DEVELOPMENT OF BI-DIRECTIONAL MIXED TRAFFIC SIMULATION MODEL FOR URBAN ROADS

Thesis
Submitted in partial fulfillment of the requirement for degree of

DOCTOR OF PHILOSOPHY
by

PUNITH B. KOTAGI

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
SURATHKAL, MANGALURU-575 025
February 2019

DECLARATION

by the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **“DEVELOPMENT OF BI-DIRECTIONAL MIXED TRAFFIC SIMULATION MODEL FOR URBAN ROADS”**, which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in Civil Engineering is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

145009CV14F07, PUNITH B. KOTAGI.,
(Register Number, Name & Signature of the Research Scholar)
Department of Civil Engineering

Place: NITK Surathkal
Date: -02-2019

CERTIFICATE

This is to *certify* that the Research Thesis entitled **“DEVELOPMENT OF BI-DIRECTIONAL MIXED TRAFFIC SIMULATION MODEL FOR URBAN ROADS”** submitted by **Mr. PUNITH B. KOTAGI**, (Register Number: 145009CV14F07) as the record of the research work carried out by him, is accepted *as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of Doctor of Philosophy.

Dr. A. Gowri
Research Guide
(Signature with Date and Seal)

Chairman - DRPC
(Signature with Date and Seal)

ACKNOWLEDGEMENTS

I would like to express my deep sense of gratitude to my research supervisor **Dr. A. Gowri**, Department of Civil Engineering, for her continuous patience, encouragement, and relentless guidance that proved instrumental in the upbringing of this thesis. Her keen engineering and scientific insight have helped me tremendously in improving the technical content and practical relevance of the thesis. Working with her has been a great learning experience for me. This research would not have been possible without her support and guidance. To accomplish my doctorate thesis under her supervision has been both a great privilege and honor for me.

I am greatly indebted to my RPAC members, **Dr. Suresha S N**, Department of Civil Engineering and **Dr. Vadivuchezhian Kaliveeran**, Department of Applied Mechanics and Hydraulics for their critical evaluation and valuable suggestions during the progress of the work.

I am thankful to **Dr. Varghese George**, Professor and Head, Department of Civil Engineering. I take this opportunity to thank former Department Head’s namely, **Prof. Katta Venkataramana, Prof. K. N. Lokesh** and **Prof. Venkat Reddy** for their timely help during my entire research period.

I gratefully acknowledge the support and help rendered by former graduate students, **Mr. Murthy Krishna, Mr. Akhil Puram, Mr. Avinash Reddy, Mr. Suresh G,** and **Mr. Shiv Prasad**. Special thanks to **Mrs. Pooja Raj** for her timely help during the data collection and extraction.

I sincerely thank faculty members of Department of Civil Engineering for their valuable guidance and encouragement during my Ph.D. research work. I also like to extend my gratitude to the office and supporting staff of Department of Civil Engineering, for their encouragement, help, and support provided during the research work.

I would like to express my sincere gratitude to the authorities of NITK Surathkal, for providing me excellent facilities and comfortable stay in the campus.

I am grateful to **Dr. S. Velmurugan**, Senior Principal Scientist, Central Road Research Institute, New Delhi, for sharing the traffic data of Mumbai and Delhi road sections. I also

thank **Dr. M. A. Saleem**, Former Additional Commissioner, Bangalore Traffic Police, India for permitting me to record traffic data necessary for the research.

I wish to thank my friends **Dr. Darshan, Mr. Basavanagowda, Mr. Kesava Rao, Mr. Vinod, Mr. Sharan, Dr. Parameshwar, Mr. Thanu, Mr. Preetham** and **Mr. Jayakesh** for their companionship and assistance during my stay at NITK. I dearly miss my friends **Mr. Renuka Prasad** and **Mr. Manu Kuttan** at this phase of my life. I thank all my friends at NITK who were always co-operative and friendly to me.

I am thankful to my friends **Mr. Bhanuprakash, Mr. Milan, Mr. Dayanand, Mr. Avinash** and **Mrs. Vani** for their constant love and support during my good and not so good times.

I express love towards my parents **Mr. Basanna Kotagi** and **Mrs. Saraswathi Kotagi** for their blessings, sacrifice, affection, guidance, support, and encouragement throughout my life. I thank my sister **Mrs. Mamatha** and my brother **Mr. Harish Kotagi** for their love and moral support.

I would like to remember The Almighty for providing such a wonderful learning experience in my life through this journey.

Finally, I thank all my well-wishers who have directly or indirectly supported me in need of the hour.

Punith B. Kotagi

ABSTRACT

Most of the cities in developing and emerging countries (e.g. India, China) consist of large proportion of undivided roads which carry mixed traffic with non-lane discipline. Vehicular manoeuvers on such roads are complex due to high lateral interactions between the vehicles moving in both directions in the absence of divider (median). Traffic congestion in cities during peak hours prolongs for longer periods each day which reduces the capacity of roads and increases delay and pollution. Possible ways to reduce these problems are to improve the operation of existing road systems through better traffic control and management measures. Microscopic simulation model is identified as a widely used tool to evaluate traffic control and management measures.

The overall objective of this research work is to develop a microscopic simulation model for bi- directional traffic on urban undivided roads in mixed traffic conditions. The simulation model consists of three major logics: vehicle generation, vehicle placement, and vehicle movement. Longitudinal and lateral movements of vehicles are modeled together to mimic the real world conditions. The concept of influence area is introduced to identify the most influencing leader vehicle in vehicle movement logic. The simulation model is implemented in MATLAB programming language using Object-Oriented Programming (OOP) concepts. The model is calibrated and validated using internal and external datasets collected from two different urban cities (Bengaluru and Kollam) in India. The statistical validation indicates that the simulation model replicates the field conditions realistically. The developed model is applied to evaluate traffic management measures such as reversible lane (tidal flow) operations and modal shift of private vehicles towards public transport.

A reversible roadway is one in which the direction of traffic flow in one or more lanes or shoulders is reversed to the opposing direction for some period of time to reduce congestion. The reversible lane operation is implemented in the model and the impact of it on capacity of roads is studied by using four different vehicular compositions commonly observed on major urban arterials in Indian cities. For this purpose, capacity of the road without and with reversible lanes are determined from simulation model. Simulation runs are performed for 24 scenarios without reversible lanes and 24 scenarios with it (total of 48 runs). Each simulation run represented one hour of traffic flow during peak period. Results show that there is an improvement in capacity during peak hours after implementing reversible lanes. For two-wheeler dominant composition, the capacity in ongoing direction during morning peak hour is increased by 20.5% and similarly, capacity in opposing direction during evening peak hour is increased by 19.20%.

The modal shift from private vehicles (two-wheelers and cars) to public transport system (bus) is implemented in the model and its impact on capacity, travel time and emissions are studied. Three different scenarios (shifting commuters, only from two-wheelers, only from cars, and both from two-wheelers and cars together) are evaluated using traffic data collected from study sections located in major urban cities such as Bengaluru, Delhi, and Mumbai. For this purpose, capacity, travel time and emissions before and after modal shift are obtained from simulation model. Simulation runs are performed for 9 scenarios before modal shift and 153 scenarios after modal shift (total of 162 runs). The optimum number of buses to be increased in these sections are also obtained. The results show that implementation of modal shift (for optimum increment in buses) improves the capacity by 16.9%, 17.8% and 45.8% for Bengaluru, Delhi, and Mumbai, respectively. Reduction in travel time observed for these sections are 17.2%, 26.9% and 19.5%, respectively. Also, there is a significant reduction in CO_2 emissions in the range of 7.3 % - 12.6 %.

The developed simulation model can serve as a tool for traffic engineers and policy makers to evaluate various other traffic control and management measures (e.g. exclusion of certain category of vehicles, implementation of lane discipline and lane segregation), which can be implemented on urban roads carrying mixed traffic as prevailing in developing and emerging countries.

Keywords: Bi-directional Traffic; Mixed Traffic; Urban Undivided Roads; Reversible Lanes; Modal Shift; Microscopic Simulation; Object-Oriented Programming

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY AND DEVELOPMENT OF BI-DIRECTIONAL SIMULATION MODEL

CHAPTER 4 DATA COLLECTION AND EXTRACTION

CHAPTER 5 MODEL CALIBRATION AND VALIDATION

CHAPTER 6 APPLICATIONS OF SIMULATION MODEL

CHAPTER 7 SUMMARY AND CONCLUSIONS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
AR	Auto-Rickshaw
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPRI	Central Power Research Institute
DOF	Degrees of Freedom
FC	Frictional Clearance
GEV	Generalized Extreme Value
GHG	Green House Gas
HC	Hydro Carbon
HCM	Highway Capacity Manual
HV	Heavy Vehicle
IPCC	Intergovernmental Panel on Climate Change
IRC	Indian Road Congress
ITE	Institute of Transportation Engineers
K-S	Kolmogorov-Smirnov
L	Leader Vehicle
LA	Left Adjacent Vehicle
LCV	Light Commercial Vehicle
MAPE	Mean Absolute Percentage Error
MATLAB	Matrix Laboratory
MES	Maximum Escape Speed
MLR	Multiple Linear Regression
MORTH	Ministry of Road Transport and Highways

ABBREVIATIONS (Contd.)

MSR	Mathikere Sampige Ramaiah
NOX	Nitrogen Oxide
O	Opposing Vehicle
OOP	Object-Oriented Programming
PCU	Passenger Car Unit
PM	Particulate Matter
RA	Right Adjacent Vehicle
RL	Reversible Lane
RN	Random Number
S	Subject Vehicle
SD	Standard Deviation
SO_2	Sulphur Dioxide
TW	Two-Wheeler
WMO	World Meteorological Organization

NOTATIONS

a	Acceleration of Subject Vehicle
b	Maximum Deceleration
b_{ij}^{*}	Deceleration of Leader as Judged by Subject Vehicle
d_{body}	Safe Distance to Stopping
g	gram
g/km	gram/kilometre
h	hour
km	kilometre
km/h	kilometre/hour
m	metre
m/s	metre/second
PCU/h	Passenger Car Unit/hour
s	second
r_1 and r_2	Random Numbers
S	Standard Normal Deviate
S_{ij}	Size of Leader
t	Time-Step Under Consideration
T	Reaction Time of Subject Vehicle
t_l	Type of Leader Vehicle
t_{la}	Type of Left Adjacent Vehicle
$t_{overtake}$	Time Taken to Overtake
t_{ra}	Type of Right Adjacent Vehicle
t_s	Type of Subject Vehicle
TTC_{ov}	Time Taken to Collide Opposing Vehicle
t_{veer}	Time Required for Veering

NOTATIONS (Contd.)

V_j	Free-Flow Speed of Subject Vehicle
v_l	Speed of Leader Vehicle
v_{la}	Speed of Left Adjacent Vehicle
v_{ra}	Speed of Right Adjacent Vehicle
v_s	Speed of Subject Vehicle
v_t	Instantaneous Speed
Veh/h	Vehicle/hour
V_{veer}	Veer Velocity
σ	Standard Deviation
α	Sensitivity Factor
μ	Mean

CHAPTER 1

INTRODUCTION

1.1 GENERAL

In most of the developed countries, the traffic stream is homogeneous and mainly consists of cars and heavy vehicles with cars constituting more than 80 % of the total vehicle composition. The proportion of heavy vehicles in such stream is very less and dynamic characteristics of these vehicles vary marginally from those of cars. The traffic flow characteristics under such fairly homogeneous traffic conditions exhibit a strict lane discipline. On the other hand, in emerging and developing countries such as in India and China, the traffic stream is composed of different categories of vehicles with widely varying operating and performance characteristics. These vehicles follow weak lane discipline and hence, tend to occupy any lateral positon within the road width. Figure 1.1 shows the difference between homogeneous and mixed traffic conditions. The vehicular composition of mixed traffic includes motorized vehicles such as two-wheelers, cars, buses, auto-rickshaws, light commercial vehicles, heavy vehicles (such as trucks and tractors), and non-motorized vehicles (such as bicycles and tricycles).

(a) Homogeneous traffic (b) Mixed traffic

Figure 1.1 Homogeneous and mixed traffic conditions

The rapidly expanding population of India is attracting a variety of economic activities in flourishing cities, which are, therefore, encountering fast escalations in urban travel demand. To meet these travel demands, variety of transport modes such as cycles, two-wheelers, public transport, cars, etc. are used. According to the Ministry of Road Transport and Highways (MORTH, 2017), the total registered motor vehicles in the country raised at a Compound Annual Growth Rate of 9.8 % between 2006 and 2016 (Table 1.1).

Table 1.1 Total number of registered vehicles in India (2006 to 2016)

Year	Two-wheelers	Cars, Jeeps and Taxis	Buses	Goods Vehicle	Others*	Total (in thousands)
2006	64,743	11,526	992	4,436	7,921	89.6
2007	69,129	12,649	1,350	5,119	8,460	96.7
2008	75,336	13,950	1,427	5,601	9,039	105.3
2009	82,402	15,313	1,486	6,041	9,710	114.9
2010	91,598	17,109	1,527	6,432	11,080	127.7
2011	101,865	19,231	1,604	7,064	12,102	141.8
2012	115,419	21,568	1,677	7,658	13,169	159.4
2013	125,694	23,515	1,736	8,146	13,825	172.9
2014	139,410	25,998	1,887	8,698	14,712	190.7
2015	154,298	28,611	1,971	9,344	15,799	210.1
2016	169,419	31,415	2,164	10,260	17,347	230.6

**Others include tractors, trailers, and three-wheelers*

(Source: MORTH, India)

Over 230 million motor vehicles are registered in India at the end of the year 2016. Figure 1.2 shows the growth rate of vehicular composition in India during the year 1951 - 2016. It can be observed that two-wheelers, which constituted only 8.8 % in the year 1951 has relatively increased at a faster rate to dominate the scene by the end of the year 2016 by constituting 73.5 % of the total registered vehicles. The combined share of vehicles in the categories of cars, jeeps and taxis, goods vehicles, and buses in the total registered vehicles has declined from 89.9 % in the year 1951 to 19 percent in the year 2016. The share of motor vehicles categorized as “Others” which include tractors, trailers, and three-wheelers has increased from 1.3 % in the year 1951 to 7.5 % in the year 2016.

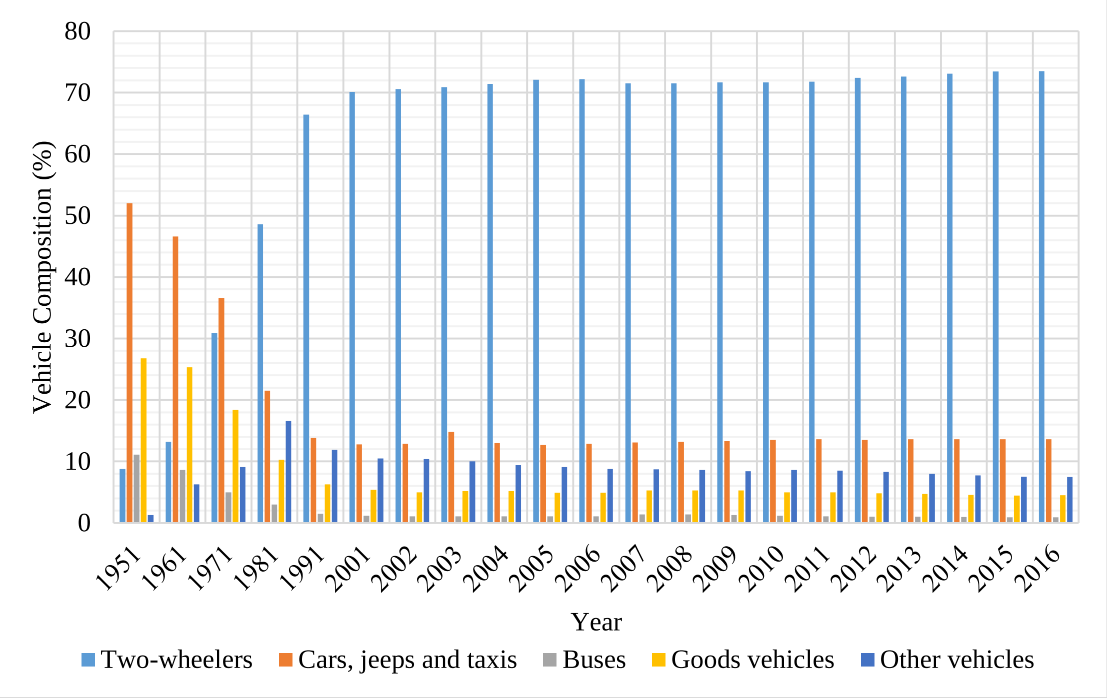


Figure 1.2 Growth rate of vehicular composition in India (1951 - 2016)

(Source: MORTH, India)

1.2 TRAFFIC SCENARIO ON URBAN ROADS

Transportation infrastructure is one of the major influencing factors for the development of any nation. In the modern context, transport demand in cities has increased extensively worldwide due to growth in urban population. Due to rapid urbanization, it is expected that by end of the year 2030, 40.8 % of India’s population is likely to live in urban areas (State of World Population, 2017). The growth rate of motorized vehicles is also increasing at a faster rate to meet the transport demand of such growing urban population. In India, the hike in vehicular growth during 1987-2017 was about 26 times while the population increase and urban population increase were merely about 1.8 times and 2.4 times, respectively (MORTH, 2017). There are several cities in India such as Mumbai, Delhi, Chennai, Bengaluru, and Kolkata which are amongst the fastest growing cities in the world. India stands at 5th position in most congested countries in the world with a traffic index of 205.31, whereas China stands at 13th position with a traffic index of 175.38 (Numbeo, 2017). Traffic Index represents a combined index of time spent in traffic during peak hours, assessment of dissatisfaction time, carbon dioxide (CO_2) consumption assessment in traffic congestion and overall inadequacies in the traffic flow (Numbeo, 2017). The recent global warming, sea level rising, and glacier melt are mainly caused by greenhouse gas (GHG) emissions generated by human activities (Intergovernmental Panel on Climate Change, 2007). Among the GHG emissions, CO_2 is the single most important anthropogenic greenhouse gas which contributes about 65 % of total GHG emissions (World Meteorological Organization, 2014). The transportation sector is a major source of CO_2 emissions and currently contributes 20 – 25 % of global CO_2 emissions. Its global share is projected to rise to 30 – 50 % by the year 2050. In India, emissions from transportation sector account 32 %, 17 %, 19 %, and 43 % of total CO_2 emissions in Delhi, Mumbai, Chennai and Bengaluru cities, respectively (Ramachandra *et al.* 2015). Increasing growth rate of vehicles is increasing the congestion, which leads to increase in road accidents as well. From Figure 1.3, it is clear that the number of deaths due to road accidents is increasing every year. A total of 1,77,423 persons were reported as dead due to road accidents in the year 2015 (National Crime Records Bureau, 2016). Hence, appropriate measures need to be taken to reduce the adverse effects of traffic congestion.

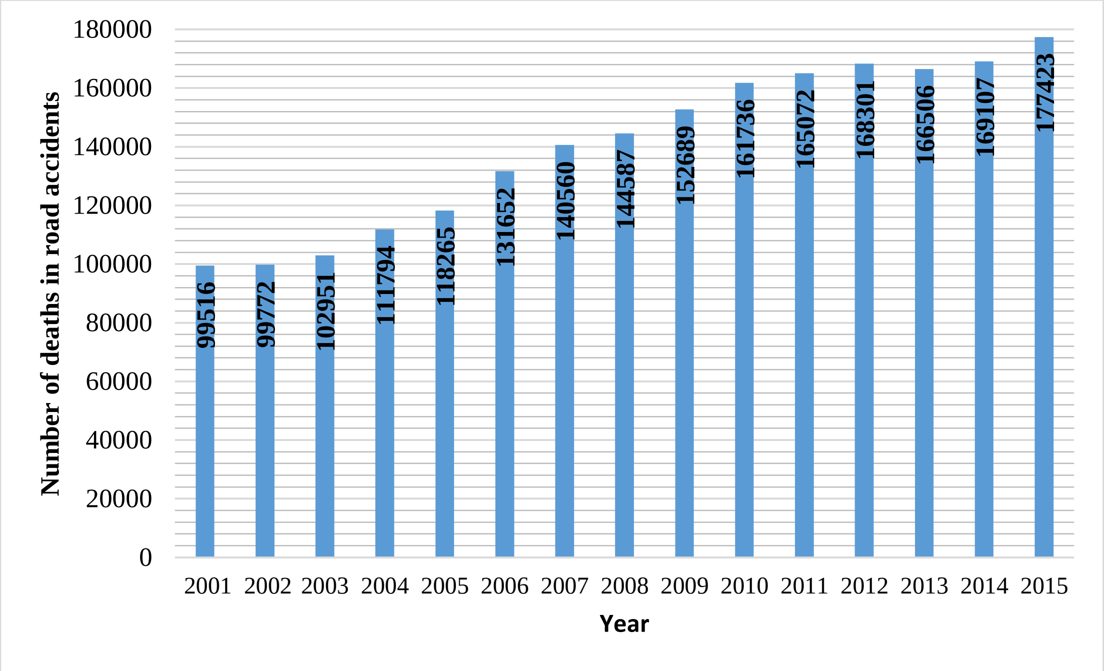


Figure 1.3 Number of deaths due to road accidents in India (2001 - 2015) (Source: Ministry of Home Affairs, India)

1.3 TRAFFIC PROBLEMS ON UNDIVIDED ROADS

Daily peak hour commuting traffic is a significant part of urban traffic and has been viewed as the most crucial factor in growing traffic-related problems in cities. Congestion during peak hours extends for longer periods each day. Congestion adversely affects mobility, safety, and air quality, causing direct economic losses due to delays and accidents, and indirect economic losses due to environmental impact. Most of the cities in India are suffering from medium to high level of traffic congestion due to uncontrolled growth of vehicles. The poor roadway conditions, encroachment of footpaths and resulting pedestrian activities, weak lane discipline, improper bus stop location, uncontrolled on-street parking are causing congestion in these cities.

The complexity is further increased in the case of urban undivided roads. About 4,44,961 kilometers of roads (8.54 % of total road length) in India come under the category of urban roads and it is observed that most of them are undivided (bi-directional) in nature. On such undivided urban roads, opposing traffic will have an influence on the movements of vehicles in the ongoing direction. They are also influenced by the positions, types, and speeds of neighboring vehicles as well as opposing vehicles and their manoeuvers. Due to lack of traffic segregation on undivided roads, vehicles try to occupy every possible space on the roads even occupying opposing lane. During the process of overtaking, vehicles try to use the opposing lane and hence, hindering the traffic flow in the opposite direction giving a chance of head-on collision. Such traffic problems can be reduced either by improving the existing roadway systems or by implementing necessary traffic management measures. In most of the cases, capacity of the existing roadway systems cannot be increased by adding additional lanes due to space, resource, or environmental constraints. From the past studies, it is found that traffic flow models effectively address the above problems. Microscopic simulation model is identified as the widely used tool to evaluate traffic control and management measures.

1.4 TRAFFIC FLOW MODELING

Traffic flow modeling is stochastic in nature due to randomness in variables such as vehicle arrivals and speeds. Due to this randomness and due to complex vehicular interactions and their maneuvers, it is really difficult to model the traffic flow through mathematical or analytical methods. Based on the previous research, simulation technique is found to be appropriate for modeling traffic flow. In India, most of the urban roads are undivided where traffic flow is bi-directional in nature with non-lane discipline. Vehicular manoeuvers on such roads are complex due to higher lateral interaction between the vehicles moving in both directions without median. Such mixed traffic streams are influenced by the positions, types, and speeds of neighboring vehicles and their manoeuvers. Also, the opposing traffic will have a different influence on the ongoing traffic which further increases the complexity of interactions between vehicles. The available simulation models for unidirectional flow of traffic cannot be applicable for modelling bi-directional traffic. Hence, there is a need for development of bi-directional simulation model for undivided roads.

Traffic simulation models are identified as widely used tool to evaluate traffic control and management measures. In recent years, simulation has emerged as an alternate tool to evaluate the performance of traffic streams. Simulation models can be subdivided into three major classes based on level of detail: macroscopic, mesoscopic and microscopic. Macroscopic simulation model looks at traffic stream from a global perspective and frames the relationships among traffic flow characteristics like density, flow, mean speed of a traffic stream. Whereas a microscopic simulation model provides a description of the movements of individual vehicles that are considered to be a result of the characteristics of drivers and vehicles, the interactions between driver–vehicle elements, the interactions between driver–vehicle elements and the road characteristics, external conditions and the traffic regulations and control. The microscopic simulation models are more effective for various applications such as evaluation of alternative treatments, testing new designs, as an element of the design process, safety analysis, etc.

1.5 NEED FOR THE STUDY

Traffic congestion is the major problem faced in many developing countries such as India. In rapidly growing cities of India (e.g., Mumbai, Delhi, Bengaluru, Chennai), the congestion during peak hours extends for longer periods each day. This congestion adversely affects mobility, safety, and air quality. These cause direct economic losses due to delays and accidents, and indirect economic losses due to environmental impact. The effect of congestion is worsening in the case of undivided roads, where the vehicles move even in the opposite lane creating complex manoeuvers. In such undivided roads, there are more chances for the head-on collision of vehicles as the traffic flow is not segregated. Such traffic problems need to be mitigated so as to improve the capacity of roads. In most of the cases, the capacity of the existing roadway systems cannot be increased by adding additional lanes due to space, resource, or environmental constraints. Possible ways to address the congestion problems are to improve the utilization of the existing systems through better traffic management and operations strategies, and improve the geometric design of roads. From the past studies, it is found that simulation models are considered as an effective tool to address the above problems.

Significant amount of research have been carried out in developing traffic flow models to address the above problems related to mixed traffic conditions on divided roads (Palaniswamy, l983; Oketch, 2000; Arasan and Koshy, 2005; Gundaliya and Mathew, 2005; Menga *et al.,* 2007; Mallikarjuna, 2007; Kanagaraj *et al.,* 2008; Asaithambi *et al.,* 2009; Mathew and Radhakrishnan, 2010; Gowri, 2011; Maurya, 2011; Mallikarjuna and Rao, 2011; Mathew and Ravishankar, 2011; Metkari *et al.*, 2013; Mathew *et al.,* 2013; Asaithambi *et al.,* 2018). Only limited studies are carried out in developing bi-directional simulation models for undivided roads (Simon and Gutowitz, 1998; Chakroborty *et al.,* 2004; Dey *et al.,* 2008; Budhkar and Maurya, 2014; Luo *et al.,* 2014). Various traffic management measures such as modal shift and reversible lanes are used to tackle traffic-related problems such as traffic congestion, pollution, accidents, etc. on urban roads (Wolshon and Lambert 2006; Huang *et al.,* 2009; Zhou 2012; Li *et al.,* 2013; Liu *et al.,* 2014; Dhar and Shukla 2015; Jiang *et al.,* 2015; Verma et al., 2015; Jaikumar *et al.,* 2017; Rahul and Verma 2017; Wang *et al.,* 2017). However, there are only few attempts made to use traffic simulation models for evaluation of traffic management measures (Papageorgiou *et al.,* 2009; Pandian *et al.,* 2009; Van *et al.,* 2009; Fathima and Kumar 2014; Tiwari *et al.,* 2015; Waleczek *et al.,* 2016).

There are significant simulation software packages available for simulating different traffic environments. The most frequently used traffic simulation software are Verkehr in Stadten–simulation (VISSIM), Simulation of Urban Mobility (SUMO), MATSIM, MAINSIM, PARAMICS, AIMSUN, CORridorSIMulation (CORSIM), Simtraffic, HUTSIM, Texas, Wide-Area Traffic Simulation (WATSIM), and INTEGRATION. Most of those models are restricted and not commercially available. Several studies assessed the strengths and weaknesses of different packages and their ability to satisfactorily simulate various pilot networks and traffic system configurations (Boxill and Yu, 2000; Barrios, *et al.*, 2001; Tian *et al.,* 2002; Choa, *et al.*,2004; Mahmud *et al.,* 2018). These software's cannot simulate mixed traffic conditions with non-lane discipline (Boxill and Yu, 2000; Gao 2008; Astarita *et al.*, 2012). None of the existing simulation software packages considered the influence of surrounding vehicles and also, the effect of non-overlapping leaders. The influence of surrounding vehicles on the movement of subject vehicle has to be considered in non-lane discipline traffic conditions since it is difficult to identify the true leader. In some cases, multiple leaders and non-overlapping (explain) leader may also affect the movement of subject vehicle since the amount of lateral manoeuvre are higher in mixed traffic conditions with non-lane discipline.

Overall, very few studies have focused exclusively on developing a bidirectional traffic simulation model for urban undivided roads. There are no studies which focus on the longitudinal and lateral behavior of vehicles together in mixed traffic. Also, the existing simulation models developed by different researchers consider the overlapping criteria for identifying a true leader. But, in mixed traffic conditions due to weak lane discipline, non-overlapping vehicles may also influence the movement of the subject vehicle. The influence of surrounding vehicles on the movement of the subject vehicle are not addressed in the previous studies. Most of the existing models are validated with the help of same dataset used for model development. The applicability of the model to other sites is ensured if the model is thoroughly validated using external data set collected from other sites. The developed model has to be applied to evaluate various traffic management measures to reduce traffic related problems on undivided roads. Therefore, these aspects have been considered as the focus of the present research work.

To address these aspects precisely in a more realistic way certain research objectives have been framed.

1.6 OBJECTIVES AND SCOPE

Detailed literature survey shows that very few studies have focused exclusively on developing a bidirectional traffic simulation model for urban undivided roads in mixed traffic. Also, there are no studies which focus on the longitudinal and lateral behavior of vehicles together in mixed traffic. The broad objective of this research work is to develop a microscopic traffic simulation model for urban undivided mid-block section (bi-directional traffic) in mixed traffic conditions with the following specific objectives:

- To develop a bi-directional mixed traffic simulator by incorporating the longitudinal and lateral behavior of vehicles using suitable models
- To evaluate reversible lane operation on undivided roads using the developed simulator
- To study the impact of modal shift of private vehicles to public transport using the developed simulator

1.7 ORGANIZATION OF THE THESIS

The rest of the thesis is structured as follows: Chapter 2 gives a detailed review of the literature focusing on studies related to traffic flow models for homogeneous traffic as well as mixed traffic. Chapter 3 explains the study methodology and the process of development of bi-directional traffic simulation model. The method of data collection, extraction and analysis is described in Chapter 4. The discussion on calibration and validation is explained in Chapter 5. Applications carried out using the developed model are explained in Chapter 6 which is followed by summary and conclusions in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Several studies have been carried out to tackle the different types of problems in the field of traffic and transportation with the help of simulation models. The literature related to traffic flow modelling carried out on both homogeneous and mixed traffic flow have been reviewed and reported in this chapter. These studies are further classified into studies on the longitudinal behavior of vehicles and studies on the lateral behaviour of vehicles. Also, the studies focusing on evaluation of traffic management and control measures have also been discussed.

2.2 STUDIES ON TRAFFIC FLOW MODELS FOR HOMOGENEOUS TRAFFIC

Many researchers have made attempts to develop various simulation models for homogeneous traffic conditions. However, these models cannot be applied directly for modelling mixed traffic conditions, as it considers only the homogeneous traffic conditions and strict lane discipline. The studies on homogeneous traffic are further classified into longitudinal movement and lateral movement studies.

2.2.1 Studies on longitudinal behavior

Chandler *et al.* (1958) proposed a linear model on the basis of stimulus-response concept. Study shows that driver’s response is proportional to the stimulus perceived by him/her. In the study the relative speed is termed as the stimulus and the driver’s response to this stimulus arises at a time delayed by the response time T. The sensitivity factor λ, is also termed as the proportionality factor.

Gipps (1981) proposed a modified car-following model which was calibrated with the help of common sense assumptions regarding behaviour of driver such as rate of acceleration, deceleration, speed etc. The developed traffic flow model is extensively preferred for simulation process.

Leutzbach *et al.* (1986) proposed a model that considers psychophysical aspects of driving behavior. The model is well recognized, especially for simulation purpose. It has two parameters to be optimized i.e. response time (T) and desired spacing (S).

Alvarez *et al.* (1990) developed a dynamic simulation model in which stochastic interactions among cars were described by means of the probability of passing. They assumed that the desired speed is characteristic of each driver, reflecting their own plans and it is not related to the presence of other cars. They established equations of motions by establishing the dynamics of the relaxation of each car towards its desired speed.

Brackstone *et al.* (1999) reported that car-following models have been extensive, with conceptual bases supported by empirical data, but generally limited by the lack of time-series following behavior. In many cases work has also been carried out to investigate model stability and the implications of each of the relationships to macroscopic flow characteristics.

Kruass (1997) proposed a model which is a variant of the Gipps model. This is a stochastic model as it includes a stochastic term that was set to zero to unify the comparison. All the parameters to be optimized are same as of Gipp's model i.e. response time (T), braking rate (b) and maximum desired speed (V).

Aycin and Benekohal (1998) assumed that drivers try to attain a steady state relation with their leader within some time interval. The steady state was characterized by preferred time headways and speeds that are equal to the leader speed. The model was calibrated as follows: the preferred time headway was computed as the average of observations in which the absolute relative speed was less than 5 ft/sec.

Hidas (1998) has described a car-following model specifically developed for urban interrupted traffic situations in microscopic simulation models with one second scanning update time. The model is based on the desired spacing criterion which is assumed to be a linear function of the speed. He derived equations for acceleration for conditions: (a) when following close to the desired distance and (b) approaching from a large distance

Aycin and Benekohal (2001) studied the stability and performance of the car-following models such as NETSIM, INTRAS, FRESIM, CARSIM and INTELSIM under congested traffic conditions. It was found that the headways of car-following vehicles are assumed as approximately equal to their reaction times in case of NETSIM and CARSIM models. They also observed certain unrealistic acceleration fluctuations and a large number of maximum decelerations in INTRAS and FRESIM.

Chandrasekar *et al.* (2002) developed a simulation model for a hypothetical bus route using PARAMICS. Bus bunching, measured in terms of disruptions to headways, is found to increase with decreases in design headway, increases in route length, and increases in traffic congestion. It was found that bus control can offer a significant reduction in headway disruptions and hence, in excess waiting time under shorter headways such as 5 and 10 minutes.

Newell (1961) proposed a simple model based on the concept that the driver of the following vehicle drives as a shifted space trajectory of the vehicle ahead. Assuming that the subject vehicle speed is a non-linear function of the spacing of the leader. The form of the G_n function specifies the car-following behavior.

Bham and Benekohal (2004) developed CELLSIM traffic simulation model based on cellular automata for a high volume of traffic at the regional level. Straightforward algorithms and efficient use of computational resources make the model suitable for real-time traffic simulation. The model formulation uses concepts of cellular automata (CA) and car-following models. It is more detailed than CA models and has realistic acceleration and deceleration models for vehicles.

Cho *et al.* (2004) proposed a motorcycle traffic flow model, which is influenced by driver characteristics, vehicle interactions, and the external environment. The longitudinal movement model is similar to the car-following model, the following vehicles try to move on and avoid an accident, but the following vehicles maybe do not keep the “safe” distance.

Jin *et al.* (2012) presented a dynamic model of the staggered car-following process using a Time-to-Collision (TTC) variable. In staggered car-following situations, TTC cannot be defined as the distance between a following and a leading vehicle divided by the relative velocity between the two vehicles. The simulation results imply that lateral separation effects have a significant impact on enhancing the stability of traffic flow.

Zhenga *et al.* (2012) evaluated several typical car-following models by using trajectory data from real traffic conditions and genetic-algorithm-based calibration method. The models with calibrated parameters were validated not only under uncongested traffic conditions but also under congested traffic conditions. It was observed that models with more parameters produce relatively lower error rate in calibration process but the over-fitting problem appears in the validation process.

Tang *et al.* (2014) developed a macro traffic flow model with consideration of varying road conditions. Results illustrate that good road condition can enhance the speed and flow of uniform traffic flow whereas bad road condition will reduce the speed and flow. The numerical results also showed that good road condition can smooth shock wave and improve the stability of traffic flow whereas bad road condition will lead to steeper shock wave and reduce the stability of traffic flow. Study results were also qualitatively accordant with empirical results, which implies that the proposed model can qualitatively describe the effects of road conditions on traffic flow.

Zhou *et al.* (2017) proposed a recurrent neural network based microscopic car following model that may accurately capture and predict traffic oscillation. Authors investigated the existing neural network based microscopic car-following models, and find out that they are generally accurate in predicting traffic flow dynamics under normal traffic operational conditions. However, they do not maintain accuracy under conditions of traffic oscillation. To overcome this author proposed four neural network based models and evaluated their applicability to predict traffic oscillation. It was found that, with an appropriate structure and objective function, the recurrent neural network based model has the capability of perfectly re-establishing traffic oscillations and distinguish driver’s characteristics.

2.2.2 Summary

From these studies it is observed that car-following models have been extensively used to simulate the longitudinal behaviour of vehicles. Several models such as NETSIM, INTRAS, FRESIM, CARSIM and INTELSIM developed for homogeneous traffic showed certain unrealistic acceleration fluctuations and a large number of maximum decelerations (Aycin and Benekohal, 2001; Chandrasekar *et al.,* 2002). Also these models developed for homogenous traffic may not be suitable to simulate mixed traffic situations with vehicle of varying static and dynamic characteristics and non-lane discipline.

2.2.3 Studies on lateral behavior

May and Pratt (1968) developed a model to simulate one directional flow in microscopic detail. The normal distribution was used to assign desired speed and Schuhl's distribution for headway generation. The model used only one class of cars and six subclasses of trucks. Only cars were allowed to overtake in accordance with an empirical gap acceptance distribution under favourable traffic conditions.

Fritzsche (1994) developed a microscopic single-lane car-following model by considering the characteristic properties of the driver and the vehicle. The model was developed for one way two lane highways by considering left to right and right to left lane changing process

Yousif and Hunt (1995) suggested an empirical model for traffic flow based on the data collected under different traffic flow conditions in U.K. A computer simulation program was developed to present the lane changing behavior with respect to the flow in multi-lane unidirectional highways. It is observed that, whenever the flow is very less, most of the vehicles utilize the first lane.

Toledo (2002) developed a model that integrates acceleration and lane changing and allows drivers to accelerate in order to facilitate lane changing. The model assumes that drivers that wish to change lanes but reject the available gap select a target gap in traffic that they plan to merge into within a few seconds. Different acceleration models apply depending on the target gap choice. The specification of these models follows the GM stimulus-response framework. Estimation results indicate that target gap accelerations differ significantly from those applied in other situations.

Gunay (2003) defined the term lane-based driving discipline as the tendency to drive within a lane by keeping to the centre as closely as possible (unless in lane changing), and introduced four possible scales to quantify this discipline.

