Parametric Study of Heterogeneous and No-Lane Disciplined Traffic Stream

Thesis submitted to the

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For the fulfillment of the requirements of the degree of

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in

Civil Engineering

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Certificate

This is to certify that dissertation entitled '**Parametric Study of Heterogeneous and No-Lane Disciplined Traffic Stream**', being submitted by Mrs. Geetimukta Mahapatra (Roll no. 126104011) to the Indian Institute of Technology Guwahati, for the award of degree of Doctor of Philosophy in Civil Engineering is a record of bonafide research work carried out by her under my supervision and guidance. In my opinion the thesis work has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy in Civil Engineering.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for award of any degree or diploma.

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Statement

I do hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam, India.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work is based on the findings of other investigators.

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Summary

Due to no-lane disciplined heterogeneous traffic in India, the drivers have to control the vehicle's position along both the longitudinal (direction of motion) and lateral direction, i.e. the width of the roadway. Both these tasks are inter-dependent and go on simultaneously known as two-dimensional (2D) driver behaviour. The existing 1D models (describing longitudinal manoeuvre i.e. car-following behaviour) are not sufficient to describe the 2D behaviour of the vehicles. Many authors have modified the 1D models for the 2D traffic interaction by incorporating lateral manoeuvre. Nonetheless, to date, no well acceptable theory exists that can model the 2D driver behaviour (i.e. longitudinal and lateral) in a comprehensive manner. One of the major challenges in driver behaviour modelling lies in identifying the parameters to describe the typical driving behaviour and vehicle manoeuvre under different traffic conditions. The mixed traffic consists of multiple types of vehicles on same traffic stream with different manoeuvring or driving capabilities and static characteristics (length or width of the vehicles). Also, the roads include different width of roads with variability in horizontal and vertical alignment and different median and shoulder types. Weak lane discipline leads lateral movements within lanes and at the same time integrated (lateral and longitudinal both) movements by interacting with all surrounding vehicles. Also, vehicles behaviour of occupying any lateral space within the entire road width may lead to multiple leaders following, weaving and filtering manoeuvre of vehicles.

The main goal of this research work is to study the vehicles lateral and longitudinal movement in the Indian heterogeneous non-lane disciplined traffic condition and also the impact of road characteristics (road width and edge conditions) on traffic parameters (like, operating speed and lateral positioning of vehicles). Firstly, a detailed analysis of vehicle dynamic parameters (operating speed, lateral acceleration and longitudinal acceleration/deceleration) is carried out and their relationship with operating speed of different type of vehicles are established. The impact of dynamic parameters on the maneouvring of different vehicles are studied using the concept of friction circle. The copula based approach is applied to model the joint distribution of all three dynamic parameters of different type of vehicles. Then the lateral placement of different type of vehicles on the entire cross section of roadways of different width, are studied. The relationship between lateral placement and operating speed of vehicles are established on roads with different width (number of lane). Thereafter, the minimum lateral gap maintaining behaviour of vehicles from median based on the median geometry are analysed. Finally the

importance of the different microscopic parameters studied from field are evaluated using a commercially available micro-simulation framework (VISSIM).

To achieve this goal, obtaining a large scale accurate data from field and their analysis in micro level is necessary to understand the driver behaviour. The dynamic parameters of different type of vehicles are collected using a high accuracy GPS based instrument named as Video VBOX installed in the subject vehicles (referred as instrumented vehicles) from five major cities of India (Kolkata, Bengaluru, Mumbai, Pune and Delhi) using the instrumented vehicles. Five different types of vehicles i.e. Hatchback cars (H-Back), Sedan cars, Sports Utility Vehicles (SUV cars), Motorized three-wheeler (3W) and two-wheeler (2W) are used as instrumented vehicles for data collection. To include the variation in vehicle maneouvre with respect to different cities, the combined data lateral and longitudinal acceleration of all cities are studied.

It is observed that road width does not have any impact on longitudinal acceleration/deceleration (A/D) of vehicles, however a significant impact is observed for lateral acceleration of different type of vehicles on roads with different width. To describe the detailed statistical properties of lateral acceleration, the lane-wise probability distribution function (PDF) for different road widths are analysed and the best fitted distributions for different vehicles' lateral and longitudinal A/D are identified. The Weibull, Gamma and Burr distributions are fitted best to the A/D data of all type of vehicles at 5% significance level based on the log-likelihood (LL), Akike's Information Criteria (AIC) and Baysian Information Criteria (BIC). However, the Gamma distribution is observed as the best fitted distribution to the lateral acceleration of all five type of vehicles. The relationship between 85th and 95th percentile lateral and longitudinal A/D with operating speed are established for all five type of vehicles to study the extreme lateral and longitudinal behavior of vehicles while travelling on straight mid-block sections. A linearly decreasing trend is observed for both longitudinal acceleration and deceleration of different type of vehicles, however, a nonlinear two-term exponential trend is fitted to the lateral acceleration of all five type of vehicles at 5% significance level. Lateral acceleration increases with the increase in speed at the lower speed ranges (i.e. less than 20 km/h) and obtains the maximum value within the speed range of 15 to 20 km/h speed, for all vehicle types. Afterwards, the lateral acceleration decreases with increase in speed.

The driving behavior of different type of vehicles are analysed using the friction circle concept (g-g diagram) based on the dynamic parameters obtained from the field data. The resultant acceleration and g-g diagram can easily demonstrate the safe or unsafe behaviour of a driver.

The acceleration trend in space illustrated the exact locations of trajectory where the driver experience sudden acceleration or braking as well as the points where lateral acceleration is above the road design lateral threshold. The safety domain defined is useful for finding those points of the roadway where driving is unsafe, in order to give him information about his behaviour and let him raise the threshold of attention to take preventive measures. This study also investigated the applicability of the copula based approach to model the joint distribution of longitudinal descriptors [operating speed, longitudinal (A/D)] and lateral descriptor (lateral acceleration) of five different type of vehicles.

The lateral placement of vehicles on the entire road cross-section are studied by collecting the vehicle position data using top-view videos from the selected road sections from five different cities of India. The vanishing point methodology based software (developed by Budhkar & Maurya, 2015) is used to convert video image coordinates into real world coordinates. To incorporate the variability in carriage way widths of Indian roads, a wide variety of roads (4-lane divided; 2-lane, 6-lane divided; 3-lane, 8-lane divided; 4-lane and 10-lane divided; 5-lane) were selected from six different cities of India. It is observed that in case of 2-lane roads (4-lane divided roads) 75% to 90% of cars travel near the median side of the roads. However, in case of 3-lane (6-lane divided road) roads, majority of the cars, travel in the median-sided lane (40% to 60%) closely followed by the middle lane (35% to 50%). The trucks and light-commercial vehicles (LCVs) move mainly along the median-sided lane in cases of 2-lane and 3-lane roads. Their proportion on the median-sided lane varies from 55% to 80%. However, in case of 4-lane (8-lane divided roads) and 5-lane roads (10-lane divided roads), they tend to move towards the shoulder side of the road. 70% of the motorized two-wheelers (2W) and three-wheelers (3W) always shifts away from the median i.e. towards the shoulder of the road If one takes up 50% of the road on the shoulder side, it can be seen that nearly 60% of 2Ws move over this portion of the road for 4-lane, 6-lane and 10-lane divided roads and nearly 85% of them move in this portion of road for 8-lane divided road. A linear model is fitted to the operating speed of each type of vehicles by taking lateral placement and flow (PCU/hr) of the stream as two independent variables for all type of roads.

A sensor-based assembly is developed to measure lateral clearances maintained by vehicles from road elements (like road edge, divider, kerb footpaths, etc.). This developed assembly helps in measuring the, (i) Lateral clearance maintained by vehicles from road elements, and (ii) Speed of the vehicles. Impact of median type (width and height) on lateral gap maintaining behaviour of vehicles are studied using a sensor based assembly. To see the minimum gap maintained by different vehicles from different medians, the lower 5% lateral gap data for different speed groups are extracted. The relationships are established between the lateral gap of cars and trucks with operating speed of each vehicle and size of median. It is observed that for a median width of 1.2m, cars feel safe to move closer to the median, which indicates that with the increase in width of medians for a standard height of 0.3m, vehicles move closer to the median. However, for 2.5m and 4.5m width medians, vehicles shifts away from the median and no significant difference is observed between their lateral gap maintaining behaviour.

The longitudinal A/D and lateral acceleration values of different types of vehicles measured from the field and the study of lateral placement of vehicles on the road cross-section, can be used in development and validation of the microscopic traffic simulation model. Further, the identified probability distribution models of A/D and lateral acceleration behaviour helps in realistic representation of such traffic stream. The model for lateral acceleration can be used for evaluation of vehicle's lateral weaving in simulated trajectories for such traffic. The lateral acceleration as a measurement of lateral comfort is directly related to the horizontal alignment and can be used to determine the applicable range of super-elevation ratios. Further, the lateral placement can be used to develop the lane distribution factor, the optimum operating speed in various lanes of the roads and the safety aspects of the road like the clearance from the edge of medians and shoulders, etc. The impact of median type on lateral gap maintaining behaviour of vehicles can also be used while generating simulation models and also a useful parameter for safety evaluation and capacity estimation of the roads.

