse Case)

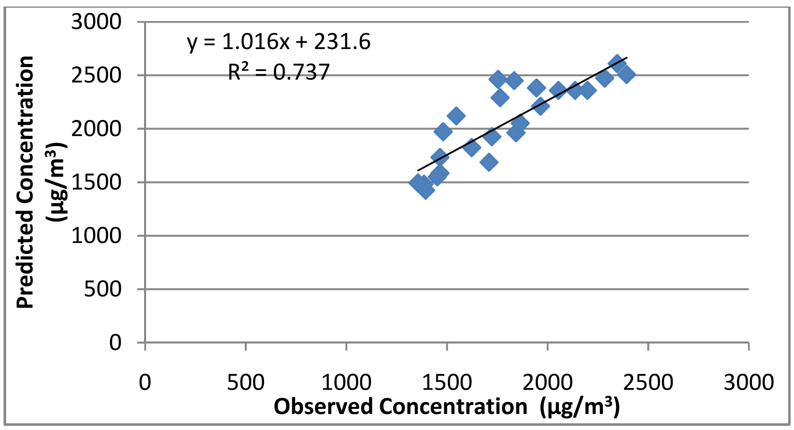


Fig. 4.8: Correlation between Predicted (using CALINE 4) and Observed 1-hour CO Concentrations using ARAI Emission Factors (Worse Case)

The brief summary of results of modelling exercise is as follows:

(i) Maximum estimated 1-hour CO concentrations using ARAI emission factors for Standard Case Run Conditions was 2040 µg/m^3 and for Worse Case Run Condition was 2610 µg/m^3. Predicted CO concentration was greater for Worse Case as compare to Standard Case because for Worse Case the model selects the wind angles that produce the highest CO concentrations at each of the receptors locations.

(ii) Similarly, maximum estimated 1-hour CO concentrations using CPCB emission factors for Standard Case Run Condition was 2017 µg/m^3 and for Worse Case Run Condition was 2496 µg/m^3**.**

(iii) **Table 4.9** shows that all the estimated 1-hour CO concentrations were within the NAAQS, 2009 (4 mg/m^3 for 1-hour) for both Run Conditions (Standard and Worse Case).

(iv) The regression coefficient (r^2) between predicted and observed 1-hour CO concentrations using CPCB emission factors for Standard Case Run Condition was 0.65 and for Worse Case Run Condition was 0.76.

(v) Similarly, the regression coefficient (r^2) between predicted and observed 1-hour CO concentrations using ARAI emission factors for Standard Case Run Condition was 0.60 and for Worse Case Run Condition was 0.73.

(vi) The comparison of predicted and observed 1-hour CO concentrations shows that the values fall within close ranges.

(vii) The predicted 1-hour CO concentrations for Worse Case Run Conditions were closer to observed CO concentration than for Standard Run Conditions.

4.3 Sensitivity Analysis of CALINE 4 Model

Sensitivity analysis provides a formalized means for checking the behaviour of the model under a various inputs variables. A sensitivity analysis of the CALINE 4 model was performed to identify the most influential input variables among the various input variables. Sensitivity analysis of CALINE 4 model was done for following inputs variables.

- **(i)** Source Strength
- **(ii)** Wind Angle
- **(iii)** Wind Speed
- **(iv)** Stability Class
- **(v)** Mixing Height
- **(vi)** Surface Roughness
- **(vii)** Highway Width
- **(viii)** Roadway Height
- **(ix)** Median Width

Since virtually all input parameters act independently within the model, interaction between two or more variables were presumed to be insignificant. Hence, for sensitivity analysis, effect of each input variable was seen by changing one input variable at a time, keeping other variables constant. The main series of sensitivity of CALINE 4 model consist of CO concentration-wind angle (PHI) graphs. Here, wind angle was taken with respect to roadway i.e., 0˚ means parallel to the roadway and 90˚ means perpendicular to roadway. Sensitivity analysis of CALINE 4 model was done for a single highway links at four distances from the mixing zone width: 1, 5, 10 and 15 m. The sensitivity was run for 19:00 - 20:00 hour (peak traffic hour) under Standard Run Condition. In parallel wind condition, CO concentrations were dispersed both side of roadway and in oblique wind condition, the CO concentrations were dispersed towards one side of roadway i.e., towards north-east direction so, CO concentrations at northeast side of roadway were less in parallel wind condition than oblique wind condition.

4.3.1 Source Strength

The source strength used in CALINE 4 is the product of the vehicles emission factor and traffic volume. It is directly proportional to the predicted CO concentrations (Benson, 1979). Hence, a two fold increase in either the vehicle emission factor or the traffic volume will result in a doubling of the predicted CO concentration. Because of this simple relationship, no sensitivity analysis was run on source strength. However, the effect on CO concentrations are less than proportional, since higher volumes also increase dilution due to vehicle-induced heat fluxes that increase vertical dispersion. The countervailing effect is stronger for winds parallel to the road, and diminishes for crosswind conditions at locations outside of the mixing zone (Batterman, 2010).

4.3.2 Wind Angle

For sensitivity analysis, wind angle was varied from 0° to 90° at an interval of 5° (viz., 0°, 5°, 10°, 15°, 20°…….). CO concentrations obtained are shown in **Table 4.10** and **Fig. 4.9**. CALINE 4 model has been found to be relatively sensitive to wind angle for small receptor distance. With every 5° increase in wind angle, average 8% decrease in CO concentrations were found for 1m to 2m distance from mixing zone width. However, at greater distances from mixing zone width, there was a less sensitivity in the model for a constant wind angle, average 4% decrease in CO concentrations for 5m to 10m distance from mixing zone width. For wind angle 30° to 90°, as the distance from mixing zone width increases from 1m to 150m, CO concentrations decreased by 85%. Similar trend (82% decreases in CO concentrations) was found by Sripraparkorn (2003). **Fig. 4.9** shows that peak concentrations occur usually in the 10° to 15° range for all receptors. No significant changes in CO concentrations (less than 5%) were occurring for crosswind conditions (20° to 80°). Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle.

Table 4.10: Predicted CO Concentrations (µg/m^3) at Receptor Locations for Wind Angle

Wind Angle (°)	Distance (D, in m) from the Edge of the Mixing Zone Width																		
	West (CO Concentrations, µg/m^3)										East (CO Concentration, µg/m^3)								
	-150	**-100**	**-50**	**-25**	**-15**	**-10**	**-5**	**-2**	**-1**	**0**	**1**	**2**	**5**	**10**	**15**	**25**	**50**	**100**	**150**
0	0	0	0	0	114	228	342	342	456		684	570	342	228	114	0	0	0	0
5	0	0	0	0	0	0	0	0	0		1368	1140	912	570	456	228	0	0	0
10	0	0	0	0	0	0	0	0	0		**1595**	**1368**	**1140**	**798**	**684**	**456**	**228**	**0**	**0**
15	0	0	0	0	0	0	0	0	0		**1481**	**1368**	**1140**	**798**	**684**	**570**	**342**	**0**	**0**
20	0	0	0	0	0	0	0	0	0		1368	1254	1026	798	684	570	342	114	0
25	0	0	0	0	0	0	0	0	0		1254	1140	1026	798	684	456	342	228	0
30	0	0	0	0	0	0	0	0	0		1140	1140	912	798	684	456	342	228	114
35	0	0	0	0	0	0	0	0	0		1026	1026	912	684	570	456	342	228	114
40	0	0	0	0	0	0	0	0	0		1026	1026	798	684	570	456	342	228	114
45	0	0	0	0	0	0	0	0	0		1026	912	798	684	570	456	342	228	114
50	0	0	0	0	0	0	0	0	0		1026	912	798	684	570	456	342	228	114
55	0	0	0	0	0	0	0	0	0		1026	912	798	684	570	456	342	228	114
60	0	0	0	0	0	0	0	0	0		1026	912	798	684	570	456	342	228	114
65	0	0	0	0	0	0	0	0	0		912	912	798	684	570	456	342	228	114
70	0	0	0	0	0	0	0	0	0		912	912	798	684	570	456	342	228	114
75	0	0	0	0	0	0	0	0	0		912	912	798	684	570	456	342	228	114
80	0	0	0	0	0	0	0	0	0		912	912	798	570	570	456	228	228	114
85	0	0	0	0	0	0	0	0	0		912	912	798	570	570	456	228	228	114
90	0	0	0	0	0	0	0	0	0		912	912	798	570	570	456	228	228	114

4.3.3 Wind Speed

Wind Speed enters CALINE 4 computations in two ways. In the Gaussian equation, the predicted concentration is inversely proportional to the wind speed. However, the wind speed also determines the time of residence within the mixing zone. This is related to the value of the vertical dispersion parameter at the edge of the roadway (Benson, 1979). In the present study, sensitivity analysis carried out for wind speeds of 0.5 to 5 m/s. Predicted CO Concentrations (μg/m^3) at Receptor Locations for Wind Speed is shown in **Table 4.11 and Fig. 4.10**. Wind speed had a considerable effect, e.g., predicted CO concentrations declined by 75% - 80% as wind speed increased from 0.5 to 5 m/s. Batterman (2010) also found that predicted CO concentration were dropped by 80% as winds increased from 1 to 10 m/s.

Wind dilutes pollutants in an inverse manner, but the initial vertical and horizontal dispersion parameters (σ_x and σ_y) also depend on wind speed, which slightly weakens the dilution effect. The predicted CO concentrations were higher for low wind speeds in all cases, despite of the slightly offsetting effect of higher initial vertical dispersion at lower wind speeds. With increase of 0.5 m/s in wind speed, average 9% decrease was observed in predicted CO concentrations. For wind speed 0.5 to 1 m/s, maximum decrease in CO concentration was 33% at 1m distance from mixing zone width (at 60° wind angle). For wind angle 10° to 90°, average decrease in CO concentrations were 40% at 1m distance, 30% at 5m distance, 10% at 10m distance and less than 5% at 15m distance from mixing zone width.

It was also found that with increase in wind speed, only small effect in CO concentrations occurs at higher distance from roadway. Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle. For all wind speeds, the maximum CO concentrations occur for 10° wind angle, these maximum CO concentrations become less evident at higher wind speeds. The location of maximum CO concentrations appears to be relatively insensitive to wind speed and receptor distance.

Table 4.11: Predicted CO Concentrations at Receptor Locations for Wind Speed

Wind Speed (m/s)	Wind Angle (°)									
	0	10*	20	30	40	50	60	70	80	90
	CO Concentration (µg/m^3)									
Distance, D = 1m										
0.5	684	1595	1368	1140	1026	1026	1026	912	912	912
1.0	570	1140	1026	912	798	798	684	684	684	684
1.5	456	798	798	684	570	570	570	456	456	456
2.0	342	684	684	570	456	456	456	456	342	342
2.5	228	570	570	456	456	342	342	342	342	342
3.0	228	456	456	456	342	342	342	342	228	228
3.5	228	456	456	342	342	342	228	228	228	228
4.0	228	342	342	342	342	228	228	228	228	228
4.5	228	342	342	342	228	228	228	228	228	228
5.0	114	342	342	228	228	228	228	228	228	228
Distance, D = 5m										
0.5	342	1140	1026	912	798	798	798	798	798	798
1.0	342	798	798	684	684	570	570	570	570	570
1.5	228	570	570	570	456	456	456	456	456	456
2.0	228	456	456	456	456	342	342	342	342	342
2.5	114	342	456	342	342	342	342	342	228	228
3.0	114	342	342	342	342	342	228	228	228	228
3.5	114	342	342	342	228	228	228	228	228	228
4.0	114	228	342	228	228	228	228	228	228	228
4.5	0	228	228	228	228	228	228	228	114	114
5.0	0	228	228	228	228	228	228	114	114	114
Distance, D = 10m										
0.5	228	798	798	798	684	684	684	684	570	570
1.0	228	570	570	570	570	456	456	456	456	456
1.5	114	456	456	456	456	342	342	342	342	342
2.0	114	342	342	342	342	342	342	342	228	228
2.5	0	228	342	342	342	228	228	228	228	228
3.0	0	228	342	228	228	228	228	228	228	228
3.5	0	228	228	228	228	228	228	228	228	228
4.0	0	228	228	228	228	228	228	114	114	114
4.5	0	114	228	228	228	114	114	114	114	114
5.0	0	114	228	228	114	114	114	114	114	114
Distance, D = 15m										
0.5	114	684	684	684	570	570	570	570	570	570
1.0	114	456	456	456	456	456	456	342	342	342
1.5	0	342	342	342	342	342	342	342	342	228
2.0	0	228	342	342	342	228	228	228	228	228
2.5	0	228	228	228	228	228	228	228	228	228
3.0	0	228	228	228	228	228	228	228	228	114
3.5	0	228	228	228	228	228	114	114	114	114
4.0	0	114	228	228	228	114	114	114	114	114
4.5	0	114	114	114	114	114	114	114	114	114
5.0	0	114	114	114	114	114	114	114	0	0

*Maximum CO Concentration at PHI = 10°

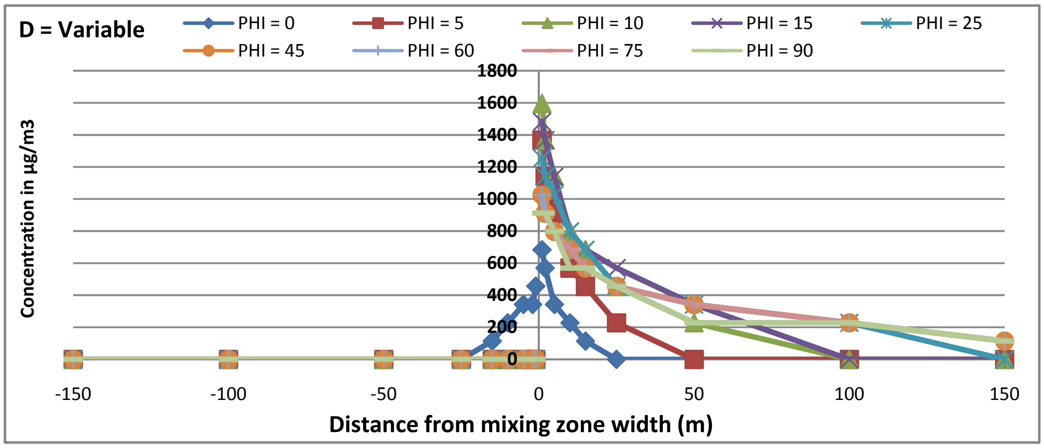


Fig. 4.9: CALINE 4 Sensitivity Analysis for Wind Angle, PHI (°)

