Traffic Flow Characteristics and Impacts on Air Quality at Urban Roundabout Junction

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By

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CERTIFICATE

This is to certify that **Suresh Pandian E** has been working under our supervision since January, 2006 as a regular registered Ph. D. student. His thesis entitled **"Traffic Flow Characteristics and Impacts on Air Quality at Urban Roundabout Junction"** is an authentic record of the results obtained from the research work carried out under our supervision in the Centre for the Environment, Indian Institute of Technology Guwahati, Assam, India. We certify that he has fulfilled all the requirements according to the rules of this institute regarding the investigations embodied in his thesis and this work has not been submitted elsewhere for a degree.

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DEDICATION

TO

SHARAD GOKHALE AND ALOKE KUMAR GHOSHAL

&

ALL MY TEACHERS

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By

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Elumalai M - *Father* (S/O Muthuswamy & alamelu)

Mallika E – *Mother* (D/O Annamalai & Aandal)

Balamurugan E (*younger brother*)

Srinivasan E (*youngest brother*)

ABSTRACT

Rapid urbanization and the unprecedented growth in vehicles have resulted in profound deterioration of air quality in urban centers. Traffic junctions of urban centers often attract large number of vehicles creating congested conditions which, as a result, generate higher carbon monoxide (CO) emissions. Since traffic flow characteristics generally observed at junctions complicate dispersion phenomena, understandings on pollutant dispersions in the close vicinity of traffic junctions are important for accurate air quality assessment. Traffic junctions in particular of type conventional roundabouts, where vehicles spiral in and out change lanes and vary speeds in circular pattern, tend to impose behavioural changes on drivers to utilize the free space on road while maneuvering. This generates a zone in which emissions are recirculated within road-width leading to the canyon-type effects between the continuous moving vehicles.

Several dispersion models exist to evaluate air quality near roadways and traffic junctions. However, complex pollutant dispersion at a conventional non-signalized roundabout cannot be described accurately by either intersection or open-terrain line source models alone. In order to simulate such a complex dispersion pattern at a non-signalized roundabout, it is proposed that a line source model is combined with street-canyon effects. This is demonstrated by estimating 1-min average CO concentration for a period of 30 min by coupling an open-terrain line source model, GFLSM with a street-canyon (SC) model, STREET to capture the combined (SC-GFLSM) effects to describe the dispersion pattern. This research involves the development of detailed methodologies to quantify traffic flow characteristics and emissions pertinent to local conditions as inputs to the SC-GFLSM model. A time-width occupancy model was developed to simulate traffic flow characteristics and semi-empirical model was developed to simulate emission pattern.

The results show that the GFLSM predicted measured concentrations almost three times higher, while the results of the SC-GFLSM matched well with the measurements and the prediction errors reduced by about 50 %. The research, further, demonstrated this with traffic characteristics and emissions calculated by field and semi-empirical methods. The SC-GFLSM model was also validated for another 30 min data set for which the results were equally promising.

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LIST OF SYMBOLS

Symbol	Description
$CF_{w,i+3}$	correction factor of vehicle category of largest time occupied
$CF_{w,i}$	correction factor of vehicle category of least time occupied
$CF_{w,i+2}$	correction factor of vehicle category of second largest time occupied
$CF_{w,i+1}$	correction factor of vehicle category of second least time occupied
C_{CS}	average street-canyon concentration, mg/m^3
C_S^W	windward side concentration, mg/m^3
C_S^L	leeward side concentration, mg/m^3
CV	coefficient of variation
d	degree of agreement
f_{PCU}	passenger-car-unit adjustment factor
FB	fractional bias
g	gravitational acceleration, m/s^2
H_m	height of the meteorology station, m
H_P	plume rise, m
h_0	initial height of pollutant dispersion, m
H_l	height of line source, m
H	height of the street-canyon, m
j	traffic entity type
K	dimensionless “best fit” constant
k_{PC}	concentration of passenger cars, passenger cars/km
k	traffic density in a stretch, veh/km
k_o	traffic density using occupancy, veh/km
k_w	traffic density using time-width occupancy, veh/km
k_j	jam density, veh/km

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Symbol	Description
L_{HDV}	average length of heavy vehicles, m
L_{PC}	average length of passenger cars, m
L_v	average vehicle length, m
l_i	length of the i^{th} vehicle, m
l_d	detector's length, m
L	longitudinal length of section of the traffic roundabout, km
n	number of sample
N_v	number of vehicles observed
N	total number of entity types in the heterogeneous traffic stream
O_{avg}	mean of observed values
O_i	time i^{th} vehicle occupied the detector, s
$O_{w,i}$	occupancy time of a vehicle type that occupies the least time, s
$O_{w,i+3}$	occupancy time of vehicle category of largest time occupied, s
$O_{w,i+2}$	occupancy time of vehicle category of second largest time occupied, s
$O_{w,i+1}$	occupancy time of vehicle category that occupied the second least time, s
PCU_j	passenger-car unit for traffic type j in Indian passenger cars per j
P_i	Modeled i^{th} values of traffic densities
Q_{SC}	emission rate per unit length within the road section, mg/m.s
Q_L	emission source strength from line source, mg/m.s
q	traffic flow across a stretch, veh/hr
$RMSE$	root mean square error
R_b	Richardson number
R	Pearson's correlation coefficient
T_a	ambient temperature, ^oC
T_H	temperature at the meteorology station, ^oC
T_O	temperature at the ground level, ^oC
T	observed time period, s

Symbol	Description
U_H	wind velocity at the height of meteorology station, m/s
u_0	wind speed correction due to traffic wake, m/s
$\bar{u}_{t,j}$	arithmetic mean speed of traffic entities comprising type *j*, km/hr
$\bar{u}_e$	mean ambient wind speed, m/s
$\bar{u}_s$	space mean speed, km/hr
u	mean ambient wind speed at source height, m/s
v_i	speed of i^{th} vehicle, m/s
V_o	maximum free-flow speed of traffic fleet, km/h
W_{85j}	85th percentile highway width that non-passenger car type *j* uses, m
W_{85PC}	85th percentile road width that passenger cars use, m
W_{LPC}	lane width for passenger cars in homogeneous traffic conditions, m
w_i	width of the i^{th} vehicle, m
W	cross-sectional road width, m
z	height of the receptor above the ground, m

Greek letters	Description
θ	angle made by road with the wind vector
ρ_a	area occupancy, s
ρ_w	time-width occupancy, s
ρ	occupancy, s
$\sigma^2_{t,j}$	speed variance of traffic entities in type *j*
σ_{ya}	atmospheric turbulence induced vertical dispersion coefficient, m
σ_{y0}	traffic generated turbulence induced vertical dispersion coefficient, m
σ_y	horizontal dispersion coefficient, m
σ_{za}	atmospheric turbulence induced horizontal dispersion coefficient, m

Greek letters	Description
σ_{z0}	traffic generated turbulence induced horizontal dispersion coefficient, m
σ_z	vertical dispersion coefficient, m
σ	standard deviation

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LIST OF ABBREVIATIONS

Syntax	Description
CAL3QHC	California Line Source for Queuing and Hotspot Calculation
CALINE	California Line Source
CARB	California Air Resources Board
CFD	Computational fluid dynamics
CO	Carbon monoxide
CORSIM	CORridor SIMulation
CPBM	Canyon Plume-Box Model
CPCB	Central Pollution Control Board
EMFAC	EMission FACtors developed by Air Resources Board
EPA	Environmental Protection Agency
FHWA	Federal HighWay Administration
GFLSM	General Finite Line Source Model
GM	General Motors Model
HBEFA	Handbook of emission factors for road traffic
HC	Hydrocarbon
HCM	Highway Capacity Manual
HCS	Highway capacity software
HDV	Heavy duty vehicles
HIWAY-2	Highway air pollution model
LCV	Light commercial vehicles
M2W	Motorized two-wheelers
M3W	Motorized three wheelers
MEASURE	Mobile Emissions Assessment System for Urban and Regional Evaluation
MOBILE	Mobile Source Emission Factor Model
NO_x	Oxides of nitrogen
PCEs	Passenger car equivalents
PCU	Passenger car units
RSPM	Respirable suspended particulate matter

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Syntax	Description
SC	Street canyon
SCOOT	Split Cycle and Offset Optimization Technique
SIDRA	Signalized & unsignalized Intersection Design and Research Aid
SMS	Space mean speed
TERI	The Energy and Resources Institute
TMS	Time mean speed
Transyt-7F	Traffic network study tool
UTC	Urban Traffic Control
VER	Vehicle emission rate
VOCs	Volatile organic compounds
WHO	World Health Organization

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Rapid economic growth and fast urbanization have increased the mobility and led to the unprecedented growth of vehicles in several developing countries. Motor vehicles are the major cause of air pollution in most urban cities. India is one of such fast developing countries and a growing hub for the information technology provides ample opportunities in urban areas. This leads to a large scale urbanization, mobility and use of vehicles. The unprecedented growth in vehicles has resulted in a profound deterioration of air quality in urban centers. While India's economy has increased 2.5 times over the past two decades, vehicular pollution has increased about eight times, and pollution from industries has quadrupled (Mukhopadhyay, 2008). The Central Pollution Control Board (CPCB), of India identified about 23 Indian cities, critically polluted. Of them, for about 12 major cities the vehicular pollution load was found alarming. For example, 352 tonnes of oxides of nitrogen (NO_x), 1916 tonnes of carbon monoxide (CO) and 672 tonnes of hydrocarbon (HC) per day (CPCB, 2000). The ambient levels of these pollutants are above the WHO safe limits (CPCB, 2001; TERI, 2001; Singh et al., 1997 and Varshney and Aggarwal, 1992). This level of pollution load in urban air will have a serious impact on the health of the community.

The transport sector in India consumes about 16.9% (36.5 mtoe: million tonnes of oil equivalent) of total energy (217 mtoe in 2005-2006) with the road traffic responsible for about 80% of emission (TEDDY, 2006). Energy consumption and the concomitant emissions, however, also vary with the modes of transport. The urban population of India is predominantly dependent on road transport with personalized vehicles such as cars and motorcycles (Economic Survey of Delhi, 2006). The number of vehicles in Delhi in 1994-95 was 2.43 million, which was higher than the number of vehicles in Kolkata (0.56 million), Mumbai (0.67 million) and Bangalore (0.80 million) put together. There has been an exponential growth in the number of vehicles, which increased from 26.30 lac in 1995-96 to 48.30 lac in 2005-06 at an annual compound growth rate of 5.84%. Decennial growth rate is substantially higher in case of private vehicles (91.62%) as compared to commercial vehicles (6.67%). In the category of private vehicles, cars and jeeps have registered a decennial growth rate of 130.18%, which is the highest among all the

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categories of vehicles followed by two wheelers (i.e. scooter, motorcycle and moped) of 76.85% (Shah et al., 2008).

The automobile emission is highest in Delhi with a total vehicular pollution load of about 629 tonnes per day that is 1.8 times that of Mumbai and 2.5 times that of Kolkata even though these cities have more people. The contribution of vehicular sources to the pollution load, in Delhi, has increased from 64% in year 1991 to 72% in year 2001, while that has from industrial sources, decreased from 29% to 20%. This fact has shifted attention more on the air quality due to vehicular pollution (Shah et al., 2008). This also indicates that more than population, the rapid urbanization as a result of growing economy is causing more vehicle growth and concomitant emissions. Several pollutants, such as respirable suspended particulate matter (RSPM), NO_2, CO, VOCs (Volatile Organic Compounds) and HC are emitted directly by vehicles in urban environments, which together with the secondary pollutants (indirectly produced through photochemical reactions), pose a serious hazard to human health. Therefore, an accurate assessment of air quality near roadways in urban centers is essential for an effective air quality management.

1.1 TRAFFIC IN INDIA

Commuters, in large cities, are faced with acute road congestion, rising air pollution, and a high level of accident risk. The traffic condition that prevails in India is entirely different from that is in developed countries. It is heterogeneous in nature, wherein, a diverse mix of vehicles including two wheelers, three wheelers, cars, buses and non-motorized vehicles (including bicycles, cargo tricycles and human and animal drawn carts) are forced to share the limited roadway space (Figure 1.1). Slow and non-motorized modes such as bicycles, hand-pulled and cycle-drawn rickshaws do not add to emissions but slow down the faster motorized modes such as cars, trucks, buses, and auto rickshaws, eventually leading to the congestion and generation of more pollutants. Thus, the modes of such different sizes, maneuverability, capacities, speeds, and other operating characteristics produce heterogeneous traffic conditions resulting into more emissions. The increasing efforts in road infrastructure are, however, counterbalanced with the rapid growth in the vehicle population and in the travel demand, virtually worsening roadway congestion and the concomitant air pollution (MoRTH, 2001).

Figure 1.1: Traffic congestion on a typical Indian road

Total road vehicles in India (March 2004) were 72.7 million (MoSRTH, 2007). During the last two decades, number of registered motor vehicles has increased dramatically from 5.4 million in 1980–1981 to 72.7 million in 2003–2004 (TEDDY, 2006; MoSRTH, 2007). Traffic composition of six mega cities of India (Delhi, Mumbai, Bangalore, Hyderabad, Chennai and Kolkata) shows that there is a significant shift from the share of slow-moving vehicles to fast-moving vehicles and similarly from public transport to private transport (Jalihal et al., 2005). Among different types of motor vehicles, percentage of two wheelers has shown rapid growth (doubling in every 5 years) and it constitutes 70% of total motor vehicles of India (MoSRTH, 2004). While the motor vehicles have grown in multi-folds, the road network has grown at a much slower rate leaving a huge short fall in the capacity required to carry the motor vehicles plying in the cities.

Traffic congestion is the most immediate transport problem caused by the increase in total vehicles. The effect of congested traffic is that it decreases overall fleet speed. For example, the average fleet speed reduced from 38 km/h in 1962 to only 15-20 km/h in 1993 in Mumbai (Gakenheimer, 2002) and in Delhi, from 20-27 km/h in 1997 to 15 km/h in 2002 (TOI, 2002). In Chennai, up to 13 km/h, and in Kolkata, in the range of 10 to 15 km/h overall but mostly about 7 km/h in the central part of the city (TOI, 2003). The more number of vehicles with such a reduced speed in these cities drastically increases the amount of exhaust emissions. Vehicular exhaust emission, besides the amount of fuel consumption, and its quality, is also affected due to varied traffic and vehicle characteristics, type of intersections (signalized intersection, priority signals, unsignalised intersection, traffic round about), type of streets (urban, rural, highway, local), driving pattern, fleet speed, age of vehicle, vehicle make, engine type, and vehicle maintenance.

1.2 AIR QUALITY AT TRAFFIC JUNCTIONS

The problems of a traffic system such as longer queues, accidents and exhaust emissions, etc., first appear at intersections. The meeting point of two or more roads is the focus of conflict since the beginnings of regular traffic (Laszlo, 1998). At these meeting points (junctions or road intersections), traffic has to be controlled. An early solution was to build up traffic signs separating major and minor roads, but with the growth of motorization and the increase in the number of vehicle users, the traffic exceeded the capacity of the sign-controlled junctions.

Vehicles that queue up at an intersection, spend a greater amount of time in idle mode generating more pollutant emissions per unit time, often leading to higher pollutant concentrations (Pandian et al., 2009; Gokhale and Khare, 2005, 2004). Other driving patterns (i.e., acceleration, deceleration and cruising) are also observed at intersections that affect the emission and the resulting pollutant concentrations. Emissions are, therefore, besides the vehicular populations, also depend on the traffic flow pattern and driving modes.

At intersections, traffic signal lights, and stop or priority signs are used to constrain car interactions. At intersections controlled by stop signs, a waiting time is imposed on cars. At signalized (traffic lights) controlled intersections, the states of green or red indicating the permission to go enter (green) or stop (red) are used. Roundabout, on the other hand, accommodates traffic flow in one direction around a central island and gives priority to the circulating flow (Virginia and Veera, 2004). Roundabouts operate on the principle of the mandatory "give-way" rule at all circular intersections, which require entering traffic to give way, or yield to circulating traffic. This rule prevents roundabouts from locking up, by not allowing vehicles to enter until there are sufficient gaps in the circulating traffic (Robinson, 2000).

Mustafa et al., (1993) have shown in their study that due to the traffic signals at intersections more emissions almost about 50% are generated than at roundabouts. During heavy traffic, signals cause higher emission of HC, which is twice of that is generated at roundabouts. Niittymaki and Hoglund (1999) also showed a reduction of almost 30% fuel-consumption at roundabouts compared with intersections. Further observations showed

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that environmentally optimized traffic control systems have energy saving potential of about 10-20%. Another similar study, conducted by Varhelyi (2002) in Sweden, shows that replacing a signalized intersection with roundabout results in about 29% average decrease in the CO emissions and 21% in the NO_x. The fuel consumption is decreased by about 28% per car within the influence of the roundabout junction. Mandavilli et al., (2008) reported that the modern roundabout performs better than the existing intersection control with stop-signs by cutting down the vehicular emissions. The effect of roundabout is that traffic is required to slow down to negotiate the curve around the center island, but unlike stop and signal controlled intersections, vehicles entering roundabout are not necessarily required to stop.

1.3 CO EMISSIONS AT TRAFFIC JUNCTIONS

As discussed earlier, junctions attract large volume of traffic and typically maneuver the junction at low speed with frequent start-stops. Such a traffic pattern produces higher CO emissions. Motor vehicles contribute largely to CO emission in urban areas. The existence of all kinds of driving modes along with more traffic congestion at traffic intersections generates higher CO emissions and hence the potential for human exposure is high. The CO levels have always been the target of investigation in most monitoring and modeling studies concerning vehicular pollution near roadways and major intersections in many cities (Bogo, 1999; Larson et al., 1996). CO is the result of incomplete fuel combustion that characterizes mobile as opposed to stationary sources and therefore can be used as an indicator for the contribution of traffic to air pollution (Comrie and Diem, 1999).

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CHAPTER 2

RESEARCH PROBLEM FORMULATION

2.1 GENERAL

The prior discussion on traffic junctions (section 1.2) motivates to design the scope of the research, which includes the development of methodologies for accurate traffic density, emission calculation and air pollutant concentration for the heterogeneous traffic condition. This chapter describes the scope and the objectives followed by the thesis outline.

2.2 SCOPE

Roundabouts impose behavioral changes on drivers. They often require drivers to decelerate from, and reaccelerate to road speeds with one or multiple stops. An immediate concern is the increase in emissions due to excessive delays, queue formation and speed change cycles for approaching traffic (Pandian et al., 2009). These occurrences have a significant impact on congestion, concomitant emissions and air quality at such traffic junctions. For accurate air quality assessment, it is utmost necessary that emission be calculated accurately. Emissions, however, depend on the number of factors related to individual vehicles, road geometry and several traffic characteristics. The most critical characteristic of traffic is the density.

Density indicates the level of congestion on roads and has direct influence on the amount of roadside emissions. It is expressed as number of vehicles per unit length of roadway. It can be adequately represented for traffic pattern when homogeneous, the conditions in which the differences in individual vehicle speeds and dimensions are assumed to be negligible. Traffic of mixed vehicles, however, when operate at junctions produces dynamic characteristics. This results in the density that is difficult to be estimated adequately with the conventional methods and thus inappropriate measure of traffic concentrations on roads. The heterogeneity, additionally, as vehicle per unit length of road can be measured only along a length, makes it further difficult when the flow pattern is complex with no strict-lane discipline. It is challenging to characterize such traffic flow arising due to heterogeneity and is essential for calculating accurate emission. In practice, however, significant differences in speed and dimension of vehicles are observed. As a result, the density estimated based on homogeneous assumption is often far from the real situations on roads of developing countries.

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Occupancy, a function of both vehicle length and traffic composition, provides a reliable indication on the area of the road being used by vehicles. The occupancy methods (Arasan and Dhivya, 2008) are mostly based on homogeneous conditions which account for strict-lane discipline. In this case, vehicles occupy the full lane-width and a vehicle fleet does not vary greatly in width. Therefore, in case of heterogeneous traffic, where road space is shared among many traffic modes with different physical dimensions, the existing occupancy methods have limited applicability. This drawback of the occupancy method can be overcome to some extent by area-occupancy method (Mallikarjuna and Rao, 2006), which uses the ratio of vehicle to road-width, only and slightly improves the density scenario observed on roads. However, it cannot be used for a mixed traffic flow characteristics. This necessitates the need of a development of more appropriate method to estimate traffic congestion for a heterogeneous traffic flow condition to study the traffic characteristics at a traffic junction.

Using traffic density actually estimated at the site with appropriate methods, traffic emissions can be calculated with the help of semi-empirical relationships with traffic flow rate, jam density and the speed of vehicles.

Study of air quality problems at micro-scale urban environment requires understanding of source-receptor relationship to reduce the pollution (James, 2002). The variability in traffic characteristics such as large traffic volumes, intersections of roads, and accelerating and decelerating fleet dynamics, at urban street intersections or roundabouts influences pollutant concentrations within such microenvironments (Lin and Ge, 2006). Further, a complex wind flow pattern and strong thermal surface conditions distort the pollutant fluxes, affecting the air pollutant levels. At roundabouts, particularly those that are non-signalized, vehicles spiral in and out, change lanes and vary speeds in a circular pattern, resulting in complex emission and dispersion pattern. This generates a zone in which emissions are re-circulated within a road-width leading to the canyon-type effect between the continuous moving vehicles. In this zone, an effect of thermally induced turbulence dominates over atmospheric turbulence causing pollutant emissions to flow within a small region resulting into more or less equal amount of pollutants upwind and downwind, particularly, during light wind conditions. Beyond this region, however, the effect of winds becomes stronger causing downwind movement of pollutants. Typical characteristic of roundabout of forcing vehicles to make a lateral displacement around central-island prior to exit has a great effect on the speed of approaching vehicles (Polus et al., 2003). Such dynamics of fleet speed of heterogeneous traffic further affects the amount and flux of emissions and the concentrations of pollutants greatly. Such a complex emission pattern and dispersion process cannot be described adequately by open-terrain line source models alone.

Most of the line source dispersion models, particularly the Gaussian based, do not account for several traffic characteristics, which are typical at traffic intersections or roundabouts microenvironment. Moreover, they simulate downwind pollutant levels and as a result tend to over-predict close to the emission sources where there is no specific flow pattern. In general, these models simulate the dispersion of pollutants near a roadway by treating continually moving vehicles as a pollutant emitting line source. A line source dispersion model treats traffic emission as uniformly distributed across the roadway. The CAL3QHC is one such model, which specifically accounts for several possible factors relevant to traffic intersections for both moving and idling vehicles (US EPA, 1995). However, a conventional non-signalized traffic roundabout, where vehicles are not expected to experience idling mode since traffic is in continuous movement, limits the usefulness of this model directly. In one of the studies of Broderick et al., (2004) near five-arm traffic roundabout at Galway city for calculating CO by CALINE4, five-arms of the roundabout were treated as five line sources meeting at a centre point like a roadway. The estimated values were far under predicted and moreover did not capture the diurnal variation. In such microenvironment, the combination of box model approach, which captures a street-canyon effects within a road section and line source dispersion model for away from road or emission source, could describe the dispersion phenomenon relatively better.

The foregoing discussion demands the necessity of quantifying traffic flow characteristics, concomitant emissions and impacts on the air quality at traffic roundabouts particularly non-signalized, where vehicular movement is continuous but interrupted very often owing to traffic operation affecting the dispersion phenomenon.

2.3 RESEARCH OBJECTIVES

1. Development of a methodology to estimate an heterogeneous traffic density at a traffic roundabout.
2. Development of a methodology to estimate the vehicular emission rates at the selected traffic roundabout.
3. Development of a suitable air quality model to calculate the CO concentration.
4. Validation of the developed air quality model.

2.3.1 Objectives breakdown

- Selection of a traffic roundabout.
- Collection of traffic count, individual vehicle speed, CO concentration and the meteorological data such as wind speed, wind direction, temperature, solar radiation and humidity for a period of 30 min with 1- min resolution.
- Collection of data on dimensions and geometry details of traffic roundabout along with line source receptor coordinate details.
- Estimation of passenger car units (PCU) for the major vehicle categories.
- Estimation of traffic parameters such on traffic flow, density and speed for each arm of the traffic roundabout using calculated PCU.
- Estimation of time-occupancy and area-occupancy based on the collected data and field observations.
- Development of time-width occupancy model by incorporating correction factor to the time-occupancy.
- Density calculation from time-width occupancy.
- Estimation of vehicle emission rate from the calculated densities by semi-empirical approach.
- Development of air quality model by combining the street-canyon effects with a line source model.
- Application of the developed air quality model.
- Validation of the developed model.

2.4 THESIS OUTLINE

The thesis is organized in 8 chapters. Chapter 1 contains a brief introduction to the topic and the problem overview. Chapter 2 discusses scope of the work and defines the objectives to be achieved. Chapter 3 provides a review of traffic and emission methods and dispersion models to assess air quality at traffic intersections, a thorough literature on traffic characteristics, emission and air quality modeling at traffic intersections. This chapter mainly concentrates on the state-of-the-art studies to understand and establish a relationship between vehicular emission and the most possible measurable or quantifiable characteristics. It, therefore, essentially demonstrates the relationships of traffic, vehicle and road intersection characteristics with the vehicular exhaust emissions. The literature review presented here begins with the effect of traffic characteristics including delay events and driving modes, road characteristics including road geometry followed by traffic flow models. Subsequently, it covers the effect of driving speed and vehicle characteristics

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on emissions followed by dispersion models. It, further, provides an overview on the problems and shortcomings of current methods of air quality models.

The chapter 4 describes the detailed methodology for estimating various traffic characteristics and specific parameters. These parameters include the locally derived PCUs to establish the basic relationship between macroscopic traffic properties such as traffic flow rate, traffic speed and traffic density. The chapter demonstrates that the current procedures ignore the effect of the additional vehicle that shares the same lane-width, which gives erroneous traffic density. It, then, proposes a new method to incorporate this factor in the model.

In chapter 5, the research investigates the effect of the roundabout traffic dynamics on the estimation of vehicular emission rates. Three different approaches to estimate the traffic density at roundabout are described. The proposed time-width occupancy approach to estimate traffic density includes the effect of aggressive driver behaviours due to heterogeneous Indian traffic conditions. The effects of different traffic characteristics and traffic density on the vehicular emission behavior are studied in chapter 6. Three different approaches to estimate emissions are explained and they differ from the input used by *viz.* instantaneous speeds of vehicles, observed density and estimated density.

The chapter 7 describes the estimation of CO pollutant concentration at the traffic roundabout. It discusses the conceptual formulation of the air quality model and its application, verification and validation using different data sets. The chapter presents the results of the developed model, termed as SC-GFLSM, that combines the STREET urban pollution street canyon (SC) model for within a road section to account for thermal and vehicle induced turbulences and the general finite line source model (GFLSM) for outside the road where atmospheric turbulence influences more. The results of this coupled model, SC-GFLSM are compared with the results of GFLSM. The study, further, demonstrates the impact of various emission calculation methodologies used in air quality modeling such as field and semi-empirical methods.

Finally, the chapter 8 provides a summary of the findings, the conclusions and discusses future scope.

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CHAPTER 3

LITERATURE REVIEW

3.1 INTRODUCTION

Urban air quality is generally poor at traffic intersections due to variations in vehicle speeds as they approach and leave and due to different driving modes. Emissions generated near traffic intersections greatly vary with the characteristics of traffic, vehicles, and the geometrical configuration. The influence of these characteristics on the exhaust emissions is not clearly understood yet. For accurate emission estimates, the fundamental issue is to understand the link between emission and various characteristics observed near traffic intersections. Hence, the present review critically examines the effect of traffic, vehicle and road characteristics on vehicular emissions with a view to understand a relation between emissions and the most likely influencing and measurable characteristics. This chapter, therefore, essentially demonstrates the relationships and effect of various characteristics with the vehicular exhaust emissions and review the traffic flow and emission models. It begins with the effect of traffic characteristics including delay events and driving modes, road characteristics including road geometry followed by traffic flow models. Subsequently, the effect of driving speed and vehicle characteristics followed by emission and dispersion models are discussed.

Air quality at any critical location is directly dependent on the amount of emissions generated. Figure 3.1 shows a tree for modeling vehicular exhaust emissions. This tree includes a root branched into three independent components of characteristics related to traffic, vehicle, and road. Some traffic characteristics, in particular, flow rate, queue length and delay events arise due to the road characteristics, depending on the configuration of a junction, or an intersection or a signalized roadway. The combination of traffic and road characteristics determine the average-fleet speeds at various driving cycles of under free-flow, interrupted, congested and maximum. Time spent by vehicles in different driving modes also determine the average-fleet speeds. Vehicle characteristics further contribute to the emissions resulting due to the traffic and road characteristics. The modeling approach for vehicular emissions uses traffic flow model, which takes the traffic (delay events and queue length) and road characteristics and mode-based driving speeds into the emission model in parallel with individual vehicle characteristics. This approach provides

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emission factors for 'vehicle types' and 'pollutants' to estimate emissions to assess air quality due to vehicular exhaust emissions.

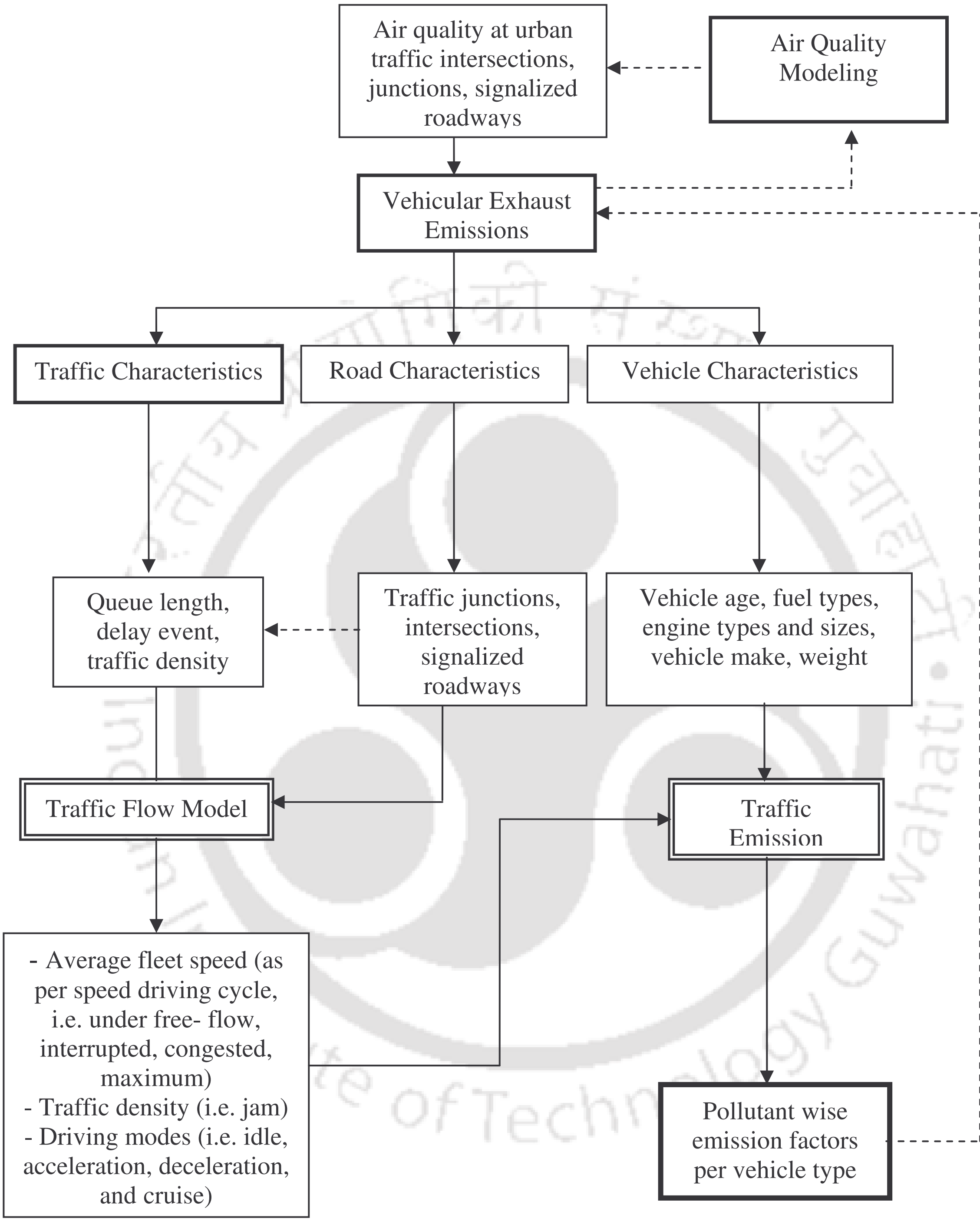

Figure 3.1: Modeling tree for air quality at junction due to vehicular exhaust emissions

3.2 TRAFFIC CHARACTERISTICS

Traffic characteristics include traffic flow rate, traffic density, fleet speed, driving mode, mean delay and queue length. Some of them such as delays and driving modes are perceived to have a direct effect on emissions because they are regularly observed at signalized intersections and dominant in comparison with others. This section brings together the studies which focused on these aspects.

3.2.1 Vehicular emission by delay events and driving modes

Delay explains the inconvenience caused by traffic signals to vehicles while traversing through the intersection (Qiao et al., 2002). It is, thus, a measure of an effective operation of traffic intersection for emission calculations. The delay-event is a weighted average of ‘idling’, ‘acceleration’ and ‘deceleration’ modes. During delay the emission rates of vehicles are higher in comparison with that during non-delay, which is primarily composed of a cruise mode. This results into a variation in emissions with the driving modes. It is impractical to monitor traffic conditions in these modes at traffic intersections, while, the delay-events like control-delay, time-in-delay and stopped-delay can easily be observed and quantified. These events are always associated with all the driving modes observed at intersections, which may therefore act as surrogate to establish relationships with vehicular emissions and delay-events.

Figure 3.2 describes the concept of delay-events on a time distance graph (Rouphail et al., 2001). A control-delay is the difference in time taken by a vehicle to reach cruising speed at a distance downstream of an intersection (after slowing down and stopping at the intersection) and time taken had the vehicle maintained its cruising speed through the intersection. The control-delay is, thus, defined as the total-delay at the intersection and it includes deceleration-delay, stopped-delay and acceleration-delay. Obtaining quantitative information on these variables is a laborious and time-consuming task (Persaud et al., 2001). The time-in-delay is defined as the time from when a vehicle first starts to slowdown until it reaches cruise speed again (is always greater than control-delay) and the stopped-delay refers to the time spent by vehicles in idling mode. The control-delay is therefore an average of a time-in-delay and a stopped-delay.

In practice, one can approximate overall delay by subtracting average travel time of unimpeded vehicles from the actually observed delayed travel times. This method, known as path-tracing, is laborious and time consuming. Another easier way to calculate overall delay is to measure the stopped-delay by counting all stationary vehicles at fixed time intervals and relating it to the overall delay.

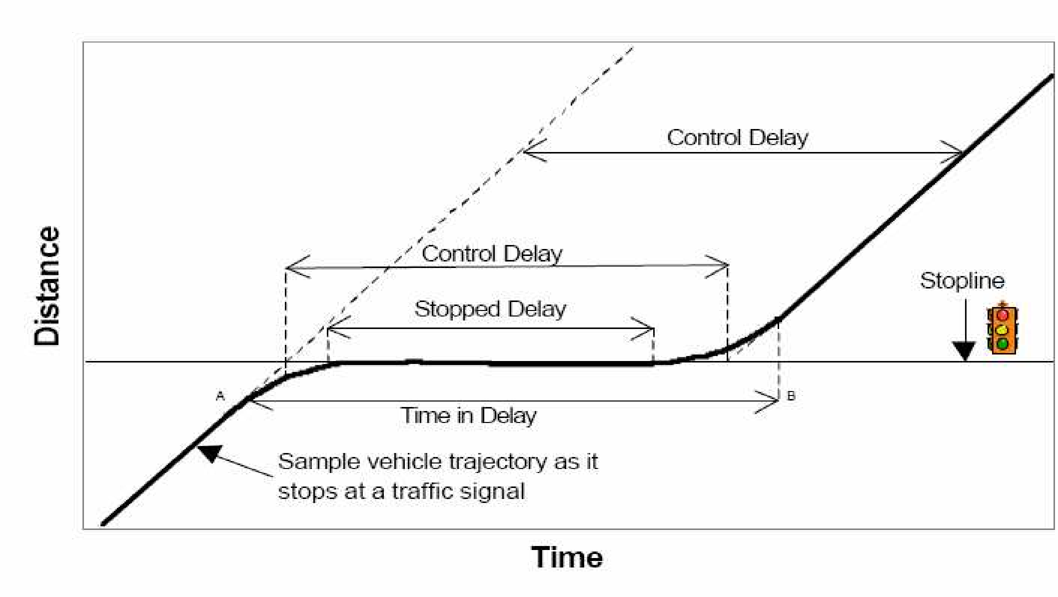

Figure 3.2: The concept of delay-events on a time-distance graph

In the highway capacity manual of 1985, a factor of a ratio of overall-delay to stopped-delay has been assumed to be constant equal to 1.3 (TRB, 1998). Several investigators questioned the use of such factors because the relationship between approach-delay and stopped-delay is not constant (Olszewski, 1993; Teply, 1989). The highway capacity manual, as a result (TRB, 1998) was later modified to eliminate the use of this factor and was replaced with the levels of service for signalized intersections in terms of control-delay. Later, Mousa (2003) found the ratio of total-delay to stopped-delay which varies between 1.5 and 3.0.

In one of the earlier studies, Saleeb and Hartley (1968) showed that both the mean-delay and the mean-queue length increase with the increase in traffic inflow rate. Further, the minimum queue length occurs for the offset of 0-60 seconds, an ideal offset corresponding to the travel time of a vehicle having the mean velocity of 30 miles per hour (mph) and the maximum queue length for the offset of 30 seconds. Much later, Yamada and Lam (1985) simulated the optimal offset between two traffic signals to achieve minimal mean delay and queue length. They identified that relationship of the delay/offset is the most sensitive to cycle split, green phase sequence and proportion of performance. In the recent past, Niittymaki (1999) further simulated the offset between two traffic signals by using fuzzy control. It was found that the importance of coordination was the highest on small intersection distances of up to 1000 meter (m). Li et al., (2004a) quantitatively evaluated the performance of signalized intersections by gray theory-based method, a type of multidisciplinary or generic theory similar to fuzzy logic deals with systems that are characterized by limited information, under mixed traffic conditions. The degree of saturation, stopped-delay, queue length, conflict ratio, and separation ratio were used as indices to represent mixed traffic features.

Hunt et al., (1982) studied the optimization of the timing of traffic signals to minimize delay in response to the fluctuating traffic levels using demand responsive Split Cycle and Offset Optimization Technique (SCOOT) and Urban Traffic Control (UTC) System. SCOOT uses a network of inductive loop detectors embedded in the road surface to measure basic traffic parameters such as flow and lane occupancy. In addition to these systems, several traffic operations software packages that provide vehicle emissions estimates (Dion et al., 2000; Husch, 1998; FHWA, 1997 and Van Aerde, 1995) based on dynamometer testing of vehicles also exist (Unal et al., 2003). These researchers have further studied the characterization of emissions at any time or any location during a trip including the local effect of signal control. These measurements were further combined to characterize emissions depending on the modes of acceleration, deceleration, idle and cruise.

Hallmark et al., (2000) studied the impact of traffic signals on emissions using MEASURE (Mobile Emissions Assessment System for Urban and Regional Evaluation) model considering ‘signal timing’ factor on the CO emissions. They observed a significant reduction in CO emissions when the delay time at traffic signals was reduced. Rakha et al., (2000) showed that the proper signal coordination can reduce emissions even up to 50%. Rouphail et al., (2001) studied the effects of traffic flow on real-time vehicle emissions. The vehicle emissions rates were evaluated during each ‘mode’ of travel of acceleration, deceleration, cruise, and idle. They further discussed the control delay in relation to vehicle emissions. The study revealed that the vehicular emissions were higher when the vehicles transited from idle to acceleration mode. The emissions were relatively lower while in idle mode. It also found that vehicle emissions were approximately twice as much during control-delay than when not-in-delay. This has further confirmed that the switching between free flow and congested flow accounts for all four driving modes leading to higher emissions. Li et al., (2004b) have proposed the integrated optimization of signal timing to reduce emissions. The study carried out by Coelho et al., (2005a) showed that the standardized driving cycles used in macroscopic models such as COPERT (Calculation Of air Pollutant Emission from Road Transport) (Ntzaichristos and Samaras, 2000), MOBILE (Mobile Source Emission Factor Model) (USEPA, 2003) and EMFAC (EMission FACtors developed by Air Resources Board) (California Air Resources Board, 2000) were less appropriate for evaluating the effects of traffic interruptions caused due to speed control traffic signals on the emissions.

Owen (2005) recently studied the impacts of speed-restricted zones on the roadside air quality. The study showed that the reduction in traffic speed results into a significant change in operational factors influencing vehicular emissions. It further showed that the speed-control signals affect emissions due to excessive delays, queue formation, and speed-change cycles for approaching traffic. Coelho et al., (2005b) also studied the performance of speed-control traffic signals using laboratory measurements and emission model. The study establish the link of reduction in the signal-control variables (e.g. minimum signal settings, speed threshold setting and minimum green call scenarios) and improved drivers' behaviour (more adherence to the speed limits) with traffic emissions and delay events. They reported that the presence of signals leads to increase in the CO emissions by 15%, NO by 10% and HC emissions by 40%. Further observations revealed that the signal control schemes that result in stopping a larger fraction of speed violators, yield higher emissions, while, the speed-control traffic signals modifying the drivers' behaviour by inducing speed reduction, decrease the relative emissions. This type of signal, therefore, may reduce high-speed crashes by slowing fast vehicles but may add excessive delays, queue formation, and speed change cycles, which increase the emissions.

It can, therefore, be explicated that the increase in traffic flow rate over the saturation capacity level increases mean delay and queue length, which as a result increases the emissions invariably. The average delay of vehicles may, therefore, be an important criterion for the evaluation of operation of signalled traffic intersections. The optimized flow of vehicles with less delay may lessen the congestion and thereby reduce the concomitant emissions at traffic signals. These characteristics, however, have varied impacts on emissions depending upon the intersection geometry and road types. It is found that the optimization of signal timing plan can improve the traffic operations as well as reduce the traffic emissions.

These studies indicate that the traffic control strategies to reduce traffic congestions and emissions are usually different and sometimes conflictive. Therefore, the effective evaluation of traffic control strategies should consider their impacts on both improving traffic performance and reducing concomitant emissions.

3.2.2 Vehicular emissions due to driving speed

Emission factors derived in laboratories describe a particular condition of emissions but in general do not match with the real-world emissions for several reasons (Joumard et al., 2000; De Haan and Keller, 2000). It is, therefore, necessary to understand the 'effect of speed' on emissions under the possible driving modes particularly, those which occur at

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traffic intersections. Benson (1992) identified the importance of isolating the emission contribution from each mode to characterize the spatial variation in emissions at traffic intersections. Kuhler and Karstens (1978) characterized driving cycles into the proportion of idle, acceleration, cruising and deceleration. They also included more variables in this study such as average acceleration, deceleration, mean length of a driving period from start to stop, and average number of acceleration-deceleration changes within one driving period.

Matzoros and Vliet (1992) added a new driving mode, ‘creeping’ to distinguish short-acceleration and deceleration. Watson (1995) showed that the positive kinetic energy is one of the important factors statistically, which explains the variance in fuel consumptions and emissions. Emissions also vary with respect to drivers’ attitude, experience, gender, physical condition, and age. Sierra Research Foundation showed that most drivers spend about 2% of total driving time in aggressive mode contributing about 40% of total emissions (Samuel et al., 2002). Austin et al., (1993) also studied the driving pattern by comparing driving behaviour of about ten drivers. The study shows great differences in individual drivers’ performances with the vehicle types. Di Genova and Austin (1994) used on-board data acquisition system and portable gas analyzer to monitor emissions as a function of vehicle operating conditions. The study revealed that the driving behaviours can alter average per-mile emissions by more than an order of magnitude. Holmen and Niemeier (1998) found that individual driving styles (e.g. intensity or duration of acceleration events) produce statistically significant differences in measured emissions. Brundell-Freij and Ericsson (2005) studied the effects of streets and traffic environment on driving behaviour in connection with driver variables and car performance. Observations revealed that the most comprehensive effects are related to four variables describing the street environment, i.e. occurrence and density of junctions are controlled by traffic lights, speed limit, street function, and type of neighbourhood. Rafael et al., (2006) studied the impact of operators’ driving style on emissions and fuel efficiency. The study identified that the technical driving is the least emissions releasing with more fuel saving compare to the normal and aggressive driving.

Andre et al., (1995) derived average driving cycles on European road networks from the registered driving patterns in real traffic, which, however, did not explain the reason why the driving patterns varied in certain characteristic ways. It was apparently clarified that the variations in driving patterns are influenced by several external conditions such as street types, number of lanes, traffic conditions, type of vehicles, and the characteristics of a driver. Some studies have reported that even the high power and load conditions such as rapid acceleration or high-speed activities also produce significant amount of emissions (De Vlieger et al., 2000; Groblicki, 1990; Benson, 1989; Kunselman et al., 1974). Carlock (1992) conducted a laboratory test to estimate the effect of acceleration driving mode on the emissions, which showed that the high acceleration rates contributed significantly to instantaneous emission rates and high pollution. However, in one of the studies, it was observed that unloaded vehicles while decelerating produce significant emissions (Darlington et al., 1992). Guensler (1993) found that a sharp acceleration increases in emission rates with the increase of air-fuel ratio. Later Bachman, (1998) also showed that a single sharp acceleration can produce as much emission as an entire trip. Rakha et al., (2000) observed that the acceleration at higher speed increases emission rates per unit time.

Joumard et al., (1999) studied the impact of slight changes in the traffic management on total emissions in an area of 30 km/h speed limit. The study revealed that average speed alone is not sufficient to model the emissions requiring instantaneous speed. Several such studies have also been carried out which combined the change in speed with emissions (Boulder and Webster, 1997; Andre et al., 1996; Abott et al., 1995). These studies further envisage that the emission models require information on average speed for the driving modes of acceleration, steady speed, and deceleration (Watson et al., 1983).

In the road network, driving-speed profile uses average emission factors for every roadway functional class or on every link. Traffic emission computations using the network-wide emission factors on average speed of a network are used in these speed profiles. An average driving speed of the fleet derived from the driving cycles of interrupted, free-flow, and congested of different modes of idling, acceleration, deceleration, and cruising influences the emissions strongly. Driving pattern, on the other hand, is a complex phenomenon influenced by driver-behaviour on the street and the environment, the traffic flow and the vehicle type.

Several studies in the recent past have used COPERT-III methodology to calculate the road emissions (Kouridis et al., 2000; Ntziachristos and Samaras, 2000). This methodology calculates pollutant emissions using information on the number of vehicles, year of introduction of regulations, fuel consumption and characteristics, average ambient temperature of the country, route distribution/driving condition (rural, urban, highway) and average speeds. Some studies have used aaSIDRA (Signalized & unsignalized Intersection Design and Research Aid) model as a pre-processor to determine the acceleration and deceleration rates, speed and distance profiles for a vehicle to estimate the emission (Akcelik & Associates, 2002; Akcelik and Besley, 2001). Some other studies

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have reported that the emission rates are higher during congested traffic conditions with characteristic stop-start conditions associated with periods of idling followed by acceleration (Marsden et al., 2001; Andre´ and Pronello, 1997; De Vlieger, 1997; Waters, 1992). Negrenti (1999) proposed a congestion correction factor in modeling the traffic emissions from the average speed. This factor represents speed variability along a link based on the easily available parameters such as link length, traffic density, link average speed, and percent of green time at the intersection.

Ericsson (2000) has found a significant variability in the urban driving patterns, the knowledge of which may be useful to devise a policy to change the driving behaviours for the reduction of exhaust emissions. De Vlieger et al., (2000) observed that aggressive driving results in a sharp increase in the fuel consumption and the emissions compared to the normal driving. The study further revealed that the fuel consumption rises by 12 to 40% and CO emissions increase by a factor of 1 to 8 for an aggressive driver compared to those of a normal driver. The increase in emissions of VOCs and NO_x due to aggressive driving ranges from 15 to 400% and 20 to 150%, respectively. Several modeling studies have reported that the significant acceleration or deceleration affects the instantaneous emissions by a factor of 2 or 3 as compared to the steady speeds (Sturm et al., 1997; Sturm and Sudy, 1996; Joumard et al., 1995; Hassel and Weber, 1993; Sorenson and Scharmm, 1992;). Andre et al., (1995) reported the marginal emission variations under the real-world traffic conditions since average acceleration does not significantly vary.

Colberg et al., (2005) showed the dependence of emission factors on vehicle speed. This study was carried out on tunnel measurements. The observations showed the increase in NO_x concentrations with the vehicle speed. Further, emission factors of CO and VOCs derived from the statistical analyses decrease with vehicle speed whereas the emission factors calculated by emission model (HBEFA, Handbook of emission factors for road traffic) increase with vehicle speed beyond the optimum range.

Rakha and Ding (2003) applied the microscopic models (VT-Micro fuel consumption and emission) to quantify the impact of vehicle stops and speeds on the fuel-consumption and emission rates. The study concluded that the vehicle fuel-consumption and emission level depends on the conditions under which the vehicle operates. The changes in the vehicle fuel-consumption and the emission rates are mostly associated with changes in the vehicle cruise speed and the driver acceleration aggressiveness. El-Shawarby et al., (2005) investigated the impacts of vehicle cruise speed and acceleration levels on the vehicle fuel-consumption and the emission rates using field data gathered under real-world driving conditions. The study showed that the parameters per-unit runs of vehicles are optimum in the range of 60-90 km/h. The study further revealed that with the level of aggressiveness for acceleration, manoeuvring increases. The fuel-consumption and emission rates per manoeuvers decrease since the vehicle spends less time during accelerating. However, over a sufficiently long run, fuel-consumption and emission rates per-unit distances increases as the level of acceleration increases.

Minocha and Saini (2003) reported that the engine speed greatly influences the vehicular fuel consumption and emissions. Generally, in the practical range of air-fuel ratio an increase in engine speed results in higher fuel consumption, which in turn leads to a reduction in air-fuel ratio, along with an increase in CO and HC emissions and a decrease in NO_x emissions.

Driving pattern is generally represented by a speed profile of the vehicle but can be expanded to include other parts of driving behaviour such as gear changing. Ericsson (2000) studied the effect of urban driving patterns on emissions and fuel usage. The study indicates that in addition to the speed, independent factors describing acceleration and power demand as well as gear changing behaviour are important explanatory variables for emission and fuel consumption. Another study by Hallmark et al., (2002) shows that the driving patterns (i.e., speeds) at different intersections are significantly influenced by queue position, downstream and upstream lane volume, incidents, percent of heavy vehicles, and posted link speed.

These studies have illuminated the fact that the aggressive driving produces most of the emissions than the smooth driving (cruising mode) because of the more time spent by vehicles in acceleration and deceleration driving modes consuming more fuel. Besides, driving speed and driving behaviour too have significant effects on emissions.

3.3 ROAD CHARACTERISTICS

This section reviews the studies carried out on the effects of the types of roads like rural, urban, local and highway, grades, speed humps, and the types of intersections on vehicular emissions. The decongestion and smoothness of the heavy-traffic flow in urban areas are dire necessities these days to reduce the emissions and the resulting roadside air quality.

3.3.1 Vehicular emissions due to effects of road geometry

One of the recent studies carried out by Rosqvist (2007) on traffic emissions in residential areas showed that the fuel consumptions and exhaust emissions were highly dependent on street design and structure of the street. Further, proper road structures may enhance air quality and as a result, suggests a simple method to evaluate the influence of road structures on air quality and to develop appropriate designs to reduce environmental

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impacts. In a few more studies *viz*., Yokoyama (1981) used an analytical model, and Moriguchi and Uehara (1995) a numerical model to assess the effect of road structures on air quality in the urban areas. Similar studies of road effects on dispersion of pollutants emitted at the ground level in street canyons were performed by Lee and Park (1994), Kim and Baik (2001), and Garcia Sagrado et al., (2002). Uehara et al., (2000) investigated the effect of an elevated road on the pollutant dispersion in street canyons using wind-tunnel simulations. The study also included the comparisons of tracer gas experiments simulated as emitted from the highway using both the analytical and numerical models.