The importance of the microscopic parameters obtained from the field data are also evaluated by comparing the parameters obtained from a simulated traffic stream using the commercially available micro-simulation framework, VISSIM. The lateral manoeuvring i.e. the lateral acceleration, lateral speed and the lateral placement of vehicles on the entire road width, etc., are not represented by VISSIM as in case of field traffic. Hence, it can be concluded that while developing a new microscopic model or simulation framework and also for modifying any existing model for such no-lane based heterogeneous traffic, these lateral parameters should be taken into account. In the present study, an attempt has been made to study the manoeuvring behaviour of different type of vehicles by identifying different lateral and longitudinal microscopic parameters of such traffic stream. Though all three studies are different based on their study methodology, these parameters are useful for evaluation of vehicles' lateral weaving in simulated trajectories and also while developing or validating simulation models for the realistic representation of such no-lane based heterogeneous traffic stream.

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Glossary of Items

x_n	Spatial position
v_n, $\dot{x}_{n-1,t-\Delta t}$, V_{FV}	Speed
(a_n) $\ddot{x}_{n.t}$	Acceleration
$K_{n.t-\xi\Delta t}$	Density of traffic at time $t - \xi\Delta t$
t_n	Time
Δx, s_n	Relative spacing
Δv	Relative speed
Δt / τ	Driver reaction time
d_{react}	Distance travelled during the reaction time
$\xi \epsilon$ [0, 1]	Parameter of sensitivity time lag
$\varepsilon_{n,t}$	Error term associated with the *(n)th* vehicle at time *t*
D_{FV}	Desired following distance
a_{FV}	Acceleration that the following vehicle wants to accept
b_{FV}	Braking that the FV wants to attempt
b_n	Desired deceleration
s_{LV}	Effective size of the leading vehicle
a_{max} n,	Maximum acceleration of vehicle
v_n^0	Desired velocity of n, δ
$T_n$is n.	Safety time gap of the vehicle
d_{veer}	Distance travelled during veering manoeuvre
t_{veer}	Time to veer laterally
LS_n	Lateral separation distance between car *n* and *n+1*
Gap_{cr}	Critical Gap between two vehicles
V_h	Vehicle Heterogeniety
D_0	Distance between the two sensors
v_0	Speed of the vehicle
t_0	Time taken by vehicle to cross the sensor,
δt	Error in the true time and recorded time
f	Braking coefficient or coefficient of friction
g	Acceleration due to gravity
$\bar{a}$	Resultant acceleration vector
a_{long}	Longitudinal acceleration
a_{lat}	Lateral acceleration
μ	Maximum permissible coefficient of friction or braking coefficient
q	Flow of traffic stream
H	Height of median kerb
LC	Lateral Clearance
NRMSE	Normalized Root Mean Square Error
1D	One Dimension
2D	Two Dimension
3D	Three Dimension
CF	Car-following
FV	Following Vehicle
LV	Leading Vehicle
OV	Optimal Velocity

OVM	Optimal Velocity Model
GFM	Generalized Force Model
FVDM	Full Velocity Difference Model
TTC	Time to Collision
TVDM	Two Velocity Difference Model
IDM	Intelligent Driver Model
CA	Cellular Automata
MES	Maximum Escape Speed
ARM	Acceleration Response Model
SRM	Steering Response Model
2W	Motorized two-wheelers
3W	Motorized three-wheelers
HMV	Heavy Motor Vehicles
LMV	Light Motor Vehicles
LCV	Light Commercial vehicle
FC	Frictional Clearance
CS	Centreline Separation
NLBCF	Non-Lane Based Car-Following model
NGSIM	Next Generation Simulation
Lp	Lateral placement of vehicles
VDDAS	Vehicle Detector Data Acquisition System
CRS	Centreline Rumble Strips
ML	Median Lane
SL	Shoulder Lane
NH	National Highway
A/D	Acceleration/Deceleration
LL	Log-likelihood value
AIC	Akaike Information Criteria
BIC	Baysian Information Criteria
RMSE	Root Mean Squared Error
MAPE	Mean Absolute Percentage Error
GUI	Graphic User Interface tool
GA	Genetic Algorithms
2-lane road	One side of 4-lane divided road
3-lane road	One side of 6-lane divided road
4-lane road	One side of 8-lane divided road
5-lane road	One side of 10-lane divided road

1 Introduction

1.1 Introduction

The road traffic in countries like India is highly heterogeneous comprising vehicles of wide ranging static (length, width and height) and dynamic (acceleration, deceleration, speed, etc.) characteristics. Due to this, vehicles do not follow lane discipline and occupy any lateral position throughout the width of the roadway. Drivers constantly perceive their immediate driving scenario while driving and react accordingly (perception-reaction mechanism of every driver). The various features that affect the driver’s behaviour are; i) Roadway features ii) Traffic features. The road features that effect driver behaviour are the road edge, road width, curves, lane markings, potholes and other static obstacles like parked vehicles, lane barriers etc. As the width of road decreases, drivers tend to veer towards the centre of the road. Further, the vehicular speed decreases as the road width reduces (Kay et al., 2000; Ma et al., 2012). The static obstacles are avoided by the vehicles by moving laterally either to the left or the right depending on the size and location of the obstacle. In mixed traffic conditions, due to the variability in vehicle characteristics, fast moving, as well as slow moving vehicles, tend to present in the traffic scenario. The vehicles travel abreast due to the variations in their size and non-standard widths. Also, due to the absence of lane behaviour vehicle continuously interact with the vehicles which are present in its neighbourhood (longitudinal as well as lateral directions). Hence on a given road section, the lateral positioning depends upon the driver behaviour, the type of the vehicle and most importantly, the traffic parameters such as the vehicle speed and it's acceleration.

In such traffic scenario the drivers have two basic tasks first is the control of vehicle’s position along longitudinal direction i.e. the direction of motion and second controlling the vehicle’s position along the lateral direction i.e. the width of the roadway. The first task is referred to as longitudinal control and is achieved by controlling the vehicle’s speed (i.e. through acceleration/deceleration). The second task of lateral control is achieved through proper choice of steering angles. Both these tasks are inter-dependent and goes on simultaneously known as two-dimensional (2D) driver behaviour. To alleviate this problem, an extensive study need to be carried out to understand and analyze the traffic stream and how they are impacted by different driver behavior.

1.2 Problem Statement

From the qualitative assumption of any road traffic, it is easy to notice that most of the vehicles are not positioned in the center of the lane. These deviations from the center become considerable where non-lane based driving is predominant. Hence, the study of longitudinal control of vehicles (Car-following) is not sufficient, and study of longitudinal and lateral control of vehicles in a comprehensive manner is necessary. The key assumption of car-following theory states that vehicles travel in the middle of the lane and each vehicle is influenced by the vehicle in the front, and no passing is allowed. Under these assumptions, only longitudinal interactions are taken into account. This assumption is valid for vehicles traveling long distances on the same road, and they do not cross the lanes maintaining a well-demarcated lane. Hence, the models which can account for both lateral and longitudinal interactions between vehicles can be used to study the interactions of vehicles with other features of the road.

Many authors have modified the 1D models for the 2D traffic interaction by incorporating lateral maneuver parameters (like Palaniswamy et al., 1985 and Ramanayya, 1988). Similarly many authors like, Chakroborty et al. (2004); Gunay (2007); Arasan & Koshy (2005); Maurya (2007); Dey et al. (2008) made an attempt to develop a comprehensive microscopic model of driver behavior by incorporating the lateral behavior along with longitudinal maneuver of vehicles. Though the lateral control model in CUTSiM, Maurya (2007) describes how a driver chooses a suitable steering angle based on the hypothesized best path, the real world traffic weaving maneuver or steering angle is not examined on the field. The impact of road features such as shoulder and median width, horizontal and vertical alignment, etc. on driver behavior also needs to be explored. Further, a large-scale validation with field data is required for all such developed models. Mathew et al. (2013), proposed a strip-based approach for simulation of heterogeneous traffic using SiMTraM, implemented on a traditional lane based simulator, SUMO. However, this model is unable to model the behaviour of two-wheeler (2W) which is common in no-lane based traffic. Nonetheless, to date, no well acceptable theory exists that can model the 2D driver behavior (i.e. longitudinal and lateral) comprehensively. Hence, literature that are mostly available in the area of traffic flow modeling cannot be directly used in mixed traffic conditions. Very limited studies have been done to develop an understanding of traffic behavior of non-lane based mixed traffic conditions in developing countries. Many researchers have worked on modeling the heterogeneous traffic and developed the microscopic simulation models. Most of these efforts were based on limited field observations and in many of these models convenient assumptions were made regarding the vehicular movement.

1.3 Motivation

One of the major challenge in driver behavior modelling lies in identifying the parameters that describe the typical driving behavior and vehicle maneuver on different traffic stream. Different parameters that impact the driver behavior can be classified as individual or circumferential parameters. The individual parameters include the impact of driver characteristics or the vehicle characteristics on driving behavior. The circumferential parameters include the impact of surrounding traffic as well as the road characteristics on driving behavior. Hence, parameters that impact the driving behavior are related to traffic characteristics and their dynamics in the immediate neighborhood.