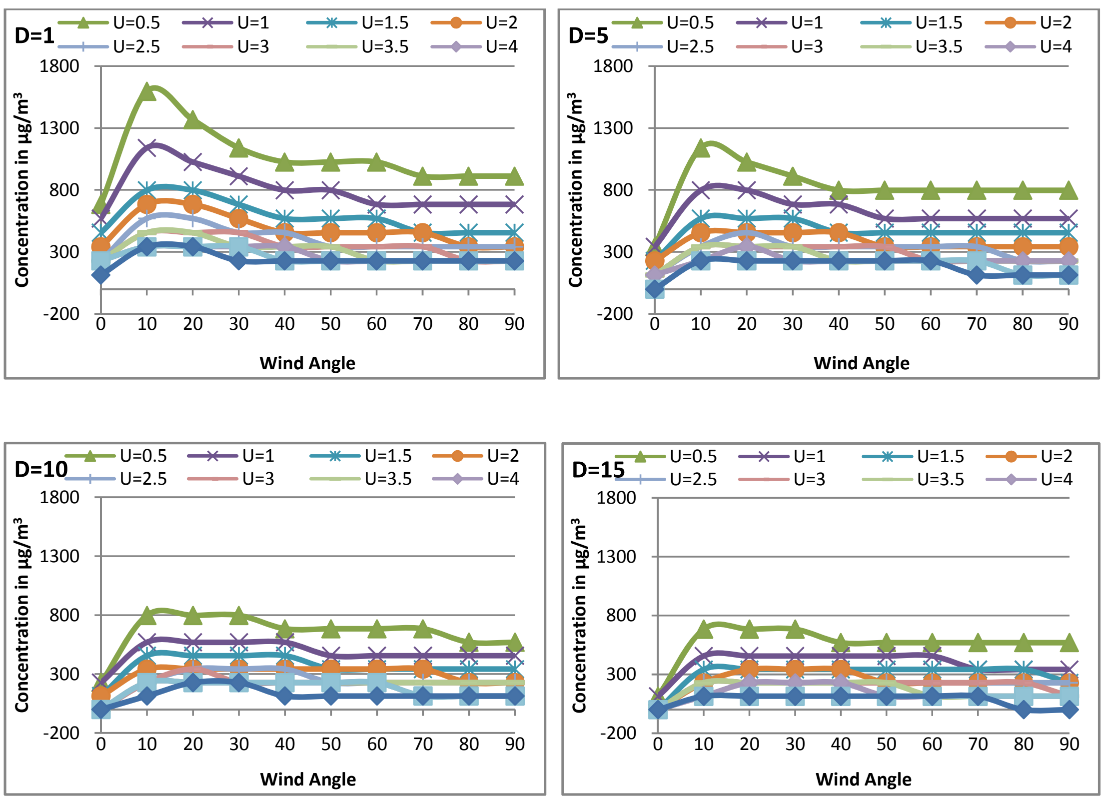


Fig. 4.10: CALINE 4 Sensitivity Analysis for Wind Speed, U (m/s)

4.3.4 Atmospheric Stability

For sensitivity analysis, stability class was varied from A to F (P-G Stability Class). Predicted CO concentrations obtained are shown in **Table 4.12** and **Fig. 4.11**. The critical wind angle at which maximum CO concentrations occurs was much more sensitive to atmospheric stability class than to wind speed. The sifting of the critical angle from near parallel to crosswind conditions can be attributed to the increases in vertical and horizontal dispersion that occur under more unstable atmospheric conditions. No significant effect was observed for 30° to 90° wind angle. Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle. At the edge of the mixing zone width (D=1m) the predicted CO concentration was less sensitive to stability class under cross wind conditions than at greater distance. This was because the vertical dispersion at this was controlled totally by the residence time over the mixing zone (Benson, 1979). At 10° wind angle, from unstable to stable conditions, average increase in CO concentrations was 43%. These increases make the contributions from distant elements less important as atmospheric instability increases, same type of result was also found by Batterman (2010). Therefore, it was a less significant input variable. Sahlodina et al. (2007) also found that atmospheric stability a less significant input variable.

Table 4.12: Predicted CO Concentrations at Receptor Locations for Stability Class

Stability Class (P-G)	Wind Angle (°)									
	0	10	20	30	40	50	60	70	80	90
	CO Concentrations (μg/m^3)									
Distance, D = 1m										
A	798	1140	1254	1140	1026	912	912	912	912	912
B	798	1368	1254	1140	1026	1026	1026	912	912	912
C	798	1481	1368	1140	1026	1026	1026	912	912	912
D	684	1595	1368	1140	1026	1026	1026	912	912	912
E	570	1595	1368	1140	1026	1026	1026	912	912	912
F	456	1709	1368	1140	1026	1026	1026	912	912	912
Distance, D = 5m										
A	570	912	912	912	798	798	798	798	798	798
B	570	912	1026	912	798	798	798	798	798	798
C	456	1026	1026	912	798	798	798	798	798	798
D	342	1140	1026	912	798	798	798	798	798	798
E	342	1140	1026	912	798	798	798	798	798	798
F	228	1140	1026	912	798	798	798	798	798	798
Distance, D = 10m										
A	342	684	684	684	684	684	570	570	570	570
B	342	684	798	684	684	684	684	570	570	570
C	342	798	798	684	684	684	684	684	570	570
D	228	798	798	798	684	684	684	684	570	570
E	114	912	798	798	684	684	684	684	570	570
F	0	912	798	798	684	684	684	684	684	684
Distance, D = 15m										
A	228	456	570	570	570	570	570	570	570	456
B	228	570	684	570	570	570	570	570	570	570
C	228	570	684	570	570	570	570	570	570	570
D	114	684	684	684	570	570	570	570	570	570
E	0	684	684	684	570	570	570	570	570	570
F	0	798	684	684	570	570	570	570	570	570

4.3.5 Mixing Height

For sensitivity analysis, mixing height was varied from 25 to 1500m. Predicted CO concentrations obtained has been shown in **Table 4.13** and **Fig. 4.12**. Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle. No significant effect was found for receptor locations at greater distance from mixing zone width. The model response for MIXH = 100m was same as to MIXH = 1500m. Model sensitivity to mixing height (MIXH) was significant only for extremely low values (less than 100m). This was essentially because of the small amount of vertical dispersion that can take place under stable conditions within the limits of the micro scale region (Benson, 1979; Batterman, 2010). Mixing height less than 100m is found in very rare cases, therefore it can be concluded that mixing height has no effect. Sripraparkon et al. (2003) and Sahlodina et al. (2007) also found that the mixing height has no or very less effect.

4.3.6 Surface Roughness

Mechanical turbulence is generated by air movement over surface roughness elements. An increase in the surface roughness increases the amount of mechanical turbulence generated. This enhances both vertical and horizontal dispersion of pollutants in the surface layer, especially for near ground releases (Benson, 1979). For sensitivity analysis, Surface roughness (i.e. Aerodynamic Roughness Coefficient) was varied from 3 to 150cm. Predicted CO concentrations obtained are shown in **Table 4.14** and **Fig. 4.13.** CALINE 4 was sensitive for very small values of Aerodynamic Roughness Coefficient (<10cm). It was found that CALINE 4 was sensitive only for near rural areas (i.e. near 10cm Aerodynamic Roughness Coefficient) (**Table 3.12**, Aerodynamic Roughness Coefficient defined for various types of landscapes). It was relatively sensitive to surface roughness for near parallel wind conditions (~10**°**). For crosswind conditions, predicted concentrations are dominated by the initial vertical mixing within the mixing zone which was independent of surface roughness. Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle. Sripraparkon et al. (2003) and Sahlodina et al. (2007) used sensitivity analysis of CALINE 4 model and also found that surface roughness was no or slight significant input variable.

Table 4.13: Predicted CO Concentrations at Receptor Locations for Mixing Height (m)

Mixing Height (m)	Wind Angle (°)									
	0	10	20	30	40	50	60	70	80	90
	CO Concentrations (μg/m^3)									
Distance, D = 1m										
25	1481	2165	1481	1140	1026	1026	1026	912	912	912
50	912	1709	1368	1140	1026	1026	1026	912	912	912
100	684	1595	1368	1140	1026	1026	1026	912	912	912
200	684	1595	1368	1140	1026	1026	1026	912	912	912
300	684	1595	1368	1140	1026	1026	1026	912	912	912
400	684	1595	1368	1140	1026	1026	1026	912	912	912
500	684	1595	1368	1140	1026	1026	1026	912	912	912
750	684	1595	1368	1140	1026	1026	1026	912	912	912
1000	684	1595	1368	1140	1026	1026	1026	912	912	912
1500	684	1595	1368	1140	1026	1026	1026	912	912	912
Distance, D = 5m										
25	1026	1823	1140	912	798	798	798	798	798	798
50	570	1254	1026	912	798	798	798	798	798	798
100	456	1140	1026	912	798	798	798	798	798	798
200	342	1140	1026	912	798	798	798	798	798	798
300	342	1140	1026	912	798	798	798	798	798	798
400	342	1140	1026	912	798	798	798	798	798	798
500	342	1140	1026	912	798	798	798	798	798	798
750	342	1140	1026	912	798	798	798	798	798	798
1000	342	1140	1026	912	798	798	798	798	798	798
1500	342	1140	1026	912	798	798	798	798	798	798
Distance, D = 10m										
25	684	1595	912	798	684	684	684	684	570	570
50	342	1026	798	798	684	684	684	684	570	570
100	228	798	798	798	684	684	684	684	570	570
200	228	798	798	798	684	684	684	684	570	570
300	228	798	798	798	684	684	684	684	570	570
400	228	798	798	798	684	684	684	684	570	570
500	228	798	798	798	684	684	684	684	570	570
750	228	798	798	798	684	684	684	684	570	570
1000	228	798	798	798	684	684	684	684	570	570
1500	228	798	798	798	684	684	684	684	570	570
Distance, D = 15m										
25	456	1481	912	684	570	570	570	570	570	570
50	228	798	684	684	570	570	570	570	570	570
100	114	684	684	684	570	570	570	570	570	570
200	114	684	684	684	570	570	570	570	570	570
300	114	684	684	684	570	570	570	570	570	570
400	114	684	684	684	570	570	570	570	570	570
500	114	684	684	684	570	570	570	570	570	570
750	114	684	684	684	570	570	570	570	570	570
1000	114	684	684	684	570	570	570	570	570	570
1500	114	684	684	684	570	570	570	570	570	570

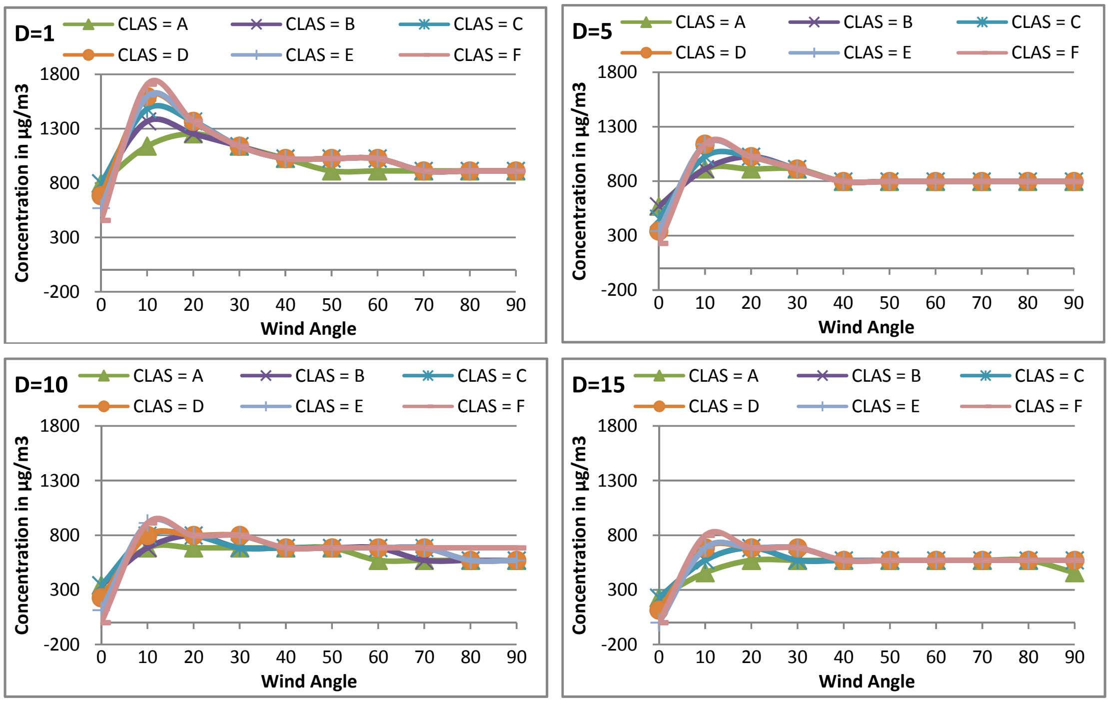


Fig. 4.11: CALINE 4 Sensitivity Analysis for Atmospheric Stability (CLAS)

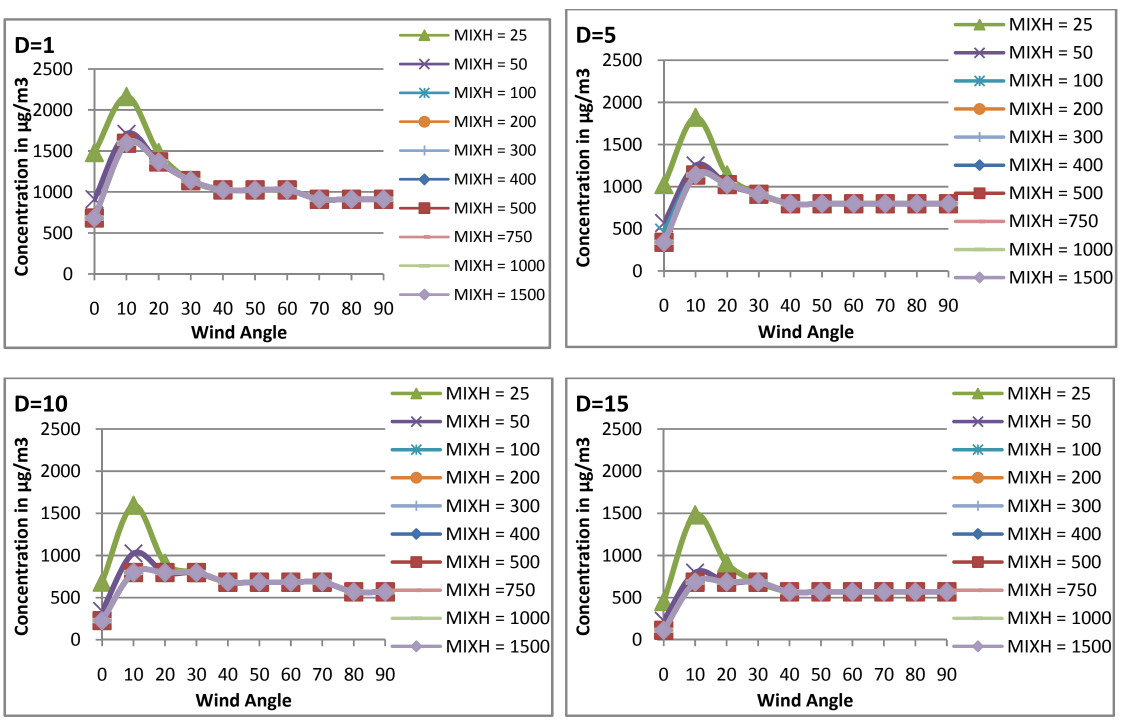


Figure 4.12 CALINE 4 Sensitivity Analysis for Mixing Height, MIXH (m)