Rosqvist (2007) also studied the emissions due to fuel consumptions in Sweden's different types of streets, junctions, humps and street configurations. The study reflects that one kilometre drive on larger streets adds somewhat less to emissions than it is on smaller streets. Further observations, however, also show that junctions and humps have reducing effects on almost all pollutants caused due to vehicular exhausts. This may not be true for developing country like India where, driving pattern is already much lower than the optimum range for least exhaust pollution. Nesamani and Subramani (2006) observed that emission rates of pollutants vary significantly from one class of road to another and the largest effect is on local streets. This is mainly because on the local streets vehicles spend more time in acceleration mode with low average speed.

Tokairin and Kitada (2004) studied the effects of fences placed on the double-decked road by using a standard k–ε turbulence model and computer code, CFX4. The study shows that the fence set at the ground always enhances emissions near the road but on the other hand, at the upper deck it results into decreased emissions near the road. Further, Nesamani and Subramani (2006) also observed that both arterial and sub-arterial roads have similar emission rates for CO and HC except for the NO_x, which was higher in arterial. They attributed this to a sharp acceleration rate in the arterial streets. The CO_2 emissions were also found to be lower in arterial streets and higher in local streets. This study thus shows that fuel consumption is high in local streets and low in arterial streets.

Studies carried out to assess the impact of speed hump and uphill driving (fly over) upon the pollutant emissions are presented in this section. Pierson et al., (1996) found that emissions of CO and NO_x were twice as high in uphill (approx 4% grade), which concludes that the grade influences the emissions significantly. Later, Kean et al., (2003) also studied the effect of uphill driving on emissions but found that increase of NO_x emissions with vehicle speed was not as much as compared with CO emissions. Study carried out by New Scientist (1999) has reported that calmer traffic, gained by implementing speed-reducing humps, reduces fuel consumptions and emissions. For most pollutants, the study shows that, the emission per meter length of a road is less for streets with speed-reducing humps than without it. This is except for emissions of NO_x, CO and HC when streets are smaller and cars are without catalytic-converters. Similar study was carried out by Richard and Steven (1991) and Hammarström (1997) revealing that an average speed reduces the emissions compared to that is generated at a fixed speed of 50 km/h.

3.3.2 Vehicular emissions due to intersection geometry

Mustafa et al., (1993) have shown in their study that the traffic signals at intersections generate more emissions almost about 50% higher than roundabouts. During heavy traffic, signals cause higher emissions of HC, almost double of that is generated at roundabouts. Niittymaki and Hoglund (1999) also found the reduction of 30% fuel-consumption at a roundabout (without traffic signals) rather than using traffic signals at intersections. Further observations indicate that environmentally optimized traffic control systems have energy saving potential of about 10-20%. Another similar study conducted by Varhelyi (2002) in Sweden reports that replacing a signalized intersection with roundabout results in 29% average decrease in the CO emission, 21% in the NO_x and the fuel consumption by 28% per car within the influence of the junction. At roundabouts replacing yield regulated junctions, CO emissions increased by 4%, NO_x emissions by 6% and fuel consumption by 3%. These results indicated that the larger reductions in emissions and fuel consumption at one former signalized intersection can compensate for the increase produced by several yield-regulated junctions rebuilt as roundabouts.

Mandavilli et al., (2008) found that the modern roundabout performs better than the existing intersection control with stop signs in cutting down vehicular emissions. Zuger et al., (2001) showed the effects of conversion of a crossing to a roundabout on crossing times, fuel consumption, emissions of pollutants etc. It depended mostly on local factors such as the amount of traffic, frequency of interruption of traffic flow by pedestrians, the ratio of traffic density on the different branches etc. Since, the traffic density varies greatly with time, a roundabout can have a favourable effect at certain times of a day contrasting with an unfavourable effect, on the variables, mentioned at other times. The effects are favourable where a light-controlled crossing is replaced by a roundabout. When a roundabout replaces a crossing without light signals, the effects on fuel consumption and harmful emissions are often unfavourable.

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3.3.3 Vehicular emissions due to effects of traffic management

Kun and Lei (2007) studied the impacts of different traffic control strategies on traffic emissions considering a separate lane for buses in order to smooth the road network. The results found a marginal reduction in the emissions of CO, HC, and NO_x from buses while there was an increase in the emissions of CO from cars and light gasoline powered vehicles significantly. Joumard et al., (1992) applied the models in conjunction with field trials in the city of Toulouse to examine the possible environmental benefits of traffic management. The study found that the better traffic control in urban areas might save up to 5% fuel, while better speed on interurban roads save up to 2 to 3% fuel, and better route guidance up to 3%. Further observations revealed from the emission modeling that better management saves fuel up to 10% and thereby greatly reduces the pollutant emissions. Noland and Quddus (2006) studied changes in road-network configurations with the aim of improving overall traffic flow, which justified that the capacity of road increases by smoothing traffic flows which further reduces vehicle emissions as well.

These studies demonstrate that the road geometry does have a great effect on the vehicular movement and thereby on emissions. Most studies have revealed that the roundabouts can significantly reduce the vehicular emissions compared with the signalized or un-signalized traffic intersections. Traffic flow model accounts particularly most of these characteristics and therefore seems a vital part of emissions estimation from vehicles.

3.4 VEHICLE CHARACTERISTICS

Vehicles plying on the road having diverse features such as design, type, fuel-driven, weight, etc. are also reported to be affecting the emissions greatly. This section reviews the studies carried out to isolate the effects of these characteristics on the emissions.

Vehicle characteristics are classified broadly into vehicle parameters, fuel parameters, vehicle operating conditions, and environmental conditions, which are known to affect the vehicle emission rates (Bin, 2003; Washburn et al., 2001; Wenzel et al., 2000). Vehicle parameters include vehicle class, weight, engine size, vintage, mileage, fuel delivery system (e.g. carburetted or fuel-injected), emission control system, on-board computer control system, control system tampering, and inspection and maintenance record. Fuel parameters mainly comprises fuel type, oxygen content, fuel volatility, sulphur content, benzene content, lead and metals content, and trace sulphur (catalyst effects). The vehicle operating conditions mainly include cold- or hot-start mode (unless treated separately), average vehicle speed, modal activities that cause enrichment, load (e.g. A/C, heavy loads, or towing), trip length and trips per day, and influence of driver behaviour. The vehicle-operating environment includes altitude, humidity, ambient temperature, and the road grades.

3.4.1 Vehicular emissions due to vehicle parameters

Most studies have found that the increasing vehicle age and more travelled mileage are associated with the increasing vehicular emissions. Vehicle age is a function of both normal degradation of emission control of properly functioning vehicles (resulting in moderate emissions increases). It is a malfunction or outright failure of emission control on some vehicles (possibly resulting in very high emissions), particularly for CO and HC (Beydoun and Guldmann, 2006; Wenzel et al., 2000; Bishop and Stedman, 1996). Anilovich and Hakkert (1996) studied the variation of CO and HC emissions with vehicle age, time elapsed since last annual test, and engine capacity. The study presented the strong correlation between vehicle age and emissions while both time since last annual test and engine capacity were of less significance on emissions. Chang and Yeh (2006) recently analysed the effect of vehicle age on emissions and found that the mean disposal age of motorcycles indicate the possibility of a serious emission problem.

Vehicular emissions also vary greatly with the changing engine load. The relationship between emissions and engine loads depends on the fuel-delivery and emissions-control technology. The NO_x emissions usually increase with the increasing engine load. Under high speed and acceleration requirements, vehicles nowadays use excess fuel into the engine cylinder. This enrichment of the air-fuel mixture leads to the elevated CO and HC emissions during combustion with no oxygen available for the conversion to CO_2 and water in the catalyst. In one of the studies, a temporary puff of higher CO and HC emissions at tailpipe were observed (Goodwin and Ross, 1996). In some vehicles, fuel injection is cut off during rapid decelerations, which often leads to the cylinder misfire and a temporary puff of high HC emissions (An et al., 1997).

Vehicle emission also varies depending on the vehicle make. The study conducted by (Beydoun and Guldmann, 2006) on seven different vehicle makes (i.e. Kia, Lexus, Infiniti, Saturn, Honda, Suzuki and Toyota) reported that the emissions are higher for old vehicles make. Beydoun and Guldmann (2006) also studied the effect of vehicle weight on emissions and observed that the likelihood of failure decreases with the increasing weight in case of cars. However, the results were not same for trucks. Commonalities across all makes and types of vehicles include the effects of the mileage, age, fuel economy, and the season. The engine size has a negative effect and the number of cylinders have a positive

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effect on car emissions, while, these effects are in general of mixed nature in case of large vehicles like trucks.

Samaras and Ntziachristos (1998) studied the effect of mileage, engine capacity, ambient temperature and air conditioning on emissions of passenger cars. Mileage also affects the emissions of almost all the pollutants significantly, especially in case of legislated cycles. Even in case of real cycles, the similar observations have been made. Further, it was found that the differences in average emissions for different mileage classes may reach to a factor of 5, as was found for VOCs for vehicles of load less than 1.4 with a low speed. Emissions from vehicles in the two middle mileage classes (> 5,000 and < 100,000 km) do not differ substantially as in the case of average speeds.

Engine capacity also has a pronounced effect on vehicular exhaust emissions. For all mileage classes, some studies have observed the low CO emissions with the increase of engine capacity, in the case of the EUDC (Extra Urban Driving Cycle). These observations were compatible with the nature of the emission function curves developed for a speed of 60 km/h by Samaras and Ntziachristos (1998) in COPERT-III. In case of UDC (Urban Driving Cycle) for a speed of 19 km/h, emissions from the real-world cycles increase as engine capacity increases. In case of real cycles, no distinct effect of capacity on emissions was observed for the speed region corresponding to that of the UDC. For NO_x and VOCs, study shows no consistent effect of capacity on emissions for the two legislated cycles. The minimal effect of capacity on emissions was also observed when real world cycles were examined. For the case of 5,000 to 50,000 km and 50,000 to 100,000 km mileage classes, no distinct variation of emissions with capacity was noticed.

Vehicle load often increases the fuel consumption and produces more emissions for a given vehicle on an individual basis or for groups of vehicles on an average basis. In the study carried out by Kim (2007) for the smaller single rear-axle vehicles, approximately 26% increase in fuel use was seen accompanied by more emissions with doubling of vehicle weight. For the larger tandems, a load increases of approximately 140% increases average fuel use and emission rates by 30–35%. McCormick et al., (1997) examined the effect of changes in vehicle loads on PM, NO_x, and CO emissions from eight heavy-duty dump trucks in which, increasing trend of NO_x and PM emissions were observed with the increase of vehicle loads.

Vehicle size and weight influences the fuel use resulting in the increase of the CO_2 emissions. The emissions of other pollutants also typically, but not always, increase by size and weight (Kim, 2007). The effect of vehicle weight on emissions has been identified as the most influencing characteristics in case of diesel driven vehicles, particularly for PM and NO_x (Keller and Fulper, 2000; Durbin et al., 1998). In addition to this, vehicle weight has similar effect on non-exhaust particle emissions from vehicles such as tyre and brake wear and particle re-suspension (Gillies et al., 2005). The reduction in the vehicle weight is inevitable for the purpose of passenger comfort and pollutant emissions, though clearly it proves the negative effect during accidental and crash times (Kahane, 1997; Kahane, 1991; Klein et al., 1991; Partyka and Boehly, 1989).

3.4.2 Vehicular emissions due to vehicle operating conditions

The operation of a vehicle during warm-up affects the rate at which the catalyst heats and the time it takes to reach catalyst light-off temperature (Austin et al., 1993; Wenzel et al., 2000). The magnitude of cold start emissions depends on time since the vehicle last operated, ambient temperature, and operation of the vehicle after starting. The ambient temperature has a direct effect on evaporative HC emissions. Very low ambient temperatures (e.g., below -6.66 ^{o}C) can influence emissions at ignition and cause the catalysts of some vehicles to cool during short stops. Wenzel et al., (2000) showed that a very high ambient temperature highly influences the fuel consumption because engine load increases by the use of air conditioner. Effects include the higher NO_x and an increase in the frequency of commanded enrichment. Roadway grade and use of air conditioning and heaters put additional loads on the engine and give rise to emissions. Small changes in how a vehicle is driven also affect the emissions. For instance, how a driver shifts gears on a vehicle with a manual transmission or how smoothly a driver depresses and releases the accelerator may affect emission rates (Holmen and Niemeier, 1998).

In case of three-way catalyst passenger cars, ambient temperature not only affects the engine parameters (wall temperatures, intake air density, etc.) but also the time after the engine starts when the catalyst reaches its light-off temperature. For this reason, some studies included extended surveys to describe explicitly the effect of temperature on the cold start emissions (Joumard and Serie, 1999). Hot emissions are, however, also affected by the low temperature but in a lesser degree.

Although there is a tendency of increasing emissions with decreasing average temperature, quite a few cases, in which, emission increase has been very low than unity index at low temperature. This effect was attributed to the different intake system concepts (mass flow or volumetric flow measurement of the intake air). Further, the change in ambient temperature also changes peak temperatures of the engine cylinders during combustions affecting mainly the NO_x emissions. The NO_x emissions tend to increase as peak combustion temperature increases (Flagan and Seinfeld, 1998). Similarly, the

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ambient humidity also affects the peak combustion temperature, which would in turn affect the NO_x formation. The NO_x emissions are expected to decrease, when the humidity increases. According to SwRI (2003), humidity has some effect on NO_x emissions for heavy-duty engines. However, Hearne (2004) found no conclusive trends between humidity and NO_x emissions.

Air conditioning compressor generally imposes the higher load on the engine and is also responsible for the increase in fuel consumption and the vehicular emissions. This effect was investigated by French ADEME (1996) and UTAC (1997) with the testing of gasoline and diesel passenger cars over the Extra Urban Driving Cycle (cold UDC and EUDC). These studies showed a large dispersion in the emissions of pollutants of gasoline cars except CO_2, for which the increase of almost 20% over the EUDC was observed. These studies, which whatsoever could not draw definite conclusions on the absolute level of emissions increase for CO and NO_x, however, concluded that HC emissions may decrease when the air conditioning compressor is in operation. Diesel vehicles show more stable increase of emissions in the range of 20-30% for CO, NO_x and CO_2. HC emissions show a very large variation with the usage of fuel and no differentiation at the driving cycle level but on the other hand CO emissions present a distinct decrease in emissions for diesel fueled vehicles.

Harrington (1997) and Wenzel et al., (2000) found that the fuel economy also affects the emissions and the effect becomes stronger as vehicle gets older. The study also showed that fuel composition can have a substantial impact on vehicle tailpipe and evaporative emission. Therefore, further suggestions of the study were to make changes in the existing regulations to reduce the emissions as a strategy. For instance, some urban areas introduce oxygenate in fuels to reduce CO emissions in winter and decrease the volatility to reduce evaporative HC emissions in summer.

Vehicle characteristics, as many studies show, have a pronounced effect on emissions in addition to the traffic characteristics. Most importantly, mileage, engine capacity affects the emissions by a large factor compared to others such as engine size, load, weight, etc.. These individual parameters affect emissions to varying degrees depending on the way the vehicle is maintained and driven. The recent version of COPERT-IV is a result of studies carried out on the effects of cumulative mileage and fuel consumptions on vehicular emissions.

3.5 TRAFFIC FLOW MODELS

Traffic flow models, usually applied to evaluate the conditions of roadway facilities, are classified into macroscopic, mesoscopic, and microscopic, based on their functionality. Recently, a hybrid traffic-assignment-flow model was developed by Balke et al., (2005) based on the traffic flow and the traffic assignment. Macroscopic model, which includes simplified mathematical equation based on the flow-density relationship, governs the vehicle movements to describe average behaviour of a fleet over a specified duration of 1, 5, or 10 min. It comprises a speed-flow, a speed-density, and the flow-density models. This type of model estimates an average vehicle speed at the traffic intersection using speed and traffic volume data.

Microscopic model incorporates the actual behaviour (i.e. car following, lane changing, merging, and diverging) of individual vehicles in short-time steps (1 second or even 1/10 of a second). The characteristics of a driver, vehicle performances, and its interactions with network geometrics and surrounding vehicles determine the vehicular movements within the system.

Mesoscopic traffic flow model on the other hand falls in between macroscopic and microscopic models and deals with the aggregate behaviour of a group of vehicles but performs simulation in small steps.

Eisele et al., (1996) and Chapin (1993) demonstrated that underestimation of traffic volumes by 10 to 30%, both overall and on local arterials, results in underestimating emissions by as much as 50%. The study thus shows that any error in estimating traffic flow rates may cause a proportional error in emissions calculation. Further, Negrenti (1999) also pointed out that the vehicle speeds derived from an underestimated flow rate may lead to a drastic increase in the emissions.

Traffic emission estimates based on the traffic-count combined with different statistical methods is often not correct and lack in reflecting the dynamic behaviour of the traffic flow. Therefore, an exact analysis of 'speed' and 'acceleration' in certain situations (e.g. stop-and-go at traffic lights, stop-and-go scenarios in overcrowded roads) performed by means of traffic-flow model provides better emission estimates (Schmidt and Schafer, 1998).

In most of the developing countries traffic flow is often heterogeneous, which takes a continuous form in motorway circulation and a discrete one in intersection ways. The continuous form of traffic flow is mainly modelled from a macroscopic point of view (Papageorgiou, 1997). In this case, the traffic flow is described by a flow rate, flow density, and flow average speed. On the other hand, the discrete form of traffic flow is

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modelled from a microscopic point of view that focuses on individual vehicle behaviours on road. This approach thus describes the traffic in a finer way, in that, vehicles individually represent by the interactions between them (Fuks and Boccara, 1998; Castillo, 1996; Nagel, 1982). Prigogine and Herman (1971) have developed statistical methods to traffic flow studies, known as the kinetic theory of traffic, which considers vehicles on road as interacting particles in traffic-flow and is described by one-dimensional compressible fluid equations. In practice, the continuum hydrodynamic approach is difficult to implement because of numerical treatments for the diffusion and advection terms and solving governing equations numerically over the road. As an alternative to this approach, equilibrium relationship between traffic density and velocity has been proposed.

By definition, traffic flow is the product of traffic density and velocity. If traffic density is zero, the traffic flow is zero. Nevertheless, when it reaches the maximum (i.e. condition of congestion) the traffic velocity decreases to zero, so traffic flow is also zero. Wong and Wong (2002), Daganzo (1994) and Newell (1993) suggested the piecewise linear relationships between the traffic flow and the vehicle density. Al-Omishy and Al-Smarrai (1988) have developed a model for simulating the traffic flow and emissions for free-flow situations using car-following theory constraining random inputs to predict emissions of gaseous pollutants emitted from different types of vehicles on the road. The study shows that emission of NO_x increases with an increase in percentage composition of heavy-duty diesel vehicles because of the higher temperature, availability of excess oxygen and long residence time, but the emission of HC decreases. Di Cesare et al., (1994) has proposed a model of six signalized intersections to implement the traffic signal control strategies and to evaluate their impacts on the traffic flow using POSES Petri Nets Simulator[1]. Many traffic flow models[2] have in-built emission models, essentially sensitive to the vehicle modal activities but not based on the actual on-road emission data. In most of the studies, changes in traffic-flow variables used in emission models are based on the relationships between delay or speed and emissions. Wood and Harrison, (1998) found that most pollutants' emission decreases with the decrease in delay, except for the NO_x, which increases with the decrease in delay. They further found that the NO_x emission decreases with increasing mean vehicle speed up to about 25 km/h but increases gradually

[1] Other studies use the simulator to provide a realistic representation of the continuous flow in inter-urban traffic networks (Tolba et al., 2001; Di Febbraro and Sacone, 1998) and to take account of discrete behaviours at intersections (Giglio and Sacco, 2001; Mancinelli et al., 2001). Schwerdtfeger (1994) in a similar vein combines the advantages of microscopic and macroscopic models using the mesoscopic traffic flow model DYNEMO.
[2] These include INTRAS (Wicks and Lieberman, 1980), FREQ (Imada and May, 1985), NETSIM (Rathi and Santiago, 1989), TRANSYT-7F (Penic and Upchurch, 1992) and INTEGRATION (Van Aerde, 1995).

in the range of 25 to 70 km/h and increases rapidly above 70 km/h. The study therefore justified that the optimum traffic conditions for emission minimization lies between two extremes of congestion and free flow.

De Angelis (1999) developed a nonlinear model of traffic flow that uses a linear diffusion term as governing equation. Their study showed that a second order flow-density relationship satisfactorily fits the experimental results of Leutzbach (1988). Bonzani (2000) and Marasco (2002) further presented a critical analysis using the same model with additional phenomenological relationship between density and velocity. Velan and Florian (2002) further explored the implications of non-smooth equilibrium flow-density relationships. Vandaele et al., (2000) developed analytical queuing model based on the traffic counts for modeling the behaviour of traffic flows as functions of density and speed of the vehicle. Dirks et al., (2003) and Gokhale and Pandian (2007) have recently developed a semi-empirical model based on second order quadratic equations to obtain the flow-density relationship. This model assesses the congestion of the traffic and its impact on the CO emissions. Later, for freeways, Highway Capacity Manual (HCM) introduced empirically derived speed-flow curves replacing the mathematical formulae. A traffic model based on the combination of traffic flow theory of a Monte Carlo simulation method and aaSIDRA model was applied for traffic flow simulations (Akcelik and Besley, 2001; Akcelik & Associates, 2002).

Transportation Research Board (TRB, 2000) and Coelho et al., (2003) presented the equations for calculating signal control and traffic performance variables such as average green time, volume to capacity ratio, average vehicle delay and probability of stopping (or proceeding) for vehicles under (or exceeding) trigger speeds. Xia and Shao (2005) have demonstrated the Lagrangian approach using traffic information database for the Hong Kong island with the traffic-flow simulation model. The study shows that specifying three types of traffic routes (random turn, preferred turn, and shortest path) in addition to the traffic flow data at selected stations, the model is capable of simulating traffic flow on the road network. The simulated traffic flow was then used as the basis for estimating the traffic-induced emission of air pollutants.

Other macroscopic traffic models, such as traffic network study tool (Transyt-7F), Passer II-90, highway capacity software (HCS), and simulation of traffic induced air pollution (SIGNAL97) do not include emission predictors since it is difficult for traffic analysts to estimate vehicle emissions in many cases (TRC, 1998).

Traffic flow models in association with emission models may provide accurate estimates of emissions, as they are traffic speed, traffic density and flow dependent. Most

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traffic flow models, however, do not facilitate the emission calculations from individual vehicle, for several reasons. The most important besides traffic flow, is the behaviour of individual vehicle dynamics, which is mainly characterised by its driving speed.

3.6 TRAFFIC EMISSION MODELS

Xia and Shao (2005) calculated emission factors for three emission modes. First, the hot emissions, i.e. the emissions from vehicles after they have warmed up to their normal operating temperature; Second, the cold-start emissions, i.e. the emissions from vehicles while they are warming up and the water temperature is below 70 ^{o}C. Finally, the evaporative emissions, i.e. the HC emissions result of gasoline vapors escaping from the vehicle's fuel system. Sturm et al., (1997) described the three approaches of compiling emission inventories based on ‘actual driving behaviour’, ‘specific streets’ and ‘vehicle miles travelled’. The parameters considered in this study were travel demand, traffic condition (congested or free flowing), vehicle operating mode (cruising, idling, accelerating or decelerating) and vehicle operating condition (cold or hot start, average speed, load, trip length, frequency of trips). Furthermore, vehicle parameters (model and year, state of maintenance, engine type and size, emission reduction devices, accrued mileage, fuel delivery system), and the fuel characteristics (type, volatility, chemical composition) were also included in the study. Besides, the driver behaviour (gentle or aggressive), the local climatic conditions (temperature, humidity), and the local topography (road grade, altitude) were considered.

SYNCHRO, a macroscopic traffic flow model with a built-in simplified emission model was applied for estimating vehicle emissions by first predicting the fuel consumption as a function of vehicle-miles, total delay in vehicles-hour per hour, and total stops in stops per hour. Fuel consumption was then multiplied with an adjustment factor (differs depending on the type of emissions) to estimate the vehicle emissions (Husch, 1998).

These studies have facilitated an advancement of emission models, which nowadays account for start emissions, roadway types, etc. For example, the latest version emission model, MOBILE6, includes recent emission rates and off-cycle emissions that reflect the real-world traffic conditions more accurately. The model accounts separately for start emissions and running emissions. The MOBILE6 model is capable of estimating emissions by roadway type (freeways, arterials, ramps, and local streets), time of day, and other characteristics (USEPA, 2003). The latest version of the EMFAC model includes low emission vehicle standards and EPA (Environmental Protection Agency) Tier II standards (CARB, 2000). It also assumes modest emission reductions for proper inspection and maintenance programs. EMFAC produces separate emission factors for cold starts, hot starts, and hot stabilized conditions. Modal emission models that are based on various vehicle operating modes (cruise, acceleration, deceleration, and idle) have also been emerged as alternatives in the recent past (Guensler et al., 1998; Barth et al., 1996a). The accuracy of these models, however, relies on the estimates of traffic-network activity data from travel forecasting models, which are still based on steady state (static) analyses. Barth et al., (1996b) developed a methodology to utilize both traffic sensor and microscopic data to estimate emissions. It does not consider road geometry data and cannot be used for links without loop detectors. The model incorporates standard conditions based on the laboratory dynamometer driving tests and predict CO, HC, and NO emissions as functions of a number of factors with vehicle speed and vehicle-miles-travelled (USEPA, 1999).

A number of microscopic traffic models estimate vehicle emissions as a function of vehicle type, speed, and acceleration on a second-to-second basis. Federal HighWay Administration (FHWA) (1997) developed CORSIM (CORridor SIMulation), a microscopic model, and used vehicle emission rates from the dynamometer testing as the basis of its emissions model. The study determined the total emissions on each link by applying the speed and acceleration related emission rates to each vehicle for each second the vehicle travelled on the given link. Van Aerde (1995) also computed the fuel consumption for each vehicle on a second-to-second basis as a function of speed and acceleration using INTEGRATION traffic emission model. The study further included the estimation of vehicle emissions on a second-to-second basis as a function of the fuel consumption, ambient air temperature, and the extent to which a particular vehicle's catalytic-converter already warmed up during an earlier portion of the trip.

Yu (1998) developed ONROAD model for estimating vehicular CO and HC emissions based on the on-road emissions data. The model establishes relationships between the on-road vehicle-exhaust emission rates and vehicle instantaneous speed profile, which is a function of different traffic demand and control scenarios. The ONROAD emissions model estimates the implications of alternative traffic control and management strategies on emissions. A traffic simulation model easily incorporates this model in a situation where vehicle's instantaneous speed profile can be tracked consistently. The study further revealed that the other emission factor models, the MOBILE and the EMFAC, underestimate the on-road vehicle emissions for all vehicle types compared to the ONROAD model. The study also included the comparison of the

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instantaneous emission rates among emission models and showed that the emissions estimates by the TRANSYT model considerably deviates from the ONROAD emissions, while, the MOBILE and the EMFAC models show consistency in their emission rate estimations.

The characteristic variation of emissions with an average vehicle speed has been clearly discussed in most studies (Barlow et al., 2001; Andre et al., 1994; Latham and Hickman, 1990). The highest emissions of CO, particulates and HC (including benzene) tend to occur at low average speeds (less than 20 km/h) as these pollutants are products of incomplete combustion. Marsden et al., (2001) demonstrated a new approach in microscopic road traffic exhaust emissions modeling for CO pollutant based on the vehicle speed and classification using vehicle operating modes (acceleration, deceleration, cruising and idle), enriched acceleration, state of repair of the vehicle emission control system and type of engine. The study showed that the vehicle exhaust emission depends on the air to fuel ratio. The petrol engine vehicle electronically controls the fuel injection systems that optimize fuel flow rates to ensure stoichiometric combustion conditions (Heywood, 1988). Under such conditions, CO_2 and NO_x are the main products of combustion. Diesel engine operates with a lesser air to fuel ratio than petrol engines using lean burning air and fuel mixtures (Al-Omishy and Al-Smarrai, 1988).

Traffic emission models estimate emissions with the help of traffic flow models outputs caused due to vehicle speed and different driving modes. Most of these models are rigid in terms of incorporating real-time information. Very often, these models can not be applied at traffic intersections for several reasons. They are too data demanding, which sometimes is very difficult to obtain at such locations.

3.7 AIR QUALITY MODELING

Estimating accurate vehicle-induced emissions is necessary for accurate air quality assessment. Because emissions relates to amount of pollutants released into the atmosphere. A study of emissions can only tell that areas in which significant sources of emissions exist are at a higher risk of air pollution than areas which are remote to sources of emissions. Air quality, however, relates to the concentrations of contaminants that people are exposed to. These concentrations result from the transport and dilution of emissions into the atmosphere.

Air quality models predict the quality of air in terms of the concentration of specified pollutants in the air at receptors. Air quality modeling is used for determining and visualizing the significance and impact of emissions on the air quality. Air quality models need two kinds of basic inputs: the amount of pollutants released in the atmosphere from the source under study and the factors that influence the dispersion of pollutants in the atmosphere. The source data is evaluated in conjunction with meteorological information such as wind speed, wind direction, temperature, etc. in the air quality model. The models use all of this information to compute concentration profiles of pollutants as a function of time and space. The models examine all of these components together to characterize the state of the atmosphere, predict transport of pollutants from the source and to estimate the concentration of these pollutants in the atmosphere.

Air quality models are either based on statistical or deterministic methods. Deterministic models are based on a fundamental mathematical description of atmospheric physical and chemical processes in which effects are generated by causes (Vautard et al., 2001; Millan et al., 1996; Simpson, 1993;). The deterministic models are preferred because they account for the detailed emission data and meteorological inputs at the region of interest. The widely used models are General Finite Line Source Model (GFLSM) for gaseous pollutants (Luhar and Patil, 1989), California Line Source (CALINE3 and CALINE4) model for CO, NO_2 and PM10 (Benson, 1992, 1980) and California Line Source for Queuing and Hotspot Calculation (CAL3QHC) for CO, NO_2 and PM_{10} (USEPA, 1995). Most of these models are recommended by US Environmental Protection Agency (EPA) for regulatory purposes.

The detailed literature review on deterministic, stochastic and hybrid vehicular exhausts models has been presented by Gokhale and Khare (2004). Alternatively, statistical models do not consider individual physical and chemical processes and are developed based on semi-empirical statistical relations among available data and measurements. They attempt to determine the underlying relationship between sets of input data (predictors) and targets (predicates). Many different statistical techniques have been proposed to predict pollutant concentrations. These include multiple linear regression (Cardelino et al., 2001; Hubbard and Cobourn, 1998; Ryan, 1995;), generalized additive models (Davis et al., 1998), classification and regression tree analysis (Ryan, 1995), and application of principal component analysis and clustering technique (Guardani et al., 2003; Davis and Speckman, 1999). However, statistical techniques do not aim to fully describe the formation and accumulation of air pollutants in their chemical, physical, and meteorological processes (Schlink et al., 2006).

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3.7.1 Line source model

Line source models include the CALINE series models i.e., CALINE3, CAL3QHC, and CAL3QHCR of the USEPA and CALINE4 of the CARB (Benson, 1989, 1979; Ward et al., 1977). Other models such as HIWAY-2 (Highway air pollution model), GM (General Motors Model) and GFLSM are also in use. These models suffer from the inherent limitations of the Gaussian equations to urban dispersion modeling within complex environments. Previous studies have shown that Gaussian line source models tend to overestimate concentrations in low wind speed conditions, and when the wind direction is parallel or nearly parallel to the road (Kono and Ito, 1990; Benson, 1992; Kukkonen et al., 2001).

The GFLSM model is applicable for all orientation of winds to a line source. Several studies presented the results of its application near traffic intersection and roundabout for heterogeneous traffic condition. This has been, for example, demonstrated in the studies carried out by Gokhale and Patil (2010), Gokhale and Khare (2005) and Luhar and Patil (1989). The model uses empirically derived mechanical turbulence, i.e. vehicle wake factor, as a function of atmospheric stability (Gokhale and Khare, 2007) and therefore does not capture adequately the intermittent fluctuations of winds and thermally induced turbulence produced in short-time. This may be one of the reasons for which it tends to over-predict when winds are low and wind directions parallel or nearly parallel to the line source as observed by Kukkonen et al., (2001), Sivacoumar and Thanasekaran (1999), Benson (1992) and Kono and Ito (1990). The prediction performance of GFLSM was compared with GM, CALINE-3 and HIWAY-2 models and a reasonable accuracy for the Indian traffic conditions was shown (Nagendra and Khare, 2002; Sharma and Khare, 2001).

Broderick et al., (2005) have modeled CO concentration in the five-arm roundabout intersection at Galway city using CALINE4. In contrary to the roadways which are modeled as one line source, the roundabout was modeled as five line sources meeting at the centre point of the roundabout. The predicted values were found to be under estimated compared to measured values as well as less successful in capturing the diurnal variations. They concluded that the composite emission factor for CO derived by them using the assumed average speed could be one of the reasons for model failure. This necessitates the need of a better integrated dispersion module with accounting for revised traffic and emission modeling in correspondence to the roundabout intersection link geometry.

Wang et al., (2006) investigated the traffic induced CO and fine particle concentrations dispersion characteristics from the typical urban roadways in Hong Kong using GFLSM. The comparison of the measured and predicted gaseous emissions of CO and particle emissions of $PM_{2.5}$ showed that the developed local GFLSM has a reasonable prediction performance for both gaseous and particle emissions with an average prediction error within 10% for CO and an average prediction error within 13% for $PM_{2.5}$ at three selected local urban roadside sites.

Ganguly and Broderick (2008) recently studied the performance of GFLSM and CALINE4 model for the CO prediction at a motorway site in Ireland using composite and hourly emission factors derived from COPERT III. They found that both the model could perform satisfactorily to predict CO concentrations for neutral stability conditions and wind speeds greater than 0.5 m/s. These studies suggest that it is necessary to quantify emissions factors based on actual traffic flow characteristics at the selected site. This also improves the prediction performances of dispersion models and may be important at junctions, which is more complex in comparison to single roadways.

3.7.2 Street-canyon models

Some of the worst air pollution caused by vehicular emissions can occur along a road edged by tall buildings (a ‘‘street canyon’’). The term street canyon ideally refers to a relatively narrow street with buildings lined up continuously along both sides (Nicholson, 1975). Air dispersion in a street canyon is different from that in an open region. The vertical and horizontal turbulence intensities have similar values in a street canyon and are much weaker than those in open land. The scale of turbulence influencing the concentration fluctuation is limited in street canyons (Ottl et al., 2001).

During the last three decades, various street canyon models have been developed. They range from simplified analytical expressions to advance and complex CFD (computational fluid dynamics) codes (Chu et al., 2005). An extensive overview of these models is given by Vardoulakis et al. (2003). In general, the concentrations in a street canyon are determined by the canyon geometry, the wind flow patterns and the pollutant dispersion within the canyon. The models simulating these processes are either parametric, which is based on empirical or semi-empirical relations, or numerical. Therefore, their application can range from a fast simple screening to a CFD application consuming large amounts of computational time.

The first and one of the earliest models for street-canyon is the STREET model developed by Johnson et al., (1973). The STREET model is of empirical nature and often

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used as a screening model to obtain a first estimate of concentration levels (Mensink et al., 2006). It takes into account the initial mixing of the pollutants and the traffic induced turbulence. The model assumes that the concentration is inversely proportional to the wind speed at roof level. An innovative approach was introduced by Yamartino and Wiegand (1986) in their Canyon Plume-Box Model (CPBM). In this model, the concentrations were calculated combining a plume model for the direct impact of vehicle emitted pollutants with a box model that enables computation of the additional impact due to pollutants recirculated within the street by the vortex flow.

AEOLIUS (Buckland, 1998) is based on the concepts and techniques previously used for the development of the Operational Street Pollution Model (Hertel and Berkowicz, 1989), which was evolved from the CPBM. AEOLIUS and OSPM are semi-empirical models that calculate concentrations of exhaust gases on both sides of a canyon assuming three different contributions: (a) the contribution from the direct flow of pollutants from the source to the receptor, (b) the recirculation component due to the flow of pollutants around the vortex generated within the recirculation zone of the canyon, and (c) the urban background contribution. A Gaussian plume algorithm is used for the calculation of the direct contribution and a simple box model for deriving the recirculation component. The OSPM model has been tested for various street configurations and meteorological conditions, e.g. in Copenhagen (Berkowicz, 2000) and in Helsinki (Kukkonen et al., 2001). The model developed by Mensink and Lewyckyj (2001) assumes a uniform concentration distribution over the street and is therefore called STREET BOX model, with the box dimensioned by the length and width of the street and the height of the surrounding built-up area. The concentration in the street is determined from a mass flux balance between a horizontal convective flux, a turbulent diffusive vertical flux and a continuous road transport emission source.

3.8 CONCLUSION

A number of factors describing various characteristics of traffic, vehicles, and street configurations affect the vehicular exhaust emissions. These characteristics have a cumulative effect on exhaust emissions. Most of the studies concentrated on limited parameters of the characteristics such as, driving speed, driving modes, road grades, driving pattern and vehicle characteristics. A few studies critically assessed the impacts of the existing control strategies and suggested that renewal of fleets, exclusive separate lane for buses, land use and traffic planning regulations can improve the air quality in urban areas. However, the lack of proper methodology in estimating emissions at traffic junctions, which incorporates the most dynamic parameters, has slowed down the advancement in emission modeling. The available research methods are scattered and have few interrelationships. As a result, dispersion modeling studies also involve a greater amount of uncertainties. Existing emission models, moreover, do not incorporate the traffic flow calculations and vice versa. Thus, it can be perceived that emission and flow models can be combined together for better estimates of emissions and may further be integrated with the urban transportation and air quality planning system.

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CHAPTER 4

FIELD WORK AND RESEARCH METHODOLOGY

4.1 GENERAL

Field work for air quality modeling involves the collection of data at the selected site. It is necessary that the method followed for site selection, location of monitoring and measurement be as per the standard practice. The data are put to statistical test to ensure their quality for the modeling studies. This chapter describes the monitoring and measurement including data interpretation and description. It, then, outlines the entire research methodology.

4.2 SELECTION OF SITE

A double-lane four-arm traffic roundabout at Rajiv chowk namely, Jalukbari roundabout has been selected to estimate one-minute average CO concentration. It is one of the busiest traffic intersections in the Guwahati city, attracts large volume of traffic and fairly urbanized. Figure 4.1 shows the traffic roundabout with a measurement location for CO and meteorological data. The four arms are divided into ‘approach stretches’, ‘circulating stretches’ and ‘exit stretches’, as described below (Figure 4.2):

1) *Approach stretches* begin before the roundabout junction where the profiles of mean speeds of all drives in the before situation and in the after situation diverge from each other (due to the speed reducing effect of traffic roundabout) and include passage through to 10 m beyond. There are four approach stretches namely N entry (Airport road), E entry (IITG road), S entry (Guwahati city road), and W entry (NH-37 Shillong highway road).
2) *Circulating stretches* begin right after the deflection from the entering path where the vehicles are forced to take lateral movement adjacent to the circle island. There are four circulating stretches denoted as NE, ES, SW and WN, formed by joining each curve formed by joining Airport-IITG road, connecting IITG-Guwahati city road, Guwahati city-NH37 Shillong highway road and Airport-NH37 Shillong highway road respectively.
3) *Exit stretches* begin right after the circulating stretches from the curved path where the vehicles again regroup to take longitudinal movement towards their destination.

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There are four exit stretches each for entering approaches namely, N exit, E exit, S exit, and W exit.

Figure 4.1: Jalukbari traffic roundabout with data monitoring locations

(Source: http://maps.google.co.in/)

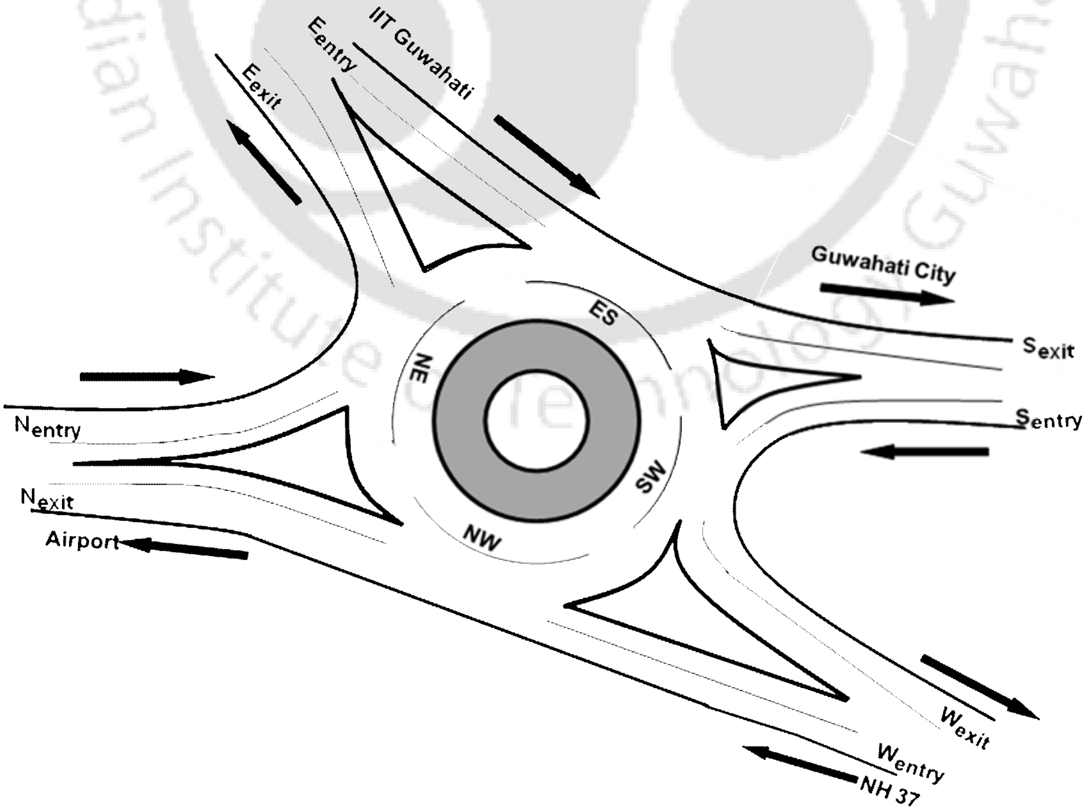

Figure 4.2: Jalukbari traffic roundabout with approaches

4.3 TRAFFIC, AIR POLLUTANT AND METEOROLOGICAL DATA

Since the aim of the research is to understand the impact of traffic that experiences different flow conditions at a roundabout on the emissions and CO concentrations, the focus of the field work was mainly on various traffic characteristics observed in short-time intervals. Concurrently, the data on CO and meteorology were collected. Several studies have reported that about 15 min of traffic characteristics fairly represent the traffic flow situation at intersections and roundabouts (FHWA, 2000 and TRB, 2000). This research included 30 min of detailed traffic data with individual vehicle speeds at two different times of a day for testing, application and validation of the air quality model. The statistical summary and the minute-wise profiles of the data collected for validation are presented in Appendix A.

Major inputs to air quality models are emission, meteorology and source-receptor geometry. Emission accounts for the amount of pollutants released from the source into the atmosphere. The primary data for the emission models include traffic count details and geometry of traffic entities with traffic fleet composition. Table 4.1 presents the details of traffic roundabout geometry and Table 4.2, the average length and width of observed vehicle types. Vehicles observed at the site are grouped into four types: (a) motorized two-wheelers (M2W) such as motorcycles, motor scooters, and mopeds; (b) motorized three wheelers (M3W) such as auto rickshaws, high capacity auto rickshaws, and tempos; (c) light commercial vehicles (LCV) *viz*. cars, vans, mini-vans, jeeps, and light pick-up trucks; and (d) heavy duty vehicles (HDV) *viz*. trucks, mini-trucks, buses; and mini-buses; Since the number of pedestrians, animals, pushcarts, pull carts, and animal-drawn carts, i.e., non-motorized traffic entities, on the site were insignificant, these are not included in this research.

Table 4.1: Details of traffic roundabout geometry

Approach name	Lane width (m)	Flare length (m)	Entry radius (m)	Entry angle (deg)
N entry	7	60	29	35
E entry	7	40	31	13
S entry	7	61	54	31
W entry	9	80	69	14

Table 4.2: Dimensions of vehicle types

Vehicle Class	M2W	M3W	LCV	HDV
Length (m)	1.8	2.6	6.1	9.35
Breadth (m)	0.6	1.4	2.1	2.5

The traffic data were collected for 30 min by video clips and analyzed to capture every 10 second characteristics of the fleet, which were later averaged to 1 min for calculating emission rates and CO concentrations. For traffic data, videos were taken from the rooftop of a building at 12 m height covering the entry and exit for vehicles during the peak times. The videos were analyzed for various traffic characteristics such as vehicle category, model, diesel or petrol powered, speed of a vehicle, traffic density based on measured space mean speed and semi-empirical method, approach time of a vehicle, travel length, travel time, exit time of a vehicle and circulatory flow of vehicles. This was done with the help of two reference lines (similar to the speed trap) and the time instances at which the vehicles enter and leave the road section.

The study includes the measurements of CO concentrations and meteorological parameters such as wind velocity, wind direction, ambient temperature, solar radiation and relative humidity. The meteorological data were measured at 12 m height and the CO concentrations and temperature were measured at 1.5 m from the ground with the help of TSI CO monitor (IAQ-CALC 7545) for every minute interval at the monitoring location. The calibration was performed prior to field measurements by adjusting auto zeroing module. All the data were collected and measured concurrently at the site. Figure 4.3 shows CO concentration data for a period of 30 minutes along with the wind speed, direction and traffic count. Figure 4.4 is a sample profile showing the variation of temperature with time.

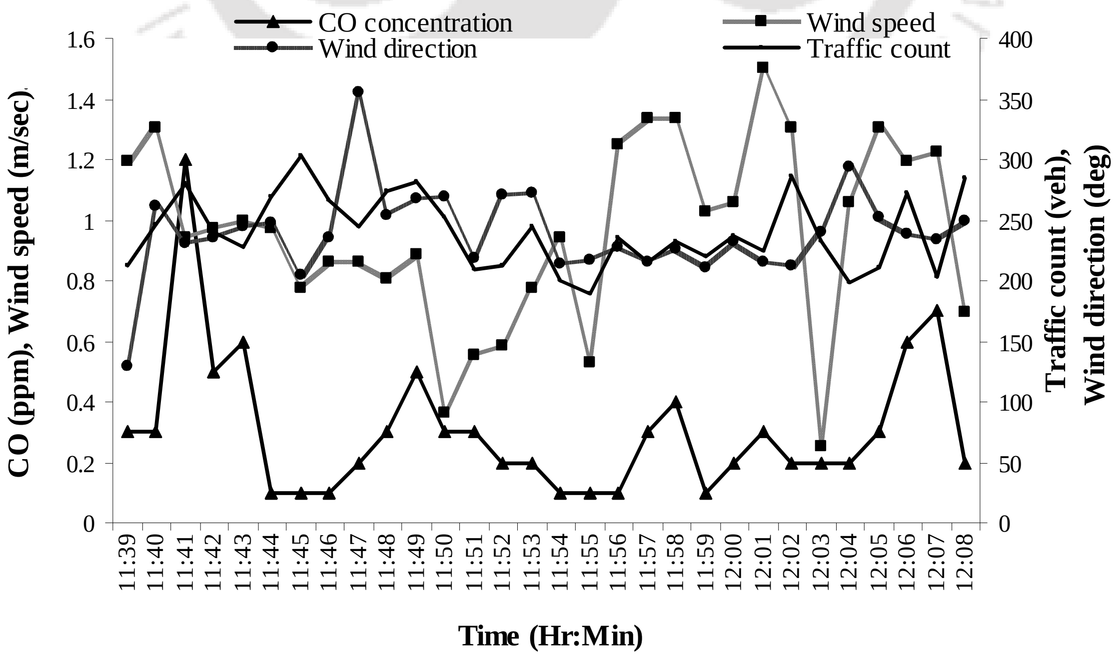

Figure 4.3: Time wise traffic, pollutant concentration and meteorological data

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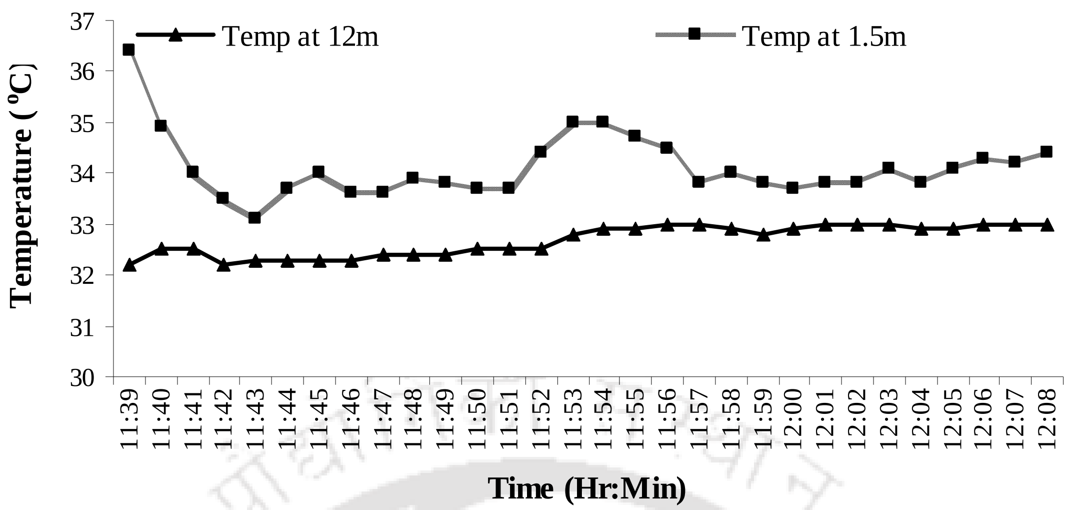

Figure 4.4: Time wise temperature data at two different heights

4.4 DATA DESCRIPTION AND INTERPRETATION

The strength of any air quality modeling study lies in the quality and resolution of input data. Since we measured all the data required for the modeling at the site simultaneously, there has been every-minute synchronization among the traffic dynamics, its variability, the wind flow vectors, thermodynamic properties and the CO concentrations. In this study, the traffic characteristics are analyzed at microscopic level from the video clips within the roundabout unlike the studies carried out by Dirks et al., (2002, 2003) and Gokhale and Pandian (2007) in which the traffic parameters were estimated only from traffic count and did not provide detailed descriptions of characteristics from microscopic viewpoint. Traffic analysis has revealed a strong dynamics within the roundabout region.

Table 4.3 presents the mean and standard deviation in % traffic composition for all the stretches of the junction. Results indicate that for most of the curve stretches, the deviations among themselves are in a narrow range in comparison to the entry and exit stretches. This is because once vehicles enter into circulating vehicles fleet, they tend to utilize the available free space more efficiently due to no-lane discipline and most importantly vehicles are forced to clear the curve stretches as fast as possible. Figures 4.5-4.7 represent the traffic composition variation (in %) between the entry, circulating and exit stretches along with standard error. The statistical values of pollutant concentrations and meteorological data are presented in Table 4.4. The higher standard deviation of the data collected indicates the wide variations in traffic scenario.