Gunay (2007) developed a car-following model considering weak discipline based on the discomfort caused by lateral friction between vehicles. The movement of the following vehicle was formulated as a function of the off-centre effects of its leader(s). The lateral discomfort model developed by Gunay realistically simulated various lateral behaviors such as lane change, overtaking, squeezing which are most commonly observed on urban undivided roads. This model uses t_{veer} (time taken to veer laterally) to analyse the overtaking process more realistically

Lv *et al.* (2012) described a microscopic lane-changing process (LCP) model. They presented a new idea of simplifying the lane-changing process by controlling fictitious cars. To verify the model, the results of flow, lane-changing frequency, and single-car velocity were extracted from experimental observations and compared them with the corresponding simulation.

Delpiano *et al.* (2014) addressed the tendency of drivers termed as a collateral anomaly, by which the drivers tend to choose different lateral positions depending on whether they are accompanied side by side by another vehicle or not. In this study, they characterized the collateral anomaly by statistical means starting from three real trajectory datasets belonging to the NGSIM (Next Generation Simulation) project.
Jin *et al.* (2018) discussed the mechanism for discretionary lane-changing behaviour in

traffic flow. NGSIM video data were collected to check the validity of different lane-changing rules, and 373 lane changes at 4 locations in US-101 highway. It was found that the classical lane-changing rules of rule-based model cannot explain many cases in the empirical dataset. Hence authors proposed one new decision rule, comparing the position after a time horizon of several seconds without a lane-change. This rule was described as “to have a further position within 9 seconds”. The tests on NGSIM data shows that this rule can explain most (76%) of the lane-changing cases. Besides, some data when lane changes do not occur were also studied. Most (81%) of non-lane-changing vehicles do not fulfill this new rule. Thus, it was considered as one sufficient and necessary condition for discretionary lane-changing.

2.2.4 Summary

Several lane changing models were proposed to simulate lateral movements of vehicles. It is observed that lateral discomfort model developed by Gunay (2007) realistically simulated various lateral behaviors such as lane change, overtaking, squeezing which are most commonly observed on urban undivided roads. However, none of these models simulated longitudinal and lateral behaviours together.

2.3 STUDIES ON TRAFFIC FLOW MODELS FOR MIXED TRAFFIC

In developing countries such as India, the vehicular mix is composed of different types of vehicles with widely varying static and dynamic characteristics. Also, in mixed traffic conditions, the drivers do not follow any lane discipline. Hence, the simulation models developed for homogenous traffic conditions may not be applicable for mixed conditions. A review of studies related to the development of simulation models incorporating various longitudinal and lateral behavior for mixed traffic conditions is presented below:

2.3.1 Studies on longitudinal behavior

Marwah (1976) proposed a simulation model to study the mixed traffic behavior on two-lane two-way roads. In another study, Marwah and Ramaseshan (l978) have discussed the interaction between vehicles in mixed traffic flow using simulation technique.

Palaniswamy (l983) developed a generalized simulation model for vehicular behavior under heterogeneous traffic conditions. The different situations considered by him in his study are single lane, intermediate lane, and two-lane roads. The study concentrated on the impact of geometry and vehicular characteristics on the traffic flow. Also, considered the fuel consumption due to the gradient, wind resistance, etc.

Arasan and Koshy (2005) developed a simulation model suitable for replicating heterogeneous traffic flow, based on the interval scanning technique with fixed increment time advance. It has been found that the method of treating the entire road space as a single unit, for the purpose of simulation, and representing the different types of vehicles as rectangular blocks on the surface, is more appropriate for simulating highly heterogeneous traffic flow. Car-following logics are adopted to update the positions of vehicles.

Dey *et al.* (2008) developed a computer program to simulate the traffic flow on a two-lane highway. The simulation program was coded in Visual Basic language and it has also been animated. The vehicles on the simulated roadway are considered to be in any one of the following states; free-flowing, decelerating with an intention to follow the lead vehicle, the following state to accelerative state, shifting laterally to overtake, running parallel with the overtaken vehicle and shifting laterally to regain its original position. Car-following rule was adopted and several simulation runs were performed to determine the capacity of a two-lane road and the effect of traffic mix on capacity and speed were studied.

Mathew and Radhakrishnan (2010) presented a methodology for representing non lane-based driving behaviour and calibrating a microsimulation model for highly heterogeneous traffic at the signalized intersection. Calibration parameters were identified using sensitivity analysis, and the optimum values for these parameters were obtained by minimizing the error between the simulated and field delay using a genetic algorithm.

Mathew and Ravishankar (2011) studied the performance of major car-following models and also evaluated them using microscopic vehicle trajectory when the lead and the following vehicle-types are different. Vehicles equipped with Global Positioning System (GPS) receivers were used to collect car-following data from two urban arterials of India. Analysis of car-following data indicated the existence of distinct behaviour for each vehicle-type combination.

Ravishankar and Mathew (2011) made an attempt to modify the widely used Gipp’s car-following model to incorporate vehicle-type dependent parameters. Performance of the model is studied at microscopic and macroscopic levels using data collected from both homogeneous and heterogeneous traffic conditions. The results indicate that the proposed modifications enhance the prediction of follower behaviour and suggest the need for incorporating vehicle-type combination specific parameters into traffic simulation models.

Chena *et al.* (2013) proposed an improved model for mixed traffic flow in real-time traffic data environment in China. Driver's characteristic was defined according to the Nagel- Schreckenberg (NS) model and the Fukui-Ishibashi (FI) model. A cellular automaton traffic model was proposed for heterogeneous traffic conditions. The traffic flow characteristics were analysed and discussed with the help of computer numerical simulation.

Metkari *et al.* (2013) made an attempt to quantify the unaccounted parameters of heterogeneity for Indian traffic into the existing car-following models to form a modified car-following model. A simulation model was developed as a software program to study the performance of the modified car-following model replicating Indian traffic conditions. The model was also used to simulate the traffic stream and some preliminary results were obtained. Validation of the model was done with field data collected from a major road in Delhi.

Kanagaraj *et al.* (2015) focused on the evaluation of different car-following models under mixed traffic conditions. Four commonly used car-following models were selected namely Gipp’s Model, Intelligent Driver Model (IDM), Krauss Model and Das and Asundi Model. These models were implemented in a microscopic traffic simulation model for a mid-block section. Each of these models was calibrated for three states: a non-steady state with constant parameters across classes, steady-state parameter and non-steady state with class wise parameters.

Asaithambi and Basheer (2016) identified different types of the following behavior based on the extent of percentage overlap between leader-follower pair. The vehicle following behavior was classified into three types: 1) Car-following 2) Staggered following and 3) Following between two vehicles. The vehicle following behavior was studied for different categories of vehicles and also, for different types of follower-leader pair. A multinomial Logistic Regression model was used to model the choices of the vehicle following behavior.

Munigety *et al.* (2016) proposed a vehicle-type dependent car-following model using the dynamics involved in the spring-mass-damper mechanical system. The component of ‘mass’ present in the spring-mass-damper system inherently replicates the ‘vehicle-type’. The proposed model when tested, behaved satisfactorily in representing the vehicle-type dependent car-following behaviour.

Asaithambi *et al.* (2018) evaluated various vehicle-following models such as Gipp’s, Intelligent Driver Model (IDM), Krauss Model and Das and Asundi under mixed traffic conditions. These models were implemented in a microscopic traffic simulation model for a mid-block section. The performance of these models was evaluated based on the basis of Measure of Effectiveness (MoE) using field data collected from a four-lane divided urban arterial road in Chennai city. The simulation model was also used to evaluate a range of traffic control measures based on vehicle type and lane (such as the exclusion of auto-rickshaws, heavy vehicles, auto-rickshaws + heavy vehicles, etc.). The results showed the ability of some measures based on vehicle class, namely, the exclusion of auto rickshaws or auto rickshaws and heavy vehicles.

2.3.2 Summary

Most of the longitudinal models developed to simulate mixed traffic flow used Gipps's car following model with vehicle type dependent parameters. The conventional Gipps's model is modified to simulate mixed traffic flows (Arasan and Koshy, 2005; Mathew and Radhakrishnan, 2010; Ravishankar and Mathew, 2011). Few attempts were made to simulate longitudinal behaviour using Intelligent Driver Model (IDM), Krauss Model and Das and Asundi car following models. However, none of the studies considered the effect of non-overlapping leaders to model longitudinal movements of subject vehicles.

2.3.2 Studies on lateral behavior

Oketch (2000) proposed a new modeling approach, suitable for mixed-traffic streams with nonstandard vehicles. The model also covers different vehicle types, including non-motorized ones, and allows for some special behaviours, such as seepage to fronts of queues by two-wheeled vehicles and simultaneous use of two lanes. The model also incorporates lateral movement with a gradual lane change manoeuver in addition to normal car-following rules, the decisions of which are ruled by fuzzy logic procedures. The model was calibrated and validated using the data collected from Nairobi, Kenya, and its results showed close agreement with the field data

Gundaliya and Mathew (2005) made an attempt to model heterogeneous traffic using cellular automata. Various lane changing rules that reflect driver behavior in mixed traffic conditions were introduced. Microscopic and macroscopic validations were carried out by using VISSIM data and field observed data respectively.

Menga *et al.* (2007) proposed a single-lane cellular automaton model to simulate mixed traffic including motorcycles. They performed numerical simulations under the periodic boundary condition, some density-flow relations and the ‘‘lane-changing’’ behavior of motorcycles were investigated. It was found that the maximum car flow decreases because of the ‘‘lane-changing’’ behaviour of motorcycles. The maximum total flow increases first and then decrease with increasing motorcycle density. The simulation results indicate that it is necessary to set a barrier or a lane for separating the motorcycle flow from the car flow except in some special density regime.

Kanagaraj *et al.* (2008) used object-oriented programming (OOP) approach to develop a simulation model for replicating heterogeneous traffic. Initially, the study reported the various logics of simulation such as vehicle generation, vehicle placement, and vehicle movement. Later on, the authors described the features of OOP, description of classes and class relationships. The model considered several operations such as movement, overtaking, car-following, etc. The validation of the model was based on headway distribution and speeds of different types of vehicles indicates that the model is satisfactorily replicating field conditions.

Maurya (2011) developed a comprehensive microscopic model for unidirectional uninterrupted traffic stream with or without lane discipline which is able to determine both steering control (lateral control) and speed control (longitudinal control) actions of the drivers. It was assumed that drivers move safely and at satisfactory speed when they choose a steering angle or path within their vicinity. The developed model was evaluated for various macroscopic features such as flow-density relationship and effect of road blockage on capacity. Also, various microscopic features such as acceleration noise and speed distribution were analyzed for real-world traffic stream and it was observed that the developed model is capable of simulating the traffic stream with no lane discipline realistically.

Mallikarjuna and Rao (2011) made an effort to develop a comprehensive methodology to model the heterogeneous traffic. In formulating the CA structure, important microscopic variables such as lateral gaps, longitudinal gaps and lateral distribution of vehicles have been utilized. The relationship between area occupancy and a variant of flow measured in terms of cells have been utilized in calibrating and validating the proposed CA model. Model validation was done using the field data collected on different road sections.

Asaithambi *et al.* (2012) studied the influence of lane discipline, intra class variability, and composition on traffic flow characteristics under heterogeneous traffic conditions.

A microscopic traffic simulation model was calibrated and validated with field data from a four-lane divided urban arterial road. In vehicle movement logic, the overtaking and car-following behaviour of vehicles were incorporated and Gipp's model was used for car-following logic. The simulation model was used to evaluate a range of traffic control measures based on vehicle type and lane, promising results were seen based on vehicle class.

Hu *et al.* (2012) proposed a model for the mixed traffic flow by introducing a new set of rules in the framework of Kerner’s three-phase theory. A series of simulations were carried out in order to disclose the formation, travel process and influence of the mixed traffic flow. The simulation results show that the proposed model can be used to study not only the travel characteristic of the mixed traffic flow but also some complex traffic problems such as traffic breakdown, moving synchronized flow pattern (MSP) and moving jam.

Mathew *et al.* (2013) proposed a space discretization–based simulation framework. A longitudinal movement model is proposed to take into account the multiple leaders and vehicle-type dependent following behaviour. The lateral movement model allows tactical overtaking manoeuvres by a vehicle, which may require multiple strip changes. Thus, the continuous lateral movement has been modelled by defining very small strip widths. The model was calibrated and validated with data from Mumbai, India, and the results indicated better representation of the mixed traffic movement.

Mahapatra and Maurya (2013) studied the lateral movement of the vehicle in case of straight road section to study the vehicular operations. The main purpose of the study was to observe the lateral acceleration, speed values in the moderate traffic conditions and to investigate the relationship between the vehicle longitude speeds with the lateral characteristics in the Indian traffic condition. It was observed that there is an inverse relation between longitudinal speed and lateral acceleration for all the three types of the vehicle except at lower speeds. At higher speeds the vehicle's rate of change of heading angle reduced.

Choudhury and Islam (2016) presented a latent leader acceleration model. This model has two components: a random utility based dynamic class membership model (latent leader component) and a class-specific acceleration model (acceleration component). The parameters of the model have been calibrated using detailed trajectory data collected from Dhaka, Bangladesh. Results indicate that the probability of a given front vehicle of being the governing leader can depend on the type of the lead vehicle and the extent of lateral overlap with the subject driver.

Mahapatra *et al.* (2016) studied lateral movements of vehicles over different types of roads in three metropolitan cities of India (Kolkata, Mumbai, and Pune) under moderate traffic conditions. Lateral acceleration variation of five different types of vehicles (SUV cars, Sedan cars, Hutch Back cars, motorized three-wheelers and two-wheeler) was recorded to investigate their relationship with vehicles longitudinal characteristics (i.e. longitudinal speed) in Indian heterogeneous and weak lane disciplined traffic. It was seen that lateral acceleration values quickly rise with an initial increase in speed afterward lateral acceleration values reduces with further increase in vehicles longitudinal speed. Impact of vehicle type and locations on the lateral manoeuvring of vehicles was also studied.

Mohan and Ramadurai (2017) first aim of the study was to propose a parsimonious model of heterogeneous traffic that can capture the unique phenomena of gap filling. The second aim was to emphasize the suitability of higher-order models for modeling heterogeneous traffic. Third, the study aims to suggest area occupancy as concentration measure of heterogeneous traffic lacking in lane discipline. The above challenges of heterogeneous traffic flow were addressed by extending an existing second-order continuum model of traffic flow, using area occupancy for traffic concentration instead of density. The extended model was calibrated and validated with field data from an arterial road in Chennai city, and the results were compared with those from few existing generalized multi-class models.

Pal and Chunchu (2017) studied the vehicular movement in mixed traffic stream with no lane discipline under the influence of the leading vehicle but also by the presence of the adjacent vehicles. Analysis of the real world field data shows that there is a wide variation in the total lateral gaps, even for a particular combination of passing/overtaking vehicle and both the adjacent vehicles. Speed and type of the passing/overtaking vehicle and the speed and type of both the adjacent vehicles were found to be having a significant influence on the total lateral gaps. The variability in the critical total lateral gaps was explained using the variables such as the speed and type of the subject vehicle, as well as the adjacent vehicles. Developed models was found to be statistically significant in replicating the field observed total lateral gaps corresponding to various types of vehicles. The impact of different lateral gap models has been studied using a CA-based simulation model and found that the gap maintaining behaviour significantly influences the flows close to capacity.

2.3.3 Summary

Most of the lateral movement models developed to simulate mixed traffic flow used certain overtaking rules to incorporate lateral movements (Oketch, 2000; Menga *et al.*, 2007; Mathew *et al.*, 2013). These model considered impact only adjacent vehicles during overtaking and most of these models are unidirectional. Also, none of these studies modelled both longitudinal and lateral movement together.

2.4 STUDIES ON BI-DIRECTIONAL TRAFFIC FLOW MODELS

Many research has been carried out to study the lateral and longitudinal behavior of vehicles in case of divided roads (unidirectional). There are only limited studies carried out to study the bi-directional traffic stream which are presented below.

Simon and Gutowitz (1998) modified the single-lane model of Nagel and Schreckenberg, to develop a cellular automaton (CA) model for traffic on a bidirectional two-lane road. They considered the interactions mediated by passing and for a distribution of vehicle speeds, choosing chose values for the various parameters to approximate the behaviour of real traffic. The density-flow diagram for the bidirectional model was compared to that of a one-lane model, showing the interaction of the two lanes. Results were also compared to experimental data.

Chakroborty *et al.* (2004) made an attempt to develop a comprehensive microscopic model of driver behaviour. Authors explained the actions of a driver in a variety of driving scenarios ranging from free-flow conditions on wide roads to forced flow conditions on narrow two-way roads. Initially, they proposed a single model which is used to describe driver behaviour in different driving scenarios and later on the response of drivers through both steering control and speed control were modelled. Acceleration Response Model (ARM) is used to predict the acceleration/ deceleration rates of Test Vehicle (TV) over time in different driving situations.

Dey *et al.* (2008) have developed simulation program for traffic flow modeling on a two-lane road. Random placement for vehicles is assigned within a lane. Moreover, some clearance is also incorporated from edge and shoulder of a roadway. Logical overtaking is implemented using a set of well-defined rules to imitate continuous decision making of drivers. This study is not limited only to the speed-flow relationship, while the model is applied to estimate the capacity of the road, to check the variation of PCU (passenger car unit) values for mix traffic, and effect of traffic mix on capacity.

Budhkar and Maurya (2014) developed a car-following model replicating bidirectional traffic conditions. Firstly, the authors developed a unidirectional model taking into account heterogeneity and ‘no lane-discipline’ nature of mixed traffic streams. Later on, certain rules for overtaking and relevant modifications were included to develop a bidirectional traffic flow model. The bi-directional rules such as time to collision for opposite vehicles, safe stopping distance and time to overtake were also defined. They considered seven different cases to study the vehicle movement considering the influence of opposing traffic. The developed model was calibrated and validated for real-world traffic data collected from an undivided state highway. The speed-flow-density characteristics of traffic, as well as microscopic relationships as generated by the model, showed a satisfactory relationship with the field data.

Luo *et al.* (2014) investigated the operational characteristics of the mixed traffic flow. They developed a cellular automaton model to replicate the travel behaviours on a bi-directional road segment with respect to the physical and mechanical features of different vehicle types. Essential parameters calibrated through the field data collection were implemented in the model, a numerical study was also carried out considering the variation in volume, density, and velocity with different compositions of mixed traffic flows.

Maurya *et al.* (2015) studied time headway distribution of vehicles for the mixed vehicular flow and for different leader-follower vehicle pairs on the basis of six traffic flow levels [0-200, 200-400, 400-600, 600-800, 800-1000 and 1000-1200] PCU/h. Analysis of collected speed data was also carried out to obtain the speed distribution patterns in mixed traffic condition and also vehicle class-wise speed analysis was performed to identify the impact of overall flow and vehicle composition on speed.

Torre *et al.* (2017) developed a reliable and reproducible simulation model in vehicular networking demand to replicate the traffic on bi-directional highway. The authors recorded real-world fine-grained measurement data from M40 highway in Madrid, Spain, to feed a realistic and properly parameterized microscopic simulation of vehicular mobility. The output is the first dataset of bidirectional highway traffic that is publicly accessible to the vehicular networking community. The dataset was used to demonstrate validity in a complete highway scenario of the three-phase law of vehicular network connectivity, which was previously considered only on single carriageways.

2.4.1 Summary

Literature review reveals that only limited attempts have been made to study bi-directional traffic flow and most of these studies are carried out for homogenous traffic (Simon and Gutowitz, 1998; Chakroborty *et al.,* 2004; Dey *et al.,* 2008; Budhkar and Maurya, 2014; Luo *et al.,* 2014). None of these models studied the effect of surrounding vehicles on subject vehicle. However, in mixed traffic (undivided sections) the surrounding vehicles have greater influence of manoeuvres of subject vehicle due to lack of lane segregation.

2.5 STUDIES ON TRAFFIC MANAGEMENT MEASURES USING SIMULATION

In this section, the studies focusing on implementation of various traffic management measures such as modal shift and reversible lanes to tackle traffic-related problems such as traffic congestion, pollution, accidents, etc. using traffic simulation models are discussed.

Papageorgiou *et al.* (2009) developed and evaluated various scenarios of dedicated bus lanes and bus priority schemes to bring back commuters to public transportation as surveys among Cypriot commuters indicated that people are willing to use buses if buses offer a fast and trustworthy service.

Pandian *et al.* (2009) observed the effect of traffic, vehicle and road characteristics on vehicular emissions to know relationship between various emissions and their most likely influencing and measurable features.

Van *et al.* (2009) used simulation models to demonstrate the traffic conditions in Ho Chi Minh City under different scenarios of levels of car and bus usage to predict the adverse effects of shifting from motorcycle to car, scenarios, i.e., 10%, 20%, 40%, 60% car use, were simulated.

Fathima and Kumar (2014) examined the impact of a new public bus transit system by applying a binary logit analysis for evaluating the possible variation in modal shift by developing study of mode-choices. The model was calibrated, and validated using socio-economic data collected from six proposed corridors in city of Bardoli, Gujarat, India.

Satiennam *et al.* (2015) developed modal split models for predicting the choices of passenger car users and motorcycle users. Study suggests that bus transit system could attract significant number of private vehicle users.

Tiwari *et al.* (2015) studied travel behaviour of three medium-size cities – Udaipur, Rajkot and Vishakhapatnam using three scenarios i.e. by improving only non-motorized transport (NMT) infrastructure, improving only public transport (PT) and improving both NMT and PT. This scenario analysis showed that maximum reduction in CO_2 emissions was achieved when both PT and NMT infrastructure are improved.

Verma *et al.* (2015) developed a model to study the impact of various transportation policies on the basis of variation in environmental, economic and social aspects. Composite Sustainability Index (CSI) were studied before and after implementation of transportation policy using several indicators such as air pollution, natural resource consumption, health, accessibility, mobility, commute, and cost. CSI was obtained by weighing them using an Analytical Hierarchy Process (AHP). The indicator value under a transportation policy scenario is obtained using the mode shift found using a mode choice model incorporated with the policy variable. Further, a case study for the city of Bangalore where the sustainability impact due to introduction of congestion pricing in the CBD, during peak hour, was performed. A choice model developed from Revealed Preference data (RP) estimated a reduction of 14.11% and 2.4%, respectively in the total trip distance travelled by car and bike trips after introduction of congestion charging. Also, there was an increase of 1.7% in CSI because of congestion pricing.

Waleczek *et al.* (2016) discussed the effects of the reversible lane system on traffic flow and road safety. The capacity of the work zone was estimated with the stochastic capacity estimation technique based on models for censored data. Authors compared the capacity of the unaffected three-lane carriageway with temporary hard shoulder running. It was observed that a decrease of capacity by around 15% was estimated for the four-lane work zone configuration including the reversible lane.

Jaikumar *et al.* (2017) presented the characterization and modelling of exhaust emissions released from the passenger cars on urban roads under mixed traffic conditions. On-board exhaust emissions measurement was made at selected corridors in a populous urban area of India. Exhaust emissions were characterized for different driving modes classified according to vehicle specific power (VSP). Results indicated that emissions at VSP modes under cruising speeds were 10–12 times less than idling (which is the mode used for emission standard certification), braking and accelerating conditions. It was also found that more than 20% of time vehicles were in idling conditions at most of the roads.

Rahul and Verma (2017) analysed the influence of environment factors such as density and diversity on the mode choice and trip distance for Bengaluru city. Two segments: respondents owning at least one personal vehicle and respondents not owning any personal vehicle were considered. These environment factors were analysed for their marginal effects in the presence of various socio-demographic and alternate specific attributes. The results for the vehicle non-owning group emphasised the requirement of a policy framework to reduce their trip distance by controlling their employment and housing location. The gender of a commuter had a significant effect on the choice of modes, and the results show that females had a higher likelihood of using NMT compared with males contradicted the results in other cities. Also, the trip distance model determined that females preferred a shorter walking distance compared with males.

2.5.1 Summary

From the literature review, it is understood that only limited evaluation studies are carried out to implement the traffic management measures using traffic simulation models. The traffic management measures such as implementation of reversible lanes, modal shift, exclusive bus lanes, etc. are studied (Papageorgiou *et al.*, 2009; Van *et al.*, 2009; Tiwari *et al.*, 2015; Rahul and Verma, 2017. However, only limited studies used traffic simulation models to study the impact of these management measures and application of the developed model to reduce traffic related problems.

2.6 SUMMARY OF THE LITERATURE

2.6.1 Summary

A detailed review of the literature has been presented in this chapter. Studies related to the development of simulation models for both homogeneous and mixed traffic conditions have been discussed in detail. The various car-following models used for the development of simulation model for homogeneous traffic conditions have been explored. Also, the lateral and longitudinal behavior of vehicles on different types of roads are reported in this chapter.

Based on the review of the literature, it is seen that most of the studies related to homogeneous traffic conditions are for unidirectional traffic. Only few studies are carried out related to lane changing and overtaking manoeuvres in case of homogeneous traffic. Various traffic simulation models and commercial software have been developed for homogeneous traffic flow conditions. The scope of applicability of these models and software to mixed traffic is not clearly mentioned in previous studies. Literature related to longitudinal behavior of vehicles discussed about various car-following models and, modification of these car-following models so as to replicate the mixed traffic conditions. Few studies explain the various lane changing and overtaking aspects associated with the mixed traffic environment. Many research works have been carried out with different approaches to model the traffic flow. Only limited studies have been done to understand and model traffic flow characteristics at urban undivided mid-block sections under mixed traffic conditions. These traffic simulation models can be used to evaluate various traffic management measures to improve the capacity of existing road systems. From the literature review, it is understood that only limited evaluation studies are carried out to implement the traffic management measures using traffic simulation models. The traffic management measures such as implementation of reversible lanes, modal shift, exclusive bus lanes, etc. are studied. However, only limited studies used traffic simulation models to study the impact of these management measures.

2.6.2 Research gaps

Only limited studies are carried out in developing bi-directional simulation models for undivided roads (Simon and Gutowitz, 1998; Chakroborty *et al*., 2004; Dey *et al*., 2008; Budhkar and Maurya, 2014; Luo *et al*., 2014). These simulation models consider the overlapping criteria for identifying a true leader. But, in mixed traffic conditions due to weak lane discipline, non-overlapping vehicles may also influence the movement of the subject vehicle. The influence of surrounding vehicles on the movement of the subject vehicle are also not addressed in these models. Thorough validation of the model and application of the developed model are also not presented in these previous studies. Therefore, these aspects have to be considered and effective ways to identify true leader considering both overlapping and non-overlapping vehicles is required. In mixed traffic condition, the amount of lateral movements is very high due to lack of lane discipline and hence modelling longitudinal and lateral movements independently may not be efficient in mixed traffic. Also, in most of developing cities the composition of two-wheelers is more than 60 % and these two-wheelers squeeze in between gaps of larger vehicles performing both lateral and longitudinal manoeuvres to attain their speeds. Hence, modelling both longitudinal and lateral movements together is more feasible in mixed traffic conditions. Most of the existing models are calibrated and validated using the data collected from the same site. Hence, thorough validation of the model using external data set collected from other sites is necessary to ensure its applicability to other sites.

CHAPTER 3

METHODOLOGY AND DEVELOPMENT OF BI-DIRECTIONAL SIMULATION MODEL

3.1 GENERAL

The overall study focuses on the development of bi-directional traffic simulation model for urban undivided roads. The study consists of various modules and the overview of the study methodology is presented in Figure 3.1.

3.2 STUDY METHODOLOGY

The study is divided into various sequential steps as follows:

3.2.1 Identification of study parameters

Initially, the study parameters required to build the simulation model are identified from the detailed literature survey as well as from field data analysis. The factors such as speeds, acceleration, longitudinal and lateral gap and headway are considered as the study parameters.

3.2.2 Identification of study location

Ideal study location which is free from side interference is identified. An undivided mid-block section located in the urban vicinities is selected for the data collection. Two different locations are selected, of which data from one location is used for model development and internal validation whereas data from another location is used for external validation.

3.2.3 Data collection and extraction

The video-graphic method is used to record the traffic data from the selected study locations. Traffic data are collected on both peak and off-peak hours on a typical weekday and the study parameters are extracted from this recorded video data using an image processing software.

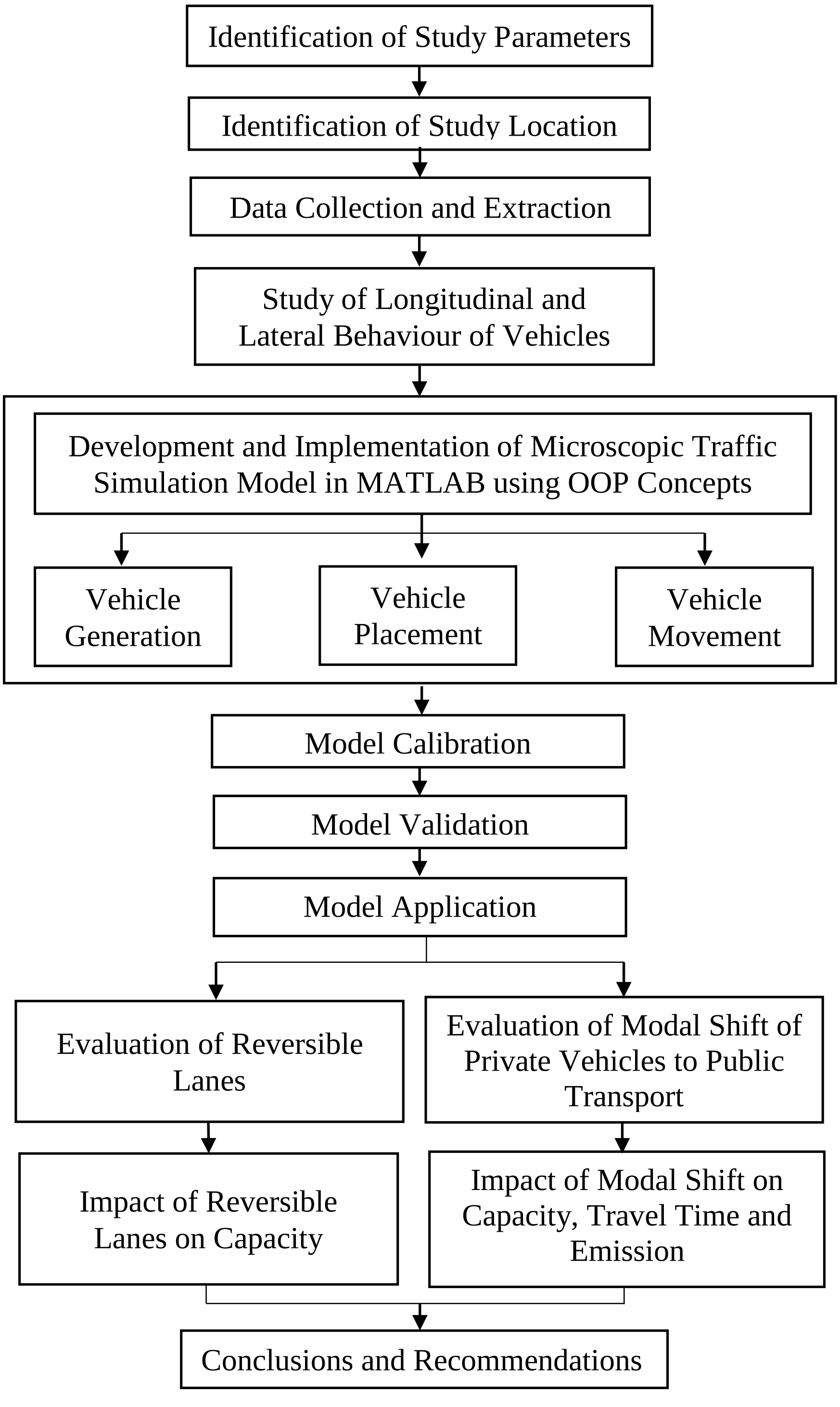


Figure 3.1 Overview of the study methodology

3.2.4 Study of the longitudinal and lateral behavior of vehicles

The longitudinal behavior (such as car following) and lateral behaviour (such as overtaking and passing) of vehicles are studied using the real world data and these behaviours are incorporated in the traffic simulator using various models (longitudinal and lateral movement models).

3.2.5 Model development

The concepts of Object-Oriented Programming (OOP) are implemented in MATLAB programming language to develop the microscopic traffic simulation model. Modelling of traffic flow at a mid-block section mainly consists of three logic: (1) vehicle generation, (2) vehicle placement, and (3) vehicle movement. The developed model is calibrated and validated using the field data. Both internal validation and external validation of the model is carried out.

3.2.6 Calibration of the model

Calibration is the iterative process of comparing the model with a real system and revising the model by making modifications to the built parameters if necessary until the model accurately represents the real system. The calibration parameters necessary for refining the developed model are identified from the real world traffic data and few parameters are adopted from the previous studies. Also, the efficiency of the model to simulate varying traffic composition is evaluated and the effect of these composition on critical parameters (speed, flow, and density) is studied.

3.2.7 Validation of the model

Model validation is the process of comparing model results with the corresponding field observed values to ensure that the simulated results realistically represent the real system. In the present study, the simulation model is validated using both internal and external data sets by considering speed as the measure of effectiveness (HCM 2010).

3.2.8 Application of the model

The developed model is used to evaluate various traffic management measures such as evaluation of reversible lanes and modal shift of private vehicles towards public transport system. In this analysis, reversible lanes are implemented in the developed model for both morning and evening peak hours and the impact of reversible lanes on peak hour capacity is studied. In another application, the commuters from private vehicles (two-wheelers and cars) are shifted to public transport system (buses) and its impact on capacity, travel time, and traffic emissions are studied.

3.3 DEVELOPMENT OF BI-DIRECTIONAL MIXED TRAFFIC SIMULATION MODEL

The microscopic traffic simulation model is developed based on the interval scanning technique with a time step of 1 s. Different vehicle types are represented as rectangular blocks with predefined dimensions whose positions are defined by coordinates with reference to an origin. Initially certain parameters such as road length, width and vehicle composition are given as input to the model. Simulation time represents the total time in seconds for which the model will run. The entire modelling framework for simulating traffic flow at a mid-block section consists of three main logics i.e. vehicle generation, vehicle placement, and vehicle movement. Both ongoing and opposing vehicles are modelled together (bi-directional) and the overall framework for the development of the traffic simulation model is shown in Figure 3.2.

3.3.1 Vehicle generation

The vehicles are generated at either ends of the simulation road stretch at the beginning of the simulation run. In this study, four different types of vehicles such as two-wheelers, cars, auto-rickshaws, and heavy vehicles are generated using vehicle type headway distribution. The vehicle generation step involves identification of the type of vehicle, generation of headway and assignment of free speed.

3.3.1.1 Headway generation

In this study, vehicles are generated using various vehicle-type dependent headway distributions. The observed headways (from the real world traffic data) of the stream fits significantly with Weibull distribution. These observed headway ranges in between 0 to 17.4 s and the cumulative frequency of headway is obtained for a class interval of 1.4 s which is given as input to the simulation model. Two random numbers are generated using “rand”, inbuilt function in MATLAB (Version R2015a). The first random number is used to identify the vehicle in the headway range of 0 to 17.4 s and the second random number is used to calculate the headway to generate the vehicle.

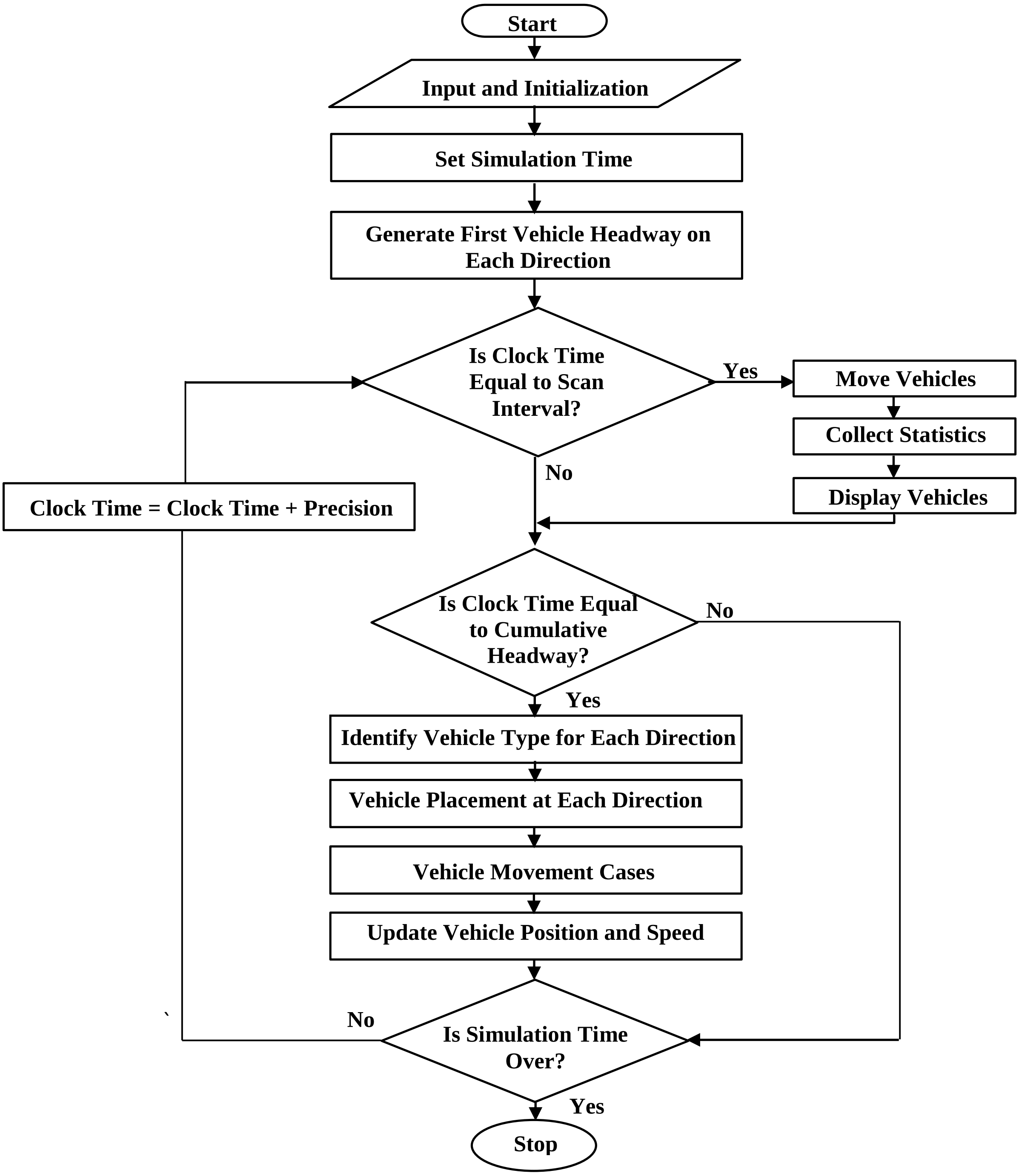


Figure 3.2 Overall structure of the simulation model

3.3.1.2 Identification of the vehicle type

The type of vehicle is identified based on the cumulative vehicular composition. The logic for identification of the vehicle type is shown in Figure 3.3. For example, if the composition is 60 % two-wheelers, 20% cars %, 10% auto-rickshaws and 10% heavy vehicle s, the threshold values are fixed as 0 to 0.60 for two-wheelers, 0.61 to 0.80 for cars, 0.81 to 0.90 for auto-rickshaws and 0.91 to 1.0 for heavy vehicles.