The driving behavior of heterogeneous no-lane based traffic is divided into three categories, i) Mixed Traffic (Vehicle heterogeneity); ii) Different Road Characteristics and, iii) Weak Lane disciplined traffic.

The mixed traffic included multiple types of vehicles on same traffic stream with different maneuvering or driving capabilities and different size (length or width) of the vehicles. Also, the roads include different width of roads with variability in horizontal and vertical alignment and different median and shoulder types. Weak lane discipline leads lateral movements with in lanes and integrated movements by interacting with all surrounding vehicles at once. Occupying any lateral space within the road width leads multiple leaders following, weaving and filtering maneuver. Hence to study the driving behavior in no-lane based mixed traffic the following parameters are important to study from field traffic.

a) Study of vehicle manoeuvring using the dynamic parameters of vehicles.
b) Study of lateral placement of vehicles on an entire cross-section of different roads.
c) The impact of median/edge geometry on lateral gap maintaining behaviour of vehicles.

To study the above-mentioned parameters from the real world traffic stream, obtaining a large scale accurate data from field and their analysis in micro level is necessary to understand the driver behavior.

1.4 Research Objective

The main goal of this research work is to study the vehicles lateral and longitudinal movement in the Indian heterogeneous non-lane disciplined traffic condition and also the impact of road characteristics (road width and edge conditions) on traffic parameters (operating speed and lateral positioning of vehicles). The proposed goal can be achieved by following objectives:

1. Study the impact of dynamic parameters (operating speed, lateral acceleration and longitudinal acceleration/deceleration) on lateral manoeuvring different vehicles on Indian roads.
    - Study of statistical distribution of longitudinal Acceleration/Deceleration (A/D) and lateral acceleration of different vehicle types individually.
    - Study of the relation between longitudinal acceleration/deceleration and lateral acceleration of different type of vehicles with their operating speed.
    - Defining the driving behaviour of a different type of vehicles with all three dynamic parameters (operating speed, longitudinal acceleration/deceleration and lateral acceleration) using friction circle concept.
    - The joint distribution of longitudinal descriptors (operating speed, longitudinal (A/D)) and lateral descriptor (lateral acceleration) of different type of vehicles using copula approach.
2. Study of lateral placement of different type of vehicles on the entire cross section of different type of roads (roads with different width)
    - Variation in the lateral placement of different type of vehicles from road edge on entire road cross-section.
    - Variation in the lateral placement of vehicles based on their operating speed.
    - The relationship between lateral placement and operating speed of vehicles on roads with a different width (number of lane).
3. Study of lateral gap maintaining behaviour of different vehicles from median based on the median geometry.
    - The impact of different median geometry (width and height of median) on operating speed and the lateral gap maintaining behaviour of a different type of vehicles.
4. Evaluating the Importance of the microscopic parameters studied from the field traffic using a commercially available micro-simulation framework, VISSIM.

1.5 Scope of the Research Work

The proposed research work includes the study of different microscopic parameters describing the lateral and longitudinal maneuver on no-lane based heterogeneous traffic stream. The microscopic parameters include the lateral acceleration, longitudinal acceleration/deceleration, lateral placement of vehicles on the entire road cross-section and the minimum lateral gap maintained by vehicles from the road edge (median). The study scope includes straight mid-block sections in urban locations in developing countries like India. The influence of any external characteristics such as intersecting or merging traffic, pedestrians and other road hindrances, gradient, horizontal or vertical curves, pavement conditions, environmental or land-use conditions, on these microscopic parameters are not considered apart from the traffic, road width, and median type, which affect driver behavior in the traffic stream. Traffic data need to be collected from different sites pertaining to this scope, to study each microscopic parameters in detail and for establishing relationships between them.

1.6 Outline of the Thesis

The rest of the dissertation is organized as follows

Chapter 2 provides a comprehensive literature review of the proposed work and highlight of the short comings.

Chapter 3 presents the methodology of field data collection and extraction of all different microscopic parameters.

Chapter 4 focuses on the detailed analysis of the vehicle dynamic parameters like lateral acceleration, longitudinal acceleration/deceleration and operating speed of different type of vehicles.

Chapter 5 evaluates the driving behavior of a different type of vehicles using their dynamic parameters and their joint Distribution modelling is proposed using the copula approach.

Chapter 6 presents the analysis of lateral placement of vehicles on an entire cross-section of the roadway and the minimum lateral gap maintained by different vehicles from the median are studied.

Chapter 7 describes the calibration and validation of the VISSIM micro-simulation framework from field data. Further, it also presents the evaluation of the importance of the microscopic parameters studied from field traffic using VISSIM.

Chapter 8 summarizes the work presented in this dissertation with an emphasis on the significant contribution of the proposed research work. It also discusses the scope of further research on lines of the issues discussed in this dissertation.

2 Literature Review

2.1 Introduction

As discussed in Chapter-1, in case of no-lane based heterogeneous traffic stream, one of the major challenge in driver behaviour modelling lies in identifying the parameters that describe the typical driving behaviour and vehicle manoeuvre on different traffic stream. The models which can account for both lateral and longitudinal interactions between vehicles can be used to study the interactions of vehicles with other features of the road. Nonetheless, to date, no well acceptable theory exist that can model the 2D driver behaviour (i.e. longitudinal and lateral) in a comprehensive manner. Many researchers have worked on modeling the heterogeneous traffic and developed the microscopic simulation models.

In the present chapter all the existing microscopic models for one dimensional (1D) traffic and their modifications made by several authors for 2D traffic interactions are discussed, to avail their suitability for modelling the 2D traffic in a comprehensive manner. A brief review is also provided on different 2D models developed by the different authors. The parameters used in different 1D microscopic models and the models developed for 2D traffic by different authors are identified and the importance of different parameters used or need to be incorporate in 2D traffic modelling to describe the driver behavior of Indian traffic are discussed.

2.2 One-Dimensional Microscopic Models

The microscopic traffic flow theory models the traffic stream behaviour by describing the individual driver's behaviour in various driving scenarios. In microscopic modeling, the dynamics of different types of vehicles and their interactions are modelled using analytical and empirical relations. The interaction between the vehicles is determined by the influence of each vehicle's movement, driver behavior, the state of surrounding vehicles, etc. (Chowdhury et al., 2000). In the past, various driver behaviour models have been proposed, and most of them were related to driver behaviour in car-following situations (One dimensional_1D) where the driver is forced to follow a leading vehicle (Longitudinal interaction only). In this present section, a brief review is presented for the existing car-following models.

Reuschel and pipes in the 1950s', first proposed the concept of CF (Reuschel, 1950 and Pipes, 1953). In CF models, vehicles are described by vector state of variables providing the spatial position (x_n), speed (v_n), and acceleration (a_n) of *nth* vehicle while they move along the road maintaining a lane over time (t_n).

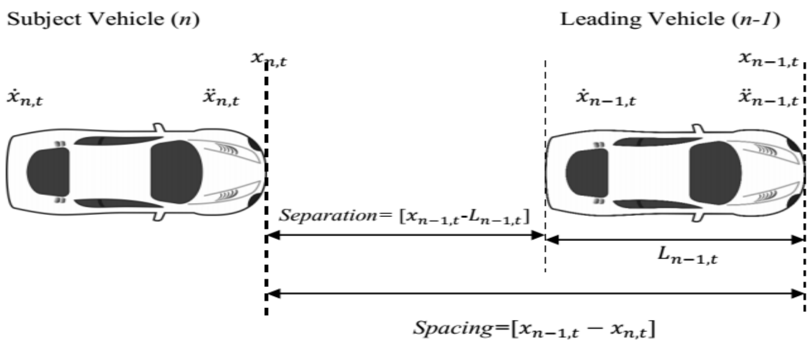


Figure 2-1 Definitions and notations used in Car-following model

Figure 2-1 illustrated the CF process of the vehicle (n) following the vehicle (n-1). The features used in CF are the distance between front bumpers of two vehicles or relative spacing ($\Delta x = x_{n-1} - x_n$) and relative speed ($\Delta v = v_{n-1} - v_n$) between *(n)th* and *(n-1)th* vehicles. The commonly used CF models are; Stimulus-response models, Safe-distance models, Psychophysical/Action point model, artificial intelligence based models, cellular automata (CA) models, etc. Many authors already presented a comprehensive bibliography of CF models (Brackstone & McDonald, 1999; Toledo, 2007; Siuhi, 2009; Li & SUN, 2012; Aghabayk et al., 2015). Here a brief discussion is made on CF models developed for lane-based traffic. Various car-following models are categorized in the following chart.