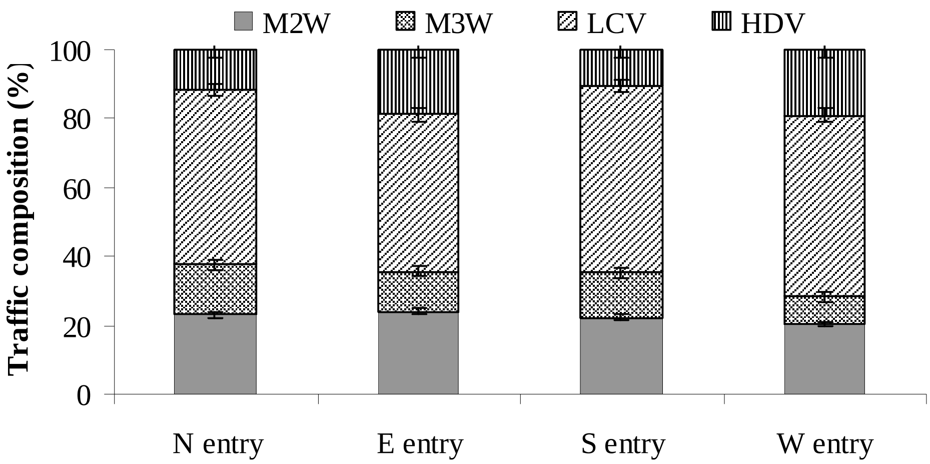

Figure 4.5: Traffic composition % for entry stretches

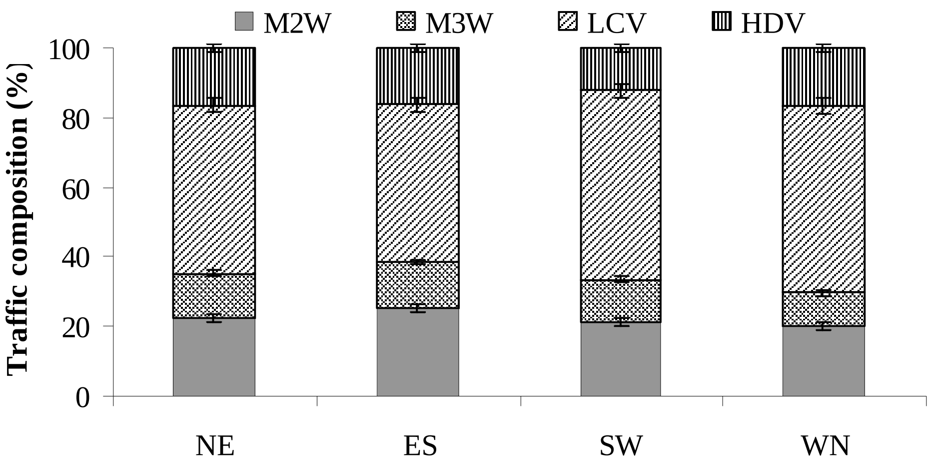

Figure 4.6: Traffic composition % for curve stretches

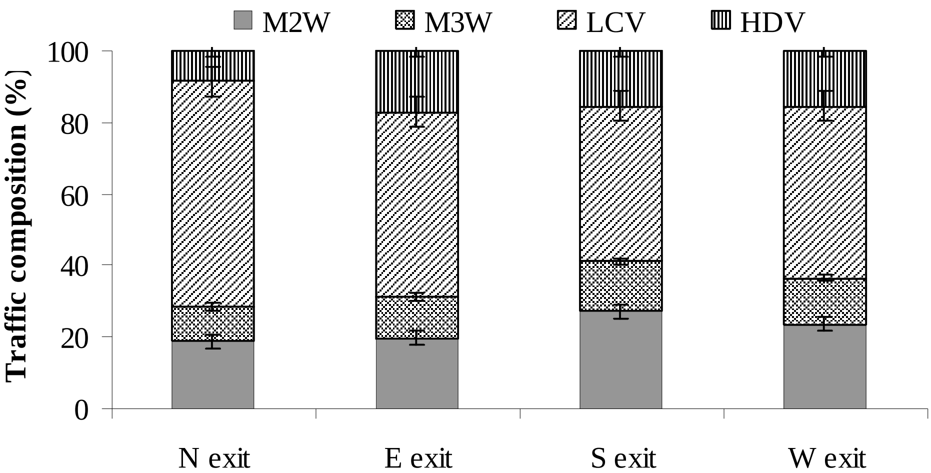

Figure 4.7: Traffic composition % for exit stretches

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Table 4.3: Mean and standard deviation[1] (SD) of traffic composition for entry, curve and exit stretches

Approach name	Traffic composition in %							
	M2W		M3W		LCV		HDV	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
N entry	23.15	19.63	14.54	10.27	50.74	17.39	11.57	9.51
E entry	23.98	14.27	11.72	17.15	45.50	16.10	18.80	11.66
S entry	22.29	7.58	13.01	5.62	54.34	12.82	10.36	9.17
W entry	20.31	14.81	7.97	9.66	52.70	15.95	19.02	14.18
NE	22.51	7.94	12.77	6.77	48.27	8.96	16.45	8.75
ES	25.36	10.75	13.20	7.28	45.15	9.07	16.30	6.91
SW	21.22	6.72	12.25	5.18	54.19	10.98	12.34	7.70
WN	20.17	8.62	9.59	7.08	53.51	9.42	16.73	9.17
N exit	18.93	13.91	9.56	7.52	63.10	14.46	8.41	8.14
E exit	19.64	10.20	11.71	7.69	51.59	14.29	17.06	12.41
S exit	27.30	12.13	13.90	6.51	43.38	9.98	15.41	8.07
W exit	23.49	15.83	13.09	12.59	47.99	20.91	15.44	14.34

Table 4.4: Statistical measures of pollutant concentration, meteorological and traffic data

Statistical parameter	CO (ppm)	Wind speed (m/sec)	Traffic count (veh)
Minimum	0.1	0.3	190
Mean	0.3	1.0	240
Maximum	1.2	1.5	303
Standard deviation	0.2	0.3	31
Coefficient of variation	0.3	1.0	240
Median	0.1	0.3	190
Percentile (95)	1.2	1.5	303

4.5 RESEARCH METHODOLOGY

The fundamental aim of dispersion modeling is to calculate pollutant concentrations related to the independent variables such as traffic parameters, the meteorological variables, intersection geometrical parameters and the vehicle parameters. This is to be achieved by an air quality modeling system which quantitatively relates the concentration to traffic flow, its dynamics, weather conditions and emissions. Figure 4.8 depicts the outline of the methodology including the inputs to the models and their inter-relationships.

The present study includes the estimation of CO concentration at a measurement point using coupled SC-GFLSM model and compares the results with those of GFLSM model (as discussed later in section 7.3). Various traffic characteristics were used to

[1] Standard deviation is estimated using ratio of mean to the total number of samples and percentile (95) means 95% of the values of collected data falls below this value.

calculate the emissions by three different methodologies. Traffic density was estimated using measured as well as semi-empirically estimated space mean speed as a means for defining congestion (All the statistical analysis and all computations related to estimation of density, emission and concentration were carried out using MS Excel 2003). The COPERT-IV methodology was used to calculate emission with traffic congestion level using semi-empirical relationships during the same time interval. These methodologies determine the relationships between the various traffic flow characteristics and emission rates. Of the three different emission calculation methodologies, the first one calculates the emission from COPERT-IV speed – emission equations, the second one from observed traffic density used with semi-empirical method and the third one on the basis of estimated density with semi-empirical method (All the regression analysis related to estimate constants required for emission estimation are carried out using MATLAB7). Air quality modeling analysis included calculation of one minute average CO concentration for a period of 30 min for the three emission scenarios by SC-GFLSM model. The results of the model have been evaluated against the measurements using correlation statistics. The detailed methodology and the development of models for traffic density, traffic emission and air quality have been discussed in the subsequent chapters.

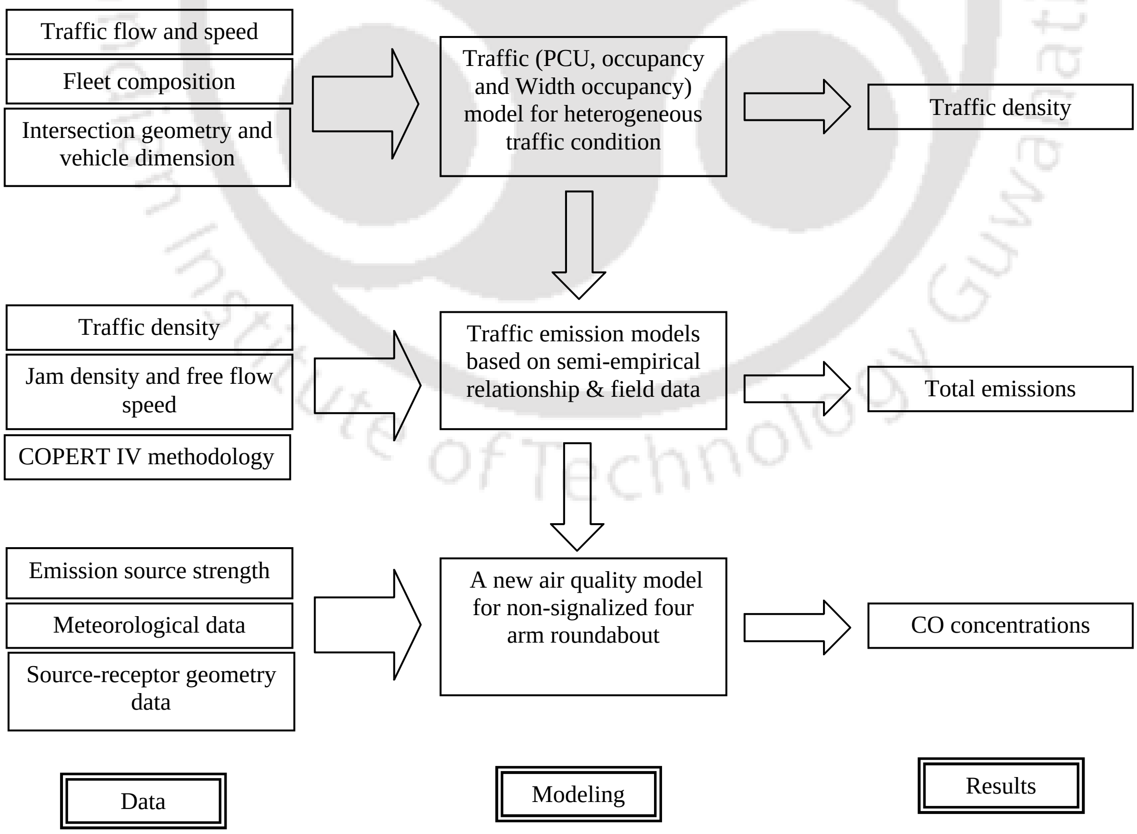

Figure 4.8: Outline of the methodology including the inputs to the models and their inter-relationships

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CHAPTER 5

TRAFFIC CHARACTERISTICS

5.1 GENERAL

Study of the various characteristics of road traffic is immensely useful for planning and design of roadway systems and operation of road traffic. Understanding of the real traffic behavior requires quantification of some of the basic traffic flow characteristics such as speed, flow and density. Amongst, speed-traffic flow rate relationship provides an efficient tool for calculating the traffic capacity of a carriageway. It is difficult to estimate the traffic flow rate when traffic is mixed. On a road of a mixed traffic fleet, different types of vehicles share the same roadway space without any physical segregation and hence the manner of interaction is often expected to change. The most intense interactions among the vehicles appear during peak periods at traffic intersections. This chapter deals with the estimation of basic traffic characteristics such as passenger car unit (PCU), fleet speed, and other traffic congestion related parameters such as occupancy, area occupancy and the development of time-width occupancy model followed by the estimation of traffic density.

The videos were analyzed (section 4.2) for various traffic characteristics such as speed of a vehicle, density, approach time of a vehicle, length of a travel, time of travel, exit time of vehicle, and individual vehicle count. This was done with the help of two reference lines (similar to the speed trap) and the time instances at which the vehicles enter and leave the road section. Traffic density is measured using the snap shots recorded for every 10 seconds interval. The 10-second, time interval observation rate allowed different entities to occupy the roadway at the given moment considered to be representing (~assuming to be), i.e., instantaneous densities of each entity type. From these measured instantaneous densities, the average density (k_{obs}) was calculated during the same 1-minute time intervals where volume and speed observations are made. Traffic flow modeling analysis included calculation of one-minute average density for a period of 30 minutes by PCU approach (k), conventional occupancy model (k_o) and time-width occupancy model (k_w). The results of the model are evaluated against the measurements (k_{obs}) using correlation statistics.

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5.2 TRAFFIC DENSITY – A PCU APPROACH

A modified density approach proposed by Tiwari et al., (2008) to estimate PCU has been used in the present study. This approach was developed by modifying the Highway Capacity Manual (HCM) 2000 density method to derive PCUs or passenger car equivalents (PCEs) for Indian heavy vehicles and recreational vehicles and thus, represents heterogeneous traffic. It includes significant percentages of motorized three-wheelers, motorized two-wheelers, light commercial vehicles and heavy duty vehicles to estimate more accurate passenger car equivalents for Indian conditions.

5.2.1 Space mean speed for heterogeneous traffic

The continuity equation of traffic flow for homogeneous traffic is (Gerlough and Huber 1975)

$$k = \frac{q}{\overline{u}_s} \tag{5.1}$$

where, q is traffic flow across a stretch in vehicles per hour (veh/hr), $\overline{u}_s$, the space mean speed (SMS) in kilometers per hour (km/hr), and k is the traffic density in a stretch in vehicles per kilometer (veh/km).

The average traffic stream speed can be computed in two different ways: a time mean speed (TMS) and a space mean speed. The difference in speed computations is attributed to the fact that the space-mean speed reflects the average speed over a spatial section of roadway, while the time mean speed reflects the average speed of the traffic stream passing a specific stationary point. Specifically, Daganzo (1997) demonstrated that the space-mean speed is a density weighted average speed, while the time mean speed is a flow weighted average speed. Given that a stationary observer will observe faster vehicles more often than slower vehicles while an aerial photograph would show more slow moving vehicles than faster vehicles over a fixed roadway length. Both mean speeds will always be different from each other except in the unlikely event that all vehicles are traveling at the same speed.

For homogeneous traffic, concentration uses unit length per lane because traffic streams usually flow in orderly columns. Concentration across the entire highway width in one traffic direction becomes a matter of adding the individual concentrations in each lane that comprises the total highway width. Many entity types comprise heterogeneous traffic. Each type has an average concentration in the highway area. The validation of the equation 5.2 uses heterogeneous traffic field data:

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$$\bar{k}_j = \frac{(q_j / W)}{\bar{u}_{s,j}} \tag{5.2}$$

where, j is the traffic entity type, $\bar{k}_j$, the average number of traffic entities of type j per unit area of highway, W, the cross-sectional width for measuring flow, q_j, the number of traffic entities of type j crossing the cross-sectional line of width W during a time interval, and $\bar{u}_{s,j}$ is the space mean speed of traffic entities of type j that completely traverse the intersection.

Since all traffic entity types share the same highway area at any time instant, the equation (5.3) holds:

$$\bar{k}_{nt} = \sum_{j=1}^{N} \bar{k}_j \tag{5.3}$$

where, $\bar{k}_{nt}$ is the average number of heterogeneous traffic entities per unit area of highway, and N is the total number of entity types in the heterogeneous traffic stream. In the present case, N equals to four as explained in section (4.3). The sum of the traffic sub-flows of the individual traffic entity types comprising heterogeneous traffic is the total heterogeneous traffic flow. Thus,

$$\frac{q_{nt}}{W} = \sum_{j=1}^{N} \frac{q_j}{W} \tag{5.4}$$

where, q_{nt} is total heterogeneous traffic flow.

Since the study measures the speed of each individual vehicle at all the stretches till its exit, space mean speed for all vehicle categories were estimated using the equation (5.5).

$$\bar{u}_{s,j} = \frac{n_j L}{\sum_{i=1}^{n_j} t_{i,j}} \tag{5.5}$$

where, i implies the i^{th} traffic; j, the traffic entity type; $\bar{u}_{s,j}$, the space mean speed of traffic entity type j; n_j, the number of traffic entities in type j; $t_{i,j}$, the time it takes the ith traffic entity of type j to travel across the length of the section, and L is the longitudinal length of section of the roundabout intersection. Equation (5.5) is used in calculating space mean speeds of each heterogeneous traffic entity type. An equivalent equation to calculate space mean speeds of heterogeneous traffic types is the harmonic mean equation:

$$\bar{u}_{s,j} = \frac{1}{\frac{1}{n_j}\sum_{i=1}^{n_j}\frac{1}{u_{i,j}}} \tag{5.6}$$

where, $u_{i,j}$ is the speed of the ith traffic entity in type j to travel across a stretch. An approximation for space mean speed from time mean speed for a particular time interval is:

$$\bar{u}_{s,j} = \bar{u}_{t,j} - \frac{\sigma_{t,j}^2}{\bar{u}_{t,j}} \tag{5.7}$$

where, $\bar{u}_{t,j}$ is the arithmetic mean speed of traffic entities comprising type j , and $\sigma_{t,j}^2$ the speed variance of traffic entities in type j .

Substituting for $\bar{k}_{nt}$ in equation (5.3) produces:

$$\frac{(q_{nt}/W)}{\bar{u}_{s,nt}} = \sum_{j=1}^{N}\bar{k}_j \tag{5.8}$$

Solving for $\bar{u}_{s,nt}$:

$$\bar{u}_{s,nt} = \frac{(q_{nt}/W)}{\sum_{j=1}^{N}\bar{k}_j} \tag{5.9}$$

Substituting $\bar{k}_j$ with equation (5.2):

$$\bar{u}_{s,nt} = \frac{(q_{nt}/W)}{\sum_{j=1}^{N}\frac{q_j/W}{\bar{u}_{s,j}}} = \frac{q_{nt}}{\sum\frac{q_j}{\bar{u}_{s,j}}} \tag{5.10}$$

Expressing heterogeneous traffic as a percent composition of total flow:

$$\bar{u}_{s,nt} = \frac{100}{\sum_{j=1}^{N}\frac{\%_j}{\bar{u}_{s,j}}} \tag{5.11}$$

where, $\%_j$ is the traffic composition percent of traffic entity type j. The space mean speed of heterogeneous traffic is not simply the weighted space mean speed of the individual heterogeneous traffic entity types by flow. Thus, it is the weighted, harmonic space mean speed of the individual heterogeneous traffic entity type by flow.

5.2.2 PCU for heterogeneous traffic

An average heavy vehicle gap approximately equals the average passenger-car gap because of almost similar operational characteristics between heavy vehicles and passenger cars on level terrain at a constant speed (Tiwari et al., 2008). According to this assumption,

$$PCU_{HDV} = \frac{L_{HDV}}{L_{PC}} \tag{5.12}$$

where, L_{PC} is the average length of passenger cars in meters, and L_{HDV} is the average length of heavy vehicles in meters.

For the heterogeneous traffic conditions on Indian roads, the PCU values suggested by HCM cannot be used as the peak hours traffic fleet comprises less than 85% passenger-cars and less than 90% cars, trucks, and buses (Fazio and Tiwari 1995). Tiwari et al., (2008) modified the density method to adjust for traffic heterogeneity in PCU calculations. In most heterogeneous traffic fleets, passenger cars do not use highway width as in homogeneous traffic. Traffic entities of similar speed and size pre-segregate into a natural distribution across the pavement width. These distribution widths can be determined by traffic entity type from field observations. From these distributions, the 85th percentile highway widths *(W_{85j})* that each traffic entity type *(j)* uses are calculated. The 85th percentile width used by Indian traffic entities allowed density derivation over a highway area instead of just length. This 85th percentile highway width is the roadway width that each traffic entity type effectively uses.

A passenger car in homogeneous traffic equivalent to passenger cars in heterogeneous traffic is given by the following relationship (Tiwari et al., 2008):

$$[f_{PCU}]_k = \left[\frac{(k_{PC}/W_{LPC})}{(k_{PC}/W_{85PC})}\right]_k \tag{5.13}$$

where, for highway type k, k_{PC} is the concentration of passenger cars in passenger cars per km, W_{85PC}, the 85th percentile highway width that passenger cars use in m, W_{LPC}, the base 3·7m lane width for passenger cars in homogeneous traffic conditions, and f_{PCU} is the passenger-car-unit adjustment factor to translate heterogeneous based PCUs into homogeneous-based PCUs. To determine PCU values for heterogeneous Indian conditions, traffic entity types other than passenger car became equivalent to Indian passenger cars. Translating this equivalence using measures from Indian field data yields the following relationship:

$$[PCU_j]_k = \left[\frac{(k_{PC}/W_{85PC})}{(q_j/\bar{u}_j)/W_{85j}}\right]_k \tag{5.14}$$

where, for highway type *k*, q_j is the heterogeneous flow of non-passenger car entity type *j* in entities per hour, $\bar{u}_j$, the space mean speed of non-passenger car type *j* in km/hr, W_{85j} is the 85th percentile highway width that non-passenger car type *j* in m, and PCU_j is the passenger-car unit for traffic type *j* in Indian passenger cars per *j*. In this study, W_{85j} for M2W, M3W, LCV and HDV were found to be 3.28, 3.35, 4.0 and 4.5 respectively.

The PCU values estimated for traffic types using equation 5.13 and 5.14 are used to calculate the heterogeneous traffic flow rate from the known vehicle count of traffic types. Further, SMS estimated using equation 5.7 from the observed TMS calculates modeled traffic density (*k*) for the traffic fleet as per continuity equation 5.1.

5.2.3 The performance evaluation of PCU approach

The modeled densities of traffic types were evaluated against the observed densities with the help of correlation statistics such as degree of agreement (*d*), root mean square error (*RMSE*), relative root mean square error (*RRMSE*) and correlation coefficient (*r*) (Willmot, 1982). The *d* value ranges between 0 and 1 with 1 indicating the model to be error-free. The optimum value of RMSE and RRMSE is zero, while *r* ranges between 0 and 1, with 0 indicating no correlation and 1 indicating a perfect agreement between estimated and measured values. The *d*, *RMSE* and *RRMSE* are given by equations 5.15 through 5.17.

$$d = 1 - \frac{\sum (P_i - O_i)^2}{\sum \left\{ \left| P_i - O_{avg} \right| + \left| O_i - O_{avg} \right| \right\}^2} \tag{5.15}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \tag{5.16}$$

$$RRMSE = \frac{RMSE}{O_{avg}} \times 100 \tag{5.17}$$

where, P_i and O_i are the modeled and observed i^{th} values of traffic densities, respectively, n is the number of sample and O_{avg} is the mean of observed values.

5.3 RESULTS

This section discusses the results of modeled traffic densities of traffic types against the observed traffic densities of each traffic type and the estimated PCU values of traffic types for stretches. PCU values found using modified density approach were used for converting the heterogeneous traffic flow rate of traffic types into equivalent homogeneous traffic flow rate. The results of estimated traffic density (*k*) of traffic fleet as per PCU approach

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are discussed in section 5.7 in comparison with other density estimating approaches namely conventional occupancy (k_o)and newly developed time-width occupancy (k_w) approaches against the measured traffic density (k_{obs}) obtained from video tape recorded.

5.3.1 Traffic densities of each traffic type

The traffic densities of each traffic type at the selected roundabout (Figure 4.2) have been estimated by equation 5.2. These were compared with the observed density obtained from video taken and evaluated with the correlation coefficient (r) and the degree of agreement (d) and others. The average densities of traffic types per road width (entities/km.m) observed and estimated are shown in Table 5.1. The observed values are denoted as 'obs' and estimated values are denoted as 'mod'. The tables of traffic type wise modeled densities against the measured ones have been shown in Appendix B. The statistical measures are shown in Tables 5.2a-c. The d is over 0.9 for all the vehicle categories of entry and curve stretches. Only for exit stretches, it is in the range of 0.7 – 0.98. The r is found to be in the range of 0.78 – 0.96 for all the traffic types of entry stretches except for HDV traffic type of South stretch as it is 0.67. The r values of circulating and exit stretches have been found to be less than entry but most of the r values are over 0.7 further indicates the better strength of the correlation. The RMSE value of similar trend has been observed and confirms the better prediction of traffic entities per unit area of road section using the modified density approach. The RMSE values are found to be in the range of 0.31 – 1.96 for entry approaches, 0.6 – 4.32 for circulating stretches and 0.32 – 4.79 for exit stretches.

Table 5.1: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m)

Approach name	M2W		M3W		LCV		HDV	
	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
N entry	1.86	1.70	1.17	1.22	4.07	4.00	0.93	0.98
E entry	2.10	1.18	1.02	0.56	3.98	2.40	1.64	1.04
S entry	4.40	4.24	2.57	2.68	10.74	10.89	2.05	2.56
W entry	1.65	1.62	0.65	0.62	4.27	3.80	1.54	2.02
NE	4.95	5.22	2.81	3.43	9.43	10.77	3.57	5.62
ES	4.62	3.41	2.43	2.07	6.64	6.40	2.98	3.24
SW	5.19	5.88	3.02	4.05	11.21	12.76	3.02	5.08
WN	4.77	4.61	2.46	2.46	10.94	10.99	3.44	4.07
N exit	2.33	1.87	1.17	0.99	6.31	5.22	1.02	0.97
E exit	2.40	2.92	1.43	1.92	5.31	7.02	2.29	4.32
S exit	3.83	2.17	1.98	1.44	4.71	3.94	2.14	1.84
W exit	1.42	3.02	0.77	1.91	2.42	5.35	0.94	2.24

Table 5.2a: The statistical indicators for entry stretches

Approach name	Statistical measures	M2W	M3W	LCV	HDV
N entry	*d*	0.98	0.99	0.98	0.98
	RMSE	0.55	0.37	1.15	0.32
	RRMSE	29.49	31.86	28.35	34.24
	r	0.92	0.96	0.88	0.93
E entry	*d*	0.91	0.90	0.93	0.95
	RMSE	1.19	0.69	1.96	0.84
	RRMSE	56.88	66.91	49.31	50.84
	r	0.78	0.90	0.86	0.92
S entry	*d*	0.99	0.99	0.99	0.94
	RMSE	0.75	0.43	1.80	1.30
	RRMSE	17.14	16.85	16.80	63.49
	r	0.94	0.94	0.91	0.67
W entry	*d*	0.98	0.97	0.98	0.95
	RMSE	0.53	0.31	1.20	1.02
	RRMSE	32.19	47.35	28.15	66.30
	r	0.87	0.91	0.86	0.91

Table 5.2b: The statistical indicators for curve stretches

Approach name	Statistical measures	M2W	M3W	LCV	HDV
NE	*d*	0.99	0.98	0.98	0.91
	RMSE	1.18	1.12	2.70	3.02
	RRMSE	23.76	39.80	28.66	84.61
	r	0.85	0.92	0.83	0.66
ES	*d*	0.93	0.95	0.96	0.94
	RMSE	2.52	1.23	2.85	1.84
	RRMSE	54.58	50.78	42.94	61.98
	r	0.74	0.71	0.78	0.84
SW	*d*	0.99	0.94	0.99	0.86
	RMSE	1.46	1.97	2.79	3.49
	RRMSE	28.15	65.10	24.91	115.31
	r	0.92	0.65	0.85	0.65
WN	*d*	0.99	0.99	0.96	0.98
	RMSE	1.07	0.60	4.32	1.31
	RRMSE	22.34	24.47	39.46	38.09
	r	0.85	0.91	0.45	0.89

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Table 5.2c: The statistical indicators for exit stretches

Approach name	Statistical measures	M2W	M3W	LCV	HDV
NE	*d*	0.98	0.98	0.97	0.98
	RMSE	0.73	0.32	1.96	0.33
	RRMSE	31.34	27.48	31.06	32.50
	r	0.94	0.94	0.77	0.92
ES	*d*	0.98	0.94	0.92	0.80
	RMSE	0.97	0.97	4.20	3.79
	RRMSE	40.39	68.11	79.06	165.71
	r	0.92	0.80	0.81	0.73
SW	*d*	0.91	0.90	0.87	0.94
	RMSE	1.96	1.29	3.69	1.09
	RRMSE	51.17	65.14	78.34	50.70
	r	0.80	0.61	0.57	0.69
WN	*d*	0.70	0.57	0.74	0.81
	RMSE	3.96	3.09	4.79	1.83
	RRMSE	279.69	400.75	198.14	195.43
	r	0.83	0.67	0.62	0.86

5.3.2 PCU

Table 5.3 presents observed TMS and estimated SMS for each vehicle type. It has been observed that curve stretches operating with higher speed variations as compared to entry and exit stretches since they operate with more difference between TMS and SMS. This exemplifies the existence of varying speed levels between the vehicle types at different stretches. It seems that variation in level of service is less for entering and exit vehicles as compared to circulating ones. Moreover, the difference in SMS can be used to estimate the level of service of intersection under operation from the estimated delay occurred to the vehicles. Table 5.4 lists the mean densities of the entity types during the observed 30 minute duration. Amongst all entry stretches, south approach observed to be highly dense by vehicles arrivals. At the same time east stretch enjoys the least dense of all. In general all of curve stretches together observed to have higher dense than entry and exit stretches. The density method requires comparison of density of the traffic entity type at the same space mean speed of passenger car. Table 5.5 shows the forecasted densities of traffic types at the LCV space mean speed on the site. This is done by plotting LCV density versus LCV speed and interpolating the density at the corresponding average speed of other traffic types (Figure 5.1 (a-l)).

The intermediate steps (numerator and denominators of equation 5.13 and 5.14) showing the estimations required for the calculation of Indian heterogeneous PCU values are presented in Tables 5.6-5.8. Table 5.6 shows traffic densities of traffic types per 85th percentile highway widths *(W_{85j})* in entities per km.m ($\left(q_j / \bar{u}_j\right) / W_{85j}$). Division of LCV density value by the standard lane width that passenger cars use in homogeneous traffic, i.e., 3·7m (Tiwari et al., 2008) produces the density-lane width ratio (k_{pc}/W_{Lpc}) as shown in Table 5.7. Table 5.8 shows unit area density after adjustment to equal passenger-car space mean speed using 85th percentile highway width (k_{PC}/W_{L85PC}).

Table 5.9 shows the Indian heterogeneous PCU values for all the stretches using equation 5.14. It has been calculated from the ratio of values of Table 5.8 and Table 5.6. Table 5.10 gives the passenger-car adjustment factor, *f*PCU, to allow conversion between heterogeneous traffic and homogeneous traffic. It has been calculated from the ratio of values of Table 5.7 and values against LCV of Table 5.8. The *f*PCU also shows how traffic dynamics change for each approach roads. The closer these values to one, the more the Indian heterogeneous traffic behaves like homogeneous traffic. Multiplying *f*PCU (Table 5.10) by the Indian PCUs (Table 5.9) converts heterogeneous traffic to its homogeneous equivalent. For example, 78 M2W, 49 M3W, 171 LCV and 39 HDV observed on North approach road was equivalent to 693 passenger cars in homogeneous traffic (Table 5.11) on east approach road, 597, on south approach road, 766 and on west approach road, was 804. This shows that west approach is slow moving or else sub-dominant either due to geometry or nature of traffic flow. The results presented in Table 5.12 show that vehicles from each approaches does not have similar level of service. The geometry and number of vehicles have clear bearings on delay caused to vehicles at roundabout. LCV tend to occupy more space on the approach roads while the other vehicle types take the remaining space to maneuver. The share of each traffic type present on the road explains the variation in PCU values for different traffic types. For example, HDV operating on North exit stretch has the maximum PCU values of 6.06, while, its traffic composition of 9.45%, was the least. Similarly, M3W operating in West entry stretch has the maximum PCU values of 6.51, while, at the same time its traffic composition 7.97% was the least.

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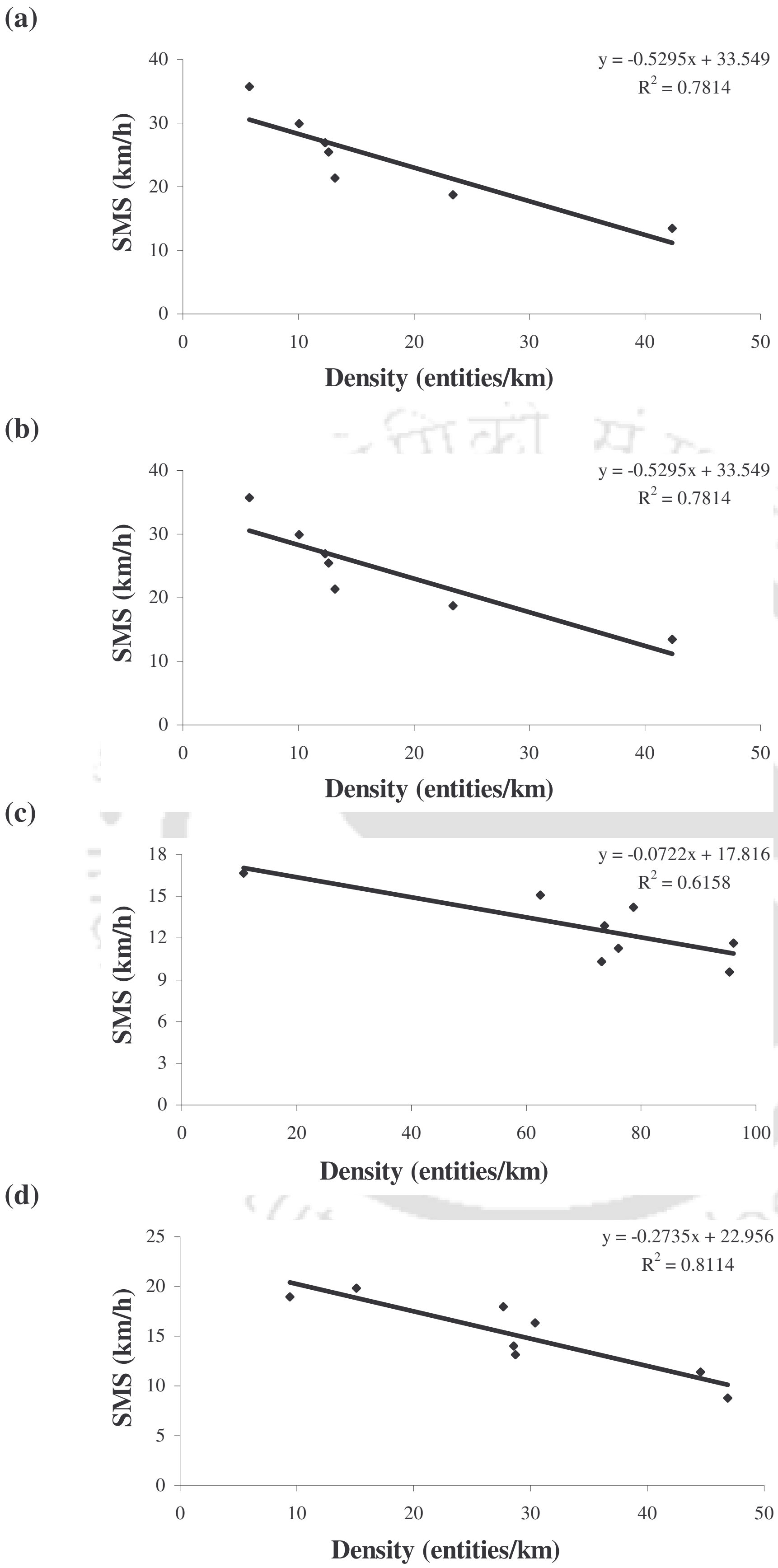
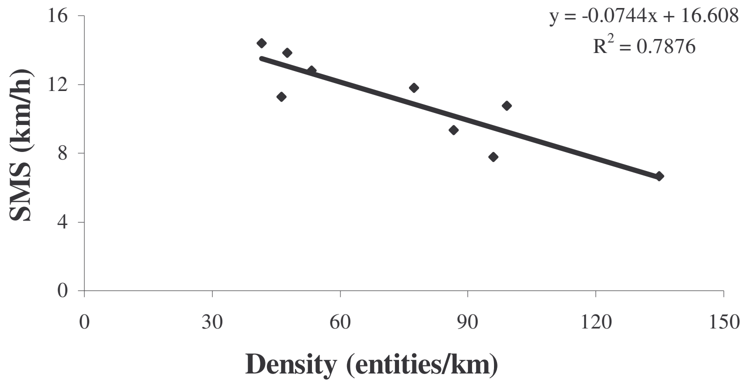


Figure 5.1 (a-d): Relationship between SMS of LCV to that of density for entry (a-N entry; b-E entry; c-S entry and d-W entry) stretches

(e)



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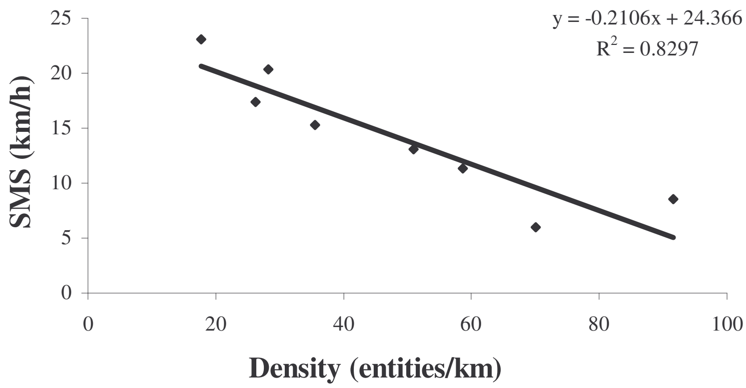

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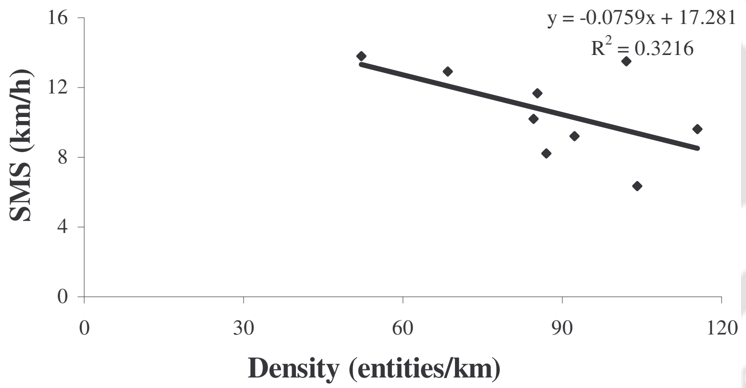

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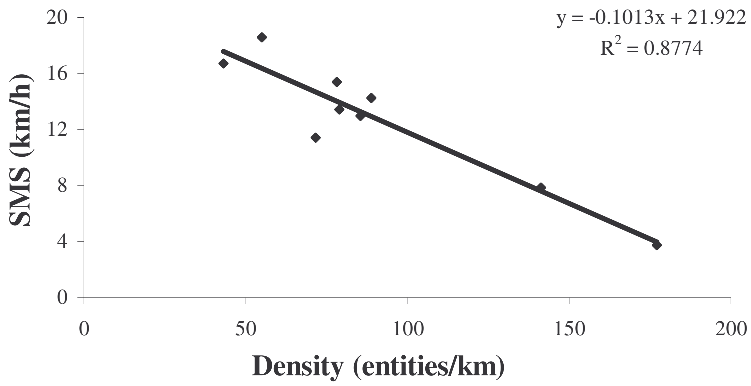

Figure 5.1 (e-h): Relationship between SMS of LCV to that of density for curve (e-NE; f-ES; g-SW and h-WN) stretches

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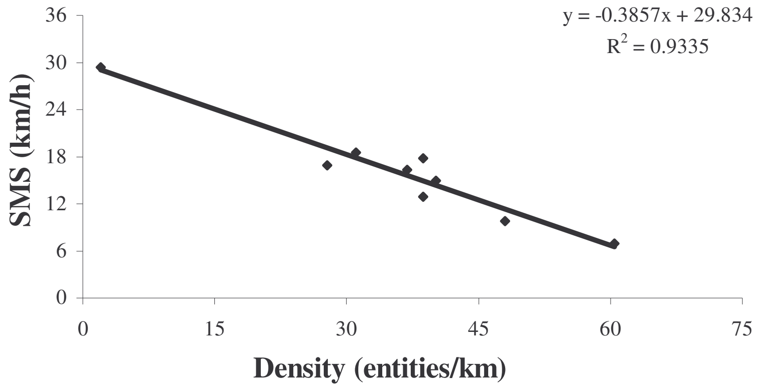
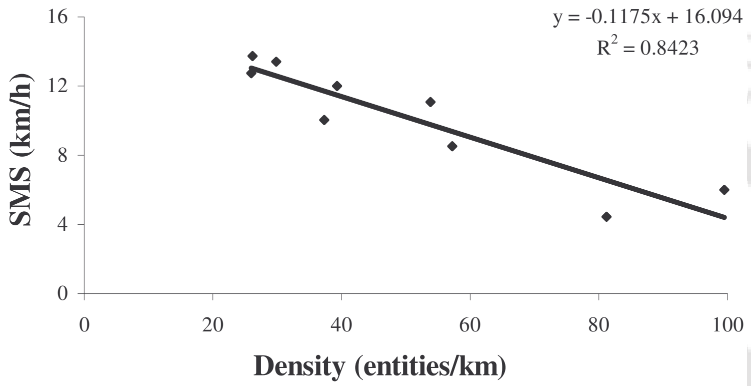
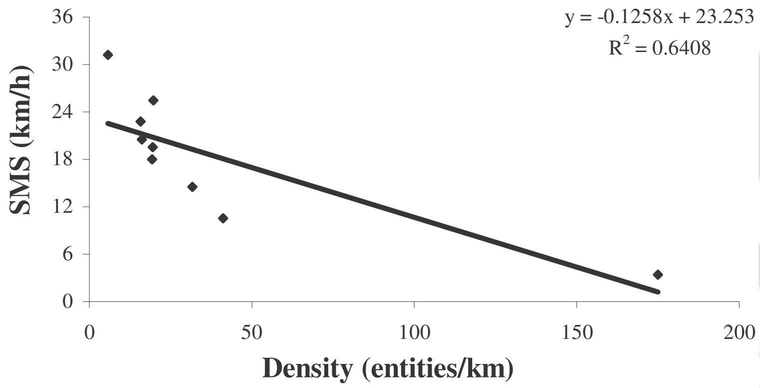
(i)



(j)



(k)



(l)

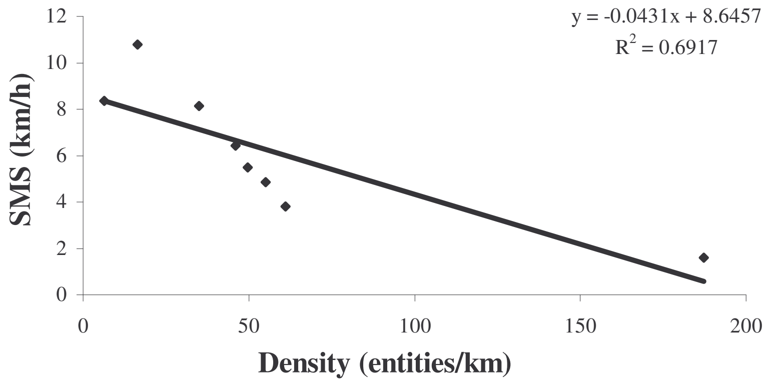


Figure 5.1 (i-l): Relationship between SMS of LCV to that of density for exit (i-N exit; j-E exit; k-S exit and l-W exit) stretches

Table 5.3: Time mean speeds (TMS) and Space mean speeds (SMS) of traffic types in km/hr

Approach name	M2W		M3W		LCV		HDV	
	TMS	SMS	TMS	SMS	TMS	SMS	TMS	SMS
N entry	14.73	13.89	12.26	12.11	13.50	12.82	12.32	11.96
E entry	26.38	24.11	24.69	24.11	24.06	22.27	22.34	21.04
S entry	13.47	12.71	12.21	11.81	12.50	12.15	11.45	10.86
W entry	15.16	13.13	14.81	13.81	16.38	14.37	11.08	10.13
NE	12.57	11.79	11.19	10.36	11.65	10.92	9.50	8.60
ES	24.84	19.87	20.56	17.29	16.96	14.20	15.11	13.05
SW	12.33	10.99	11.10	10.02	11.59	10.91	9.75	8.39
WN	14.74	12.96	13.56	12.59	14.24	13.15	11.47	10.80
N exit	17.52	15.79	15.35	14.86	16.72	15.39	14.50	13.75
E exit	11.53	10.48	10.75	10.06	10.88	10.16	8.58	7.90
S exit	27.84	23.49	23.12	20.97	20.30	17.96	18.16	16.18
W exit	8.92	7.59	8.73	7.52	8.65	6.61	6.07	5.81

Table 5.4: Traffic concentrations (density) in entities/km

Approach name	Traffic density, entities/km			
	M2W	M3W	LCV	HDV
N entry	11.87	8.51	28.01	6.84
E entry	8.25	3.92	16.80	7.28
S entry	29.71	18.78	76.24	17.89
W entry	12.98	4.99	30.41	16.16
NE	36.57	23.99	75.39	39.34
ES	23.86	14.47	44.78	22.69
SW	41.16	28.33	89.34	35.55
WN	36.85	19.66	87.92	32.57
N exit	13.06	6.95	36.52	6.76
E exit	20.41	13.46	49.15	30.27
S exit	15.18	10.08	27.55	12.88
W exit	24.19	15.25	42.78	17.92

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Table 5.5: Traffic density forecasts at LCV space mean speeds

Approach name	Traffic density, entities/km M2W	M3W	LCV	HDV
N entry	25.87	33.47	30.43	34.10
E entry	17.66	17.67	20.38	22.19
S entry	70.75	78.42	75.54	86.53
W entry	34.62	32.59	30.94	43.52
NE	67.13	82.21	76.33	100.89
ES	25.77	35.93	48.11	52.64
SW	86.30	90.40	86.63	97.29
WN	88.72	92.01	87.08	107.49
N exit	36.38	38.62	37.35	41.31
E exit	48.10	51.13	50.44	66.60
S exit	12.52	25.36	40.72	49.76
W exit	34.58	35.73	50.28	63.12

Table 5.6: Unit area concentrations using 85th percentile road-width

Approach name	Traffic density, entities/(km.m) M2W	M3W	LCV	HDV
N entry	4.27	2.97	7.47	1.52
E entry	2.97	1.37	4.48	1.62
S entry	10.69	6.54	20.33	3.98
W entry	4.67	1.74	8.11	3.59
NE	13.15	8.36	20.10	8.74
ES	8.58	5.04	11.94	5.04
SW	14.81	9.87	23.82	7.90
WN	13.25	6.85	23.44	7.24
N exit	4.70	2.42	9.74	1.50
E exit	7.34	4.69	13.11	6.73
S exit	5.46	3.51	7.35	2.86
W exit	8.70	5.31	11.41	3.98

Table 5.7: PCU area concentrations using homogeneous traffic lane width

Approach name	Traffic density, entities/(km.m)
N entry	7.57
E entry	4.54
S entry	20.60
W entry	8.22
NE	20.38
ES	12.10
SW	24.15
WN	23.76
N exit	9.87
E exit	13.28
S exit	7.45
W exit	11.56

Table 5.8: Unit area concentration forecasts at LCV space mean speeds

Approach	Traffic density, entities/(km.m)			
name	M2W	M3W	LCV	HDV
N entry	9.30	11.66	8.11	7.58
E entry	6.35	6.16	5.43	4.93
S entry	25.45	27.33	20.14	19.23
W entry	12.45	11.35	8.25	9.67
NE	24.15	28.65	20.36	22.42
ES	9.27	12.52	12.83	11.70
SW	31.04	31.50	23.10	21.62
WN	31.91	32.06	23.22	23.89
N exit	13.08	13.46	9.96	9.18
E exit	17.30	17.81	13.45	14.80
S exit	4.50	8.84	10.86	11.06
W exit	12.44	12.45	13.41	14.03

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Table 5.9: PCU for heterogeneous traffic

Approach name	PCU, pc/j M2W	M3W	LCV	HDV
N entry	2.18	3.93	1.09	4.99
E entry	2.14	4.51	1.21	3.05
S entry	2.38	4.18	0.99	4.84
W entry	2.67	6.54	1.02	2.69
NE	1.84	3.43	1.01	2.56
ES	1.08	2.48	1.07	2.32
SW	2.10	3.19	0.97	2.74
WN	2.41	4.68	0.99	3.30
N exit	2.79	5.56	1.02	6.11
E exit	2.36	3.80	1.03	2.20
S exit	0.82	2.52	1.48	3.86
W exit	1.43	2.34	1.18	3.52

Table 5.10: PCU adjustment factor

Approach name	*fPCU*
N entry	0.93
E entry	0.84
S entry	1.02
W entry	1.00
NE	1.00
ES	0.94
SW	1.05
WN	1.02
N exit	0.99
E exit	0.99
S exit	0.69
W exit	0.86

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Table 5.11: Equivalent homogeneous traffic from heterogeneous traffic

Approach name	Traffic count, veh/30 minutes					
	M2W	M3W	LCV	HDV	Existing	Equivalent
N entry	78	49	171	39	337	693
E entry	88	43	167	69	367	664
S entry	185	108	451	86	830	1795
W entry	79	31	205	74	389	818
NE	208	118	396	150	872	1573
ES	194	102	279	125	700	993
SW	218	127	471	127	943	1742
WN	229	118	525	165	1037	2219
N exit	98	49	265	43	455	1069
E exit	101	60	223	96	480	895
S exit	161	83	198	90	532	673
W exit	68	37	116	45	266	413

Table 5.12: PCU for equivalent homogeneous traffic

Approach name	PCU in pc/j			
	M2W	M3W	LCV	HDV
N entry	2.03	3.67	1.01	4.65
E entry	1.79	3.77	1.01	2.55
S entry	2.44	4.27	1.01	4.95
W entry	2.66	6.51	1.01	2.68
NE	1.84	3.43	1.01	2.57
ES	1.02	2.34	1.01	2.19
SW	2.19	3.33	1.01	2.86
WN	2.46	4.79	1.01	3.38
N exit	2.76	5.51	1.01	6.06
E exit	2.33	3.75	1.01	2.17
S exit	0.57	1.72	1.01	2.65
W exit	1.23	2.02	1.01	3.04

5.4 TRAFFIC DENSITY – AN OCCUPANCY APPROACH

Occupancy, a function of both vehicle length and traffic composition, provides a reliable indication of the area of the road being used by vehicles. The occupancy methods (Arasan and Dhivya, 2008) are mostly based on homogeneous conditions which account for strict-lane discipline, vehicles occupy the full lane-width and a vehicle fleet that does not vary greatly in width. Therefore, in case of heterogeneous traffic, where road space is shared

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among many traffic modes with different physical dimensions, the existing occupancy methods have limited applicability. This drawback of the occupancy method can be overcome to some extent by using area-occupancy method (Mallikarjuna and Rao, 2006) which uses the ratio of vehicle to road width, only marginally reduces the deviation of the estimated and observed densities. In this research, therefore, the aim is to develop an appropriate method to estimate traffic congestion for a heterogeneous traffic flow conditions at a two-lane conventional traffic roundabout. We propose a model which modifies the occupancy by a correction factor of vehicles ability to effectively occupy the road-width during the operation in a given time period. This improves the temporal density and describes the real-world heterogeneous traffic flow pattern at such junctions. The results of the modified model have been validated against the observed density.

5.4.1 Occupancy and area occupancy

Traffic density (k), is the number of vehicles observed on a specified length of road at a given time instance. If N_v vehicles are observed at a given time instance and the covered distance is L, then

$$k = \frac{N_v}{L} \qquad (5.18)$$

The density obtained from the equation 5.18 provides fairly accurate estimates of traffic flow behaviour only when the vehicles are of same category and of more or less same dimensions. Measurement of traffic density only along a length is a difficult task. In the light of this, density is often estimated either from the concept of occupancy or from traffic speed and flow. Traffic density from the traffic flow and speed (Arasan and Dhivya, 2008) is given by equation 5.18. Traffic density from the occupancy (Gerlaugh and Huber, 1983) is given by equation 5.19.

$$k_o = 1000 \times \frac{\rho}{L_v} \qquad (5.19)$$

where, k_o is the traffic density from the occupancy; ρ is the occupancy and L_v is the average vehicle length measured over time and space in m.

Occupancy means the percentage of the given time period the road section is occupied by a vehicle is given by equation 5.20. (TRB, 1997)

$$\rho = \frac{\sum_{i=1}^{N} O_i}{T} \qquad (5.20)$$

$$O_i = \frac{l_i + l_d}{v_i} \qquad (5.21)$$

where, O_i, the time i^{th} vehicle occupied the detector in s; l_i, the length of the i^{th} vehicle in m; v_i, the speed of i^{th} vehicle in m/s; T, the observed time period in s and l_d is the detector's length in m.