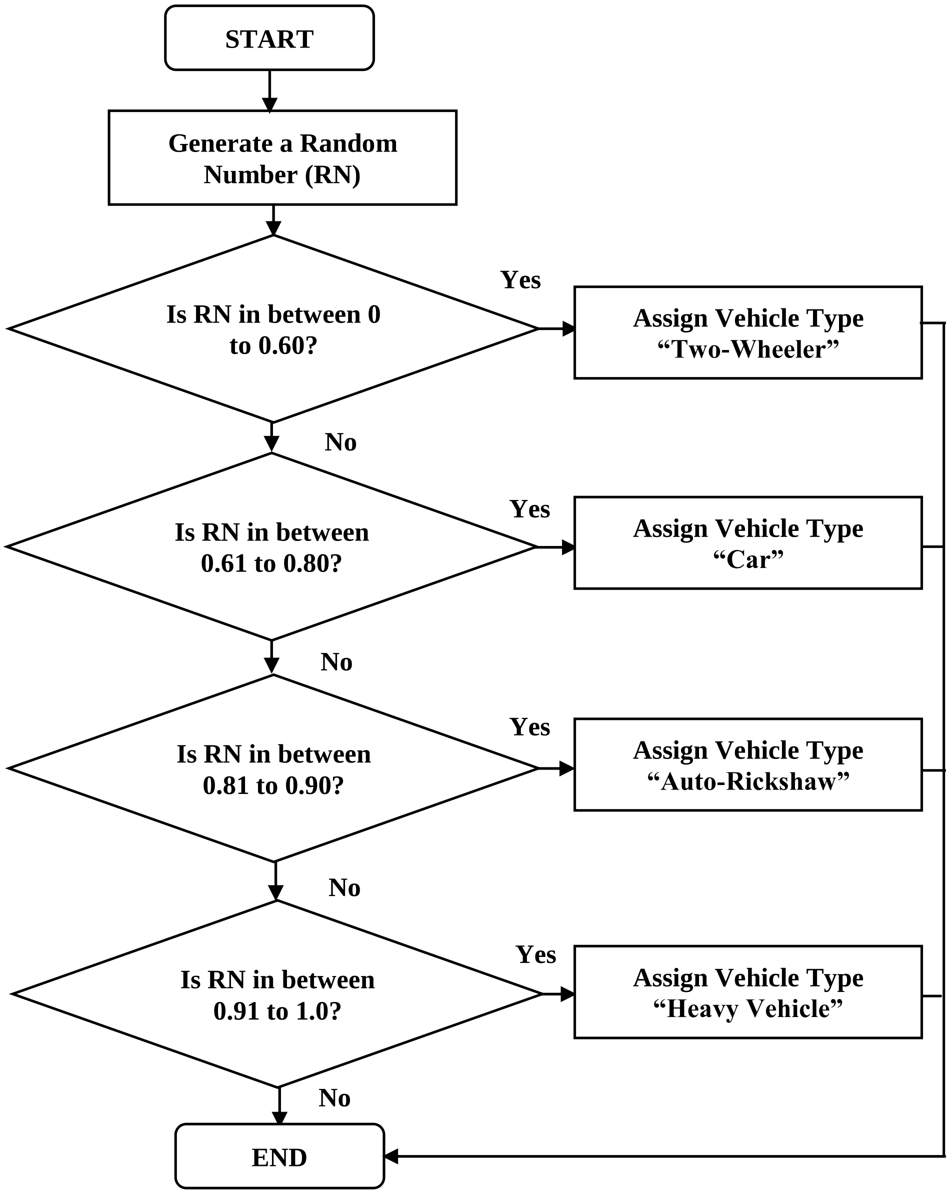


Figure 3.3 Logic for vehicle type identification

A random number (RN) in the range of 0 to 1 is generated in MATLAB using inbuilt function *"rand"*. If the generated RN is in range of 0 to 0.6 (cumulative vehicle composition) the generated vehicle is assigned as type "two-wheeler". If generated RN is in the range of 0.61 to 0.80 the vehicle type is assigned as "car". The vehicle type "auto-rickshaw" is assigned if generated RN ranges in between 0.81 to 0.90. Similarly, if the RN ranges in 0.91 to 1, the generated vehicle is assigned as type "heavy vehicle".

3.3.1.3 Assignment of free speed

Once the vehicle type is identified, the static (e.g., length, width) and dynamic characteristics (e.g., speeds, acceleration, gaps) of vehicles are assigned to each generated vehicle. The logic for assignment of free speed is shown in Figure 3.4.

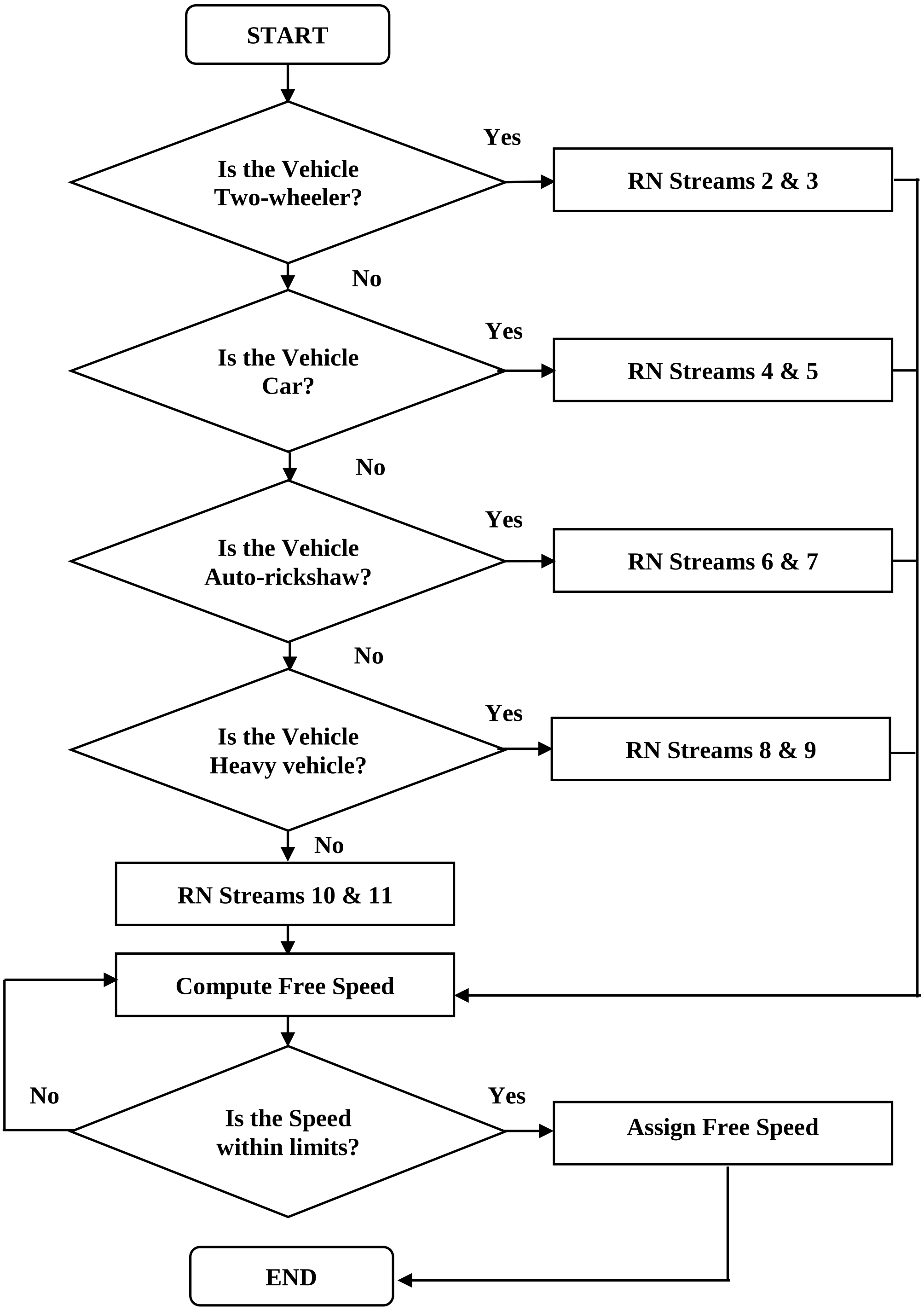


Figure 3.4 Logic for assignment of free speeds

Free speed of each generated vehicle is assigned using Box-Muller transformation method to generate normal deviates using the following equation:

$$S = (-2 \text{ In } r_1)^{1/2} \cos (2\pi r_2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

where,

r_1 and r_2 = Random numbers from two different random streams

S = Standard normal deviate

A sample *u* from a normal distribution, with a specified mean (μ) and standard deviation (σ) can be obtained as:

$$u = \sigma S + u \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.2)$$

This value of *u* is assigned as the free speed of the generated vehicle under consideration. Figure 3.4 shows the logic for assignment of free speeds. Based on the vehicle type, two random number r_1 and r_2 are generated from two different random number streams. For example, if the generated vehicle is two-wheeler, two random numbers are generated from random number streams 2 and 3, respectively. These random numbers are fed in the Box-Muller transformation and the free speed (*u*) is calculated for each generated vehicle type.

3.3.2 Vehicle placement

Vehicle placement implies positioning of vehicles at the start of simulation road stretch in a suitable coordinate across the width and along the length of the road based on the longitudinal and lateral gaps. The lateral placement of vehicles on simulation stretch is decided based on the real world traffic data collected from a 12 m wide urban undivided mid-block section. The road width is laterally divided into strips of 2 m each as shown in Figure 3.5. Vehicles are placed on these strips according to the vehicular proportion and speeds. From the data, it is observed that most of the vehicles prefer to travel at higher speeds near the middle of the study section. Hence, strip 3 is the most preferred strip for vehicle placement followed by strip 2, strip 4, strip 5, strip 1, and strip 6. On the basis of this priority, the vehicles are placed on the study section at the beginning of the simulation road stretch.

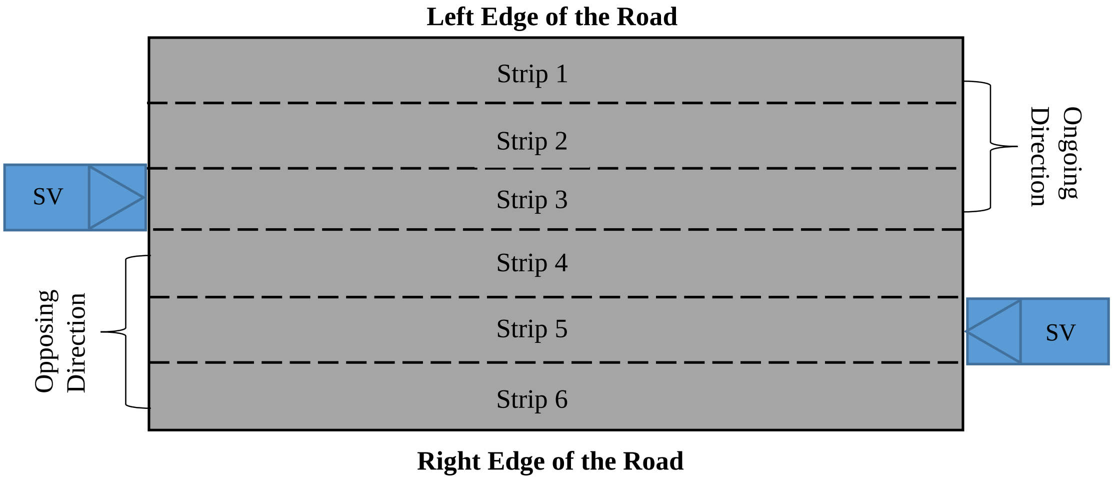


Figure 3.5 Strip based vehicular placement

The logic for vehicle placement is shown in Figure 3.6. The vehicles are placed on either ends (ongoing and opposing direction) of the road stretch simultaneously. Initially, the first preferred strip (strip 3) is selected for vehicle placement at the beginning of the simulation road stretch.

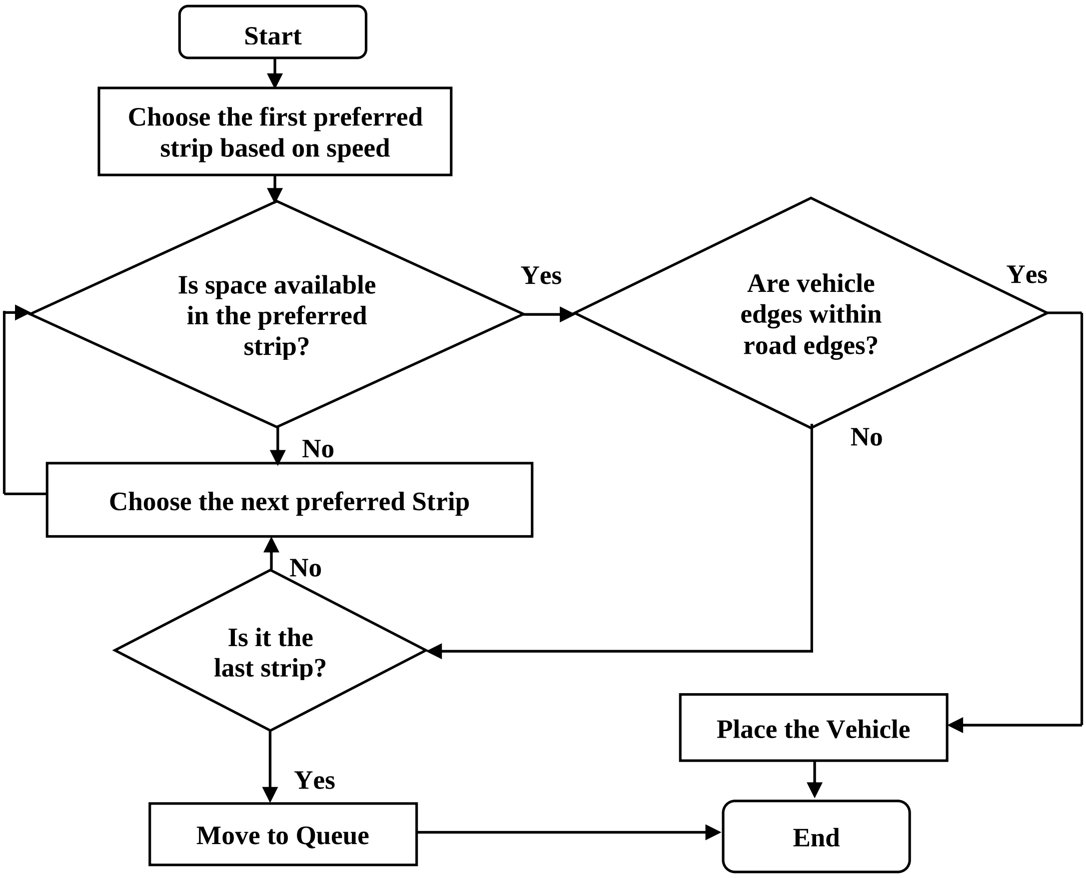


Figure 3.6 Logic for vehicle placement

The presence and absence of vehicles on the preferred strip is scanned before placing the generated vehicle. The absence of a vehicle in a strip causes the generated vehicle to be placed in that strip at its free speed. If suppose, a vehicle is already present in the preferred strip, the next strips are scanned as per the preference order. If the generated vehicle cannot be placed in any of the strips, the vehicle is added to the virtual queue and the availability of a strip for placement is checked again in the next time step.

3.3.3 Vehicle movement

Vehicle movement logic involves updating positions and speeds of vehicles at every scan interval. The movement of the subject vehicle are influenced by the surrounding vehicles and opposing vehicles. Depending on the positions and speeds of the surrounding vehicles, namely, the leader vehicle, adjacent vehicles, and opposing vehicles, the appropriate manoeuvres are performed by the subject vehicle. The influence while performing a movement is based on the response to the movement of surrounding vehicles. To identify the most influencing surrounding vehicle a concept of influence area is introduced in this study.

3.3.3.1 Influence area

A boundary which encloses the most influencing surrounding vehicles which affect the maneuvers of a subject vehicle is referred as an influence area. The explanatory variables such as type and speed of subject vehicle, type and speed of leader vehicle, type and speed of adjacent (left and right) vehicle, longitudinal and lateral gaps are extracted from the real world traffic data. In order to predict the influence area at every time step, multiple linear regression (MLR) models are developed for left adjacent, right adjacent, and longitudinal boundaries, separately. The most influencing surrounding vehicles and its characteristics (e.g. type, speeds, and gaps) may be the explanatory variables for defining the boundary of influence area. 75% are used to develop the model and remaining data are used to validate the developed model. Correlation analysis is done to select the most influencing variables and to eliminate the irrelevant variables. After performing the correlation analysis, it is found that type of subject vehicle, speed of the subject vehicle, type of adjacent vehicle, and speed of the adjacent vehicle are the most influencing variables and hence, they are considered for developing the model. The model to fix the longitudinal boundary of the influence area is shown below:

$$\text{Longitudinal boundary (m)} = 1.97 - 0.03*(t_s) + 0.22*(v_s) + 1.11*(t_l) + 0.46*(v_l) \text{ ..(3.3)}$$

where,

t_s = Type of subject vehicle

v_s = Speed of subject vehicle

$t_{l,}$ = Type of leader vehicle, and

v_l = Speed of leader vehicle

Any regression model is accepted based on the model goodness of fit, the significance of overall model and significance of independent variables. The R^2 value (goodness of fit) of the model is obtained as 0.63. The model has *F - observed* more than the critical value (F_{obs}=6.36, F_{crit} = 3.72, degree of freedom (*dof*) =248) implying that the model is statistically significant. However, the longitudinal boundaries are limited to 30 m from the front or rear edge of the subject vehicle, as vehicles that fall outside this region are empirically observed to have very little influence on the given vehicle's decisions.

The left adjacent boundary is taken as the left edge of the nearest vehicle on the left hand side of the subject vehicle. The model to fix the left adjacent boundary of the influence area is shown in following equation:

$$\text{Left adjacent (m)} = 2.48 + 0.07*(t_s) + 0.05*(v_s) - 0.26*(t_{la}) - 0.08*(v_{la}) \text{ ....(3.4)}$$

where,

t_{la} = Type of left adjacent vehicle, and

v_{la} = Speed of left adjacent vehicle

The R^2 value of the model is obtained as 0.61. The model has *F - observed* more than the critical value (F_{obs}=6.21, F_{crit} = 3.37, *dof* =275) implying that the model is statistically significant.

The right adjacent boundary is fixed as the right edge of the nearest vehicle on the right hand side of the subject vehicle. The model to fix the right adjacent boundary of the influence area is as shown in following equation:

$$\text{Right adjacent (m)} = 3.17 - 0.15 * (t_s) + 0.06 * (v_s) + 0.15 * (t_{ra}) - 0.08 * (v_{ra}) \text{ ………}(3.5)$$

where,

t_{ra} = Type of right adjacent vehicle, and

v_{ra} = Speed of right adjacent vehicle

The R^2 value of the model is obtained as 0.71. The model has *F- observed* more than the critical value (F_{obs}=7.24, F_{crit} = 3.08, *dof* =255) implying that the model is statistically significant. Whenever these left and right adjacent boundaries are farther than 3 m from the subject vehicle, these boundaries are restricted by a lateral gap that does not exceed 3 m on each side. The rectangular area formed by these boundaries is considered as the influence area for a given subject vehicle as shown in Figure 3.7. Any vehicle which is fully or partly present in this influence area is considered as an influencing vehicle.

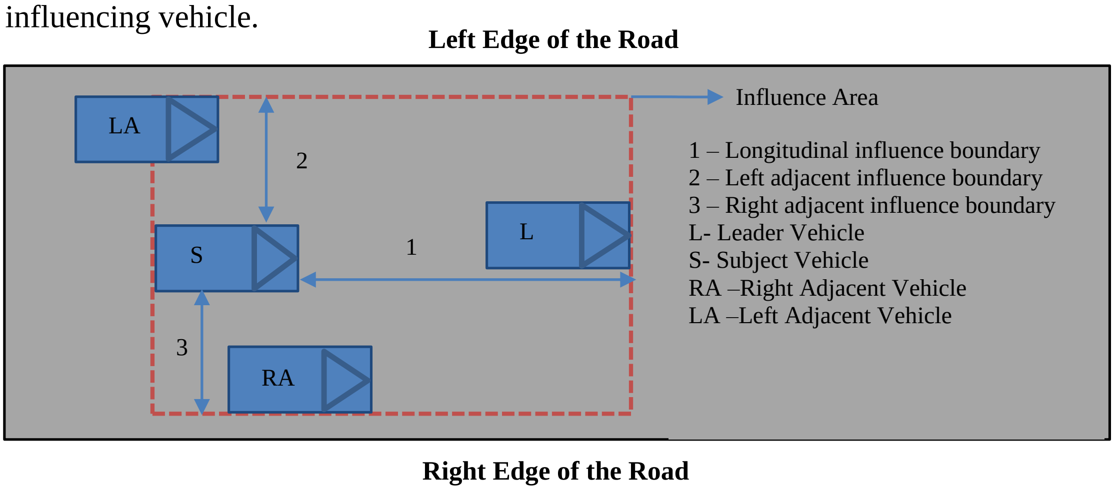


Figure 3.7 Subject and surrounding vehicles in the influence area

3.3.3.2 Vehicle movement cases

Based on influencing surrounding vehicles present in the influence area, certain cases are identified (Figure 3.8) which are considered to update positions and speeds of vehicles and logics are as shown in Figure 3.9. In proposed model, longitudinal movements are governed by Gipp's model (Gipps, 1981) with vehicle type dependent parameters, whereas lateral movements are governed by Gunay's model (Gunay, 2007).

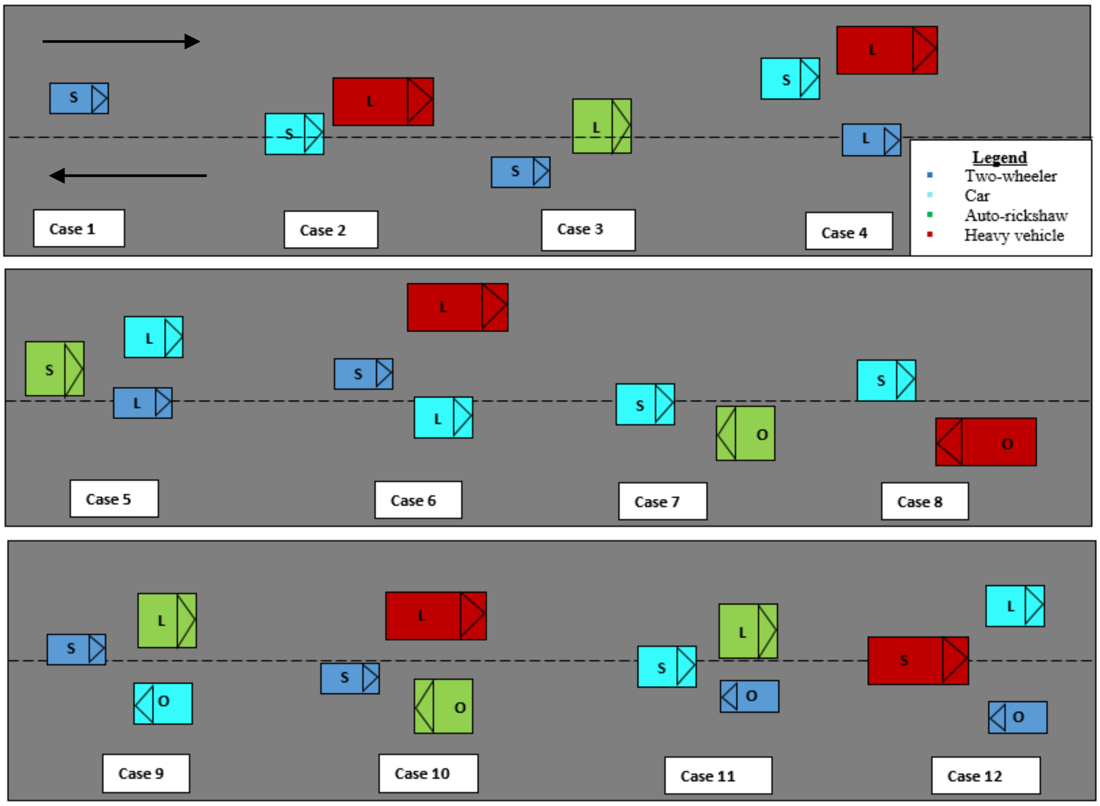


Figure 3.8 Vehicle movement cases

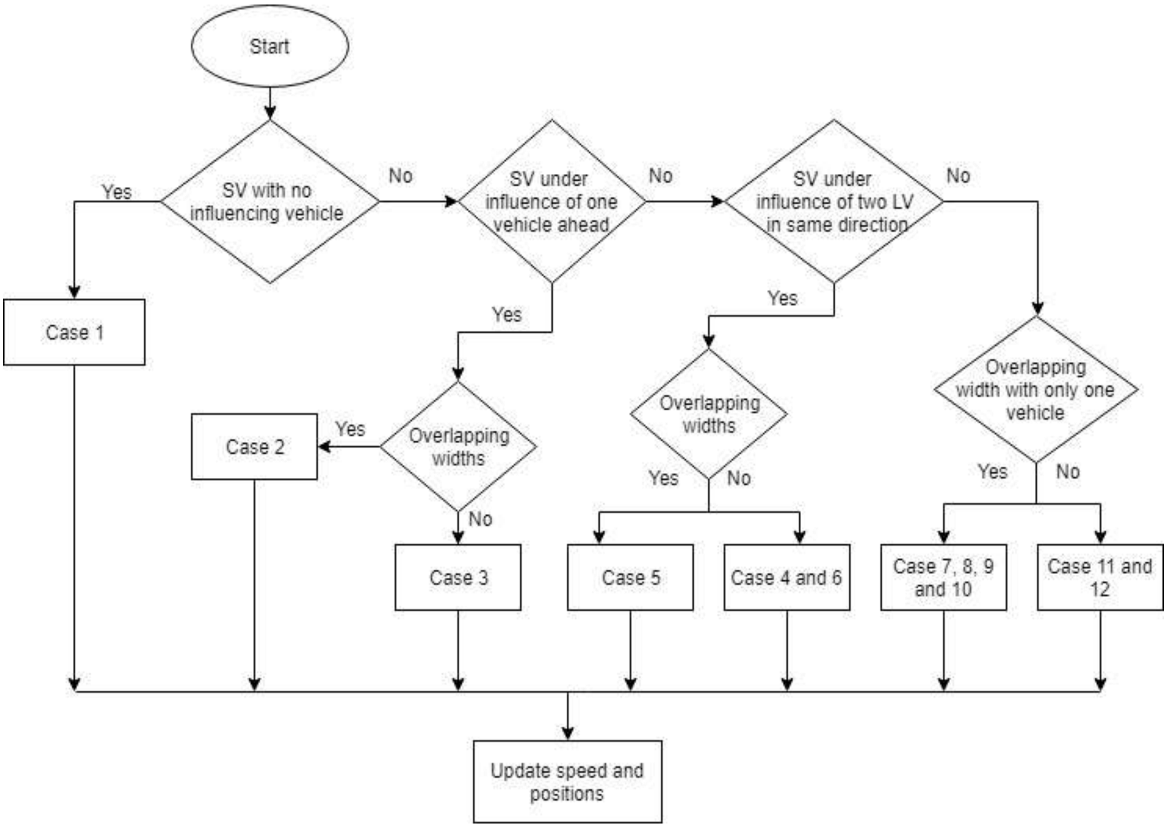


Figure 3.9 Vehicle movement logics

Case 1: In this case, the subject vehicle (S) is not influenced by any other surrounding vehicles in the influence area as shown in Figure 3.8. This vehicle is free to move at its desired speed. Such movement is formulated as per the Gipp's model (Gipps 1981).

$$v_{t+Tj}=v_T^f+2.5a_jT_j(1-\frac{v_t^f}{V_j})\sqrt{0.025+\frac{v_t^f}{V_j}} \quad \text{……………………(3.6)}$$

Case 2: The subject vehicle is influenced only by the leader vehicle (L) and the widths of both vehicles overlap with each other.

Case 3: In this case, the subject vehicle is influenced only by a non-overlapping leader vehicle.

In the above cases 2 and 3, if the subject vehicle has lesser speed than the leader, it follows the leader which is formulated by incorporating vehicle type dependent model parameters in Gipp's model (Gipps 1981).

$$v_{t+T_i}=b_{ij}T_j+\sqrt{b_{ij}^2T_j^2-b\left[2\left(x_t^l-x_t^f-\alpha_{ij}S_i\right)-v_t^fT_j-\frac{\left(v_t^l\right)^2}{b_{ij}^*}\right]} \quad \text{………..(3.7)}$$

If the subject vehicle has greater speed than the leader, subject vehicle initiates lateral shift which is formulated using the Gunay's model (Gunay 2007).

$$v_{t+T_j}\leq 2\left[\frac{(x_t^l-\frac{(v_t^l)^2}{2b_{ij}^*})-x_t^f-\frac{v_t^fT}{2}-\frac{t_{veer}}{2}MES_{ij}-\alpha_{ij}d_{body}}{t_{veer}+T}\right] \quad \text{………...(3.8)}$$

Case 4: The subject vehicle is influenced by two vehicles ahead i.e. the width of the subject vehicle is overlapping with any one of the leaders.

Case 5: The subject vehicle in under the influence of two leaders ahead and width of both the leaders are overlapping with the subject vehicle.

Case 6: The subject vehicle is influenced by two non-overlapping leader vehicles.

In cases 4 - 6, if subject vehicle has a speed greater than the leader with an available lateral gap equal to its width (with side clearance), it squeezes easily at its free flow speed. This movement is formulated using the Gunay’s model.

$$v_{t+T_j} = b_{ij}T_j + \sqrt{b_{ij}^2T_j^2 - b_{ij}\{2[x_t^l - x_t^f - \alpha_{ij}S_i] - v_t^f T_j - \frac{(v_t^l)^2}{2b_{ij}^*} - \frac{MES_{ij}^2}{b_{ij}}\}} \quad \ldots\ldots\ldots\ldots(3.9)$$

Case 7: The subject vehicle is influenced only by the opposing vehicle and the widths of the subject and opposing vehicles are overlapping.

Case 8: The subject vehicle is under influence of a non-overlapping opposing vehicle. In cases 7 and 8, the subject vehicle initiates lateral shift so as to avoid collision with opposing vehicle. This movement is formulated using the Gunay’s model (Gunay 2007).

$$v_{t+T_j} \leq 2\left[\frac{x_t^l - \frac{(v_t^l)^2}{2b_{ij}^*} - x_t^f - \frac{v_t^f T}{2} - \frac{t_{veer}}{2} MES_{ij} - \alpha_{ij} d_{body}}{t_{veer} + T}\right] \quad \ldots\ldots\ldots\ldots(3.10)$$

Case 9: The subject vehicle is influenced by two vehicles ahead, out of which one of the vehicles is from opposite direction and the width of the subject vehicle is overlapping only with a width of leader.

Case 10: The subject vehicle is influenced by an overlapping opposing vehicle and a non-overlapping leader vehicle.

Case 11: In this case, subject vehicle width is overlapping with the widths of both leader and opposing vehicle.

Case 12: The subject vehicle is influenced by two non-overlapping vehicles ahead out of which one is from opposing direction

In cases 9 - 12, if the subject vehicle has a speed greater than both leader and opposing vehicle with an available lateral gap equal to its width (with side clearance), it squeezes easily at its free flow speed which is formulated using the following equation.

$$v_{t+T\,j} = b_{ij}T_j + \sqrt{b_{ij}^2 T_j^2 - b_{ij}\{2[x_t^0 - x_t^f] - v_t^f T_j - \frac{(v_t^0)^2}{2b_{ij}^*} - \frac{MES_{ij}^2}{b_{ij}}\}} \quad \text{......(3.11)}$$

The variables used in the above equations are as follows:

V_j = free-flow speed of subject vehicle j (m/s)

v_t = instantaneous speed (m/s)

T_j = reaction time of subject vehicle j (s)

t = time-step under consideration (s)

t_{veer} = time required for veering (s)

a_j = acceleration of subject vehicle j (m/s^2)

b_{ij} = maximum deceleration (m/s^2)

b_{ij}^* = deceleration of leader as judged by subject vehicle (m/s^2)

α_{ij} = sensitivity factor

S_{ij} = size of leader (m)

d_{body} = safe distance to stopping (m)

MES_{ij} = maximum escape speed (m/s)

Superscripts *l*, *f*, and *o* represents leader, follower and opposing vehicles, respectively. Subscripts *i* and *j* correspond to vehicle type of interacting vehicle and subject vehicle under consideration and *ij* denotes usage of that parameter for vehicle pair of type *i* and *j*. The longitudinal and lateral position of the vehicle is represented as x and y, respectively.

3.4 OBJECT-ORIENTED PROGRAMMING CONCEPTS

The logic for simulating bidirectional traffic will be implemented in MATLAB R2015a using Object-Oriented Programming (OOP) concepts. OOP has gained lots of popularity in developing scientific programs in recent days. The components of OOP such as objects, classes, inheritance, encapsulation, and polymorphism helps the programmer to develop more intelligible, maintainable and expandable codes. OOP concepts are being used for developing traffic simulation models (Kanagaraj *et al.,* 2008; Asaithambi *et al.,* 2009; Yang *et al.,* 2017). *Objects* are the basic run-time entities in OOP. Figure 3.10 shows the class flow diagram for modeling bidirectional mixed traffic. The *Objects* such as two-wheelers, cars, auto-rickshaws and heavy vehicles represent the data of different vehicle types. A *class* can be defined as a collection of objects of similar type. Classes are user-defined data types and behave like the built-in types of the programming language. In the present framework, the code is split up into several *virtual functions* to carry out necessary tasks while the overall approach remains to be object oriented with two *super classes*. The properties of vehicles are in the form of *objects,* which are inherited from the *Vehicle* class. Both the super classes i.e. *Vehicle class* and *Traffic class* are associated with the main *Simulator class* and *Animation class*. The functions of each class are discussed in the following section.

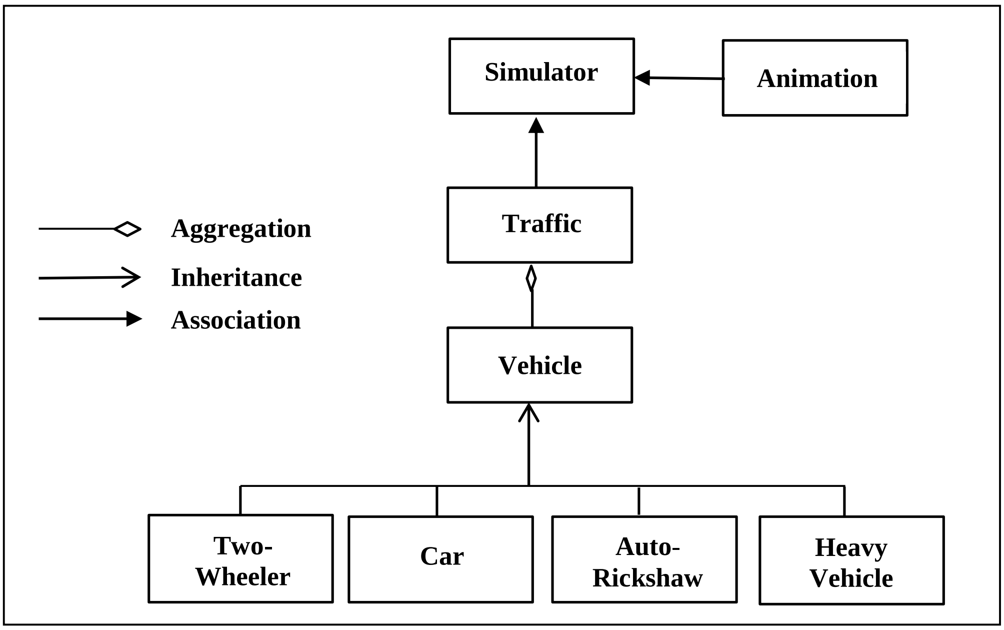


Figure 3.10 Class diagram for bi-directional mixed traffic simulation

3.4.1 Vehicle class

The super class, *Vehicle* encapsulates the common components of a vehicle running on the road stretch with some pre-defined set of values for each vehicle. These instances are nothing but the objects of the *Vehicle* class. This class is defined by several properties which build the road network and vehicle structure. The properties of *Vehicle* class are shown in Figure 3.11. Details of properties of *Vehicle Class* are listed out as follows:

- x and y: Represents the co-ordinates of the subject vehicle at each time step
- V_x and V_y: Shows the lateral and longitudinal speed values of each subject vehicle during the simulation run
- MES, v_{veer}, and d_{body}: These are the parameters used for calibration of the model
- Veh_{len} and Veh_{width}: Represents the length and width of each vehicle type
- Lane: The lane on which vehicles are placed at the beginning of the simulation
- Max_b, Max_{Vy}, and Lat_{clr}: Represents the maximum deceleration, maximum velocity and lateral clearance, respectively
- Dir: The direction of the traffic flow is represented as “Dir”, the ongoing traffic flow is represented as “DirN” and opposing traffic flow as “DirS”.

```
classdef Vehicle
    properties
        x %Lateral position
        y %Longitudinal position
        Vx %Lateral Velocity
        Vy %Longitudinal Velocity
        Ax
        Ay
        Max_b = %Max Deceleration
        A =  % Sensitivity Factor(alpha)
        MES =  % Maximum Escape Speed
        v_veer =  % Max velocity to veer laterally
        d_body =  %Safe Stopping Distance
        Type %Vehicle Type
        Veh_len %Vehicle length
        Veh_width %Vehicle width
        Lane %Lane being occupied by the vehicle
        Dir %Direction of travel
        Lat_clr %Lateral Clearance
        Max_Vy
    end
```

Figure 3.11 Properties of *Vehicle* class

3.4.2 Traffic class

The class, *Traffic* encapsulates the behavior of traffic flow. The most common vehicular maneuvers such as longitudinal and lateral movement, overtaking, and car-following are scripted in this class. The main task of *Traffic* class is to execute the logics of the model i.e. vehicle generation, vehicle placement and vehicle movement. This class also updates the speeds and positions of vehicles at every time step. The *Traffic* class is built with the help of various virtual functions such as listed in Table 3.1. These virtual functions carry out the required operations to simulate traffic flow in both directions.