Table 4.14 Predicted CO Concentrations at Receptor Locations for Surface Roughness

Surface Roughness (cm)	Wind Angle (°)									
	0	10	20	30	40	50	60	70	80	90
	CO Concentrations (µg/m^3)									
Distance, D = 1m										
3	798	1709	1368	1140	1026	1026	1026	912	912	912
5	798	1595	1368	1140	1026	1026	1026	912	912	912
10	684	1595	1368	1140	1026	1026	1026	912	912	912
25	684	1595	1368	1140	1026	1026	1026	912	912	912
50	684	1595	1368	1140	1026	1026	1026	912	912	912
75	684	1595	1368	1140	1026	1026	1026	912	912	912
100	684	1595	1368	1140	1026	1026	1026	912	912	912
125	684	1595	1368	1140	1026	1026	1026	912	912	912
150	684	1595	1368	1140	1026	1026	1026	912	912	912
Distance, D = 5m										
3	456	1140	1140	912	912	798	798	798	798	798
5	456	1140	1140	912	912	798	798	798	798	798
10	456	1140	1026	912	912	798	798	798	798	798
25	456	1140	1026	912	798	798	798	798	798	798
50	456	1140	1026	912	798	798	798	798	798	798
75	342	1140	1026	912	798	798	798	798	798	798
100	342	1140	1026	912	798	798	798	798	798	798
125	342	1140	1026	912	798	798	798	798	798	798
150	342	1140	1026	912	798	798	798	798	798	798
Distance, D = 10m										
3	228	912	912	798	684	684	684	684	684	684
5	228	912	798	798	684	684	684	684	684	684
10	228	912	798	798	684	684	684	684	684	684
25	228	912	798	798	684	684	684	684	684	570
50	228	798	798	798	684	684	684	684	570	570
75	228	798	798	798	684	684	684	684	570	570
100	228	798	798	798	684	684	684	684	570	570
125	228	798	798	798	684	684	684	684	570	570
150	228	798	798	798	684	684	684	684	570	570
Distance, D = 15m										
3	114	798	684	684	570	570	570	570	570	570
5	114	684	684	684	570	570	570	570	570	570
10	114	684	684	684	570	570	570	570	570	570
25	114	684	684	684	570	570	570	570	570	570
50	114	684	684	684	570	570	570	570	570	570
75	114	684	684	684	570	570	570	570	570	570
100	114	684	684	684	570	570	570	570	570	570
125	114	684	684	684	570	570	570	570	570	570
150	114	684	684	684	570	570	570	570	570	570

4.3.7 Highway Width

For sensitivity analysis, highway width was varied from 10 to 50m at an interval of 10m (viz., 10, 20, 30, 40, and 50). Predicted CO concentrations obtained have been shown in **Table 4.15** and **Fig. 4.14.** During increase in highway width, the relative distance of receptor locations from mixing zone width were remains same. Traffic volume will dispersed over variable highway width. Given constant source strength, and a receptor distance referenced from the downwind edge of the roadway, the model consistently predicts lower concentrations for greater highway widths. This effect was most apparent for receptors near the roadway edge. This was due to widening of the highway, the residence time over the mixing zone and the initial horizontal distribution of the source increases. Thus, both vertical and horizontal dispersions are enhanced and more dilution occurs (Benson, 1979). As the highway width increases from 10 to 50m, average decrease in CO concentration was 77%. The sensitivity of the model to highway width was relatively independent of the wind angle. The value of the critical angle for maximum CO concentrations was relatively insensitive to highway width. Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle.

Table 4.15 Predicted CO Concentration at Receptor Location for Highway Width (m)

Highway Width (m)	Wind Angle (°)									
	0	10*	20	30	40	50	60	70	80	90
	CO Concentrations (μg/m^3)									
Distance, D = 1m										
10.0	3191	3875	2963	2393	2165	2051	1937	1709	1709	1595
20.0	1254	2279	1937	1595	1368	1368	1254	1254	1254	1140
30.0	684	1595	1368	1140	1026	1026	1026	912	912	912
40.0	456	1140	1026	912	798	798	798	798	798	798
50.0	342	1026	912	798	684	684	684	684	684	684
Distance, D = 5m										
10.0	1026	1823	1595	1481	1368	1254	1140	1140	1140	1140
20.0	570	1368	1254	1140	1026	1026	1026	912	912	912
30.0	342	1140	1026	912	798	798	798	798	798	798
40.0	228	912	912	798	684	684	684	684	684	684
50.0	228	798	798	684	570	570	570	570	570	570
Distance, D = 10m										
10.0	456	1254	1026	1026	912	912	798	798	798	798
20.0	342	1026	912	912	798	798	798	684	684	684
30.0	228	798	798	798	684	684	684	684	570	570
40.0	114	684	684	684	570	570	570	570	570	570
50.0	114	570	684	570	570	570	456	456	456	456
Distance, D = 15m										
10.0	342	912	798	798	684	684	684	684	570	570
20.0	228	798	798	684	684	684	456	570	570	570
30.0	114	684	684	684	570	570	570	570	570	570
40.0	0	570	570	570	570	456	456	456	456	456
50.0	0	456	570	570	456	456	456	456	456	456

*Maximum CO Concentration at PHI = 10°

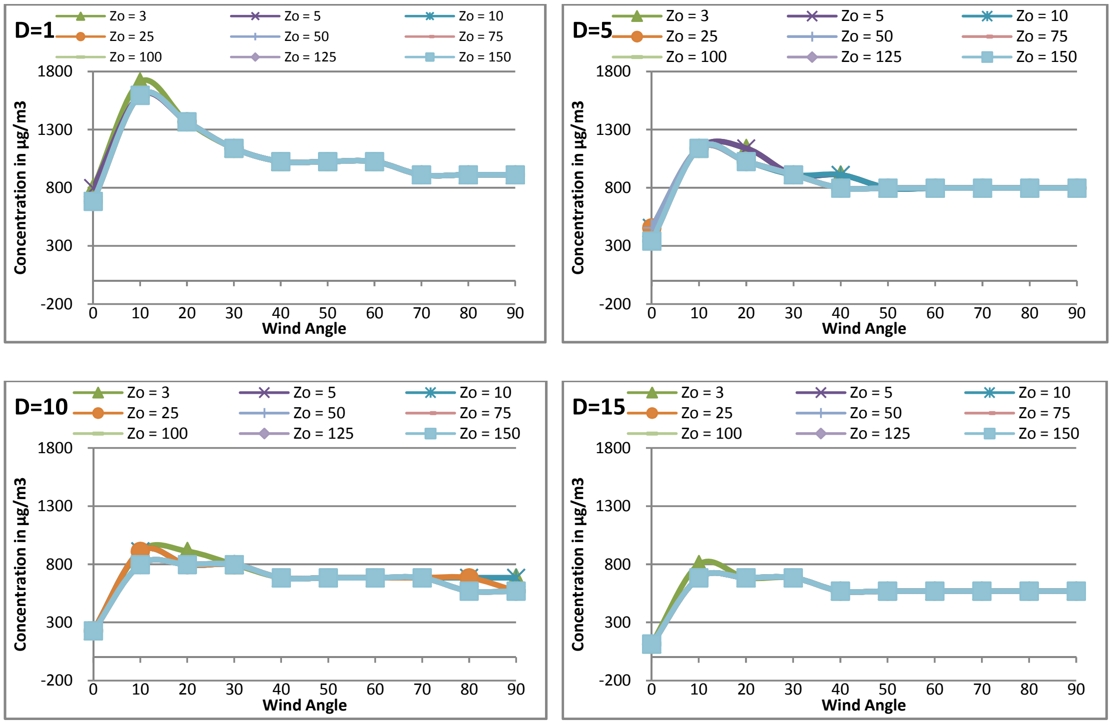


Fig. 4.13: CALINE 4 Sensitivity Analysis for Surface Roughness, Zo (cm)

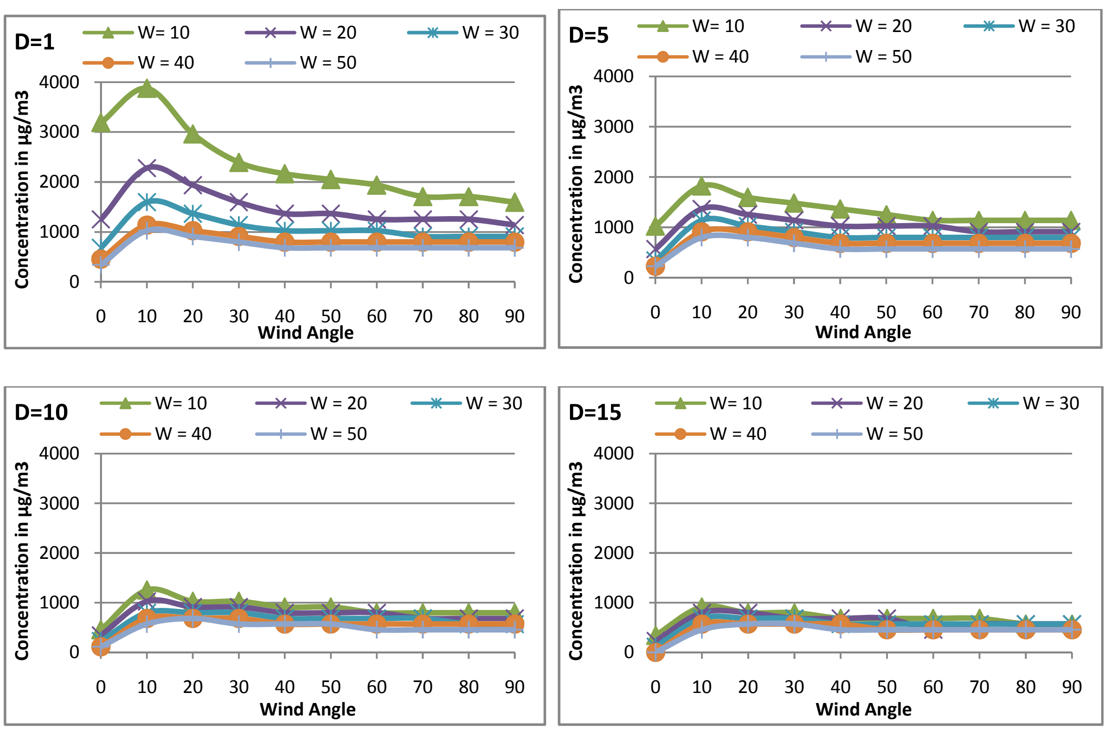


Fig. 4.14: CALINE 4 Sensitivity Analysis for Highway Width, W (m)

For all highway width, the maximum CO concentrations occur for 10° wind angle. Average decrease in predicted CO concentrations was 16.9% at 1m distance, 13.8

% at 5m distance, 11.3% at 10m distance and 9.5% at 15m distance from mixing zone width with increase of 10m in highway width. Batterman et al. (2010) in similar study has also found that wider the mixing zone width lesser the CO concentrations i.e. increasing the mixing zone width from 30 to 45 m decreases the CO concentrations by 24%.

If receptor distances for this analysis were not adjusted for the varying widths (i.e., D= W/2+constant), the effects of enhanced dispersion over the mixing zone would be more than offset by the increasing closeness of the mixing zone to the receptor.

4.2.8 Roadway Height

For sensitivity analysis, roadway height was varied from -10 to 10m. Predicted CO concentrations obtained have been shown in **Table 4.16** and **Fig. 4.15.** The model response to changes in roadway height is quite complex, though based on simple underlying assumptions (Benson, 1979). CO concentrations were sensitive to road height, particularly near-road receptors. Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle. For all highway width, the maximum CO concentrations occur for 10° wind angle.

For elevated (as a bridge above a receptor) section (10m), lower than normal CO concentration for near receptor location i.e. average decrease in CO concentrations was 16% for receptor location at 1m distance for mixing zone. But as the distance of receptor location increases no significant change was observed. The decrease in CO concentrations predicted near the elevated section become more prominent as the wind angle approaches perpendicular wind conditions. This is because longer residence time creates more initial mixing thereby higher the impact on receptor locations near the mixing zone width. CALINE4 assumes uninterrupted wind flows beneath the bridge, thus elevating the plume over near-road receptors. The size of these effects depends on the vertical distance above or below grade level. Decrease in CO concentration at receptor locations was much more significant for crosswind conditions than for parallel wind conditions. Under parallel wind conditions, this effect was less significant because of the larger distances over which pollutants must travel.

Table 4.16: Predicted CO Concentrations at Receptor Locations for Roadway Height (m)

Wind Angle (°)	Roadway Height (m)								
	-10*	-5	-2	-1	0	1	2	5	10**
	CO Concentrations (µg/m³)								
Distance, D = 1m									
0	1254	912	684	684		684	684	684	570
10	2393	1823	1481	1595		1595	1595	1481	1140
20	1823	1481	1254	1368		1368	1368	1140	798
30	1368	1254	1026	1140		1140	1140	1026	570
40	1254	1026	912	1026		1026	1026	798	456
50	1140	1026	912	1026		1026	1026	798	342
60	1140	1026	912	1026		1026	912	684	342
70	1140	1026	912	912		912	912	684	228
80	1026	912	798	912		912	912	684	228
90	1026	912	798	912		912	912	684	228
Distance, D = 5m									
0	570	342	342	342		342	342	342	342
10	1481	1026	912	1140		1140	1140	1026	1026
20	1254	912	912	1026		1026	1026	1026	798
30	1026	684	798	912		912	912	798	570
40	912	684	684	798		798	798	684	456
50	798	570	684	798		798	798	684	456
60	798	570	684	798		798	798	684	342
70	798	570	684	798		798	798	570	342
80	798	570	684	798		798	798	570	342
90	798	570	684	798		798	684	570	228
Distance, D = 10m									
0	228	114	228	228		228	228	228	228
10	912	456	684	798		798	798	798	798
20	798	456	684	798		798	798	798	684
30	684	342	684	798		798	798	684	570
40	570	342	570	684		684	684	684	456
50	570	342	570	684		684	684	570	456
60	570	342	570	684		684	684	570	342
70	570	342	570	684		684	684	570	342
80	570	342	570	570		570	570	570	342
90	570	342	570	570		570	570	570	342
Distance, D = 15m									
0	114	114	114	114		114	114	114	114
10	570	456	570	684		684	684	684	684
20	456	342	570	684		684	684	684	570
30	342	342	570	684		684	684	570	570
40	342	342	456	570		570	570	570	456
50	342	228	456	570		570	570	570	456
60	342	228	456	570		570	570	456	342
70	342	228	456	570		570	570	456	342
80	342	228	456	570		570	570	456	342
90	342	228	456	570		570	570	456	342

*Maximum CO Concentration at Roadway Height = -10m
**Minimum CO Concentration at Roadway Height = 10m

For depressed section (-10m), higher than normal CO concentration within the depressed section i.e. average increase in CO concentrations was 79% for receptor location at 1m distance for mixing zone. But as the distance of receptor location increases no significant change was observed. The increased concentrations predicted within and near the depressed section become more prominent as the wind angle approaches parallel wind conditions. This is because longer residence time creates more initial mixing thereby higher the impact on receptor locations near the mixing zone width.