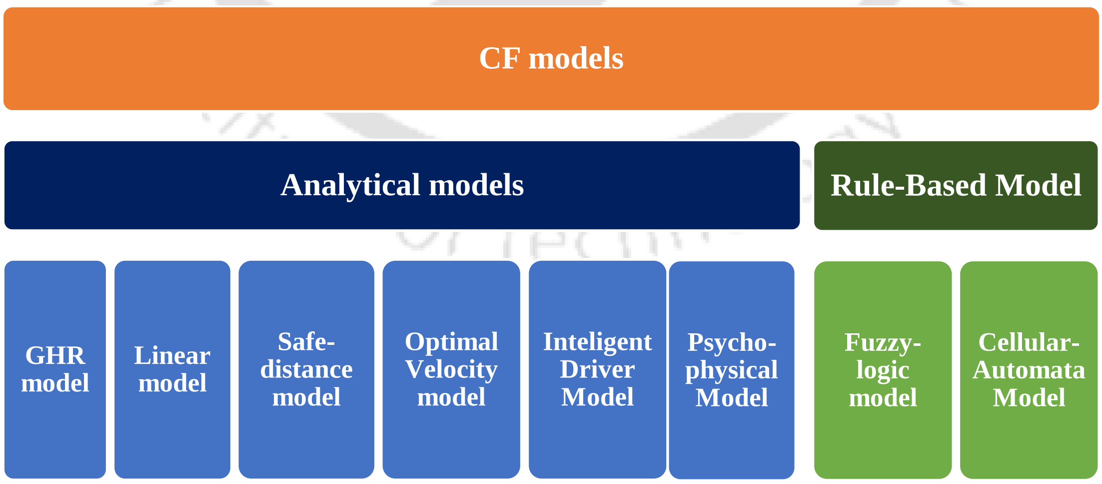


Figure 2-2 Classification of CF models developed for Lane-based traffic condition

2.2.1 GHR Model

Chandler et al. and Kometani and Sasaki in the year 1958, first introduces the GHR (Gazis-Herman-Rothery) model (Chandler et al., 1958 and Kometani & Sasaki, 1958) . The model defines stimulus as the relative speed between the two following vehicles. Negative relative speed, when the leading vehicle travels slower than the following vehicle, triggers a deceleration response. On the contrary, a positive relative speed, when the leading travels faster than the following vehicle, triggers an acceleration response. The magnitudes of the acceleration/deceleration depend on sensitivity term which includes speed and vehicle spacing. The formulation of this model is;

$$a_n = cv_n^m(t)\frac{\Delta v(t-T)}{\Delta x^l(t-T)} \qquad \text{2-1}$$

Where, a_n is acceleration of *(n)th* vehicle at time *t*, v_n is velocity of (n)th vehicle, T is the driver's reaction time, and c, m and l are model calibration parameters. Many authors like Chandler et al. (1958) and Herman & Potts (1959) also proposed the model calibration parameters. Edie (1960), applied this GHR model to match with a new set of macroscopic data. He found that if the incorporation of the term relative speed of vehicles in the microscopic equation can improve the calibration. Afterwards, many other authors calibrated the model with different sets of data in different methods (May & Keller, 1967; Heyes & Ashworth, 1972; Hoefs, 1972; Treiterer & Myers, 1974; Ceder & May, 1976; Aron, 1988; Ozaki, 1993). Subramanian (1996), extended the GHR model in order to capture driver's behavior in both car-following and free-flow regimes. Again, Ahmed (1999) addressed the limitations of the GHR model by incorporating traffic density of traffic into sensitivity term and allowed for non-linearity in the stimulus term. The model is defined as follows;

$$\ddot{x}_{n.t} = \propto \frac{[\dot{x}_{n,t-\xi\Delta t}]^{\beta}}{[x_{n-1,t-\xi\Delta t} - x_{n,t-\xi\Delta t}]^{\gamma}}[K_{n,t-\xi\Delta t}]^{\lambda}[\dot{x}_{n-1,t-\Delta t} - \dot{x}_{n.t-\Delta t}]^{\rho} + \varepsilon_{n,t} \qquad \text{2-2}$$

Where, Δt is the driver reaction time, $\ddot{x}_{n.t}$ is the acceleration/deceleration of a following vehicle *n* at time *t*. $\dot{x}_{n,t-\Delta t}$ is the speed of the following vehicle *n* at time $t-\Delta t$ and $\dot{x}_{n-1,t-\Delta t}$ is the speed of leading vehicle *n-1* at time $t-\Delta t$. $[K_{n.t-\xi\Delta t}]$ is the density of traffic at time $t-\xi\Delta t$, α is the driver sensitivity constant, β is the speed parameter, γ is the spacing parameter, λ is the traffic density parameter and ρ is the relative speed parameter. $\xi \epsilon$ [0, 1] is the parameter of sensitivity time lag, $\varepsilon_{n,t}$ is the error term associated with the *(n)th* vehicle at time *t*. Toledo pointed out the several major limitations in the existing driving behavior models in the year 2003 (Toledo, 2003). The models ignores the effect of lane changing in acceleration and deceleration response behavior. Siuhi (2009) and Aghabayk et al. (2015) also stated the model ignores the difference in vehicle type while assuming the reaction time. They stated that these models does not capture the individual difference between different drivers and different vehicle type. This type of stimulus-response model does not have any acceleration or deceleration limits furthermore has no preferred distance.

2.2.2 Linear Model

Helly (1959), proposed a linear model which specified that acceleration of the following vehicle is related to the relative speeds between leading vehicle and following vehicle, speed of the following vehicle, the deviation of relative spacing and the desired following distance, and driver's reaction time. The formulation of the model is as follows:

$$a_{FV}(t+\tau) = C_1 \Delta v(t) + C_2\left(\Delta x(t) - D_{FV}(t+\tau)\right) \quad \text{...2-3}$$

Where C_1 and C_2 are model calibration parameters and D_{FV} is the desired following distance formulated by $D_{FV}(t+\tau) = \alpha + \beta v_n(t) + \gamma a_{FV}(t)$, α, β *and* γ are the calibration parameters. The model was calibrated on an urban freeway for both congested and uncongested traffic conditions by Hanken & Rockwell (1967) and Rockwell et al. (1968). The simulation results showed that the model could describe low acceleration patterns quite well; however it produced larger headways when the magnitudes of the fluctuations are increased. Bekey et al. (1977) calibrated the model by tracking 125 vehicles over 4 minutes. It was reported that though the model calibrated vehicle trajectories fairly good, it was smooth in the transition region between acceleration and deceleration. It was further suggested that decision of the following driver is based on the behaviour of any two vehicles ahead out of three. Aron (1988), extended the model by splitting his data into two phases of acceleration and deceleration. Xing (1995), developed a model combining both linear and GHR models and calibrated the model. The linear model has advantages over the GHR model in its calibration of the parameters and also the degree of agreement between the various values found for the magnitude of response to Δv. The linear model becomes valid for low acceleration patterns but headways different from reality are obtained for fluctuating acceleration.

2.2.3 Safe-Distance Model

Kometani & Sasaki, (1959), first formulated CF model using physical motion equations, based on safe following distance. According to this model, the collision cannot be avoidable, if the leading vehicle acts uncertainly, and the space headway of subject vehicle would be shorter than the safe distance. The next major development of this model was by Gipps (1981). Gipp's model assumed that the subject vehicle tends to choose a velocity that can avoid rear end collision if leading vehicle performs emergent braking. This model is based on two constraints for the follower's velocity: *(a)* the speed never exceeds its desired speed, and its free acceleration initially increases with speed and then decreases to zero as the vehicle reaches its desired speed, *(b)* the FV must stop safely if the leading vehicle suddenly applies brakes. The speed attained by a vehicle at a given time instant *(t+ τ)* is formulated as

$$v_{FV}(t+\tau) = \min\begin{cases} v_{FV}(t) + 2.5a_{FV}\tau\left(1-\frac{v_{FV}(t)}{V_{FV}}\right)\sqrt{\left(0.025+\frac{v_{FV}(t)}{V_{FV}}\right)} \\ b_{FV}\tau + \sqrt{b_{FV}^2(\tau)^2 - b_{FV}\left[2(x_{LV}(t) - s_{LV} - x_{FV}(t)) - v_{FV}(t)\tau - \frac{v_{LV}^2(t)}{\hat{b}}\right]} \end{cases} \quad \ldots\ldots\ldots \text{2-4}$$

where a_{FV} is the maximum acceleration that the following vehicle (FV) driver wants to accept, b_{FV} is the most severe braking that the FV wants to attempt, s_{LV} is the effective size (physical size + some margin) of the leading vehicle, V_{FV} is the desired speed of the following vehicle, $\hat{b}$ is the estimation of b_{FV} applied by the driver of FV and τ is driver's reaction time. Gipp's model does not involve calibration of parameters, which instead has led to widespread use of this model both in simulation packages and in different research studies (Barcelo, 2002; Liu, 2010; Silcock, 1993); Ciuffo et al., 2008). One of the major reasons behind the popularity of this model is the realistic behaviour either for a pair of vehicles or platoons. Although the base of Gipp's model is reasonable, in reality a driver can not, estimate the safe distance accurately. This type of models does not consider the driver and vehicle heterogeneity.