The physical significance of the occupancy is thus the ratio of the sum of time occupied by all the vehicles to the total observed time period, when only one vehicle occupies the lane at a time. It is clearly the measure that describes the nature of traffic in longitudinal direction making its use unsuitable for heterogeneous traffic conditions where vehicles of different sizes occupy the road and also travel alongside with other vehicles utilizing the lane width. It is, therefore, essential to consider the width of a vehicle. For this, however, it is required to find an active lane-width to capture the real traffic situation i.e. time spent by vehicles in lateral direction. Mallikarjuna and Rao (2006) modified the occupancy for the heterogeneous case by adding the ratio of vehicle width to the road width and termed it as area occupancy (equation 5.22). Area occupancy, thus, is the amount of time a vehicle with a given area occupies the road section. The authors reported better performance of the area-occupancy for heterogeneous traffic compared with occupancy since the former depended on the traffic composition and speeds of vehicles.

$$\rho_a = \frac{\sum_{i=1}^{N} O_i \times w_i \times d}{T \times W \times d} \tag{5.22}$$

where, ρ_a is the area occupancy; O_i, the time the i^{th} vehicle occupied the detector in s; w_i, the width of the i^{th} vehicle in m; W, the road width in m; d, the length of the road section under consideration in m; and T, is the observed time period in s.

The major drawback of the area-occupancy is that like occupancy it cannot be used to estimate density though it represents the percentage proportion of area covered by the vehicles. To estimate the density, vehicles occupied in length scale need to be known only. Then density would be estimated using the average vehicle length from the known occupancy values.

5.5 DEVELOPMENT OF A TIME - WIDTH OCCUPANCY MODEL

We modified the occupancy to account for the width of a vehicle termed here as time-width occupancy to determine the traffic flow behaviour for heterogeneous traffic. It is the occupancy multiplied by the ratio of individual vehicle width to the total vehicle width sharing the road in lateral direction. This modification accounts only for active lane width rather than entire road width unlike area occupancy. Figure 5.2 describes the relationship between occupancy times of vehicles of different categories and their physical width in

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determining width occupancy. The detailed formulation steps are given in equations 5.23 to 5.27a.

$$\rho_w = \frac{\sum_{w,i}^{i+3} O_{w,i} \times CF_{w,i}}{T} \tag{5.23}$$

where, ρ_w is width occupancy; $O_{w,i}$, is the occupancy time of a vehicle type that occupies the least time; $O_{w,i+1}$ is the occupancy time of vehicle category that occupied the second least time; $O_{w,i+2}$ is the occupancy time of vehicle category of second largest time occupied; $O_{w,i+3}$ is the occupancy time of vehicle category of largest time occupied; $CF_{w,i}$ is the correction factor of vehicle category of least time occupied; $CF_{w,i+1}$ is the correction factor of vehicle category of second least time occupied; $CF_{w,i+2}$ is the correction factor of vehicle category of second largest time occupied; and $CF_{w,i+3}$ is the correction factor of vehicle category of largest time occupied.

These correction factors capture heterogeneities in the most probable traffic fleet composition. Occupancies for each vehicle category obtained by equation 5.20 are arranged in ascending order, denoted as $O_{w,i}$, $O_{w,i+1}$, $O_{w,i+2}$ and $O_{w,i+3}$. The corresponding width of a vehicle category as per their estimated occupancy time are denoted as $w_{w,i}$, $w_{w,i+1}$, $w_{w,i+2}$ and $w_{w,i+3}$, respectively. The correction factors of each vehicle category can be estimated by equations 5.24 to 5.27a.

$$CF_{w,i} = \frac{O_{w,i}}{O_{w,i}} \times \frac{w_{w,i}}{w_{w,i} + w_{w,i+1} + w_{w,i+2} + w_{w,i+3}} \tag{5.24}$$

$$CF_{w,i} = \frac{O_{w,i}}{O_{w,i}} \times \frac{w_{w,i}}{\sum_{i}^{i+3} w_{w,i}} \tag{5.24a}$$

$$CF_{w,i+1} = \left(\frac{O_{w,i}}{O_{w,i+1}} \times \frac{w_{w,i+1}}{w_{w,i} + w_{w,i+1} + w_{w,i+2} + w_{w,i+3}} \right) + \left(\frac{O_{w,i+1} - O_{w,i}}{O_{w,i+1}} \times \frac{w_{w,i+1}}{w_{w,i+1} + w_{w,i+2} + w_{w,i+3}} \right) \tag{5.25}$$

$$CF_{w,i+1} = \left(\frac{O_{w,i}}{O_{w,i+1}} \times \frac{w_{w,i+1}}{\sum_{i}^{i+3} w_{w,i}} \right) + \left(\frac{O_{w,i+1} - O_{w,i}}{O_{w,i+1}} \times \frac{w_{w,i+1}}{\sum_{i+1}^{i+3} w_{w,i}} \right) \tag{5.25a}$$

$$CF_{w,i+2} = \left(\frac{O_{w,i}}{O_{w,i+2}} \times \frac{w_{w,i+2}}{w_{w,i} + w_{w,i+1} + w_{w,i+2} + w_{w,i+3}} \right) + \left(\frac{O_{w,i+1} - O_{w,i}}{O_{w,i+2}} \times \frac{w_{w,i+2}}{w_{w,i+1} + w_{w,i+2} + w_{w,i+3}} \right)$$

$$+\left(\frac{O_{w,i+2}-O_{w,i+1}}{O_{w,i+2}}\times\frac{w_{w,i+2}}{w_{w,i+2}+w_{w,i+3}}\right) \tag{5.26}$$

$$CF_{w,i+2}=\left(\frac{O_{w,i}}{O_{w,i+2}}\times\frac{w_{w,i+2}}{\sum_{i}^{i+3}w_{w,i}}\right)+\left(\frac{O_{w,i+1}-O_{i}}{O_{w,i+2}}\times\frac{w_{w,i+2}}{\sum_{i+1}^{i+3}w_{w,i}}\right)+\left(\frac{O_{w,i+2}-O_{w,i+1}}{O_{w,i+2}}\times\frac{w_{w,i+2}}{\sum_{i+2}^{i+3}w_{w,i}}\right) \tag{5.26a}$$

$$CF_{w,i+3}=\left(\frac{O_{w,i}}{O_{w,i+3}}\times\frac{w_{w,i+3}}{w_{w,i}+w_{w,i+1}+w_{w,i+2}+w_{w,i+3}}\right)+\left(\frac{O_{w,i+1}-O_{w,i}}{O_{w,i+3}}\times\frac{w_{w,i+3}}{w_{w,i+1}+w_{w,i+2}+w_{w,i+3}}\right)$$

$$+\left(\frac{O_{w,i+2}-O_{w,i+1}}{O_{w,i+3}}\times\frac{w_{w,i+3}}{w_{w,i+2}+w_{w,i+3}}\right)+\left(\frac{O_{w,i+3}-O_{w,i+2}}{O_{w,i+3}}\times\frac{w_{w,i+3}}{w_{w,i+3}}\right) \tag{5.27}$$

$$CF_{w,i+3}=\left(\frac{O_{w,i}}{O_{w,i+3}}\times\frac{w_{w,i+3}}{\sum_{i}^{i+3}w_{w,i}}\right)+\left(\frac{O_{w,i+1}-O_{w,i}}{O_{w,i+3}}\times\frac{w_{w,i+3}}{\sum_{i+1}^{i+3}w_{w,i}}\right)+\left(\frac{O_{w,i+2}-O_{w,i+1}}{O_{w,i+3}}\times\frac{w_{w,i+3}}{\sum_{i+2}^{i+3}w_{w,i}}\right)+\left(\frac{O_{w,i+3}-O_{w,i+2}}{O_{w,i+3}}\times\frac{w_{w,i+3}}{w_{w,i+3}}\right) \tag{5.27a}$$

These correction factors are based on the occupancy time of each observed vehicle category. It is, therefore, a function of speed and length of that vehicle category. The vehicle category $(O_{w,i})$, which occupies the road for the least time uses a correction factor given by equation 5.24 or 5.24a. It signifies that a vehicle shares the road width with the other vehicle categories observed during that time period. The vehicle category $(O_{w,i+1})$ uses a correction factor given by equation 5.25 or 5.25a. The first term indicates that this vehicle category shares the road width with all other vehicle categories observed till $O_{w,i}$ vehicles travel the road section under consideration. The second term signifies the remainder of time period $(O_{w,i+1}-O_{w,i})$, vehicle category $(O_{w,i+1})$ shares the road-width with the other three vehicle categories $(O_{w,i+1}, O_{w,i+2}, O_{w,i+3})$. Similarly, vehicle category $(O_{w,i+2})$ uses a correction factor by equation 5.23 or 5.23a, which involves three terms. The first term signifies that $O_{w,i+2}$ vehicles share the road-width with the other vehicle categories observed till $O_{w,i}$ travel the road section under consideration. The second term signifies that for the $\left(\frac{O_{w,i+1}-O_{w,i}}{O_{w,i+3}}\right)$ fraction of time period, $O_{w,i+2}$ vehicles share the road-width with the other three vehicle categories $(O_{w,i+1}, O_{w,i+2}, O_{w,i+3})$. The last term indicates that for the remaining time period till the vehicle category $(O_{w,i+2})$ travels completely the road section under consideration and it shares the road-width with the only vehicle category $O_{w,i+2}$ and $O_{w,i+3}$. The vehicle category $(O_{w,i+3})$ uses a correction factor given by equation 5.27 or 5.27a, which similarly involves four terms. The first term signifies that $O_{w,i+3}$ vehicle shares the road-width with all vehicle categories observed during that period, the second term indicates sharing of the road-width with the remaining vehicle categories other than the least time occupied vehicle category. Similarly, the third term indicates that $O_{w,i+3}$ vehicle shares the road-width with $O_{w,i+2}$ and $O_{w,i+3}$, and the last term indicates the remaining time left for $O_{w,i+3}$ vehicles to complete its travel the road section.

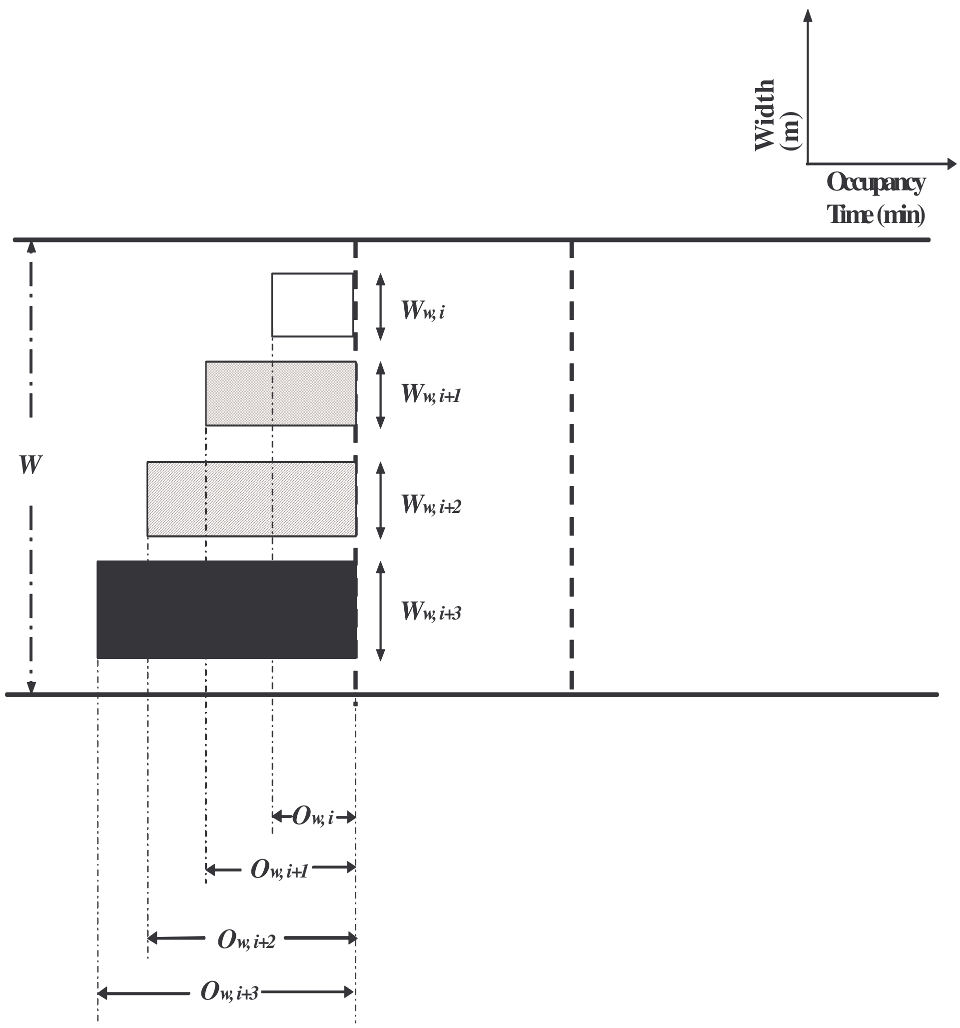

Figure 5.2: Graphical representation of factors considered in width occupancy measurements

5.5.1 Assumptions and criteria

It is not straightforward to model the occupancy on lateral directions because of the implicit no-lane discipline of mixed traffic on the road. The challenge, therefore, is to unravel the eccentricity of driver's ability to utilize unoccupied road space to the maximum extent. Under certain assumptions, this very characteristic may be captured by the proposed time – width occupancy model.

i. Vehicles have been categorized into M2W, M3W, LCV and HDV, which shares the most possible fleet composition. The traffic flow was assumed to be anisotropic (Daganzo, 1995) meaning a driver reacts only to stimuli ahead of him and that the traffic situation behind his vehicle does not influence driving behaviour. On the other hand, the anisotropic property remains valid for each individual vehicle. The anisotropic condition for each of the category prevents the distortions by averaging over total traffic flow. The complex nature of mixed traffic (vehicles of varying length and width) was simplified into four major vehicle categories. Vehicle within each category was homogeneous making it suitable to estimate occupancy (Logghe and Immers, 2008).
ii. Vehicles of each mode observed are set to progress only on longitudinal direction. In other words only the total time occupancy of that vehicle category was considered. This assumption was well supported by our field observations as for most time either of LCV or HDV vehicle category occupied the road which ensured that two vehicles of the same mode cannot share the lane-width at the same time.
iii. The vehicle categories observed in 1-minute of time are assumed to start travel at same time to share the road-width equally. This assumption gives the equal priority for the entire vehicle category observed during the time duration under consideration. After the O_i time, the remaining three vehicle categories share the road-width and so on.
iv. Since spatial measurement is practically difficult, in this research, the term time - width occupancy refers to the temporal measurements only.

5.5.2 Estimation of traffic density

Traffic density (or link vehicle-count), the most crucial variable, is the basis of many traffic flow models. The level and the quality of service are often reduced when the traffic density on the road increases. In other words, for a given roadway, the quality and pattern of traffic flow changes with the traffic density. Thus, the measure 'density' provides a clear indication of both the level of service being provided to the users and the productive level of facility use. Hence, there is a need for in-depth understanding of traffic flow characteristics with specific reference to density.

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In particular, measuring traffic density on roads is practically not convenient but instead can be estimated from other data that are readily available. Here, we discuss how this can be done along with some practical issues that arise in the process. Measurement of a spatial traffic density is not practical, as it requires instantaneous observation of a substantial length of road. Instead, as suggested in the study of Hall (2001), it can be estimated from the proportion of time for which a vehicle is present at a fixed length, known as occupancy, which can be measured conveniently by repeated sampling of the state of the detector. The occupancy measured in this way provides a time-based estimate of the proportion of the road that is covered by vehicles, and this is related to density through the relationship given by equation 5.19.

The major shortcoming in the occupancy-derived density is that they do not represent the additional vehicles traveled along with the running vehicles which are common in heterogeneous traffic pattern. Hence the improved density (k_w) can be estimated using the time-width occupancy by equation 5.28.

$$k_w = 1000 \times \frac{\rho}{L_v} \times \left(\frac{\rho}{\rho_w} \right) \tag{5.28}$$

where, k_w is the traffic density using time-width occupancy; ρ_w is the width occupancy and L_v is the average vehicle length measured over time and space, which can be estimated using equation 5.29 as given by (Papageorgiou and Vigos, 2008; Cassidy and Coifman ,1997)

$$L_v = \frac{\sum_i \left(\frac{l_i}{v_i} \right)}{\sum_i \left(\frac{1}{v_i} \right)} \tag{5.29}$$

Equation 5.19 indicates that the measured occupancy is roughly proportional to traffic density, which was empirically verified by Cassidy and Coifman (1997) and more recently by Kim and Hall (2004) for freeway. From equation 5.28., it can be observed that k_w will always be greater than k_o derived from occupancy and they remain equal only when the number of vehicles observed is 1. Thus, k_w is able to incorporate the additional congestion caused by vehicles effectively utilizing the already occupied lanes.

5.5.3 The performance evaluation of occupancy approach

The modeled densities of traffic fleet were evaluated against the observed densities with the help of correlation statistics such as *d*, *RMSE*, Pearson's correlation coefficient (*R*), fractional bias (FB) and coefficient of variation (CV) (Marmur and Mamane, 2003). The *R* value ranges between −1 to 1, where ±1 means a perfect correlation, and 0 means no correlation. The optimum value of FB is zero, while FB ranges between -2 and 2, with -2 represents extreme under-prediction, and +2 is extreme over-prediction.0 indicating no correlation and 1 indicating a perfect agreement between estimated and measured values. The R, FB and CV are given by equations 5.28 through 5.30.

$$R = \frac{\left(O_i - O_{avg}\right)\left(P_i - P_{avg}\right)}{\sigma_P \sigma_O} \qquad (5.28)$$

$$FB = 2\frac{P_{avg} - O_{avg}}{P_{avg} + O_{avg}} \qquad (5.29)$$

$$CV = \frac{\sigma}{O_{avg}} \times 100 \qquad (5.30)$$

Where, P_i and O_i are the modeled and observed ith values of traffic densities, respectively, n is the number of sample, σ stands for the standard deviation and O_{avg} is the mean of measured values.

5.6 RESULTS AND DISCUSSION

Traffic analysis results show that the traffic pattern exhibits the dynamic vehicle flow characteristics. It has been observed that within the junction, fleet speed varies with time as well as at different locations as and when vehicles enter and leave (Table 4.1). Traffic flow was always near to congestion on all the stretches as the average density varies from 147 veh/km to 492 veh/km (Table 5.13). The geometrical characteristics of traffic roundabout near entries and exits such as lane width, flare length, entry angle and radius could also be one of the contributing factor for different fleet speed. For example, east approach particularly at the time of entry fleet speed was relatively more due to smaller road angles (Table 5.3). It was observed that the variation in the fleet speeds was more for vehicles having larger dimensions. This implies that different service levels exist with different vehicle categories. The different PCU values (Table 5.13) for all the stretches also confirms the operational variations. In all the categories, M3W was slow moving vehicle and shows inability to pick up the speed after negotiating the geometry delay followed by HDV. They are naturally tend to wait long to sneak in to the main stream of moving vehicles before reaching their final destination.

The occupancy, area-occupancy and width-occupancy are influenced by vehicle length, vehicle area and vehicle width besides the traffic fleet speed. The traffic analysis results show that the variations in the three occupancies are not of the same order. This has

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been shown in Figures 5.3-5.14 for occupancy, width-occupancy and area-occupancy over 30 minute time period for the entry, curve and exit stretches. The occupancy values are higher. Because it accounts for the vehicle occupancy time by assuming that only one occupies lane-width. This is, as discussed earlier, suitable mostly for homogeneous traffic conditions where only one vehicle occupies the lane width. This gives the occupancy values always less than 100%. However, in case of heterogeneous traffic conditions where, no strict-lane discipline is observed occupancy values often exceeds 100% on the time-scale. Such a situation can be visualized when two vehicles sharing the lane width and the given time.

A correction factor, based on the fraction of vehicle-width in relation to the total-width of vehicles sharing the road at given time, reduces the actual occupancy of vehicle in a given lane-width and in given time. The resulting density as a result will always be higher and more precisely representing the heterogeneous traffic condition. The trend of width-occupancy moreover may not always follow the other types of occupancies as it also depends on the composition of traffic fleet at a given time (Figures 4.5-4.7). For example, an increase in HDV vehicles could allow smaller vehicles to share the road-width while it moves slowly. This will result in the reduction of width-occupancy. With the same logic the total time occupied by slow moving vehicles like HDV would result in higher occupancy and area-occupancy. On the other hand, fast moving vehicles would produce less occupancy as observed at several other instances.

Figures 5.15-5.26 show the densities calculated with occupancy and width-occupancy for all the stretches of the junction. These densities have been compared with the observed densities. The observed densities were obtained from a snap shot of 30 minute video at every 10 seconds intervals at the traffic roundabout. The scatter plots of modeled densities against the observed are presented in Figures 5.27 (a-l). The results show that the estimated densities match well with the observed for most of the stretches such as NE, ES, SW and WN. Further, the mean of densities using width-occupancy was in good agreement with the mean of observed density particularly for circulating stretches. Further, the mean of densities using PCU was also in good agreement with the mean of observed density particularly for entry, circulating and exit stretches and their results are in comparison with the densities estimated using width-occupancies. This may be because once vehicles enter into circulating vehicles fleet they tend to utilize the available free space more efficiently due to no-lane discipline. Figures 5.19-5.22 for circulating stretches show this where as for some stretches, for example, S entry, N exit, W exit, slight variation in trend with vibrant gaps were observed, which may be attributed to entry and exit patterns at the roundabout. It has been observed that the estimated occupancies as well as width-occupancies exhibit the similar pattern as that of observed densities. But those simulated by width-occupancy match well.

The observed densities were higher than the estimated densities for most of the time. With width-occupancy and PCU, the difference was reduced to marginal. This small difference may be due to the differences of the methods in approach to time scale of estimated and the observed densities. Both PCU and width-occupancy methods additionally takes care of the spatial section of roadway like usage of space mean speed in PCU and correction factor for road width utilization by smaller vehicles in width-occupancy. The fractional bias (FB) values for the width-occupancy based densities were in the range of -1.06 to 0.02 for exit stretches against –1.09 to 0.01 by PCU and –1.48 to -0.63 by occupancy. FB values for the width-occupancy were in the range of -0.42 to 0.02 for circular stretches against -0.56 to 0.04 by PCU and -1.07 to -0.57 by occupancy. In case of entry stretches FB values for the width-occupancy were in the range of -0.67 to -0.39 against -0.82 to -0.27 by PCU and -1.26 to -0.99 by occupancy. Similarly, other descriptive statistics included in Table 5.13, show that the modified occupancy represents non-homogeneities observed in dynamic traffic flow at traffic roundabout.

The incorporation of lateral space equal to lane-width in width-occupancy improved the densities against those of occupancy. It means among all the stretches, the performance of width-occupancy was the best for circulating stretches followed by entry and exit stretches. The reason may be at circulating stretches, vehicles are able to utilize the available spaces more efficiently than entry and exit stretches. It was observed that a particular stretch having dense traffic fleet determine the waiting time required for vehicles to access the circulating flow. Besides, traffic composition and the vehicles types mixed with fast moving smaller vehicles and slow moving larger vehicles help occupying the gaps on circulating stretches when the fleet maneuvers the entire junction. On exit stretches, fleet speed increases compared with the entry and circulating stretches resulting in decrease in densities. This has also been clearly represented by the width-occupancy.

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Table 5.13: Correlation statistics for density predictions of entry, curve and exit stretches

Evaluation statistics	k_{obs}	k_o	k_w	k	k_{obs}	k_o	k_w	k	k_{obs}	k_o	k_w	k
	N entry				**NE**				**N exit**			
Mean	153.52	51.98	96.26	110.49	348.44	149.53	320.80	315.48	236.83	60.37	106.27	158.11
Std Dev	64.01	24.43	45.59	56.99	62.15	40.25	105.42	98.15	66.27	22.08	39.37	63.20
CV	0.42	0.47	0.47	0.52	0.18	0.27	0.33	0.31	0.28	0.37	0.37	0.40
d		0.51	0.72	0.86		0.34	0.55	0.69		0.36	0.45	0.65
RMSE		110.86	66.14	47.80		205.21	102.21	84.18		186.30	140.91	89.51
FB		-0.99	-0.46	-0.33		-0.80	-0.08	-0.10		-1.19	-0.76	-0.40
R		0.82	0.84	0.91		0.55	0.37	0.58		0.39	0.56	0.75
	E entry				**ES**				**E exit**			
Mean	147.13	33.13	73.26	61.90	140.10	77.59	171.86	145.10	198.16	103.57	201.45	199.32
Std Dev	71.83	21.30	49.16	41.27	43.85	38.18	95.01	73.59	56.62	52.44	106.52	93.91
CV	0.49	0.64	0.67	0.67	0.31	0.49	0.55	0.51	0.29	0.51	0.53	0.47
d		0.47	0.69	0.62		0.61	0.74	0.77		0.49	0.70	0.72
RMSE		126.83	82.98	93.14		66.13	69.76	52.73		105.02	83.17	73.89
FB		-1.26	-0.67	-0.82		-0.57	0.20	0.04		-0.63	0.02	0.01
R		0.76	0.83	0.88		0.84	0.81	0.67		0.62	0.59	0.58
	S entry				**SW**				**S exit**			
Mean	397.46	132.75	227.52	301.50	409.09	157.83	313.67	360.88	177.00	50.28	109.65	81.98
Std Dev	72.41	32.81	53.47	67.17	69.73	41.05	111.20	89.66	58.24	25.76	53.07	45.99
CV	0.18	0.25	0.24	0.22	0.17	0.26	0.35	0.25	0.33	0.51	0.48	0.56
d		0.31	0.39	0.64		0.29	0.55	0.79		0.43	0.64	0.54
RMSE		272.46	185.22	105.79		257.93	133.84	73.81		133.33	79.16	103.24
FB		-1.00	-0.54	-0.27		-0.89	-0.26	-0.13		-1.12	-0.47	-0.73
R		0.41	0.31	0.77		0.51	0.51	0.75		0.73	0.69	0.69
	W entry				**WN**				**W exit**			
Mean	181.12	60.12	121.65	128.65	491.49	148.40	305.10	277.22	492.50	74.33	151.21	145.17
Std Dev	61.07	26.90	55.32	49.85	101.70	50.22	130.69	100.48	338.22	32.47	88.48	92.83
CV	0.34	0.45	0.45	0.39	0.21	0.34	0.43	0.36	0.69	0.44	0.59	0.64
d		0.44	0.63	0.74		0.34	0.54	0.50		0.47	0.53	0.53
RMSE		130.89	81.49	62.59		351.98	210.65	225.93		521.46	449.61	450.52
FB		-1.00	-0.39	-0.34		-1.07	-0.47	-0.56		-1.48	-1.06	-1.09
R		0.55	0.51	0.80		0.61	0.63	0.72		0.66	0.54	0.58

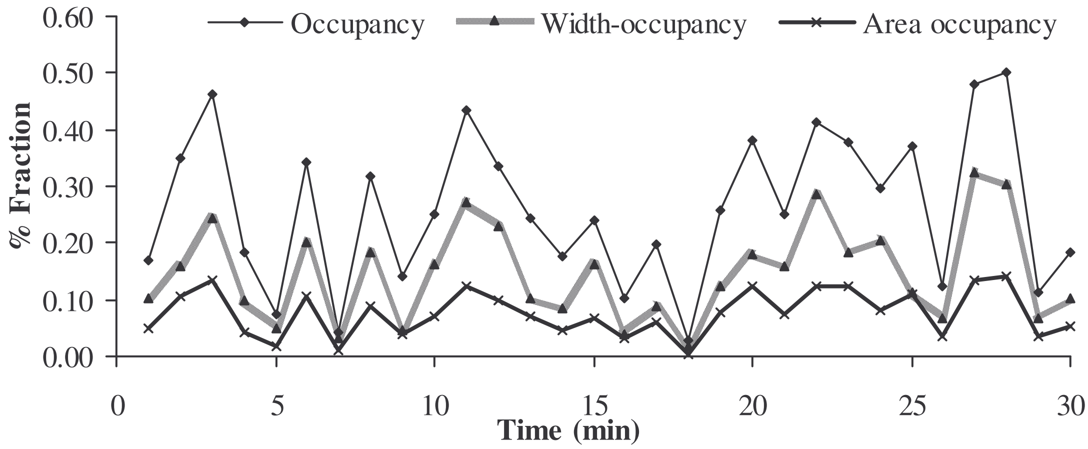

Figure 5.3: Occupancy, area occupancy and width occupancy over time for North entry stretch

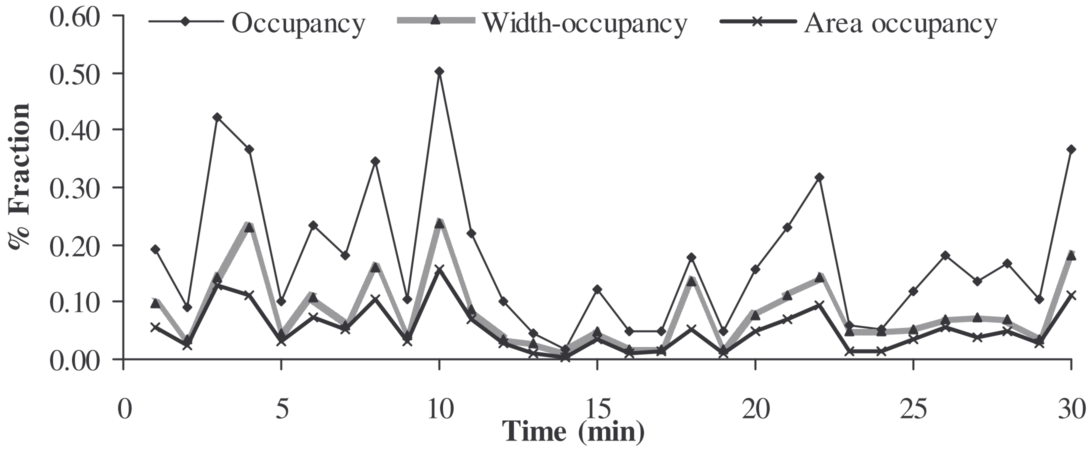

Figure 5.4: Occupancy, area occupancy and width occupancy over time for East entry stretch

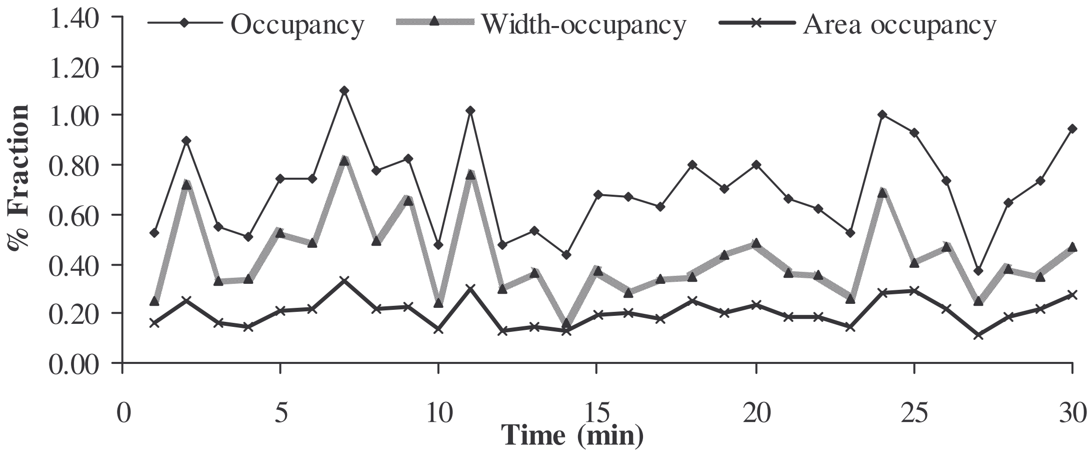

Figure 5.5: Occupancy, area occupancy and width occupancy over time for South entry stretch

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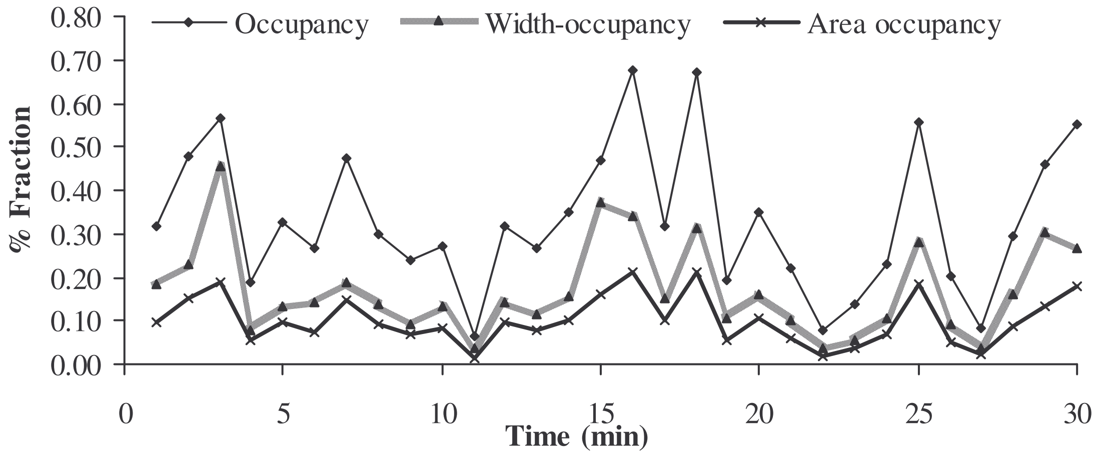

Figure 5.6: Occupancy, area occupancy and width occupancy over time for West entry stretch

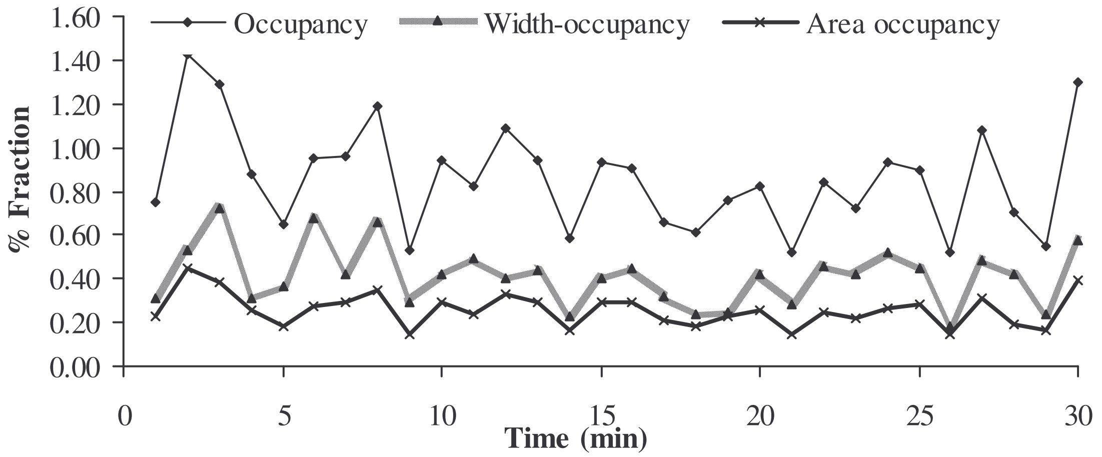

Figure 5.7: Occupancy, area occupancy and width occupancy over time for NE curve stretch

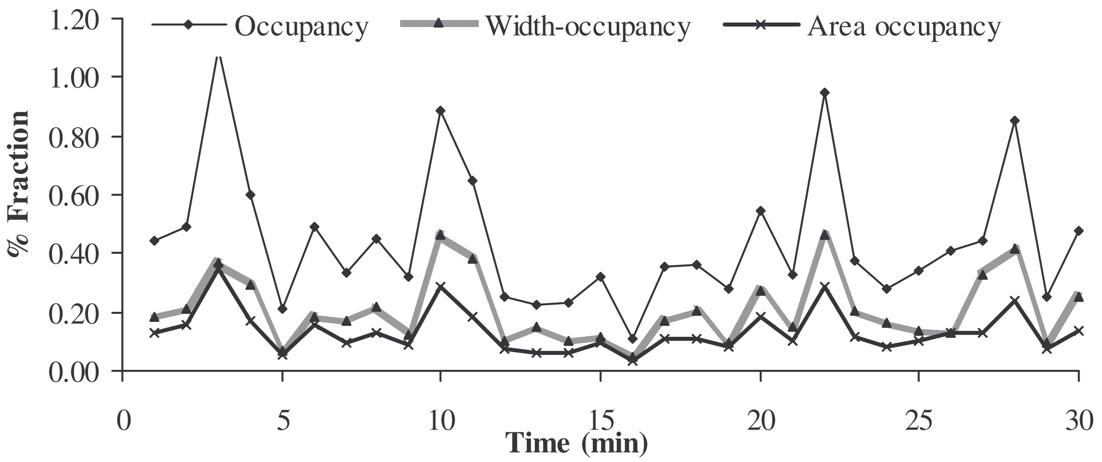

Figure 5.8: Occupancy, area occupancy and width occupancy over time for ES curve stretch

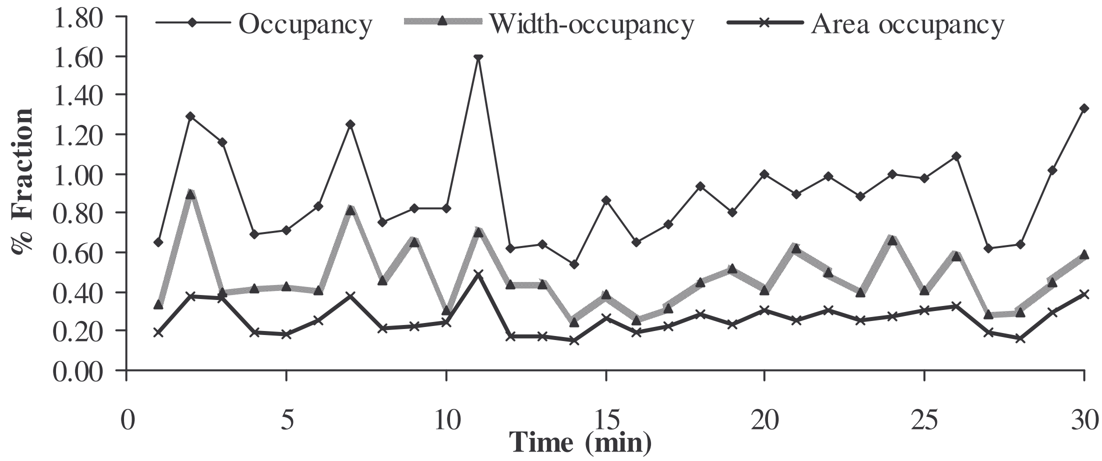

Figure 5.9: Occupancy, area occupancy and width occupancy over time for SW curve stretch

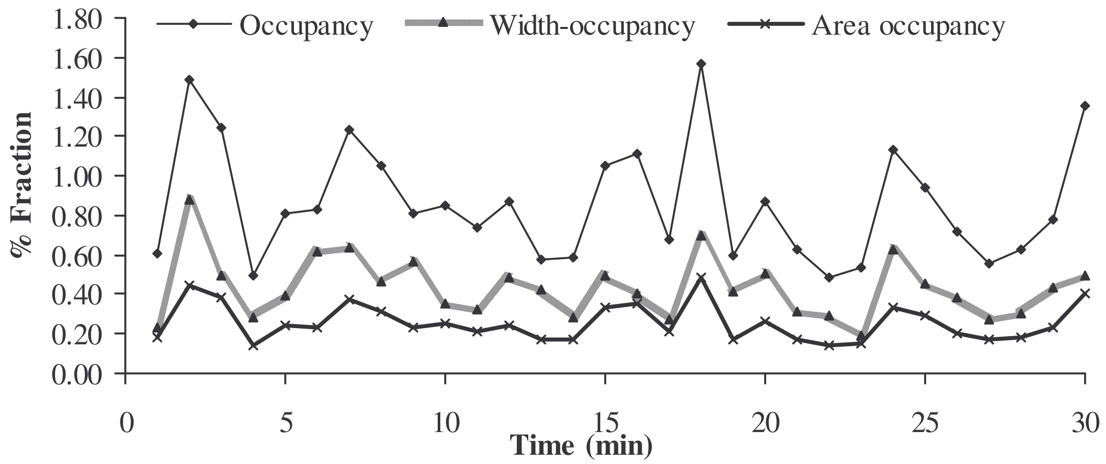

Figure 5.10: Occupancy, area occupancy and width occupancy over time for WN curve stretch

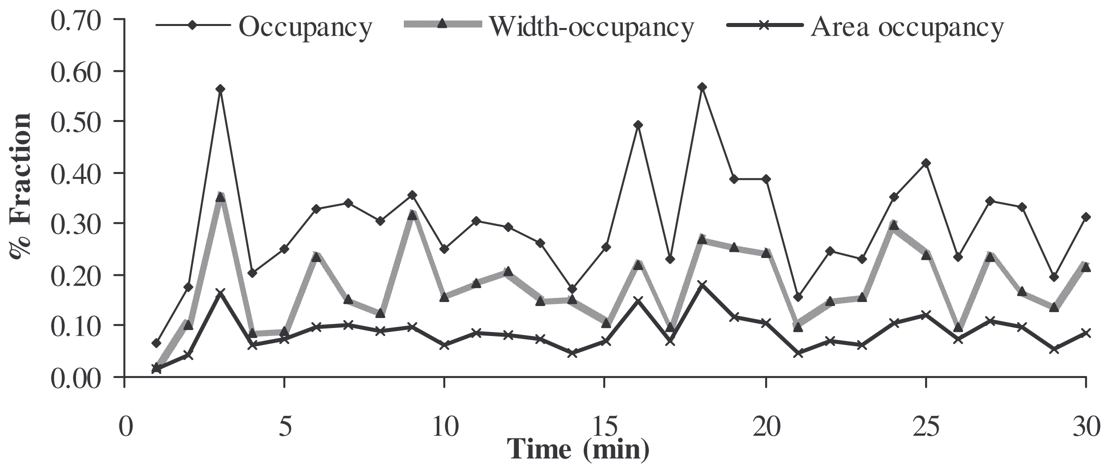

Figure 5.11: Occupancy, area occupancy and width occupancy over time for North exit stretch

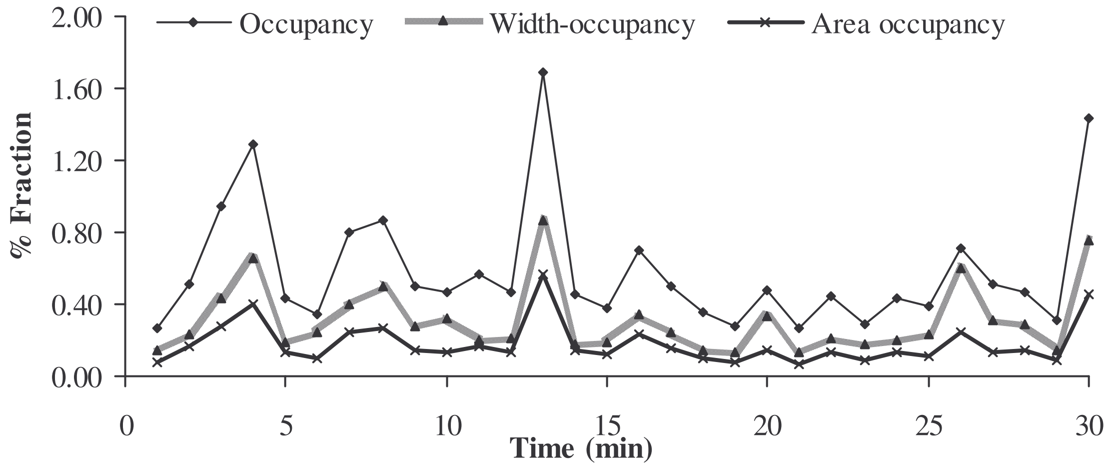

Figure 5.12: Occupancy, area occupancy and width occupancy over time for East exit stretch

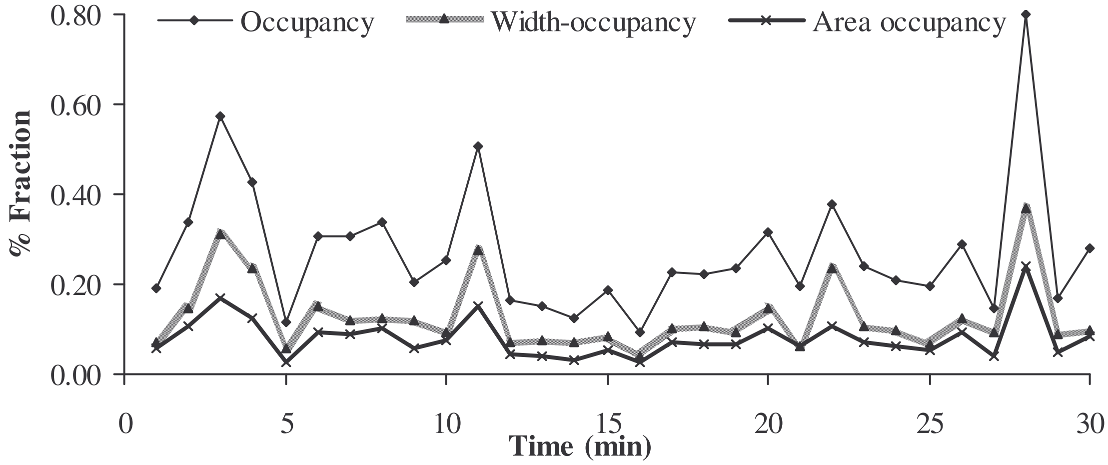

Figure 5.13: Occupancy, area occupancy and width occupancy over time for South exit stretch

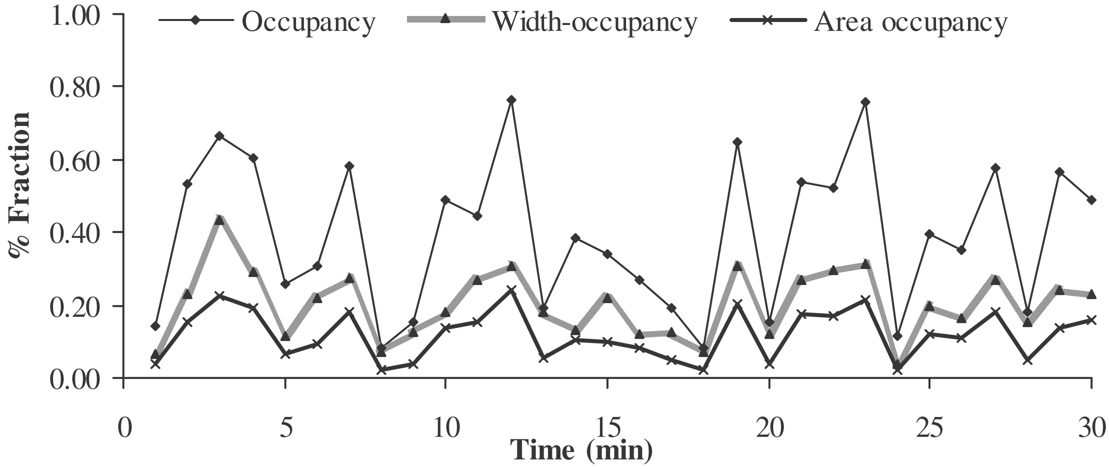

Figure 5.14: Occupancy, area occupancy and width occupancy over time for West exit stretch