Similar type of result was also found by Sripraparkon et al. (2003). Batterman, 2010, also found that when the roadway was depressed below grade, concentrations decreased by 45% close to the road; the decrease was smaller (17%) at long downwind distances. For elevated roads/bridges, CO concentrations are low at receptors very near the road, but at longer distances, CO concentrations are identical to those attained for roads at grade.

4.2.9 Median Width

Because of the link capabilities of CALINE 4, it is no longer necessary to incorporate medians as part of the mixing zone. A divided roadway may be modelled as either two separate links or a single link with the median incorporated in the highway width specification (this assumes identical link specifications for both directions of flow). For cases where there is a significant median involved, the two link computation gives slightly higher predicted concentrations over the single link model. This holds true for virtually all wind angles, but tends to be slightly more pronounced for crosswind conditions (Benson, 1979).

For sensitivity analysis, median width was varied from 0 to 10m at an interval of 2.5 (viz., 0, 2.5, 5, 7.5, and 10). Predicted CO concentrations obtained have been shown in **Table 4.17** and **Fig. 4.16.** CALINE 4 model was relatively sensitive to median width. It was seen that with increase in median width, CO concentrations decreases due to the dispersion increase with increase in median width, i.e. with increase in median width of 2.5m, CO concentration was decreases by 11%. With increase in median width from 0 to 10m, average drop in CO concentration was 37% at near receptor locations. At greater receptor distances from mixing zone width, there was a slight sensitivity in the model to median width i.e. average CO concentration decreases less than 10%. Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle. For all highway width, the maximum CO concentrations occur for 10° wind angle.

Table 4.17: Predicted CO Concentrations at Receptor Locations for Median Width (m)

Median Width (m)	Wind Angle (°)									
	0	10*	20	30	40	50	60	70	80	90
	CO Concentrations (μg/m³)									
Distance, D = 1m										
0.0	798	1709	1481	1254	1140	1140	1026	1026	1026	1026
2.5	684	1481	1368	1140	1026	1026	1026	912	912	912
5.0	684	1481	1254	1140	1026	912	912	912	912	912
7.5	570	1368	1140	1026	912	912	912	798	798	798
10.0	456	1254	1140	1026	912	798	798	798	798	798
Distance, D = 5m										
0.0	456	1140	1140	1026	912	912	798	798	798	798
2.5	342	1026	1026	912	798	798	798	798	798	798
5.0	342	1026	1026	912	798	798	798	798	684	684
7.5	342	1026	912	798	798	684	684	684	684	684
10.0	342	912	912	798	684	684	684	684	684	684
Distance, D = 10m										
0.0	228	912	798	798	684	684	684	684	684	684
2.5	228	798	798	798	684	684	684	684	570	570
5.0	228	798	798	684	684	684	684	570	570	570
7.5	228	798	798	684	684	570	570	570	570	570
10.0	228	684	684	684	570	570	570	570	570	570
Distance, D = 15m										
0.0	114	684	684	684	570	570	570	570	570	570
2.5	114	684	684	684	570	570	570	570	570	570
5.0	114	684	684	570	570	570	570	570	570	570
7.5	114	570	684	570	570	570	570	456	456	456
10.0	0	570	570	570	570	570	456	456	456	456

*Maximum CO Concentration at PHI = 10°

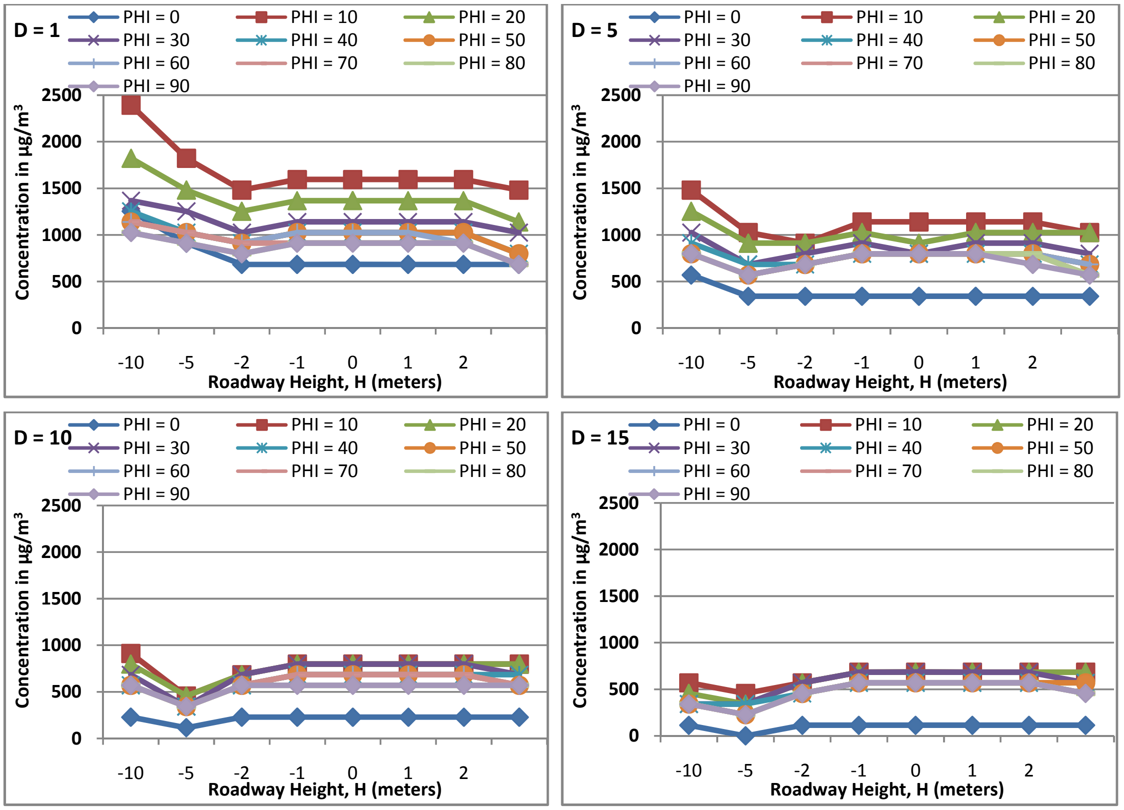


Fig. 4.15: CALINE 4 Sensitivity Analysis for Roadway Height, H (m)

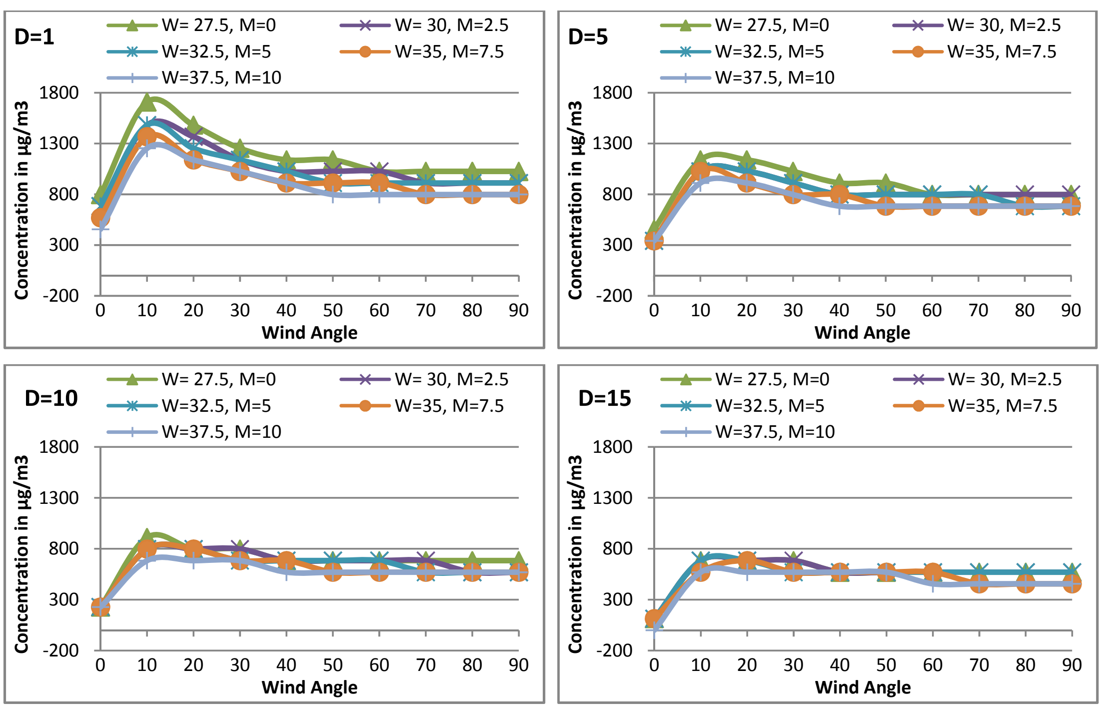


Fig. 4.16: CALINE 4 Sensitivity Analysis for Median Width, M (m)

4.4 Summary of Results

The sensitivity analysis of CALINE 4 model was done for various inputs variables (viz., Source Strength, Wind Angle, Wind Speed, Stability Class, Surface Roughness, Mixing Height, Highway Width, Roadway Height, and Median Width). A summary of sensitivity analysis of CALINE 4 for various input variables is shown in **Table 4.18** and **Fig. 4.17.**

Table 4.18: Sensitivity Analysis of CALINE 4 for Various Input Variables

S. NO.	Parameter	Sensitivity of CALINE 4 model
1	**Source Strength**	The source strength was directly proportional to the predicted CO concentration. Hence, a two fold increase in either the vehicle emission factor or the traffic volume will result in a doubling of the predicted CO concentration.
2	**Wind Angle**	CALINE 4 model has been found to be relatively sensitive to wind angle for small receptor distance. With every 5° increase in wind angle, average 8% decrease in CO concentrations were found for 1m to 2m distance from mixing zone width. However, at greater distances from mixing zone width, there is a less sensitivity in the model for wind angle. For wind angle 30° to 90°, as the distance from mixing zone width increases from 1m to 150m, CO concentrations decreased by 85%. Average CO concentrations increased by 20% from parallel (0°) to perpendicular (90°) wind angle.
3	**Wind Speed**	Wind speed had a considerable effect, e.g., predicted CO concentrations were dropped by 75% - 80% as wind speed increased from 0.5 to 5 m/s. With increase of 0.5 m/s in wind speed, average 9% decrease was observed in predicted CO concentrations. It was also found that with increase in wind speed, moderate increase in CO concentrations occurs at higher distance from roadway. For all wind speeds, the maximum CO concentrations occur for 10° wind angle, these maximum CO concentrations become less evident at higher wind speeds.
4	**Stability Class**	The average increases in CO concentrations were less than 5% with stability class changes from A to F. No significant effect was observed for 30° to 90° wind angle. At the edge of the mixing zone width (D=1m) the predicted CO concentration was less sensitive to stability class under cross wind conditions than at greater distance. At 10° wind angle, from unstable to stable conditions, average increase in CO concentration was 43%.
5	**Mixing Height**	No significant effect was found for receptor locations at greater distance from mixing zone width. The model response for MIXH = 100m was same as to MIXH = 1500m. Mixing height less than 100m is found in very rare cases, therefore it can be concluded that mixing height has no effect.
6	**Surface Roughness**	CALINE 4 was sensitive for very small values of Aerodynamic Roughness Coefficient (<10cm). It was found that CALINE 4 was sensitive only for near rural areas (i.e. near 10cm Aerodynamic Roughness Coefficient) It was relatively sensitive to surface roughness for near parallel wind conditions (~10°).

7	**Highway Width**	As the highway width increases from 10 to 50m, average decrease in CO concentration was 77%. The sensitivity of the model to highway width was relatively independent of the wind angle. Average decrease in predicted CO concentration was 16.9% at 1m distance, 13.8 % at 5m distance, 11.3% at 10m distance and 9.5% at 15m distance from mixing zone width with increase of 10m in highway width.
8	**Roadway Height**	For elevated section (10m from ground level), lower than normal CO concentrations for near receptor location i.e. average decrease in CO concentrations was 16% for receptor location at 1m distance for mixing zone. But as the distance of receptor locations increases no significant change was observed. The decrease in CO concentrations predicted near the elevated section become more prominent as the wind angle approaches perpendicular wind conditions. For depressed section (-10m from ground level), higher than normal CO concentrations within the depressed section i.e. average increase in CO concentrations was 79% for receptor location at 1m distance for mixing zone. But as the distance of receptor locations increases no significant change was observed. The increased CO concentrations predicted within and near the depressed section become more prominent as the wind angle approaches parallel wind conditions.
9	**Median Width**	CALINE 4 model was relatively sensitive to median width. It was seen that with increase in median width, CO concentrations decreases due to the dispersion increase with increase in median width, i.e. with every 2.5m increase in median width, CO concentrations decreased by 11%. With increase in median width from 0 to 10m, average drop in CO concentrations was 37% at near receptor locations. At greater receptor distances from mixing zone width, there was a very less sensitivity in the model to median width i.e. average CO concentrations decreases less than 10%.

Sensitive Analysis of CALINE 4 had also revealed that source strength, wind speed, highway width and median width were most significant input variable and wind direction, roadway height, distance of receptor to roadway and atmospheric stability were the less significant input variables. Surface roughness, mixing height has negligible effect on predicted CO concentrations.