2.2.4 Optimal Velocity Model

Bando et al. in 1993, proposed an Optimal Velocity (OV) model based on the consideration that each following vehicle moves at his/her own optimum/desired velocity depending on the relative spacing with the leader and the following vehicle controls acceleration in a manner that the desired velocity is maintained according to the motion of leading vehicle (Bando et al., 1995). The acceleration of following vehicle is related to the difference between the optimum velocity and current velocity of following vehicle and is formulated as $a_{FV} = c[V(\Delta x) - v_{FV}]$ where c is the calibration parameter representing the driver's sensitivity to the difference between optimal and current velocities, V is the optimal velocity function of Δx and v_{FV} is the current velocity of following vehicle. A $\tanh(x)$ type curve was adopted as a candidate for V and the velocity function was chosen as$V(\Delta x) = \tanh(\Delta x - 2) + \tanh(2)$. The potential velocity function was modified for the convenience to fit the function with observed data (Bando et al., 1995). Helbing & Tilch, (1998) calibrated OVM with the empirical data but the model produced too high accelerations and unrealistic deceleration. Therefore they proposed a generalized force model (GFM) which reached better agreement with field data than OVM. But GFM does not behave well in all aspects because it does not consider the impact of positive Δv on traffic dynamics. Taking the positive Δv factor into account. Jiang et al. (2001) developed the OVM by taking both positive and negative velocity differences into account and adding an additional term $\lambda\Delta v$ into the car-following equation, λ is sensitivity constant and they called it a Full Velocity Difference Model (FVDM). In another study Lenz et al. (1999) incorporated multi-anticipative driving behaviour into the model to predict traffic flow on highways.

The OVM has recently gained more attention due to its simple differential equation formulation and the single variable OV function. The model has also been developed for non-lane based traffic by considering lateral separation effects and TTC variable. The recent modifications in the OVM are due to its simplicity in understanding the dynamics of the evolution of traffic congestion, stop and go waves, etc.

Several car following models considering with more than leading car information provided by ITS has been proposed an extended CF model with the contemplation of a random number of vehicles ahead on a single lane highway, resembling to the multi anticipative car following model (Nagtani, 1999; Hasede et al., 2003; Ge et al., 2004; Li & Zhang, 2013) . In order to improve the OVM and considering ITS applications, two velocity difference model (TVDM) was developed by (Ge, et al., 2008), and the formulation of the model is;

$$\ddot{x}_n(t) = a[V((\Delta x)) - \dot{x}_n(t)] + \lambda G(\Delta v_n, \Delta v_{n+1}) \quad \text{......2-5}$$

G (.) is a generic monotonically increasing function and is $G(\Delta v_n, \Delta v_{n+1}) = p\Delta v_n + (1-p) \Delta v_{n+1}$ where p is the weighting value. *P* denotes the impact of vehicle the ahead on the subject vehicle motion and it reduces gradually as the relative distance between the subject vehicle and leading vehicle decreases. Several modifications in the FVD model were also conducted by various researchers (Jing et al., 2011; Li et al., 2011; Peng et al., 2011). In a later date the FVD, model was extended by including driver's reaction time delay into the equation to understand the mechanism of traffic jams because driver's reaction time may lead to unstable traffic flow (Xu, 2015 and Zhou et al., 2014).

2.2.5 Intelligent Driver Model

Treiber et al. (2000a), developed a continuous microscopic single lane model known as Intelligent Driver Model (IDM) for describing the congested traffic forming near road in-homogeneities on German freeways. The model combines both free-road acceleration and deceleration strategies of the following vehicle and is a function of the velocity, gap and the velocity difference to the preceding vehicle. The acceleration function is given by;

$$a_n = a_{max}\left(1 - \left(\frac{v_n}{v_n^0}\right)^{\delta} - \left(\frac{s^*(v_n, \Delta v_n)}{s_n}\right)^2\right) \quad \text{2-6}$$

Where a_{max} is the maximum acceleration of vehicle *n*, v_n^0 is the desired velocity of *n*, δ is a parameter of the model (fixed as 4) which is used to characterize the decrease in maximum acceleration of a vehicle with increase in operating speed, s_n is the actual gap available between the front bumper of the following vehicle and the rear bumper of the leading vehicle, s^* is the desired minimum gap. In this model, the free road acceleration term is defined by, $a_{max}\left(1 - \left(\frac{v_n}{v_n^0}\right)^{\delta}\right)$ whilst the deceleration term is $-a_{max}\left(\left(\frac{s^*(v_n, \Delta v_n)}{s_n}\right)^2\right)$. When a vehicle *n* comes too close to the preceding vehicle, the tendency to decelerate will depend upon the actual gap available and the desired minimum gap. The desired minimum gap is a function of v_n *and* Δv_n and is given by;

$$s^*(v_n, \Delta v_n) = s_n^0 + T_n v_n - \frac{v_n \Delta v_n}{2\sqrt{a_n b_n}} \quad \text{2-7}$$

Where, b_n is the desired deceleration of the vehicle *n*, s_n^0 is the jam distance of the vehicle *n* and T_n is the safety gap of the vehicle *n*. The validation of the model was done on a Dutch freeway for different percentage of cars and trucks (Treiber et al., 2000b). Again Treiber & Kesting (2013) made an improvement in the model considering the situation that when the desired space gap exceeds the actual gap in the high speed range, drivers tend to be more defensive. Some researchers modified the desired time gap T by adding some additional term and considering it as a stochastic quantity changing its value at each simulation step rather than a constant value (Jiang et al., 2014; Derbel et al., 2012). Although this model has been primarily used for single lane traffic with road inhomogeneity, the applicability of the model for multilane traffic still needs further exploration. The model does not consider risk explicitly, though some aspects are handled in the deceleration factor and time gap implicitly.

2.2.6 Psychophysical Model (Action-Point Model)

The psychophysical car-following model was introduced by Michaels (1963), who assumed that drivers could sense the changes in the relative speeds of the leading and following vehicles by analysing the change in apparent size of the leading vehicles and react according to the visual angle changes subtended by the vehicle ahead. To quantify the threshold requirements, Evans & Rothery (1973) investigated a perception based experiment. The visual angle models consider the safe following distance to increase with the increasing width of leading vehicle (Ferrari, 1989; Yousif & Al-Obaedi, 2011) . Many other studies were carried out to investigate the thresholds and the following vehicle acceleration (Wiedemann, 1974; Lee, 1976; (Bekey et al., 1977; Wiedemann & Schwerdtfeger, 1987; Wiedemann & Reiter, 1992; Reiter, 1994; Krauss et al., 1999). Wiedemann (1974), considered four car-following regimes including free driving, closing process, following process and emergency braking. These regimes have different perceptual thresholds with 15 calibration parameters. The driving behaviour in the four regimes are listed as follows;

i. Free driving: A vehicle accelerates to reach its desired speed when it travels uninfluenced of the surrounding traffic.
ii. Closing in: The point where the FV approaches a slower vehicle, the driver decelerates.
iii. Following regime: Relative speed, minimum/maximum following distances, a point describing the driver approaching a slower vehicle constitute the thresholds. A FV decelerates when he approaches a slower vehicle, and following distance is minimum whereas he accelerates if relative speed is high and the following distance is maximum.
iv. Emergency regime: When the front to rear distance is smaller than the minimum desired distance at low speed differences, the driver decelerates at maximum braking rate

The psychophysical model addresses two unrealistic inferences of the GHR model: (i) FV follow their LV even when the spacing is large, and they response to small changes in the stimuli, (ii) although the magnitude of the vehicle's acceleration/deceleration could be estimated, calibration of the parameters has been less successful. This approach is undoubtedly better than other models as it can coherently describe real driving conditions, but calibration of the parameters is more difficult.

2.2.7 Fuzzy logic Model

In the fuzzy logic model, the driver is conceptualised as a fuzzy controller with the action of the LV as an input and the decision made through a sequence of thinking as an output. The first fuzzy model was applied by Kikuchi & Chakroborty (1992) with the fuzzy inputs as relative spacing, relative speed and the acceleration of the LV. Many other car-following models have also been developed based on the fuzzy logic rules (Chakraborty & Kikuchi, 1999; Chakroborty & Kikuchi, 2003; Gao et al., 2008; Hatipkarasulu & Wolshon, 2003; McDonald et al., 1997; Zheng & McDonald, 2005). However, the difficulty with these models is the definition of the fuzzy sets/rules and the calibration of the membership functions. Unless the drivers' perception is not applied to the model properly, the model may lead to unrealistic results. Moreover, none of the models incorporated the vehicle heterogeneity in car-following behaviour.

2.2.8 Cellular Automata (CA) model

The CA model was first proposed by Nagel & Schrecknberg (1992), for freeway traffic to replicate the basic features of traffic flows, considering spacing, speed, acceleration and time as distinct variables. CA considers time and space as discrete variables, and a road lane is represented by a number of cells of equal sizes (typically 7.5 m long) which can either be empty or occupied by at least one vehicle. The longitudinal movement of vehicles at each time step is described by applying acceleration, braking, randomization and driving rules for all vehicles. The single lane model is however inadequate for realistic modelling purposes. Thereafter models for two lane traffic were introduced by Nagel et al. (1998). A considerable number of researches have been conducted by modifying NaSch models to account for different road sections (Chowdhury et al., 1997; Knopse W. et al., 2002; Jiang & Wu, 2002; Nagel et al., 2003; Bham & Benekohal, 2004). CA models use a minimal set of driving rules which makes it computationally efficient and hence it can be used for large scale dynamic traffic modelling applications. But the discretization of the cells of constant size causes vehicles to update speed, acceleration/deceleration, gap requirements and position in multiples of cell size. The major disadvantage of the model includes loss of detail because of the discretization. Coarser cell sizes may not represent all vehicle types however smaller cell sizes may increase computational power. More importantly, the constant cell size makes it difficult to account for the variability in gap requirements with vehicle speeds.