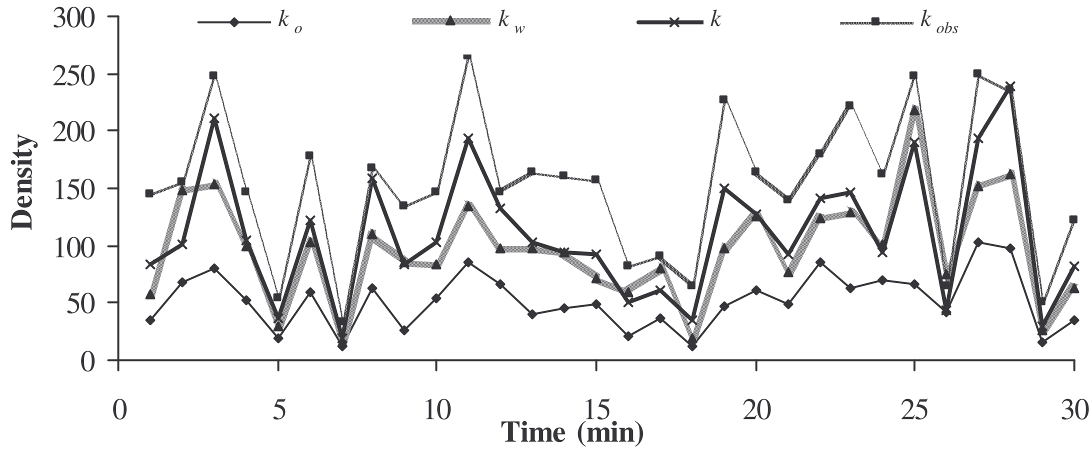

Figure 5.15: Observed and estimated densities for North entry stretch

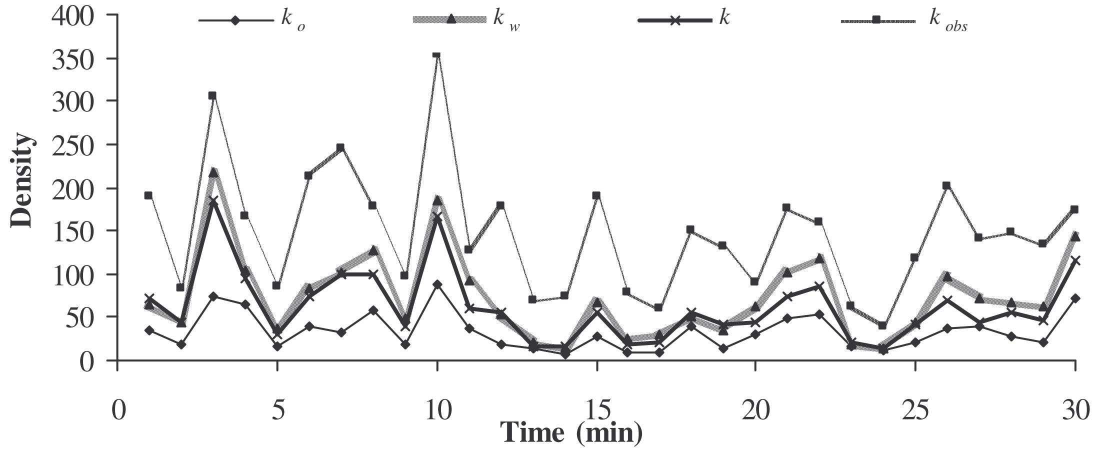

Figure 5.16: Observed and estimated densities for East entry stretch

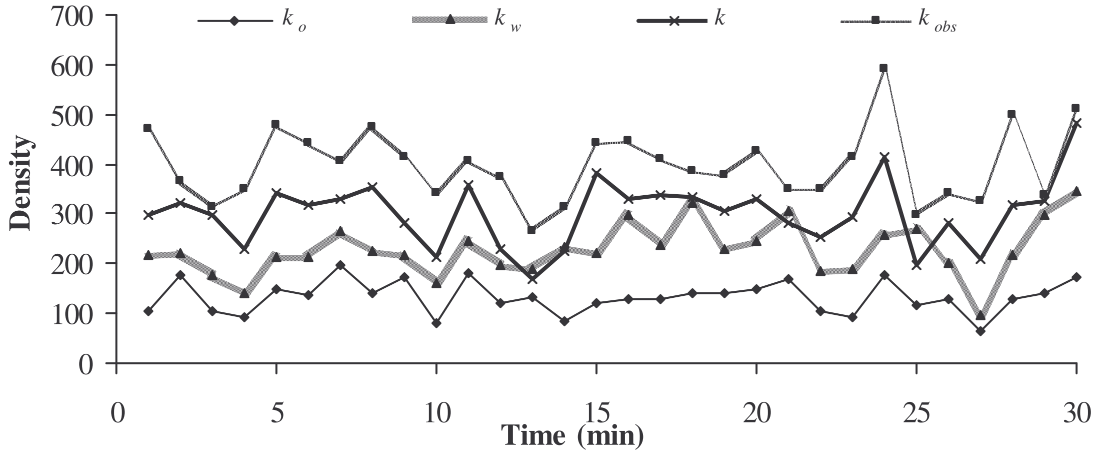

Figure 5.17: Observed and estimated densities for South entry stretch

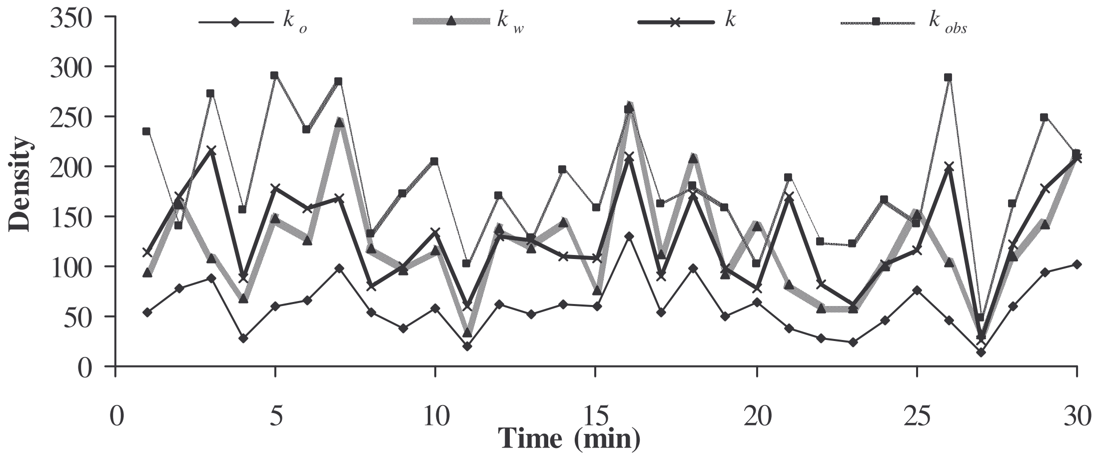

Figure 5.18: Observed and estimated densities for West entry stretch

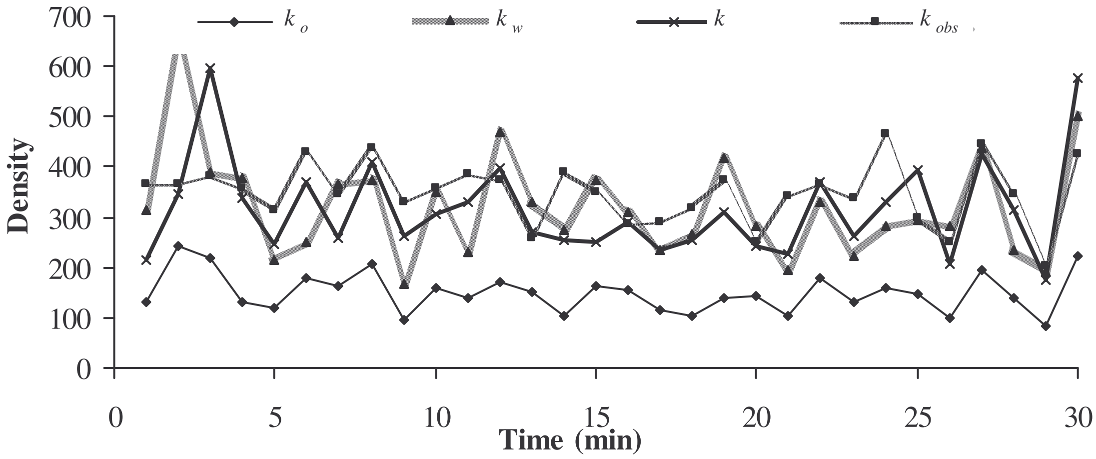

Figure 5.19: Observed and estimated densities for NE curve stretch

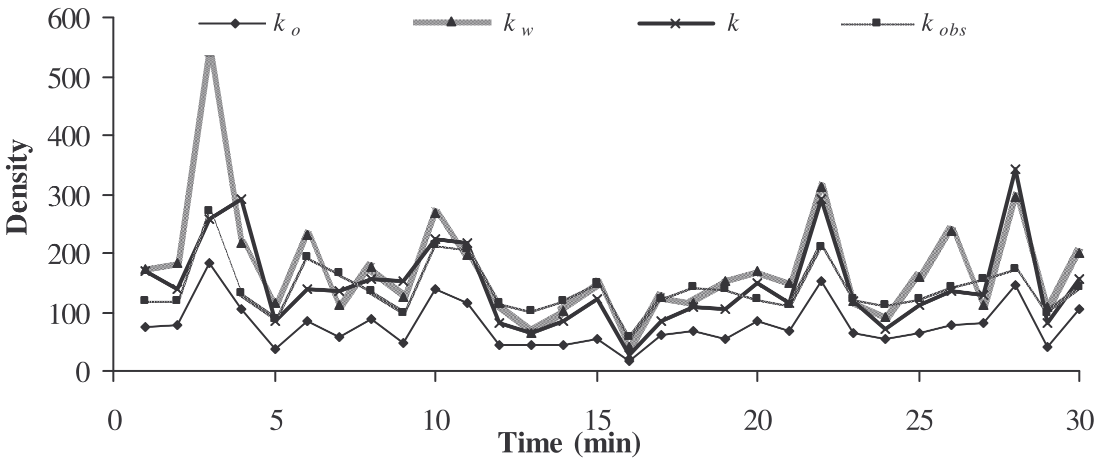

Figure 5.20: Observed and estimated densities for ES curve stretch

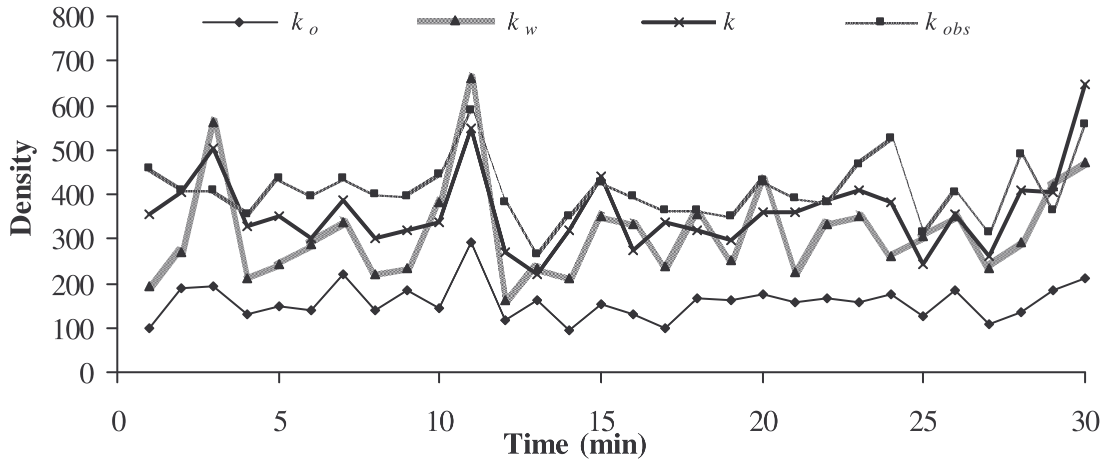

Figure 5.21: Observed and estimated densities for SW curve stretch

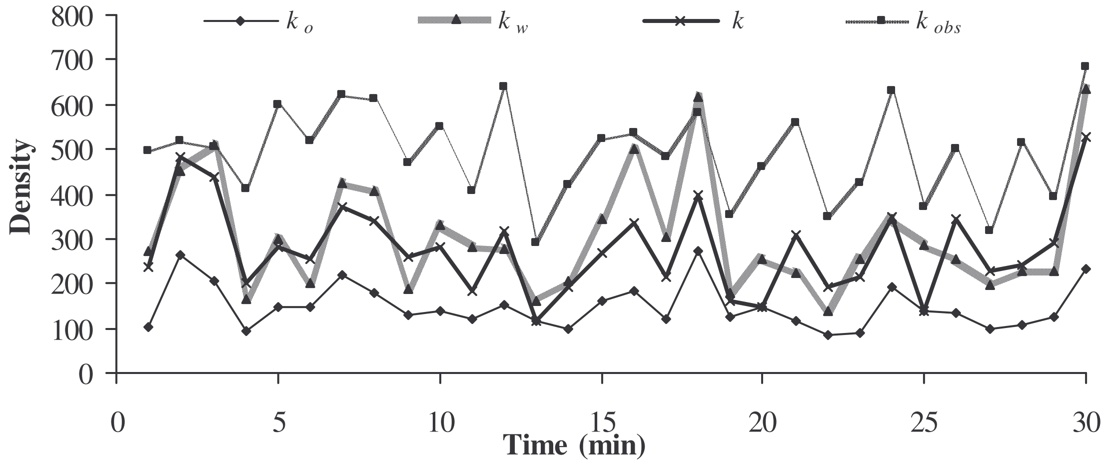

Figure 5.22: Observed and estimated densities for WN curve stretch

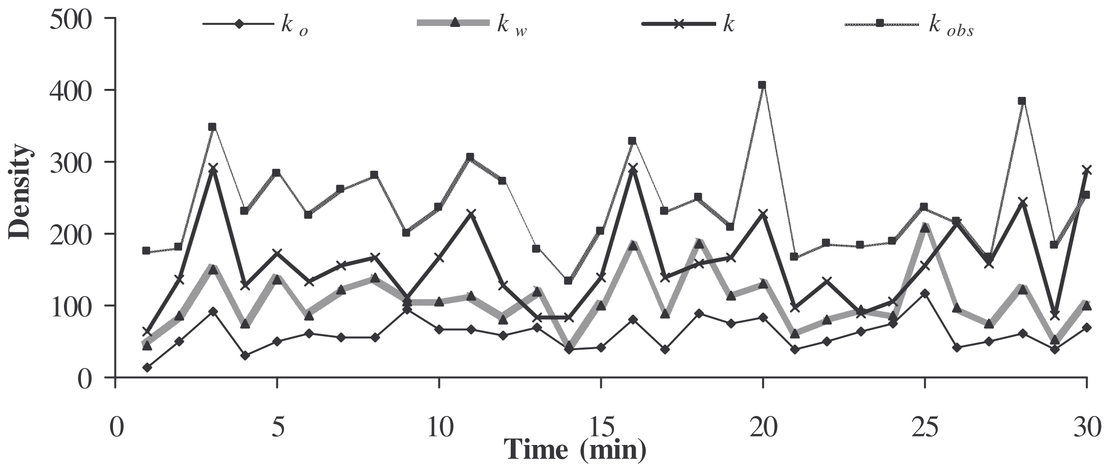

Figure 5.23: Observed and estimated densities for North exit stretch

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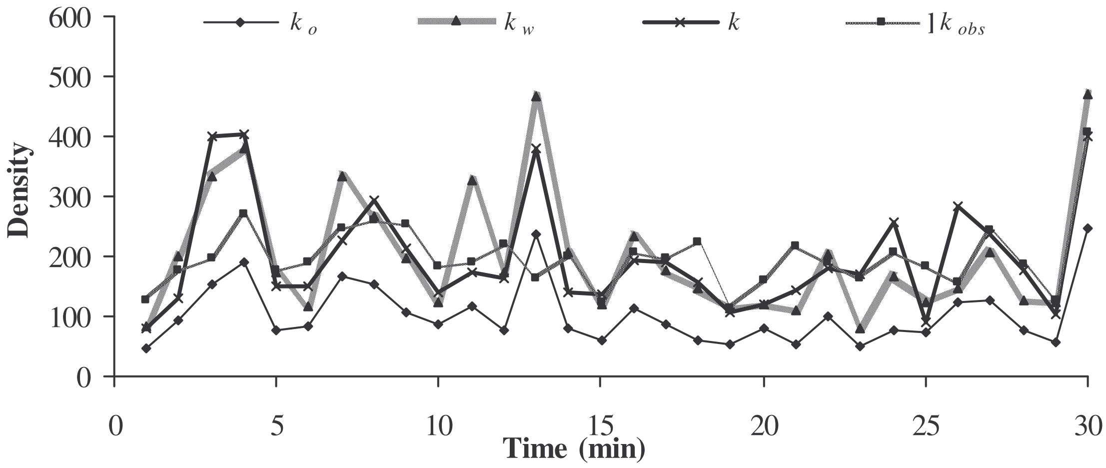

Figure 5.24: Observed and estimated densities for East exit stretch

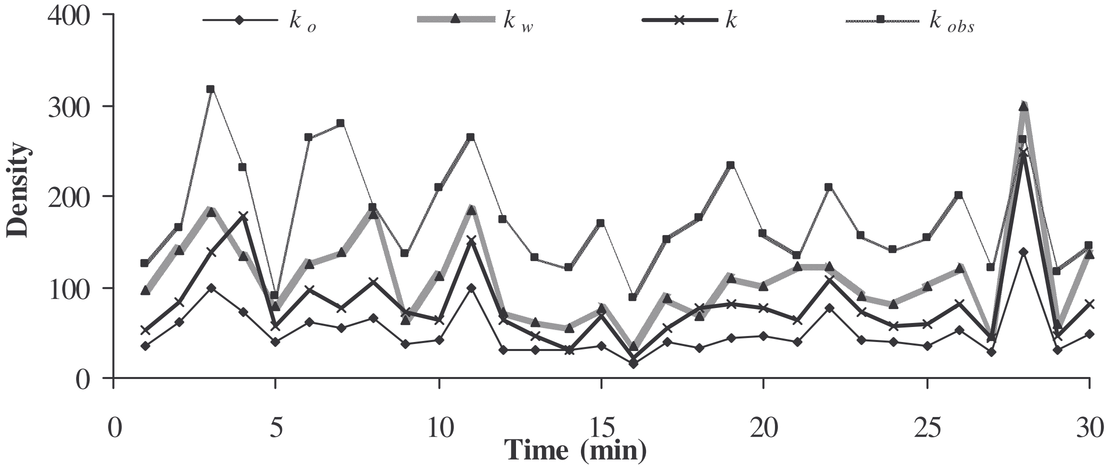

Figure 5.25: Observed and estimated densities for South exit stretch

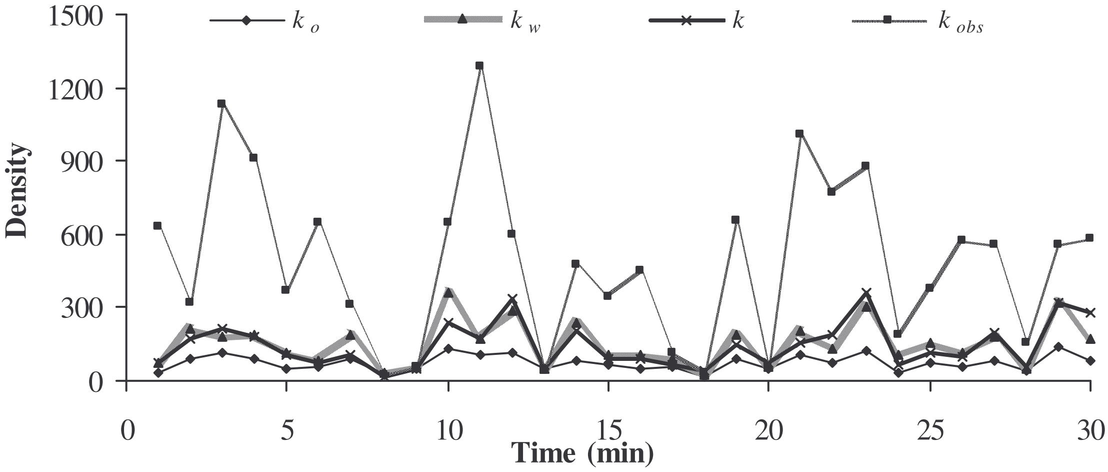

Figure 5.26: Observed and estimated densities for West exit stretch

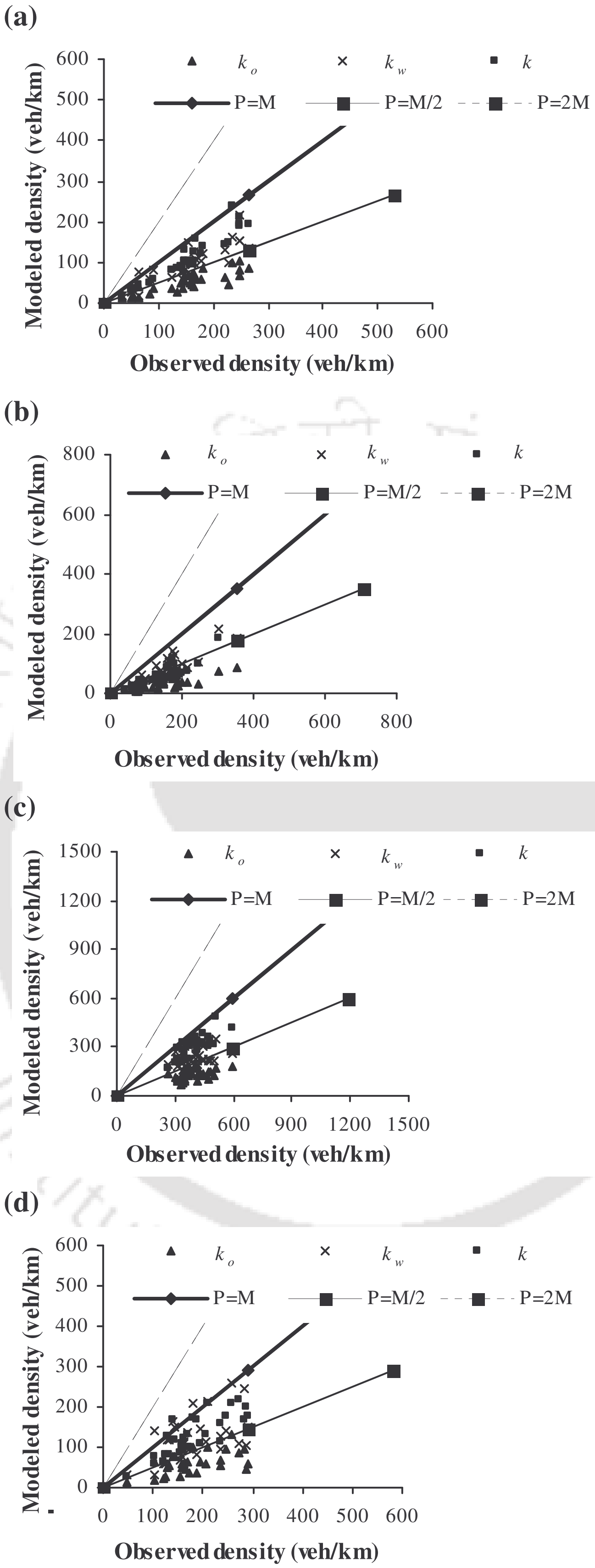

Figure 5.27 (a-d): Scatter plots of modeled densities against observed density for entry stretches

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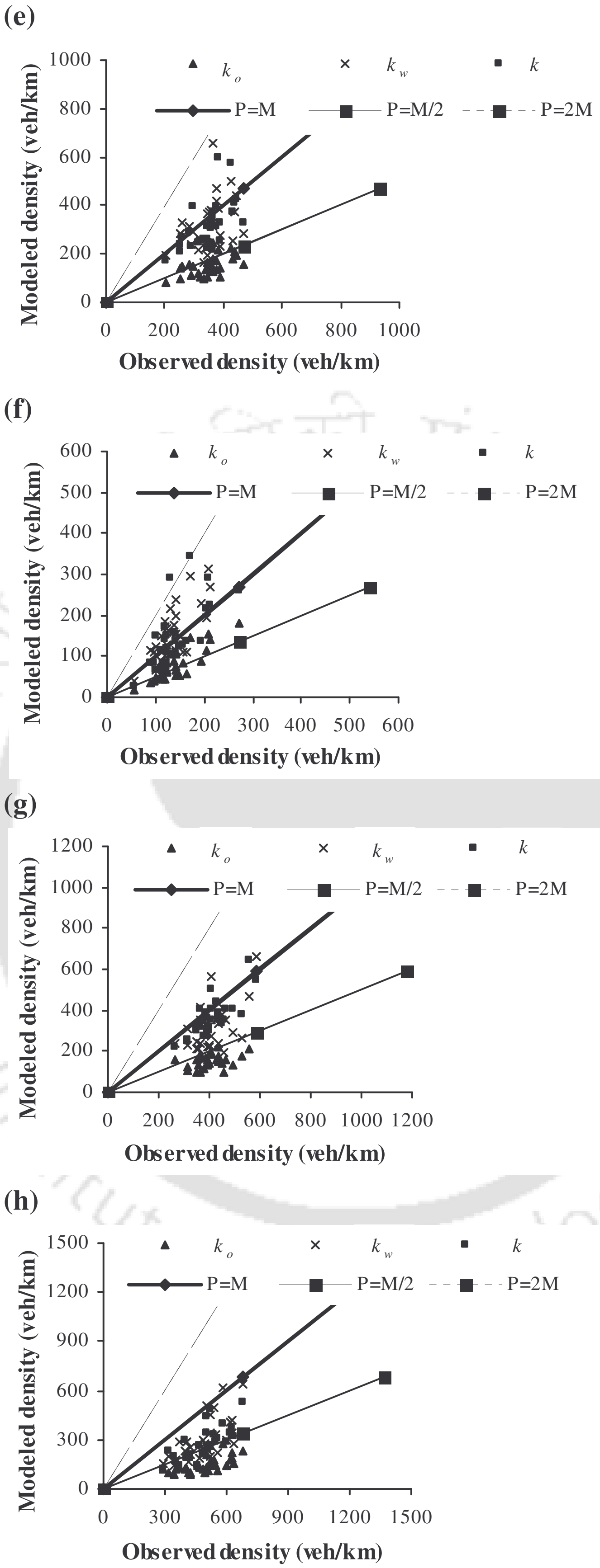
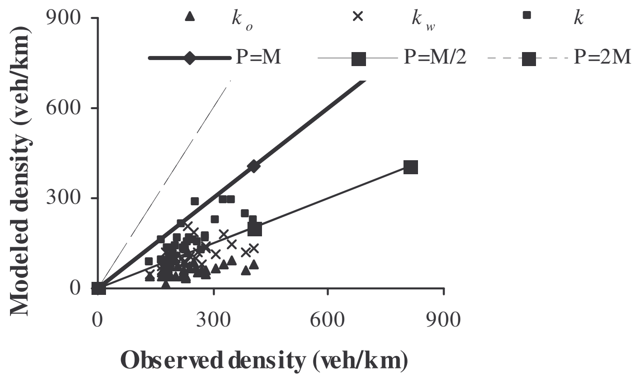
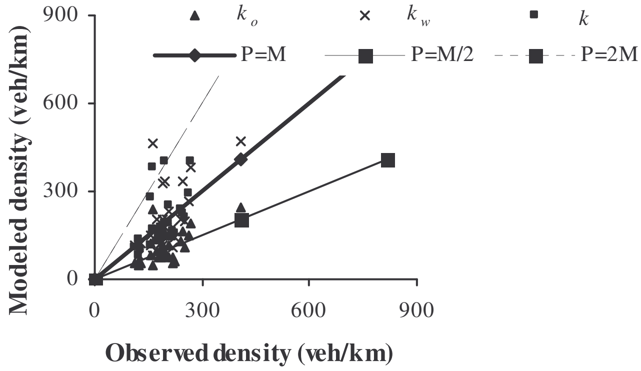


Figure 5.27 (e-h): Scatter plots of modeled densities against observed density for curve stretches

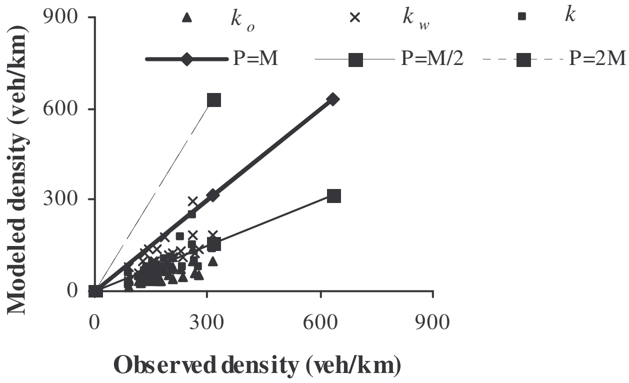
(i)



(j)



(k)



(l)

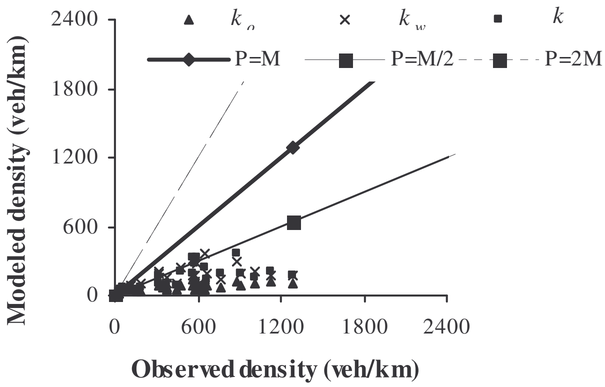


Figure 5.27 (i-l): Scatter plots of modeled densities against observed density for exit stretches

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CHAPTER 6

TRAFFIC EMISSIONS

6.1 GENERAL

Followed by the rigorous traffic analysis, estimation of traffic emission is the next important step of the air quality modeling study. As air quality at roadsides is directly influenced by the emissions generated, it is necessary to estimate traffic emissions accurately. For the accurate estimation of emissions, it is utmost necessary to work out the accurate emission rate for each vehicle category. This is because the emission rates are sensitive to the traffic flow pattern and operation. Emission rates for vehicles relate the amount of pollutants released from the vehicular exhausts in one kilometer (km) travel. It is expressed as g/km. It depends on the vehicle type, fuel type, speed of the vehicle, age and weight of the vehicle, engine condition and operating modes. Emission rates, further, changes with the type and capacity of junction and the traffic composition. It has been observed from the literature (section 3.3) that recently developed semi-empirical models incorporate most features relating to the manner traffic is operated at junctions (Gokhale and Pandian, 2007; Dirks et al., 2003).

This chapter describes the detailed methodology of the development of emission models followed by the results.

6.2 TRAFFIC EMISSIONS – A SEMI-EMPIRICAL APPROACH

Emissions have been calculated for the traffic fleet on each arm of the traffic roundabout, taking into account the effect of changes in traffic flow as well as an individual vehicle category (i.e. fleet composition). The methodology has been described below:

6.2.1 Traffic

This component estimates the vehicle density (veh/km), i.e. k, as a function of the traffic flow rate (veh/h), i.e. q, the jam density (veh/km), i.e. kj, and the maximum free-flow speed of traffic fleet (km/h), i.e. Vo. The relationship between k and q is determined using a standard traffic flow calculation theory (Greenshield, 1935; Dirks, et al., 2003). As per the standard traffic flow theory the flow is classified as either uninterrupted or interrupted. Uninterrupted flow means no obstructions to the vehicular movement. Freeway is one example for this type of flow. In this research, the traffic roundabout is unsignalized and hence the relationship between the traffic density and traffic flow is assumed to be quadratic as discussed by Greenshields (1935). The equations expressing the relationship between the *k* with the *q* as a function of constants V_o and k_j are described below (Dirks, et al., 2003; Salter 1989):

$$k = \frac{q}{V} \tag{6.1}$$

The relationship between the *k* and the *V* in terms of V_o and k_j, represented by equation 6.2.

$$V = V_0\left(1 - \frac{k}{k_j}\right) \tag{6.2}$$

The quadratic relationship obtained by combining equation 6.1 and equation 6.2 in equation 6.3.

$$q = k.V_0\left(1 - \frac{k}{k_j}\right) \tag{6.3}$$

The *D* may be calculated for any *q* by solving the equation 6.3 for *k* as given in equation 6.4.

$$k = \frac{k_j}{2}\left(1 \pm \sqrt{1 - \frac{4q}{V_0\, k_j}}\right) \tag{6.4}$$

Equation 6.4, yields two densities one corresponds to free flow condition and the other to congested condition. Since the traffic roundabout used in this study found to be congested in nature as often it has been decided to adopt the field derived constants from density – traffic flow rate relationships. The curve showing the relationship between traffic density and traffic flow rate are presented in Figures 6.1 – 6.3 (a-l). Moreover the usage of constants V_o and k_j are required only in the absence of field data. The necessary constants required for the estimation of modeled densities from traffic flow rate is given in Tables 6.1. The quadratic relationship as given by equation 6.5 is adopted.

$$k = aq^2 + bq + c \tag{6.5}$$

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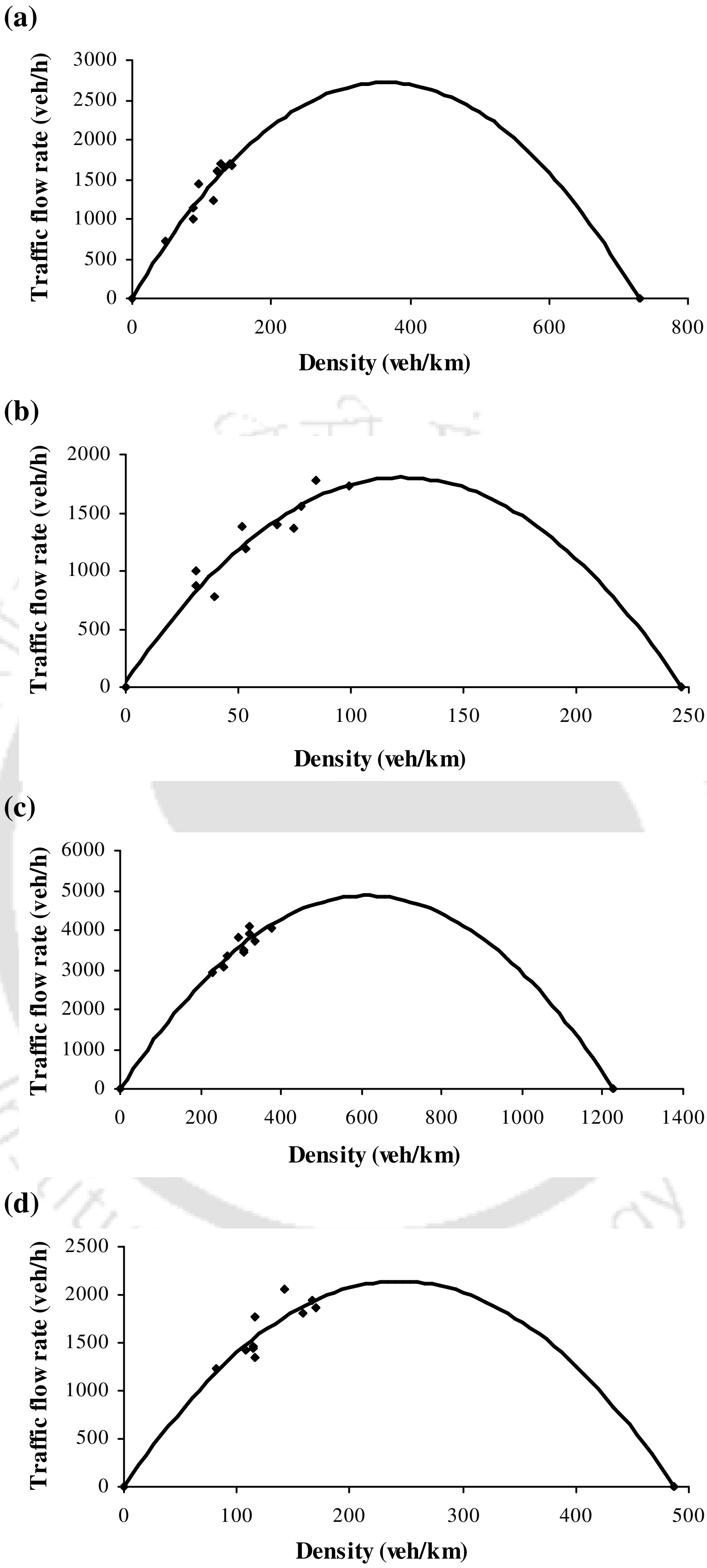

Figure 6.1 (a-d): Traffic flow rate against traffic density using PCU approach for entry stretches (a-N entry; b-E entry; c-S entry and d-W entry)

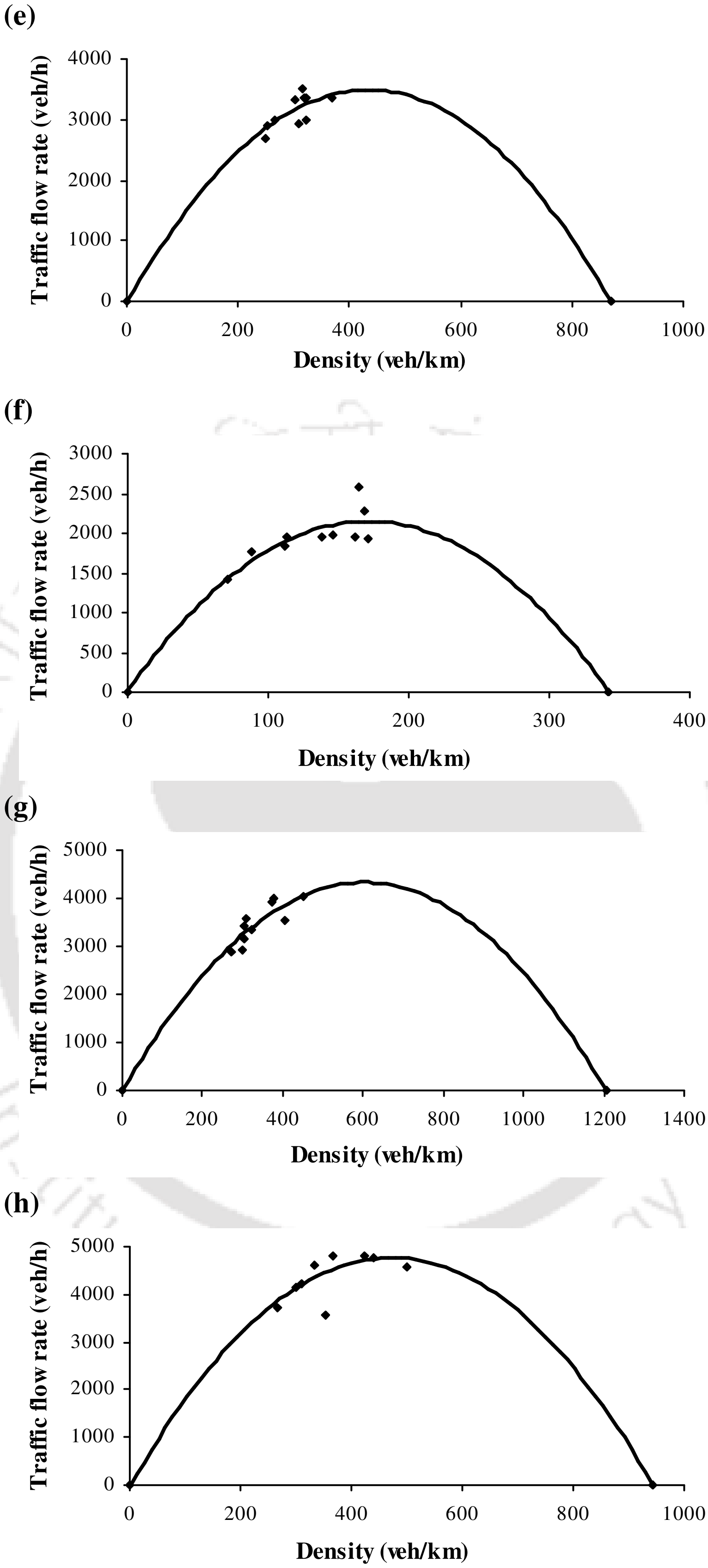

Figure 6.1 (e-h): Traffic flow rate against traffic density using PCU approach for curve stretches (e-NE; f-ES; g-SW and h-WN)

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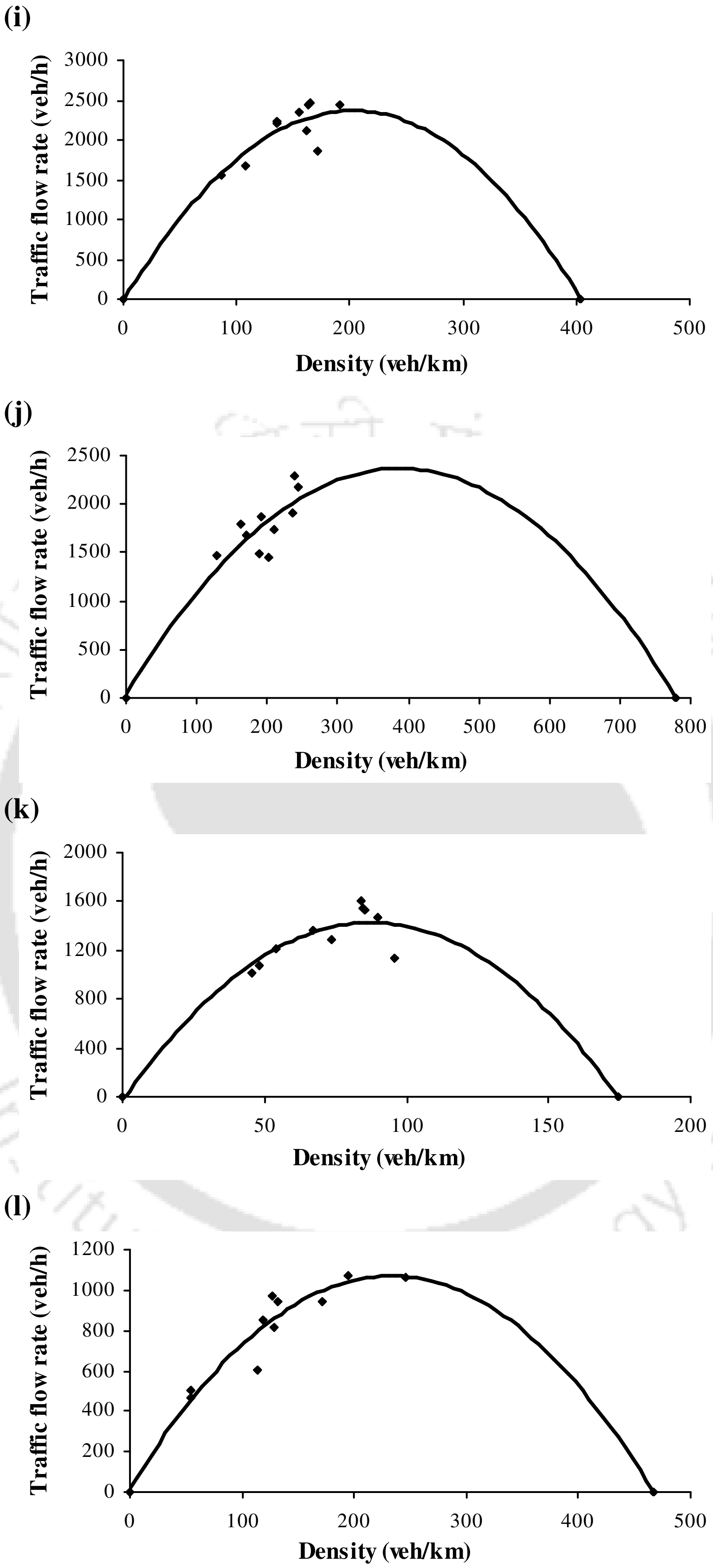

Figure 6.1 (i-l): Traffic flow rate against traffic density using PCU approach for exit stretches (i-N exit; j-E exit; k-S exit and l-W exit)

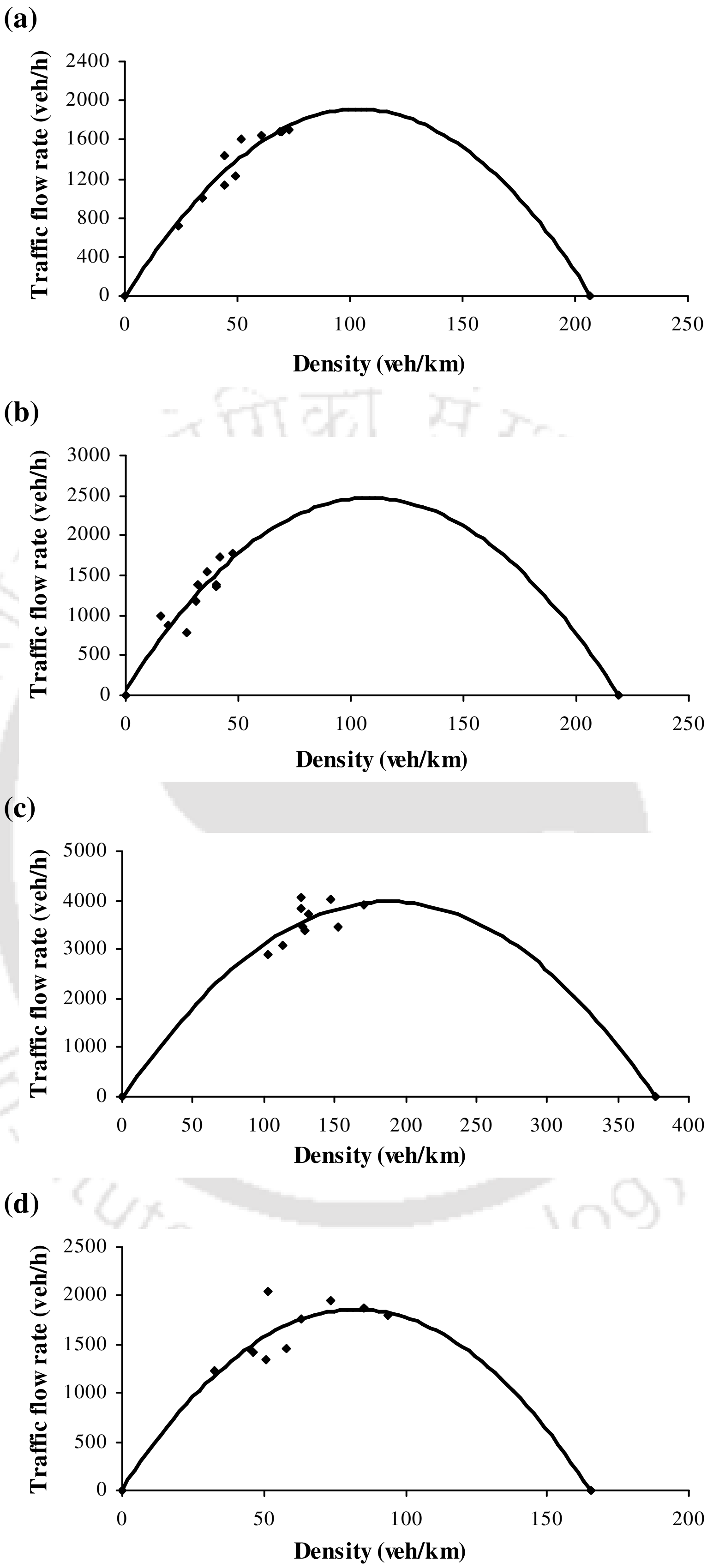

Figure 6.2 (a-d): Traffic flow rate against traffic density using occupancy approach for entry stretches (a-N entry; b-E entry; c-S entry and d-W entry)

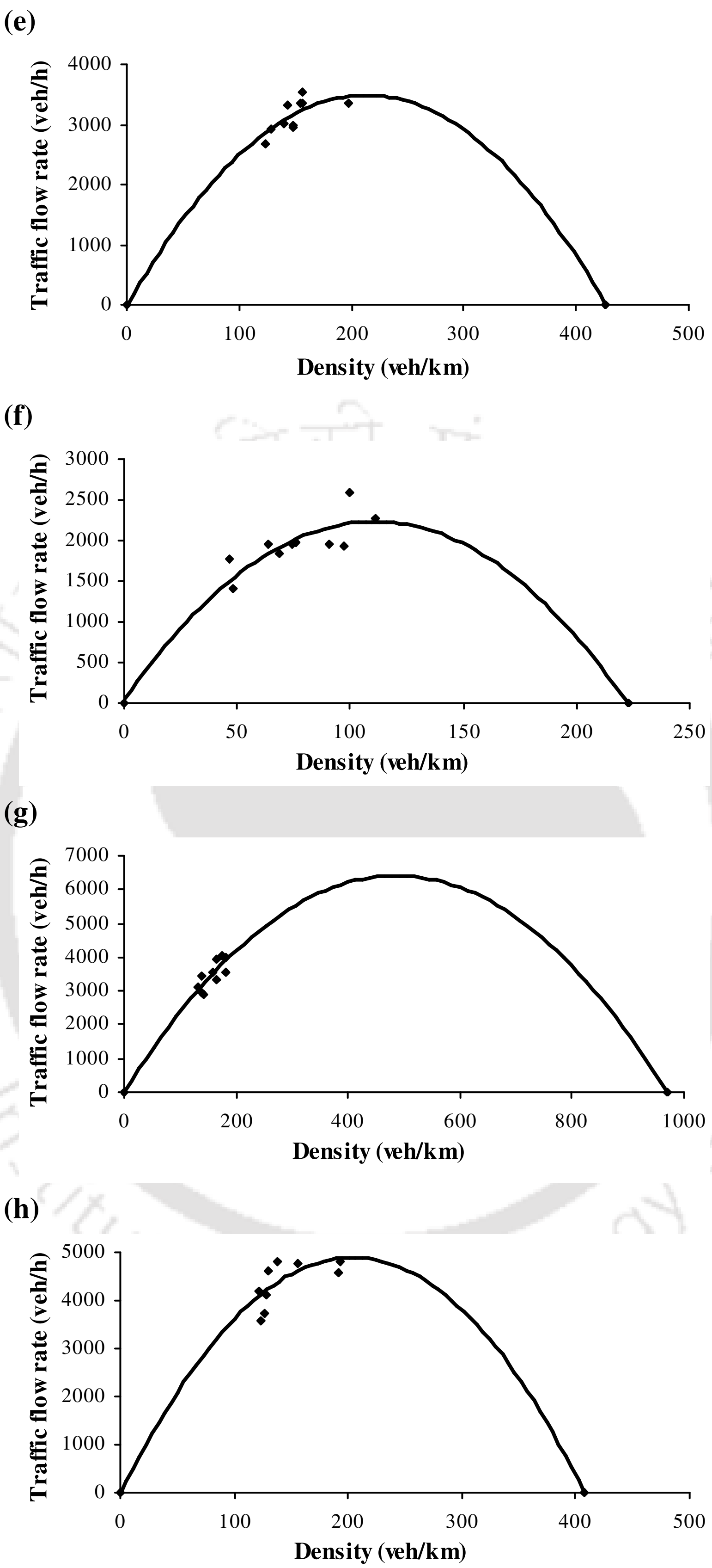

Figure 6.2 (e-h): Traffic flow rate against traffic density using occupancy approach for curve stretches (e-NE; f-ES; g-SW and h-WN)

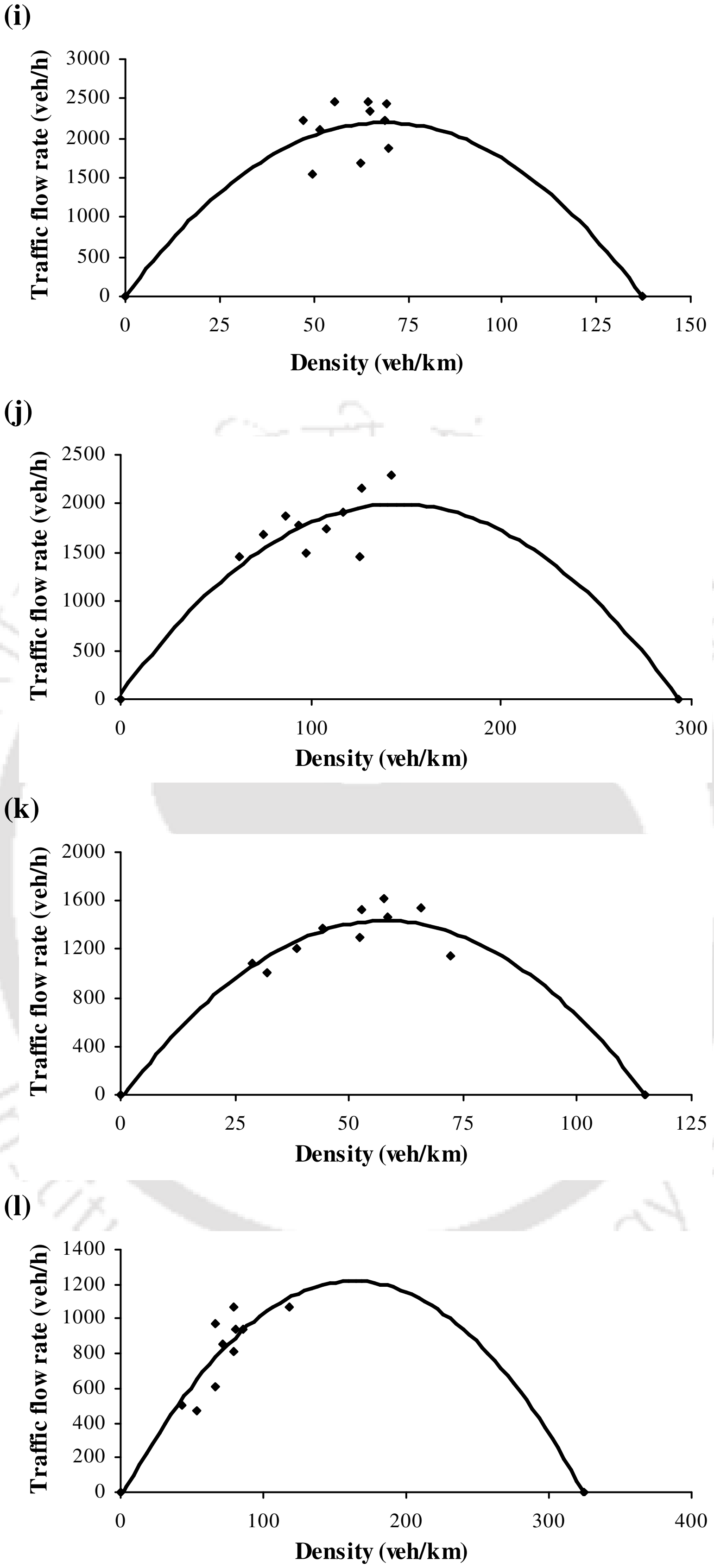

Figure 6.2 (i-l): Traffic flow rate against traffic density using occupancy approach for exit stretches (i-N exit; j-E exit; k-S exit and l-W exit)