Table 3.1 Description of *Traffic* Class functions

Virtual Function	**Role**
Genheadway ( )	Generates headway distribution based on vehicle type.
CheckBestStrip ( )	Checks the ideal strip for vehicle placement in each direction.
RunSim ( )	Initiates the simulation process to generate the output.
UpdateVehN (traffic)	Updates speed and position of vehicles (ongoing direction) at each time step.
UpdateVehS (traffic)	Updates speed and position of vehicles (opposing direction) at each time step.
SimOut (traffic)	Trajectory and speeds of vehicles are displayed using this function.

A *traffic* class is comprised of various user-defined properties which are shown in the Figure 3.12.The important properties of the *Traffic class* are listed as follows:

- len and width: Represents the length and width of the simulation road stretch
- time: Total simulation time in seconds
- ScanTime: Scan interval (time step) at which the vehicles are updated in the model
- NumberVeh$_N$: Total number of vehicles updated in the ongoing direction
- NumberVeh$_S$: Total number of vehicles updated in the opposing direction
- Veh$_N$: Records the trajectory data of vehicles moving in the ongoing direction
- Veh$_S$: Records the trajectory data of vehicles moving in opposing direction
- Result: Stores the simulation run results in .csv file

```
classdef Traffic < handle
     properties
        len
        width
        flow
        time
        ScanTime = 1 %Time ScanTime scan interval
        ReactionTime = 0.8 %Reaction time of driver
        NumberVehN = 1 %Number of vehicles Northbound
        NumberVehS = 1 %Number of vehicles Southbound
        velocity = [] % Velocity as a function of lane
        cur_time
VehN = Vehicle.empty(0,10000) %trajectory data for Northbound
VehS = Vehicle.empty(0,10000) %trajectory data for Southbound
        Result %Traffic Trajectory
        res = 1
        StartN = 1 %For storing Vehicle ID North direction
        StartS = 1 %For storing vehicle ID South direction
        proportionN = [0 0 0 0] % [TW Auto Car HV] Northbound
        proportionS = [0 0 0 0] % [TW Auto Car HV] Southbound
        h1
        h2
        constLatVel =
        SimSwitch = false;
        mu = [1 2 3 4] %average headways based on type
    end
```

Figure 3.12 Properties of *Traffic* class

3.4.3 Simulator class

The *Simulator class* defines various attributes responsible for flow of various modules of the simulation. The virtual function, *traffic* declared in the simulator class process the attributes such as length and width of the simulation stretch, traffic flow, total simulation time, vehicular composition in both ongoing and opposing directions, and simulation switch (to initiate animated output). Figure 3.13 shows the definition of *Simulator class*. The main function *RunSim* initiates the simulation run and executes the overall logic of the model.

```
function traffic =
Traffic(len,width,flow,time,proportionN,proportionS,SimSwitch)

% Simulator class parameters
            if(nargin~=0)
                traffic.len = len; %Length
                traffic.width = width; %Width
                traffic.flow = flow; %Traffic flow
                traffic.time = time; %Simulation Time

            if(sum(proportionN) == 1) %Check proportion

                  traffic.proportionN = proportionN;
                end
                if(sum(proportionS) == 1)
                    traffic. proportionS = proportionS;
                end
                traffic.SimSwitch = SimSwitch;
            end
        end
function RunSim(traffic) %Simulation output figure
          traffic.h1 = figure; %Main figure holding simulation
            traffic.h2 = axes;
set(traffic.h2,'Xtick',[],'YTick',[],'XTickLabel',[],'YTickLabel'
,[]) %Disabling axes marking
            xlim([0 traffic.len]) %Setting display length
            ylim([-traffic.width/2 traffic.width/2]) %Setting
display width
            set(traffic.h1,'Color',[0 0 0]) %Background colour
            set(traffic.h2,'Color',[0.8 0.8 0.8]) %Setting grey
road colour
            set(traffic.h1,'Position',[0 50 3000 100]) %Setting
position of simulation window
            daspect([1 1 1]) % Keeping both x and y in the same
ratio for good render of vehicle lengths vs widths
```

Figure 3.13 Definition of *Simulator Class*

3.4.4 Animation class

The animated simulation output is displayed during the run time by updating the speeds and positions of vehicles at each scan interval. The virtual function, *SimOut* executes the animated output of simulation. The resolution ratio of the simulation window, display properties of the simulation stretch and vehicles are defined as shown in Figure 3.14.

```
function SimOut(traffic)
            hold on traffic.h1
            hold on traffic.h2
            persistent initial;
            if(isempty(initial)==1)
                initial = 1;
            end
            f = gobjects(1,(traffic.res - initial - 1)); %Creating
graphic objects for display at current ScanTime
            for loop = initial:traffic.res - 1
                if(traffic.Result(loop,1) == 0)
                    f(loop - initial + 1) =
rectangle('Position',[traffic.Result(loop,5)-
traffic.vehN(traffic.Result(loop,2)).VehLen -
(traffic.Result(loop,4)-
traffic.vehN(traffic.Result(loop,2)).VehWidth/2)
traffic.vehN(traffic.Result(loop,2)).VehLen
traffic.vehN(traffic.Result(loop,2)).VehWidth],'FaceColor',[0 0
1],'Visible','off');
                else
                    f(loop - initial + 1) =
rectangle('Position',[traffic.Result(loop,5)-
traffic.vehS(traffic.Result(loop,2)).VehLen -
(traffic.Result(loop,4)-
traffic.vehS(traffic.Result(loop,2)).VehWidth/2)
traffic.vehS(traffic.Result(loop,2)).VehLen
traffic.vehS(traffic.Result(loop,2)).VehWidth],'FaceColor',[1 0
0],'Visible','off');
                end
            end
            set(f(:),'Visible','on')
            pause(0.5)
            set(f(:),'Visible','off')
            hold on traffic.h1
            hold on traffic.h2
                    clear f;
                    initial = traffic.res;
        end
```

Figure 3.14 Definition of *Animation Class*

3.4.5 Inputs and initialization

The model requires certain data describing the traffic properties to be fed as input to simulate traffic flow. Certain other field data are given as inputs to the model and these include various parameters such as:

- Total simulation time
- Scan interval
- Length and width of the road stretch

- Vehicular composition
- Free-speed of each category of vehicles
- Strip width
- Initial speed based on strip
- Rate of acceleration and deceleration
- Headway distribution
- Influence lengths (look ahead distance)
- Minimum lateral and longitudinal clearances

These inputs are fed in the class using the virtual function, *Traffic ( )* as shown in Figure 3.15. The constructor *Traffic ( )* takes care of the initialization process based on user input. Field data describing given traffic conditions are scripted into the model.

```
function traffic = 
Traffic(len,width,flow,time,proportionN,proportionS,SimSwitch)
       % Simulation parameters input
       if(nargin~=0)
       traffic.len = len; %Length of road stretch
       traffic.width = width; %Width of road stretch
       traffic.flow = flow; %Traffic flow expected in road stretch
       traffic.time = time; %Simulation Time
       if(sum(proportionN) == 1) %Check if veh proportion is valid
         traffic.proportionN = proportionN;
            end
       if(sum(proportionS) == 1)
                    traffic. proportionS = proportionS;
            end
       traffic.SimSwitch = SimSwitch;
            end
```

Figure 3.15 Description of virtual function *Traffic ( )* for scripting input parameters

3.4.6 Outputs from the model

The vehicular trajectory for each scan interval is obtained in .csv format at the end of simulation time. The outputs from the developed model are as follows:

- Vehicle trajectories
- Average class-wise speed of vehicles in both directions
- Flow and density

- Capacity
- Animated output of the simulation

3.4.7 Updation of positions and speeds

The positions and speeds of vehicles are updated at each scan interval. The classical equations of motion are used to generate new values of position. This update is carried out at every time step and hence, the accuracy of the model lies in the appropriate use of the time step. Smaller the time step, higher is the number of iterations in updating vehicle’s position based on the logic, and therefore more accurate is the trajectory. The trajectory of all vehicles at each time step is stored in the code and the abstract function, *SimOut ( )* is invoked to display the vehicles on the road segment at that instant of time in the simulation.

The vehicles are represented as rectangles using different colours and different sizes based on the vehicle type. The snapshot of the animated output of vehicles at a random time step is shown in Figure 3.16. The trajectories of the vehicles in ongoing and opposing direction at different time steps are shown in Figures 3.17 – 3.19.

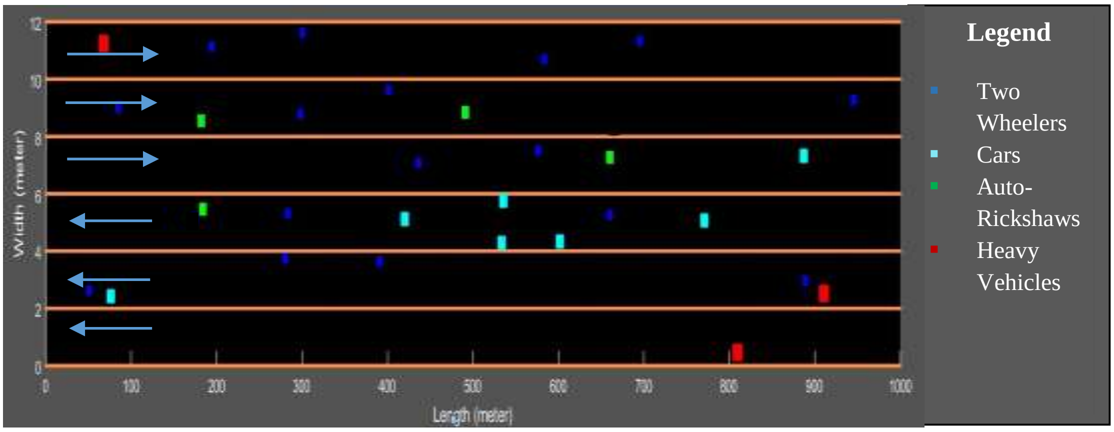
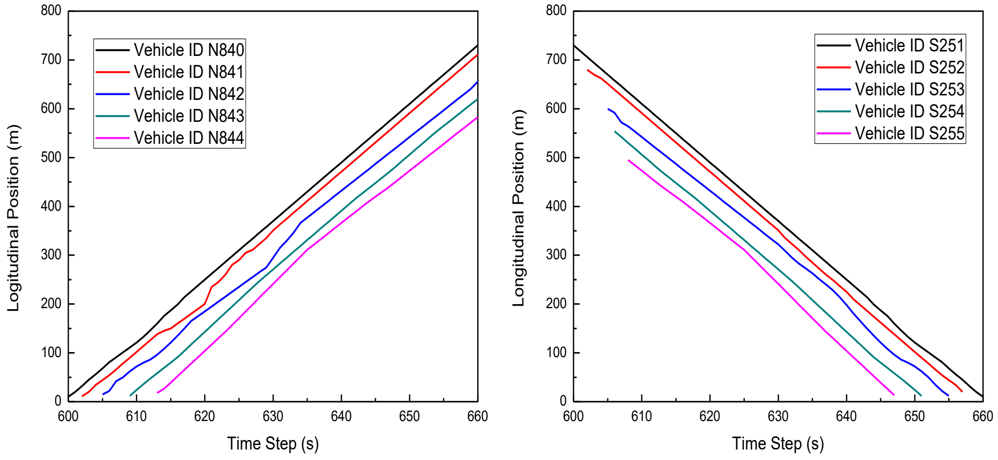
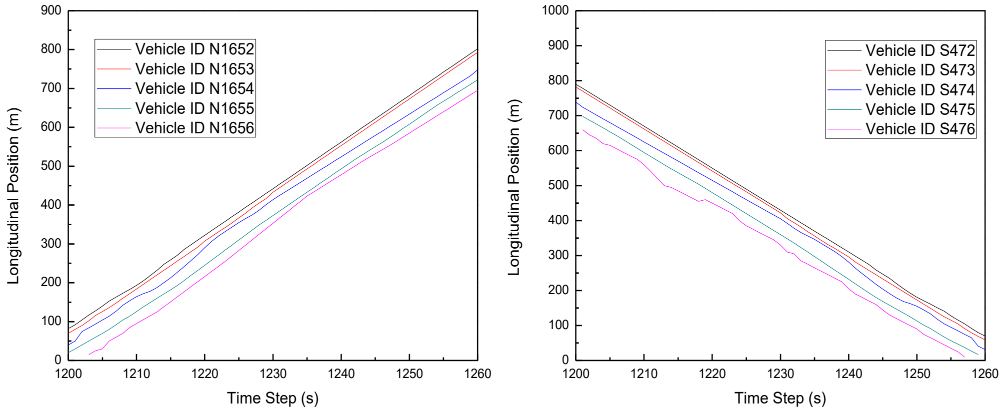


Figure 3.16 Snapshot of animation of vehicles



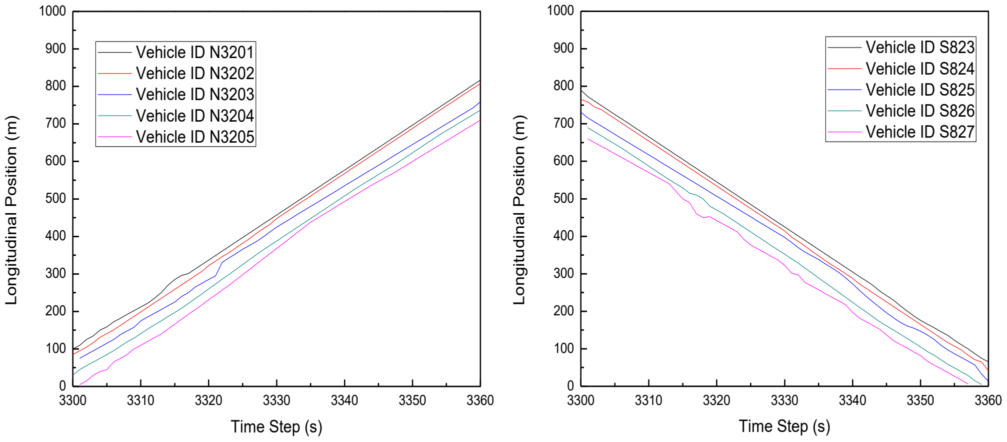
(i) Ongoing direction (ii) Opposing direction

Figure 3.17 Trajectories of vehicles during the time interval of 600 – 660 s



(i) Ongoing direction (ii) Opposing direction

Figure 3.18 Trajectories of vehicles during the time interval of 1200 – 1260 s



(i) Ongoing direction (ii) Opposing direction

Figure 3.19 Trajectories of vehicles during the time interval of 3300 – 3360 s

3.5 SUMMARY

In this section, the overall framework for the development of bi-directional traffic simulation model is explained. Various logics involved in this process such as vehicle generation, vehicle placement, and vehicle movement are explained in detail. The concept of influence area is introduced to identify the most influencing surrounding vehicles in the vehicle movement logic. Several vehicle movement cases are identified to replicate the field observed traffic conditions reasonably. These logics are implemented in the traffic simulator developed in MATLAB using OOP concepts.

CHAPTER 4

DATA COLLECTION AND EXTRACTION

4.1 GENERAL

In this chapter, the methodology adopted for collection, extraction, and analysis of the traffic data is presented. The video-graphic method is adopted to collect traffic flow data from urban undivided mid-block sections. A high-resolution wide-angle camera is mounted on vantage points to record the video of the vehicles passing through the section. The data are collected during peak and off-peak periods of traffic on weekdays so as to represent the typical traffic flow characteristics. These video data are utilized to extract and analyse various study parameters which are required to build the simulation model.

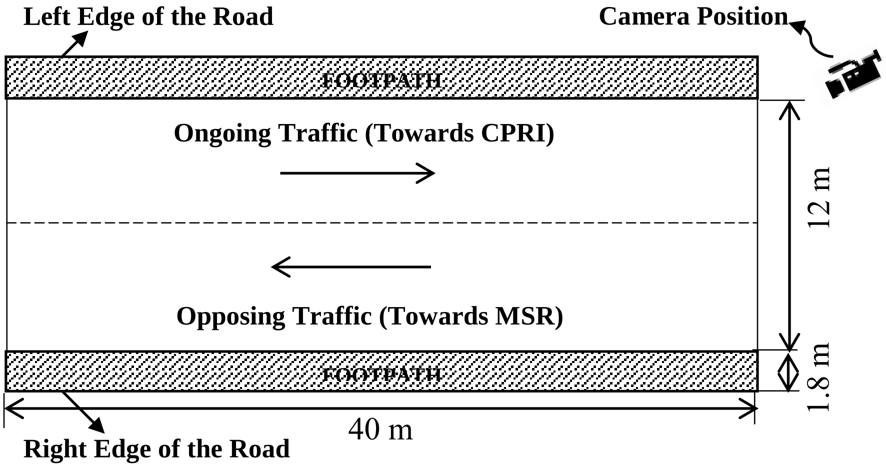
4.2 IDENTIFICATION OF THE STUDY LOCATION

Initially, the reconnaissance survey is carried out in various parts of Karnataka and Kerala to identify the study location which satisfies the following criteria:

- Two-lane or four-lane undivided urban midblock sections
- Level and straight mid-block sections
- Site free from any side interferences (e.g. parking, bus-stops, etc.)
- Absence of on-street parking
- Absence of minor roads near the selected section
- The section should be at least 100 m away from intersection and bus stops
- Pedestrian road crossing activities should be less
- Availability of vantage points for mounting the video camera

After preliminary analysis of sample data collected from various parts of Karnataka and Kerala, two ideal locations are selected for the study. The data for model development is recorded from an urban undivided mid-block section located in Bengaluru, Karnataka (Figure 4.1a). The study section is 40 m long and 12 m wide (two-way traffic) located on undivided section (New BEL Road) as shown in Figure 4.1b. The traffic data collected from this study location is used for development of the simulation model and also, for internal validation of the model. The ongoing traffic flows towards Central Power Research Institute (CPRI) and the opposing traffic flows towards Mathikere Sampige Ramaiah (MSR) Hospital.

(a) Photograph of the study section



(b) Layout of the study section

Figure. 4.1 Photograph and layout of the study section selected at Bengaluru city

4.3 METHOD OF DATA COLLECTION

Initially, the length and width of the selected study stretch is measured using the measuring tape and then, reference points along with the entry and exit points are marked on the stretch. The video camera is mounted near the selected study stretch at a vantage point with the help of camera clamp setup. Once the swing angle and location of the camera are fixed, the reference points are recorded using manual flag off method (same location of the camera has to be used for collecting the video data). The traffic flow data are collected from Bengaluru location during both peak (8.30 am to 9.30 am) and off-peak (5:30 am to 6:30 am) hours of traffic for two consecutive weekdays.

4.4 DATA EXTRACTION

The study parameters required for the development of bi-directional simulation model such as traffic volume and composition, free speeds, headway, rate of acceleration and deceleration, longitudinal and lateral position of vehicles and lateral clearances for both ongoing and opposing directions are extracted using an image processing software, Irfanview (Version 4.38). It is an open source package that can view, edit and convert an ordinary image file or video file into a graphical image, which makes it possible to obtain the coordinates of all the points in terms of pixels (X, Y) on the image. This software converts the video data into image frames (25 frames for one-second video data). The image coordinates are obtained by overlaying gridlines over the video. These gridlines are plotted in AutoCAD (Figure 4.2) with sufficient scaling and then overlaid on video data by using Ulead Video Studio 10.0 editor. The overlaid gridline video is converted to frames using Irfanview and the image coordinates of each grid block are extracted.

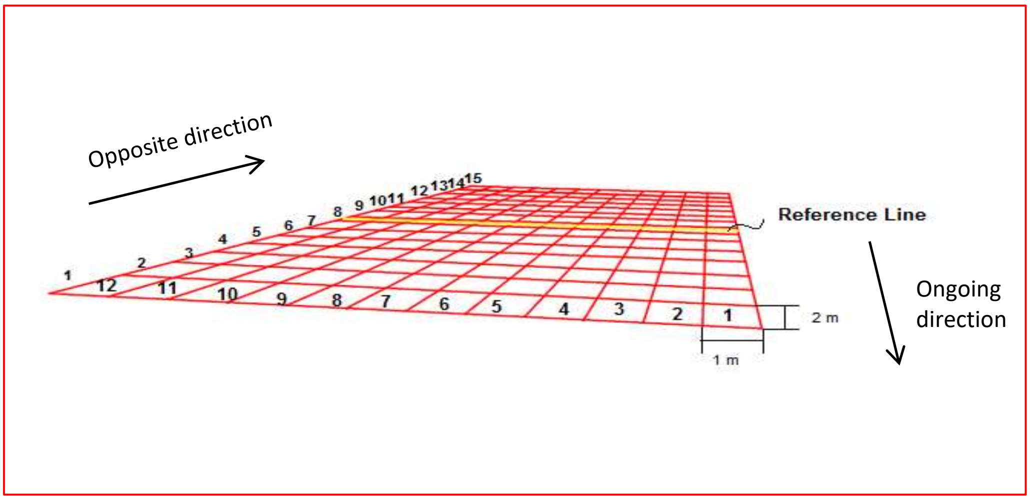


Figure 4.2 Layout of the gridlines used to overlay on video frame

The study parameters such as free-flow speed, speed, rate of acceleration and deceleration, longitudinal and lateral gaps, lateral positions of different types of vehicle in both ongoing direction and opposing vehicles are extracted. For extracting speed, rate of acceleration and deceleration, the gridlines overlaid on the study section is divided into blocks of 1 m each in the lateral direction, and 4 m each in the longitudinal direction at the entry and exit of study section (Figure 4.3a). Lateral and longitudinal gaps, and lateral separation values are extracted using gridlines which are divided into lateral blocks of 1 m each and longitudinal blocks of 2 m each (Figure 4.3b). Gridlines overlaid on the study section are divided into blocks of 0.5 m each laterally to extract the lateral positions of the vehicle (Figures 4.3c). The lateral shifts of vehicles are extracted using the gridlines overlaid on the video frame of the study section as shown in Figure 4.3d.

(a) Gridlines for extracting speed, rate of acceleration and deceleration

(b) Gridlines for longitudinal and lateral gaps

(c) Gridlines for extracting lateral placement

(d) Gridlines for extracting lateral shift

Figure 4.3 Gridlines overlaid on video frames to extract study parameters

In order to remove the parallax effect due to camera angle, certain correction factors are used (Gowri, 2011). These factors are calculated for each grid block using the known distance on the ground and corresponding coordinates on the screen. An example of the calculation of correction factors is shown in Appendix A. Table 4.1 gives the sample of correction factors for each grid used for converting image coordinates to ground coordinates.

Table 4.1 Correction factors to remove parallax effect

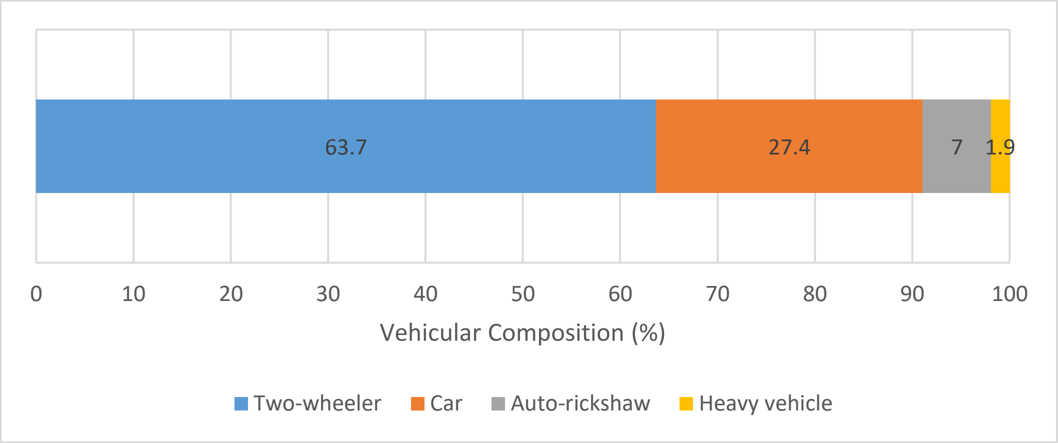
Block No.		**Distance in cm for one pixel**	
Longitudinal	**Lateral**	**Longitudinal**	**Lateral**
1	1	2.69	11.02
1	2	2.69	11.18
1	3	2.69	10.82
1	4	2.69	9.84
1	5	2.69	8.93
1	6	2.69	7.70
1	7	2.69	6.79
1	8	2.69	6.14
1	9	2.73	5.51
1	10	2.69	4.96
1	11	2.73	4.51
1	12	2.69	4.13
2	1	2.97	15.18
2	2	2.97	15.18
2	3	2.97	14.46
2	4	3.02	13.02
2	5	2.97	11.49
2	6	2.97	11.02
2	7	2.97	10.07
2	8	3.02	8.75
2	9	3.02	7.84
2	10	2.97	7.20
2	11	3.07	6.54
2	12	3.02	5.90

4.5 DATA ANALYSIS AND RESULTS

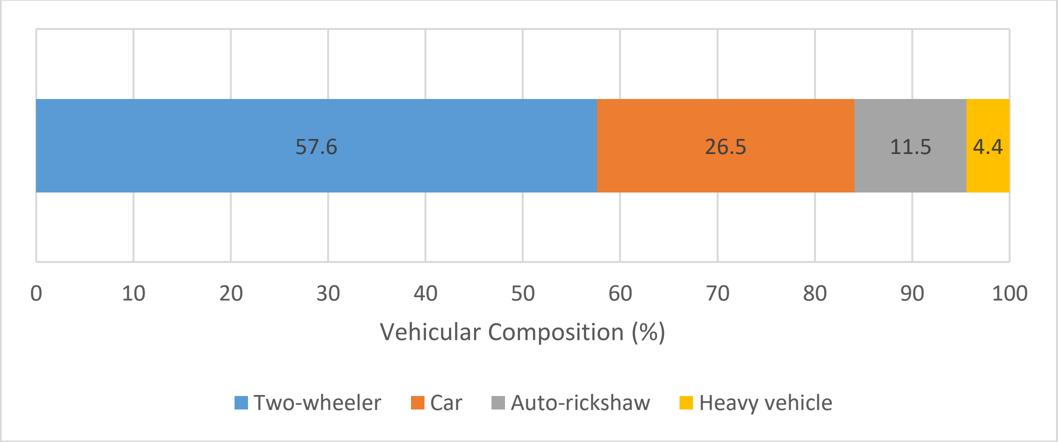
The traffic data collected from the urban undivided road (New BEL Road) located in Bengaluru city, Karnataka, are used to extract the study parameters and develop the simulation model. In this section, analysis of various study parameters such as vehicular composition, free speeds, space mean speed, headway, the rate of acceleration and deceleration, lateral and longitudinal gaps of vehicles is discussed. These parameters are used as inputs and initialization parameters for the simulation model.

4.5.1 Vehicular composition

The traffic flow video recorded from the camera is transferred to a computer and by playing this video on monitor various data are extracted. The volume counts of vehicles in both ongoing (towards CPRI) and opposing (towards MSR hospital) direction is carried out by counting the number of vehicles manually by playing the recorded video data. The on-going traffic at the section moving towards CPRI comprises about 3541 motorized vehicles per hour, where two-wheelers accounted for the largest share of 63.7% and heavy vehicles (LCV, Trucks, Buses) with the least share of 1.9%. The traffic in the opposing direction (towards MSR Hospital) at the section comprises about 908 motorized vehicles per hour, where two-wheelers accounted for the largest share of 57.6% and heavy vehicles with the least share of 4.4 %. The traffic composition for each direction is shown in Figure 4.4.



(a) Ongoing direction (towards CPRI)



(b) Opposing direction (towards MSR)

Figure 4.4 Vehicular composition observed in the study section – Bengaluru city

4.5.2 Free speeds of vehicles

Free speed is defined as the average speed that a driver would travel if there are no influencing factors and other restrictions by surrounding vehicle in the stream. Free speeds of different vehicle types are necessary to place the vehicles on the simulation road stretch. Table 4.2 shows the free speed statistics for different vehicle types and it is observed that two-wheelers travel at a higher mean free speed (16.5 m/s) followed by cars (15.9 m/s) and auto-rickshaw (15.3 m/s). Different probability distribution functions are fitted to the aggregate and class-wise data of free speed using EasyFit statistical tool and the goodness-of-fit test for each probability density function is conducted by Kolmogorov-Smirnov (K-S) test at 5 % significance level.

Table 4.2 Descriptive statistics for free speed of vehicles

Vehicle Type	**Free Speed (m/s)**				**Distribution**	**K-S Value**
	Mean	**SD***	**Min.**	**Max.**		
Two-wheelers	16.59	3.81	11.91	21.26	GEV	-0.02
Auto-rickshaws	15.30	2.28	12.50	18.10	Normal	-0.04
Cars	15.92	2.53	12.82	19.02	GEV	-0.03
Heavy Vehicles	13.54	0.74	12.63	14.45	GEV	-0.06
Stream	15.33	1.07	11.91	21.26	GEV	-0.04

**SD = Standard Deviation, Min. = Minimum, Max. = Maximum,*
K-S = Kolmogorov–Smirnov value, GEV= Generalized Extreme Value

4.5.3 Mean speed during peak hours of traffic

Space mean speed is defined as the arithmetic mean of the speed of vehicles occupying a given length of road at a given instant. The descriptive statistics of speeds for different vehicle types are shown in Table 4.3. Different probability distribution functions are also fitted for each vehicle type for speeds observed during peak hours and the goodness-of-fit test for each probability density function is conducted by K-S test at 5 % level of significance. It is observed that mean speed of two-wheelers is higher (12.9 m/s) because of their smaller sizes and higher manoeuvrability. Cars also maintain higher speeds which is obtained as 12.8 m/s. Heavy vehicles (HV) travel with a minimum mean speed (11.7 m/s) due to their larger size and lower manoeuvrability. The one-way Analysis of variance (ANOVA) test indicates that the speeds of vehicle types are significantly different (F_{obs}= 3.651, F_{crit}=2.61, degrees of freedom (*dof*) =6345) from each other at 0.05 level of significance.

Table 4.3 Descriptive statistics for observed speeds during peak hours

Vehicle Type	Speed (m/s)				Distribution	K-S Value
	Mean	SD	Min.	Max.		
Two-wheelers	12.9	2.0	3.3	16.7	GEV	-0.03
Auto-rickshaws	11.9	1.8	5.1	16.7	Normal	-0.05
Cars	12.8	2.2	4.6	16.7	GEV	-0.04
Heavy vehicles	11.7	2.4	5.2	16.3	GEV	-0.08
Stream	12.3	2.1	3.3	16.7	GEV	-0.03

4.5.4 Headway distribution

Headway is defined as the time interval between the arrivals of two successive vehicles at a reference point on the road section. The headways of vehicles are extracted using the image frames, which are used for generation of vehicles in the simulation model. Table 4.4 and 4.5 show the descriptive statistics of headway of different types of vehicles in both ongoing and opposing direction. The headway values obtained for each vehicle type is fitted to obtain the best distribution. From the tables, it can be seen that for ongoing direction, headway of two-wheelers is lesser (1.06 s) when compared to other types of vehicles. Cars have a mean headway of 1.16 s, whereas heavy vehicles have a greater headway of 1.59 s.

Table 4.4 Descriptive statistics for headway - Ongoing direction

Vehicle Type	Headway (s)				
	Mean	SD	Min.	Max.	Distribution
Two-wheelers	1.06	1.35	0.04	17.48	GEV
Auto-rickshaws	1.18	1.2	0.04	8.6	GEV
Cars	1.16	1.2	0.04	12.36	Gamma
HVs	1.59	1.82	0.08	13.72	Weibull
Stream	1.24	1.31	0.04	17.48	Weibull

Table 4.5 Descriptive statistics for headway - Opposing direction

Vehicle Type	Headway (s)				
	Mean	SD	Min.	Max.	Distribution
Two-wheelers	1.2	1.3	0.03	12.32	GEV
Auto-rickshaws	1.3	1.2	0.05	7.8	Gamma
Cars	1.3	1.2	0.06	11.22	GEV
HVs	1.8	1.6	0.07	12.74	Weibull
Stream	1.4	1.3	0.03	12.74	Weibull

4.5.5 Vehicle acceleration

Acceleration is termed as the rate of change of speed of a vehicle. The descriptive statistics for acceleration rate of different types of vehicles are shown in Table 4.6. The acceleration rate of two-wheelers is higher (1.9 m/s^2) as they can quickly change their speeds due to their smaller sizes and higher manoeuvrability. The mean acceleration rate of cars is also higher (1.8 m/s^2) due to their higher performance capability. Heavy vehicles (1.3 m/s^2) and auto-rickshaws (1.5 m/s^2) have lower acceleration capability due to their lower operating characteristics. The mean acceleration rate of the stream is observed to be 1.6 m/s^2. The one-way ANOVA test indicates that the acceleration rate of vehicle types is significantly different (F_{obs}= 9.08, F_{crit}=2.61, dof =3577) from each other at 0.05 level of significance.

Table 4.6 Descriptive statistics for acceleration rate of different type of vehicles

Vehicle Type	**Acceleration Rate (m/s^2)**			
	Mean	**SD**	**Min.**	**Max.**
Two-wheelers	1.9	1.3	0.03	11.9
Auto-rickshaws	1.5	1.1	0.3	9.3
Cars	1.8	1.2	0.11	11.3
Heavy vehicles	1.3	0.7	0.08	3.47
Stream	1.6	1.3	0.03	11.9

4.5.6 Vehicle deceleration

The deceleration rate of different vehicle types is also obtained. Table 4.7 shows the descriptive statistics for deceleration rate of vehicles. The mean deceleration rate of two-wheelers is higher (3.1 m/s^2) because when they find an opposing vehicle, they have the capability to decelerate immediately due to their smaller sizes and higher manoeuvrability and shift laterally in-order to avoid a collision. Cars are also found to have a higher mean deceleration rate of 3.0 m/s^2 due to their higher operating characteristics. Heavy vehicles travel at a lower speed and then gradually decelerate due to their larger size and lower manoeuvrability and hence, their mean rate of deceleration is minimum (2.1 m/s^2). The mean deceleration rate of stream is 2.7 m/s^2. The one-way ANOVA test indicates that the deceleration of vehicle types is significantly different (F_{obs} = 3.42, F_{crit} = 2.61, dof = 2011) from each other at 0.05 level of significance.

Table 4.7 Descriptive statistics for deceleration rates of different type of vehicles

Vehicle Type	**Deceleration Rate (m/s^2)**			
	Mean	**SD**	**Min.**	**Max.**
Two-wheelers	3.1	3.9	0.01	23.2
Auto-rickshaws	2.8	3.7	0.2	15.9
Cars	3.0	3.0	0.1	22.5
HVs	2.1	1.8	0.4	8.9
Stream	2.7	3.0	0.01	23.2

4.5.7 Lateral gaps

Lateral gap is defined as the lateral distance between two vehicles moving in the same direction which are overlapping longitudinally with each other. The lateral gap for each subject vehicle with respect to the adjacent vehicles is extracted. Knowing the image coordinates of the subject vehicle and surrounding vehicle in pixels, ground coordinates can be obtained by applying the correction factors. Table 4.8 shows the lateral gap values for different types of vehicle. Most of the two-wheelers travel at higher speeds throughout the road width and hence, maintain a higher mean lateral gap (3.2 m) to avoid collision with surrounding vehicles. Heavy vehicles traveling at lower speeds maintain a minimum lateral gap (2.1 m). Mean lateral gap of cars is 2.4 m and the mean lateral gap of auto-rickshaws is about 2.8 m. The one-way ANOVA test indicates that the lateral gap of different vehicle types is significantly different (F_{obs} = 18.76, F_{crit} = 2.62, *dof* =1189) from each other at 0.05 level of significance.

Table 4.8 Descriptive statistics for lateral gaps of different type of vehicles

Vehicle Type	**Lateral Gaps (m)**			
	Mean	**SD**	**Min.**	**Max.**
Two-wheelers	3.2	1.8	0.6	9.2
Auto-rickshaws	2.8	1.5	0.6	6.4
Cars	2.4	1.1	0.5	5.7
HVs	2.1	0.9	0.5	4.5
Stream	2.6	1.5	0.5	9.2

The effect of speeds of adjacent vehicles on the lateral gap is also studied. The speeds of the subject vehicles are grouped into different speed ranges (20 - 30, 30 - 40, 40 - 50 and 50 - 60). The lateral gap maintaining behavior of the subject vehicle (based on different speed ranges) versus speeds of the adjacent vehicle is analysed (Figure 4.5).

It is observed that at higher speeds, driver of the subject vehicle tries to be cautious by maintaining a higher lateral gap with the adjacent vehicle.

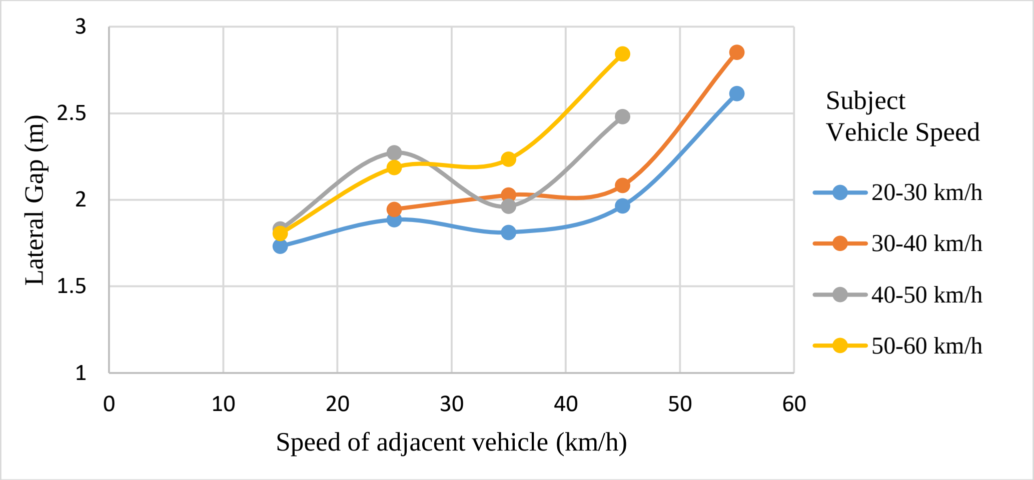


Figure 4.5 Relationship between the speed of adjacent vehicle, subject vehicle, and lateral gap

4.5.8 Longitudinal gaps

The clear distance between the back bumper of the leader vehicle and front bumper of the subject vehicle is termed as longitudinal gap. Longitudinal gaps for each type of vehicles are shown in Table 4.9. Generally, two-wheelers have higher braking efficiency and hence, they maintain lower mean longitudinal gap (10.7 m). Heavy vehicles travel at a lower speed and maintain comparatively higher mean longitudinal gap (11.9 m). The mean longitudinal gaps of cars and auto-rickshaws are 10.8 m and 11.1 m, respectively. The one-way ANOVA test indicates that the longitudinal gaps of vehicle types are significantly different (F_{obs} = 3.47, F_{crit} =2.62, *dof* =1309) from each other at 0.05 level of significance.