2.2.9 Summary

A great deal of literature existing in the field of traffic flow modelling mainly addresses the vehicle following behaviour for homogeneous conditions in lane-based traffic stream where the subject vehicle interacts only longitudinally with the vehicle ahead. Analytical models have been considered to be more flexible than the rule-based models because those models do not involve a complex set of rules and the dynamic behaviour of the subject vehicles can be predicted just on the basis of a set of mathematical equations which is easier to comprehend than the rule based models. However several mathematical formulations for the analytical models have been developed by many researchers. Most of the analytical models like GHR model, linear model, optimal velocity, Intelligent Driver Model (IDM) and psychophysical models mainly describe the dynamics of the subject vehicle in terms of acceleration or deceleration. However, the safe distance models like the Gipps model describes the vehicular dynamics of the subject vehicle in terms of speed. This model is very popular because of its ease in calibrating the parameters. Summary of the capabilities and issues of all the CF models developed for 1D traffic is described briefly in Table 2.1. All the models have been primarily developed for homogeneous conditions comprising of only cars in the traffic stream. Though the microscopic models are a better alternate for describing the mixed traffic stream, it requires more intensive and detailed parametric evaluation, and understanding is required to develop an efficient behavioural model. Many of these models made the simple assumptions of the homogeneity of vehicle classes and drivers while developing the models. To simplify the model's different models have a different assumption like, (CF model only reacts according to the vehicle in front, safe distance approach reacts according to the leading and following vehicle distance, and also in most of the lane change models the driver respond only to the vehicles in their immediate vicinity, the distance between leader and follower vehicle is based on the reaction time of the driver and the speed of following vehicle, etc.). No single model is found, which can consider all the above mentioned assumptions, which are taken for different models. Hence, these models cannot be directly used in mixed traffic conditions, unless certain modifications are made.

Table 2.1 Summary of Capabilities and Issues of all existing CF models developed for 1D Traffic

Model Names	Capabilities	Issues
GHR model	-Simple to understand and use. -Considers reaction time.	-No conclusive findings for the calibrated parameters. -No change in relative positions for zero relative speed
Linear model	-Calibrated parameters yield realistic results than GHR model. -Provides good fit to observed trajectories.	-Model is valid for describing only low acceleration patterns
Safe distance model	-Easy to use as it excludes calibration of parameters. -Considers reaction time in Gipp's model.	-Drivers do not always keep the safe-distance
Optimal velocity model	-Reasonable theory -Simple to understand the dynamics of traffic congestion, stop-go waves, etc.	-Validation of the model has not been done.
Intelligent Driver Model	-Suitable for traffic with road inhomogeneity -Replicates traffic quite well, validation still needs further consideration.	-Does not consider risk factor explicitly
Psychophysical model	-Driver behaviour and acceleration/ deceleration can be estimated realistically.	-Difficult to Calibrate perceptual threshold parameters -Difficult to apply the model without computers. -Different thresholds required for different vehicles.
Fuzzy-logic	-Considers imprecise human perception.	-Difficulties in the validation of membership functions. -Existing models do not consider different vehicles -Difficulties in determining fuzzy rules.
Cellular Automata Model	-Easy to implement -Less computational effort	-Vehicle sizes, speeds, acceleration are given in multiple cells. -Loss of detail with large cell size -More computational intensive with smaller sizes.

2.3 Two-Dimensional Microscopic Models

The developed car-following models for homogeneous conditions cannot be directly applied to describe non-lane-based traffic streams. In order to model the staggered car-following behaviour in non-lane based traffic, a lot of effort has been made by the researchers to modify the existing car-following models. Some studies have also considered heterogeneity in vehicles.

2.3.1 Modified GHR Approach

Siuhi & Kaseko (2016), incorporated vehicle mix in stimulus-response (GHR) car-following model. Two separate models were estimated for acceleration and deceleration responses for different vehicle pairs including cars following trucks, car following trucks and trucks following cars on a single lane. In mixed traffic streams where multiple leaders (direct front, left the front and right front) exist for a single follower, the FV driver is subjected to multiple sources for stimulus and reacts only to the stimulus of the governing leader. The identification of governing leader vehicle is studied by Choudhury & Islam (2016) using discrete choice approach, and the acceleration component for the leader uses the GM model frame work.

2.3.2 Modified Safe-Distance Approach

With a view to incorporate the lateral separation effects in car-following models, Gunay (2007) considered the concept of rear-end collision with the LV modified the Gipp's car-following model, where the maximum allowed speed of FV at the end of reaction time is resolved by confining the two factors: (1) Maximum Escape Speed (MES)- the speed at which FV decelerates at the time of passing with maximum speed allowed through the escape corridor, and (2) speed which permits FV sufficient time to veer laterally (t_{veer}) so as to avoid a rear-end collision. The simulation briefs the speed of the following vehicle according to Equation 2-8 or Equation 2-9, whichever regulates the circumstance.

$$v_n(t+\tau) \leq b_n\tau + \sqrt{(b_n\tau)^2 + 2b_n\left\{v_n(t)\frac{\tau}{2} + \frac{MES^2}{2b_n} + \frac{v_{n-1}^2(t)}{2b_{n-1}} + y_n(t) - y_{n-1}(t) + s_{n-1}\right\}} \qquad \text{2-8}$$

$$v_n(t+\tau) \leq 2\frac{y_{n-1}(rest) - y_n(t) - 0.5\tau v_n(t) - \frac{t_{veer}}{2}MES - d_{body}}{t_{veer}+\tau} \qquad \text{2-9}$$

where b_n,b_{n-1} are the deceleration rates of the FV and LV respectively, d_{react} is the distance travelled during the reaction time, d_{veer} is the distance travelled during veering manoeuvre. The development of this model is a potential breakthrough of all the pre-existing car-following models, essentially for non-lane-based disciplined traffic. The validation of the model for describing the speed, flow and density diagrams of a 3-lane carriageway in Istanbul was extended for a simulation time of 60 min considering light and heavy vehicles (Gunay, 2009). A similar type of study was conducted by Xu (2015) giving full considerations to the effect of FC on car-following behaviour. Ravishankar & Mathew (2011), modified the Gipp's model to incorporate vehicle-type dependent parameters for different combinations of cars, trucks, motorised three-wheelers (3W) and buses on a single lane traffic. Lenorzer et al. (2015), modelled the mixed traffic conditions of the entrance sections of Cadbury junction, Thane at evening peak hours by modifying the Gipp's car-following model. They modified the Gipps model by taking the reaction time as the minimum of reaction time and time required for swerving. The effect of lateral clearance into the model has also been considered by Gunay (2007). The model was then made to run on a software package AIMSUN and the results on traffic counts indicated that there was less variation in the simulated and the observed counts (less than 5%).

2.3.3 Modified Optimal Velocity Approach

Jin et al. (2010), modified the full velocity difference (FVD) model by considering lateral separation characteristics between LV and the FV on a single lane and proposed a non-lane based full velocity difference car-following model.

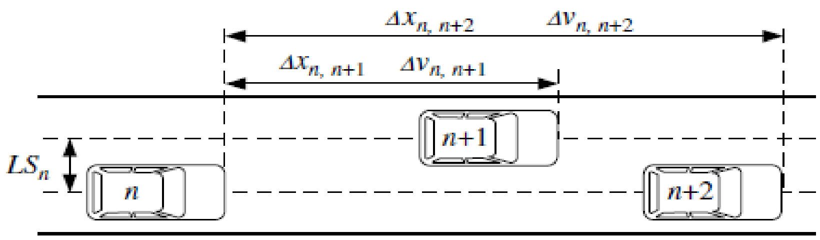


Figure 2-3 Staggered pattern of vehicles (direct front and left front vehicles), Jin et al. (2010)

The dynamics of FV is a function of lateral separation effects of its leader and is formulated as follows;

$$a_n(t) = \alpha\{V[\Delta x_{n,n+1}(t), \Delta x_{n,n+2}(t)] - v_n(t)\} + \kappa G[\Delta x_{n,n+1}(t), \Delta x_{n,n+2}(t)] \ldots\ldots\ldots \quad 2\text{-}10$$