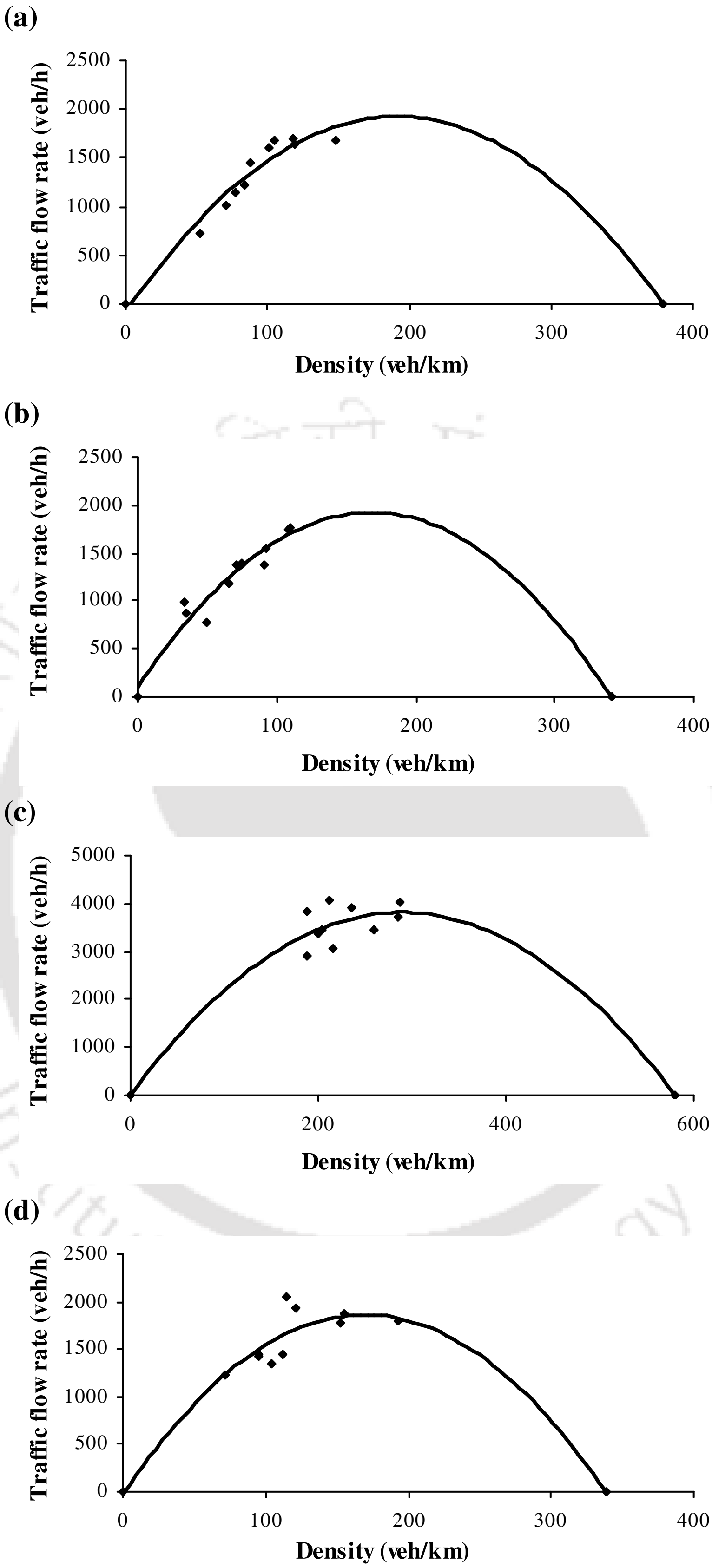

Figure 6.3 (a-d): Traffic flow rate against traffic density using time-width occupancy approach for entry stretches (a-N entry; b-E entry; c-S entry and d-W entry)

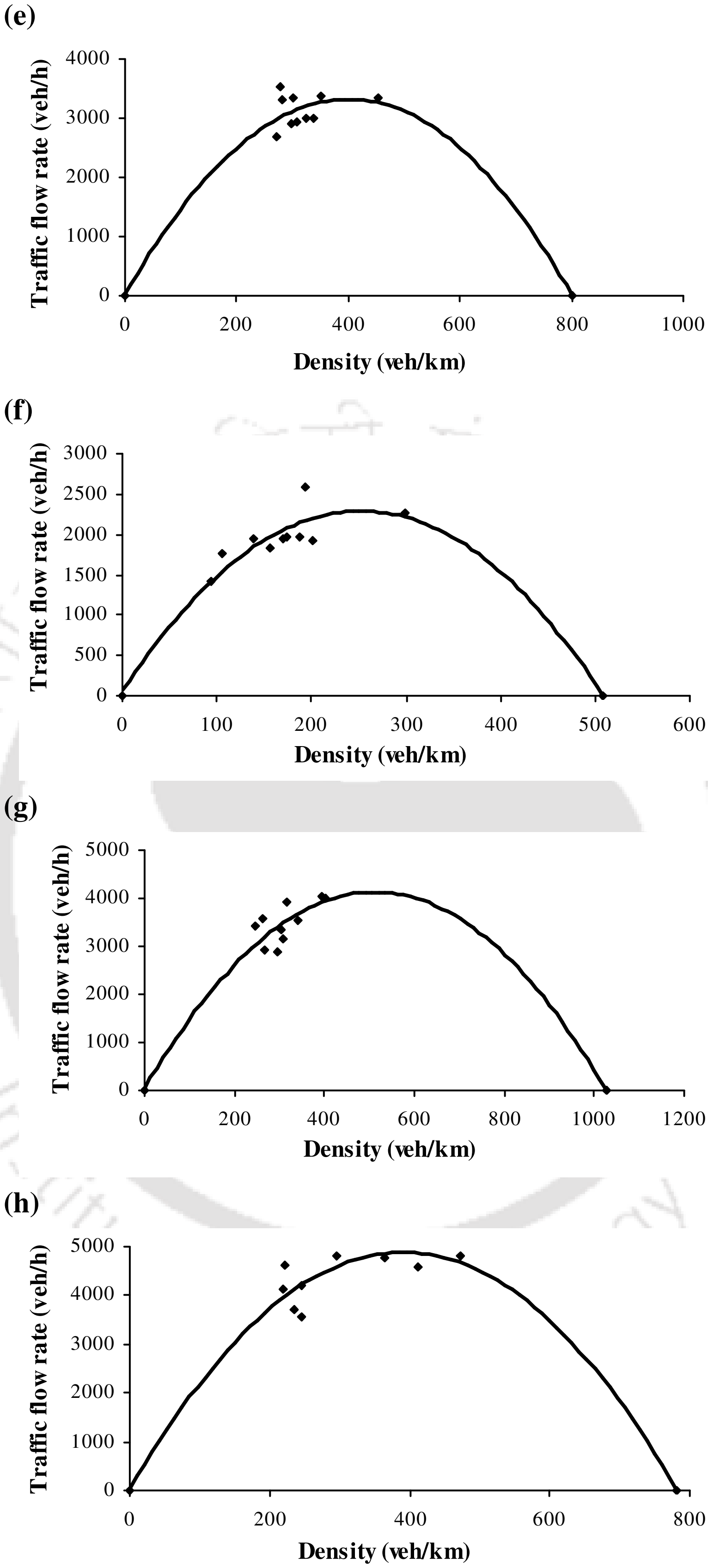

Figure 6.3 (e-h): Traffic flow rate against traffic density using time-width occupancy approach for curve stretches (e-NE; f-ES; g-SW and h-WN)

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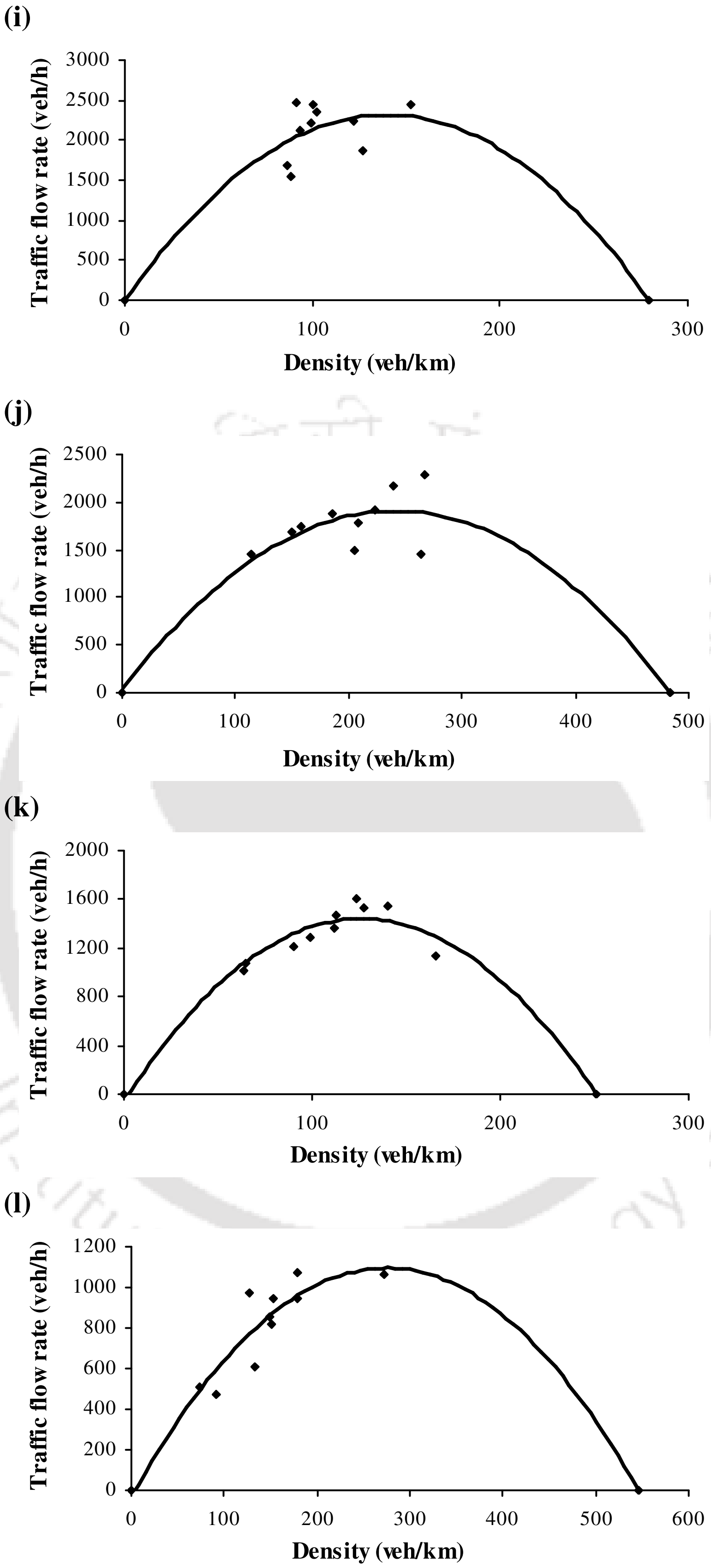

Figure 6.3 (i-l): Traffic flow rate against traffic density using time-width occupancy approach for exit stretches (i-N exit; j-E exit; k-S exit and l-W exit)

Table 6.1: Correlation parameters for roundabout approaches to estimate density from traffic rate

Density	Parameter	Approach				Circle				Exit			
		N	E	S	W	NE	ES	SW	WN	N	E	S	W
k_o	a	7.1E-05	6.7E-05	1.3E-05	3.3E-05	2.2E-05	3.3E-05	3.8E-05	1.2E-05	5.1E-06	4.3E-05	3.2E-05	2.5E-04
	b	-1.4E-01	-1.5E-01	-6.2E-02	-6.8E-02	-9.1E-02	-8.2E-02	-2.3E-01	-6.7E-02	-1.5E-02	-1.0E-01	-4.9E-02	-3.3E-01
	c	1.0E+02	1.1E+02	1.9E+02	8.2E+01	2.1E+02	1.1E+02	4.9E+02	2.0E+02	6.9E+01	1.5E+02	5.7E+01	1.6E+02
	r^2	9.4E-01	8.8E-01	8.9E-01	7.1E-01	9.1E-01	8.3E-01	9.6E-01	8.5E-01	8.4E-01	7.7E-01	7.0E-01	8.3E-01
k_w	a	1.2E-04	1.3E-04	1.7E-05	6.1E-05	2.3E-05	8.4E-05	4.2E-05	3.0E-05	1.9E-05	6.2E-05	1.1E-04	5.0E-04
	b	-2.5E-01	-3.0E-01	-7.8E-02	-1.3E-01	-9.9E-02	-2.2E-01	-2.1E-01	-1.5E-01	-5.7E-02	-1.4E-01	-1.7E-01	-5.8E-01
	c	1.9E+02	2.3E+02	2.9E+02	1.7E+02	4.0E+02	2.7E+02	5.1E+02	3.9E+02	1.4E+02	2.4E+02	1.4E+02	2.7E+02
	r^2	9.4E-01	9.0E-01	9.1E-01	8.2E-01	8.9E-01	8.8E-01	9.8E-01	8.4E-01	8.7E-01	8.4E-01	8.4E-01	9.1E-01
k	a	2.3E-04	8.9E-05	5.1E-05	9.3E-05	4.7E-05	4.8E-05	5.2E-05	4.2E-05	5.3E-05	8.5E-05	6.0E-05	4.4E-04
	b	-5.1E-01	-1.9E-01	-2.7E-01	-2.3E-01	-1.9E-01	-1.3E-01	-2.8E-01	-1.9E-01	-1.9E-01	-2.4E-01	-1.1E-01	-5.3E-01
	c	3.6E+02	1.5E+02	6.1E+02	2.4E+02	4.3E+02	1.9E+02	6.6E+02	4.4E+02	3.0E+02	3.4E+02	1.1E+02	2.5E+02
	r^2	9.4E-01	8.9E-01	9.9E-01	9.7E-01	9.7E-01	8.4E-01	9.9E-01	9.4E-01	9.6E-01	9.6E-01	8.3E-01	9.2E-01

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6.2.2 Emissions

Prior to the values of *k*, the relationship between the *k* and the vehicle emission rate (*VER*) is obtained using a semi-empirical relation as given in equation 6.6 (Dirks, et al., 2003) for all the vehicle types. This starts with the estimation of near-zero flow vehicle emission rate (*VERo*). The function, in the equation 6.6, relates the *VER* with the *k* within the range of zero to k_j and it varies from VER_0 to infinity, which is a constraint of this equation.

$$VER = \frac{(ak^2 + bk + c)k}{k_j - k} + VER_0 \tag{6.6}$$

where, *a*, *b* and *c* are the constants to be determined from the set of *VER* corresponding to the four driving cycles (maximum free-flow, under free-flow, interrupted and congested). This is done by using COPERT-IV methodology, wherein, the speed dependent emission rates are estimated for the four categories of the vehicles. Thus, the VER_0 values were obtained for the traffic fleet as well as for all the vehicle categories.

The emission, *Q* (g/km/s) for the traffic fleet is calculated using the respective V_0, VER_0, *k* and k_j (from density-flow rate graphs) and constants *a*, *b*, and *c* values as given by equation 6.7.

$$Q = \frac{VER \times q}{3600} \tag{6.7}$$

This methodology of estimating emission factor has been validated for Indian traffic conditions at one of the traffic intersection of New Delhi (Gokhale and Pandian, 2007).

6.3 TYPES OF EMISSION COMBINATIONS

Based on the field observed parameters, semi-empirical approach, COPERT-IV methodology, and occupancy dependent densities various possible combinations for estimating emissions have been worked out. They are described below:

1) The COPERT-IV methodology which uses speed–dependent equations for calculating emission rates was used, termed as E1 (TMS).
2) Emissions E1 were further improved with the field measured traffic volume, density and driving speeds as per different vehicle category by a semi-empirical equation, termed as E2. Equation 6.1 was used to estimate density from the traffic volume and speed (Arasan and Dhivya, 2008). The relationship between *k* and vehicle emission rate (i.e. VER) has been obtained from a semi-empirical method

given in equation 6.6 (Dirks et al., 2003). The necessary constants required of equation 6.6 for estimating emissions E2 (k) have been shown in Table 6.2. The traffic composition and traffic speed are found to be highly varying in nature between each arms of the roundabout. The heterogeneity nature of the existing traffic is reflected from the variations of jam density. Moreover, the non existence of lane discipline and lane markings also significantly contributes to the wide variations of jam density in different stretches. The same procedure applied for the emission calculation, based on densities from PCU, occupancy and width occupancy has been termed as E2 (k), E2 (k_o) and E2 (k_w) respectively.

3) Emissions E1 were improved using estimated traffic density by a quadratic equation, termed as E3. In this case, traffic density was estimated by equation 6.5 considering only traffic flow rate. The same procedure applied for the emission calculation, based on densities from PCU, occupancy and width occupancy has been termed as E3 (k), E3 (k_o) and E3 (k_w) respectively.

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Table 6.2: Traffic and emission component parameters for roundabout regions as per line sources

Density	Parameter	Approach				Circle				Exit			
		N	E	S	W	NE	ES	SW	WN	N	E	S	W
k_o	a	-1.6E-04	-3.5E-04	-3.9E-05	-2.5E-04	-3.2E-05	-2.1E-04	-5.5E-06	-3.9E-05	-3.7E-04	-6.8E-05	-1.2E-03	-4.8E-05
	b	4.2E-04	8.2E-02	-3.8E-03	5.7E-03	-2.1E-03	1.9E-02	-1.6E-03	-4.6E-04	3.3E-04	-4.9E-04	1.1E-01	-3.2E-03
	c	6.7E+00	-7.5E-01	7.0E+00	6.1E+00	7.0E+00	6.4E+00	7.0E+00	6.9E+00	7.0E+00	6.3E+00	3.3E+00	6.3E+00
	$k_{o,j}$	206.95	218.72	376.31	165.36	426.59	222.64	971.90	407.89	137.35	293.39	114.90	324.35
k_w	a	-4.6E-05	-1.5E-04	-1.6E-05	-6.0E-05	-9.1E-06	-4.0E-05	-4.9E-06	-1.1E-05	-8.9E-05	-2.5E-05	-2.4E-04	-1.7E-05
	b	2.5E-04	5.2E-02	-2.5E-03	2.8E-03	-1.1E-03	8.2E-03	-1.5E-03	-2.4E-04	1.5E-04	-3.0E-04	4.9E-02	-1.9E-03
	c	6.7E+00	-7.5E-01	7.0E+00	6.1E+00	7.0E+00	6.4E+00	7.0E+00	6.9E+00	7.0E+00	6.3E+00	3.3E+00	6.3E+00
	$k_{w,j}$	378.58	340.76	579.41	338.27	801.51	509.05	1027.03	781.88	279.48	484.47	251.04	546.28
k	a	-1.3E-05	-2.8E-04	-4.2E-06	-1.4E-05	-7.7E-06	-8.8E-05	-3.6E-06	-7.4E-06	-4.2E-05	-9.7E-06	-5.0E-04	-2.3E-05
	b	1.4E-04	7.2E-02	-1.5E-04	-1.4E-02	-1.0E-03	1.2E-02	-1.3E-03	-2.0E-04	9.5E-05	-1.7E-04	7.0E-02	-2.2E-03
	c	6.7E+00	-7.5E-01	6.6E+00	1.0E+01	7.0E+00	6.4E+00	7.0E+00	6.9E+00	7.0E+00	6.3E+00	3.3E+00	6.3E+00
	k_j	729.65	246.95	1225.22	486.93	869.50	342.55	1204.31	944.10	404.07	778.99	174.36	467.54
	VER_0	8.3	6.1	9.4	7.7	11.0	8.2	11.1	9.0	7.8	10.2	7.5	13.9
	V_0	30.4	53.1	26.2	30.7	23.0	36.5	22.2	28.2	32.2	22.9	45.3	16.9

6.4 RESULTS AND DISCUSSION

Three emission combinations (E1, E2 and E3) are used in this research result in varying vehicle emission rates. Table 6.3 shows the statistics of emission calculations for the various combinations. Figure 6.5 (a-c) shows the scatter plots of modeled emissions (E3) using traffic flow rate as input against modeled emissions (E2) using observed densities. It has been observed that the estimated emissions (E3) using width-occupancies as well as observed densities exhibit the similar pattern as that of E2 followed by PCU. Statistics of the emission models indicate that the second case of emission, E2, measured and E3, estimated matched well. The fractional bias (FB) value for the width-occupancy emissions is 0.03, for PCU emissions is 0.04 and for occupancy emissions is 0.02. Similarly, *d* value for occupancy emissions is 0.97 where as for other emissions, it is above 0.9. With width-occupancy, mean value of emission is found to be higher than PCU and occupancy based emissions.

A marginal difference observed between E2 and E3 which might be because of the fact that they are more or less similar cases with traffic characteristics measured in E2 and estimated in E3. This indicates that for more accurate predictions, it may be necessary to obtain vehicle and traffic characteristics by field measurements and or semi-empirical methods incorporating fundamental field variables. The incorporation of lateral space utilized by vehicle types under heterogeneous conditions in width-occupancy improved the densities and congestion measures as against those of occupancy. Hence, the performance of width-occupancy based densities was the best for estimation of traffic emissions compared to that of density based emissions. Besides, E2 and E3 emission methodologies contributed to significant rise in the estimated emissions, which were improved with the semi-empirical relationship.

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Table 6.3: Correlation statistics for emission methodologies

Evaluation Statistics	*TMS*	k_o	k_w	k
E1				
Mean	88.02			
Std Dev	18.42			
CV	0.21			
E2				
Mean		76.00	79.12	75.87
Std Dev		14.31	16.01	15.27
CV		0.19	0.20	0.20
E3				
Mean		77.90	81.94	78.60
Std Dev		14.82	19.36	15.45
CV		0.19	0.24	0.20
d		0.97	0.93	0.95
RMSE		4.58	8.82	6.70
FB		0.02	0.03	0.04
R		0.93	0.87	0.89

(a)

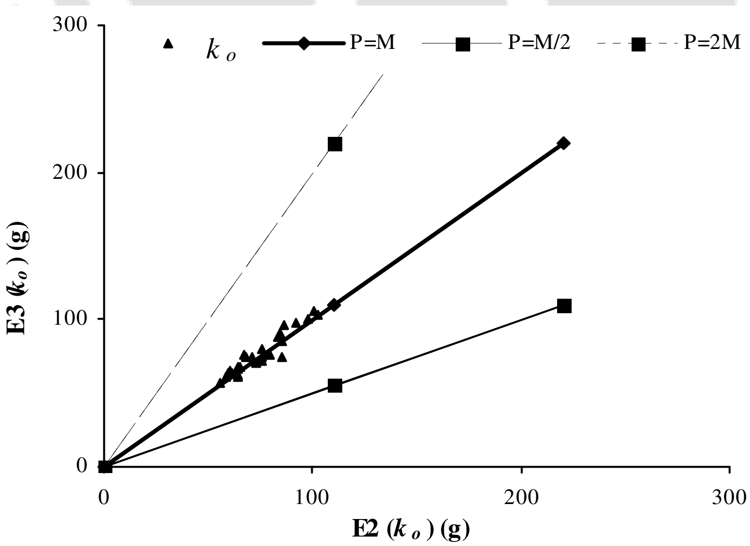
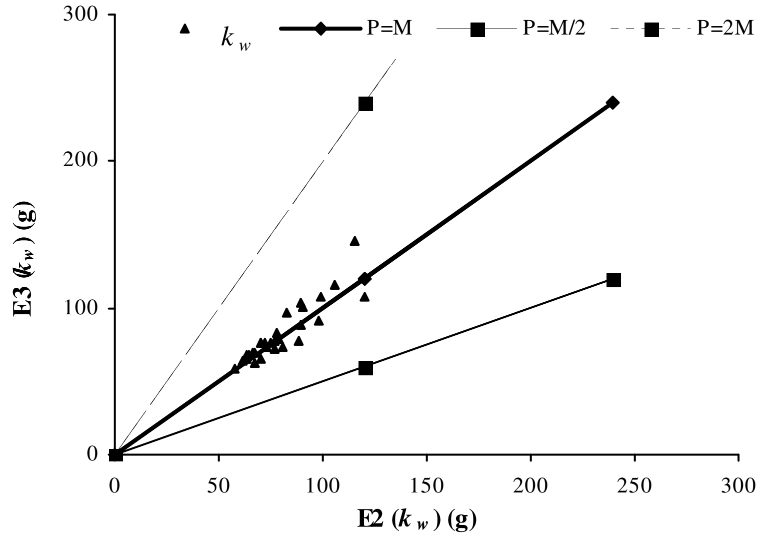


Figure 6.5 (a): Scatter plots of modeled emissions (E3) using traffic flow rate against the modeled emissions using the occupancy densities

(b)



(c)

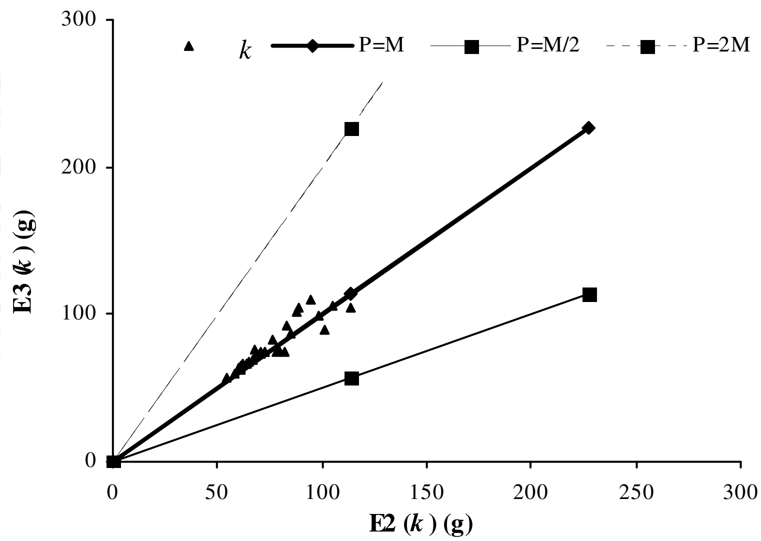


Figure 6.5 (b-c): Scatter plots of modeled emissions (E3) using traffic flow rate against the modeled emissions using the observed time-width occupancy and PCU densities

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CHAPTER 7

AIR QUALITY MODELING

7.1 GENERAL

Understandings on exhaust dispersions in the close vicinity of urban traffic intersections are important for mitigating vehicular pollution effects. Depending upon the manner of traffic operation, particularly at traffic junctions, dispersion phenomena are affected. This requires a model particularly tuned to the local conditions. This chapter presents the development of a new dispersion model at traffic roundabout with its application and validation results. Further, the results of the developed model demonstrate the impact of dynamic traffic characteristics and different emission calculation methodologies used in air quality modeling such as field and semi-empirical methods. The most influential parameters that affect dispersions are emission rates, meteorology and source-receptor relationship. The development and application of the air quality model presented in this chapter (Pandian et al., 2011) are published in Science of the Total Environment (volume number: 409; year: 2011 and pages: 1145-1153).

7.2 DEVELOPMENT OF AIR QUALITY MODEL

The rational of the air quality modeling is based on the understanding that at roundabouts, particularly those that are non-signalized, vehicles spiral in and out, change lanes and vary speeds in a circular pattern, resulting in complex emission and dispersion patterns. This generates a zone in which emissions are recirculated within a road width leading to the canyon-type effect between the continuous moving vehicles. Further, the turbulence caused by the continuously moving vehicles dominates within the road-width and emission often circulated. This understanding has been described with the help of the concept of a street canyon because of the similar phenomenon.

An assumption of the street-canyon effect specifically within lane-width takes care of an additional turbulence caused by the vehicular movements and temperature gradients. This rational has been restricted to lane-width and beyond that a simple line source model has been applied since the pollutant dispersion thereafter is affected by the winds.

The SC-GFLSM has been developed at the selected roundabout. It combines the STREET urban pollution street canyon (SC) model for within a road section to account for thermal and vehicle induced turbulences and the GFLSM for outside the road where the influence of atmospheric turbulence is more. The traffic roundabout, which consists of two

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lanes were treated like a canyon covered by the continuously moving vehicles on both sides in which emission may be re-circulated. The total concentration occurring at the receptor location was, therefore, calculated in two stages: the first stage, when dispersion of emission is in close proximity of the source from vehicular exhaust. In this case, dispersion is influenced by the movement of vehicles and the dominant buoyancy flux. Hence, concentrations generated within this section were determined by street canyon both leeward and windward side equations. In the second stage, which includes the domain beyond the canyon up to the receptor, dispersion is mostly influenced by the atmospheric turbulence and follows downwind movement. Hence, the concentration generated in this domain was calculated by a line source model, GFLSM. Thus, the combination was termed SC-GFLSM in which the existing outlet boundary conditions of street-canyon equations become the inlet boundary conditions for the second stage GFLSM model. The pictorial view depicting the application of this concept upon the single stretch is shown in Figure 7.1.

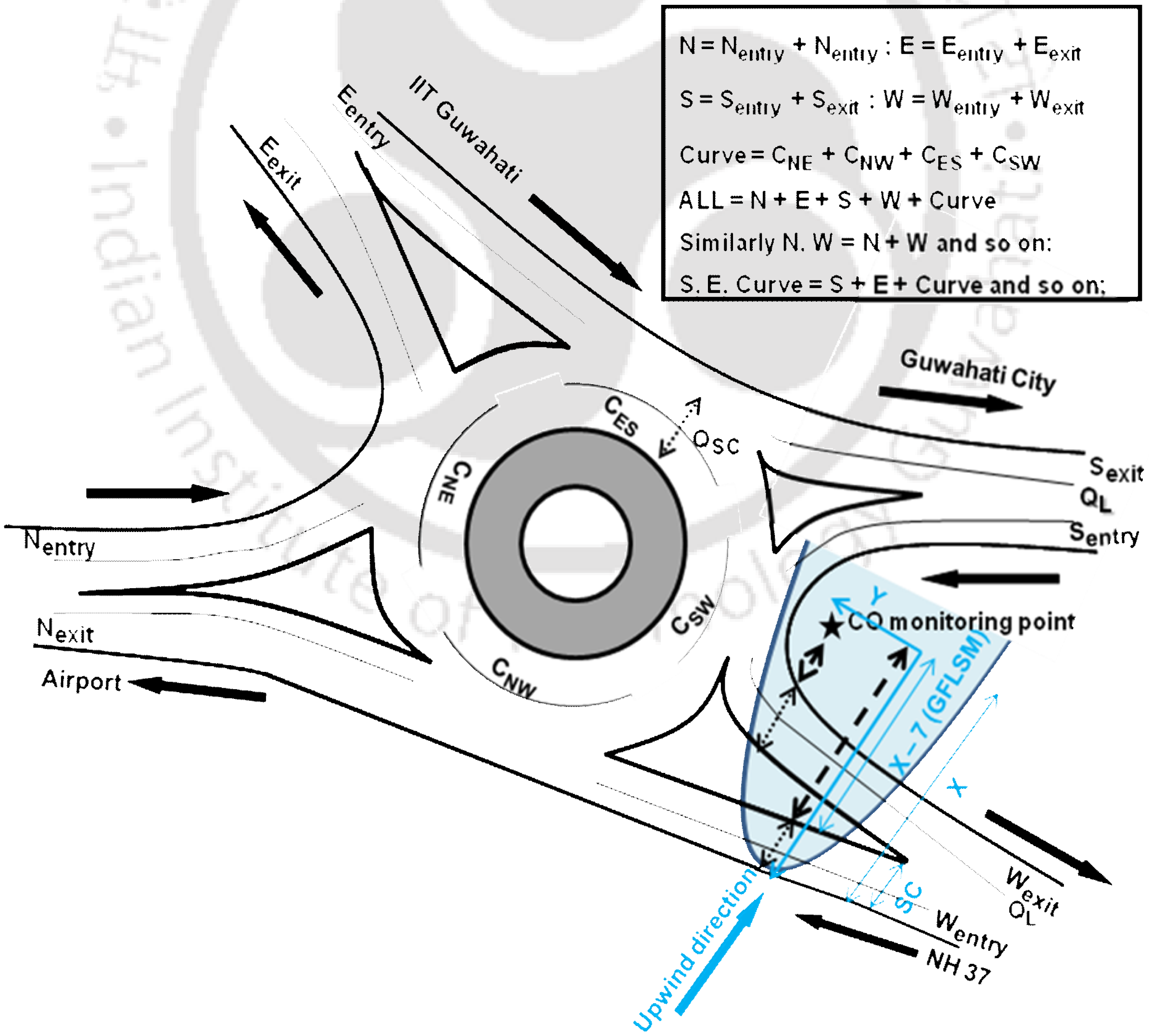

Figure 7.1: Methodology for SC-GFLSM modeling

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The equations 7.1 through 7.3 were used to calculate one-minute average concentration for a period of 30 min due to street canyon effects (Jhonson et al., 1973) in the first stage.

$$C_S^L = \frac{KQ_L}{\bar{u}_e\left(\sqrt{x^2+z^2}+h_0\right)} \tag{7.1}$$

where, C_S^L is the leeward side concentration (mg/m^3); $\bar{u}_e$, the mean ambient wind speed (m/s); K is dimensionless "best fit" constant (suggested to be 7) (Mensink et al., 2006; Jhonson et al., 1973); Q_L, the emission source strength (mg/m.s) from line source and h_0 is initial height of pollutant dispersion (Mensink et al., 2006; Jhonson et al., 1973)

$$C_S^W = \frac{KQ_L}{W(\bar{u}_e)}\left(\frac{H-z}{H}\right) \tag{7.2}$$

where, C_S^W is windward side concentration (mg/m^3); H, the height of the canyon (taken as 4 m as equivalent to height of tallest vehicle from ground); and W is width of the canyon (taken as 7 m as equivalent to road-width).

The arithmetic average concentration of pollutant in the domain is given by equation 7.3

$$C_{SC} = \frac{C_S^L + C_S^W}{2} \tag{7.3}$$

where, C_{CS} is average street-canyon concentration (mg/m^3). C_{SC} calculated in the first stage, emission Q_{SC} was recalculated by dividing with the constant, K. This emission at road section was then used to calculate the concentration at the receptor location using GFLSM model. Thus, equation 7.4 describes the SC-GFLSM model.

$$C_{SC-GFLSM} = \frac{Q_{SC}}{2\sqrt{2\pi}\sigma_z\bar{u}_e}\left\{\exp\left[-\frac{1}{2}\left(\frac{z-h_0}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+h_0}{\sigma_z}\right)^2\right]\right\}$$
$$\times\left\{erf\left[\frac{\sin\theta\left(\frac{L}{2}-y\right)-(x-W)\cos\theta}{\sqrt{2}\sigma_y}\right]+erf\left[\frac{\sin\theta\left(\frac{L}{2}+y\right)+(x-W)\cos\theta}{\sqrt{2}\sigma_y}\right]\right\} \tag{7.4}$$

where, Q_{SC} is the emission rate per unit length within the road section; L, the finite length of road; θ, the angle made by road with the wind vector; z, the height of the receptor above the ground; $h_0 = H_l + H_P$; H_l, the height of line source; H_P, the plume rise; σ_z and σ_y, the vertical and horizontal dispersion coefficients, respectively; u, the mean ambient wind speed at source height H; u_0, the wind speed correction due to traffic wake (Chock, 1978); $\bar{u}_e = u\sin\theta + u_0$; *erf*, the error function and *W* is the lane width.

Besides, the GFLSM was also applied alone in conventional manner to the whole roundabout. The results of the so called SC-GFLSM model were then compared with the GFLSM. The equation 7.5 describes the GFLSM model, details of which including several applications are discussed in the studies of Luhar and Patil, 1989; Gokhale, (2005), and Gokhale and Khare (2005).

$$C_{GFLSM} = \frac{Q_L}{2\sqrt{2\pi}\sigma_z \bar{u}_e}\left\{\exp\left[-\frac{1}{2}\left(\frac{z-h_0}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+h_0}{\sigma_z}\right)^2\right]\right\}$$

$$\times\left\{erf\left[\frac{\sin\theta\left(\frac{L}{2}-y\right)-x\cos\theta}{\sqrt{2}\sigma_y}\right] + erf\left[\frac{\sin\theta\left(\frac{L}{2}+y\right)+x\cos\theta}{\sqrt{2}\sigma_y}\right]\right\} \quad (7.5)$$

Important parameters of these models such as atmospheric stability, dispersion coefficients were estimated using standard theory and formulae as described below.

7.2.1 Dispersion coefficients

Dispersion coefficients were estimated as the functions of stability conditions using Richardson number. The lateral and vertical dispersion coefficients σ_y and σ_z, respectively are written as (Zimmerman and Thompson, 1975; Chock, 1978):

$$\sigma_y^2 = \sigma_{ya}^2 + \sigma_{y0}^2 \quad (7.6)$$

$$\sigma_z^2 = \sigma_{za}^2 + \sigma_{z0}^2 \quad (7.7)$$

The '*a*' and '*0*' refer to atmospheric turbulence and traffic generated turbulence, respectively. The atmospheric turbulence has been evaluated at an effective distance from a line source and at effective source height using equations 7.8 through 7.12. The dispersion coefficients due to traffic generated turbulence have been calculated using the equations 7.13 through 7.15 (Zimmerman and Thompson, 1975).

$$\sigma_{ya} = \frac{X\sin\lambda}{2.15\cos\lambda} \quad (7.8)$$

λ depends on atmospheric stability conditions and is given by:

$\lambda = 18.3 - 1.81\ln(x/1000)/57.3$ for unstable condition (7.9)

$\lambda = 14.3 - 1.8\ln(x/1000)/57.3$ for neutral condition (7.10)

$\lambda = 12.5 - 1.1\ln(x/1000)/57.3$ for stable condition (7.11)

Here, X is in meters and λ in radians. Then,

$$\sigma_{za} = \left(a + \frac{b}{\sin\theta} \times X \right)^{c} \quad (7.12)$$

The constants $\frac{1}{\sin\theta}$, *a*, *b* and *c* are based on stability and taken from the GM experimental results (Chock, 1978). The other expressions are given by

$$\sigma_{z0} = 3.57 - 0.53U_c \quad (7.13)$$

$$\sigma_{y0} = 2\sigma_{z0} \quad (7.14)$$

$$U_c = 1.85u^{0.164}\cos^2\theta \quad (7.15)$$

7.2.2 Richardson number

The Richardson number uses wind speed, temperature difference and the time of a day to determine atmospheric conditions. Considering the importance of convective as well as wind driven turbulence at the crowded urban traffic junctions, Richardson number was used. This method simulates the changes in temperature and wind with altitude classifying the atmospheric stability condition reasonably accurate at a shorter time scale. The dominant convective turbulence creates unstable atmospheric condition. This condition changes to neutral when convection decreases and mechanical or wind driven turbulence dominates. This state of atmosphere may further change when convective and mechanical turbulences are almost absent creating highly stable condition with no vertical mixing. The Richardson number, R_b is defined by equation 7.16 (Uehara et al., 2000).

$$R_b = \frac{gH_m\left(T_H - T_O\right)}{\left\{U_H^{\,2}\left(T_a + 273\right)\right\}} \quad (7.16)$$

where, g is the gravitational acceleration (m/s^2), H_m, the height of the meteorology station (m) , T_H, the temperature at the meteorology station (^{o}C), T_O, the temperature at the ground level, T_a, the reference (ambient) temperature, and U_H is the wind velocity at the meteorology station (m/s).

The stability criteria are shown in Table 7.1 which defines the atmospheric stability condition within the region where canyon effects are generated. Uehara et al., (2000) have reported that atmospheric condition was weak when the Richardson number was in the range of 0.4 and 0.8. The R_b values are shown in Figure 7.2. The values ranged from −0.14 to −6.77 with an average of −1.02. In one of the studies on the temperature distribution in a street canyon, Nakamura and Oke (1988) observed the R_b values between −0.45 and −0.17 on a clear mid-summer afternoon for U_H>0.5. While the R_b values estimated in the present study are much lower (larger negative) than those reported by Nakamura and Oke (1988), they result in the same class of stability (i.e. extremely unstable).

Table 7.1: Stability criteria as per Richardson number (R_b)

Stability Condition	Richardson number (R_b)
Extremely unstable and unstable	$R_b < -0.04$
Slightly unstable	$-0.03 < Rb < 0$
Neutral	$R_b = 0$
Slightly stable	$0 < R_b < 0.25$
Stable and extremely stable	$R_b > 0.25$

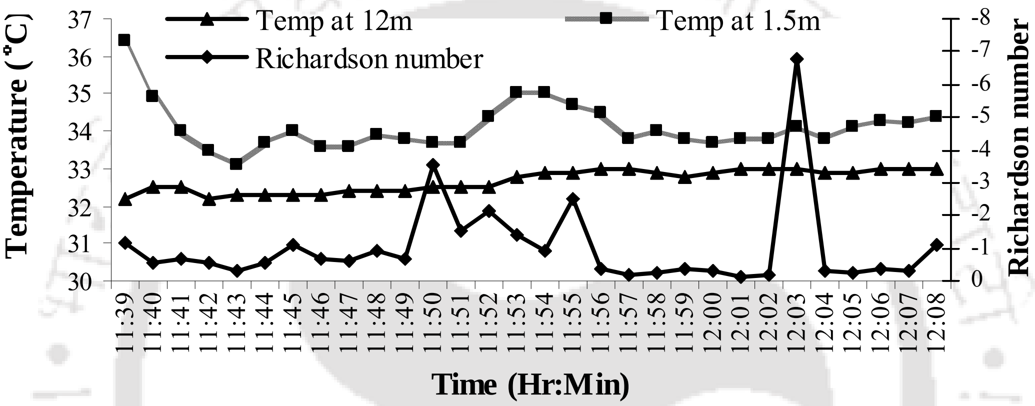

Figure 7.2: Temperature variations and Richardson number (R_b)

7.3 TESTING AND APPLICATION OF SC-GFLSM MODEL

The central idea of the research was to capture the emissions generated within the roundabout under actual traffic flow conditions. Since line source model (deterministic nature) inadequately predicts close to the source, the influenced area was divided into two zones having significantly different impacts of traffic movement, emission, wind speed and direction. The solution has been sought based on the assumption of a street canyon effect combined with a line source effect and not exclusively by street canyon model. Therefore, the street canyon effect was applied only to a zone in which mechanical turbulence dominates (within the lane width). Therefore, the SC-GFLSM model basically retains the essential nature of the GFLSM. The assumption of street canyon effects provides emission rate (Q_{SC}) (refer equation 7.4) to the GFLSM model corrected due to the influence of vehicular movement and direct exhaust emissions (Q_L). This eliminates the limitations of GFLSM of inadequate predictions close to the emission source.

The GFLSM and SC-GFLSM models were applied to estimate 1-min average CO concentration contributed from each line source to the receptor point. The emission inputs used in the models are PCU (k) and time-width occupancy (k_w) based emissions methodologies, i.e. E2 (field study approach) and E3 (semi-empirical approach). Assuming that there are no sources of CO other than twelve line sources (Figure 7.1) affecting the concentration at the receptor, we added the concentration calculated from all the line sources (i.e. ALL) to compare with the measured concentrations. Figures 7.3 - 7.6 show the time variation of concentrations by both models against the measured concentrations. Figures 7.7 – 7.10 shows the scatter plots of GFLSM and SC-GFLSM modeled concentrations against the measured concentrations for E2 and E3 emissions. The statistics for ALL are given in Table 7.2. The results showed that the combined model (SC-GFLSM) reduced the degree of prediction error produced in the estimation of the line source model (GFLSM) by a large extent. For example, E2 emissions using width-occupancy based density (k_w) the d was 0.18 for GFLSM which improved up to 0.48 for SC-GFLSM and similar improvements were observed by *RMSE* and FB statistics. The statistics are matched well for emissions of PCU based density (k). It means that the combined model estimated the concentrations better than the single line source model. From the table, d of CO predictions using E3 (k_w) found to be acceptable in comparison with E3 (k) are Emissions using E3 methodology. Further, the conventional correlation coefficient R, which measures the strength of a relation between two variables, has also been calculated. However, the R fails to provide agreement between two entities as observed from its values for CO concentrations obtained by two different ways.

Table 7.2: Correlation statistics for ALL

Evaluation statistics	***k*** GFLSM	***k*** SC-GFLSM	***kw*** GFLSM	***kw*** SC-GFLSM
ALL (E2)				
Mean	2.03	0.71	2.06	0.71
Std Dev	0.67	0.30	0.66	0.30
CV	0.33	0.43	0.32	0.42
d	0.19	0.49	0.18	0.49
R	0.45	0.45	0.40	0.42
RMSE	1.82	0.49	1.85	0.50
FB	1.47	0.79	1.48	0.79
ALL (E3)				
Mean	2.08	0.77	2.15	0.77
Std Dev	0.74	0.48	0.73	0.45
CV	0.35	0.63	0.34	0.57
d	0.19	0.41	0.19	0.49
R	0.22	0.20	0.49	0.50
RMSE	1.89	0.64	1.95	0.60
FB	1.49	0.86	1.50	0.87

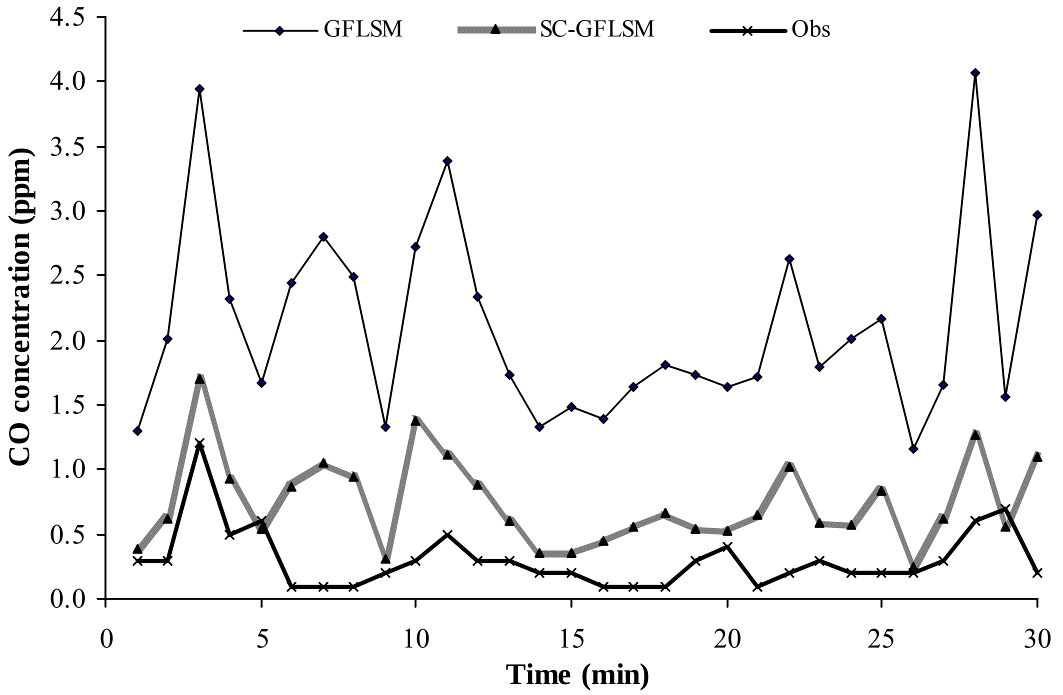

Figure 7.3: The comparison of modeled CO concentration with the measured for the ALL using E2 (k)

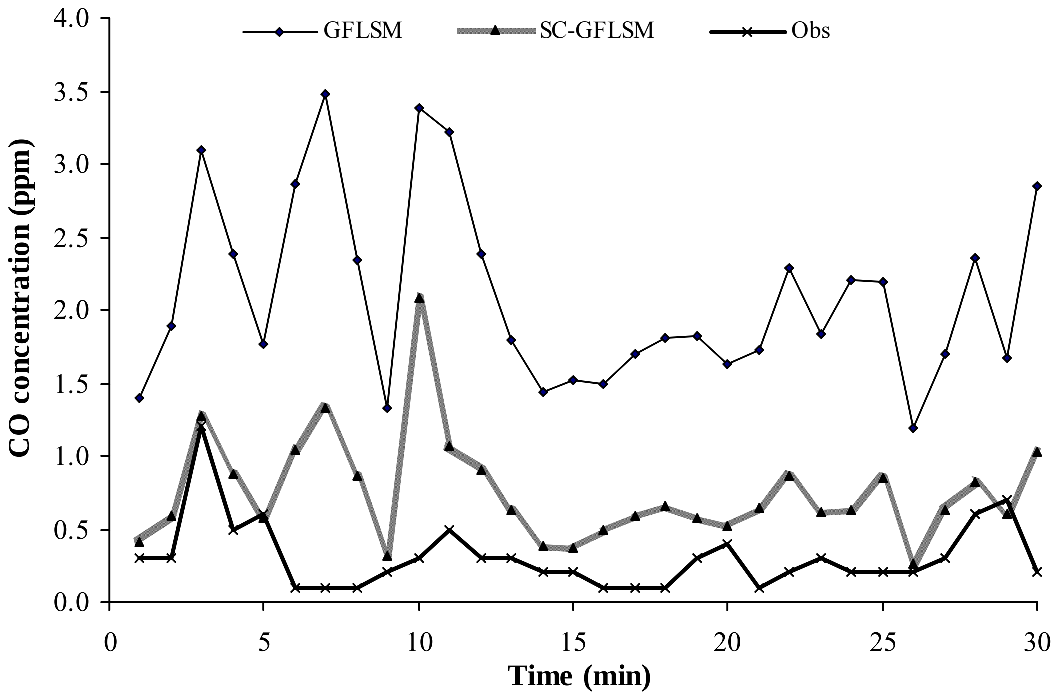

Figure 7.4: The comparison of modeled CO concentration with the measured for the ALL using E3 (k)

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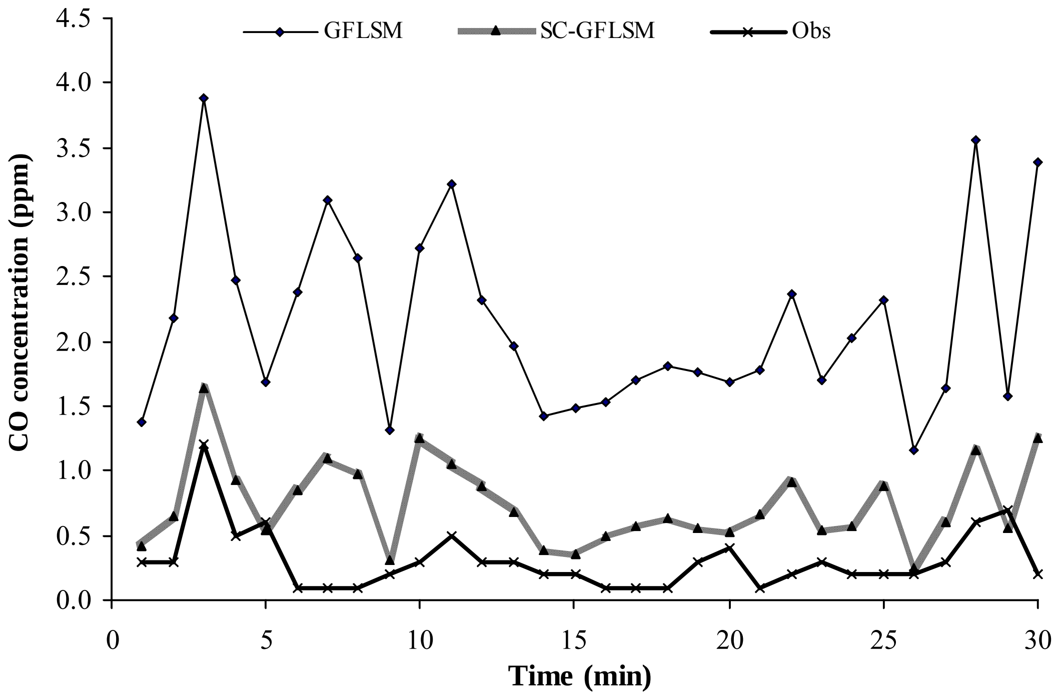

Figure 7.5: The comparison of modeled CO concentration with the measured for the ALL using E2 (k_w)

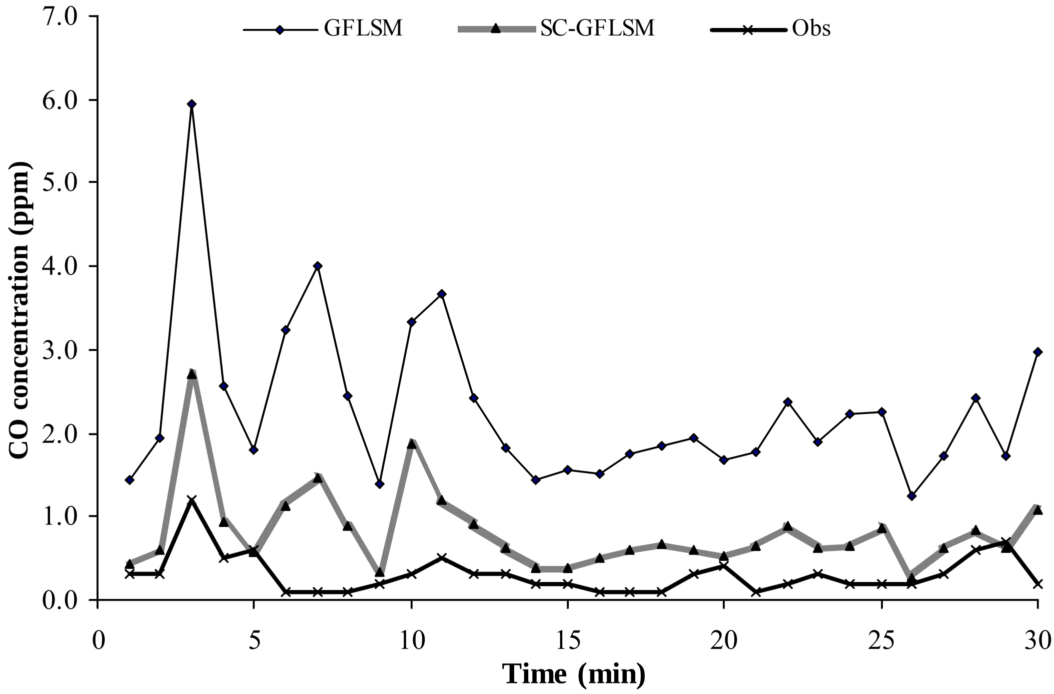

Figure 7.6: The comparison of modeled CO concentration with the measured for the ALL using E3 (k_w)