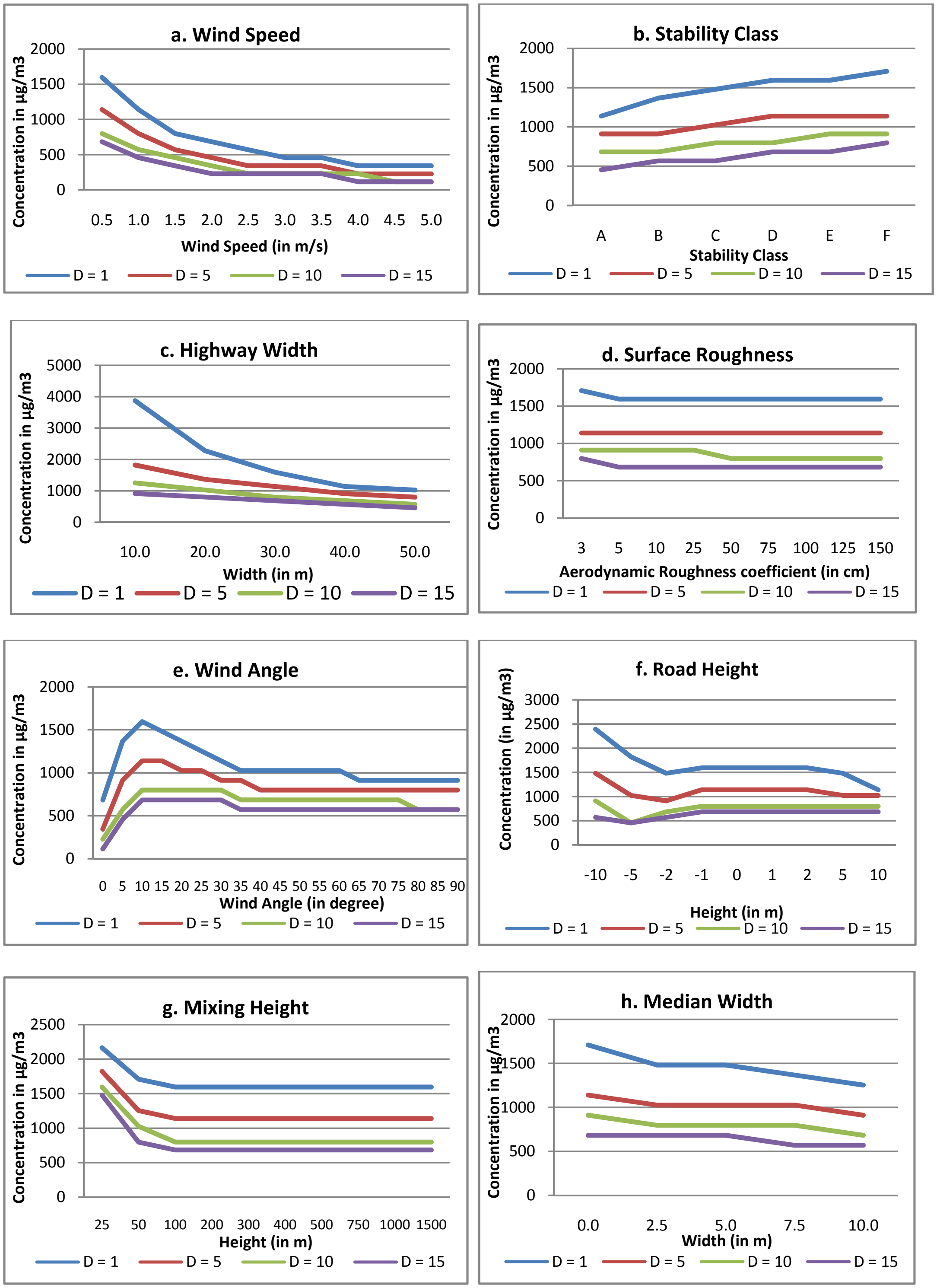


Fig. 4.17: Sensitive Analysis of CALINE 4 Model

5.0 CONCLUSIONS AND SCOPE FOR FUTURE STUDIES

1.1 Conclusions

- The estimated Weighted Emission Factor along the Ashram Chowk-CRRI highway corridor of NH-2 using ARAI (2007) emission factors was 2.96µg/m^3 per vehicle and using CPCB (2000) emission factors was 2.67µg/m^3 per vehicle.
- The maximum predicted CO concentrations at receptor locations (at distance 1 meter from the edge of mixing zone width) are given in **Table 5.1**.
- It was found that dispersion of predicted 1-hour and 8-hour CO concentration for both emission factors was maximum in the North-East direction for standard run condition as average wind direction was from South-West direction.
- Predicted 1-hour CO concentration was found to be maximum in peak hours (17:00-20:00).
- The dispersion of CO concentrations was found to be present upto a distance of 150 meters from the edge of the mixing zone width (road width + 3 meters on each side of the road).
- Predicted CO concentrations was greater for Worse Case as compare to Standard Case because for Worse Case the model selects the wind angles that produce the highest CO concentrations at each of the receptors locations

Table 5.1: Maximum Predicted CO Concentration at Receptor Location

Emission Factors	Duration	Standard Run Condition	Worse Case Condition
ARAI's	(1-hour)	1025.6 µg/m^3	1595 µg/m^3
CPCB's	(1-hour)	911.7 µg/m^3	1481µg/m^3
ARAI's	(8-hours)	797.7 µg/m^3	1254 µg/m^3
CPCB's	(8-hours)	797.7 µg/m^3	1140 µg/m^3

- Maximum estimated 1-hour CO concentrations using ARAI emission factors for Standard Case Run Conditions was 2040 µg/m^3 and for Worse Case Run Condition was 2610 µg/m^3.
- Similarly, maximum estimated 1-hour CO concentrations using CPCB emission factors for Standard Case Run Condition was 2017 µg/m^3 and for Worse Case Run Condition was 2496 µg/m^3**.**

- All the estimated 1-hour CO concentrations were within the NAAQS, 2009 (4 mg/m^3 for 1-hour) for both Run Conditions (Standard and Worse Case).
- The regression coefficient (r^2) between predicted and observed 1-hour CO concentrations using CPCB emission factors for Standard Case Run Condition was 0.65 and for Worse Case Run Condition was 0.76.
- Similarly, the regression coefficient (r^2) between predicted and observed 1-hour CO concentrations using ARAI emission factors for Standard Case Run Condition was 0.60 and for Worse Case Run Condition was 0.73.
- The comparison of predicted and observed 1-hour CO concentrations shows that the values fall within close ranges.
- The predicted 1-hour CO concentrations for Worse Case Run Conditions were closer to observed CO concentration than for Standard Run Conditions.
- CALINE 4 model has been found to be relatively sensitive to wind angle for small receptor distances. With every 5° increase in wind angle, average 8% decrease in CO concentrations were found for 1m to 2m distance from mixing zone width. However, at greater distances from mixing zone width, there is a slight sensitivity in the model for wind angle. For wind angle 30° to 90°, as the distance from mixing zone width increases from 1m to 150m, CO concentrations decreased by 85%. Average CO concentrations were increased by 20% from parallel (0°) to perpendicular (90°) wind angle.
- Wind speed had a considerable effect, e.g., predicted CO concentrations were dropped by 75% - 80% as wind speed increased from 0.5 to 5 m/s. With increase of 0.5 m/s in wind speed, average 9% decrease was observed in predicted CO concentrations. For wind speed 0.5 to 1 m/s, maximum decrease in CO concentration was 33% at 1m distance from mixing zone width (at 60° wind angle).
- The location of the maximum CO concentrations appears to be relatively insensitive to wind speed and receptor distance.
- Higher traffic volume increases CALINE 4 predictions due to its proportional relationship with emission rates.
- The average increase in CO concentrations was less than 5% with stability class from A to F. Therefore it was a less significant input variable. At the edge of the

mixing zone width (D=1m) the predicted concentration was less sensitive to stability class under cross wind conditions than at greater distance.

- The model consistently predicts lower concentrations for greater highway widths. This effect was most apparent for receptors near the roadway edge. Average decrease in predicted concentration was 16.9% at 1 meter distance, 13.8 % at 5 meters distance, 11.3% at 10 meters distance and 9.5% at 15 meters distance from mixing zone width with increase of 10 meters in highway width. This was due to both vertical and horizontal dispersion enhanced and more dilution would occur.
- Roadway height had very less effect for small change in height but has strong effect for more deeper or elevated roadway height. For elevated section (10m), lower than normal CO concentration for near receptor location i.e. average decrease in CO concentrations was 16% for receptor location at 1m distance for mixing zone. But as the distance of receptor location increases no significant change was observed. The decrease in CO concentrations predicted near the elevated section become more prominent as the wind angle approaches perpendicular wind conditions.
- For depressed section (-10m), higher than normal CO concentration within the depressed section i.e. average increase in CO concentrations was 79% for receptor location at 1m distance for mixing zone. But as the distance of receptor location increases no significant change was observed.
- CALINE 4 was sensitive for very small values of Aerodynamic Roughness Coefficient (<10cm). It was found that CALINE 4 was sensitive only for near rural areas (i.e. near 10cm Aerodynamic Roughness Coefficient).
- No significant effect was found for receptor locations at greater distance from mixing zone width. The model response for MIXH = 100m was same as to MIXH = 1500m. Mixing height less than 100m is found in very rare cases, therefore it can be concluded that mixing height has no effect.
- Surface Roughness and Mixing height had negligible effect on predicted CO concentrations.
- Sensitive Analysis of CALINE 4 revealed that source strength, wind speed, highway width and median width were most significant input variable and wind

direction, roadway height, distance of receptor to roadway and atmospheric stability were the less significant input variables.

5.2 Recommendations for Future Work

Any research begets new series of research in order to establish facts and reach (new) conclusions. Consequent upon fine-tuning of methodology and need of the new horizon of problems, further investigations may be needed. A preview of further research which may be needed in this area is presented hereunder:

(i) Comparison of different models can be done using actual field data.

(ii) There is always scope of realistic emission factor for in-use vehicles pertaining to Indian traffic condition (i.e. city specific driving cycle).

(iii) Traffic volume should be measured at few more major intersections along the highways to have the realistic traffic counts on the corridors and surveys have to be conducted in different seasons.

(iv) Sensitivity analysis of CALINE 4 for 8-hour CO concentrations and under Worse Case Condition can also be done.

REFERENCES

- **Anjaneyulu M.V.L.R., Harikrishna M., and Chenchuobulu, S. (2006)**. Modeling Ambient Carbon Monoxide Pollutant Due to Road Traffic, World Academy of Science, Engineering and Technology, 17, 103-106.
- **ARAI (2007)**. Emission Factor Development for Indian Vehicles. Project Report No. AEF/2006-07/IOCL/Emission Factor Project. Automotive Research Association of India, Pune (available on www.cpcb.nic.in).
- **Batterman, S. A., Zhang, K. and Kononowech, R. (2010).** Prediction and analysis of near-road concentrations using reduce-form emission/dispersion model, Environmental Health, 9-29.
- **Benson, P. E., Nokes, W. A., Cramer, R. L. (1986).** Evolution of the CALINE 4 Line Source Dispersion Model for Complex Terrain Application, Transportation Research Record N1058, 7-13.
- **Briant, R. and Korsakissok, I. (2011).** Christian Seigneur An improved line source model for air pollutant dispersion from roadway traffic, Atmospheric Environment, 30, 1-9.
- **CERC.** Robins, *A*. (2000), Discussion of the Building Modules in ADMS 3 and PRIME, Cambridge Environmental Research Consultant Report.
- **Counihan, J. (1975)**. Adiabatic Atmosphere Boundary Layer: A review and Analysis of Data from the Period 1880-1973. Atmospheric Environment, 9 (10), 871-905.
- **CPCB, (2000a)**. Transportation Fuel Quality for year 2005. *PROBES/78/2000-01*, Central Pollution Control Board, Ministry of Environment and Forest, New Delhi, Govt. of India.
- **CPCB, (2000b)**. Air Quality Status and Trends in India. National Ambient Quality Monitoring Series, *NAAQMS/14/1999-2000*, Central Pollution Control Board, Ministry of Environment and Forest, New Delhi, Govt. of India.
- **CPCB, (2010).** Status of the Vehicular Pollution Control Programme in India. Central Pollution Control Board, Ministry of Environment and Forest, New Delhi, Govt. of India.
- **CRRI, (2001).** Impact Assessment of Vehicular Pollution between Mathura-Delhi and Mathura-Agra Corridors. Central Road Research Institute Report.

- **CRRI, (2005).** Measurement of Vehicular Pollution at Selected Intersection in Delhi. Central Road Research Institute Report.
- **Dejun L. and Wang, X. (2007)**. Nitric oxide emission from a typical vegetable field in the Pearl River Delta, China, Atmospheric Environment 41, 9498–9505.
- **EEA (2010).** Sources of Air Pollution: Local Authorities, Health and Environment, European Environmental Agencies Report.
- **Elsom, D. M. (1994)**. The Development of Air Quality Management System in the United Kingdom. In: Baldasano, J. M., Brebbia, C. A., Power, H. and Zannetti, P. (Eds). Air Pollution Control and Monitoring, II, 22-29.
- **Eskridge, R. E. and Rao, S. T. (1983)**. Measurement and prediction of Traffic Induced Turbulence and Velocity Fields Near Roadways. Journal of Applied Meteorology, 22, 1431-1440.
- **Eskridge, R. E. and Rao, S. T. (1986).** Turbulent diffusion behind vehicles: experimentally determined turbulence mixing parameters. Atmospheric Environment, 20 (5), 851-860.
- **Eskridge, R. E. and Thampson, R. S. (1982).** Experimental and Theoretical Study in the Wake of a Block Shaped Vehicle in Shear Free Boundary Flow, Atmospheric Environment, 16 (12), 2821- 2836.
- **Farrugia, P. S. and Micallef, A. (2006).** Comparative analysis of estimators for wind direction standard deviation, Meteorological Application, 13, 29–41.
- **Ganguly, R., Broderick, B. M. and O'Donoghue, R. (2009)**. Assessment of a General Finite Line Source Model and CALINE 4 for Vehicular Pollution Prediction in Ireland, Environ Model Assess, 14, 113–125, *DOI10.1007/s10666-008-9152-8*.
- **Gilbert M. M. (1997)**. Introduction to Environmental Engineering and Science, Second Edition, Prentice Hall, USA.
- **Goyal, P. and RamaKrishna, T.V.B.P.S. (1999)**. A Line Source Model for Delhi, Transportation Research Part D 4, 241-249.
- **Gramotnev, Galina, Brown, Richard J., Ristovski, Zoran, Hitchins, Jane, & Morawska, Lidia (2003)**. Determination of Average Emission Factors for Vehicl es on a Busy Road, Atmospheric Environment, 37(4), 465-474.

- **Hanna, S. R. (1982).** Review of Atmospheric Diffusion Models for Regulatory Applications, Technical Note No. 177, World Meteorological Organization, Geneva, Switzerland.
- **Hayes, S. R. and Moore, G. E. (1985).** Air quality model performance: A comparative analysis of 15 model evaluation studies. Systems Applications, Inc., 101 Lucas Valley Road, San Rafael, California 94903, U.S.A.
- **Jungers, B. D. et al. (2006).** A Survey Of Air Quality Dispersion Models For Project- Level Conformity Analysis, UC Davis-Caltrans Air Quality Project, Air Quality and Conformity Coordination, Division of Transportation Planning, Sacramento, CA.
- **Kadiyali, L. R. (1983)**. Traffic Engineering and Transport Planning. Khanna Publishers, Delhi, Second Edition, 499.
- **Kathuria, V. (2005)**. Vehicular Pollution Control-Concept note, Madras School of Economics, Gandhi Mandapam Road, Chennai 600 025.
- **Kenty, K. L. et al. (2007).** Application of CALINE4 to roadside NO/NO2 transformation, Elsevier, Atmospheric Environment, 4270-4280.
- **Kenneth, E. N., Terry, L. M. and Claggett, M. (1977).** A comparison of three highway line source dispersion models, Pritzker Department of Environmental Engineering, Illinois Institute of Technology, Chicago, IL 60616, U.S.A.
- **Khanna, S. K. (2001)**. Highway Engineering. Nem Chand and Bros., Roorkee, Eighth Edition, 190.
- **Levitina, J., Harkonenb, J., Kukkonenb, J. and Nikmob, J. (2005).** Evaluation of the CALINE4 and CAR-FMI models against measurements near a major road, Atmospheric Environment, 39, 4439–4452.
- **Lin, J. and Ge, Y (2006).** Impacts of traffic heterogeneity on roadside air pollution concentration, Transportation Research Part D 11, 166–170.
- **Longhurst, J. W. S., Elsom, D. M. and Power, H. (2000)**. Air Quality Management, WIT Press, Southampton, Boston (USA).
- **Luhar, A. K. and Patil, R.S. (1989).** A General Finite Line Source Model for vehicular pollution prediction, Atmospheric Environment, 23 (3), 555-562.
- **Majumdar, B. K., Dutta, A., Chakrabarty S. and Ray, S. (2008).** Correction Factors of CALINE 4: A Study of Automobile Pollution in Kolkata, Indian Journal of Air Pollution Control, 8 (1), 1-7.