Table 4.9 Descriptive statistics for longitudinal gaps of different type of vehicles

Vehicle Type	**Longitudinal Gaps (m)**			
	Mean	**SD**	**Min.**	**Max.**
Two-wheelers	10.7	5.59	2.34	28.16
Auto-rickshaws	11.1	5.82	2.55	23.41
Cars	10.8	5.01	2.43	25.8
HVs	11.9	6.14	4.58	23.36
Stream	11.1	5.7	2.34	28.16

4.5.9 Lateral placement

Lateral placement of a vehicle is defined as the closest lateral position of the vehicle from the left edge of the pavement when the vehicle is in motion. When the vehicle touches the reference line on the middle of the road section, the closest lateral position of the vehicle from the left edge of the pavement was noted. Frequency distribution for the lateral position of vehicles in ongoing direction is shown in Figure 4.6.

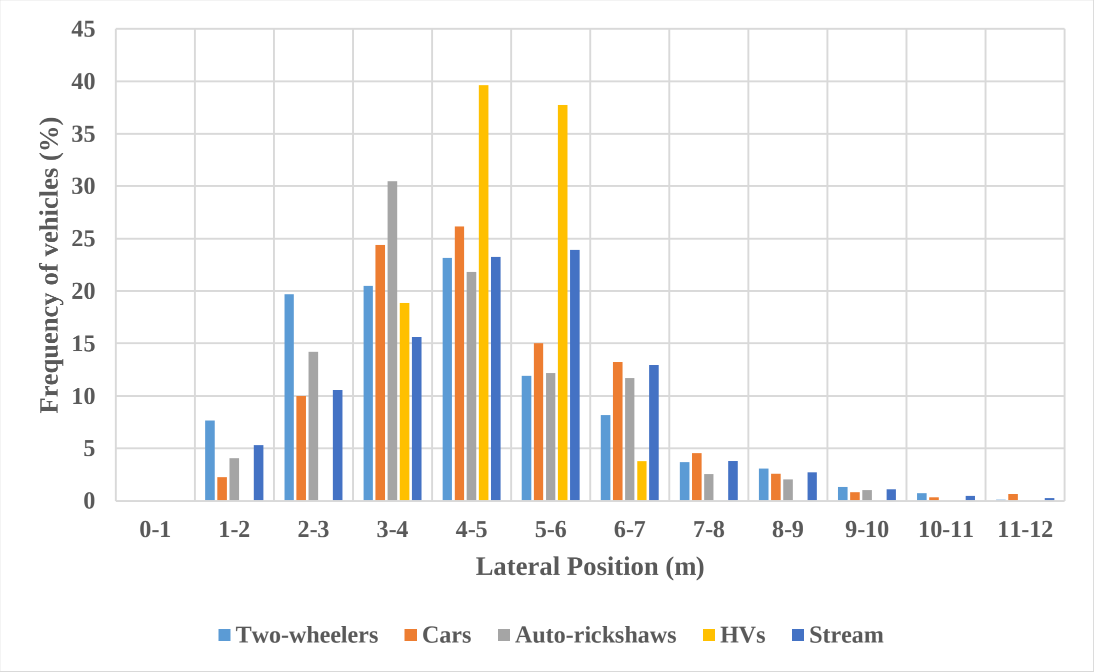


Figure 4.6 Frequency distribution for lateral position of vehicles in the ongoing direction

It is observed that majority of the vehicles (70.9%) are preferred to travel in the middle of the road (3-7 m). Two-wheelers and auto-rickshaws occupy almost the entire width of the road as they have a tendency to occupy every lateral gap available on the road due to their smaller sizes and higher manoeuvrability. Most of the cars (78.8%) prefer to travel near the middle of the road compared to two-wheelers (63.7%) and auto-rickshaws (76.1%) so as to maintain higher speeds. All the heavy vehicles are concentrated near the middle of the road (3-7 m) so as to avoid side interferences from other vehicles. Descriptive statistics for lateral placement of each vehicle type is shown in Table 4.10. The one-way ANOVA test indicates that the lateral positions of vehicle types are significantly different (F_{obs}= 8.61, F_{crit}=2.61, degrees of freedom (dof) = 1848) from each other at 5% level of significance.

Table 4.10 Descriptive statistics for lateral placement of different type of vehicles

Vehicle Type	**Lateral Position (m)**			
	Mean	**SD**	**Min.**	**Max.**
Two-wheelers	4.4	1.9	1.3	11.5
Auto-rickshaws	4.4	1.6	1.3	9.6
Cars	4.8	1.7	1.3	11.8
HVs	4.6	1.3	3.1	7.1
Stream	4.5	1.8	1.3	11.8

The generated vehicles are placed in the starting point of the simulation road stretch based on some assumptions and observations from field. The placement of vehicles is unpredictable and also, depends on many factors such as types and speeds of subject and opposing vehicles. A model is developed using regression analysis to predict the lateral placement of vehicles on undivided roads. This regression model can be used in vehicle placement logics to develop traffic simulation model. The variables considered for model development includes presence of each category of vehicle (Two-Wheeler, car, Auto-rickshaw, heavy vehicle), speed of each category of vehicle (both as subject vehicle and opposing vehicle). Correlation analysis are carried out to select the most influencing variables and to eliminate the irrelevant variables. It is found that presence of two-wheeler, car and auto-rickshaw as subject and opposing vehicle type and their speeds are most influencing variables and hence, they are considered for developing the model. The model is developed using 75% of the total data and the rest (25% of data) is used for validation. The developed model has the following specification as shown in equation 4.1

$$\textit{Lateral placement of subject vehicle } (Y) = b_0 + b_1 * X_1 + b_2 * X_2 + b_3 * X_3 + b_4 * X_4 + b_5 * X_5 + b_6 * X_6 + b_7 * X_7 + b_8 * X_8 \quad \ldots\ldots\ldots\ldots (4.1)$$

where, b_0 is a constant, b_1, b_2, b_3, b_4, b_5, b_6, b_7 and b_8 are the coefficients of independents variables. X_1, X_2, X_3, X_4, X_5, X_6, X_7 and X_8, X_1, X_2 and X_3 represents presence of two-wheelers, cars and auto-rickshaws as ongoing vehicle types. X_5, X_6, X_7 represents presence of two-wheelers, cars and auto-rickshaws as opposing vehicle types. X_4 represents speed of ongoing vehicle and X_8 represents speed of opposing vehicle. The significance of overall model and significance of independent variables are tested using model goodness of fit. The R^2 value of the model is obtained as 0.55. The model has *F-statistics* more than the critical value (F_{obs} = 19.42, F_{crit} = 2.42, *dof* =889) implying that the model is statistically significant. The parameter estimate signifies that for every unit increment in independent variable there is an average change in dependent variable provided other variables are held constant. The values of coefficients, t-statistics and p-value for the developed model are investigated to identify the significant variables. After checking for significance, regression analysis is repeated with using those variables which are significant and the model coefficients are estimated for the revised model (Table 4.11).

Table 4.11 Estimation of coefficients for MLR model

Explanatory Variables	**Coefficients (b)**	**Standard Error**	**t Stat**	**p-value**
Constant	11.9	1.26	9.4	0.00
Presence of Two-wheeler (Ongoing)	3.8	0.56	6.8	0.00
Presence of Auto-Rickshaw (Ongoing)	3.6	0.51	7.0	0.00
Speed of Ongoing Vehicle	0.3	0.09	3.7	0.00
Speed of Opposing Vehicle	-1.1	0.10	-11.7	0.00

When the speed of the subject vehicle (ongoing vehicle) increases, it will move towards the middle of the road or to the opposing lane when there is no opposing vehicle mainly for the purpose of overtaking. Subject vehicle shifts towards the left side of road when speed of opposing vehicles increases in order to avoid collision with the opposing vehicles. Two-wheelers and auto-rickshaws as ongoing vehicles has significant influence on lateral placement as they occupy almost entire road width due to their smaller sizes and higher manoeuvrability. The Mean Absolute Percentage Error (MAPE) values are calculated by comparing predicted and observed values and it is found to be less than 15% which shows that the model replicates the field conditions reasonably.

4.5.10 Lateral separation

Lateral separation is the parameter which helps to study the gaps maintained by vehicles in the ongoing direction when opposed by an opposing vehicle. When two vehicles oppose each other within the study stretch, the closest distance between these vehicles when their lengths overlap each other is recorded as the lateral separation. Descriptive statistics for lateral separation of different types of vehicles are shown in Table 4.12. It is observed that lateral separation decreases as the size of the subject vehicle increases. From the table, it is found that two-wheelers have a higher mean lateral separation of 4.7 m whereas heavy vehicles have a minimum mean lateral separation of 2.7 m.

Table 4.12 Descriptive statistics for lateral separation of different type of vehicles

Vehicle Type	**Lateral separation (m)**			
	Mean	**SD**	**Min**	**Max**
Two-wheelers	4.7	1.8	0.9	8.6
Auto-rickshaws	4.2	1.2	0.9	7.8
Cars	2.9	1.4	0.6	8.0
HVs	2.7	1.4	1.4	6.7
Stream	3.6	1.6	0.6	8.6

4.6 SUMMARY

The methodology adopted for collection, extraction, and analysis of the traffic data is discussed in this section. Initially, ideal study locations are identified and traffic data are collected using the video-graphic method. These traffic data are extracted manually using image processing technique to obtain study parameters such as headway, free speed, space mean speed, acceleration and deceleration, longitudinal and lateral gaps. These parameters are further used as input variables in model development.

CHAPTER 5

MODEL CALIBRATION AND VALIDATION

5.1 MODEL CALIBRATION

Calibration is the iterative process of comparing the model with a real system and revising the model by making modifications to the built parameters if necessary until the model accurately represents the real system. The developed model is calibrated thoroughly to ensure that it replicates the field observed traffic conditions on a midblock section of urban undivided road. The parameters such as headway, free speeds, rate of acceleration and rate of deceleration, lateral acceleration, maximum escape speed (MES), the time required for veering (t_{veer}), longitudinal gaps and lateral gaps are used to calibrate the model. The calibrated parameters are either general or vehicle-specific based on the influence of these parameters on traffic flow. The common parameters used in general for all vehicles types are defined as follows:

5.1.1 Reaction time

Reaction time (T) is referred as the time taken by the subject vehicle to adjust its speed based on the variations in the speed of leader vehicle so as to avoid rear-end collisions. Previous studies show that drivers require about 1.5 to 2 seconds under normal conditions and 0.7 to 1.5 seconds under congested conditions (Chakroborty *et al.,* 2004; Dey *et al.,* 2008; Treiber *et al.,* 2010; Budhkar and Maurya 2014). In this study, a reaction time of 0.8 sec is adopted so as to represent the response time of driver during congested conditions (Asaithambi *et al.,* 2009).

5.1.2 Deceleration of leader as judged by subject vehicle

The deceleration of leader as judged by subject vehicle (b*) is defined as maximum rate of deceleration of leader as estimated by the subject vehicle during car following mode. This value is adopted from the previous study carried out by Ravishankar and Mathew (2011).

5.1.3 Sensitivity parameter

The sensitivity parameter (α) represents the variability in the gaps maintained by different types of subject vehicle - leader vehicle type combinations because the subject vehicle headway depends on the type of leader vehicle (Brackstone *et al.,* 2009).

5.1.4 Safe distance to stopping

The safe longitudinal distance maintained by the subject vehicle so as to avoid collision with leader vehicle is termed as safe distance to stopping (d_{body}). In this study, this parameter (2.5 m) is adopted from previous work (Asaithambi *et al.,* 2009).

5.1.5 Time required for veering

The time required by the subject vehicle to shift laterally with a distance equivalent to its width is termed as t_{veer} (Gunay, 2007). This time is updated in the model based on the lateral movements of type of subject vehicle.

5.1.6 Maximum escape speed

A speed at which the vehicle can decelerate (at time of passing) to the maximum speed allowed by the width of this escape corridor is termed as Maximum Escape Speed (MES). It is calculated as a function of frictional clearance (FC). If FC is smaller than 0.5 m, then MES is assumed to be zero, the use of the escape corridor is not practical if FC is less than 0.5 m (Gunay, 2007). If FC is between 0.5 and 1.5 m, the equation shown in Figure 5.1 is used. The program picks the corresponding speed value for a given current FC by fitting a second order curve to the plots with $R^2 = 0.60$. If FC is greater than 1.5 m, it is assumed that the effect of the neighboring vehicle is negligible, and thus, MES is taken as the current speed of subject vehicle.

5.1.7 Acceleration and deceleration during overtaking

The rate of acceleration (a_o) and rate of deceleration (b_o) are calculated in the model during the time of overtaking. These values depend on the time taken to collide opposing vehicle (TTC_{ov}) and time taken to overtake ($t_{overtake}$).

Certain vehicle-specific parameters are also used for calibrating the model. The parameters such as maximum deceleration (b), acceleration (a), veer velocity (V_{veer}), lateral gap and longitudinal gap are calibrated from the traffic data collected from Bengaluru city. The calibrated parameters used in this study are shown in Table 5.1.

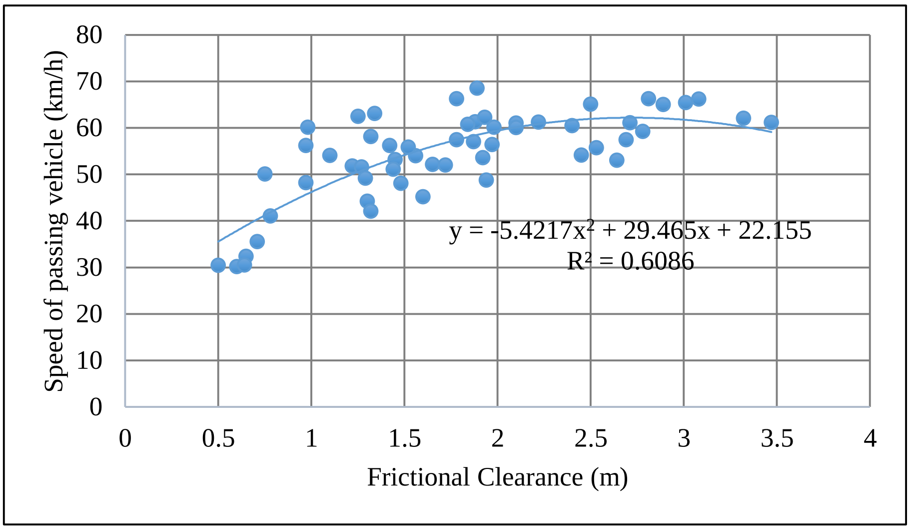


Figure 5.1 Relationship between frictional clearance and passing speed

Table 5.1 Calibrated parameters used in the model

Common Parameters	
Calibration Parameters	**Values**
Reaction time (T)	0.8 s
Deceleration of leader as judged by subject vehicle (b*)	2.5 m/s^2
Sensitivity factor (α)	1.0
Safe distance to stopping (d_{body})	2.5 m
Time required for veering (t_{veer})	Veer distance/V_{veer}
Maximum escape speed (MES)	MES = -5.4217(FC)^2 + 29.465(FC) + 22.155
Acceleration during overtaking (a_o)	a_o = 0.05 * (1.5 * (TTC_{ov} - $t_{overtake}$) + 50)
Deceleration during overtaking (b_o)	b_o = (10 - TTC_{ov})

Vehicle-Specific Parameters				
Calibration Parameters	**Two-wheelers**	**Auto-rickshaws**	**Cars**	**Heavy vehicles**
Maximum deceleration (b), m/s^2	3.1	2.8	3.0	2.1
Acceleration (a), m/s^2	1.9	1.5	1.8	1.3
Lateral gap, m	3.2	2.8	2.4	2.1
Longitudinal gap, m	10.7	11.1	10.8	11.9
V_{veer}, m/s	1.2	1.2	1.0	0.8

**FC= Frictional Clearance, $t_{overtake}$ = Time taken to overtake, TTC_{ov} = Time taken to collide with opposing vehicle, Veer distance = Equivalent to width of vehicle*

5.2 MODEL VALIDATION

Model validation is the process of comparing model results with the corresponding field observed values to ensure that the simulated results realistically represent the real system. In the present study, the developed traffic simulation model is validated using both internal and external traffic data sets. Internal validation is carried out using the same traffic data which is used for model development (Bengaluru study section). For external validation of the model, another data is collected from Kollam city. Speed is the parameter used for validation, which is considered as the measure of effectiveness (HCM 2010) for mid-block section of roads.

5.2.1 Internal Validation

The data collected at a mid-block section of two-way urban undivided road located in Bengaluru city which is used to develop the model is also used for internal validation. Table 5.2 shows the statistical comparison of simulated and observed mean speed of vehicles in ongoing and opposing direction.

Table 5.2 Comparison of simulated and observed mean speeds - Bengaluru city

Vehicle Type		**Mean Speed Values (m/s)**		**MAPE (%)**	***t-stat***	***t-critical***
		Simulated	**Observed**			
Ongoing Direction	Two-wheelers	14.01	12.9	8.60	-2.67	2.83
	Cars	11.75	11.9	1.26	-2.38	2.46
	Auto-rickshaws	11.95	12.8	6.64	-2.25	2.55
	Heavy vehicles	10.52	11.7	10.08	-2.74	2.23
	Stream	12.05	12.32	2.19	-2.82	2.59
Opposing Direction	Two-wheelers	12.37	11.08	11.64	-1.20	2.74
	Cars	10.78	11.30	4.60	-2.93	2.58
	Auto-rickshaws	10.24	10.58	3.21	-2.10	2.60
	Heavy vehicles	10.06	10.75	6.41	-2.88	2.11
	Stream	10.86	10.92	0.54	-2.78	2.54

Independent t-test is performed for 0.05 level of significance to check the statistical validation of the model. It is observed that for each vehicle type the *t-critical* value is found to be greater than the *t-stat* value indicating that model replicates the field conditions realistically. Overall, the Mean Absolute Percentage Error (MAPE) for ongoing direction is found to be 2.19 % and the MAPE value of opposing direction is

0.54 %. MAPE values for cars in ongoing direction is found to be less when compared to other vehicle types. Two-wheelers in opposing direction showed higher MAPE values (11.64 %) indicating that speeds are sensitive to lateral movements. Also, the distribution of speeds obtained from real world data are compared with simulated speeds as shown in Table 5.3. MAPE values for speed range 10 m/s to 15 m/s is higher (20.89 %) due to higher frequency of vehicles. Observed vs simulated speeds are plotted with a linear fit having R^2 value of 0.88 as shown in Figure 5.2.

Table 5.3 Comparison of distribution of speeds (Observed and Simulated)

Speed Range (m/s)	**Observed (Frequency)**	**Simulated (Frequency)**	**Mean Observed Speed (m/s)**	**Mean Simulated Speed (m/s)**	**MAPE (%)**
0 to 5	02	02	3.6	4.02	11.66
5 to 10	205	208	7.87	9.12	15.88
10 to 15	1624	1618	11.2	13.54	20.89
15 to 20	482	478	15.28	17.23	12.76

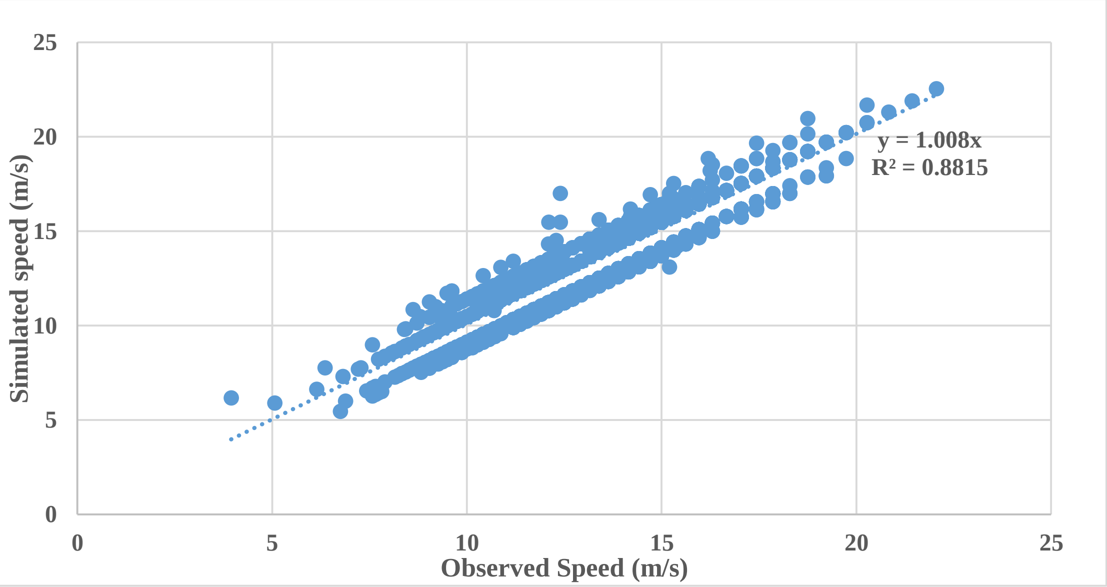


Figure 5.2 Simulated speed Vs observed speed

5.2.2 External Validation

Another set of data is used for external validation of the model, which is collected from a two-lane undivided mid-block section located in Kollam city, Kerala. A study stretch of 30 m length with 7 m road width is selected (Figure 5.3). Both peak and off-peak hour traffic data are collected using video camera located on a vantage point. The peak hour data are collected during 8.15 am - 9.15 am and off-peak hour data are collected in the early morning (5.00 am – 6.00 am). Figure 5.4 shows the composition of vehicles observed on the study section. It is observed that two-wheelers shared higher proportion both in ongoing (59.64%) and opposing (57.08) direction followed by cars (30.43 % in ongoing direction and 32.54 % in opposing direction) during peak hours.

Figure 5.3 Study section selected for external validation – Kollam city, India

The input parameters such headway distribution, free-flow speeds, speeds of different vehicle types are also extracted from the data which is shown in Table 5.4. It is observed that two-wheelers travel at a higher free-flow speed of 16.89 m/s followed by cars (16.05 m/s). The mean free-flow speed considering all types of vehicles is found to be 15.45 m/s. The observed speed values during peak hours are also obtained and it is found that cars travel at higher speeds (11.12 m/s) when compared to other vehicle types. The time gap or headway values are also extracted and the mean headway observed on the study section is 1.23 s. Different probability distribution functions are fitted to the aggregate and class-wise data of free-flow speed and the goodness-of-fit test for each probability density function is conducted by K-S test at 5 % level of significance.

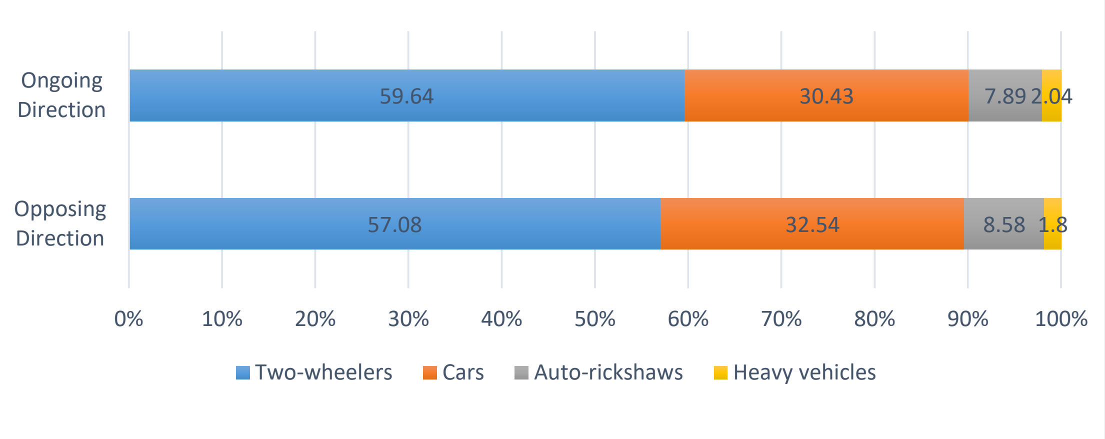


Figure 5.4 Vehicular composition observed on the study stretch, Kollam city

Table 5.4 Traffic flow variables extracted for external validation

Traffic Flow Variables		**Stream**	**Two-wheelers**	**Auto-rickshaws**	**Cars**	**Heavy Vehicles**
Free-flow Speed (m/s)	Mean	15.45	16.89	16.01	16.05	12.88
	SD	3.9	3.8	2.2	2.5	0.7
	Fit	GEV	GEV	Normal	GEV	GEV
	K-S	-0.03	-0.04	-0.04	-0.05	-0.07
Speed (m/s)	Mean	10.45	10.46	9.24	11.12	11.01
	SD	2.3	1.9	1.7	2.4	2.5
	Fit	GEV	GEV	Normal	GEV	GEV
	K-S	-0.04	-0.03	-0.04	-0.04	-0.08
Headway (s)	Mean	1.23	1.32	1.27	1.08	1.27
	SD	1.22	1.35	1.21	1.22	1.72
	Fit	Weibull	GEV	Gamma	GEV	Weibull
	Parameters	$\alpha=1.3$ $\beta=0.6$	$k=0.2$ $\sigma=0.6$ $\mu=0.7$	$\alpha=0.8$ $\beta=1.3$	$k=0.2$ $\sigma=0.2$ $\mu=0.5$	$\alpha=0.7$ $\beta=1.3$ $\gamma=0.06$

** SD = standard deviation, K-S = Kolmogorov–Smirnov value, GEV= generalized extreme value*

The statistical comparison of the simulated and observed speed of vehicles in both ongoing and opposing direction is shown in Table 5.5. Independent *t-test* is performed for 0.05 level of significance to check the statistical validation of the model. It is observed that for each vehicle type, the *t-critical* value is found to be greater than the *t-stat* value indicating that model replicates the field conditions realistically. The overall MAPE value for ongoing direction is found to be 4.68 % whereas the MAPE value for opposing direction is 3.61 %.

Table 5.5 Comparison of simulated and observed mean speeds - Kollam city

Vehicle Type		**Mean Speed Values (m/s)**		**MAPE (%)**	***t* stat**	***t* critical**
		Simulated	**Observed**			
Ongoing Direction	Two-wheelers	12.18	10.46	13.38	-2.45	2.71
	Cars	10.86	11.12	2.33	-2.30	2.48
	Auto-rickshaws	10.26	9.24	11.03	-1.95	2.06
	Heavy vehicles	10.46	11.01	4.99	-2.04	2.85
	Stream	10.94	10.45	4.68	-2.11	2.75
Opposing Direction	Two-wheelers	11.49	12.71	9.59	-1.98	2.88
	Cars	10.31	10.93	5.67	-2.08	2.92
	Auto-rickshaws	10.86	10.08	7.73	-2.10	2.75
	Heavy vehicles	10.05	10.58	5.00	-2.14	2.47
	Stream	10.67	11.07	3.61	-2.20	2.69

5.3 EFFECT OF COMPOSITION ON CRITICAL PARAMETERS

The efficiency of the developed model to simulate varying traffic composition is evaluated and the effect of traffic composition on capacity is studied. The following compositions are considered which correspond to different compositions observed on arterial roads in India (Asaithambi *et. al.*, 2012):

C (observed composition): 58% Two-wheelers, 26% Cars, 12% Auto rickshaws, and 4% Heavy vehicles

C1: 50% Two-wheelers, 14% Cars, 34% Auto-rickshaws, and 2% Heavy vehicles

C2: 30% Two-wheelers, 50% Cars, 15% Auto-rickshaws, and 5% Heavy vehicles

C3: 30% Two-wheelers, 45% Cars, 10% Auto-rickshaws, and 15% Heavy vehicles

Same vehicular composition is used for both the direction of traffic. The traffic flow observed (3374 veh/h) in Bengaluru location is used for all four compositions. The composition C represents observed traffic composition at Bengaluru location in which two-wheelers are dominant. Similarly, C1, C2, and C3 represent the dominant proportion of auto-rickshaws, cars, and heavy vehicles, respectively. From the analysis, it is observed that capacity is higher when there is a larger proportion of two-wheelers in the mix and decreases when the stream contained a larger proportion of cars and heavy vehicles. The composition C had a capacity of 5106 veh/h (4353 PCU/h). Passenger Car Unit (PCU) values suggested by Indian Road Congress are used to convert different vehicle types into an equivalent passenger car values (IRC-106-1990). IRC PCU values for two-wheeler is 0.75, car is 1.0, auto-rickshaw is 1.2 and heavy vehicle is 2.2. For composition C1, there is 1.6 % reduction in capacity (4786 PCU/h) resulting from a slight decrease in the two-wheeler percentage from 58% to 50% and an increase in auto-rickshaws from 12 % to 34 %. The capacity reduction is larger (9.10%) in case of C2 due to increment in cars percentage from 26 % to 50 %. The capacity reduced to 13.20 % for composition C3, due to increase in heavy vehicle percentage from 4% to 15%. Table 5.6 shows the critical parameters for different compositions. It is observed that critical density is higher for compositions comprising of a higher proportion of two-wheelers and auto-rickshaws i.e. C and C1, which indicates the ability of this vehicle to squeeze in between the gaps of larger vehicles. The critical density for C2 and C3 is smaller indicating that presence of a higher proportion of cars and heavy vehicles significantly reduces the squeezing behaviour of smaller two-wheelers and auto-rickshaws. From this analysis, it is observed that the developed model is efficient and valid to simulate any varying traffic composition.

Table 5.6 Critical parameters for different compositions

Composition	**Flow [veh/h (PCU/h)]**	**Density [veh/km (PCU/km)]**	**Speed (km/h)**
C	5106 (4353)	196 (167)	26.14
C1	5023 (4786)	185 (174)	27.21
C2	4641 (4594)	169 (167)	27.56
C3	4432 (4530)	155 (160)	28.64

5.4 EFFECT OF COMPOSITION ON SPEED-FLOW AND SPEED-DENSITY RELATIONSHIPS

The relationship between speed-flow and speed-density values are plotted for varying compositions i.e. C, C1, C2, and C3. Figures 5.5 – 5.7 shows the speed-flow and speed-density relationships for varying traffic compositions on ongoing direction, opposing direction and both direction, respectively.

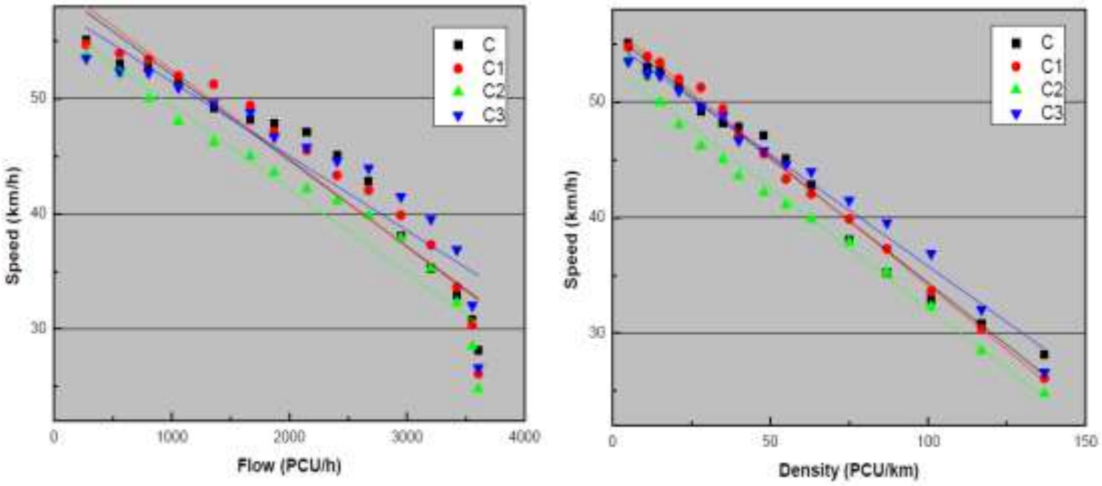


Figure 5.5 Speed-flow and speed-density relationships - Ongoing direction

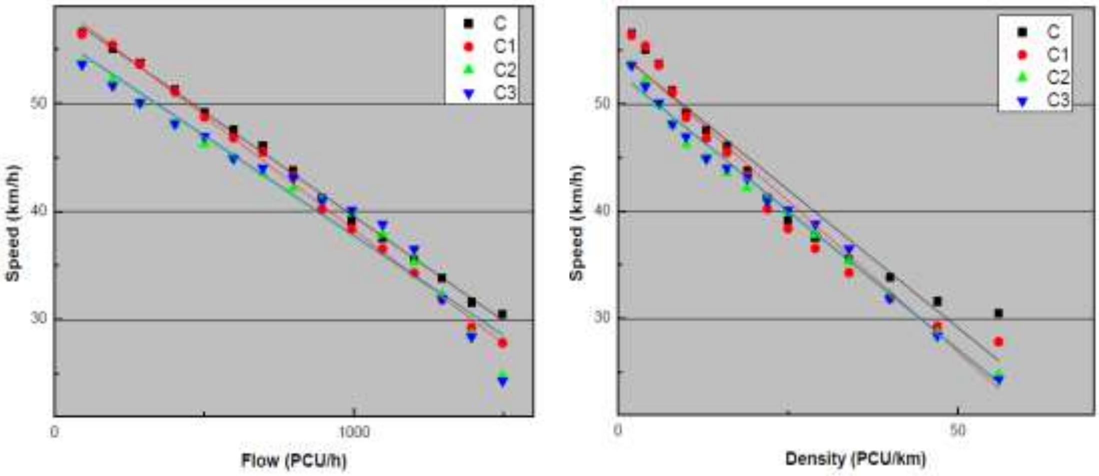


Figure 5.6 Speed-flow and speed-density relationships - Opposing direction

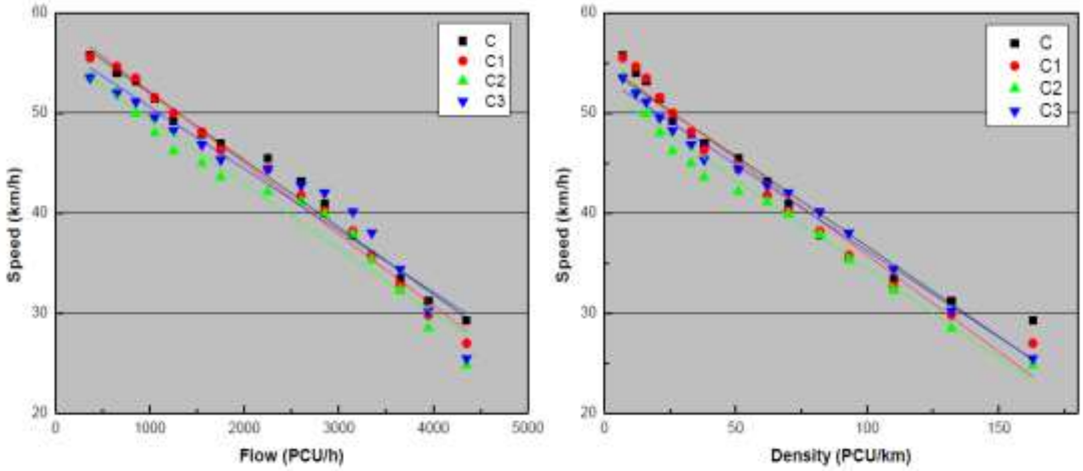


Figure 5.7 Speed-flow and speed-density relationships – Both direction combined

For ongoing direction, the intercept is smallest for C2 because of its large share of cars

(50 %), which resulted in a mean free-flow speed of 54 km/h. Whereas in the case of opposing direction, the intercept is smallest for C2 and C3, in which the proportion of cars and heavy vehicles is 50 % and 15%, respectively. For combination of traffic on both direction, C2 is having a smallest intercept, in which the proportion of cars is 50 %. The rate of decrease in speed with increasing density is largest for C2 for all three cases (ongoing, opposing and both direction).

This shows that cars are most affected by increasing the number of vehicles. This effect may be attributed due to their higher manoeuvrability and conflicts with opposing traffic. A significant influence of composition on speed-flow relationships is also observed. For any given flow level for all three cases, the maximum speed occurs for compositions C and C1, in which the proportion of two-wheelers and auto-rickshaws are 58 % and 34 %, respectively (Minh *et al.*, 2005; Asaithambi et al. 2012; Dey and Das, 2015). Similar results were obtained by Asaithambi *et al.* 2018, where speed is maximum for higher proportion of two-wheelers. For combined traffic on both direction, for any flow level, speed was lowest for C2 (with a high car share). Speeds of C, C1, and C3 are nearly identical and much higher than C2.

5.5 SUMMARY

In this section, the developed model is calibrated using various parameters such as headway, free speeds, rate of acceleration and rate of deceleration, lateral acceleration, maximum escape speed (MES), the time required for veering (t_{veer}), longitudinal gaps and lateral gaps. The model is validated using both internal and external data sets. The data used for model development (Bengaluru location) is also for internal validation of the model and external validation using another data collected from Kollam location. Statistical results prove that developed model replicates the real world conditions satisfactorily. The efficiency of the developed model to simulate varying compositions is also performed and the effect of these composition on critical parameters is analysed.

CHAPTER 6

APPLICATIONS OF SIMULATION MODEL

6.1 GENERAL

This chapter discusses the application of the developed simulation model to evaluate various traffic management measures such as reversible lanes and modal shift of private vehicles towards public transport system. The impact of reversible lanes on capacity of roads during morning and evening peak hours is studied. Also, the impact of modal shift of private vehicles towards public transport on capacity, travel time, and traffic emissions are studied.

6.2 EVALUATION OF REVERSIBLE LANES (TIDAL FLOW OPERATIONS)

During peak hours most of the urban roads operate at or near capacity which results in forced flow at low speeds and increased travel times. Also, it is observed that the traffic flow in one direction is predominant (tidal flow) compared to other direction in peak hours which further reduces the capacity. Most of these roads have restricted right-of-way and narrow shoulders which makes it either impossible or extremely expensive to increase the capacity by constructing additional lanes. In such cases, implementation of better traffic control and management measures may solve the problem. One such measure is applying reversible lanes to create a contraflow lane which provides additional capacity during peak hours. Hence, the model is applied to study the benefits of reversible lane operation in mixed traffic conditions on urban undivided roads.

The Institute of Transportation Engineers (ITE) defines the reversible lanes as “potentially one of the most effective methods of increasing peak hour capacity of existing roadways under the proper conditions” (Wolshan and Lambert, 2006). A reversible roadway is one in which the direction of traffic flow in one or more lanes or shoulders is reversed to the opposing direction for some period of time. Its utility is derived by taking advantage of the unused capacity of the minor flow direction to increase capacity in the major flow direction, avoiding the need to construct additional lanes.

6.2.1 Modification of simulation model to implement reversible lanes

The traffic data collected from an undivided urban mid-block section located in Bengaluru city are used for evaluating the reversible lane (RL) operations. The selected study stretch is 12 m wide, which is divided into 6 equal strips of each 2 m wide. In the case of without reversible lanes, strips 1 to 3 accommodate traffic flowing in ongoing direction and strips 4 to 6 accommodate traffic flow in opposite direction as shown in Figure 6.1. On undivided roads, due to lack of lane segregation, it is noticed that most of the vehicles traveled in opposing lanes as well. It is observed that during morning peak hours, traffic flow in ongoing direction is 2666 veh/h and in opposing direction it is 988 veh/h. In contrast, during evening peak hours, the flow in ongoing direction is 680 veh/h and opposing direction is 1904 veh/h. According to AASHTO (2001), reversible lane operations can be suggested when "65 percent or more of the traffic moves in one direction during peak hours. So, in this study, an attempt has been made to evaluate reversible lanes and study its effect on capacity during peak hours (both morning and evening).