(a)

(b)

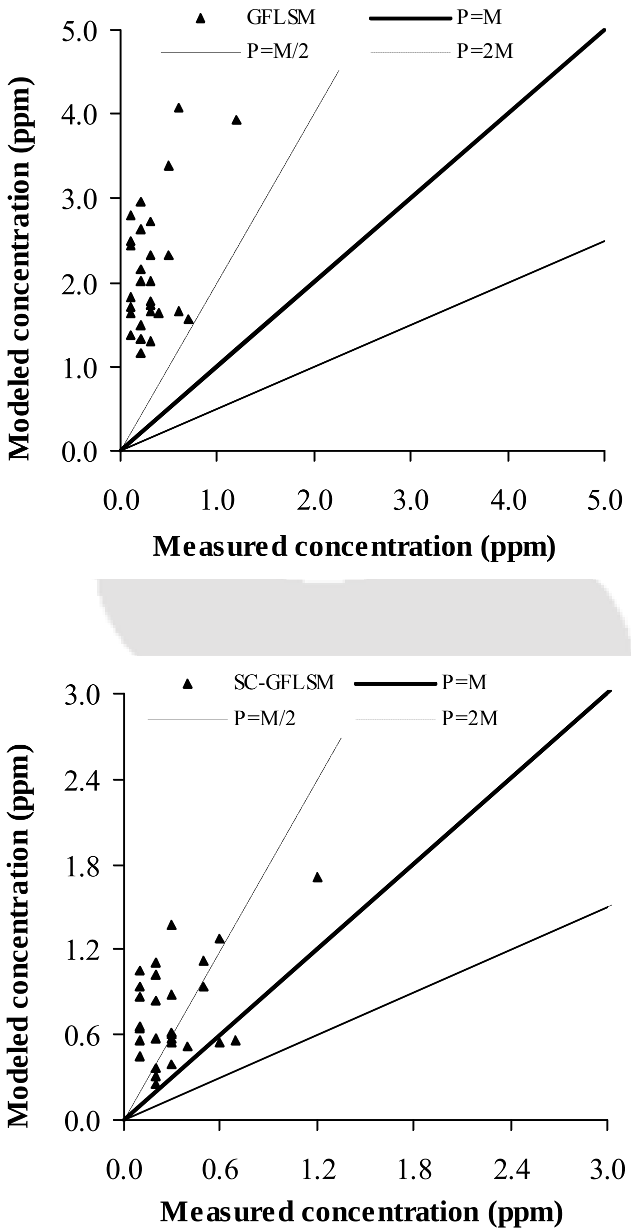

Figure 7.7: The scatter plots with an envelope of FAC2 between modeled and measured CO for ALL using E2 (*k*) by (a) GFLSM and (b) SC-GFLSM

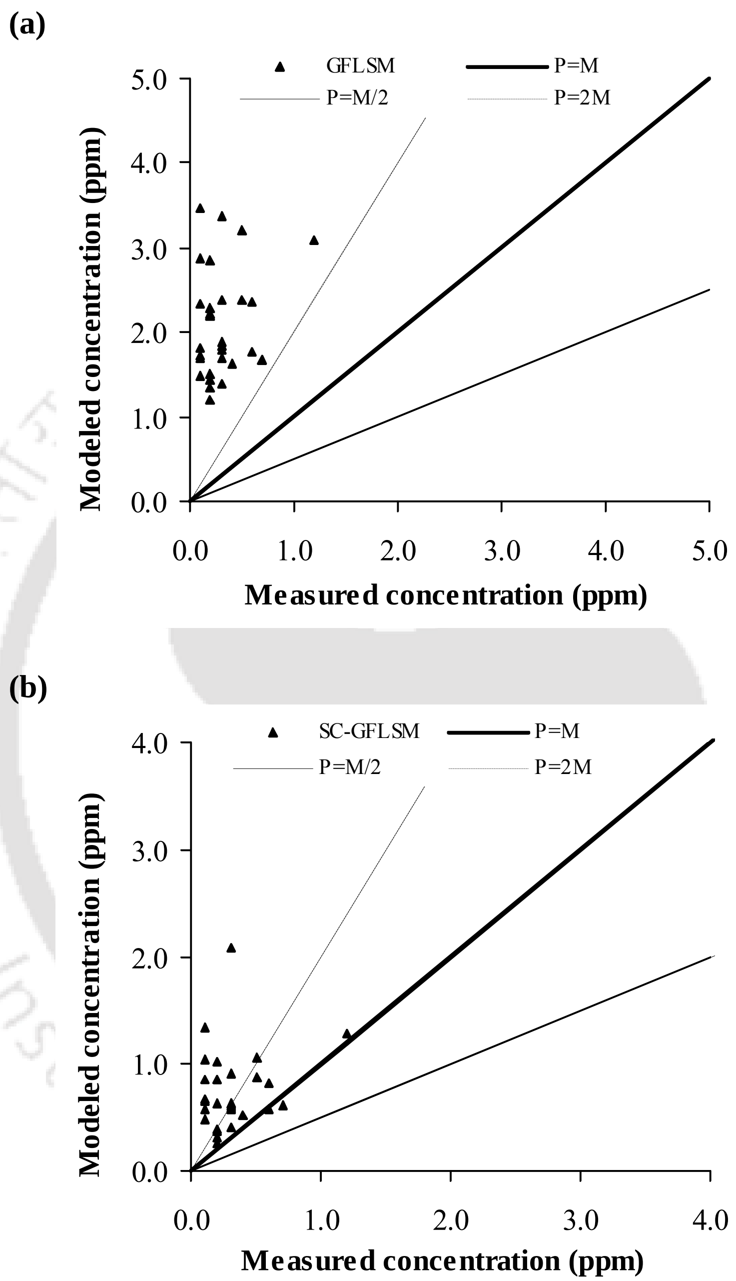

Figure 7.8: The scatter plots with an envelope of FAC2 between modeled and measured CO for ALL using E3 (*k*) by (a) GFLSM and (b) SC-GFLSM

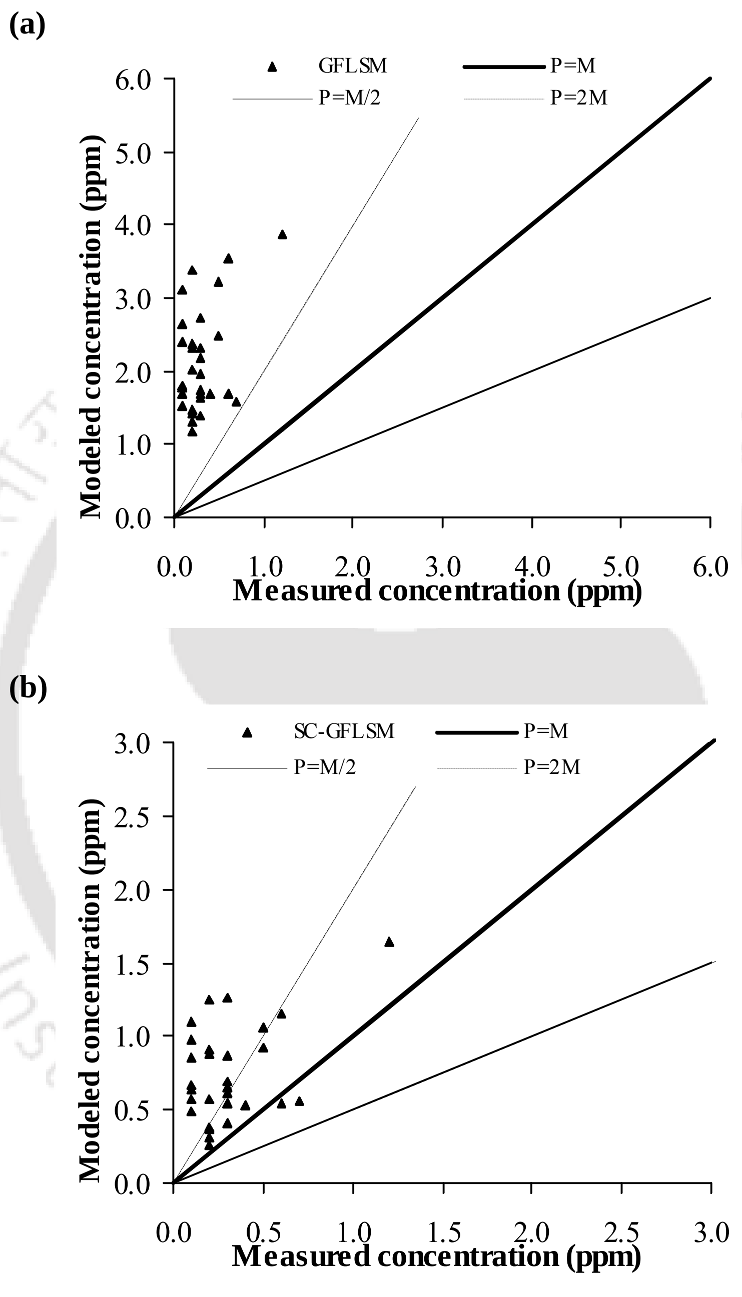

Figure 7.9: The scatter plots with an envelope of FAC2 between modeled and measured CO for ALL using E2 (k_w) by (a) GFLSM and (b) SC-GFLSM

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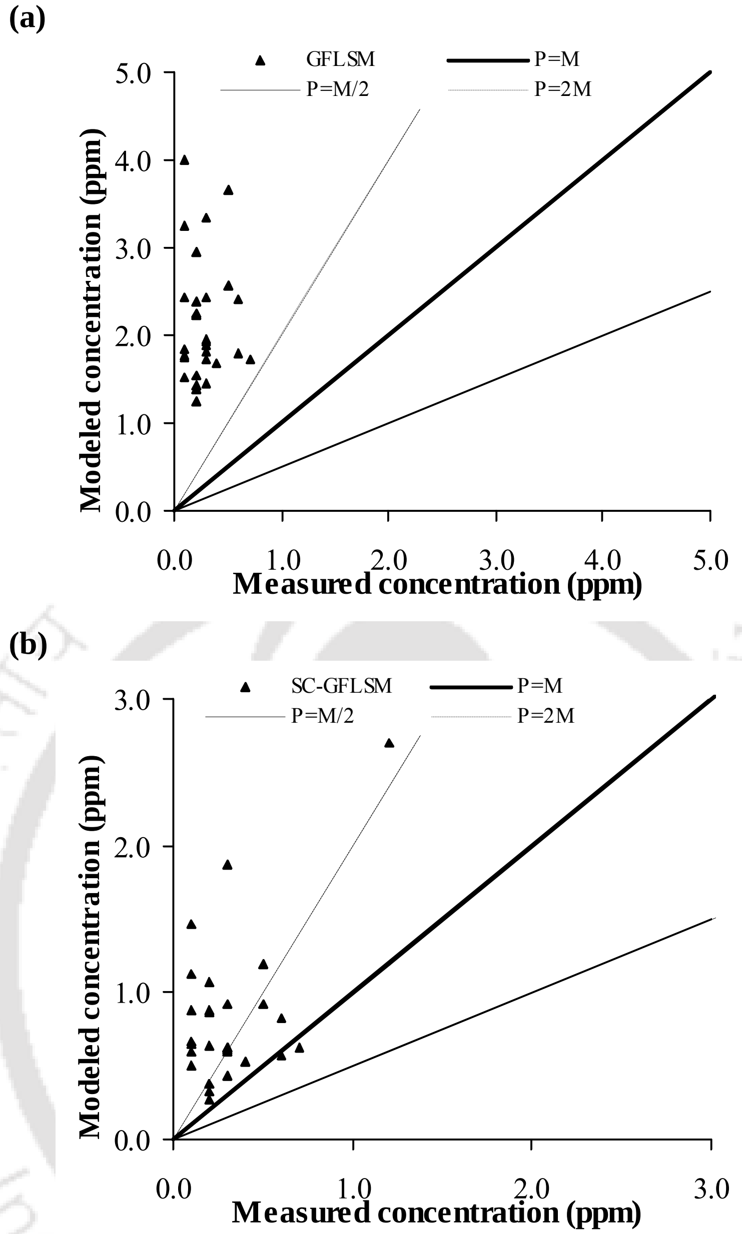

Figure 7.10: The scatter plots with an envelope of FAC2 between modeled and measured CO for ALL using E3 (k_w) by (a) GFLSM and (b) SC-GFLSM

However, it was perceived that due to constant variability in wind flow pattern, mostly in wind direction, and instantaneous changes in turbulence and traffic dynamics all of the line sources may not contribute fully to the concentration at the receptor. The nature of moving vehicles in various directions with different speeds makes it further difficult to understand the pattern of pollutant dispersion even at such a shorter time average. That is why, we identified line sources to determine the best possible combinations, which might be contributing at the receptor, by adding concentrations from those line sources together. The concentrations from approach and exit stretches were combined together and named as per their positions (N, E, S and W) where N indicates the concentration from entering and leaving vehicles from the North approach (for example, N – entry and exit together from north) and so on. Similarly, the concentrations from four circulating stretches were combined together named as Curve (for example, adding C_{NE}, C_{NW}, C_{ES}, C_{SW} together) and the contribution from all the twelve line sources were named as ALL. Similarly N, W means adding N and W together while N, W, Curve means adding N, W and Curve together and so on. These nomenclatures have been shown in Figure 7.1.

The results showed that the concentration from the combination of S and W (i.e. S, W) matched well and even better than from ALL as shown in Table 7.3. It is clear that the line sources S, W alone contributed to CO concentration at the receptor. This indicates that the complicated dispersion pattern at the roundabout overpowers the forces of prevailing winds preventing the movement of pollutants in the downwind. This further verifies the assumption of canyon effects at the roundabout. The comparisons of one - minute average CO concentrations estimated by models with the measured concentrations are shown in Figures 7.12 – 7.15 for emissions E2 and E3, respectively. Scatter plots showing the more correlation of modeled CO concentrations for S-W are presented in Figures 7.16 – 7.19. It was observed that both models more or less captured the pattern but the one that was simulated by SC-GFLSM model was much closer to the measured concentration pattern. For the case of emission using measured densities, which is E2, the estimated concentrations matched well with the measured and thus reproduced the trend relatively better than other cases of emissions. There has also been a drastic reduction in the fractional bias as evident from the values for S, W (see Table 7.3). This emphasizes the importance of field observed pertinent traffic characteristics at a shorter time scale.

Table 7.3: Correlation statistics for S-W

Evaluation statistics	***k*** GFLSM	***k*** SC-GFLSM	***kw*** GFLSM	***kw*** SC-GFLSM
S-W (E2)				
Mean	0.86	0.24	0.86	0.24
Std Dev	0.34	0.09	0.30	0.09
CV	0.39	0.39	0.35	0.35
d	0.44	0.59	0.41	0.52
R	0.47	0.50	0.45	0.48
RMSE	0.63	0.20	0.62	0.22
FB	0.95	-0.23	0.95	-0.24
S-W (E3)				
Mean	0.86	0.24	0.88	0.25
Std Dev	0.31	0.09	0.28	0.08
CV	0.36	0.37	0.32	0.33
d	0.47	0.61	0.44	0.57
R	0.16	0.22	0.52	0.54
RMSE	0.60	0.20	0.62	0.21
FB	0.94	-0.23	0.97	-0.21

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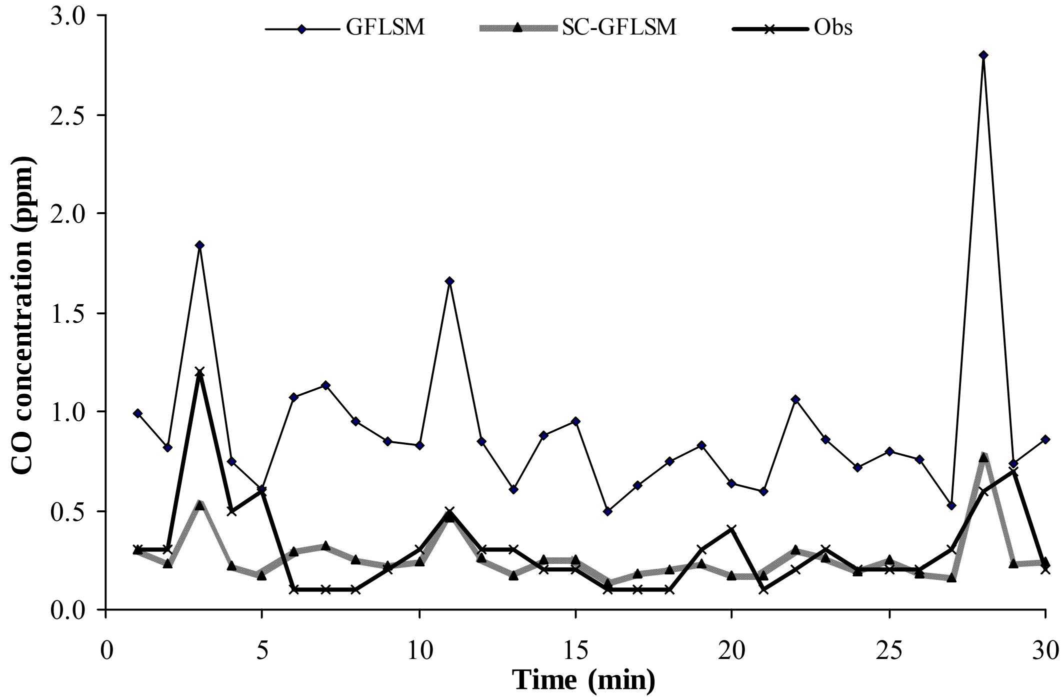


Figure 7.11: The comparison of modeled CO concentration with the measured for the S-W using E2 (k)

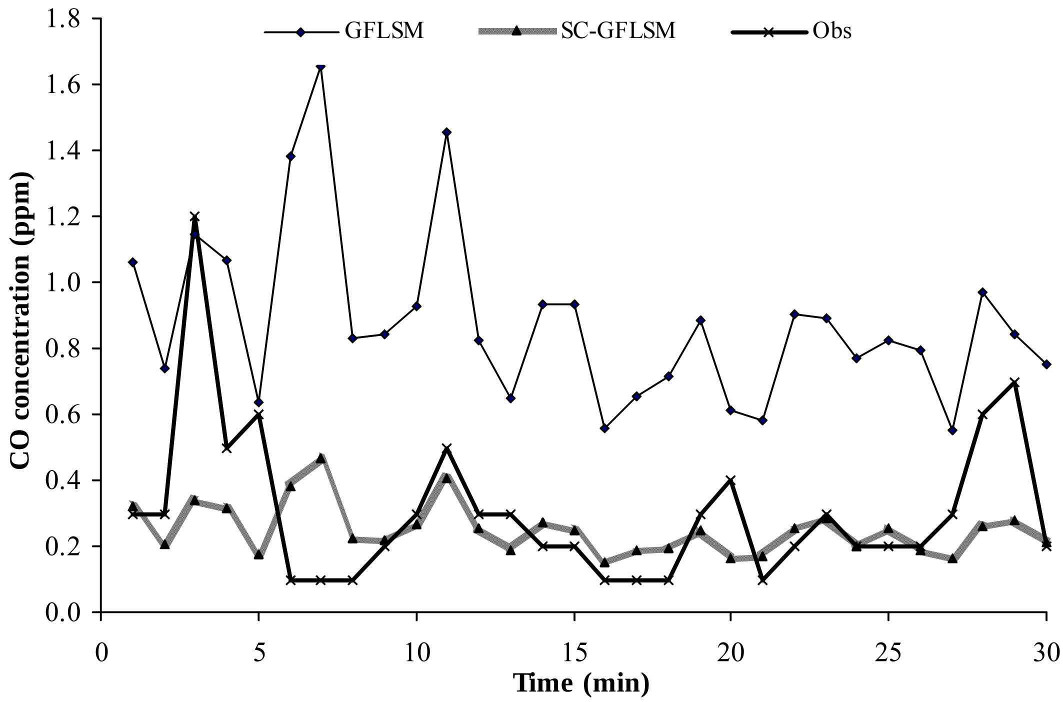


Figure 7.12: The comparison of modeled CO concentration with the measured for the S-W using E3 (k)

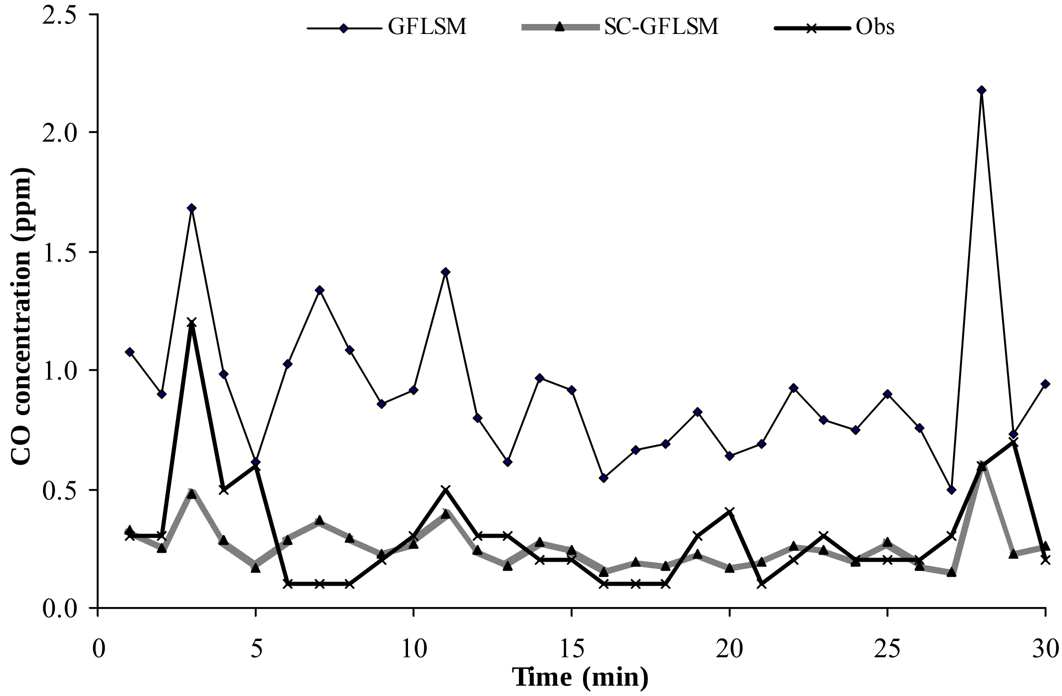


Figure 7.13: The comparison of modeled CO concentration with the measured for the S-W using E2 (k_w)

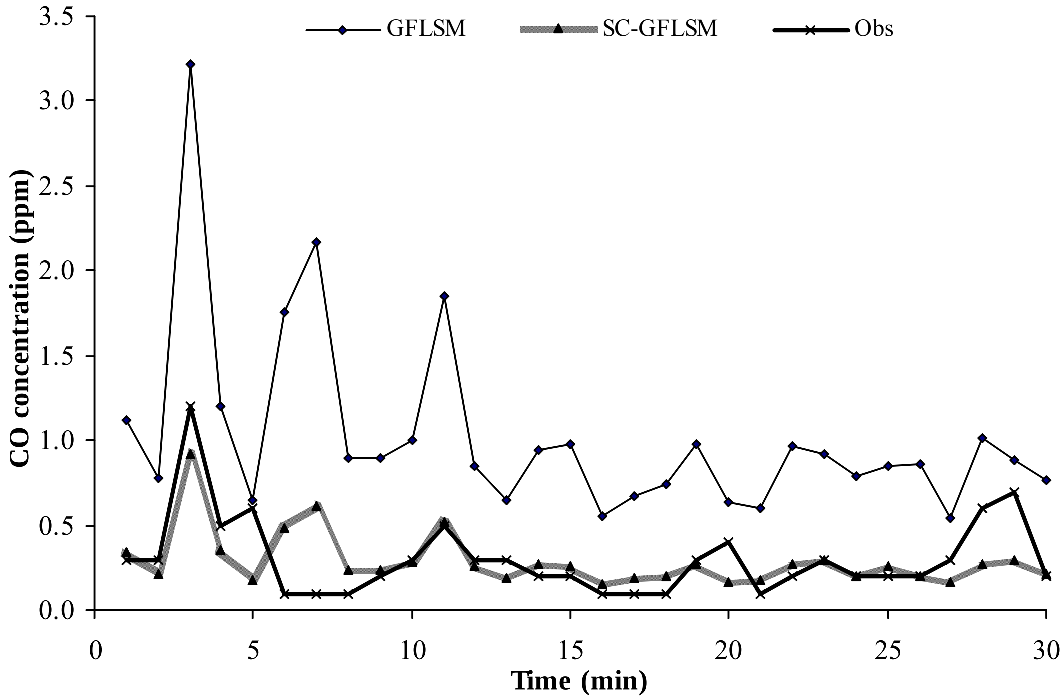
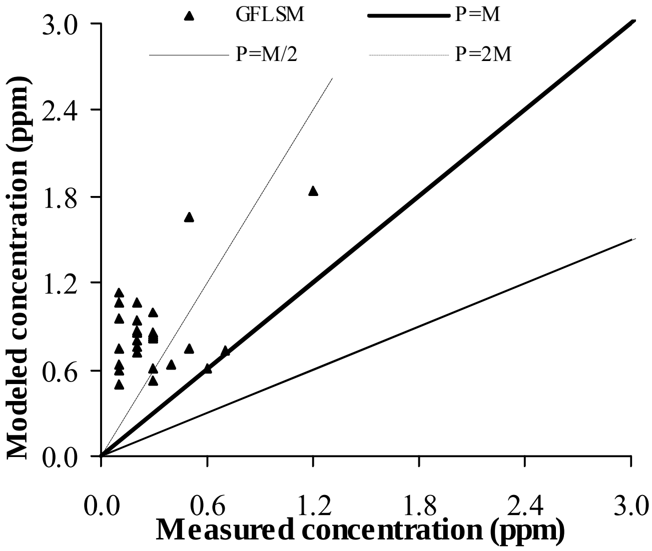


Figure 7.14: The comparison of modeled CO concentration with the measured for the S-W using E3 (k_w)

(a)



(b)

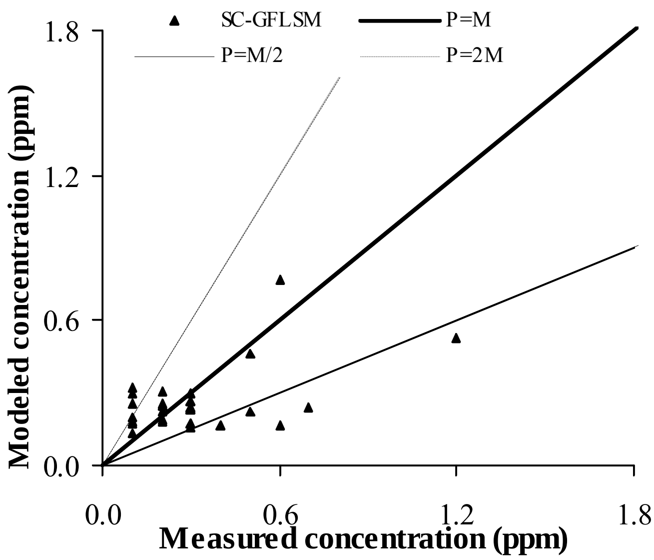
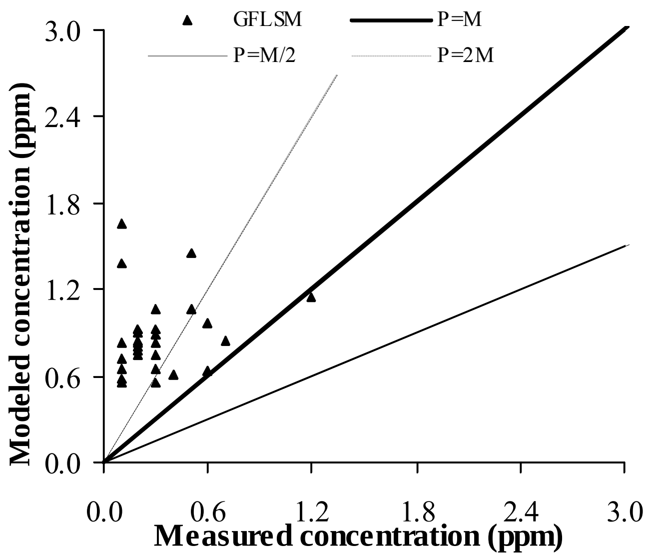


Figure 7.15: The scatter plots with an envelope of FAC2 between modeled and measured CO for S-W using E2 (*k*) by (a) GFLSM and (b) SC-GFLSM

(a)



(b)

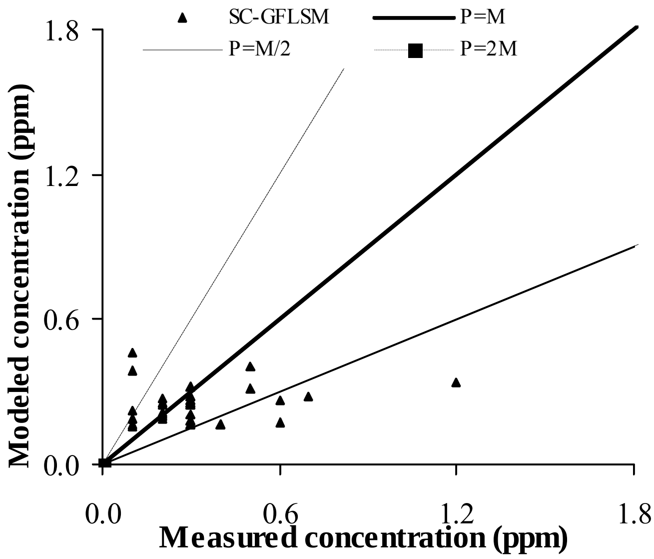


Figure 7.16: The scatter plots with an envelope of FAC2 between modeled and measured CO for S-W using E3 (*k*) by (a) GFLSM and (b) SC-GFLSM

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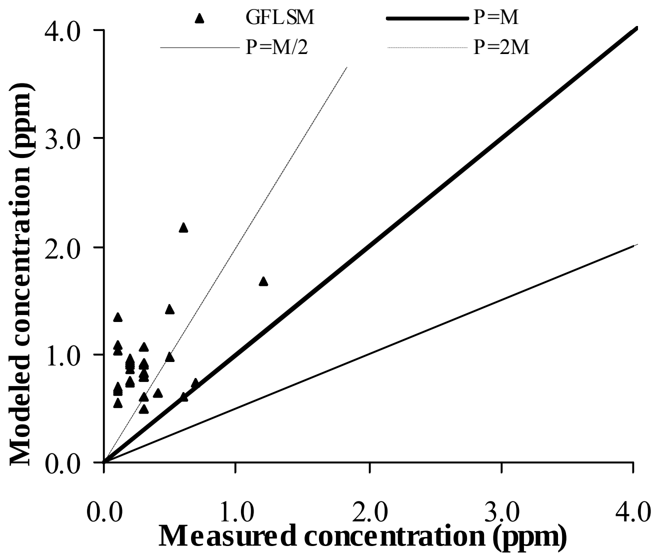
(a)



(b)

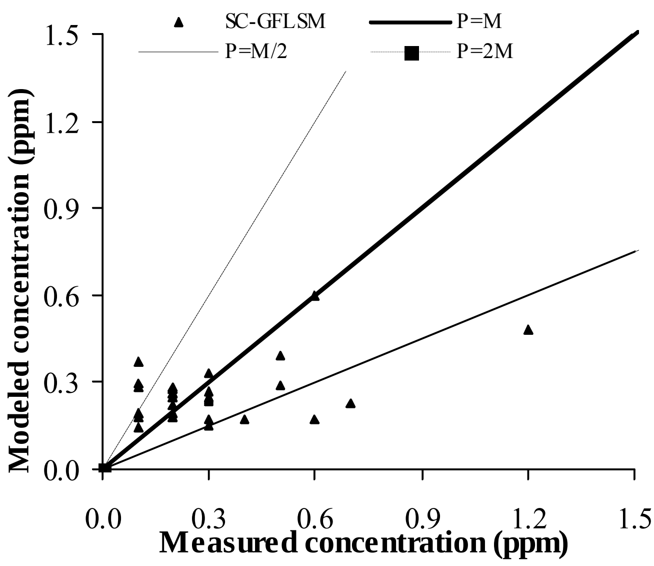


Figure 7.17: The scatter plots with an envelope of FAC2 between modeled and measured CO for S-W using E2 (k_w) by (a) GFLSM and (b) SC-GFLSM

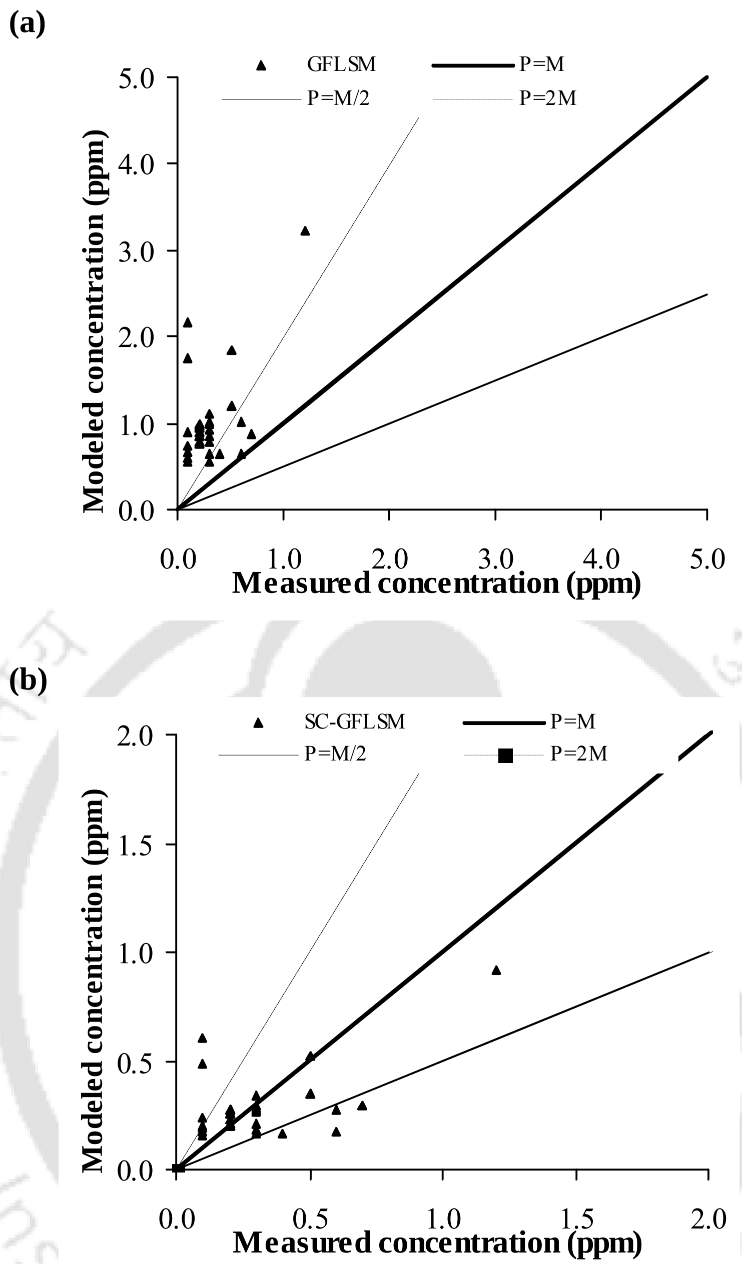


Figure 7.18: The scatter plots with an envelope of FAC2 between modeled and measured CO for S-W using E3 (k_w) by (a) GFLSM and (b) SC-GFLSM

Both models over-estimated the concentration as observed from the diurnal variations for a period of 30 min. However, the relative degree of over-prediction by SC-GFLSM was much less compared with GFLSM model. It has been observed that the SC-GFLSM model has FB values closer to zero indicating good correlation between estimated and measured one-minute average CO values. In comparison with GFLSM model, the difference in FB values was large. It is noticeable here that application of GFLSM alone resulted in high over-prediction, for example, for S, W in the range of 0.97 to 1.08 while it was only -0.15 to -0.06 after combined with the street-canyon effects. It has been further

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observed that *d* values for SC-GFLSM model were relatively higher, that is, improved up to 0.73.

Statistics of the SC-GFLSM model indicate that the E2, method of emissions matched well compared to E3. A marginal difference was observed between E2 and E3 which might have been because of the fact that they are more or less similar cases with a difference of traffic characteristics measured in E2 and estimated in E3. This confirms the accuracy of time-width density model developed for Indian heterogeneous traffic condition. This also indicates that for more accurate predictions it may be necessary to obtain vehicle and traffic characteristics by field measurements and or semi-empirical methods incorporating fundamental field variables. This is because the traffic dynamics particularly traffic flow, speed, heterogeneity, vehicle composition and driving modes vary place to place. *RMSE* values were close to optimum value from 0.19 to 0.23 for SC-GFLSM models.

The variation in wind direction tends to increase with decreasing wind speed, causing increased plume meandering. Substantial meandering can cause measured concentrations at a certain point to be much lower than those computed assuming a homogeneous wind flow (Benson, 1992) as in the case of GFLSM model. It is also difficult to evaluate atmospheric conditions, the extent of vertical mixing and atmospheric dispersion processes at very low or calm winds. The effects of these limitations seem to have been reduced after combining street canyon and line source models and with traffic and atmospheric dynamics at shorter-time scale. This is of course within the road sections where continuous moving vehicles of about average 4 m height form a street-canyon and pollutants undergo faster mixing in vertical direction than advection in the direction of wind. The higher negative values of Richardson number support this assumption.

7.4 VALIDATION OF SC-GFLSM MODEL

Another set of data for a period of 30 min was used for validating the model at the same site. The GFLSM and SC-GFLSM models were applied to estimate 1-min average CO concentration contributed from each line source to the receptor point using E3 (semi-empirical approach). The estimated CO concentrations were evaluated against the measured CO concentration. Figures 7.19 - 7.22 show the time variation of concentrations by both models against the measured concentrations. The statistics for ALL and S-E are given in Table 7.4 - 7.5. The results showed that the SC-GFLSM modeled the average CO concentrations of 1.17 (ppm) for ALL against the measured of 0.56 ppm as compared to from 2.81 (ppm) to 2.94 (ppm) by GFLSM. The mean of CO concentration modeled was found to be in close agreement with the measured concentration for S-E with the over prediction drastically reduced i.e. from 0.13 to 0.85. The densities estimated using time-width occupancy closely resembles the predictions of density obtained from PCU. This analysis clearly shows that additional element representing the worst case of driving behavior due to heterogeneous traffic was able to predict the wide variations in CO predictions even for variations in minute-wise traffic, road and meteorology (Figures 7.22 – 7.25). It means that the SC-GFLSM model along with time-width occupancy emissions estimated the concentrations better in comparison with density based emissions.

Table 7.4: Correlations statistics for ALL

Evaluation	***k***		***kw***	
statistics	GFLSM	SC-GFLSM	GFLSM	SC-GFLSM
ALL (E3)				
Mean	2.81	1.17	2.94	1.20
Std Dev	0.73	0.42	0.74	0.40
CV	0.26	0.36	0.25	0.33
d	0.27	0.55	0.24	0.52
R	0.41	0.48	0.40	0.42
RMSE	2.43	0.85	2.58	0.88
FB	1.41	0.83	1.44	0.85

Table 7.5: Correlations statistics for S-E

Evaluation	***k***		***kw***	
statistics	GFLSM	SC-GFLSM	GFLSM	SC-GFLSM
S-E (E3)				
Mean	1.24	0.55	1.39	0.59
Std Dev	0.47	0.29	0.55	0.29
CV	0.37	0.52	0.40	0.48
d	0.54	0.66	0.41	0.58
R	0.50	0.55	0.40	0.41
RMSE	0.91	0.46	1.12	0.51
FB	0.88	0.13	0.97	0.20

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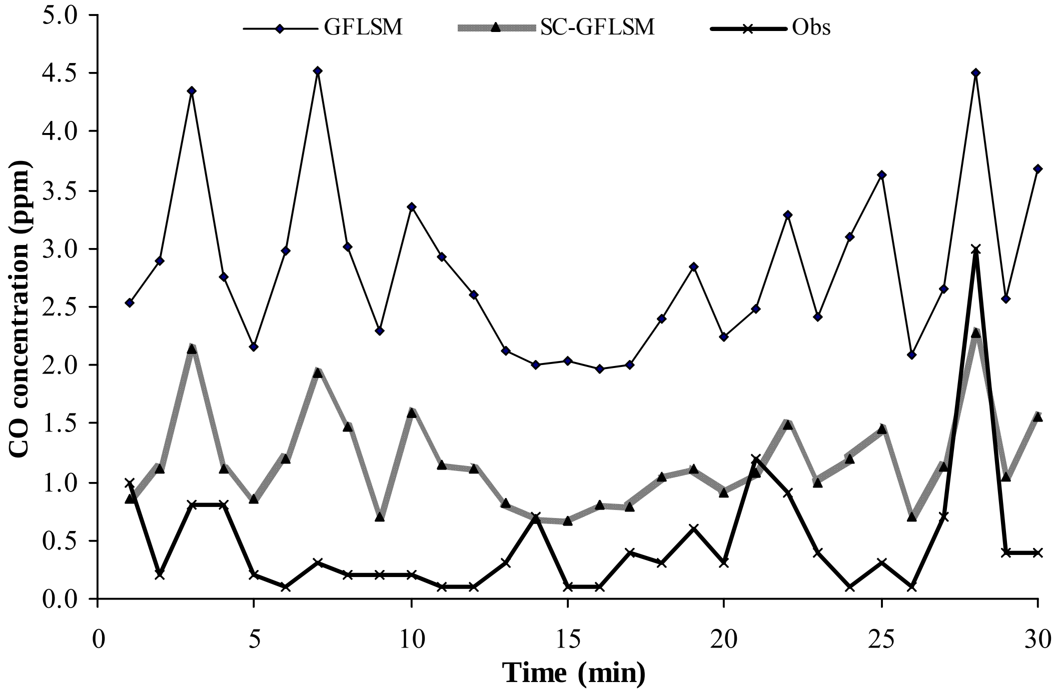

Figure 7.19: The comparison of modeled CO concentration with the measured for the ALL using E3 (k)

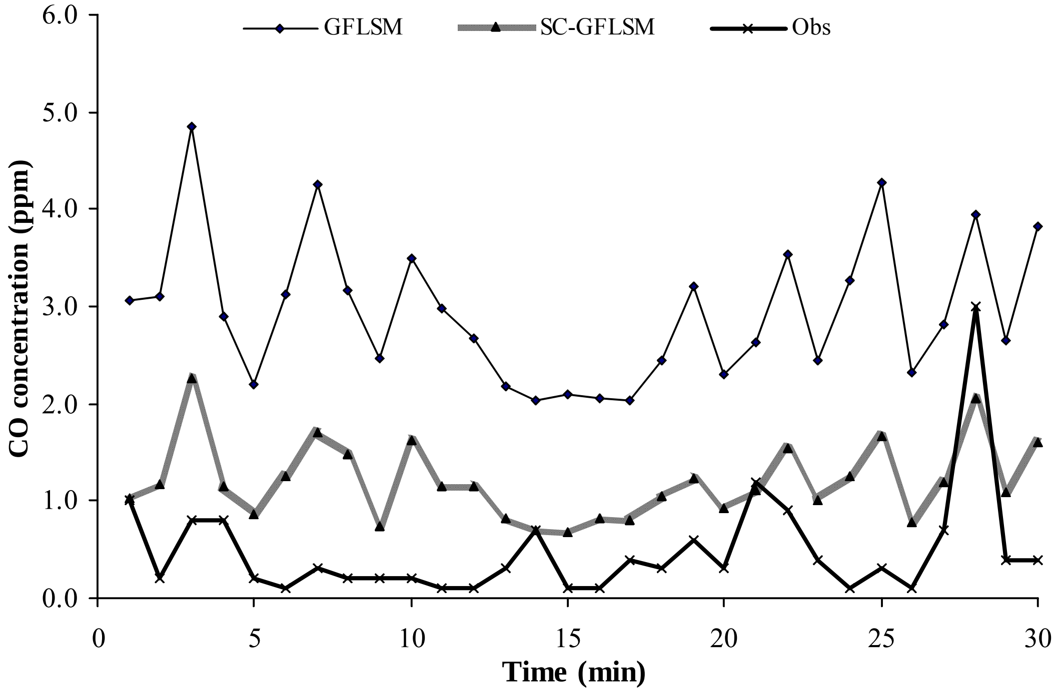

Figure 7.20: The comparison of modeled CO concentration with the measured for the ALL using E3 (k_w)

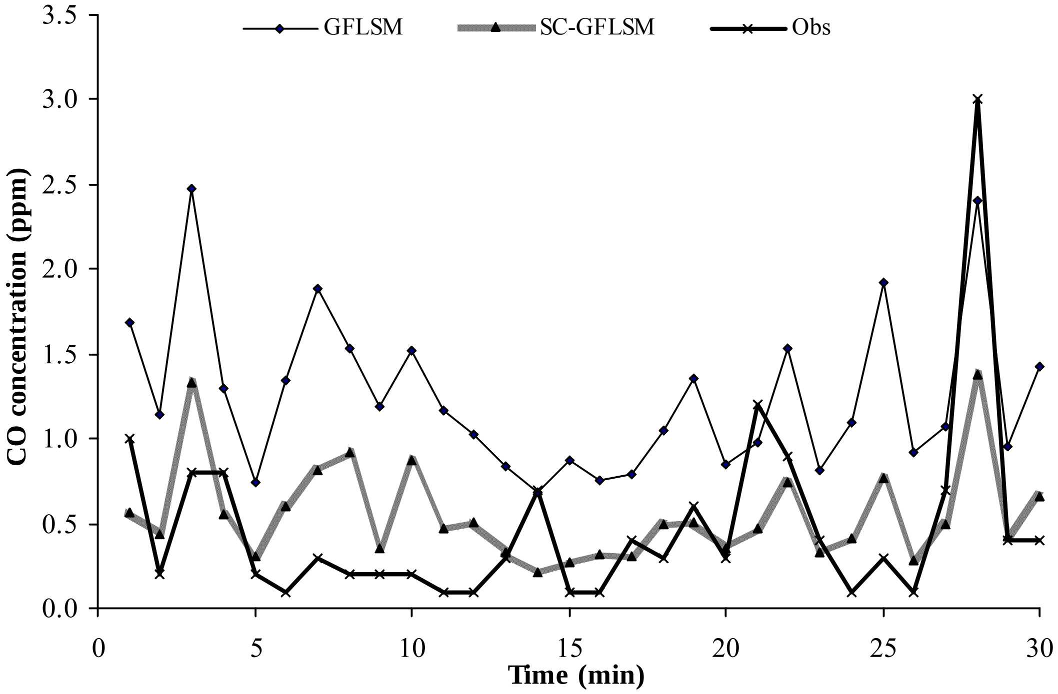

Figure 7.21: The comparison of modeled CO concentration with the measured for the S-E using E3 (k)

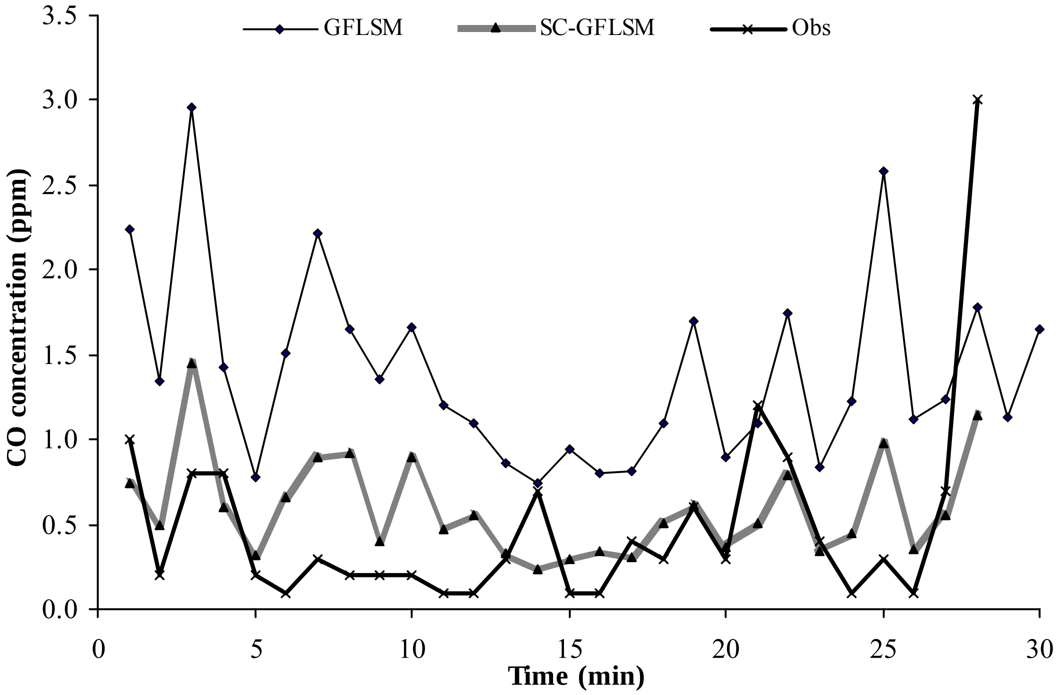

Figure 7.22: The comparison of modeled CO concentration with the measured for the S-E using E3 (k_w)

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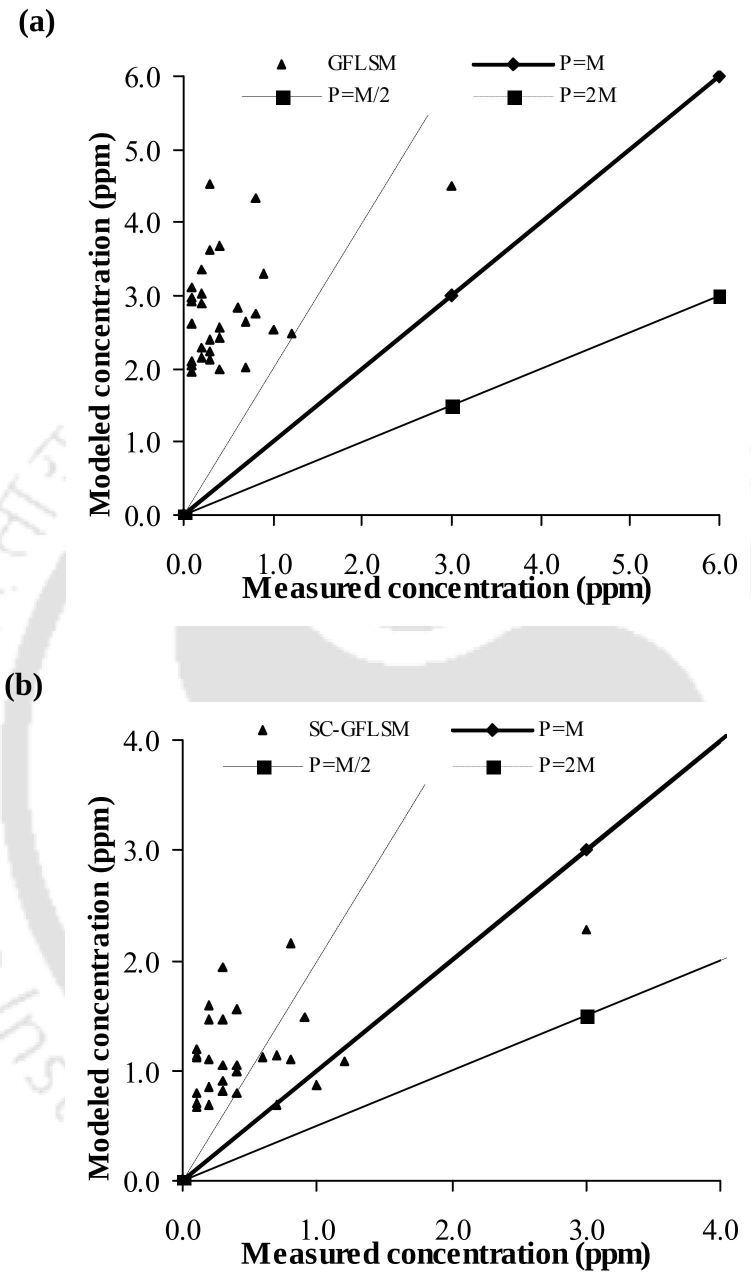
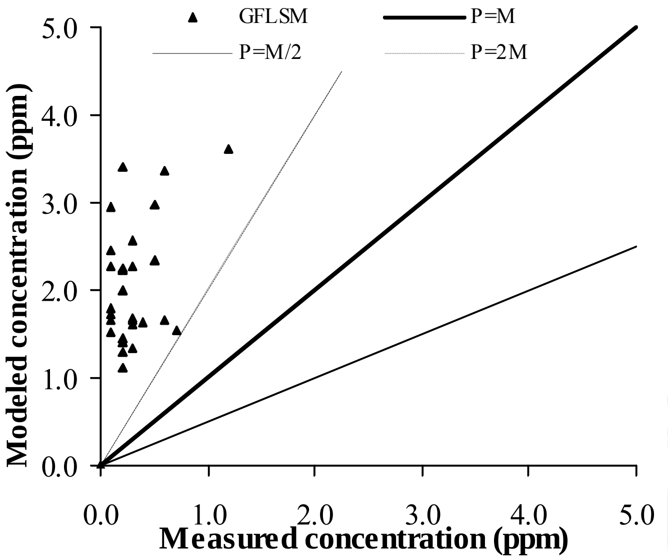