Where, $V[\Delta x_{n,n+1}(t), \Delta x_{n,n+2}(t)] = V[(1-p_n)\Delta x_{n,n+1}(t) + p_n \Delta x_{n,n+2}(t)]$

$$G[\Delta x_{n,n+1}(t), \Delta x_{n,n+2}(t)] = [(1-p_n)\Delta x_{n,n+1}(t) + p_n \Delta x_{n,n+2}(t)]$$

$$V[\Delta x] = 0.5 v_{max}[\tanh(\Delta x - h_c) + \tanh(h_c)]$$

Where $\alpha = {}^{1}/_{\tau}$ is the sensitivity coefficient to the difference between optimal and current velocities of a driver, $\kappa = {}^{\lambda}/_{\tau}$ is the sensitivity coefficient of response to the stimulus G (.). The lateral separation effect of the leader and follower is incorporated in $p_n = \frac{LS_n}{LS_{max}}$; LS_n is the lateral separation distance between car *n* and *n+1,* and LS_{max} is the maximum lateral separation distance that the leading car has no impact on the following car. $p_n = 0$ Corresponds to the FVD model where *n* only follows *n+1*; whereas $p_n = 1$ indicates that *n* follows *n+2* as *n+1* is on another lane. Again (Jin, et al., 2012) developed a staggered car-following model using time to collision (TTC) variable into the optimal velocity model to describe the lateral separation effects of a pair of consecutive vehicles maintaining the same lateral distance and moving on a steady state on a single lane highway. Similar work was carried out by Zheng et al. (2012) to study the impact of lateral friction on 2-lane unidirectional traffic flow. Visual angle is considered as one type of stimulus of a following driver to reflect the imperfect perception of distance, speed and acceleration. The FVD model is modified by replacing the original headway distance and relative velocity term with the visual angles and their changing rates respectively. The Full Velocity Difference (FVD) model was extended by considering the effects of two-sided lateral gaps on a road without lane disciplined traffic (Jin et al., 2010; Li et al., 2015). The model however does not consider the lateral separation of the direct leader with respect to the following vehicle. He et al. (2015), extended the optimal velocity model by taking into consideration the effects of lateral separation (LS) and overtaking expectation through the escape corridor (Gunay, 2007). The study mainly focussed on the effect of overtaking expectation on car-following behaviour. It does not necessarily guarantee the overtaking manoeuvre. An overtaking parameter is introduced considering the width of the escape corridor and the width of the FV expecting to overtake. The new model is developed with the LS parameter and the overtaking parameter. Calibration of the model is done using the trajectory data set from NGSIM (a program funded by the Federal Highway Administration of USA) using Genetic Algorithm approach. Summary of all modified models for 2D traffic is listed below in the following Table 2.2.

2.3.4 Modified Cellular Automata Approach

Motor bikers often travel in an erratic manner, the manoeuvrability of which has been studied by Lan & Chang (2003). They developed a particle-hopping model based on pre-assigned cellular-automata (CA) rules in a mixed traffic flow with only cars and motorbikes. To accommodate different vehicle types, Lan & Hsu (2005) first proposed the generalized definitions for occupancy, flow and speed, in a spatiotemporal sense to precisely capture the collective behaviour of traffic features (Lan & Hsu, 2006). A similar study on a single-lane traffic was conducted using cellular automaton model to simulate mixed traffic with motorcycles (Meng et al., 2007). Lan et al. (2009), introduced the concept of limited deceleration capability of vehicles into their CA simulations which were seldom used in conventional CA models. Again Mallikarjuna & Rao (2009) extended the CA model by modifying the acceleration value as a function of vehicle type and vehicle speed in order to incorporate heterogeneous traffic flow characteristics. Based on the refined CA model, a sophisticated CA model is proposed by Lan et al. (2009) to elucidate the erratic motorcycle behaviours in mixed traffic conditions (Lan et al., 2010).

2.3.5 Other Modelling Approaches Developed for 2D Traffic

The models built for lane based homogeneous traffic would not be able to replicate the Indian heterogeneous and no-lane based traffic. In mixed traffic, the drivers continuously look for the opportunities to filter through the available gaps by maintaining a safe distance with the surrounding vehicles. Many attempts were made in 1980’s to develop heterogeneous traffic simulation models (Palaniswamy et al., 1985; Ramanayya, 1988), by combining the car-following and the lane changing models together. Palaniswamy et al. (1985), modified and developed a discrete event-based simulation model, based on Swedish Road Traffic Simulation Model (SWERTS). They have incorporated different road conditions, different shoulder conditions, terrain, power-to-mass ratio, overtaking gap acceptance, passing speed, etc. Four types of roads were considered in this study (single lane bidirectional traffic with 3.75 m width, intermediate lane road with 5.50 m width, 2-lane road with 7.5 m width and 4-lane road). Ramanayya (1988), modelled mixed traffic moving on one lane roads using car-following concept. He has added overtaking criteria and lateral clearance adequacy in the developed model.

Chakroborty et al. (2004), attempted to develop a comprehensive microscopic model in various driving scenarios (free flow to forced flow conditions) in two-way traffic by using Potential field approach. Two response models are presented (i) Steering Response Model (SRM) to predict the steering angles over time, (ii) Acceleration Response Model (ARM) to predict the acceleration/deceleration rates in a given traffic scenario over time. One of the key feature of this model is the potentials on the road are defined by the potentials originated by obstacles and the road features. The potential is described through the potential field function for that obstacle or road features through which it originated. Though this type of model generation was an initial attempt, driver behaviour in near-capacity or stop-and-go conditions has not been studied due to less observation on driver behaviour in such conditions.

Again Arasan & Koshy (2005) developed a simulation model for representing heterogeneous traffic flow, based on the interval scanning technique with a fixed time increment. Dey et al. (2008) also developed a simulation program for modelling of 2-lane traffic flow.

Even though these modelling approaches made an effort to model specific vehicle-type dependent behaviour in traffic simulation, the impact of vehicle-type on lane changing and non-lane based movement of vehicles also needs to be considered. CUTSiM (Comprehensive Unidirectional Traffic Simulation Model) was developed as a comprehensive microscopic model in Indian perspective (Maurya, 2007). The lateral control model in CUTSiM describes how a driver selects a suitable steering angle based on the hypothesized best path. The real world traffic weaving manoeuvre or steering angle is not examined on the field. The impact of road features such as shoulder and median width, horizontal and vertical alignment, etc. on driver behaviour needs to be studied. Full-fledged Comprehensive simulation model considering the complex behaviour of vehicle interaction in non-lane based movement, need to be developed and a large scale validation with field data is required.

Mathew et al. (2013), proposed a strip-based approach for simulation of mixed traffic conditions using SiMTraM (Simulation of Mixed Traffic Mobility), implemented on a traditional lane based simulator, SUMO. The road is divided into small strips, which allows continuous lateral movement rather than conventional discrete lane changing. For a lateral movement that calculated a factor called 'benefit' as the difference between the safe speeds on the neighbouring and on the current strips. It is calculated using the CF model and normalized by maximum velocity. A positive 'benefit' leads to lateral movement and vice-versa. They also observed that reduction of strip width increases the throughput; indicates better utilization of empty space. But this model is unable to model the behaviour of 2W which is common in no-lane based traffic (Lan et al., 2010).

2.3.6 Summary

Several modifications in the existing vehicle-following models have been made by different researchers by incorporating vehicle heterogeneity and lateral separation effects. More studies have been conducted by modifying GHR model and optimal velocity model. Researchers have incorporated vehicle heterogeneity (trucks, cars) and identification of governing leader using the GHR model framework. In a similar manner, some of the researchers have considered the effects of lateral separation into optimal velocity model. This model is only suitable to capture the dynamics of the evolution of traffic congestion, stop and go waves, etc. but it cannot be used to describe uninterrupted traffic. Although CA model can provide a better representation of mixed traffic and easier to implement, the main disadvantage of the model is a loss of detail because of the discretisation. A major contribution in describing the mixed traffic stream was made by Gunay (2007), by considering lateral discomfort in the Gipps car-following model. Though the variability in road geometry as well as the effect or road edge in considered by Chakroborty et al. (2004), the variability in edge conditions are not included. The available CA models do not mimic the dynamic behaviour of the vehicles on the real world traffic stream. Hence, it results in misestimating the microscopic behaviours of drivers observed in the mixed traffic stream.

In the case of Indian traffic conditions, the roads are having different types of geometric features with various types of edge conditions. Most of these models did not represent the driving behaviour of the mixed traffic stream. This is due to the absence of proper comprehension of drivers' behaviour in mixed no-lane based traffic streams. A comprehensive and complete model still need to be developed. The performance of microscopic model is mainly depends on accuracy of the data obtained from the real world traffic stream (field study). Due to weak lane discipline, vehicles manoeuvring in mixed traffic exhibit complex driving patterns of maintaining shorter headways, tailgating, swerving and filtering, etc. This complex driving behaviour can be modelled by the data collected from the real traffic stream. It is always a challenge for the traffic modellers to use an adequate number of parameters for describing the driving behaviour precisely with simplifying the implementation and calibration process. Hence a brief study on the real traffic data of heterogeneous no-lane based traffic is important.