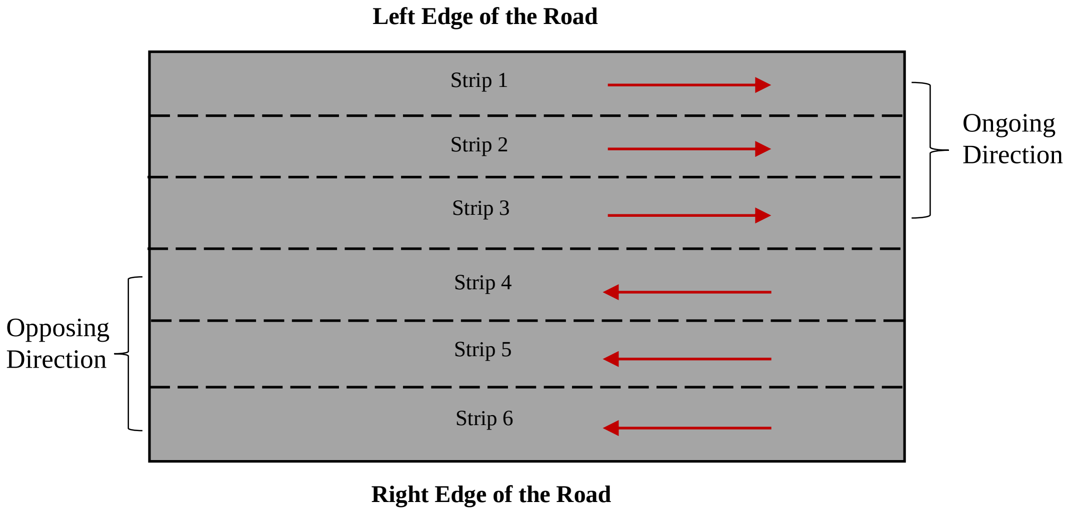


Figure 6.1. Traffic flow without reversible lanes

The vehicle placement logic is modified in the developed simulation model to simulate tidal flow operations. Strips 3 and 4 are converted to reversible lanes so that strips 1 to 4 can be used by the ongoing traffic in morning peak hours with an additional strip as shown in Figure 6.2. Similarly, strips 3 to 6 can be used by the ongoing traffic in evening peak hours. For this purpose, a total of 24 simulation runs without reversible lanes and 24 simulation runs with reversible lanes are obtained. The evaluation process involves comparison of capacity with and without implementing reversible lanes for the observed flow (Bengaluru study section) and four different compositions (Refer Section 5.3) as shown in Table 6.1.

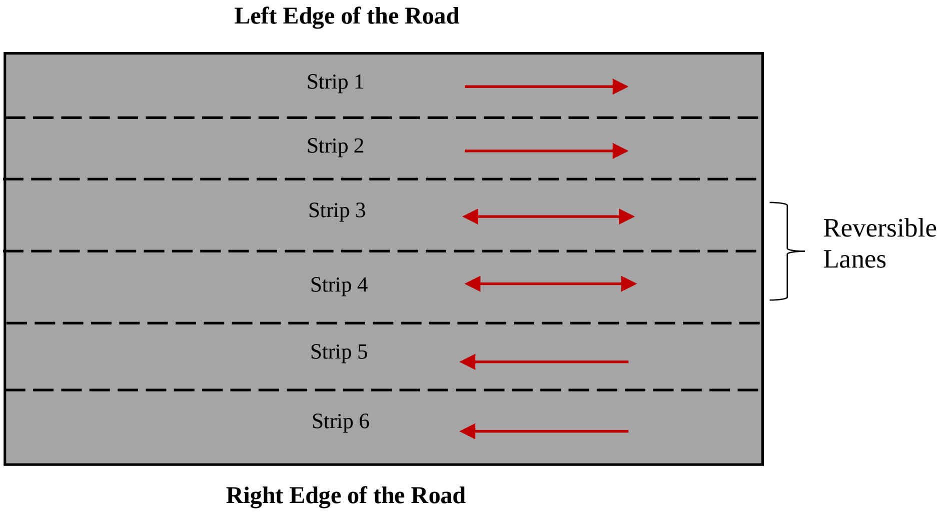


Figure 6.2 Traffic flow with reversible lanes

6.2.2 Results and discussion on reversible lanes

From the analysis, it is observed that there is an improvement in capacity during peak hours after implementing reversible lanes. For composition C (Observed), the capacity in ongoing direction during morning peak hour is increased by 20.5 %, similarly capacity in opposing direction during evening peak hour is increased by 19.20 %. Overall, there is an increment of 568 veh/h (485 PCU/h) during morning peak hour and 396 veh/h (338 PCU/h) during evening peak hour for composition C after implementing reversible lanes. Similar trends were obtained by studies carried out under homogeneous (Lambert and Wolshon, 2010) and heterogeneous traffic conditions (Bede *et al*, 2010). For composition C1 (auto-rickshaw dominant), there is an overall increment of 189 veh/h (180 PCU/h) during morning peak hour and 334 veh/h (318 PCU/h) during evening peak hours. Improvement in capacity for this composition during morning peak hour is 3.7 % and during evening peak hour it is found to be 7.8 %. In case of car dominant composition (C2), higher improvement in capacity is observed during evening peak hour (5.1 %) with an increment of 211 veh/h (209 PCU/h). Similarly, for all the compositions there is a certain amount of improvement in capacity during peak hours for reversible lane operations. It is also seen that improvement in capacity is significant for compositions, C (two-wheeler dominant) and C1 (auto-rickshaw dominant). This is mainly due to the restriction of lateral movements of aggressive vehicles on the opposing lanes.

Table 6.1 Comparison of capacity with and without implementing reversible lanes for different compositions

Composition	**Peak Period**	**Scenarios**	**Capacity [veh/h (PCU/h)]**		
			Ongoing Direction	**Opposing Direction**	**Combined**
C	Morning	Without RL	3608 (3076)	1498 (1278)	5106 (4353)
		With RL	4348 (3707)	1326 (1131)	5674 (4838)
	Evening	Without RL	1342 (1145)	3242 (2764)	4584 (3908)
		With RL	1108 (945)	3872 (3301)	4980 (4246)
C1	Morning	Without RL	3562 (3394)	1461 (1392)	5023 (4786)
		With RL	3892 (3709)	1320 (1258)	5212 (4966)
	Evening	Without RL	1250 (1191)	3102 (2956)	4272 (4071)
		With RL	1121 (1068)	3485 (3321)	4606 (4389)
C2	Morning	Without RL	3382 (3348)	1259 (1247)	4641 (4594)
		With RL	3625 (3588)	1160 (1149)	4785 (4736)
	Evening	Without RL	1192 (1180)	3084 (3053)	4171 (4129)
		With RL	1026 (1016)	3356 (3322)	4382 (4338)
C3	Morning	Without RL	3265 (3338)	1167 (1193)	4432 (4531)
		With RL	3520 (3598)	1058 (1082)	4578 (4680)
	Evening	Without RL	1104 (1129)	2958 (3024)	4062 (4152)
		With RL	1078 (1102)	3120 (3190)	4198 (4291)

Practical implementation of reversible lanes need a movable barrier to establish a physical separation between ongoing and opposing vehicles. In addition to that overhead traffic lights and lightened street signs can be provided to alert the driver to indicate which strips are open or closed for driving.

6.3 IMPACT OF MODAL SHIFT OF PRIVATE VEHICLES TOWARDS PUBLIC TRANSPORT SYSTEM

In most of the developing and emerging cities, increase of private vehicles ownership is generally uncontrolled. The number of two-wheelers in Indian cities are increasing at a faster rate and currently, traffic in many metro cities are composed of more than 50 % of two-wheelers (Chadchan and Shankar, 2012). Moreover, car ownership has also been increasing in such cities. As a result, traffic congestion in these cities is getting worsened which affects the travel time, speeds, capacity and traffic emissions. Such traffic problems need to be resolved so as to improve the capacity of the existing road network and also, to reduce the amount of emissions from road transport. Promotion of public transport system is a mitigation measure to address the above problems. In the present study, the developed traffic simulation model for urban undivided road is used to study the impact of modal shift of private vehicles (two-wheelers and cars) towards public transport system (bus) on traffic capacity, travel time and emissions for three different road sections located in metropolitan cities of India namely, Bengaluru, Delhi and Mumbai. The traffic data such as vehicular composition, speed, and flow are collected from a typical weekday during peak hours for these locations. The traffic data from Delhi and Mumbai are obtained from the previous study carried out by Central Road Research Institute, India for Indo-HCM project.

The details of the three study sections are shown in Table 6.2. The observed traffic composition in Bengaluru study section (used for model development and internal validation) is two-wheeler dominant (64.02%) followed by cars (27.60 %), auto-rickshaws (7.30 %) and buses (1.08 %). The observed flow in this study section during morning peak hour is 3374 veh/h (3142 PCU/h). Traffic data from Delhi city is recorded from a four-lane undivided urban road (Ashoka road) on a typical weekday during morning peak hour. The study location is a 14 m wide with an observed flow of 3708 veh/h (3623 PCU/h). The observed traffic composition in Delhi is car dominant

(52.45%) followed by two-wheelers (33.97 %), auto-rickshaws (13.12 %) and buses (0.46 %). Another traffic data is collected from an urban undivided mid-block section (Bapura Jagtap Marg) located in Mumbai city on a typical weekday during morning peak hour. This study location is a two-way undivided section with a road width of 7.5 m. The observed traffic composition in Mumbai comprises 41.46 % two-wheelers, 50.42 % cars, 5.74 % auto-rickshaws and 2.38 % buses. The observed flow during morning peak hour is 2230 veh/h (2140 PCU/h).

Table 6.2 Details of study sections selected for implementing modal shift scenario

Study Section	**Observed Flow (PCU/h)**	**Road Width (m)**	**Vehicular Composition (%)**			
			Two-wheeler	**Car**	**Auto-rickshaw**	**Bus**
Bengaluru City	3142	12	64.02	27.6	7.3	1.08
Delhi City	3623	14	33.97	52.45	13.12	0.46
Mumbai City	2140	7.5	41.46	50.42	5.74	2.38

6.3.1 Modification of simulation model to implement modal shift scenario

The process of modal shift is performed in the developed model by shifting the commuters (persons) using private vehicles (two-wheelers and cars) to public transport (buses) by increasing the number of buses. To achieve this, total number of commuters (occupancy) using each type of vehicle are calculated from the observed traffic flow. The average occupancy values for each type of vehicle for different cities is shown in Table 6.3. These average occupancy values are multiplied by a total number of vehicles to obtain the occupancy of each vehicle type. Modal shift is implemented for observed flow values for each study section. A total of 9 simulation runs are performed before implementing modal shift and 153 simulation runs are performed after implementing modal shift considering all three study sections for three different scenarios:

Scenario I: Only the two-wheeler commuters are shifted to buses by incrementing the number of buses (in the order of 5, 10, 15, 20, 25, and 30) and proportionately reducing the number of two-wheelers occupants from the observed composition.

Scenario II: Only the commuters using cars are shifted to buses by increasing the number of buses in the order of 2, 4, 6, 8, 10 and 12 with a proportionate reduction in cars from the observed composition.

Scenario III: Both two-wheeler and car commuters are equally shifted to buses by increasing the number of buses by 6, 8, 10, 12, 14, 16, 18, and 20 with the proportionate reduction of two-wheelers and cars.

Table 6.3 Average occupancy values for different types of vehicle for different cities

City	**Average occupancy (persons/vehicle)**			
	Two-wheeler	Auto-rickshaw	Car	Bus
Bengaluru	1.5	1.76	2.67	70
Delhi	1.5	1.76	2.68	68
Mumbai	1.5	1.76	1.57	65

(Source: Motor Transport Statistics of India, 2010)

6.3.2 Capacity and travel time improvement due to modal shift

All the three scenarios discussed above are implemented in the developed model and the impact of these on capacity and travel time are analysed for all three study sections (Bengaluru, Delhi, and Mumbai). The observed flow level is given as input and it is increased further until the values are saturated (considered as capacity) by obtaining 36 simulation runs. The travel time of each type of vehicle is obtained for a simulation road stretch of 1 km length.

6.3.2.1 Bengaluru study section

In Scenario I, only commuters of two-wheelers are shifted to buses by incrementing the number of buses in order of 5, 10, 15, 20, 25 and 30 till the optimum increment in the bus is achieved. The optimum increment indicates the higher improvement in capacity. The improvement in capacity (e.g. 3.4% for increment of 5 bus) comparing before and after modal shift is shown in Figure 6.3. It is observed that as the number of commuters shifted to buses increases, the capacity also increases and after a certain point further increment in buses reduces the capacity. In this scenario, capacity is higher (3674

PCU/h) for increment of 20 buses (16.9 % increase in capacity compared to before modal shift) and further increment in buses reduces the capacity and hence, 20 buses are selected as optimum number of buses. It is also seen that for optimum buses, there is an overall reduction in stream travel time (14.2 % reduction when compared to before modal shift) per kilometre during peak hour (Figure 6.4). Also, the travel time is reduced by 4.59 s, 19.81 s, 15.2, and 17.91s for two-wheelers, cars, auto-rickshaws, and buses, respectively. This reduction in travel time and improvement in capacity is mainly due to reduction in the number of squeezing manoeuvres by two-wheelers.

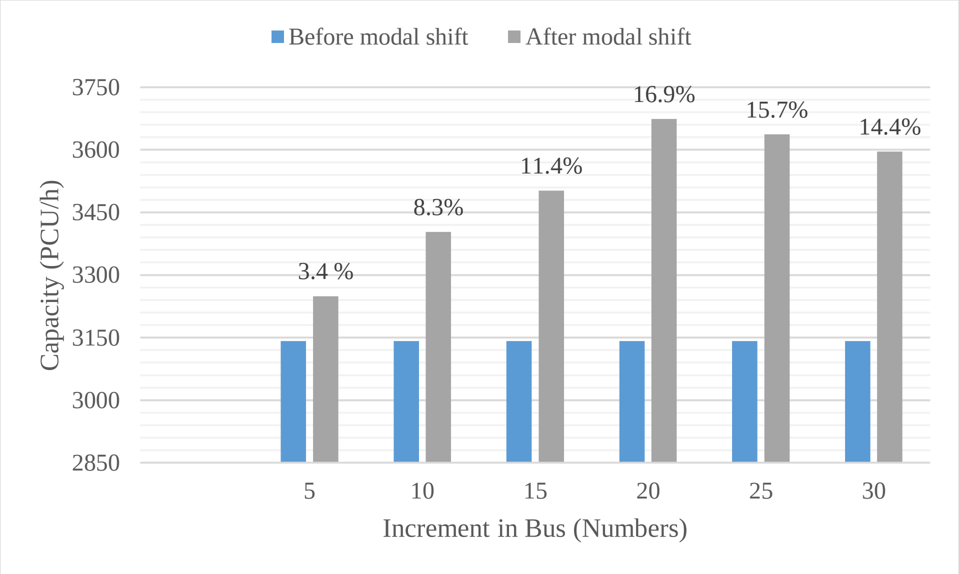


Figure 6.3 Capacity after implementing modal shift – Scenario I – Bengaluru

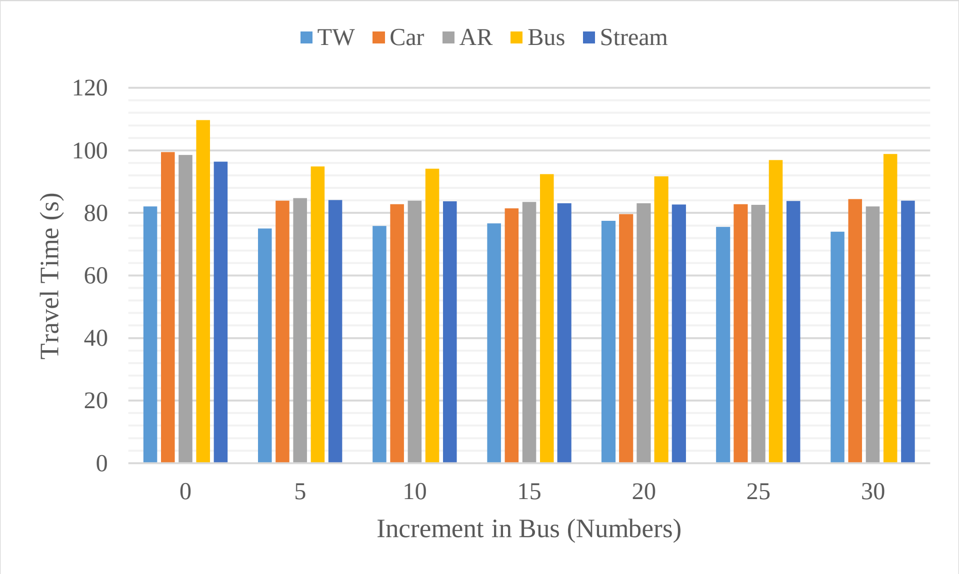


Figure 6.4 Travel time after implementing modal shift – Scenario I – Bengaluru

When the commuters from only cars are shifted to buses (Scenario II), it is observed that higher capacity (3433 PCU/h) is achieved for increment of 6 buses as shown in Figure 6.5. For this optimum increment in buses, improvement in capacity (9.2 %) is observed when compared to before modal shift. From Figure 6.6 it can be seen that there is a reduction in stream travel time (per kilometre) by 16.56 s (17.2 % reduction when compared to before modal shift) for optimum increment in buses during peak hour. Also, travel time is reduced by 6.52 s, 20 s, 17.68, and 25.75 s for two-wheelers, cars, auto-rickshaws, and buses, respectively.

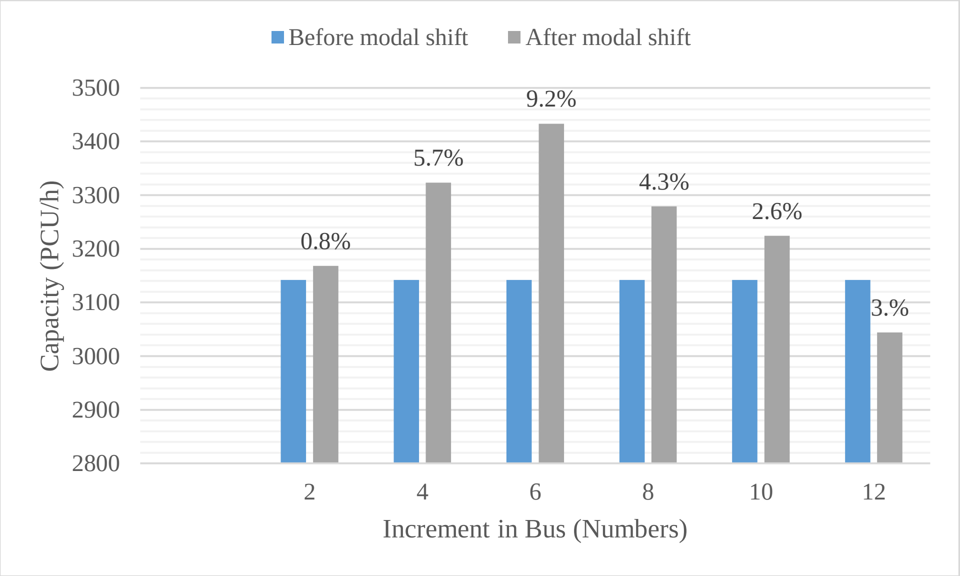


Figure 6.5 Capacity after implementing modal shift – Scenario II – Bengaluru

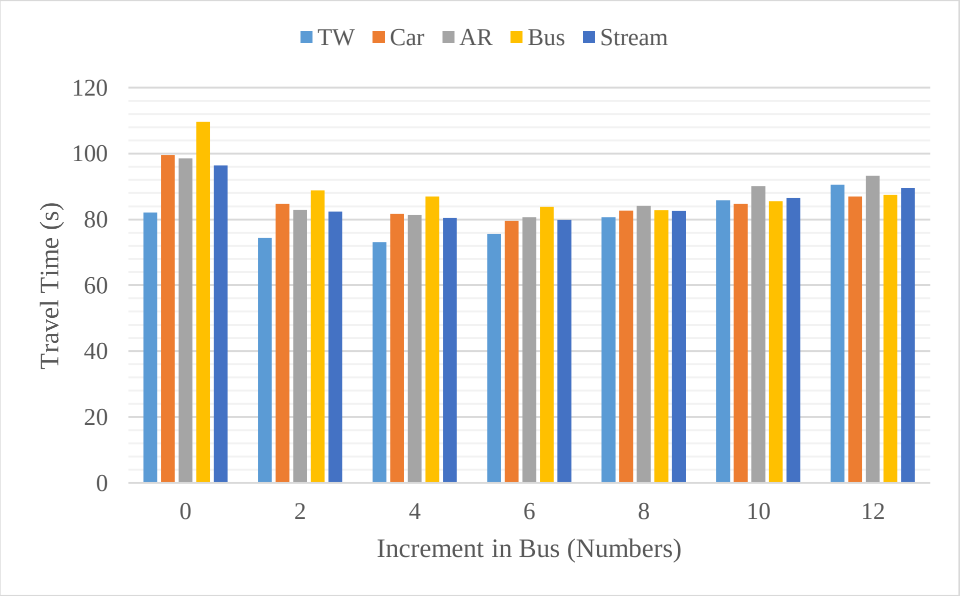


Figure 6.6 Travel time after implementing modal shift – Scenario II – Bengaluru

For Scenario III (commuters from both two-wheelers and cars were shifted to buses), improvement in capacity (9.9 %) is seen when compared to before modal shift for increment of 16 buses during peak hour (Figure 6.7). Due to modal shift of both two-wheeler and car, the capacity increases to 3456 PCU/h. There is a significant amount of reduction in travel time per kilometre (15.4 s) for optimum increment in buses (15.9 % reduction when compared to before modal shift) as shown in Figure 6.8. Travel time is reduced by 14.54 s, 23.05 s, and 21.69 s for two-wheelers, cars, and buses, respectively. The travel time of auto-rickshaws remained almost same (98 s) before and after modal shift.

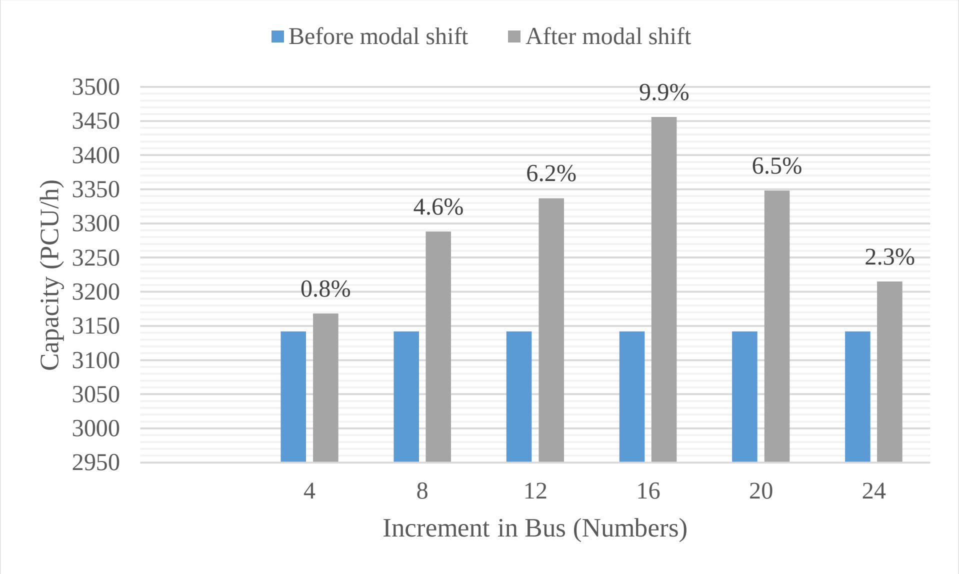


Figure 6.7 Capacity after implementing modal shift – Scenario III – Bengaluru

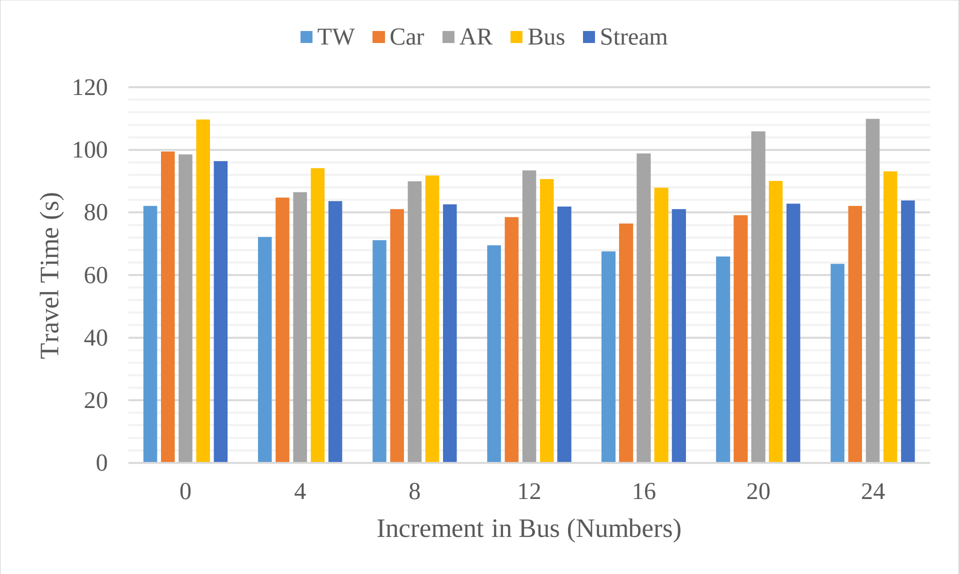


Figure 6.8 Travel time after implementing modal shift – Scenario III – Bengaluru

6.3.2.2 Delhi study section

For Scenario I, it is observed that capacity increases to 4140 PCU/h (14.3 % increase in capacity when compared to before modal shift). This improvement in capacity is achieved for an optimum increment of 20 buses as shown in Figure 6.9. A total of 43.63 s of reduction in travel time (per kilometre) is attained during peak hour for optimum increment in buses (22.2 % reduction when compared to before modal shift) as shown in Figure 6.10. Travel time reduction is achieved for all categories of vehicles during peak hours.

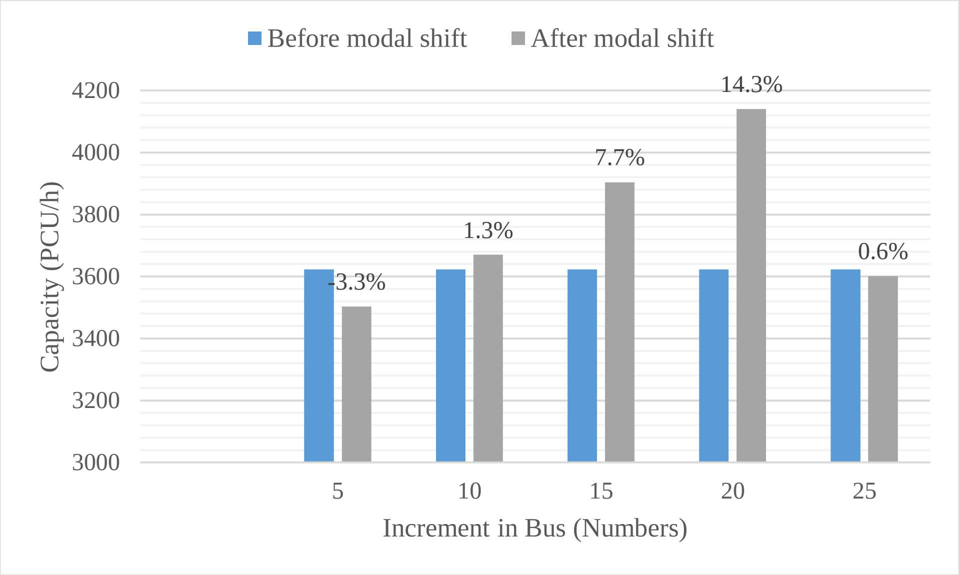


Figure 6.9 Capacity after implementing modal shift – Scenario I – Delhi

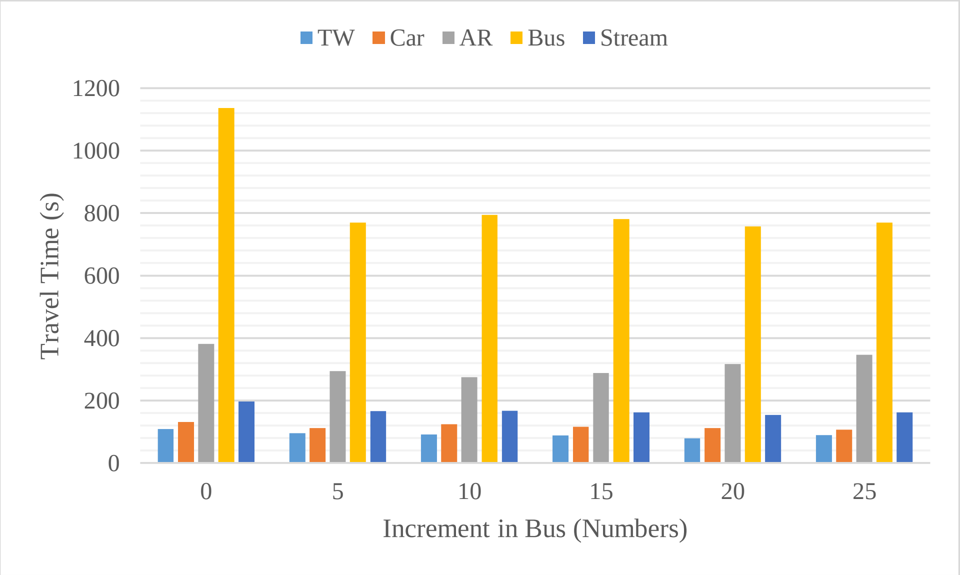


Figure 6.10 Travel time after implementing modal shift – Scenario I – Delhi

In Scenario II, commuters from cars are shifted to buses by incrementing the number of buses in order of 2, 4, 6, 8, 10, 12 and 14. For an optimum increment of 10 buses, higher capacity (3927 PCU/h) is observed (8.4 % increment when compared to before modal shift) as shown in Figure 6.11. The travel time of the stream is reduced by 53 s (per kilometre) for optimum increment in buses during peak hours. Overall, 26.9 % of reduction in travel time of the stream is achieved when compared to before modal shift (Figure 6.12).

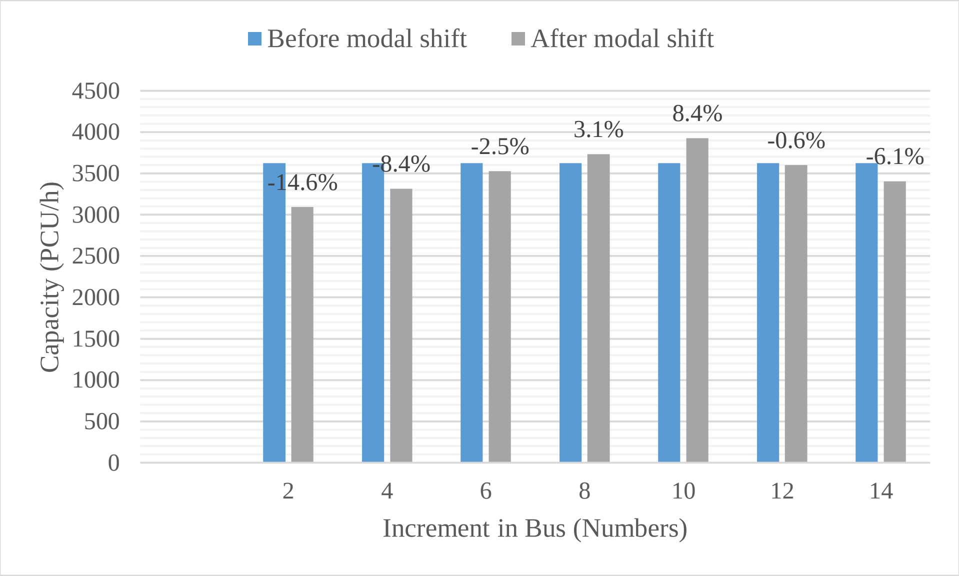


Figure 6.11 Capacity after implementing modal shift – Scenario II – Delhi

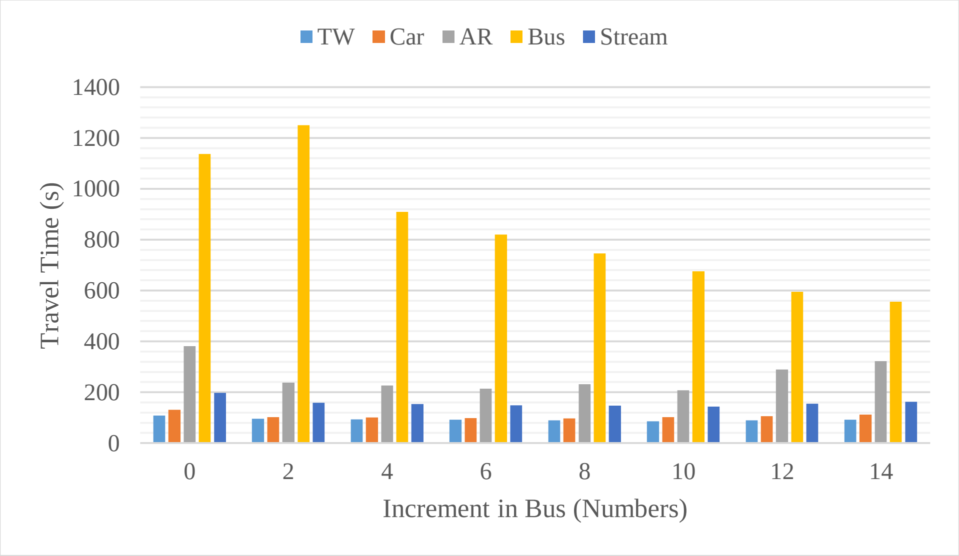


Figure 6.12 Travel time after implementing modal shift – Scenario II – Delhi

For Scenario III, when commuters from both two-wheelers and cars are shifted to buses, an improvement in capacity by 17.8 % is achieved for optimum increment of 16 buses during peak hour. From Figure 6.13, it can be noticed that capacity increases to 4265 PCU/h when compared to before modal shift. There is an overall reduction in travel time of the stream by 26.2 % (51.5 s reduction per kilometre when compared to before modal shift) as shown in Figure 6.14.

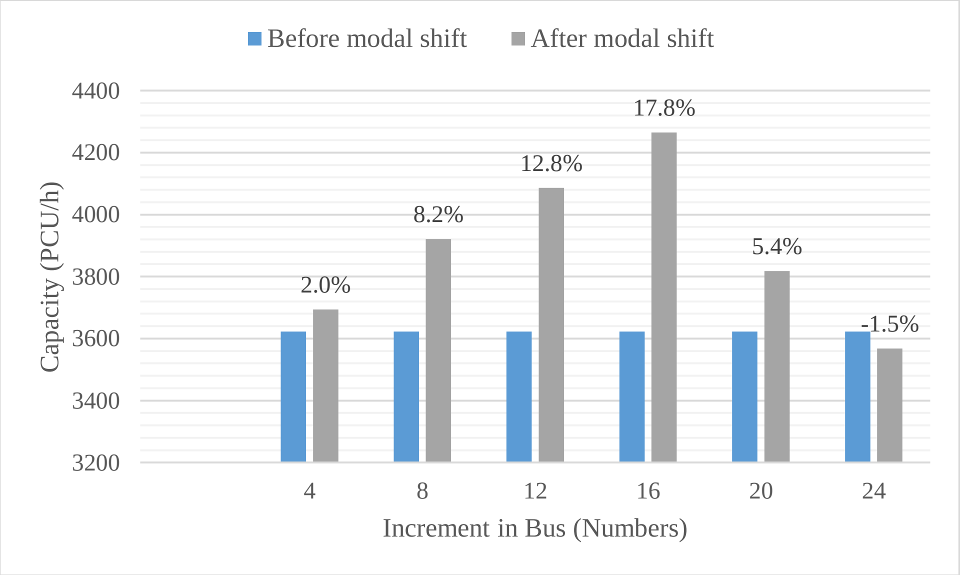


Figure 6.13 Capacity after implementing modal shift – Scenario III – Delhi

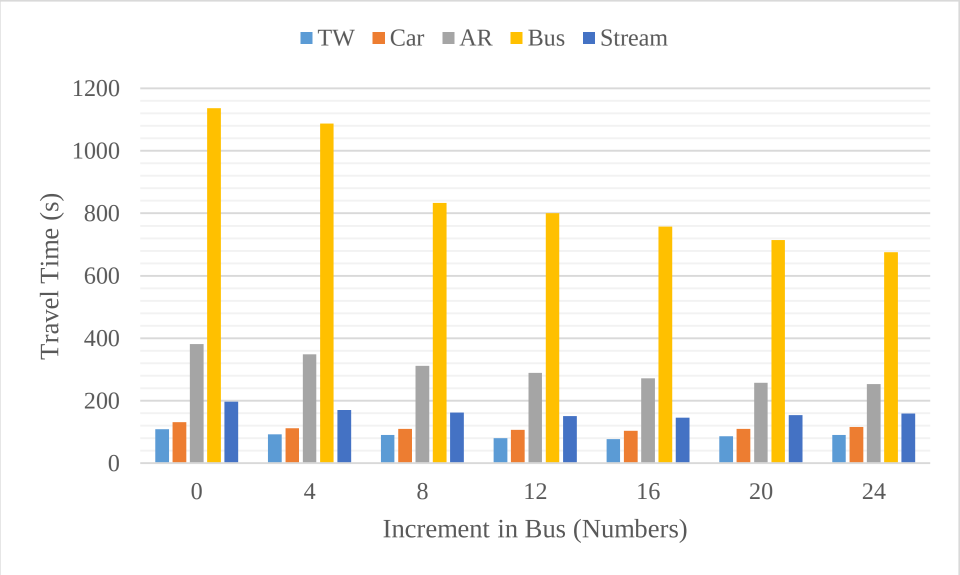


Figure 6.14 Travel time after implementing modal shift – Scenario III – Delhi

6.3.2.3 Mumbai study section

Modal shift of private vehicles to public transport is also carried out for study section in Mumbai. For Scenario I (when commuters from only two-wheelers are shifted to buses), higher capacity (2398 PCU/h) is achieved for optimum increment of 10 buses. Further increment in buses reduces the capacity as observed in Figure 6.15. Hence, increment of 10 buses is selected as optimum with an improvement in capacity by 12.1 % during peak hour. For optimum number of buses, it is seen that there is a reduction in travel time of stream by 30 s (17.7% reduction when compared to before modal shift) shown in Figure 6.16.