- **Majumdar, B. K., Dutta, A., Chakrabarty S. and Ray, S. (2010)**. Assessment of Vehicular Pollution in Kolkata, India using CALINE 4 Model. Environ Monit Assess, 70, 33-43.
- **Makra, L., et al (2008).** Modelling Air Pollution of Vehicular Traffic in Szeged, Epidemiology, 19 (6), S85-S86.
- **Marmur, A. and Mamane, Y. (2003).** Comparison and evaluation of several mobile-source and line-source models in Israel, Transportation Research part D, 8, 249-265.
- **Nagendra, S. M. S. and Khare, M. (2002).** Line Source Emission Modelling, Atmospheric Environment, 36, 2083–2098.
- **Nagendra, S. M.S., Venugopal, K. and Jones S. L. (2007).** Assessment of Air Quality Near Traffic Intersections in Bangalore City using Air Quality Indices**.** Transportation Research Part D: Transport and Environment, 12 (3), 167-176.
- **NPTEL. Khare, M. (2004)**. Air Quality Modelling, National Programme on Technology Enhancement Learning.
- **NTIS. Benson, P. E. (1979).** CALINE 3 – A Versatile Dispersion Model for Predicting Air Pollutant Levels Near Highways and Arterial Streets, National Technical Information Service.
- **NTIS. Coe, D. L. (1998).** User’s Guide for CL4: A user-Friendly Interface for the CALINE 4 Model for Transportation Project Impact Assessments, National Technical Information Service.
- **Park, J.Y. (2005).** Microscopic Modelling of Air Pollution from Road Traffic, Doctor of Philosophy thesis, Imperial College London.
- **Pasquill, F. and Smith, F. B. (1983)**. Atmospheric Diffusion, 3rd Edition, New York, USA: John Wiley & Sons Inc.
- **Patel, I, Kumar, A, Manne, G (2003).** Sensitivity Analysis of CAL3QHC Roadway Intersection Mode, Transportation Research Record, 109-117.
- **Rao, K. S. (2002).** Roadway-2: A Model for Pollutant Dispersion near Highways, Water, Air, and Soil Pollution: Focus, 2, 261–277.
- **Rao, M. N. and Rao, H. V. N. (1989)**. Air Pollution, Mc-Grow Hill, India.
- **Robet, V. R. (2002).** A Study on Transport Related Air Pollution, M. Tech. Dissertation, IIT – Roorkee.

- **Sarin, S. M. Singh, A. Sharma, N. Sharma, K. and Shanmugum, P. (2001)**. Evaluation of emission characteristics and compliance of emission standards for in-use petrol driven vehicles in Delhi, Indian J Environ Health, 43(1), 1-20.
- **Sahlodina, A. M., Sotudeh, R. Gharebagha and Zhub, R. (2007).** Modeling of dispersion near roadways based on the vehicle-induced turbulence concept, Atmospheric Environment, 41, 92–102.
- **Sharma, N. (2004)**. Physical Simulation of Vehicular Pollution Dispersion in an Isolated Urban Street Canyon under Heterogeneous Traffic Conditions, Ph.D. thesis, IIT- Delhi.
- **Sharma, N., Chaudhry, K. K. and Rao, C. V. C. (2004).** Vehicular Pollution Prediction Modelling: A Review of Highway Dispersion Models, Transport Reviews, 24 (4), 409–435.
- **Sharma, N., Chaudhry, K. K. and Rao, C. V. C. (2005).** Vehicular Pollution Modelling in India. IE (I) Journal- EN, 85, 46-53.
- **Sharma, N., Gangopadhyay, R. and Dhyani, R. (2010)**. Methodology for Estimation of CO2 Reduction from Mass Rapid Transit System (MRTS) Project, Journal of Scientific & Industrial Research, 69, 586-593.
- **Sharma, P. and Khare, M. (2001).** Modelling of vehicular exhausts-a review, Transportation Research Part D, 6, 179-198.
- **SIAM (2011)**. Market Share. Society of Indian Automobile Manufacturers.
- **Singh, B.K., Singh, R.P., Singh, A.K. and Prashad, S.C. (2006).** Deterministic Models for Line Source Emission: A Review, Journal IAEM, 33 (3), 163-167.
- **Sivacoumar, R. and Thanasekaran, K. (1998).** Line source model for vehicular pollution prediction near roadways and model evaluation through statistical analysis, Environmental Pollution, 104, 389-395.
- **Sripraparkorn, C., Jinsart, W. and Hooper, M. (2003)**. Application of CALINE 4 Air Quality Model and the TSI DustTrak for the Prediction and Measurement of Roadside Particulate Matter and Carbon Monoxide Levels in Bankok, Proceedings of the 2nd Regional Conference on Energy Technology Towards a Clean Environment 12-14 February 2003, Phuket, Thailand.
- **Sunil (2008)**. Vehicular Pollution Modelling Along a Highway Corridor Under Mixed Traffic Condition. M.Tech. dissertation, Guru Jambheshwar University of Science and Technology.

- **Sunil, Sharma, N. and Kaushik, C. P. (2008).** Vehicular Pollution Modelling along a Highway Corridor under Mixed Traffic Conditions, National Conference on Sustainable Urban Environment: Issues & Management Strategies.
- **Turmer, D. B. (1970)**. Workbook of Atmospheric Dispersion Estimates. AP-26, Office of Air Programs, US Environmental Protection Agency, Research Triangle Park, NC.
- **USEPA (2008)**. Emission and Air Quality Modelling Tool for Near-Roadway Application, *EPA/600/R-09/001*, United State Environmental Protection Agency.
- **USEPA (2000).** Environmental Protection Planning and Standards Agency Research Triangle Park, *EPA-454/R-99-005*, United State Environmental Protection Agency.
- **USEPA (2000).** Meteorological Monitoring Guidance for Regulatory Modeling Applications**,** *EPA-454/R-99-005*, United State Environmental Protection Agency.
- **USEPA (2004).** Summary Descriptions of Alternative Air Quality Models, United State Environmental Protection Agency.
- **USEPA (2005)**. Air Quality, Draft EIR Downtown Specific Plan July 2005. Ch – 4, 4.4.1 – 4.4.13.
- **Wahab, S. A. A. (2004).** An Application and Evaluation of the CAL3QHC Model for Predicting Carbon Monoxide Concentrations from Motor Vehicles Near a Roadway Intersection in Muscat, Oman, Environmental Management, 34 (3), 372–382.
- **Wikimapia**. http://www.wikimapia.org.
- **Yura, E. A., Kear, T. and Niemeier, D. (2007).** Using CALINE dispersion to assess vehicular $PM_{2.5}$ emissions, Atmospheric Environment, 41, 8747–8757.

APPENDIX I

National Ambient Air Quality Standards (NAAQS), 2009

Pollutants	Time-Weighted Average	Concentration in Ambient Air		Method of measurement
		Industrial, Residential, Rural and Other Area Areas	Ecologically sensitive Area (notified by Central Government)	
Sulphur Dioxide (SO_2)	Annual*	50 µg/m^3	20 µg/m^3	- Improved West and Geake Method - Ultraviolet Fluorescence
	24 hours**	80 µg/m^3	80 µg/m^3	
Nitrogen Dioxide (NO_2)	Annual*	40 µg/m^3	30 µg/m^3	-Modified Jacob & Hochheiser (Na-Arsenite) – Chemiluminescence
	24 hours**	80 µg/m^3	80 µg/m^3	
Particulate Matter (size less than 10µm) or PM_{10}	Annual*	60 µg/m^3	60 µg/m^3	-Gravimetric -TOEM -Beta attenuation
	24 hours**	100 µg/m^3	100 µg/m^3	
Particulate Matter (size less than 2.5µm) or $PM_{2.5}$	Annual*	40 µg/m^3	40 µg/m^3	-Gravimetric -TOEM -Beta attenuation
	24 hours**	60 µg/m^3	60 µg/m^3	
Ozone (O_3)	8 hours**	100 µg/m^3	100 µg/m^3	-UV Photometric -Chemilminescence -Chemical Method
	1 hours**	180 µg/m^3	180 µg/m^3	
Lead (Pb)	Annual*	0.50 µg/m^3	0.50 µg/m^3	-ASS Method after sampling using EPM 2000 or equivalent Filter paper -ED-XRF using Teflon filter
	24 hours**	1.0 µg/m^3	1.0 µg/m^3	
Ammonia (NH_3)	Annual*	100 µg/m^3	100 µg/m^3	-Chemiluminescence -Indophenol Blue Method
	24 hours**	400 µg/m^3	400 µg/m^3	
Carbon Monoxide (CO)	8 hours**	02 mg/m^3	02 mg/m^3	-Non Dispersive Infra Red (NDIR) Spectroscopy
	1 hour**	04 mg/m^3	04 mg/m^3	
Benzene (C_6H_6)	Annual*	05 µg/m^3	05 µg/m^3	-Gas Chromatography based continuous analyzer -Adsorption and Description followed by GC analysis
Benzo(α) Pyrene (BaP)-particulate phase only	Annual*	01 ng/m^3	01 ng/m^3	-Solvent extraction followed by HPLC/GC analysis
Arsenic (As)	Annual*	06 ng/m^3	06 ng/m^3	-AAS/ICP method after sampling on EPM 2000 or equivalent filter paper
Nickel (Ni)	Annual*	20 ng/m^3	20 ng/m^3	--AAS/ICP method after sampling on EPM 2000 or equivalent filter paper

*Annual Arithmetic Mean of minimum 104 measurements in a year taken twice a week 24 hourly at uniform interval.

**24-hourly/8-hourly values should be met 98% of the time in a year. However, 2% of the time, it may exceed but not on the two consecutive days.

APPENDIX II A

Suggested Passenger Car Unit (PCU) Value for Urban Roads

(Source Khanna, S. K. 2001)

S. No.	Vehicle Class	PCU values for urban roads		
		(i) Urban roads, mid-block section	(ii)Signalised intersection	(iii) Kerb Parking (parallel and angle)
1	Car	1.0	1.0	1.0
2	Bus and Truck	2.2	2.8	3.4
3	Auto rickshaw	0.5	0.4	0.4
4	Two wheeler automobile	0.4	0.3	0.2
5	Pedal cycle	0.7	0.4	0.1
6	Bullock cart	4.6	3.2	1.2
7	Hand cart	4.6	3.2	0.3

APPENDIX II B

Passenger Car Unit (PCU) Equivalents as per Indian Practice

(Source Kadiyali, 1983)

S. No.	Vehicle Type	Equivalents
1	Passenger car, tempo, auto rickshaw and tractor	1.0
2	Cycle, motor cycle/ scooter	0.5
3	Lorry, bus and agricultural tractor-tailor unit	3.0
4	Cycle rickshaw	1.5
5	Horse-drawn vehicle	4.0
6	Bullock cart	8.0

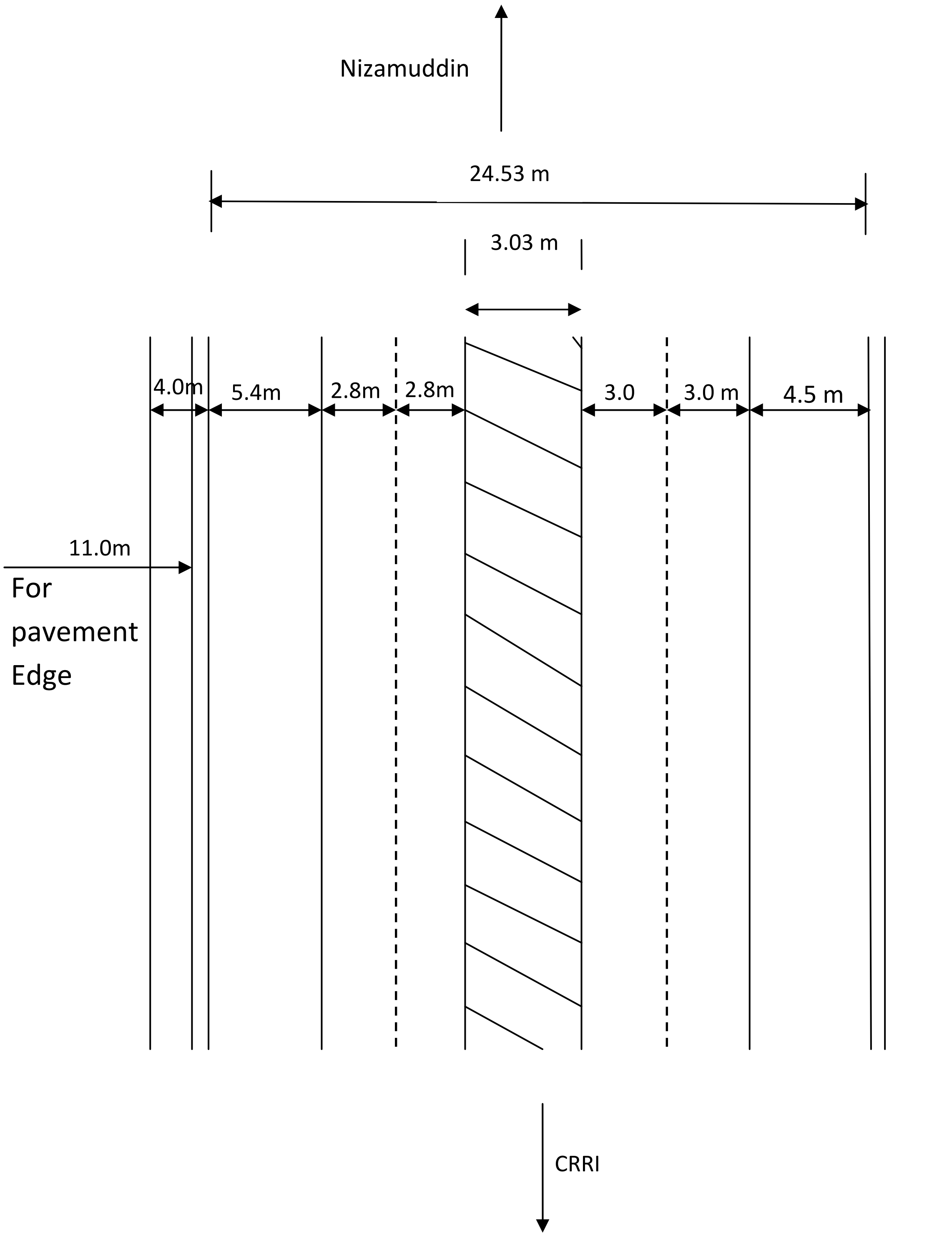
APPENDIX III

Age Profile of Vehicles Based on Fuel Station Survey (CRRI, 2010)