Figure 7.23: The scatter plots with an envelope of FAC2 between modeled and measured CO for ALL using E3 (*k*) by (a) GFLSM and (b) SC-GFLSM

(a)



(b)

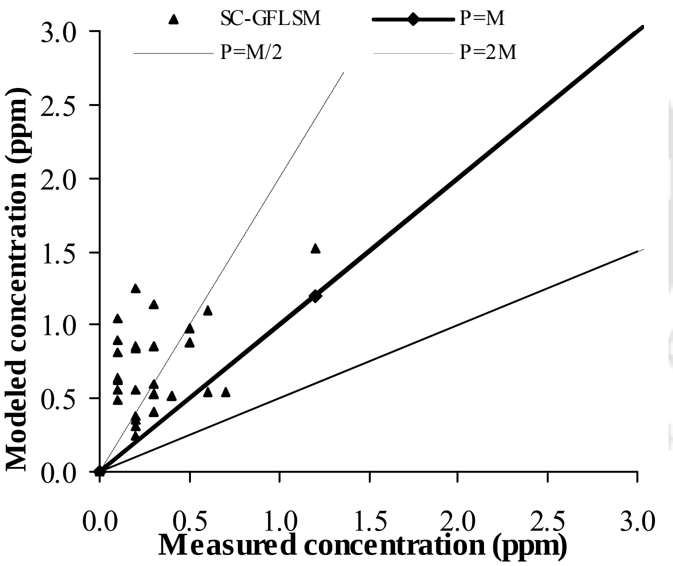


Figure 7.24: The scatter plots with an envelope of FAC2 between modeled and measured CO for ALL using E3 (k_w) (a) GFLSM and (b) SC-GFLSM

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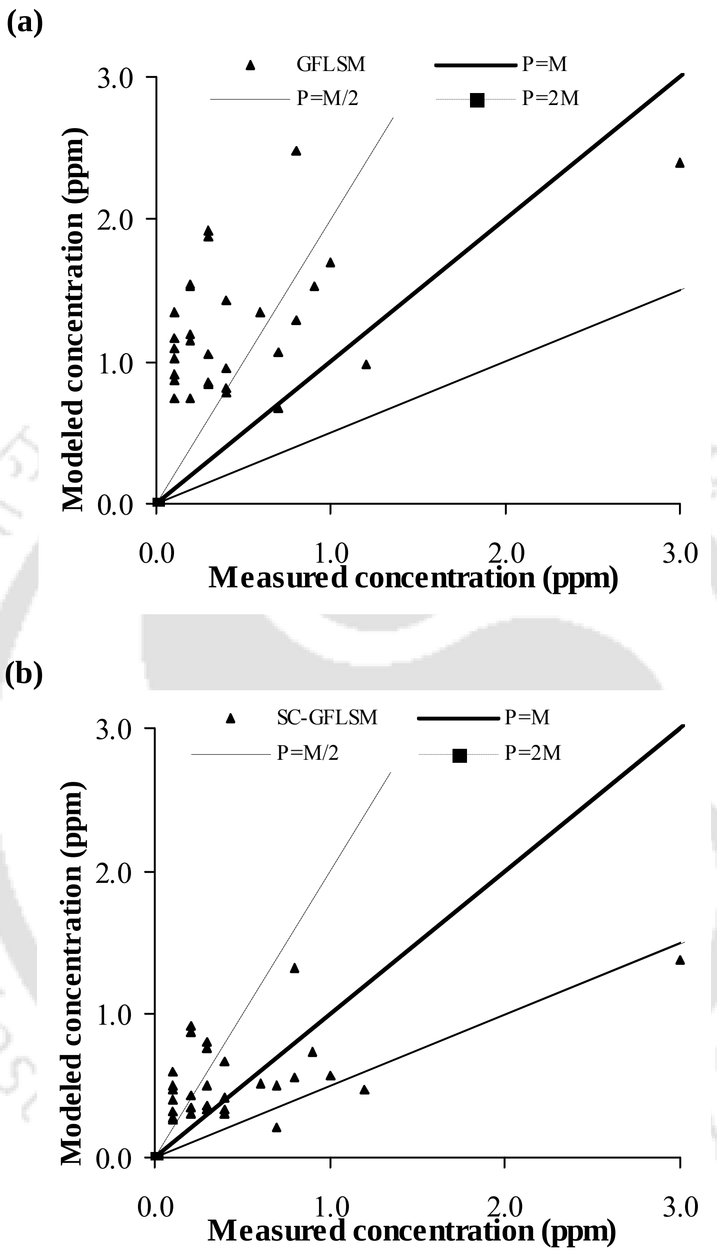

Figure 7.25: The scatter plots with an envelope of FAC2 between modeled and measured CO for S-E using E3 (*k*) (a) GFLSM (b) SC-GFLSM

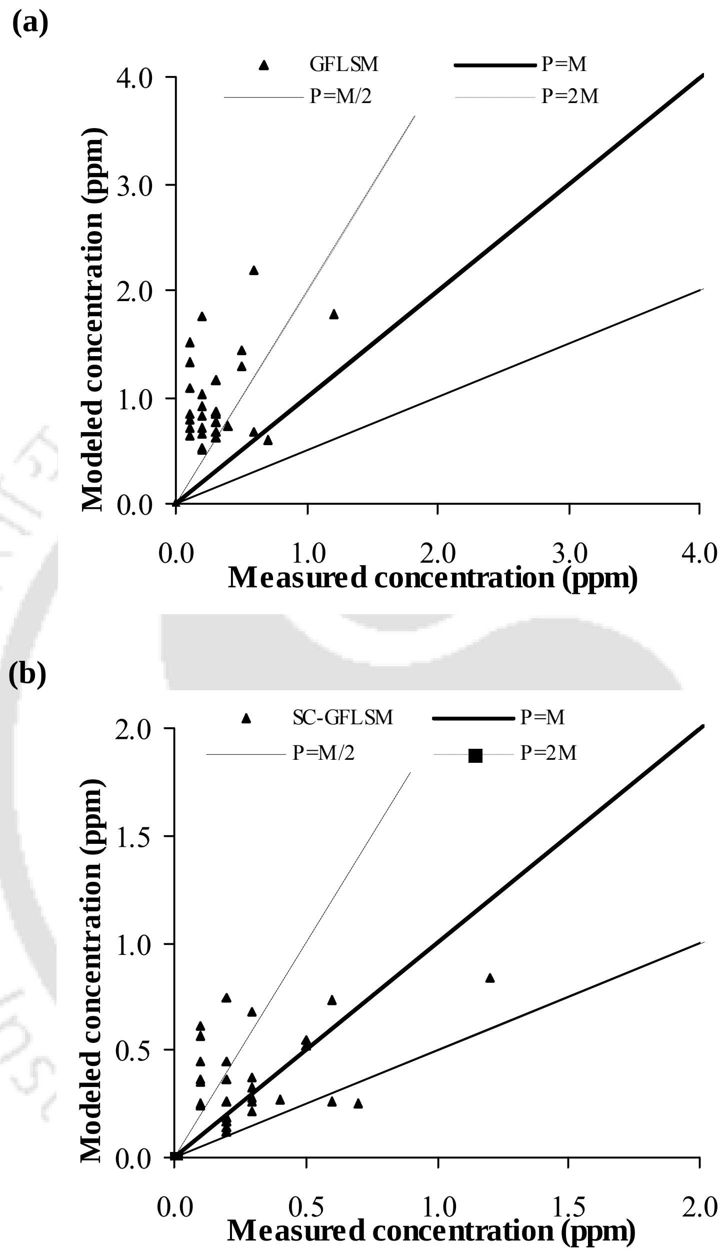

Figure 7.26: The scatter plots with an envelope of FAC2 between modeled and measure CO for S-E using E3 (k_w) by (a) GFLSM and (b) SC-GFLSM

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CHAPTER 8

CONCLUSION AND FUTURE SCOPE

8.1 GENERAL CONCLUSION

The model SC-GFLSM predicts the temporal variations of CO concentrations at the micro environment of traffic roundabout, where widely used open-terrain line source models may fail to do so adequately. The SC-GFLSM model captures the complex dispersion phenomena as an effect of traffic flow characteristics observed at non-signalized traffic roundabout.

8.2 TECHNICAL CONCLUSION

8.2.1 Traffic and air quality

The traffic flow pattern was dynamic at the traffic roundabout. The fleet speed and traffic composition were different on each arm of the roundabout. The traffic fleets were mostly comprised of petrol and diesel driven vehicles with a large share of personalized vehicles such as cars and two-wheelers. The CO concentrations were in commensurate with the traffic volume.

8.2.2 Traffic characteristics

The traffic densities were obtained from the video tapes and also calculated using standard traffic flow theory and a PCU approach. The results showed that the calculated densities were much less than the observed densities. Recognizing the need of better method to represent the traffic flow pattern at junctions, a conventional occupancy approach was used which gave promising results than PCU and standard traffic flow theory approaches. However, it was noticed that at Indian traffic junctions, densities are invariably affected by drivers tendency of occupying the free space available on roads during maneuvering due to no-strict lane discipline observed. In light of this, the conventional occupancy method was modified to time-width occupancy. The results of this method were in close agreement with the observed densities.

8.2.3 Traffic emissions

Three methodologies were used for estimating traffic emissions by combining different observed densities and estimated densities by different approaches using semi-empirical relationships with COPERT-IV methodology. The semi-empirical model has been

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developed at the selected traffic roundabout. With the help of this model, the relationship between the traffic flow and the densities by different approaches were developed. This analysis helped to represent the emissions scenarios correctly at the traffic roundabout for heterogeneous traffic condition.

8.2.4 Air quality model

The air quality model, SC-GFLSM developed in this research adequately simulated the CO concentrations generated at the traffic non-signalized roundabout as a result of traffic flow characteristics and a complex dispersion phenomenon. Further, the results of the SC-GFLSM were compared with the GFLSM model. The degree of overprediction by GFLSM was reduced to a great degree with respect to means and the overall prediction errors were reduced by about 50 %. The SC-GFLSM model was validated for another set of data. The results of the validation were further promising. Therefore, it is utmost necessary that the emissions be calculated on the basis of actual traffic flow characteristics observed at the traffic junctions. This modeling study envisions that the combinations of such two models may satisfactorily evaluate air quality even from multilane roadways where similar dispersion phenomenon occurs.

8.3 FUTURE SCOPE

- Further verification of the methodology and the model with measurements at multiple locations under different meteorological conditions may be carried out.
- A detailed characterization of atmospheric stability and the turbulence driven by temperature, vehicular movement and wind flow may be explored to estimate accurate dispersion parameters.
- Direct measurement of tail pipe emissions and the development of speed dependent emission rates at traffic junctions may demonstrate the emission scenario precisely. This may further improve the prediction performance of the SC-GFLSM.
- Similar study on higher averaging period say upto 1-hour or 8-hour by analyzing traffic and its level of service at different times of a day for varying traffic composition at traffic junctions may provide further insight.
- Recently, some changes have been observed at the roundabout such as introduction of signal system and some minor structural changes. The methodologies developed

in this research for analyzing traffic characteristics, emission and dispersion would fundamentally remain same under most conditions. It would, however, be interesting to study the response of these models to the changes.

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APPENDIX

APPENDIX A

Table A-1: Mean and standard deviation of traffic composition for entry, curve and exit stretches (validation)

Approach name	Traffic composition in %							
	M2W		M3W		LCV		HDV	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
N entry	20.27	19.63	7.66	10.27	57.88	17.39	14.19	9.51
E entry	18.61	14.27	16.67	17.15	46.39	16.10	18.33	11.66
S entry	27.79	7.58	12.16	5.62	48.34	12.82	11.72	9.17
W entry	22.63	14.81	7.26	9.66	52.79	15.95	17.32	14.18
NE	23.11	7.94	9.49	6.77	51.97	8.96	15.44	8.75
ES	21.90	10.75	10.42	7.28	52.22	9.07	15.46	6.91
SW	25.32	6.72	12.66	5.18	46.54	10.98	15.47	7.70
WN	24.14	8.62	10.61	7.08	52.03	9.42	13.22	9.17
N exit	22.46	13.91	10.14	7.52	58.45	14.46	8.94	8.14
E exit	22.24	10.20	13.27	7.69	48.16	14.29	16.33	12.41
S exit	23.32	12.13	9.30	6.51	54.79	9.98	12.59	8.07
W exit	26.00	15.83	12.80	12.59	34.40	20.91	26.80	14.34

Table A-2: Statistical measures of pollutant concentration, meteorological and traffic data (application)

Statistical parameter	CO (ppm)	Wind speed (m/sec)	Traffic count (veh)
Minimum	0.1	0.3	190
Mean	0.3	1.0	240
Maximum	1.2	1.5	303
Standard deviation	0.2	0.3	31
Coefficient of variation	0.3	1.0	240
Median	0.1	0.3	190
Percentile (95)	1.2	1.5	303

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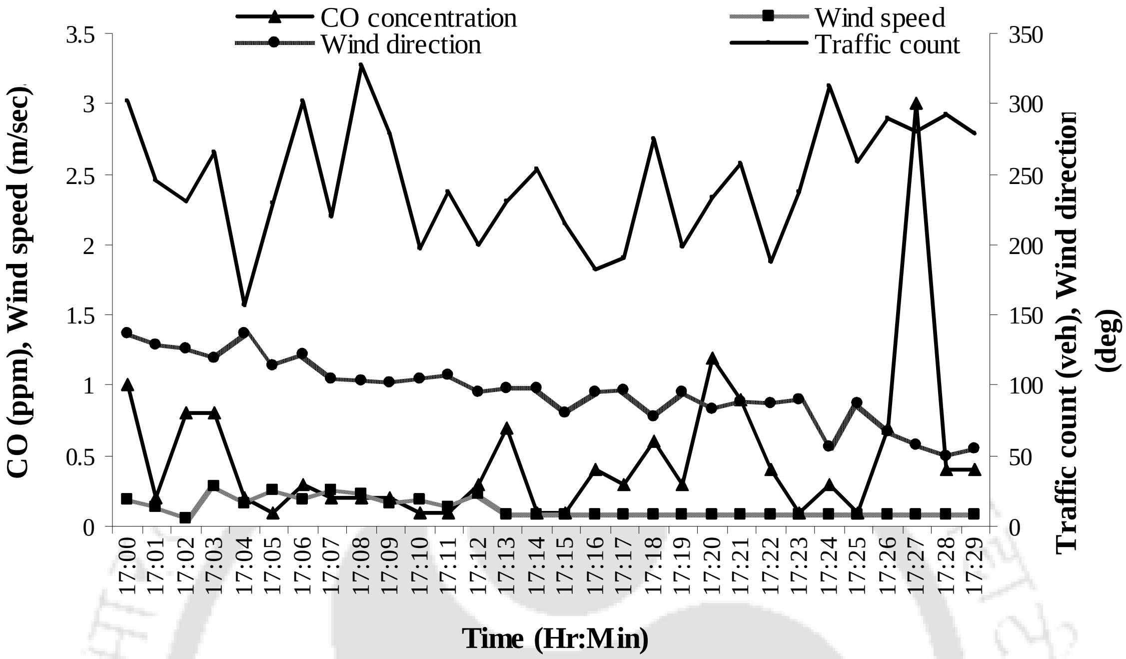

Figure A-1: Time wise traffic, pollutant concentration and meteorological data

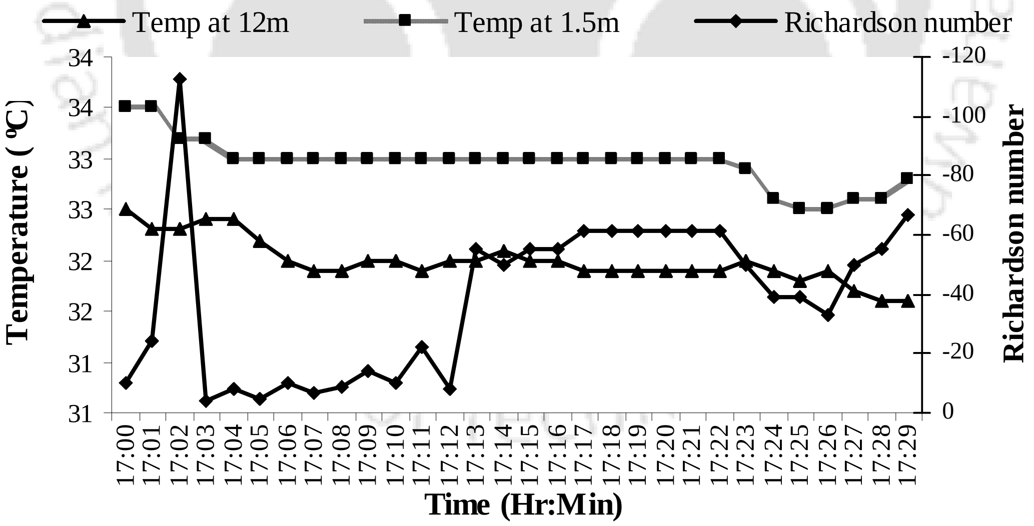

Figure A-2: Time wise temperature data at two different heights and Richardson number

APPENDIX - B

Table B-1: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for N entry

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	0.71	0.54	2.14	1.58	2.86	2.45	0.71	0.46
2	1.43	1.31	0.00	0.00	7.14	6.04	1.43	1.33
3	2.14	1.80	2.86	3.24	5.00	6.50	1.43	1.80
4	5.00	4.64	0.71	0.88	2.86	2.68	0.00	0.00
5	2.14	2.10	0.00	0.00	1.43	1.18	0.00	0.00
6	0.71	0.43	1.43	1.15	5.71	5.74	1.43	1.40
7	1.43	0.93	0.00	0.00	0.71	0.74	0.00	0.00
8	2.86	3.07	1.43	2.35	3.57	4.72	0.71	0.86
9	2.14	1.61	1.43	1.41	1.43	1.06	0.71	0.81
10	1.43	1.12	1.43	1.34	4.29	4.29	0.71	0.64
11	0.71	0.53	4.29	4.71	7.86	7.38	0.71	0.72
12	0.71	0.84	1.43	1.89	5.71	6.70	0.71	0.86
13	3.57	2.83	0.00	0.00	3.57	2.97	1.43	1.40
14	2.86	2.00	2.14	1.97	3.57	2.80	0.00	0.00
15	2.86	2.20	0.71	0.70	5.00	3.89	0.71	0.58
16	0.71	0.58	0.71	0.65	1.43	1.08	0.71	0.57
17	1.43	1.22	0.00	0.00	3.57	3.02	0.71	0.87
18	2.14	1.50	0.71	0.51	0.00	0.00	0.00	0.00
19	2.14	2.01	2.14	2.20	2.14	1.49	2.14	2.03
20	0.00	0.00	0.71	0.73	5.00	4.98	2.14	2.46
21	0.71	0.73	1.43	1.31	5.00	4.08	0.71	0.76
22	1.43	1.81	0.71	0.69	7.14	7.37	1.43	1.35
23	1.43	1.22	0.00	0.00	4.29	3.78	3.57	3.12
24	2.14	1.56	1.43	1.01	7.86	6.28	0.00	0.00
25	2.86	2.28	2.14	2.30	2.86	3.61	2.14	2.38
26	0.71	0.68	0.71	0.52	2.86	2.63	0.00	0.00
27	1.43	3.57	2.86	4.25	10.00	8.96	0.71	0.56
28	5.71	6.02	0.71	0.58	4.29	9.27	1.43	2.94
29	0.00	0.00	0.00	0.00	2.14	1.56	0.71	0.70
30	2.14	1.74	0.71	0.51	2.86	2.78	0.71	0.69
Mean	1.86	1.70	1.17	1.22	4.07	4.00	0.93	0.98

Table B-2: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for E entry

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	3.57	1.76	1.43	0.73	5.00	2.49	1.43	0.82
2	2.14	1.58	0.00	0.00	1.43	2.81	1.43	0.57
3	3.57	4.62	2.86	2.12	6.43	3.97	3.57	3.40
4	1.43	0.88	0.71	0.42	7.14	6.31	2.14	1.63
5	1.43	0.64	0.00	0.00	2.86	1.31	1.43	0.66
6	0.00	0.00	2.14	0.92	5.71	2.69	3.57	1.64
7	3.57	3.56	2.86	1.20	3.57	1.57	2.14	1.16
8	2.14	1.37	0.00	0.00	7.86	7.12	2.86	1.63
9	0.71	0.31	0.71	0.25	2.86	1.59	1.43	0.65
10	5.00	2.51	1.43	0.74	7.14	4.81	6.43	4.92
11	0.71	0.26	0.71	1.11	4.29	2.76	2.14	2.62
12	2.86	1.02	2.14	0.77	2.14	0.76	1.43	0.66
13	1.43	0.57	0.71	0.26	2.14	0.82	0.00	0.00
14	1.43	0.54	1.43	0.51	0.00	0.00	0.00	0.00
15	4.29	1.42	1.43	0.83	3.57	1.27	1.43	0.59
16	2.86	1.25	0.00	0.00	1.43	0.43	0.71	0.21
17	0.71	0.21	0.71	0.37	0.71	0.44	0.71	0.31
18	2.14	1.23	0.71	0.31	7.86	3.54	0.71	0.32
19	1.43	0.53	2.86	1.52	0.71	0.32	0.00	0.00
20	0.71	0.36	0.00	0.00	2.86	1.79	2.14	1.29
21	2.14	1.38	0.71	0.41	5.00	2.99	2.86	1.35
22	2.86	1.68	0.00	0.00	6.43	5.47	2.14	1.39
23	2.14	0.93	0.00	0.00	2.86	1.18	0.00	0.00
24	0.71	0.26	0.00	0.00	2.86	1.21	0.00	0.00
25	2.86	1.65	0.00	0.00	2.14	0.87	2.14	1.00
26	1.43	0.62	2.14	0.94	3.57	1.70	2.86	1.37
27	1.43	0.63	1.43	0.65	7.14	2.87	0.00	0.00
28	3.57	1.82	0.00	0.00	5.71	2.61	1.43	0.72
29	2.86	1.24	1.43	0.97	2.14	1.00	0.71	0.54
30	0.71	0.50	2.14	1.78	5.71	5.28	1.43	1.76
Mean	2.10	1.18	1.02	0.56	3.98	2.40	1.64	1.04

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Table B-3: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for S entry

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	5.00	3.84	2.14	1.70	4.29	3.96	5.00	4.52
2	5.00	5.27	2.14	2.89	14.29	17.03	0.71	0.94
3	3.57	3.27	2.86	3.50	5.71	9.43	1.43	1.80
4	3.57	3.10	3.57	3.42	10.00	8.22	0.71	1.08
5	5.00	5.02	4.29	4.20	13.57	12.53	1.43	1.30
6	3.57	3.24	3.57	3.98	12.86	12.07	2.14	1.94
7	2.86	3.09	1.43	2.01	20.00	20.49	2.14	3.04
8	4.29	3.82	5.00	5.26	12.14	11.87	1.43	2.05
9	5.71	5.49	2.14	1.87	17.86	16.05	0.71	0.57
10	5.00	4.30	1.43	1.14	7.86	6.17	2.14	2.23
11	3.57	3.59	2.14	2.00	15.00	19.00	2.14	2.60
12	5.71	4.48	3.57	2.95	10.71	8.84	0.00	0.00
13	3.57	3.50	1.43	1.74	13.57	10.85	0.00	0.00
14	3.57	3.08	0.71	0.60	4.29	4.98	3.57	3.09
15	8.57	11.55	0.71	0.73	9.29	9.81	2.86	2.97
16	2.86	2.17	3.57	3.76	7.86	8.27	3.57	3.62
17	4.29	4.45	3.57	4.02	7.86	8.93	2.14	2.16
18	2.14	2.03	2.14	2.21	9.29	10.85	3.57	4.88
19	2.86	3.19	2.86	3.32	10.71	11.20	2.14	2.24
20	5.71	5.43	1.43	1.78	11.43	11.98	2.86	3.15
21	2.86	2.62	4.29	4.62	12.14	13.41	0.00	0.00
22	2.14	1.50	2.86	2.62	9.29	9.49	2.14	2.63
23	7.14	7.02	2.14	1.88	7.14	6.62	2.14	2.06
24	7.86	7.46	3.57	3.54	18.57	16.47	2.14	2.50
25	3.57	3.05	1.43	1.46	13.57	11.44	0.71	6.07
26	2.86	2.41	2.14	1.93	10.00	12.45	2.14	2.37
27	3.57	3.00	0.71	0.55	2.14	1.54	4.29	4.08
28	5.00	4.40	4.29	3.95	12.14	9.76	2.14	1.99
29	5.00	5.10	1.43	2.84	7.14	9.29	2.14	4.51
30	5.71	6.86	3.57	4.01	11.43	13.77	2.86	6.30
Mean	4.40	4.24	2.57	2.68	10.74	10.89	2.05	2.56

Table B-4: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for W entry

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	2.50	1.52	0.63	0.27	6.25	4.29	1.88	1.32
2	1.25	2.63	0.00	0.00	3.13	5.10	2.50	3.52
3	2.50	1.92	1.25	0.81	0.63	1.18	3.75	6.57
4	0.00	0.00	1.25	2.50	3.13	1.92	1.25	0.88
5	1.88	1.53	1.88	1.65	5.00	3.71	1.88	1.88
6	1.88	1.58	1.88	1.84	5.00	4.41	0.00	0.00
7	1.88	1.90	1.25	0.98	6.88	4.63	2.50	2.85
8	1.25	1.55	0.00	0.00	5.63	4.00	1.25	1.43
9	2.50	1.86	0.63	0.54	3.75	2.62	0.63	1.27
10	1.25	1.03	1.25	1.03	4.38	3.63	1.25	1.46
11	3.13	2.72	0.00	0.00	1.25	0.81	0.00	0.00
12	2.50	3.03	0.00	0.00	2.50	2.72	2.50	2.14
13	1.88	2.21	0.00	0.00	3.75	5.54	1.25	1.39
14	2.50	1.88	0.00	0.00	10.00	7.27	0.63	0.68
15	0.00	0.00	0.00	0.00	3.13	2.09	4.38	5.29
16	0.63	0.34	1.25	1.02	7.50	8.92	2.50	3.34
17	0.00	0.00	0.63	0.83	4.38	2.83	2.50	2.24
18	1.88	2.37	0.00	0.00	6.88	7.81	1.88	4.44
19	0.63	0.62	1.25	1.88	5.00	3.66	0.00	0.00
20	0.63	0.70	0.00	0.00	6.25	5.99	0.63	1.06
21	3.13	4.57	0.63	0.62	1.88	1.76	1.25	1.65
22	0.63	0.54	1.25	1.31	1.88	1.52	0.00	0.00
23	2.50	1.84	0.00	0.00	3.13	1.89	0.63	0.58
24	1.88	1.28	0.63	0.36	3.13	2.74	1.25	1.56
25	0.63	0.76	0.00	0.00	5.00	4.35	2.50	5.18
26	2.50	2.92	2.50	2.20	2.50	2.19	0.63	0.41
27	0.63	0.44	0.00	0.00	1.25	0.80	0.63	0.47
28	1.25	1.04	0.63	0.46	4.38	4.56	1.25	1.77
29	3.13	3.17	0.63	0.40	7.50	7.20	1.25	1.25
30	2.50	2.70	0.00	0.00	3.13	3.89	3.75	5.99
Mean	1.65	1.62	0.65	0.62	4.27	3.80	1.54	2.02

Table B-5: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for NE

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	3.57	3.57	2.86	2.01	10.00	8.56	5.00	4.92
2	2.86	3.65	1.43	4.15	14.29	17.95	5.71	11.90
3	5.71	8.44	3.57	4.43	10.71	19.26	2.86	7.04
4	7.86	7.79	2.86	4.89	8.57	8.40	2.14	7.58
5	5.00	5.34	2.86	3.22	9.29	9.01	2.14	2.48
6	2.86	2.73	5.71	7.52	15.71	17.45	2.14	1.96
7	4.29	4.20	2.14	2.64	12.86	13.09	3.57	5.29
8	4.29	4.14	5.71	8.26	12.14	17.29	2.86	4.67
9	5.00	4.18	4.29	4.66	7.86	7.22	1.43	1.49
10	3.57	3.42	2.14	1.93	11.43	12.13	5.00	6.74
11	2.86	3.95	5.00	6.27	13.57	12.30	2.14	3.31
12	5.71	6.72	3.57	3.93	10.00	13.07	2.86	8.82
13	5.00	4.73	0.00	0.00	9.29	15.24	3.57	7.41
14	8.57	7.44	2.86	2.53	7.14	5.95	3.57	3.20
15	5.00	4.27	0.71	0.70	9.29	9.84	6.43	7.54
16	2.86	3.93	1.43	1.18	5.71	8.88	5.71	8.11
17	2.86	2.33	2.14	2.68	5.71	4.98	5.00	6.08
18	5.71	4.89	2.86	2.92	6.43	6.84	2.86	3.66
19	3.57	4.06	4.29	5.19	7.86	8.39	4.29	5.26
20	1.43	1.27	0.71	0.73	10.71	11.53	4.29	4.86
21	5.71	4.88	4.29	4.65	7.86	6.86	1.43	1.49
22	3.57	4.48	4.29	5.44	10.71	12.88	2.86	3.45
23	5.71	6.01	1.43	1.54	4.29	4.14	6.43	6.86
24	7.86	6.43	4.29	4.60	13.57	13.83	2.86	3.63
25	4.29	4.52	2.14	2.30	5.71	7.18	4.29	13.30
26	5.00	5.18	2.86	3.39	4.29	4.56	1.43	3.57
27	5.71	9.13	4.29	7.27	13.57	14.75	3.57	6.95
28	8.57	8.14	2.14	1.84	8.57	11.29	2.14	2.86
29	5.00	5.11	0.00	0.00	7.14	6.84	2.14	3.80
30	8.57	11.83	1.43	1.96	8.57	13.38	6.43	10.39
Mean	4.95	5.22	2.81	3.43	9.43	10.77	3.57	5.62

Table B-6: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for ES

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	4.29	3.25	2.86	3.04	4.29	5.41	2.86	2.56
2	3.57	4.57	0.71	0.66	7.14	5.35	2.86	5.93
3	6.43	3.04	5.00	3.88	11.43	12.01	7.86	9.01
4	7.14	7.92	2.14	2.81	5.00	10.01	2.86	3.59
5	5.00	4.73	2.14	1.35	2.86	1.94	1.43	1.07
6	0.71	0.45	3.57	1.79	10.71	6.55	5.00	3.23
7	6.43	3.95	4.29	1.87	7.14	7.76	2.14	1.43
8	5.71	4.66	0.71	0.96	7.14	5.96	3.57	2.24
9	4.29	4.63	2.86	6.59	2.86	2.20	2.14	4.45
10	6.43	3.11	2.14	0.72	8.57	9.41	7.86	14.89
11	2.86	1.27	6.43	7.15	10.00	9.91	2.86	2.86
12	5.00	1.93	2.86	1.50	4.29	2.79	2.14	1.52
13	5.71	2.87	1.43	0.73	5.71	3.81	0.71	0.42
14	5.71	2.71	3.57	2.53	5.00	2.77	0.71	0.82
15	7.86	5.37	2.14	1.68	6.43	3.50	2.86	2.03
16	3.57	1.23	0.00	0.00	2.86	1.34	1.43	0.75
17	2.14	0.98	1.43	0.69	7.14	5.22	2.86	2.03
18	5.00	2.20	2.14	1.05	8.57	8.02	1.43	1.49
19	3.57	1.75	5.00	2.45	4.29	2.49	2.86	2.25
20	0.71	0.24	1.43	1.21	5.71	5.23	5.00	9.15
21	2.86	2.83	0.71	0.38	5.00	2.85	4.29	2.96
22	6.43	5.09	2.86	2.94	12.14	23.08	3.57	4.94
23	4.29	3.38	0.71	0.34	7.14	8.49	2.86	1.87
24	3.57	2.15	1.43	0.72	7.14	4.25	1.43	1.06
25	6.43	2.86	1.43	1.97	4.29	4.32	3.57	3.06
26	1.43	1.60	3.57	2.32	5.71	4.49	4.29	2.97
27	3.57	1.47	2.86	2.43	10.71	8.55	0.71	0.78
28	10.00	18.52	2.14	1.62	7.86	12.17	2.86	4.64
29	2.86	1.26	1.43	2.43	5.00	3.39	2.14	1.53
30	5.00	2.23	2.86	4.17	7.14	8.63	2.14	1.71
Mean	4.62	3.41	2.43	2.07	6.64	6.40	2.98	3.24

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Table B-7: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for SW

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	6.43	8.14	2.86	4.16	4.29	3.96	5.71	6.08
2	6.43	8.15	2.14	2.89	17.14	22.07	1.43	3.29
3	3.57	4.26	2.86	3.50	7.86	14.88	5.00	14.57
4	3.57	3.10	4.29	5.19	10.71	13.08	1.43	2.01
5	7.14	10.21	4.29	4.20	11.43	10.66	1.43	1.30
6	3.57	3.24	3.57	3.98	12.14	11.29	2.86	4.61
7	4.29	4.26	1.43	2.01	19.29	21.22	3.57	7.22
8	4.29	3.82	5.00	5.26	11.43	11.18	1.43	2.05
9	5.71	5.49	2.86	5.01	17.86	15.56	0.71	0.57
10	7.14	6.26	2.14	4.32	9.29	8.84	4.29	5.80
11	3.57	3.61	4.29	10.89	17.14	21.09	6.43	11.53
12	5.71	4.45	4.29	3.50	11.43	11.65	0.71	0.86
13	4.29	6.93	1.43	1.74	14.29	13.21	0.00	0.00
14	4.29	4.37	2.86	8.21	2.86	3.75	4.29	4.65
15	8.57	11.55	0.71	0.73	8.57	11.44	4.29	5.92
16	3.57	3.16	4.29	4.46	7.14	7.21	3.57	3.62
17	4.29	4.45	3.57	4.02	7.14	9.66	2.86	4.39
18	2.86	3.82	2.14	2.21	10.00	12.72	4.29	5.64
19	2.86	3.19	3.57	4.32	11.43	12.99	2.14	2.24
20	5.71	5.43	1.43	1.78	10.71	12.41	5.00	8.17
21	4.29	4.66	4.29	4.62	12.86	15.87	1.43	1.90
22	2.86	4.29	2.86	2.62	12.14	15.46	3.57	5.60
23	9.29	12.46	2.14	1.88	9.29	10.75	3.57	5.80
24	8.57	8.92	3.57	3.78	17.86	15.78	2.14	2.50
25	3.57	3.05	2.14	3.85	13.57	12.40	1.43	13.17
26	3.57	3.81	2.86	2.97	12.86	16.23	3.57	5.53
27	3.57	3.00	0.71	0.55	5.00	7.89	5.00	5.29
28	10.00	12.31	4.29	3.95	8.57	7.45	2.14	1.99
29	5.71	6.56	2.14	6.39	8.57	13.38	2.86	5.49
30	6.43	9.42	5.71	8.46	13.57	18.79	3.57	10.54
Mean	5.19	5.88	3.02	4.05	11.21	12.76	3.02	5.08

Table B-8: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for WN

Observed Minute	M2W		M3W		LCV		HDV	
	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	6.25	4.08	1.25	0.66	8.13	5.67	5.00	3.99
2	4.38	6.99	2.50	5.07	13.13	24.31	3.75	5.77
3	5.63	5.71	2.50	2.82	6.88	16.35	4.38	7.33
4	2.50	2.68	3.75	3.55	8.13	6.24	1.88	1.31
5	4.38	3.41	4.38	3.83	11.88	10.78	3.75	3.35
6	3.75	3.13	4.38	4.06	14.38	12.77	1.25	1.12
7	4.38	3.50	2.50	2.51	18.75	15.67	5.00	5.65
8	4.38	4.41	4.38	4.80	13.13	11.86	3.75	4.74
9	5.00	4.55	2.50	2.55	15.63	12.33	1.25	2.20
10	6.88	5.79	2.50	1.95	10.00	8.98	3.75	5.72
11	6.25	6.85	0.00	0.00	14.38	11.37	2.50	1.85
12	8.13	7.53	3.75	3.18	11.25	11.40	3.13	2.89
13	3.13	3.40	0.63	0.40	12.50	10.29	1.25	1.39
14	6.25	4.27	0.63	0.47	10.63	6.87	3.13	2.80
15	6.88	5.85	0.00	0.00	8.75	8.55	6.88	8.15
16	3.13	3.29	3.13	2.44	8.75	9.77	5.63	7.87
17	1.25	1.23	3.75	4.06	7.50	5.19	5.00	4.77
18	3.75	4.18	1.88	2.30	15.00	16.90	6.25	9.17
19	1.25	1.18	2.50	2.71	11.88	9.16	1.88	1.37
20	4.38	3.68	1.25	0.95	13.75	11.34	3.75	3.54
21	6.88	6.52	4.38	4.21	8.13	7.20	1.88	2.09
22	1.88	1.28	3.13	3.39	8.75	7.28	1.25	1.34
23	6.25	5.59	1.88	1.95	6.88	5.28	2.50	3.15
24	5.63	4.46	3.13	3.29	17.50	14.91	3.75	4.09
25	3.13	2.73	1.25	1.01	12.50	11.50	2.50	5.18
26	4.38	4.34	4.38	4.18	6.88	22.12	2.50	2.65
27	3.13	5.01	0.63	0.74	4.38	4.87	4.38	4.63
28	5.63	5.03	3.13	2.31	8.75	7.87	3.13	2.75
29	6.25	7.06	0.63	0.40	10.00	9.79	2.50	3.08
30	8.13	10.48	3.13	3.93	10.00	13.05	5.63	8.17
Mean	4.77	4.61	2.46	2.46	10.94	10.99	3.44	4.07

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Table B-9: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for N exit

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	3.57	1.74	0.71	0.31	0.71	0.29	0.71	0.40
2	2.86	2.57	1.43	1.84	3.57	3.04	0.00	0.00
3	4.29	3.87	2.14	1.74	5.00	8.64	1.43	1.92
4	0.00	0.00	2.14	1.49	4.29	3.12	1.43	0.86
5	2.14	1.51	1.43	1.15	3.57	2.37	2.14	1.90
6	1.43	1.01	1.43	1.20	7.86	5.90	0.71	0.77
7	2.86	2.05	0.00	0.00	7.14	5.29	2.14	1.58
8	2.86	1.83	1.43	1.36	5.71	3.99	1.43	1.62
9	3.57	3.05	0.00	0.00	11.43	7.67	0.00	0.00
10	5.71	4.84	0.71	0.36	5.71	5.20	0.00	0.00
11	5.00	5.50	0.71	0.63	6.43	4.63	1.43	1.06
12	3.57	2.40	1.43	1.12	7.14	5.09	0.71	0.54
13	0.71	0.36	1.43	1.03	9.29	5.76	0.00	0.00
14	2.86	1.70	0.00	0.00	6.43	4.54	0.00	0.00
15	4.29	3.10	0.00	0.00	5.71	3.87	0.71	0.82
16	2.86	2.73	1.43	1.19	6.43	6.22	2.14	2.95
17	0.00	0.00	2.14	1.62	4.29	3.07	1.43	1.69
18	0.00	0.00	0.71	0.50	10.00	9.94	2.14	2.70
19	0.71	0.71	0.71	0.97	7.86	7.44	1.43	1.40
20	3.57	2.83	2.86	2.55	9.29	6.31	1.43	0.89
21	0.71	0.60	1.43	1.06	3.57	2.52	0.71	0.45
22	2.14	2.79	0.71	0.99	5.71	4.50	0.71	0.77
23	2.86	1.84	0.71	0.68	7.86	5.18	0.00	0.00
24	0.71	0.47	0.71	0.46	10.00	7.41	0.71	0.48
25	2.14	1.49	1.43	1.15	11.43	9.50	0.00	0.00
26	0.00	0.00	2.14	2.53	2.86	3.98	1.43	1.75
27	0.00	0.00	0.00	0.00	5.00	8.23	2.14	1.88
28	3.57	2.55	2.14	1.43	6.43	4.28	2.14	1.57
29	2.86	1.91	0.71	0.45	3.57	3.25	0.71	0.48
30	2.14	2.53	2.14	1.99	5.00	5.28	0.71	0.48
Mean	2.33	1.87	1.17	0.99	6.31	5.22	1.02	0.97

Table B-10: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for E exit

Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	1.43	1.28	0.71	0.43	4.29	3.80	1.43	1.28
2	1.43	2.51	0.71	0.86	5.00	4.92	3.57	4.27
3	3.57	6.36	1.43	3.11	4.29	11.60	1.43	5.15
4	2.86	3.02	1.43	4.75	12.14	30.41	2.14	7.35
5	1.43	1.42	1.43	1.35	5.71	5.61	2.14	2.42
6	0.71	0.76	2.86	2.81	6.43	5.98	0.71	0.55
7	1.43	3.28	1.43	1.72	11.43	12.18	2.86	4.21
8	1.43	1.95	2.86	4.74	9.29	13.53	2.14	3.42
9	1.43	1.33	3.57	4.05	7.14	7.05	1.43	2.55
10	1.43	1.34	1.43	1.65	7.86	8.04	1.43	1.26
11	2.14	3.74	0.71	1.99	6.43	5.83	2.86	5.63
12	3.57	4.27	2.14	1.95	5.71	5.55	0.71	2.34
13	0.71	1.27	0.00	0.00	6.43	15.98	4.29	18.28
14	2.86	2.61	0.71	0.54	4.29	5.58	3.57	3.20
15	1.43	1.60	0.00	0.00	2.14	2.37	3.57	4.14
16	3.57	4.54	0.00	0.00	2.86	4.00	5.00	7.74
17	0.71	0.80	2.14	2.66	3.57	4.30	3.57	4.75
18	3.57	3.42	2.14	2.31	2.86	2.63	2.14	2.52
19	1.43	2.09	0.71	0.89	2.86	3.88	1.43	1.98
20	1.43	1.27	0.71	0.56	7.86	8.52	1.43	1.64
21	4.29	3.36	2.14	2.58	3.57	3.18	0.71	0.76
22	0.71	1.14	2.86	3.03	5.00	5.79	1.43	2.54
23	2.86	3.89	1.43	1.83	0.71	0.67	2.14	2.83
24	4.29	5.14	0.71	0.89	5.00	5.33	2.14	2.57
25	2.14	2.22	2.14	2.68	5.00	5.63	0.71	1.14
26	0.71	0.68	2.14	2.81	0.71	1.25	2.86	13.39
27	6.43	7.24	1.43	4.01	5.71	9.22	0.00	0.00
28	3.57	3.39	0.71	0.70	2.86	2.78	2.86	6.89
29	2.14	2.47	0.71	0.55	4.29	3.74	0.71	1.64
30	6.43	9.08	1.43	2.22	7.86	11.26	7.14	13.30
Mean	2.40	2.92	1.43	1.92	5.31	7.02	2.29	4.32

Table B-11: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for S exit

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	2.14	0.69	1.43	0.97	2.14	2.63	2.14	1.50
2	2.14	1.35	1.43	0.70	6.43	4.50	2.14	2.15
3	6.43	2.86	4.29	2.89	9.29	8.82	2.86	2.28
4	6.43	5.63	2.14	4.19	2.14	3.15	4.29	4.01
5	3.57	2.84	1.43	0.93	2.86	1.65	0.00	0.00
6	0.71	0.45	4.29	2.03	8.57	4.16	2.86	1.68
7	5.00	2.48	4.29	1.63	6.43	4.97	2.86	1.61
8	4.29	3.60	0.71	0.96	5.00	3.31	3.57	2.74
9	4.29	3.46	1.43	0.96	1.43	0.97	2.14	2.37
10	5.71	2.23	2.14	0.77	4.29	2.56	2.86	1.66
11	2.86	1.27	3.57	3.14	8.57	8.87	2.86	3.68
12	4.29	1.63	2.86	1.36	3.57	2.06	1.43	0.73
13	5.71	2.98	1.43	0.73	3.57	2.03	0.71	0.42
14	5.71	2.42	1.43	0.65	4.29	2.14	0.00	0.00
15	6.43	5.79	1.43	0.75	5.00	2.21	1.43	0.86
16	4.29	1.38	0.00	0.00	2.14	0.82	1.43	0.75
17	2.14	0.98	1.43	0.69	5.00	3.11	2.14	1.23
18	4.29	2.66	2.14	1.05	5.71	3.43	1.43	1.36
19	3.57	1.75	4.29	1.87	2.86	1.63	2.86	1.71
20	0.71	0.24	1.43	1.21	5.00	3.04	2.86	6.92
21	0.71	0.40	0.71	0.38	4.29	2.10	2.86	1.51
22	4.29	2.82	2.86	2.94	7.14	6.71	1.43	1.22
23	4.29	2.64	0.71	0.34	3.57	2.19	2.86	1.86
24	2.86	1.49	1.43	0.72	5.00	2.62	1.43	1.06
25	6.43	2.70	0.71	0.52	3.57	2.25	2.14	1.66
26	0.71	0.19	2.86	1.40	3.57	2.68	3.57	2.55
27	3.57	1.47	1.43	0.68	4.29	2.22	0.71	0.37
28	4.29	3.63	3.57	7.11	7.14	25.01	2.86	4.82
29	2.86	1.23	0.71	0.26	4.29	2.52	1.43	0.87
30	4.29	1.77	0.71	1.39	4.29	3.72	2.14	1.62
Mean	3.83	2.17	1.98	1.44	4.71	3.94	2.14	1.84

Table B-12: Observed (Obs) and modeled (Mod) heterogeneous traffic density of traffic types (entities/km.m) for W exit

Observed	M2W		M3W		LCV		HDV	
Minute	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
1	1.25	1.57	1.25	1.66	0.00	0.00	1.25	1.12
2	2.50	5.40	0.00	0.00	3.13	6.83	0.63	2.73
3	0.63	0.59	1.25	1.10	2.50	5.32	2.50	6.47
4	1.25	2.47	1.25	2.47	3.13	4.10	1.88	4.76
5	2.50	4.60	0.63	0.57	1.88	4.81	0.63	0.82
6	1.88	2.11	1.25	1.37	0.63	0.60	1.25	2.92
7	1.25	1.33	0.00	0.00	4.38	7.85	0.63	2.77
8	0.63	0.72	0.00	0.00	1.25	1.52	0.00	0.00
9	1.88	1.99	0.00	0.00	2.50	2.55	0.00	0.00
10	0.63	1.48	1.25	15.17	2.50	7.81	1.25	2.08
11	0.63	0.66	0.63	1.75	0.00	0.00	3.13	5.67
12	0.63	0.57	3.13	11.16	3.13	23.41	0.63	5.13
13	0.63	0.66	0.00	0.00	3.13	5.52	0.00	0.00
14	1.25	11.38	1.88	4.79	1.88	3.97	0.63	1.43
15	1.25	2.01	0.63	0.81	1.25	4.65	0.63	1.00
16	0.63	0.80	1.88	2.00	1.25	1.61	0.63	1.83
17	1.88	2.14	0.63	0.62	1.88	5.68	0.00	0.00
18	0.63	0.62	0.00	0.00	1.88	1.79	0.00	0.00
19	1.25	3.01	1.25	1.52	2.50	6.29	1.25	4.63
20	1.88	2.12	0.00	0.00	1.88	3.91	0.00	0.00
21	0.63	1.07	0.00	0.00	2.50	4.38	2.50	4.82
22	0.00	0.00	0.00	0.00	3.75	8.94	1.88	3.45
23	5.63	14.30	0.00	0.00	4.38	12.40	1.88	4.10
24	3.13	3.90	1.25	1.50	0.63	0.72	0.00	0.00
25	1.25	1.25	0.63	1.62	4.38	5.68	0.63	1.61
26	0.00	0.00	0.63	0.88	2.50	4.26	1.25	2.29
27	1.88	2.43	0.00	0.00	3.75	8.76	1.25	3.69
28	0.00	0.00	1.25	1.39	3.13	3.38	0.00	0.00
29	5.00	21.52	1.88	5.77	3.75	6.15	0.63	1.01
30	0.00	0.00	0.63	1.03	3.13	7.53	1.25	2.86
Mean	1.42	3.02	0.77	1.91	2.42	5.35	0.94	2.24

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LIST OF PUBLICATIONS

- Gokhale, S., Pandian, S., 2007. A semi-empirical box model approach for predicting the carbon monoxide concentrations at an urban traffic intersection. **Atmospheric Environment** 41, 7940-7950

- Pandian, S., Gokhale, S., 2008. Capacity Estimation of Roundabout Traffic Intersection using Alternative Analytical Models. **International Congress on Environmental Research**, 'ICER-2008', Goa, India.

- Pandian, S., Gokhale, S., Ghoshal, A.K., 2009. Evaluating effects of traffic and vehicle characteristics on vehicular emissions near traffic intersections. **Transportation Research Part D: Transport and Environment** 14 (3), 180-196

- Pandian, S., Gokhale, S., Ghoshal, A.K., 2011. An open-terrain line source model coupled with street-canyon effects to forecast carbon monoxide at traffic roundabout. **Science of the Total Environment** 409 (6), 1145-1153.

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- Thiru Kamaraj Municipal Higher Secondary School – Villupuram
  Course studied: **HSC**
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- Arunai Engineering College – Tiruvannamalai (University of Madras)
  Course studied: **Chemical Engineering (B.Tech)**
  Year Passed: 2002 Percentage: 77.57%

- Pondicherry Engineering College – Pondicherry (Pondicherry University)
  Course studied: **Environmental Engineering (M.Tech)**
  Year Passed: 2005 CGPA: 8.47

- Indian Institute of Technology – Guwahati
  Course studied: **Air Quality Modeling (PhD)**
  Year Passed: 2011

WORK EXPERIENCE

• Working as **Assistant Professor** in the **Department of Environmental Science & Engineering (Centre of Mining Environment)** at Indian School of Mines (**ISM**), Dhanbad-826004. From June 23rd -2011 to **Till date**

• Worked as a Project Assistant in **NEERI**, CSIR Complex, Chennai-113. From Sep-2005 to Dec-2005

• Worked as a **GET** in Padhmam Herbal Care PVT Ltd, Korkadu, Puducherry. From Jan-2003 to June 2003

AWARDS/HONOURS

• Qualified in **GATE** (2002) with **86.63** Percentile

• **First Prize** in Technical Quiz, held at C.I.T., Coimbatore in Feb, 2002

• Participation of Paper Presentation in following Colleges: CECRI, Karaikudi and C.I.T., Coimbatore.

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