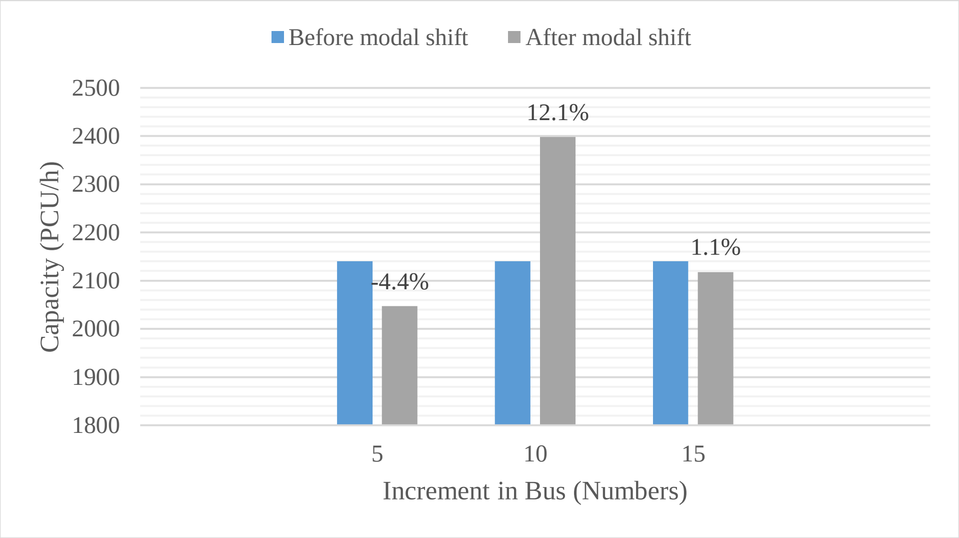


Figure 6.15 Capacity after implementing modal shift – Scenario I – Mumbai

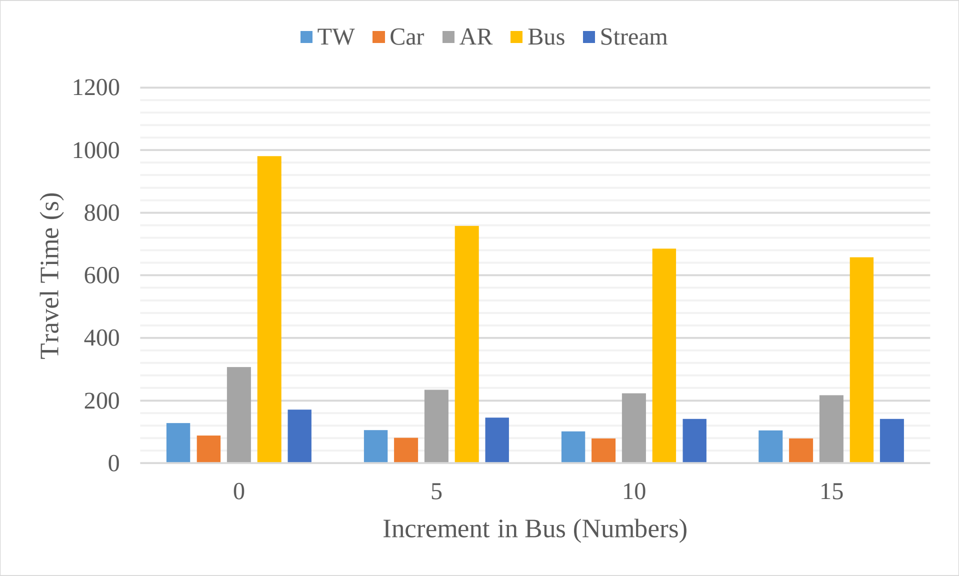


Figure 6.16 Travel time after implementing modal shift – Scenario I – Mumbai

For Scenario II, increment of 10 buses is considered as optimum with an improvement in capacity by 45.8 % when compared to before modal shift. For this optimum case, the capacity rises to 3121 PCU/h (Figure 6.17) and further increment reduces the capacity. Also, the travel time of stream reduces by 33.3 s (per kilometre) during peak hour for optimum increment in buses. Overall, there is a reduction in the travel time by 19.5% in comparison to before modal shift (Figure 6.18).

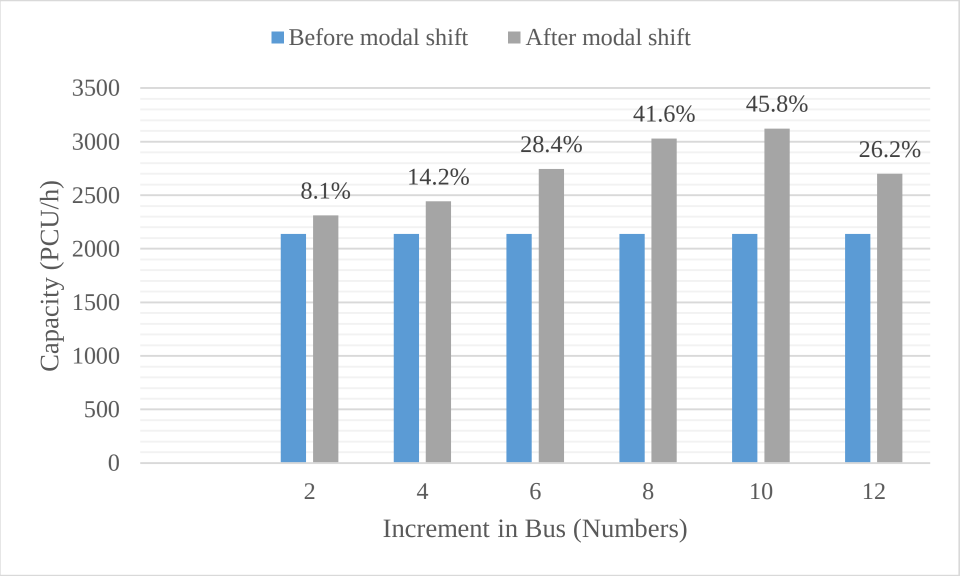


Figure 6.17 Capacity after implementing modal shift – Scenario II – Mumbai

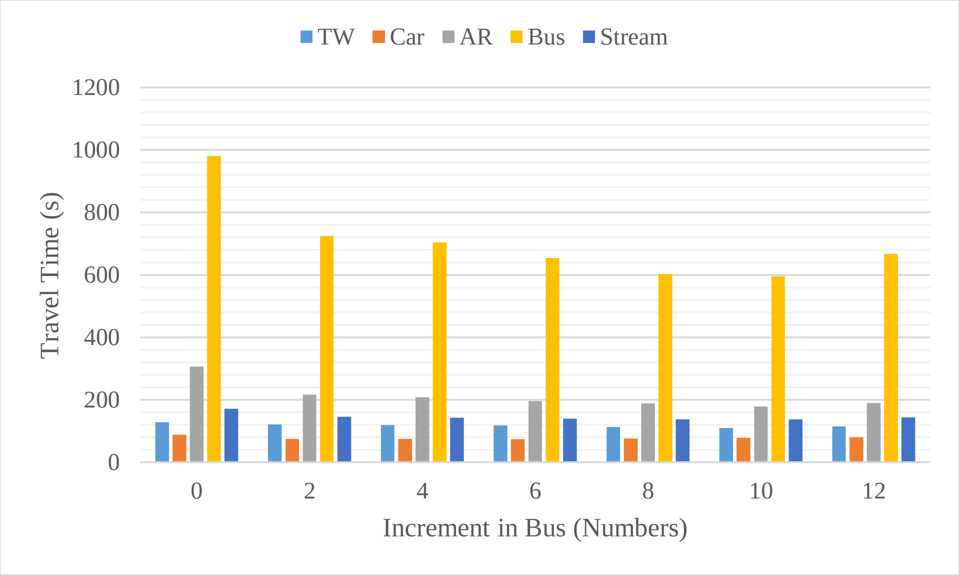


Figure 6.18 Travel time after implementing modal shift – Scenario II – Mumbai

When commuters from both two-wheelers and cars are shifted to buses (Scenario III), capacity increases to 2894 PCU/h for an increment of 12 buses during peak hour. From Figure 6.19, it is observed that there is an improvement in capacity by 35.3 % when compared to before modal shift. Further, 26.2 s of reduction in travel time (15.3 %) of the stream is observed per kilometre during peak hour (Figure 6.20).

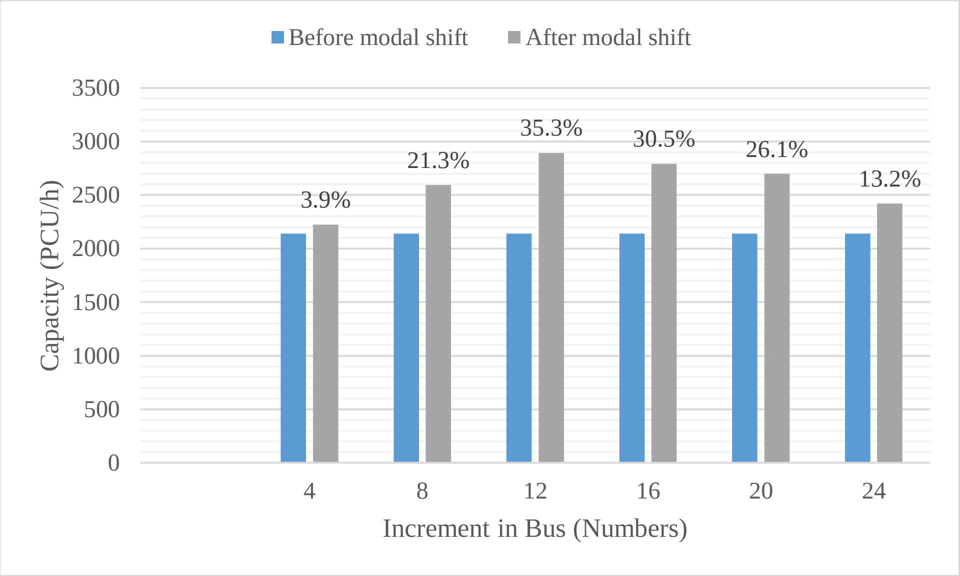


Figure 6.19 Capacity after implementing modal shift – Scenario III – Mumbai

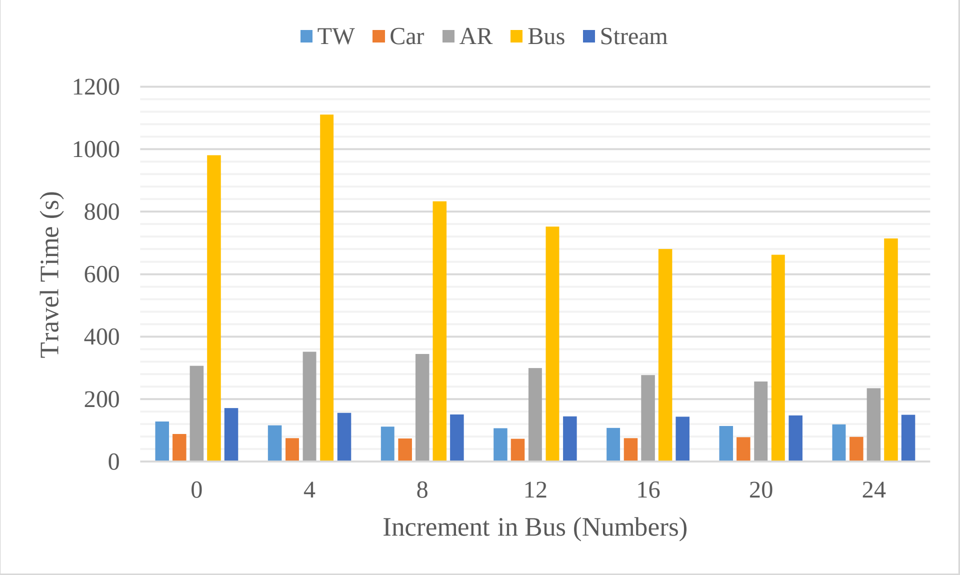


Figure 6.20 Travel time after implementing modal shift – Scenario III – Mumbai

The results of modal shift of private vehicles to public transport proves that there is a significant improvement in capacity and reduction in travel time for all three study sections. For the study section located in Bengaluru, higher improvement in capacity (16.9 %) is observed for Scenario I due to the reduction of two-wheelers which are dominant in the traffic stream. In Delhi study section, capacity improvement is higher (17.8 %) for Scenario III when both two-wheelers and cars are reduced from the vehicular composition. In case of Mumbai study section, when car (dominant) users are shifted, higher improvement in capacity (41.6 %) is observed for Scenario II. The travel times are also reduced by 14.2 %, 26.2 %, and 19.5 % for Bengaluru, Delhi, and Mumbai, respectively. Previous studies performed in various other developing countries showed similar trends, and significant improvements in travel time were observed due to modal shift of private vehicle to public transport (Nurdden *et al.*, 2007; Vedagiri and Arasan 2009; de Sá *et al.*, 2015; Anwar and Yang, 2017).

6.3.3. Reduction in traffic emissions due to modal shift

The results obtained from the previous section (Section 6.3.2) gives insights on the optimum number of buses to be increased after modal shift by investigating capacity and travel time considering all three scenarios. In this section, the impact of the modal shift of private vehicles towards public transport on various traffic emissions is analysed. Table 6.4 shows the various traffic emission compound generated (per kilometer) by different types of vehicle. These emission compounds are multiplied with the number of vehicles observed at the study section to obtain the total emissions during the peak hour of traffic flow.

Table 6.4 Emission compound for different vehicle types

Emission Compound (g/km)	**Vehicle Type**			
	Two-wheeler	**Car**	**Auto-rickshaw**	**Bus**
Carbon dioxide (CO_2)	26.6	223.6	60.3	515.2
Carbon monoxide (CO)	2.2	1.98	5.1	3.6
Nitrogen oxide (NOX)	0.19	0.2	1.28	12
Methane (CH_4)	0.18	0.17	0.18	0.09
Sulphur dioxide (SO_2)	0.013	0.053	0.029	1.42
Particulate matter (PM)	0.05	0.03	0.2	0.56
Hydro carbon (HC)	1.42	0.25	0.14	0.87

(Source: Central Pollution Control Board of India, 2012)

From the analysis, it is estimated that modal shift of private vehicles towards public transport system considerably reduces the transportation emissions during peak hours. The total emissions emitted during peak hours (one hour) per day before and after implementing modal shift are listed in Table 6.5. It is observed that there is a reasonable reduction in CO_2 emission by 12.60%, 7.30% and 7.62% for study locations in Bengaluru, Delhi, and Mumbai, respectively. Similarly, there is a reduction in CO emission by 21.81%, 18.53% and 21.45% for Bengaluru, Delhi, and Mumbai, respectively. However, there is a slight increase in NOX and SO_2 emissions for all the cities after modal shift because the emission compound values of buses are considerably higher when compared to other vehicle types. For the selected study locations in Bengaluru, Delhi, and Mumbai, CH_4 emissions during peak hours is reduced by 24.8 %, 22.2 %, and 24.0 %, respectively. It is also seen that there is a reduction in emission values of other compounds such as PM, and HC after performing the modal shift of private vehicles.

Table 6.5 Impact of implementing modal shift (for optimum scenario) on transportation emissions for different cities

Emission Compound	**Emissions for peak hours per day (g/km)**					
	Bengaluru section		**Delhi section**		**Mumbai section**	
	Before modal shift	After modal shift	Before modal shift	After modal shift	Before modal shift	After modal shift
CO_2	237255.3	207348.1	412315.4	382184.6	293991.5	271561.1
CO	6326.54	4946.22	7459.34	6077.04	4824.64	3789.4
NOX	1070.48	1135.28	1186.23	1250.83	1133.54	1182.14
CH4	471.33	354.29	526.15	408.94	364.31	276.53
SO2	108.205	118.133	128.588	138.463	142.21	149.656
PM	162.98	140.82	185.78	163.59	127.79	111.17
HC	2668.07	1860.79	1918.87	1111.34	1567.27	961.81

The recent global warming, sea level rising, and glacier melt are mainly caused by greenhouse gas (GHG) emissions generated by human activities. Among the GHG emissions, CO_2 is the single most important anthropogenic greenhouse gas which contributes about 65 % of total GHG emissions (WMO, 2014). The CO_2 emissions from transportation currently contributes 20–25 % of global CO_2 emissions. Hence, reduction of CO_2 emissions from transportation is the major concern. From the present study, it is estimated that yearly around 61.92, 107.6, and 76.73 tonnes per kilometre of CO_2 emissions are generated in the selected study sections during peak hours without implementing modal shift in Bengaluru, Delhi, and Mumbai, respectively. From Figure 6.21, it is observed that implementation of modal shift reduces the CO_2 emissions to 54.1, 99.7, and 70.8 tonnes per kilometre for the selected study sections during peak hour. Similar trends are observed by Verma et al., 2015; Jaikumar et al., 2017; Rahul and Verma 2017. Overall, there is reduction in CO_2 emissions by 7.8 %, 7.9 %, and 5.9 % for Bengaluru, Delhi, and Mumbai, respectively after modal shift (during peak hours per year).

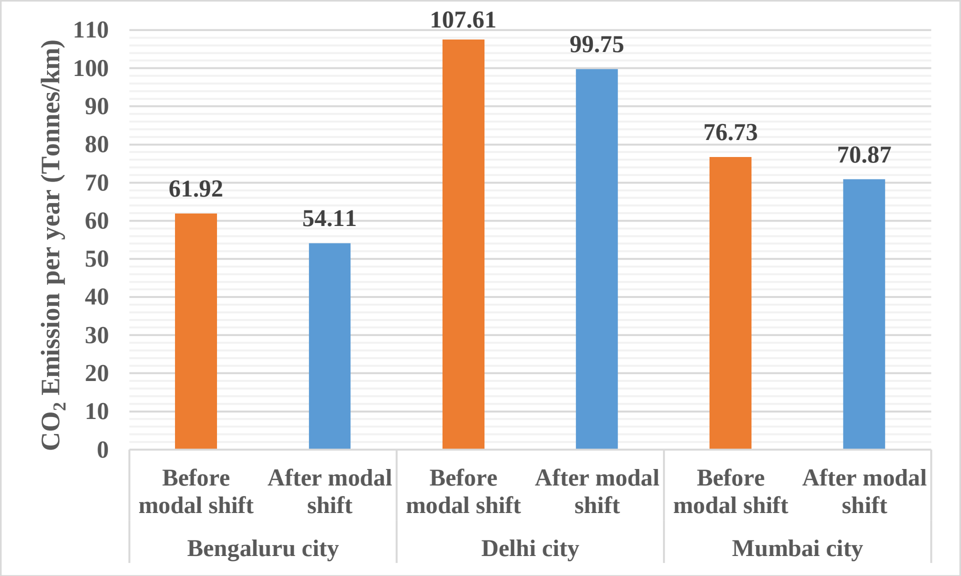


Figure 6.21 Reduction in CO_2 emissions per year after implementing modal shift (for optimum scenario)

The improvement in capacity, travel times and emissions will not be achieved only by increasing the number of buses and frequency. Rather, it is essential to improve the quality of buses, in-vehicle travel time, and provide real-time traffic information at bus stops and on board to make the bus service an attractive alternative to choice riders (Maitra et al. 2014).

6.4 SUMMARY

The results and discussion of evaluation of various traffic management measures are discussed in this section. Implementation of reversible lanes improved the capacity during peak hours for all compositions. For observed composition, the capacity in ongoing direction during morning peak hour is increased by 20.5 %, similarly capacity in opposing direction during evening peak hour is increased by 19.20 %. The results of modal shift of private vehicles to public transport proves that there is considerable amount of improvement in capacity, reduction in travel time, and reduction in traffic emissions for all three study sections.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 SUMMARY

Traffic congestion is the major problem faced in many developing countries such as India. In rapidly expanding cities, the congestion during peak hours extends for longer periods each day. This congestion adversely affects mobility, safety, and air quality. On undivided roads, the problems are worsening due to lack of lane segregation. Possible ways to address the congestion problem are to improve the utilization of the existing systems through better traffic management and operations strategies and improve the geometric design of roads. Microscopic simulation is the widely used tool for evaluating traffic control and management measures. Only limited studies have focused on bi-directional traffic flow on undivided roads considering the effect of opposing vehicles in mixed traffic conditions. Most of these studies are carried out on the mid-block sections of National Highways and State Highways. In all these studies, overlapping criteria is used for identifying the true leader. Also, these studies considered longitudinal and lateral movement separately while modelling. There are limited studies available on evaluation of traffic management measures on undivided roads. Hence, these aspects have been considered as the focus of this research work.

The overall objective of the research work is to develop a bi-directional mixed traffic simulation model for urban undivided roads. The simulation model for urban undivided roads involves three major logics i.e. vehicle generation, vehicle placement and vehicle movement. Vehicles are generated on either end of simulation stretch using vehicle-type dependent headways. Vehicles are placed on simulation road stretch based on vehicular proportion and speeds. The concept of influence area is introduced in vehicle movement logic to consider the influence of surrounding vehicles. This influence area is modelled using multiple linear regression (MLR) technique to identify the most influencing surrounding vehicles which affects the longitudinal and lateral movement of the subject vehicle. The longitudinal and lateral gaps obtained from the field data are used to develop MLR models. The longitudinal movements are governed by Gipps model with vehicle-type dependent parameters and lateral movements are incorporated using the Gunay's model. Microscopic traffic simulator is developed using Object-Oriented Programming (OOP) concepts in MATLAB computing environment. The developed model is calibrated and sensitive analysis is carried out to obtain more accurate results. Headway, free speeds, rate of acceleration and deceleration, lateral acceleration, maximum escape speed (MES), time required for veering (t_{veer}), longitudinal gaps and lateral gaps are the parameter used to calibrate the model. Both internal and external validation of the model is performed using field data collected from road sections located in Indian cities (Bengaluru and Kollam). The statistical tests prove that developed model replicates the field conditions satisfactorily. The effect of traffic composition on critical parameters such as speed, flow and density are also studied. Then, the developed model is used to evaluate tidal flow operations (reversible lanes) using data collected from Bengaluru city. The developed model is modified to implement reversible lanes and a total of 48 simulation runs are performed to study the impact of reversible lanes. The model is also used to study the impact of modal shift of private vehicles (two-wheelers and cars) towards public transport system (buses) using data collected from three metropolitan cities (Bengaluru, Delhi, and Mumbai). A total of 162 simulation runs are performed and the impact of modal shift on capacity, travel time, and emissions are studied.

7.2 CONCLUSIONS

The major conclusions derived from the study are listed below:

- A microscopic traffic simulation model is developed to simulate bi-directional mixed traffic scenario using OOP concepts implemented in MATLAB
- A concept of influence area is developed to identify the most influencing surrounding vehicles which effects the longitudinal and lateral movements of subject vehicles
- Capacity is higher when there is larger proportion of two-wheelers in the mix and lower when the stream contained a larger proportion of cars and heavy vehicles

- For composition C1 (auto-rickshaw dominant), there is an improvement in capacity (4786 PCU/h) when compared to observed capacity (4353 PCU/h). This may be due to lower operating characteristics of auto-rickshaws
- For composition C3 (heavy vehicle dominant), there is a higher improvement in capacity (4530 PCU/h) when compared to observed capacity (4353 PCU/h). This is mainly due to restriction of lateral movements of two-wheelers and auto-rickshaws
- Critical density is higher for compositions comprising higher proportion of two-wheelers and auto-rickshaws i.e. C and C1, which indicates the ability of these vehicle to squeeze in between the gaps of larger vehicles
- For any given flow level for all three cases (ongoing, opposing, and combined direction), the maximum speed occurs for compositions C and C1, in which the proportion of two-wheelers and auto-rickshaws are 58% and 34%, respectively due to their higher operating characteristics
- The evaluation of tidal flow operations proves that there is an improvement in capacity during peak hours after implementing reversible lanes. For composition C (two-wheeler proportion dominant), the capacity in ongoing direction during morning peak hour is increased by 20.5%, similarly capacity in opposing direction during evening peak hour is increased by 19.20%
- For Bengaluru study section, higher capacity (3674 PCU/h) is achieved when only two-wheeler commuters are shifted to buses (Scenario I) for an optimum number of 20 buses. This is believed to be due to higher proportion of two-wheelers and their higher maneuverability
- For Delhi study section, capacity is higher (4265 PCU/h) when both two-wheeler and car commuters are shifted to buses (Scenario III) and there is an improvement in capacity by 17.8% for increment of 16 buses
- In case of Mumbai study section, capacity is higher (3121 PCU/h) when only car commuters are shifted to buses (Scenario II) and there is an improvement in capacity by 45.8% for optimum increment of 10 buses
- Travel time reduction is higher when only car commuters are shifted to the bus (Scenario II) by 17.2%, 26.9% and 19.5% for Bengaluru, Delhi, and Mumbai

study sections, respectively

- Reasonable reduction in CO_2 emission is witnessed for optimum increment in buses for Bengaluru (12.60 %), Delhi (7.30 %), and Mumbai (7.62 %) study sections after implementing modal shift

7.3 LIMITATIONS OF THE STUDY

The microscopic simulation model developed in this study is specifically limited to undivided mid-block sections on urban roads carrying mixed traffic. The vehicle movement cases adopted in the study is limited to overlapping and non-overlapping leader vehicle and opposing vehicle. The influence of cross roads, bus stops, pedestrians, and climatic factors are not considered in the developed model.

7.4 DIRECTIONS FOR FUTURE RESEARCH

The present study considers the influence of overlapping, non-overlapping leader and opposing vehicles on subject vehicle’s movement. However, due to weak lane discipline the presence of adjacent vehicles may also influence the movement of subject vehicle. Hence, it is necessary to consider the influence of surrounding vehicles in future studies. Calibration and validation of the developed model using microscopic traffic trajectory data may fine tune the model. The developed simulation model can be used to evaluate various other traffic management measures such as segregation of lanes, implementation of lane discipline, and exclusion of slow moving vehicles on urban roads in emerging and developing countries carrying mixed traffic.

APPENDIX A

SAMPLE CALCULATION OF CORRECTION FACTOR

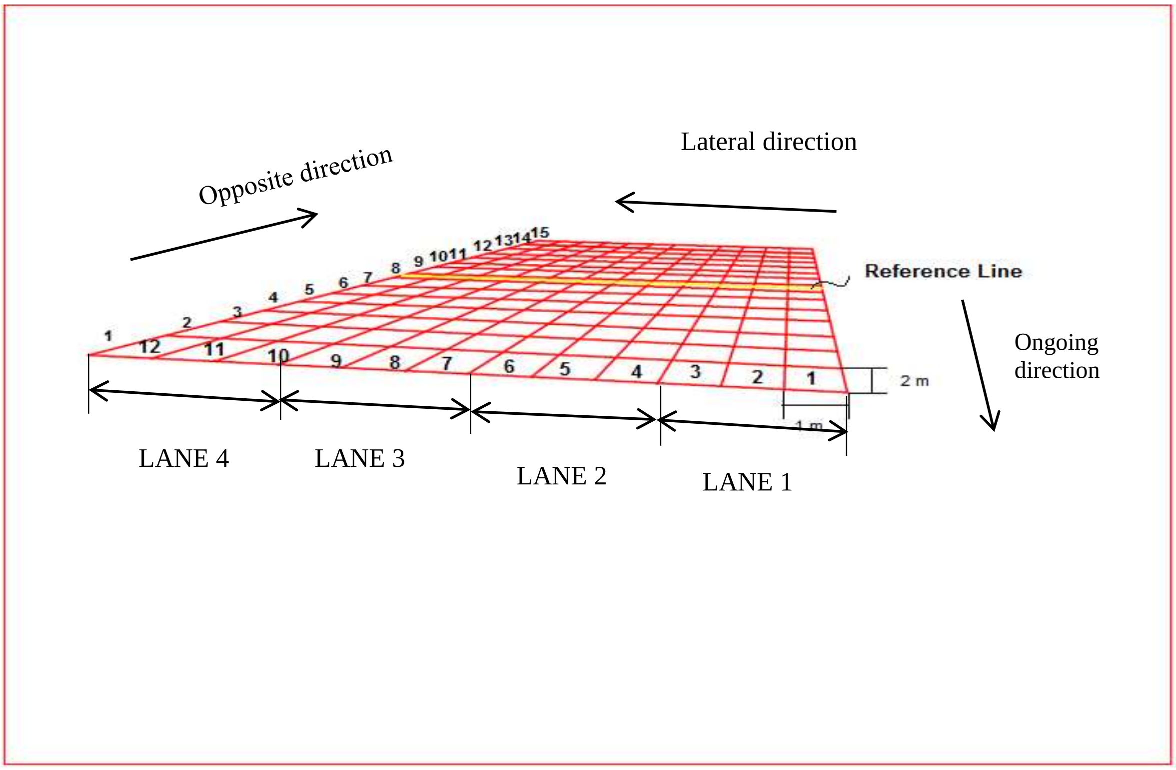


Figure A.1 Gridline image of the study section

Figure A.1 shows the gridline image of the study section. The sample calculations for the corresponding image are shown below for block 1, 1 (longitudinal grid line number, lateral grid line number).

Distance between two points = $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$ -----------A.1

From above, distance AB = $\sqrt{(520 - 517)^2 + (294 - 276)^2}$

= 18.25 pixels

Similarly, DC=18.03 pixels,

BC= 39.05 pixels,

AD= 35.06 pixels.

Longitudinal distance = Mean of AB, DC
= (18.25 +18.03)/2
=18.14 pixels
Actually 18.14 pixels = 200 cm
So, 1 pixel=11.03 cm

Lateral distance = Mean of BC, AD
= (39.05 +35.06)/2
=37.05 pixels
Actually 37.05 pixels = 100 cm
so, 1 pixel = 2.69 cm

For block 1, 1 correction factor in longitudinal direction is 11.03 cm, and correction factor in lateral direction is 2.69 cm.

APPENDIX B

Table B.1 Sample data sheet for extraction of rate of acceleration and deceleration, and speed

Vehicle id	Subject Vehicle Type	Stretch 1		Stretch 2		Exit lateral block no.	Rate of acc/dec (m/s^2)	Speed (m/s)
		Entry Frame No. (1)	Exit Frame No. (2)	Entry Frame No. (3)	Exit Frame No. (4)			
1	CAR	1	5	44	51	7-9	-5.35	15
4	TW	21	32	69	76	6	2.36	13.63
7	TW	43	51	109	118	7	-0.46	10
10	CAR	124	132	185	195	5-6	-0.88	10.56
13	TW	166	171	227	236	8	-3.17	10.71
16	CAR	218	222	278	288	6-7	-5.35	10.71
19	TW	251	262	314	322	3	1.20	10.56
25	TW	378	392	453	464	3	0.56	8.72
28	CAR	451	458	502	510	6-7	-0.75	12.71
31	TW	580	591	646	654	3	1.15	10.13
34	CAR	662	666	704	710	7-8	-4.34	15.62
37	TW	1333	1352	1412	1423	3	1.06	8.33
40	TW	1547	1556	1597	1602	8	4.04	13.63
49	CAR	2046	2051	2087	2093	5-7	-1.77	15.95
52	CAR	2184	2192	2229	2235	4-6	2.04	14.70
58	CAR	2407	2417	2467	2474	5-7	1.59	11.19
61	TW	2557	2563	2608	2615	4	-1.02	12.93
64	CAR	2579	2586	2624	2629	6-8	2.85	15
67	TW	2664	2671	2705	2709	4	5.95	16.66
70	TW	2755	2766	2825	2833	4	1.092	9.61
73	CAR	2913	2940	2980	2986	5-7	4.43	10.27
76	TW	2958	2964	3013	3021	4	-1.65	11.90
79	TW	3065	3074	3112	3118	5	2.62	14.15
82	AUTO	3150	3156	3207	3215	5	-1.60	11.53
85	TW	3201	3206	3248	3257	7	-3.96	13.39
88	TW	3252	3263	3303	3310	5	2.23	12.93
94	CAR	3395	3404	3447	3455	5-6	0.57	12.5
97	CAR	3496	3519	3605	3616	2-4	0.98	6.25
100	TW	3610	3618	3675	3684	3	-0.46	10.13

Table B.2 Sample data sheet for extraction of lateral position of subject vehicle

Sl. No.	Subject Vehicle Type	Speed (m/s)	Lateral Position (m)	Opposed/ Unopposed	Opposing Vehicle Type
1	CAR	15	4.92	U	
4	TW	13.63	4.82	U	
7	TW	10	5.72	U	
10	CAR	10.56	3.63	U	
13	TW	10.71	4.65	O	BUS
16	CAR	10.71	3.76	O	AUTO
19	TW	10.56	2.13	U	
22	TW	11.02	1.89	U	
25	TW	8.72	2.20	U	
28	CAR	12.71	3.75	O	BUS
31	TW	10.13	2.07	U	
34	CAR	15.62	4.80	U	
37	TW	8.33	2.18	U	
40	TW	13.63	4.59	U	
43	TW	11.02	1.95	U	
46	TW	9.14	2.588	U	
49	CAR	15.95	3.56	O	TW
52	CAR	14.70	2.614	U	
55	TW	14.42	4.89	U	
58	CAR	11.19	3.72	U	
61	TW	12.93	2.67	U	
64	CAR	15	4.57	U	
67	TW	16.66	2.87	U	
70	TW	9.61	2.51	O	AUTO
73	CAR	10.27	3.56	O	CAR
76	TW	11.90	2.97	U	
79	TW	14.15	2.71	O	AUTO
82	AUTO	11.53	2.87	U	
85	TW	13.39	4.76	U	
88	TW	12.93	2.97	U	
91	CAR	11.36	3.43	O	CAR
94	CAR	12.5	3.04	O	BUS

Table B.3 Sample data sheet for extraction of lateral and longitudinal gaps

Sl. No.	**Frame No.**	**Subject Vehicle Type**	**Frame**		**Longitudinal Block No.**	**Lateral Block No.**	**Entry Frame No.**	**Exit Frame No.**	**Gaps with correction factors (m)**	
			X	**Y**					**Lateral gap (x)**	**Longitudinal gap (y)**
1	98	AUTO	417	424	2	3	32	107	2.22	8.38
2	195	CAR	406	422	1	5	113	205	2.26	6.94
3	195	CAR	319	421	1	7	113	205	2.34	5.81
4	235	TW	388	375	5	7	189	255	3.33	12.39
5	282	TW	486	420	2	3	218	293	2.22	8.38
6	400	TW	509	413	2	3	336	412	2.89	8.38
7	446	CAR	441	384	3	5	389	473	2.88	10.43
8	446	CAR	390	388	3	6	389	473	2.34	9.23
9	495	CAR	422	385	4	5	449	518	3.07	13.34
10	495	CAR	366	378	4	7	449	518	3.07	10.65
11	662	CAR	391	380	4	6	610	683	3.07	11.99
12	978	CAR	325	414	1	7	923	986	2.34	5.81
13	1897	CAR	378	415	2	6	1866	1903	2.49	7.91
14	1990	TW	514	316	12	4	1983	2052	6.66	24.01
15	2078	CAR	408	368	5	6	2044	2098	3.32	13.12
16	2379	CAR	459	359	7	5	2350	2403	3.92	20.92
17	2411	TW	345	411	2	7	2366	2419	2.62	7.20
18	2466	TW	329	391	3	8	2421	2473	2.77	7.422
19	2522	BUS	434	344	9	7	2497	2556	4.44	22.17
20	2764	TW	448	409	2	4	2720	2772	3.00	7.81
21	2816	TW	487	384	4	4	2755	2838	3.11	14.36
22	2876	CAR	449	341	9	6	2850	2911	4.34	25.52
23	2969	CAR	412	362	6	6	2932	2991	3.56	15.59
24	3011	TW	401	386	4	6	2970	3024	3.07	11.99
25	3053	CAR	433	358	7	6	3016	3080	3.84	19.30
26	3191	AUTO	389	407	2	6	3131	3201	2.49	7.91
27	3269	CAR	436	378	4	5	3220	3290	3.07	13.342
28	3269	CAR	385	381	4	7	3220	3290	3.07	10.65
29	3303	TW	453	397	3	4	3250	3313	2.84	11.64
30	3329	TW	431	404	2	5	3273	3313	2.52	8.78

Table B.4 Sample data sheet for extraction of lateral separation

Sl. No.	**Subject Vehicle**			**Opposite Vehicle**			**Lateral Separation (m)**
	Vehicle Type	**Speed (m/s)**	**Speed (km/h)**	**Vehicle Type**	**Speed (m/s)**	**Speed (km/h)**	
1	TW	11.36	40.89	AUTO	10.86	39.13	3.11
2	TW	11.53	41.50	CAR	11.53	41.53	5.74
3	TW	13.88	49.96	BUS	12.09	43.54	4.65
4	TW	13.2	47.52	CAR	11.90	42.85	4.91
5	CAR	14.15	50.94	TW	12.93	46.55	5.75
6	TW	11.51	41.43	BUS	13.15	47.36	3.30
7	CAR	15.2	54.72	AUTO	13.15	47.36	1.09
8	TW	15.01	54.03	AUTO	10.27	36.98	2.82
9	CAR	14.12	50.83	CAR	9.37	33.75	0.97
10	TW	11.02	39.67	CAR	12.29	44.26	5.20
11	TW	10.71	38.55	CAR	9.03	32.53	7.16
12	CAR	12.11	43.59	BUS	8.52	30.68	3.06
13	CAR	10.36	37.29	TW	10.71	38.57	4.36
14	TW	10.71	38.55	TW	8.82	31.76	8.03
15	TW	11.11	39.99	AUTO	10.71	38.57	4.51
16	AUTO	11.10	39.96	TW	13.15	47.36	2.56
17	TW	15.32	55.15	CAR	13.39	48.21	1.44
18	CAR	14.42	51.91	CAR	11.90	42.85	1.63
19	CAR	13.88	49.96	BUS	6.69	24.10	1.35
20	TW	11.53	41.50	BUS	9.74	35.06	0.90
21	AUTO	15	54	AUTO	10.56	38.02	4.12
22	TW	15.62	56.23	AUTO	12.71	45.76	1.40
23	CAR	14.70	52.92	CAR	12.29	44.26	2.67
24	TW	11.53	41.50	CAR	11.02	39.70	1.93
25	TW	10.71	38.55	CAR	10.71	38.57	2.23
26	CAR	12.5	45	BUS	12.71	45.76	4.35
27	CAR	11.90	42.84	TW	12.29	44.26	1.82
28	TW	10.86	39.09	TW	9.740	35.06	1.92
29	TW	11.53	41.50	AUTO	9.25	33.33	1.89
30	CAR	10.27	36.97	TW	13.63	49.09	2.56
31	TW	15.30	55.08	CAR	10.86	39.13	1.44
27	CAR	11.90	42.84	TW	11.53	41.53	1.63
28	TW	10.86	39.09	TW	12.09	43.54	1.35
29	AUTO	9.88	35.56	TW	11.90	42.85	0.90
30	TW	11.67	42.01	AUTO	12.93	46.55	4.12