Year	Two Wheelers 100%			Four Wheelers 100%		Buses	Auto (CNG)	LCV 100%		HCV 100%	
	2-Stroke (2S) (40%)	4-Stroke (4S) (60%)	Petrol (P) (60%)	Diesel (D) (38%)	CNG (2%)			Diesel	CNG	Diesel	CNG
1992	0.5	0.3									
1993	0.5	0.4									
1994	1.22	1.07									
1995	1.32	1.2									
1996	0.71	1.2									
1997	0.71	0.72	3.15	0.53							
1998	1.42	1	5.51	1.59							
1999	2.13	1.72	1.57	0.53							
2000	1	3.45	6.3	0.53	1.72						
2001	2.13	1.72	9.45	1.5	7.19						
2002	3.55	1.72	4.72	1.06	11.41	5.15	0.8	2.17		3.6	
2003	4.64	8.62	9.54	6.35	4.22	6.45	0.8	10.87		4.2	
2004	12.07	18.97	11.02	3.7	4.22	10.33	7.45	8.7		11.6	
2005	10.64	3.45	7.09	10.58	7.19	19.22	28.34	9.78		10.19	
2006	13.48	6.9	7.87	11.09	9.06	20	25.22	8.7		10.33	
2007	9.93	11.98	9.24	22.42	11.1	7.35	11.12	17.39		7.74	
2008	11.57	15.4	9.24	20.56	18.1	9.75	13.51	18.47		28.11	
2009	12.06	10.34	7.21	10.21	13.91	12.25	6.5	13.05	50	20.55	50
2010	10.42	9.84	8.09	9.35	11.8	9.5	6.26	10.87	50	3.68	50
Total (%)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	100	100	100	100

APPENDIX IV

Road Geometry at New Friends Colony Petrol Pump



APPENDIX V A

Emission Factor for Carbon Monoxide (in gm/km) as per ARAI (2007)

Year	Two Wheelers		Four Wheelers			Buses (CNG)	Auto (CNG)	LCV		HCV	
	100%		100%					100%		100%	
	2-Stroke	4-Stroke	Petrol	Diesel	CNG			Diesel	CNG	Diesel	CNG
	(2S) (40%)	(4S) (60%)	(P) (60%)	(D) (38%)	(2%)						
1992	6	3.12	4.75								
1993	6	3.12	4.75								
1994	6	3.12	4.75								
1995	6	3.12	4.75								
1996	5.1	1.58	4.825	0.87							
1997	5.1	1.58	4.825	0.87							
1998	5.1	1.58	4.825	0.87							
1999	5.1	1.58	4.825	0.87							
2000	5.1	1.58	4.825	0.87							
2001	3.435	1.48	3.01	0.72							
2002	3.435	1.48	3.01	0.72	0.06	3.72	0.69	3.66		12.14	
2003	3.435	1.48	3.01	0.72	0.06	3.72	0.69	3.66		12.14	
2004	3.435	1.48	3.01	0.72	0.06	3.72	0.69	3.66		12.14	
2005	3.435	1.48	3.01	0.72	0.06	3.72	0.69	3.66		12.14	
2006	0.16	0.72	3.01	0.06	0.06	3.72	1	3.66		3.92	
2007	0.16	0.72	3.01	0.06	0.06	3.72	1	3.66		3.92	
2008	0.16	0.72	3.01	0.06	0.06	3.72	1	3.66		3.92	
2009	0.16	0.72	3.01	0.06	0.06	3.72	1	3.66	3.2	3.92	3.72
2010	0.16	0.72	3.01	0.06	0.06	3.72	1	3.66	3.2	3.92	3.72

(Source: Sharma, 2010)

APPENDIX V B

Emission Factors for different categories of Vehicle (CPCB, 2000)

Year	Type	Specified pollutant (gm/km)					
		CO	HC	NOx	PM	Benzene	Butdn
1986-1990	2W 2T	6.5	3.9	0.03	0.2	.226/.074	.010/.008
1991-1995		6.5	3.9	0.03	0.23	.226/.074	.010/.008
1996-2000		4	3.3	0.06	0.1	.191/.062	.008/.007
2001-2005		2.2	2.13	0.07	0.05	.123/.040	.005/.004
2006-2010		1.4	1.32	0.08	0.05	.076/.025	.003/.003
1986-1990	2W 4T	3	0.8	0.31	0.07	.061/.036	.008/.007
1991-1995		3	0.8	0.31	0.07	.061/.036	.008/.007
1996-2000		2.5	0.7	0.3	0.06	.056/.031	.007/.006
2001-2005		2.2	0.7	0.3	0.05	.056/.031	.007/.006
2006-2010		1.4	0.7	0.3	0.05	.056/.031	.007/.006
1986-1990	3W 2T	14	8.3	0.05	0.35	.481/.157	.021/.019
1991-1995		14	8.3	0.05	0.35	.481/157	.021/.019
1996-2000		8.6	7	0.09	0.15	.406/.133	.018/.016
2001-2005		4.3	2.05	0.11	0.08	.118/.038	.005/.004
2006-2010		2.45	0.75	0.12	0.08	.043/.014	.002/.001
1986-1990	PCG*	9.8	1.7	1.8	0.06	.130/.076	0.019/.014
1991-1995		9.8	1.7	1.8	0.06	.130/.076	019/.014
1996-2000		3.9	0.8	1.1	0.05	.061/.036	009/.007
2001-2005		1.98	0.25	0.2	0.03	.019/.011	003/.002
2006-2010		1.39	0.15	0.12	0.02	.011/.006	.001/.001
1986-1990	PCD*	7.3	0.37	2.77	0.84	0.022	0.007
1991-1995		7.3	0.37	2.77	0.84	0.022	0.007
1996-2000		1.2	0.37	0.69	0.42	.022	0.007
2001-2005		0.9	0.13	0.5	0.07	.007	0.002
2006-2010		0.58	0.05	0.45	0.05	.003	0.001
1986-1990	LCV	8.7	0.34	3.15	0.8	.017	0.005
1991-1995		8.7	0.34	3.15	0.8	.017	0.005
1996-2000		6.9	0.28	2.49	0.5	.014	0.004
2001-2005		5.1	0.14	1.28	0.2	.007	0.002
2006-2010		0.72	0.063	0.59	0.07	.003	0.001
1986-1990	HCV	5.5	1.78	9.5	1.5	.01	0.002
1991-1995		5.5	1.78	9.5	1.5	.01	0.002
1996-2000		4.5	1.21	8.4	0.8	.006	0.001
2001-2005		3.6	0.87	6.3	0.28	.004	0.0008
2006-2010		3.2	0.87	5.5	0.12	.004	0.0008
1986-1990	Bus	5.5	1.78	19	3	.01	0.002
1991-1995		5.5	1.78	19	3	.01	0.002
1996-2000		4.5	1.21	16.8	1.6	.006	0.00
2001-2005		3.6	0.87	12	0.56	.004	0.0008
2006-2010		3.2	0.87	11	0.24	.004	0.0008

*PCG/PCD - Passenger car (Gasoline/Diesel driven)

** LCV – Light Commercial Vehicles

APPENDIX VI A

Deterioration Factor for Gasoline Vehicles (Source: CPCB, 2000)

Age of vehicles (years)	CO, HC, NOx, PM			
	2 wheelers	3 wheelers	Passenger car gasoline	Multi utility vehicle gasoline
15-20			1.355	
10-15	1.4		1.17	1.275
5-10	1.3	1.7	1.28	1.255
0-5	1.2	1.475	1.097	1.19

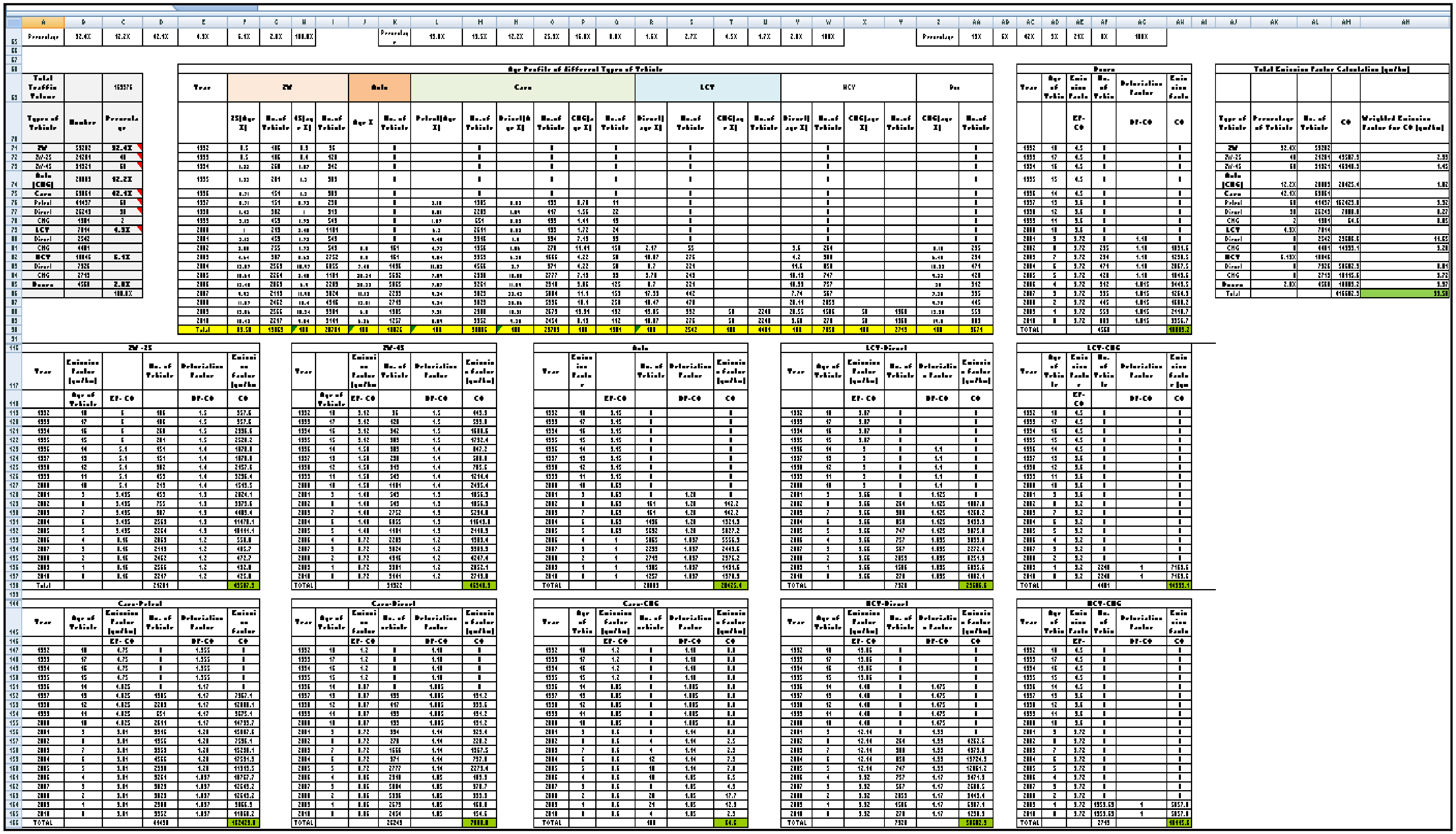
APPENDIX VI B

Deterioration Factor for Diesel Vehicles (Source: CPCB, 2000)

Age of vehicles (years)	CO, HC, NOx, PM			
	Passenger Car	**Buses**	**HCV**	**LCV**
15-20	1.18			
10-15	1.085		1.475	.1
5-10	1.14	1.18	1.33	.125
0-5	1.05	1.015	1.17	.095

APPENDIX VII

Spreadsheet for Estimation of Weighted Emission Factor along the Ashram Chowk - CRRI Highway Corridor of NH-2



Types of Vehicle	Number	Percentage
Total Traffic Volume		169376
2W	59202	32.4%
2W-2S	24284	40
2W-4S	34924	60
Auto (CNG)	20883	12.2%
Cars	69064	42.4%
Petrol	44457	60
Diesel	26249	38
CNG	1984	2
LCV	7044	4.3%
Diesel	2542	
CNG	4481	
HCV	10046	6.1%
Diesel	7926	
CNG	2749	
Buses	4560	2.8%
		100.0%

Total Emission Factor Calculation (gm/km)

Type of Vehicle	Percentage of Vehicle	No. of Vehicle	CO	Weighted Emission Factor for CO (gm/km)
2W	32.4%	59202		
2W-2S	40	24284	45507.9	2.99
2W-4S	60	34924	46340.3	1.45
Auto (CNG)	12.2%	20883	20425.4	1.02
Cars	42.4%	69064		
Petrol	60	44457	162429.8	3.92
Diesel	38	26249	7080.8	0.27
CNG	2	1984	64.6	0.05
LCV	4.3%	7044		
Diesel	0	2542	29606.6	11.65
CNG	0	4481	14399.1	3.20
HCV	6.19%	10046		
Diesel	0	7926	58682.9	8.04
CNG	0	2749	10445.6	3.72
Buses	2.8%	4560	40089.2	9.97
Total			416682.9	33.50

APPENDIX VIII

Estimation of Carbon Monoxide (CO) Weighted Emission Factor through Ashram Chowk - CRRI Highway Corridor of NH-2 Using ARAI (2007) Emission Factors

Table 1 Calculation of CO Emission Factor by 2W-2S

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	6	106	1.5	957.6
1993	17	6	106	1.5	957.6
1994	16	6	260	1.5	2336.6
1995	15	6	281	1.5	2528.2
1996	14	5.1	151	1.4	1078.8
1997	13	5.1	151	1.4	1078.8
1998	12	5.1	302	1.4	2157.6
1999	11	5.1	453	1.4	3236.4
2000	10	5.1	213	1.4	1519.5
2001	9	3.435	453	1.3	2024.1
2002	8	3.435	755	1.3	3373.6
2003	7	3.435	987	1.3	4409.4
2004	6	3.435	2569	1.3	11470.1
2005	5	3.435	2264	1.3	10111.1
2006	4	0.16	2869	1.2	550.8
2007	3	0.16	2113	1.2	405.7
2008	2	0.16	2462	1.2	472.7
2009	1	0.16	2566	1.2	492.8
2010	0	0.16	2217	1.2	425.8
Total			21281		49587.3

Table 2 Calculation of CO Emission Factor by 2W-4S

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	3.12	96	1.5	449.3
1993	17	3.12	128	1.5	599.0
1994	16	3.12	342	1.5	1600.6
1995	15	3.12	383	1.5	1792.4
1996	14	1.58	383	1.4	847.2
1997	13	1.58	230	1.4	508.8
1998	12	1.58	319	1.4	705.6
1999	11	1.58	549	1.4	1214.4
2000	10	1.58	1101	1.4	2435.4
2001	9	1.48	549	1.3	1056.3
2002	8	1.48	549	1.3	1056.3
2003	7	1.48	2752	1.3	5294.8
2004	6	1.48	6055	1.3	11649.8
2005	5	1.48	1101	1.3	2118.3
2006	4	0.72	2203	1.2	1903.4
2007	3	0.72	3824	1.2	3303.9
2008	2	0.72	4916	1.2	4247.4
2009	1	0.72	3301	1.2	2852.1
2010	0	0.72	3141	1.2	2713.8
TOTAL			31922		46348.9

Table 3 Calculation of CO Emission Factor by Auto

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	3.15	0		0
1993	17	3.15	0		0
1994	16	3.15	0		0
1995	15	3.15	0		0
1996	14	3.15	0		0
1997	13	3.15	0		0
1998	12	3.15	0		0
1999	11	3.15	0		0
2000	10	0.69	0		0
2001	9	0.69	0	1.28	0
2002	8	0.69	161	1.28	142.2
2003	7	0.69	161	1.28	142.2
2004	6	0.69	1496	1.28	1321.3
2005	5	0.69	5692	1.28	5027.2
2006	4	1	5065	1.097	5556.3
2007	3	1	2233	1.097	2449.6
2008	2	1	2713	1.097	2976.2
2009	1	1	1305	1.097	1431.6
2010	0	1	1257	1.097	1378.9
TOTAL			20083		20425.4

Table 4 Calculation of CO Emission Factor by Cars-Petrol

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	4.75	0	1.355	0
1993	17	4.75	0	1.355	0
1994	16	4.75	0	1.355	0
1995	15	4.75	0	1.355	0
1996	14	4.825	0	1.17	0
1997	13	4.825	1305	1.17	7367.1
1998	12	4.825	2283	1.17	12888.1
1999	11	4.825	651	1.17	3675.1
2000	10	4.825	2611	1.17	14739.7
2001	9	3.01	3916	1.28	15087.6
2002	8	3.01	1956	1.28	7536.1
2003	7	3.01	3953	1.28	15230.1
2004	6	3.01	4566	1.28	17591.9
2005	5	3.01	2938	1.28	11319.5
2006	4	3.01	3261	1.097	10767.7
2007	3	3.01	3829	1.097	12643.2
2008	2	3.01	3829	1.097	12643.2
2009	1	3.01	2988	1.097	9866.3
2010	0	3.01	3352	1.097	11068.2
TOTAL			41438		162423.8

Table 5 Calculation of CO Emission Factor by Cars-Diesel

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	1.2	0	1.18	0
1993	17	1.2	0	1.18	0
1994	16	1.2	0	1.18	0
1995	15	1.2	0	1.18	0
1996	14	0.87	0	1.085	0
1997	13	0.87	139	1.085	131.2
1998	12	0.87	417	1.085	393.6
1999	11	0.87	139	1.085	131.2
2000	10	0.87	139	1.085	131.2
2001	9	0.72	394	1.14	323.4
2002	8	0.72	278	1.14	228.2
2003	7	0.72	1666	1.14	1367.5
2004	6	0.72	971	1.14	797.0
2005	5	0.72	2777	1.14	2279.4
2006	4	0.06	2910	1.05	183.3
2007	3	0.06	5884	1.05	370.7
2008	2	0.06	5396	1.05	339.9
2009	1	0.06	2679	1.05	168.8
2010	0	0.06	2454	1.05	154.6
TOTAL			26243		7000.0

Table 6 Calculation of CO Emission Factor by Cars-CNG

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	1.2	0	1.18	0.0
1993	17	1.2	0	1.18	0.0
1994	16	1.2	0	1.18	0.0
1995	15	1.2	0	1.18	0.0
1996	14	0.85	0	1.085	0.0
1997	13	0.85	0	1.085	0.0
1998	12	0.85	0	1.085	0.0
1999	11	0.85	0	1.085	0.0
2000	10	0.85	24	1.085	21.9
2001	9	0.6	99	1.14	67.9
2002	8	0.6	158	1.14	107.8
2003	7	0.6	58	1.14	39.9
2004	6	0.6	58	1.14	39.9
2005	5	0.6	99	1.14	67.9
2006	4	0.6	125	1.05	78.8
2007	3	0.6	153	1.05	96.6
2008	2	0.6	250	1.05	157.5
2009	1	0.6	192	1.05	121.0
2010	0	0.6	164	1.05	103.4
TOTAL			1381		902.6

Table 7 Calculation of CO Emission Factor by LCV- Diesel

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	3.07	0		0
1993	17	3.07	0		0
1994	16	3.07	0		0
1995	15	3.07	0		0
1996	14	3	0	1.1	0
1997	13	3	0	1.1	0
1998	12	3	0	1.1	0
1999	11	3	0	1.1	0
2000	10	3	0	1.1	0
2001	9	3.66	0	1.125	0
2002	8	3.66	55	1.125	227.1
2003	7	3.66	276	1.125	1137.8
2004	6	3.66	221	1.125	910.7
2005	5	3.66	249	1.125	1023.7
2006	4	3.66	221	1.095	886.4
2007	3	3.66	442	1.095	1771.7
2008	2	3.66	470	1.095	1881.8
2009	1	3.66	332	1.095	1329.6
2010	0	3.66	276	1.095	1107.5
TOTAL			2542		10276.2

Table 8 Calculation of CO Emission Factor by LCV-CNG

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	4.5	0		0
1993	17	4.5	0		0
1994	16	4.5	0		0
1995	15	4.5	0		0
1996	14	4.5	0		0
1997	13	3.6	0		0
1998	12	3.6	0		0
1999	11	3.6	0		0
2000	10	3.6	0		0
2001	9	3.6	0		0
2002	8	3.2	0		0
2003	7	3.2	0		0
2004	6	3.2	0		0
2005	5	3.2	0		0
2006	4	3.2	0		0
2007	3	3.2	0		0
2008	2	3.2	0		0
2009	1	3.2	2240	1	7169.6
2010	0	3.2	2240	1	7169.6
TOTAL			4481		14339.1

Table 9 Calculation of CO Emission Factor by HCV-Diesel

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	13.06	0		0
1993	17	13.06	0		0
1994	16	13.06	0		0
1995	15	13.06	0		0
1996	14	4.48	0	1.475	0
1997	13	4.48	0	1.475	0
1998	12	4.48	0	1.475	0
1999	11	4.48	0	1.475	0
2000	10	4.48	0	1.475	0
2001	9	12.14	0	1.33	0
2002	8	12.14	264	1.33	4262.6
2003	7	12.14	308	1.33	4973.0
2004	6	12.14	850	1.33	13724.3
2005	5	12.14	747	1.33	12061.2
2006	4	3.92	757	1.17	3471.9
2007	3	3.92	567	1.17	2600.5
2008	2	3.92	2059	1.17	9443.4
2009	1	3.92	1506	1.17	6907.1
2010	0	3.92	270	1.17	1238.3
TOTAL			7328		58682.3

Table 10 Calculation of CO Emission Factor by HCV-CNG

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	4.5	0		0
1993	17	4.5	0		0
1994	16	4.5	0		0
1995	15	4.5	0		0
1996	14	4.5	0		0
1997	13	3.6	0		0
1998	12	3.6	0		0
1999	11	3.6	0		0
2000	10	3.6	0		0
2001	9	3.72	0		0
2002	8	3.72	0		0
2003	7	3.72	0		0
2004	6	3.72	0		0
2005	5	3.72	0		0
2006	4	3.72	0		0
2007	3	3.72	0		0
2008	2	3.72	0		0
2009	1	3.72	1360	1	5057.8
2010	0	3.72	1360	1	5057.8
TOTAL			2719		10115.6

Table 11 Calculation of CO Emission Factor by Buses

Year	Age of Vehicle	Emission Factor (gm/km)	No. of Vehicle	Deterioration Factor	Emission factor (gm/km)
		EF- CO (A)	(B)	DF-CO (C)	CO (A)*(B)*(D)
1992	18	4.5	0		0
1993	17	4.5	0		0
1994	16	4.5	0		0
1995	15	4.5	0		0
1996	14	4.5	0		0
1997	13	3.6	0		0
1998	12	3.6	0		0
1999	11	3.6	0		0
2000	10	3.6	0		0
2001	9	3.72	0	1.18	0
2002	8	3.72	235	1.18	1031.6
2003	7	3.72	294	1.18	1290.5
2004	6	3.72	471	1.18	2067.5
2005	5	3.72	420	1.18	1843.6
2006	4	3.72	912	1.015	3443.5
2007	3	3.72	335	1.015	1264.9
2008	2	3.72	445	1.015	1680.2
2009	1	3.72	559	1.015	2110.7
2010	0	3.72	889	1.015	3356.7
TOTAL			4560		18089.2

Table 12 Calculation of CO Weighted Emission Factor

Type of Vehicle	Percentage of Vehicle	No. of Vehicle	CO	Weighted Emission Factor for CO (gm/km)
2W-2S	40	21281	49587.3	2.33
2W-4S	60	31921	46348.9	1.45
Auto (CNG)	12.2%	20083	20425.4	1.02
Cars-Petrol	60	41437	162423.8	3.92
Cars-Diesel	38	26243	7000.0	0.27
Cars-CNG	2	1381	64.6	0.65
LCV-Diesel		2542	29606.6	4.04
LCV-CNG		4481	14339.1	3.20
HCV-Diesel		7326	58682.3	8.01
HCV-CNG		2719	10115.6	3.72
Buses	2.8%	4560	18089.2	3.97
Average				2.96

APPENDIX IX A

Sample Output Screen of CALINE 4 for Standard Case Input

CALINE4: CALIFORNIA LINE SOURCE DISPERSION MODEL

JUNE 1989 VERSION

PAGE 1

JOB: abc

RUN: Hour 1

POLLUTANT: Carbon Monoxide

I. SITE VARIABLES

```
   U=    .5 M/S           Z0= 100. CM          ALT=   216. (M)
 BRG= 180.0 DEGREES        VD=   .0 CM/S
CLAS=     4 (D)            VS=   .0 CM/S
MIXH=  656. M              AMB=   .0 PPM
SIGTH=   10. DEGREES       TEMP= 21.0 DEGREE (C)
```

II. LINK VARIABLES

```
    LINK      *  LINK COORDINATES (M)   *            EF     H     W
 ESCRIPTION  *   X1    Y1    X2    Y2  * TYPE  VPH  (G/MI)  (M)   (M)
----------------*-------------------------*------------------------------
A. Link A     *  1245  1975  2090  1250 *  AG  10724   1.7     .0  30.5
```

III. RECEPTOR LOCATIONS AND MODEL RESULTS

```
           *                  * PRED
           *   COORDINATES (M)    * CONC
 RECEPTOR  *    X      Y      Z   * (PPM)
------------*-----------------------*------
 1. Recpt 1  *   1681   1626   1.8   *   .8
 2. Recpt 2  *   1682   1627   1.8   *   .8
 3. Recpt 3  *   1685   1630   1.8   *   .7
 4. Recpt 4  *   1690   1635   1.8   *   .6
 5. Recpt 5  *   1695   1640   1.8   *   .5
 6. Recpt 6  *   1705   1650   1.8   *   .4
 7. Recpt 7  *   1730   1675   1.8   *   .3
 8. Recpt 8  *   1780   1725   1.8   *   .2
 9. Recpt 9  *   1830   1775   1.8   *   .1
10. Recpt 10 *   1649   1594   1.8   *   .0
11. Recpt 11 *   1648   1593   1.8   *   .0
12. Recpt 12 *   1645   1590   1.8   *   .0
13. Recpt 13 *   1640   1585   1.8   *   .0
14. Recpt 14 *   1635   1580   1.8   *   .0
15. Recpt 15 *   1625   1570   1.8   *   .0
16. Recpt 16 *   1600   1545   1.8   *   .0
17. Recpt 17 *   1550   1495   1.8   *   .0
18. Recpt 18 *   1500   1445   1.8   *   .0
```

APPENDIX IX B

Sample Output Screen of CALINE 4 for Worse Case Input

```
CALINE4: CALIFORNIA LINE SOURCE DISPERSION MODEL
JUNE 1989 VERSION
PAGE   1
JOB: CRRI
RUN: Hour 1          (WORST CASE ANGLE)
POLLUTANT: Carbon Monoxide

I.  SITE VARIABLES

    U=    .5 M/S          Z0= 100. CM        ALT=   216. (M)
   BRG= WORST CASE          VD=   .0 CM/S
  CLAS=     4 (D)          VS=   .0 CM/S
  MIXH=  656. M            AMB=   .0 PPM
 SIGTH=   10. DEGREES       TEMP= 21.0 DEGREE (C)

II.  LINK VARIABLES

   LINK      *  LINK COORDINATES (M)   *            EF     H     W
  DESCRIPTION  *   X1    Y1    X2    Y2  * TYPE  VPH  (G/MI)  (M)   (M)
 ----------------*-------------------------*------------------------------
   A. Link A      *  1245  1975  2090  1250 *  AG  10724   1.7     .0  30.5

III. RECEPTOR LOCATIONS AND MODEL RESULTS (WORST CASE WIND ANGLE)

            *                          * PRED
       *    COORDINATES (M)    *  BRG  * CONC
RECEPTOR  *    X      Y      Z    * (DEG) * (PPM)
 ------------*-----------------------*--------*-------
 1. Recpt 1  *   1681   1626    1.8 *  301. *   1.3
 2. Recpt 2  *   1682   1627    1.8 *  300. *   1.2
 3. Recpt 3  *   1685   1630    1.8 *  299. *    .9
 4. Recpt 4  *   1690   1635    1.8 *  298. *    .7
 5. Recpt 5  *   1695   1640    1.8 *  297. *    .6
 6. Recpt 6  *   1705   1650    1.8 *  146. *    .5
 7. Recpt 7  *   1730   1675    1.8 *  149. *    .3
 8. Recpt 8  *   1780   1725    1.8 *  162. *    .2
 9. Recpt 9  *   1830   1775    1.8 *  278. *    .1
10. Recpt 10 *   1649   1594    1.8 *  119. *    .8
11. Recpt 11 *   1648   1593    1.8 *  119. *    .8
12. Recpt 12 *   1645   1590    1.8 *  118. *    .7
13. Recpt 13 *   1640   1585    1.8 *  117. *    .6
14. Recpt 14 *   1635   1580    1.8 *  116. *    .5
15. Recpt 15 *   1625   1570    1.8 *  328. *    .4
16. Recpt 16 *   1600   1545    1.8 *  111. *    .3
17. Recpt 17 *   1550   1495    1.8 *  342. *    .2
18. Recpt 18 *   1500   1445    1.8 *   94. *    .1
```