Table B.5 Sample data sheet for extraction of free-flow speeds

Vehicle id	Subject Vehicle Type	Entry Frame No. (1)	Exit Frame No. (2)	Free-Flow Speed (m/s)	Free-Flow Speed (km/h)
1	CAR	4	7	21.26	76.56
2	TW	24	34	19.22	69.22
3	TW	46	53	19.26	69.36
4	CAR	127	134	19.94	71.81
5	TW	169	173	17.73	63.85
6	CAR	221	224	18.23	65.66
7	TW	254	264	19.90	71.64
8	TW	381	394	17.81	64.13
9	HV	454	460	15.87	57.16
10	TW	583	593	19.56	70.43
11	CAR	665	668	18.35	66.08
12	TW	1336	1354	17.41	62.69
13	TW	1550	1558	19.03	68.54
14	CAR	2049	2053	17.98	64.75
15	HV	2187	2194	16.12	58.04
16	CAR	2410	2419	20.18	72.65
17	TW	2560	2565	20.40	73.45
18	CAR	2582	2588	16.93	60.97
19	TW	2667	2673	18.67	67.23
20	TW	2758	2768	17.33	62.41
21	CAR	2916	2942	17.25	62.12
22	TW	2961	2966	13.12	47.24
23	TW	3068	3076	17.14	61.71
24	AUTO	3153	3158	18.35	66.06
25	HV	3204	3208	16.26	58.54
26	TW	3255	3265	17.50	63.01
27	CAR	3398	3406	17.97	64.72
28	CAR	3499	3521	17.46	62.86
29	TW	3613	3620	19.44	70.01
30	CAR	3708	3732	19.05	68.58
31	TW	3804	3822	20.11	72.41
32	CAR	3941	3952	18.62	67.05
33	TW	4025	4036	19.71	70.98

APPENDIX C

Table C.1 Trajectory and speed values obtained from the simulation model – ongoing direction

Ongoing Direction					
Time Step	**Vehicle ID**	**Vehicle Type**	**x (m)**	**y (m)**	**Speed (m/s)**
95	1	HV	128.63	7.211	13.54
95	5	TW	27.5409	6.5018	22.31
95	6	AR	5.2200	7.02	7.020
96	1	HV	129.984	7.211	13.54
96	5	HV	30.2482	6.501	27.07
96	6	AR	6.0719	7.02	8.51
97	1	HV	131.338	7.211	13.54
97	5	TW	32.236	6.501	19.88
97	6	AR	6.47707	7.02	4.05
98	1	HV	132.692	7.211	13.54
98	5	TW	33.608	6.50	13.71
98	6	AR	7.9204	7.02	14.43
99	1	HV	134.046	7.211	13.54
99	5	TW	35.084	6.501	14.75
99	6	AR	8.0714	7.023	1.51
100	1	HV	135.4	7.21177	13.54
100	5	TW	37.395	6.50185	23.11
100	6	AR	8.5609	7.02307	4.89
101	1	HV	136.754	7.21177	13.54
117	6	AR	25.74271	7.023078	14.21
118	1	HV	159.772	7.211775	13.54
118	5	TW	75.01824	6.501859	17.54
118	6	AR	26.67945	7.023078	9.36
119	1	HV	161.126	7.211775	13.54
119	5	TW	77.57262	6.501859	25.54
119	6	AR	27.92482	7.023078	12.45
120	1	HV	162.48	7.211775	13.54
120	5	TW	79.91438	6.501859	23.41
120	6	AR	28.44535	7.023078	5.20
121	1	HV	163.834	7.211775	13.54
121	5	TW	81.26838	6.501859	13.54
121	6	AR	30.03735	7.023078	15.92
122	1	HV	165.188	7.211775	13.54

Table C.2 Trajectory and speed values from the developed simulation model – opposing direction

Opposing Direction					
Time Step	**Vehicle ID**	**Vehicle Type**	**x (m)**	**y (m)**	**Speed (m/s)**
11	2	HV	984.022	4.6455	24.37
11	3	TW	999.040	1.7314	9.59
12	2	HV	981.595	4.6455	24.26
12	3	TW	998.469	1.7314	5.71
13	2	HV	979.092	4.6455	25.03
13	3	TW	997.936	1.7314	5.32
14	2	HV	976.731	4.6455	23.60
14	3	TW	997.365	1.7314	5.71
15	2	HV	974.421	4.64559	23.09
15	3	TW	996.165	1.73146	11.99
16	2	HV	972.936	4.64559	14.85
16	3	TW	995.659	1.73146	5.06
17	2	HV	970.295	4.64559	26.40
17	3	TW	994.728	1.73146	9.31
18	2	HV	967.905	4.64559	23.90
18	3	TW	993.379	1.73146	13.48
19	2	HV	965.947	4.64559	19.57
19	3	TW	992.896	1.73146	4.82
20	2	HV	964.220	4.64559	17.27
58	2	HV	890.9107	4.645597	13.54
58	3	TW	955.8794	1.731467	16.59
58	4	C	992.04	3.740942	15.92
59	2	HV	889.5567	4.645597	13.54
59	3	TW	954.2204	1.731467	16.59
59	4	C	990.448	3.740942	15.92
60	2	HV	888.2027	4.645597	13.54
60	3	TW	952.5614	1.731467	16.59
60	4	C	988.856	3.740942	15.92
61	2	HV	886.8487	4.645597	13.54
61	3	TW	950.9024	1.731467	16.59
61	4	C	987.264	3.740942	15.92
62	2	HV	885.4947	4.645597	13.54
62	3	TW	949.2434	1.731467	16.59
62	4	C	985.672	3.740942	15.92
63	2	HV	884.1407	4.645597	13.54

APPENDIX D

Table D.1 Results from simulation runs for reversible lane operations (morning peak hours)

Ongoing Direction						
Correction Factor	**Flow (PCU/h)**	**Simulated Speeds (m/s)**				
		TW	**Car**	**AR**	**HV**	**Stream**
0.2	732	16.04	15.42	14.66	12.32	14.61
0.4	1345	15.12	15.02	13.04	11.85	13.75
0.6	2205	14.25	13.88	12.82	11.2	13.03
0.8	2840	14.05	12.24	12.11	10.95	12.33
1	3522	12.84	11.04	11.52	9.54	11.23
1.2	3847	11.58	10.32	10.82	8.84	10.39
1.4	4125	10.24	9.24	8.87	7.28	8.90
1.6	4260	9.14	8.82	7.08	6.35	7.84
1.8	4348	8.2	7.24	6.88	6.1	7.10
Opposing Direction						
Correction Factor	**Flow (PCU/h)**	**Simulated Speeds (m/s)**				
		TW	**Car**	**AR**	**HV**	**Stream**
0.2	238	14.88	15.44	15.2	13.42	14.73
0.4	495	14.02	13.84	14.16	12.1	13.53
0.6	732	13.21	12.3	12.58	10.87	12.24
0.8	972	12.82	10.98	11.04	9.66	11.12
1	1216	12.22	9.4	9.42	8.84	9.97
1.2	1464	11.32	8.64	8.77	7.8	9.13
1.4	1702	9.88	8.14	7.05	7.21	8.07
1.6	1948	8.1	7.88	6.84	6.5	7.33
1.8	2042	7.54	7.32	6.1	5.88	6.71

Table D.2 Results from simulation runs for reversible lane operations (evening peak hours)

Ongoing Direction						
Correction Factor	**Flow (PCU/h)**	**Simulated Speeds (m/s)**				
		TW	**Car**	**AR**	**HV**	**Stream**
0.2	221	15.92	14.96	15.33	12.92	14.78
0.4	424	14.63	13.74	13.23	11.24	13.21
0.6	684	13.44	12.55	12.01	10.59	12.12
0.8	852	12.92	11.81	11.51	9.12	11.34
1	1024	11.92	10.92	10.28	9.55	10.67
1.2	1228	11.63	10.10	9.63	8.56	9.98
1.4	1458	10.20	9.64	8.35	7.66	8.96
1.6	1640	9.47	8.76	7.41	6.88	8.13
1.8	1708	8.60	7.64	6.62	5.65	7.13
Opposing Direction						
Correction Factor	**Flow (PCU/h)**	**Simulated Speeds (m/s)**				
		TW	**Car**	**AR**	**HV**	**Stream**
0.2	534	16.16	14.30	15.18	13.40	14.76
0.4	1154	15.21	13.22	13.25	12.93	13.66
0.6	1495	13.86	12.44	12.33	11.62	12.56
0.8	1820	12.56	11.84	10.33	10.36	11.27
1	2254	11.21	10.40	9.55	8.98	10.04
1.2	2578	10.45	9.86	8.88	8.02	9.30
1.4	3014	10.08	8.54	8.33	7.11	8.49
1.6	3584	9.65	7.55	7.48	6.25	7.73
1.8	3672	8.30	7.10	6.58	5.88	6.97

Table D.3 Results from simulation runs for implementation of modal shift – Bengaluru study section

Scenario – I

Run	Increment in Buses	Capacity (veh/h)	Capacity (PCU/h)	Speed (m/s)				
				TW	Car	AR	BUS	Stream
R1	5	3685	3249	13.32	11.92	11.8	10.54	11.89
R2	10	3788	3403	13.18	12.08	11.92	10.62	11.95
R3	15	3810	3502	13.04	12.28	11.98	10.82	12.03
R4	20	3887	3674	12.9	12.56	12.03	10.9	12.09
R5	25	3715	3637	13.24	12.08	12.1	10.32	11.93
R6	30	3510	3596	13.52	11.84	12.18	10.12	11.91

Scenario – II

Run	Increment in Buses	Capacity (veh/h)	Capacity (PCU/h)	Speed (m/s)				
				TW	Car	AR	BUS	Stream
R1	2	3658	3168	13.44	11.8	12.06	11.26	12.14
R2	4	3844	3323	13.68	12.24	12.3	11.5	12.43
R3	6	3980	3433	13.23	12.56	12.4	11.92	12.52
R4	8	3810	3279	12.4	12.1	11.88	12.08	12.11
R5	10	3754	3224	11.65	11.8	11.1	11.7	11.56
R6	12	3552	3044	11.04	11.5	10.72	11.44	11.17

Scenario – III

Run	Increment in Buses	Capacity (veh/h)	Capacity (PCU/h)	Speed (m/s)				
				TW	Car	AR	BUS	Stream
R1	4	3621	3168	13.86	11.8	11.56	10.62	11.96
R2	8	3722	3288	14.05	12.34	11.12	10.89	12.1
R3	12	3738	3337	14.38	12.74	10.7	11.03	12.21
R4	16	3824	3456	14.8	13.08	10.12	11.37	12.34
R5	20	3652	3348	15.16	12.64	9.44	11.1	12.08
R6	24	3448	3215	15.72	12.18	9.1	10.74	11.93

Table D.4 Results from simulation runs for implementation of modal shift – Delhi study section

Scenario – I								
Run	**Increment in Buses**	**Capacity (veh/h)**	**Capacity (PCU/h)**	**Speed (m/s)**				
				TW	**Car**	**AR**	**BUS**	**Stream**
R1	5	3627	3503	10.5	8.93	3.4	1.3	6.03
R2	10	3714.9	3670	10.95	8.04	3.64	1.26	5.97
R3	15	3849.45	3904	11.36	8.64	3.47	1.28	6.18
R4	20	3957.4	4140	12.69	8.9	3.16	1.32	6.51
R5	25	3678.92	3601	11.2	9.36	2.89	1.3	6.18
Scenario – II								
Run	**Increment in Buses**	**Capacity (veh/h)**	**Capacity (PCU/h)**	**Speed (m/s)**				
				TW	**Car**	**AR**	**BUS**	**Stream**
R1	2	3264.8	3092	10.42	9.84	4.2	0.8	6.31
R2	4	3501.6	3316	10.68	9.92	4.4	1.1	6.52
R3	6	3727.1	3529	10.9	10.1	4.66	1.22	6.72
R4	8	3943.8	3733	11.2	10.24	4.32	1.34	6.77
R5	10	4149	3927	11.64	9.82	4.8	1.48	6.93
R6	12	3802.4	3599	11.2	9.45	3.45	1.68	6.44
R7	14	3597.75	3405	10.89	8.9	3.1	1.8	6.17
Scenario – III								
Run	**Increment in Buses**	**Capacity (veh/h)**	**Capacity (PCU/h)**	**Speed (m/s)**				
				TW	**Car**	**AR**	**BUS**	**Stream**
R1	4	3856	3694	10.8	8.92	2.87	0.92	5.87
R2	8	4041	3921	11.04	9.12	3.21	1.2	6.14
R3	12	4153	4086	12.4	9.36	3.46	1.25	6.61
R4	16	4266	4265	12.88	9.58	3.68	1.32	6.86
R5	20	3752	3818	11.52	9.1	3.88	1.4	6.47
R6	24	3436	3568	11.08	8.64	3.95	1.48	6.28

Table D.5 Results from simulation runs for implementation of modal shift – Mumbai study section

Scenario – I								
Run	**Increment in Buses**	**Capacity (veh/h)**	**Capacity (PCU/h)**	**Speed (m/s)**				
				TW	**Car**	**AR**	**BUS**	**Stream**
R1	5	2118	2047	9.45	12.42	4.26	1.32	6.86
R2	10	2382	2398	9.88	12.61	4.48	1.46	7.10
R3	15	1993	2118	9.62	12.62	4.62	1.52	7.09
Scenario – II								
Run	**Increment in Buses**	**Capacity (veh/h)**	**Capacity (PCU/h)**	**Speed (m/s)**				
				TW	**Car**	**AR**	**BUS**	**Stream**
R1	2	2470	2312	8.25	13.26	4.62	1.38	6.87
R2	4	2611	2443	8.39	13.36	4.8	1.42	6.99
R3	6	2936	2746	8.46	13.54	5.1	1.53	7.15
R4	8	3242	3030	8.84	13.2	5.3	1.66	7.25
R5	10	3341	3121	9.08	12.74	5.6	1.68	7.27
R6	12	2890	2699	8.72	12.4	5.26	1.5	6.97
Scenario – III								
Run	**Increment in Buses**	**Capacity (veh/h)**	**Capacity (PCU/h)**	**Speed (m/s)**				
				TW	**Car**	**AR**	**BUS**	**Stream**
R1	4	2336	2223	8.62	13.25	2.84	0.9	6.40
R2	8	2676	2594	8.9	13.48	2.9	1.2	6.62
R3	12	2920	2894	9.35	13.65	3.34	1.33	6.91
R4	16	2745	2792	9.3	13.4	3.61	1.47	6.94
R5	20	2569	2698	8.8	12.8	3.9	1.51	6.75
R6	24	2217	2422	8.42	12.66	4.26	1.4	6.68

REFERENCES

AASHTO (2001). "Policy on geometric design of highways and streets." *American Association of State Highway and Transportation Officials,* Washington, D. C., USA, 1(990), 158.

Alvarez, A.J.J.B., Brey, J.J. and Casado, J.M. (1990). "A simulation model for traffic flow with passing." *Transportation Research Part B: Methodological,* 24(3), 193–202.

Anwar, A. M., and Yang, J. (2017). "Examining the effects of transport policy on modal shift from private car to public bus." *Procedia engineering, 180,* 1413-1422.

Arasan, V.T. and Vedagiri, P. (2009). "Simulating heterogeneous traffic flow on roads with and without bus lanes." *Journal of Infrastructure Systems, ASCE,* 15(4), 305–312.

Arasan, V.T. and Koshy, R.Z. (2005). "Methodology for modeling highly heterogeneous traffic flow." *Journal of Transportation Engineering, ASCE,* 131(7), 544–551.

Asaithambi, G. and Basheer, S. (2016). "Analysis and modeling of vehicle following behavior in mixed traffic conditions." In *14th World Conference on Transport Research,* Shanghai, China.

Asaithambi, G., Kanagaraj, V., Srinivasan, K.K. and Sivanandan, R. (2012). "Characteristics of mixed traffic on urban arterials with significant volumes of motorized two-wheelers." *Transportation Research Record: Journal of the Transportation Research Board,* 2317(1), 51–59.

Asaithambi, G., Kanagaraj, V., Srinivasan, K.K. and Sivanandan, R. (2018). "Study of traffic flow characteristics using different vehicle-following models under mixed traffic conditions." *Transportation letters,* 10(2), 92-103.

Aycin, M.F. and Benekohal, R.F. (2001). "Stability and performance of car-following models in congested traffic." *Journal of Transportation Engineering, ASCE,* 127(1), 2–12.

Aycin, M.F. and Benekohal, R.F. (1998). "A linear acceleration car-following model development and validation." *Preprints of 77th Annual Meeting of the Transportation Research Board,* Washington, D. C., USA.

Badarinath, K.M. (1992). "Urban traffic system model for managing traffic in mixed mode environment." Ph.D. Thesis, Kakatiya University, Warangal, India.

Bando, M., Hasebe, K., Nakayama, A., Shibata, A. and Sugiyama, Y. (1995). "Dynamical model of traffic congestion and numerical simulation." *Physical Review E,* 51, 1035–1042.

Bede, Z., Szabó, G., & Péter, T. (2010). "Optimalization of road traffic with the applied of reversible direction lanes." *Periodica Polytechnica Transportation Engineering, 38*(1), 3-8.

Benekohal, R. and Treiber, J. (1988). "Carsim: Car-following model for simulation of traffic in normal and stop-and-go conditions." *Transportation Research Record,* 1194, 99–111.

Bham, G.H. and R.F. Benekohal. (2004). "A high fidelity traffic simulation model based on cellular automata and car-following concepts." *Transportation Research Part C: Emerging Technologies,* 12, 1-32.

Brackstone, M. and McDonald, M. (1999). "Car-following: a historical review." *Transportation Research Part F: Traffic Psychology and Behaviour*, 2(4), 181-196.

Brackstone, M., Waterson, B. and McDonald, M. (2009). "Determinants of following headway in congested traffic." *Transportation Research Part F: Traffic Psychology and Behaviour,* 12(2), 131–142.

Budhkar, A. and Maurya, A.K. (2014). "Modeling of bidirectional mixed traffic stream with weak lane discipline." In *93rd Annual Meeting of the Transportation Research Board*, Washington, D.C.

Chadchan, J. and Shankar, R. (2012). "An analysis of urban growth trends in the post-economic reforms period in India." *International Journal of Sustainable Built*

Environment, 1(1), 36–49.

Chakroborty, P., Agrawal, S. and Vasishtha, K. (2004). “Microscopic modeling of driver behavior in uninterrupted traffic flow.” *Journal of Transportation Engineering,* 130(4), 438–451.

Chandler, R.E., Herman, R. and Montroll, E.W. (1958). “Traffic dynamics: studies in car-following.” *Operations Research Society of America,* 6(2), 165–184.

Chandrasekar, P., Cheu, R.L. and Chin, H.C. (2002). “Simulation evaluation of route-based control of bus operations.” *Journal of Transportation Engineering,* 128(6), 519–527.

Chena, G., Meng, F., Fu, G., Deng, M. and Li, L. (2013). “A cell automation traffic flow model for mixed traffic.” *Procedia-Social and Behavioral Sciences,* 96, 1412–1419.

Cho, H.J. and Wu, Y.T. (2004). “Modeling and simulation of motorcycle traffic flow.” In *Systems, Man and Cybernetics, IEEE International Conference on Systems,* 7, 6262–6267.

Choudhury, C.F. and Islam, M.M. (2016). “Modelling acceleration decisions in traffic streams with weak lane discipline: a latent leader approach.” *Transportation Research Part C: Emerging Technologies*, 67, 214–226.

de Sá, T. H., Parra, D. C., and Monteiro, C. A. (2015). “Impact of travel mode shift and trip distance on active and non-active transportation in the São Paulo Metropolitan Area in Brazil.” *Preventive medicine reports*, *2*, 183-188.

Delpiano R., Herrera J.C.M. and Coeymans A.J.E. (2015). “Characteristics of lateral vehicle interaction.” *Transportmetrica A: Transport Science,* 11(7), 636–647.

Dey, P.P., Chandra, S. and Gangopadhyay, S. (2008). “Simulation of mixed traffic flow on two-lane roads.” *Journal of Transportation Engineering*, 134(9), 361–369.

Fatima, E. and Kumar, R. (2014). “Introduction of public bus transit in Indian cities." *International Journal of Sustainable Built Environment,* 3(1), 27–34.

Fritzsche, H.T. (1994). "A model for traffic simulation." *Traffic Engineering and Control,* 35(5), 317–21.

Gazis, D.C., Herman, R. and Rothrey, R.W. (1961). "Nonlinear follow-the-leader models of traffic flow." *Operations Research,* 9(4), 545–567.

Gipps, P.G. (1981). "A behavioral car-following model for computer simulation." *Transportation Research B: Methodological*, 15(2), 105–111.

Government of India (2012). "Air quality in India 2012." *Central Pollution Control Board, Ministry of Environment and Forest*, New Delhi, India.

Gowri, A. (2011). "Evaluation of turn lanes at signalized intersection in heterogeneous traffic using microscopic simulation model." Ph.D. Thesis, IIT Madras, India.

Gunay, B. (2003). "Methods to quantify the discipline of lane-based-driving." *Traffic Engineering and Control,* 44(1), 22–27.

Gunay, B. (2007). "Car-following theory with lateral discomfort." *Transportation Research Part B: Methodological,* 41(7), 722–735.

Gundaliya P.J., Mathew V.T. and Dhingra S.L. (2008). "Heterogeneous traffic flow modeling for an arterial using grid based approach." *Journal of Advances in Transportation,* 42(4), 467–491.

Hidas, P. (1998). "A car-following model for urban traffic simulation." *Traffic Engineering Control*, 39(5).

Highway Capacity Manual. (2000). "Transportation Research Board." *National Research Council,* Washington, D.C., USA, 113, 10.

Highway Capacity Manual. (2010). "Transportation Research Board." *National Research Council,* Washington, D. C., USA.

Hu, X., Wang, W. and Yang, H. (2012). "Mixed traffic flow model considering illegal lane-changing behavior: simulations in the framework of kerner's three-phase theory." *Physica A: Statistical Mechanics and its Applications,* 391(21), 5102–5111.

Indian Road Congress (1990). "Guidelines for capacity of urban roads in plain areas." *IRC code of Practice* 106, New Delhi, India.

IPCC (2007). "Climate change assessment report." *The Fourth Intergovernmental Panel on Climate Change,* Geneva, Switzerland.

Jaikumar, R., Nagendra, S.S. and Sivanandan, R. (2017). "Modeling of real time exhaust emissions of passenger cars under heterogeneous traffic conditions." *Atmospheric Pollution Research,* 8(1), 80–88.

Jin, C.J., Knoop, V.L., Li, D., Meng, L. Y. and Wang, H. (2018). "Discretionary lane-changing behavior: empirical validation for one realistic rule-based model." *Transportmetrica A: Transport Science,* 1–19.

Jin, S., Wang, D.H., Xu, C. and Huang, Z.Y. (2012). "Staggered car-following induced by lateral separation effects in traffic flow." *Physics Letters A*, 376(3), 153–157.

Kanagaraj, V., Gowri, A., Srinivasan, K.K. and Sivanandan, R. (2011). "Vehicle class-wise analysis of time gaps and headways under heterogeneous traffic." In *90th Annual Meeting of the Transportation Research Board*, Washington, D.C., USA.

Kanagaraj, V., Asaithambi, G., Kumar, C.N., Srinivasan, K.K., and Sivanandan, R. (2013). "Evaluation of different vehicle following models under mixed traffic conditions." *Procedia-Social and Behavioral Sciences*, 104, 390–401.

Katti, B.K. and Pathak, R.H. (1985). "A study on headway distribution models for urban road sections under mixed traffic conditions." *Highway Research Bulletin,* 26, 1–31.

Krauss, S. (1997). "Microscopic modeling of traffic flow: investigation of collision free vehicle dynamics." Ph.D. Thesis, University of Cologne, Cologne, Germany.

Lambert, L., and Wolshon, B. (2010). "Characterization and comparison of traffic flow on reversible roadways.” *Journal of advanced transportation*, *44*(2), 113-122.

Leutzbach, W. and Wiedemann, R. (1986). “Development and application of traffic simulation models at karlsruhe institute.” *Traffic Engineering and Control,* 27(5), 270–278.

Luo, Z., Liu, Y. and Guo, C. (2014). “Operational characteristics of mixed traffic flow under bi-directional environment using cellular automaton.” *Journal of Traffic and Transportation Engineering (English edition),* 1(6), 383–392.

Lv, W., Songa, W.G, Liu, X.D. and Ma, J. (2013). “A microscopic lane changing process model for multilane traffic.” *Physica A: Statistical Mechanics and its Applications,* 392(5), 1142–1152.

Maitra, B., Dandapat, S., and Chintakayala, P. (2014). “Differences between the perceptions of captive and choice riders toward bus service attributes and the need for segmentation of bus services in urban India.” *Journal of Urban Planning and Development*, *141*(2), 04014018.

Mahapatra, G. and Maurya, A.K. (2013). “Study of vehicles lateral movement in non-lane discipline traffic stream on a straight road.” *Procedia-Social and Behavioral Sciences,* 104, 352–359.

Mahapatra, G., Maurya, A.K. and Minhans, A. (2016). “Lateral movement of vehicles under weak-lane discipline heterogeneous traffic.” *JURNAL TEKNOLOGI,* 78(4), 27–35.

Mallikarjuna, Ch. and Rao, K.R. (2009). “Cellular automata model for heterogeneous traffic.”, *Journal of Advanced Transportation,* 43(3), 321–345.

Mallikarjuna, Ch. and Rao, K.R. (2011). “Heterogeneous traffic flow modelling: a complete methodology.” *Transportmetrica,* 7(5), 321–345.

Marwah, B.R. and Rameshan, S. (1978). “Interaction between vehicles in mixed traffic flow using simulation.” *Highway Research Bulletin Indian Roads Congress,* 8, 25–41.

Marwah, B.R. (1976). “Studies on stochastic modelling and simulation of mixed vehicular traffic.” Ph.D. Thesis, IIT, Kanpur, India.

Mathew, T. and Ravishankar K. (2011). “Car-following behavior in traffic having mixed vehicle-types.” *Transportation Letters,* 3(2), 109–112. .

Mathew, T.V. and Radhakrishnan, P. (2010). “Calibration of microsimulation models for nonlane-based heterogeneous traffic at signalized intersections.” *Journal of Urban Planning and Development,* 136(1), 59–66.

Mathew, T.V., Munigety, C.R. and Bajpai, A. (2013). “Strip-based approach for the simulation of mixed traffic conditions.” *Journal of Computing in Civil Engineering,* 29(5), 04014069.

Maurya, A.K. (2011). “Comprehensive approach for modeling of traffic systems with no lane discipline.” In *2nd International Conference on Models and Technologies for Intelligent Transportation Systems,* Leuven, Belgium.

Maurya, A.K., Dey, S., and Das, S. (2015). “Speed and time headway distribution under mixed traffic condition.” *Journal of the Eastern Asia Society for Transportation Studies,* 11, 1774–1792.

May, A.D. and Pratt, D. (1968). “A simulation study of load factor at signalized intersections.” *Traffic Engineering and Control.*

Menga, J.P., Dai, S.Q., Donga, L.Y. and Zhang, J.F. (2007). “Cellular automaton model for mixed traffic flow with motorcycles.” *Physica A: Statistical Mechanics and its Applications,* 380, 470–480.

Metkari, M., Budhkar, A. and Maurya, A.K. (2013). “Development of simulation model for heterogeneous traffic with no lane discipline.” *Procedia-Social and Behavioral Sciences,* 104, 360–369.

Minh, C. C., Sano, K., and Matsumoto, S. (2005). “The speed, flow and headway analyses of motorcycle traffic.” *Journal of the Eastern Asia Society for Transportation Studies, 6,* 1496-1508.

Mohan, R. and Ramadurai, G. (2017). “Heterogeneous traffic flow modelling using second-order macroscopic continuum model.” *Physics Letters A*, 381(3), 115–123.

MORTH (2017). “Annual Report 2017-2018.” *Ministry of Road Transport and Highways*, India.

Munigety, C.R., Gupta, P.A., Gurumurthy, K.M., Peeta, S. and Mathew, T.V. (2016). “Vehicle-type dependent car following model using spring-mass-damper dynamics for heterogeneous traffic.” In *95th Annual Meeting of the Transportation Research Board*, Washington, D.C., USA.

NCRB (2016). “National Crime Records Bureau Report 2016.” *Ministry of Home Affairs*, India.

Newell, G.F. (1961). “Nonlinear effects in the dynamics of car-following.” *Operations Research*, 9(2), 209–229.

Nurdden, A., Rahmat, R. A. O. K., and Ismail, A. (2007). “Effect of transportation policies on modal shift from private car to public transport in Malaysia.” *Journal of applied Sciences*, *7*(7), 1013-1018.

Numbeo (2017). https://www.numbeo.com/traffic/rankings_by_country.jsp (accessed July 21, 2017)

Oketch, T. (2000). “New modeling approach for mixed-traffic streams with nonmotorized vehicles.” *Transportation Research Record: Journal of the Transportation Research Board*, 1075, 61–69.

Pal, D. and Chunchu, M. (2017). “Modeling of lateral gap maintaining behavior of vehicles in heterogeneous traffic stream.” *Transportation Letters*, 1–9.

Palaniswamy, S.P. (1983). “A generalised simulation model for vehicular behaviour under heterogeneous traffic conditions.” Simulation Research Project, IIT, Kanpur, India.

Pandian, S., Gokhale, S. and 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.

Papageorgiou, G., Ioannou, P., Pitsillides, A., Aphamis, T. and Maimaris, A. (2009). “Development and evaluation of bus priority scenarios via microscopic simulation models.” *IFAC Proceedings Volumes*, 42(15), 434–441.

Rahul, T.M. and Verma, A. (2017). “The influence of stratification by motor-vehicle ownership on the impact of built environment factors in Indian cities.” *Journal of Transport Geography*, 58, 40–51.

Ramachandra, T.V., Aithal, B.H. and Sreejith, K. (2015). “GHG footprint of major cities in India.” *Renewable and Sustainable Energy Reviews*, 44, 473–495.

Ravishankar, K.V.R. and Mathew, T.V. (2011). “Vehicle-type dependent car-following model for heterogeneous traffic conditions.” *Journal of Transportation Engineering*, 137(11), 775–781.

Satiennam, T., Jaensirisak, S., Satiennam, W. and Detdamrong, S. (2016). “Potential for modal shift by passenger car and motorcycle users towards Bus Rapid Transit (BRT) in an Asian developing city.” *IATSS Research*, 39(2), 121–129.

Sharma, N., Arkatkar, S.S. and Sarkar, A.K. (2011). “Study on heterogeneous traffic flow characteristics of a two-lane road.” *Transport*, 26(2), 185–196.

Simon, P.M. and Gutowitz, H.A. (1998). “Cellular automaton model for bidirectional traffic.” *Physical Review E*, 57(2), 2441.

SWF (2017). “State of World Population Report 2017.” *United Nations Population Fund*.

Tang, T.Q., Caccetta, L., Wu, Y.H., Huang, H.J. and Yang, X.B. (2014). “A macro model for traffic flow on road networks with varying road conditions.” *Journal of Advanced Transportation*, 48(4), 304–317.

Tiwari, G., Jain, D. and Rao, K.R. (2016). “Impact of public transport and non-motorized transport infrastructure on travel mode shares, energy, emissions and safety: Case of Indian cities.” *Transportation Research Part D: Transport and Environment*, 44, 277–291.

Toledo, T. (2002). “Integrated driving behaviour modelling.” Ph.D. Thesis, Department of Civil and Environmental Engineering, MIT, USA.

Torre, A.C., Fiore, M., Casetti, C., Gramaglia, M. and Calderón, M. (2017). “Bidirectional highway traffic for network simulation.” In *Vehicular Networking Conference (VNC), IEEE*, 77–80.

Treiber, M., Kesting, A. and Helbing, D. (2010). “Three-phase traffic theory and two-phase models with a fundamental diagram in the light of empirical stylized facts.” *Transportation Research Part B: Methodological*, 44(8–9), 983–1000.

Van, T.H., Schmoecker, J.D. and Fujii, S. (2009). “Upgrading from motorbikes to cars: Simulation of current and future traffic conditions in Ho Chi Minh City.” In *Proceedings of the Eastern Asia Society for Transportation Studies*, 7, 335–335.

Vedagiri, P., and Arasan, V. T. (2009). “Estimating modal shift of car travelers to bus on introduction of bus priority system.” *Journal of transportation systems engineering and information technology*, *9*(6), 120-129.

Venkatesan, K., Gowri, A. and Sivanandan, R. (2008). “Development of microscopic simulation model for heterogeneous traffic using object oriented approach.” *Transportmetrica*, 4(3), 227–247.

Verma, A., Rahul, T. M. and Dixit, M. (2015). “Sustainability impact assessment of transportation policies-A case study for Bangalore city.” *Case Studies on Transport Policy*, 3(3), 321–330.

Waleczek, H., Geistefeldt, J., Cindric-Middendorf, D. and Riegelhuth G. (2016). “Traffic flow at a freeway work zone with reversible median lane.” *Transportation Research Procedia*, 15, 257–266.

WMO (2014). “World Meteorological Organization greenhouse gas bulletin.” *World Meteorological Organization,* Geneva.

Wolshon, B. and Lambert II, L. (2006). “Planning and operational practices for reversible roadways.” *Institute of Transportation Engineers. ITE Journal,* 76(8), 38.

Yang, Q., Balakrishna, R., Morgan, D. and Slavin, H. (2017). “Large-scale, high-fidelity dynamic traffic assignment: framework and real-world case studies.” *Transportation Research Procedia,* 25, 1290–1299.

Yousif, S. and Hunt, J. (1995). “Modelling lane utilisation on British dual-carriageway roads: effects on lane–changing.” *Traffic Engineering and Control.*

Zhenga, J., Suzuki, K. and Fujita, M. (2012). “Evaluation of car-following models using trajectory data from real traffic.” *Procedia-Social and Behavioral Sciences,* 43, 356-366.

Zhou, M., Qu, X. and Li, X. (2017). “A recurrent neural network based microscopic car following model to predict traffic oscillation.” *Transportation Research Part C: Emerging Technologies,* 84, 245–264.

List of Publications Based on Ph.D. Research Work

Sl. No.	**Title of the Paper**	**Authors (In the same order as in the paper, underline the Research Scholar's name)**	**Name of the Journal / Conference / Symposium, Vol., No., Pages**	**Month & Year of Publication**	**Category***
	Study of Impact of Modal Shift of Private Vehicles towards Public Transport using Microscopic Simulation Model: A Case Study of Three Metropolitan Cities in India	**Punith B. Kotagi**, and Gowri Asaithambi	In 98th Transportation Research Board Annual Meeting, Washington DC. (Reviewed by TRB's Standing Committee on Traffic Flow Theory and Characteristics)	January 2019	3
1	Modeling Lateral Placement and Movement of Vehicles on Urban Undivided Roads in Mixed Traffic: A Case Study of India	**Punith B. Kotagi**, Pooja Raj and Gowri Asaithambi	Journal of Traffic and Transportation Engineering, Elsevier	Accepted in 2018	1
2	Development of Microscopic Simulation Model for Bidirectional Mixed Traffic on Urban Roads	**Punith B. Kotagi**, Gowri, Asaithambi and Krishna Murthy Gurumurthy	In 97th Transportation Research Board Annual Meeting, Washington DC. (Reviewed by TRB's Standing Committee on Traffic Flow Theory and Characteristics)	January 2018	3
3	Simulation Framework for Modeling Bidirectional Mixed Traffic	**Punith B. Kotagi**, and Gowri Asaithambi	In 9th International Conference on Communication Systems and Networks, IEEE, Bengaluru pp. 443-447	June 2017	3
4	Analysis of Lateral Placement and Movement of Vehicles on Urban Undivided Roads in Mixed Traffic	**Punith B. Kotagi**, Pooja Raj and Gowri Asaithambi	In Proceedings of 12th Transportation Planning and Implementation Methodologies for Developing Countries, IIT Bombay	December 2016	3
5	Simulation Model for Bi-directional Traffic on Urban Undivided Roads under Mixed Traffic Conditions	**Punith B. Kotagi** and Gowri Asaithambi	In Proceedings of 2nd International Conference on Green Urban Futures, Bengaluru	November 2014	4

Category*

1 : Journal paper, full paper reviewed
3 : Conference/Symposium paper, full paper reviewed
2 : Journal paper, Abstract reviewed
4 : Conference/Symposium paper, abstract reviewed

Research Scholar

Punith B. Kotagi

Research Guide

Dr. A. Gowri

List of Papers Communicated

1. Punith B. Kotagi and Gowri, Asaithambi. “Microsimulation Approach for Evaluation of Reversible Lane Operation on Urban Undivided Roads in Mixed Traffic” *Transportmetrica A: Transport Science, Taylor and Francis*. (Under Second Review)

2. Punith B. Kotagi and Gowri, A. “Microsimulation Approach for Evaluation of Impacts of Modal Shift of Private Vehicles towards Public Transportation System” *Transportation in Developing Economies, Springer.* (Under Review)

3. Punith B. Kotagi and Gowri, A. “Impact Assessment of Modal Shift of Private Vehicles to Public Buses using Microscopic Simulation Model: A Case Study of Three Metropolitan Cities in India”, *Sustainable Cities and Society, Elsevier* (Communicated)

CURRICULUM VITAE

PUNITH B. KOTAGI
#8-R/1305/111, Shanker Nilay,
R.S.Colony, Near TV Station,
Humnabad Road,
Gulbarga-585 104
Email: punithk9@gmail.com
Mobile: +91-9986998227

Education:

Qualification	Institution	University/Board	Aggregate
Ph.D. (Transportation Engineering)	National Institute of Technology, Karnataka, Surathkal, Mangaluru	NITK, Surathkal	-
M.Tech. (Highway Technology)	RASTA, Center for Road Technology, Bengaluru	Visvesvaraya Technological University, Belgaum (2013)	First Class with Distinction
B.E. (Civil Engineering)	P D A College of Engineering, Gulbarga	Visvesvaraya Technological University, Belgaum (2011)	First Class with Distinction
12th (PUC)	Shree Guru PU College, Gulbarga	Board of Pre-University Education, Karnataka (2007)	First Class
10th (SSLC)	Chandrakant Patil English Medium School, Gulbarga	Central Board of Secondary Education (2005)	First Class

Work Experience:

- Currently working as Assistant Professor in Dept. of Civil Engineering at The National Institute of Engineering, Mysuru. (August 2018 – till date)
- Worked as Site Engineer (Consultant) at RASTA Center for Road Technology, Bangalore, Karnataka for QMC/PMC Road Projects (Karnataka Industrial Area Development Board) during September 2013- July 2014.