Table 2.2 Summary on the modification made in basic CF models for mixed traffic conditions

Basic CF model	Vehicle types	Type of study	Parameters added	Data modelled	Calibration	Simulation platform	Final model representation	Reference
GHR Model	C, T	Single lane car-following model considering acceleration and deceleration responses	Different leader-follower pairs were considered: C-C, C-T, T-C	NGSIM 45-min data	Non-linear regression	-	Parameters for space headway, speed, and relative speed were estimated.	(Siuhi & Kaseko, 2016)
GHR Model	HMV, LMV, 2W	Investigating governing leader from • Direct front vehicle • Left front vehicle • Right front vehicle	• Choice of governing leader using discrete choice model (space headway, lateral overlap, subject vehicle type, relative speed) • 9 vehicle-pair combinations were considered to determine the deceleration/acceleration responses	90-min trajectory data from Dhaka	Broyden–Fletcher–Goldfarb–Shanno (BFGS) an algorithm using Oxmetrics 6	-	Deceleration functions for different vehicle pairs were estimated; Acceleration function for all vehicles	(Choudhury & Islam, 2016)
Safe distance Model	Cars	Staggered car-following One right front leader	• LS, FC • Maximum Escape speed (speed required for passing through the escape corridor) • Veering distance	Multilane highway in Istanbul, Turkey	Assumptions of Gipp's model	C++	Space-time trajectories, Gunay (2007) Speed, Flow, Density diagrams (Gunay, 2009)	(Gunay, 2007) (Gunay, 2009)
Safe distance Model	Cars	Staggered car-following • Right front vehicle • Left front vehicle	• FC is proportional to escape speed • FC is inversely related to following time and minimum following safe distance. • CS separation with the leader	2-lane	Assumptions of Gipp's model	Matlab	Space-time diagrams for different FC, CS.	(Xu, 2015)
Safe distance Model	C, 3W, T, B	Staggered car-following considering swerving manoeuvre (when duration of swerving is less than the reaction time)	• Lateral clearances of LV and FV • Maximum lateral speed of FV	Near Cadbury Junction, Thane at evening peak hour	Assumptions of Gipp's model	AIMSUN simulator	15-minutes traffic counts were compared	(Lenorzer et al., 2015)
Safe distance Model	C, 3W, T, B	Different leader-follower vehicle types in Gipp's model	• Reaction time, deceleration, maximum acceleration, desired speed of FV • Assumed deceleration, effective size of LV • Sensitivity-gap maintaining behaviour of different vehicle pairs	Single lane, NGSIM data and Mumbai data	Genetic Algorithm	C	Simulated speed-flow diagrams for different vehicle pairs	(Ravishankar & Mathew, 2011)

Basic CF model	Vehicle types	Type of study	Parameters added	Data modelled	Calibration	Simulation platform	Final model representation	Reference
Optimal velocity Model	Cars	Staggered car-following Two leaders : • Direct front vehicle • Left front	• LS effect between the leader and follower. • Visual angles	Single lane	Trial and error	Numerical simulation	Space-time trajectories Headway and velocity variations for different lateral separation parameter	(Jin et al., 2010) (Zheng et al., 2012)
		Staggered car-following One Right front leader	Time-to-collision variable using visual angle and visual gap angle.				Headway and speed evolution with time	(Jin et al., 2012)
		Staggered car-following • Direct front • Left front • Right front	• Two sided LS effects • LS_n for the right front and left front vehicles are equal. • p_n = 0, 0.5, 1 are taken				Space headway of cars at different time steps	(Li et al., 2015)
		Staggered car-following Two leaders : • Direct front vehicle Left front vehicle	• LS between the subject and the leader • Escape corridor	NGSIM 25-min data	Genetic Algorithm		Comparison of Gap, velocity variations with time for proposed model, OVM and IDM	(He et al., 2015)

Note: **C**: Cars, **2W**: Motorized two-wheelers, **3W**: Motorized three-wheelers, **T**: Trucks, **B**: Buses**; HMV**: Heavy Motor Vehicles, **LMV**: Light Motor Vehicles; **LS**: Lateral Separation, **FC**: Frictional Clearance, **CS**: Centreline Separation; **NLBCF**: Non-Lane Based Car-Following model, **FVD**: Full Velocity Difference model, **OVM:** Optimal Velocity Model; **IDM**: Intelligent Driver Model; **NGSIM**: Next Generation Simulation (US Highway 101 dataset); **AIMSUN**: Transportation Simulation Software

2.4 Studies on Lane Changing Models

Lane changing models describe the lateral movement of drivers. This behaviour consists of two steps, Lane selection model and gap acceptance model respectively.

2.4.1 Lane Selection Model

Lane selection models can broadly divided into rule based models and fuzzy logic models. In case of rule based models the drivers select a lane according to the prioritized rules. Most of the existing simulators (VISSIM, PARAMICS, and AIMSUN) employ rule based sequential process to illustrate the lane changing manoeuvre. Oketch (2000), first used the fuzzy logic rules for lane selection behaviour of vehicles. Hidas (2002) and Wei et al. (2000) also used the fuzzy rules to describe the lane selection behaviour. Yang (1997), Ahmed (1999) and Toledo (2003) described the lane changing behaviour as a sequence of decision making process. However the difficulty with these models is the definition of the fuzzy sets/rules and the calibration of the membership functions. Unless the drivers' perception are not applied into the model properly, the model may lead to unrealistic results. Moreover none of the models incorporated the vehicle heterogeneity in car-following behaviour. In their approach, lane changing was considered as sequence of decision making process. Following are the various issues of the rule based and fuzzy logic models during lane selection in mixed traffic stream.

1. There is no solid framework for calibrating the model parameters and it is difficult to capture the interaction between the rules. Interaction between different rules plays a very important role in capturing the mixed traffic drivers' lateral movement behaviour.
2. It is difficult while abstracting the fuzzy rules in mixed traffic as numerous fuzzy rules have to be abstracted if all peculiar behaviour exhibited by drivers during modelling their lateral movements.

2.4.2 Gap Acceptance Model

After selecting a lane, drivers search for an acceptable gap to execute their lateral movements. The probability of either accepting or rejecting a gap of particular size under a specific set of prevailing traffic condition is calculated by the gap acceptance models. Basic gap acceptance models were formulated as a binary choice problem. The basic assumption behind these models is, driver accept longitudinal gaps available in the target lane which are equal to or greater than the critical gap. The critical gap is the minimum gap that a driver is ready to accept. Many authors have assumed the various different distributions like exponential, lognormal, normal, etc. for the critical gap (Herman & Weiss, 1961; Drew et al., 1967; Miller, 1972). Gipps (1986) used the deceleration rate of lag vehicle as the threshold for gap acceptance. Madanat et al. (1994) used the queuing time to investigate the effects of impatience on gap acceptance behaviour. The important issues to consider while applying traditional gap acceptance models in mixed traffic conditions are;

1. Requirement of lateral width of a gap are different for drivers in mixed traffic conditions.
2. Gap acceptance cannot be dealt as a separate step in modelling lateral movement behaviour of drivers in mixed traffic as they tend to perceive both speed gain and space gap simultaneously, before making a lane change decision.

2.5 Parameters Used in Existing Microscopic Models

Though the microscopic modelling is a better approach for describing mixed traffic streams, it requires more intensive and detailed data to understand the behaviour exhibited by individual drivers under different traffic conditions and to develop efficient behavioural models. The performance of a microscopic model highly depends on the accuracy of data obtained from the field traffic. The peculiar driving behaviour of 2D traffic (no-lane based mixed traffic i.e. lateral/longitudinal movement) can be modelled by collecting empirical data from real traffic streams. The factors that influence drivers' perception and decision making are mainly related to traffic characteristics and in their immediate neighbourhood.

2.5.1 Parameters used in Existing Modified 1D Models (CF/Lane Changing)

In the above sections a brief review on the driver behavioural models developed for both lane-based and non-lane based traffic conditions are discussed briefly. After understanding the advantages and disadvantages of microscopic approach for 1D traffic, the data/parameters required for developing them are identified. Table 2.3 describes the parameters used in the existing microscopic models developed for 1D traffic and later modified for 2D traffic by different authors.

Table 2.3 Microscopic Parameters used in Different Models

	Δ_v	Δ_d	*A/D*	T_r	D_r	T_v	D_v	*TTC*	Lat_d	Gap_{cr}	V_h	Micro-Simulation Models
Stimulus-Response	*	*	*	*								
Collision-Avoidance	*	*	*	*	*						*	AIMSUN, CORSIM, SIMTRAFFIC,
Optimal-Velocity	*	*	*	*	*	*	*	*	*			
Psychophysical	*	*	*	*	*						*	PARAMICS, VISSIM
Lane Changing	*	*	*	*					*	*		

Δ_v-Relative speed, Δ_d-Relative Spacing, A/D-Longitudinal Acceleration/Deceleration of each vehicles, T_r-Reaction Time, D_v-Distance travelled during reaction time, TTC-Time To Collision, Lat_d-Lateral Spacing, Gap_{cr}-Critical Gap between two vehicles for lane change, V_h-Vehicle Heterogeniety

The parameters mentioned in Table 2.3, describes the car-following and lane changing behaviour of the vehicles on the traffic stream. The relative spacing (Δ_v), Relative spacing (Δ_d), Acceleration/Deceleration, Reaction time (T_r), Distance travelled during reaction time (D_r) and Time To Collision (TTC), etc. mainly used to describe the vehicle-following or the longitudinal manoeuvre of the vehicles on a traffic stream in micro level. Several modifications in the existing vehicle-following models have been made by different researchers by incorporating vehicle heterogeneity and lateral separation effects like the Veering Distance (D_v), Time taken to veer (T_v), lateral distance between vehicles, etc. to describe the overtaking or passing manoeuvre of vehicles. Also the lane changing manoeuvre of vehicles are incorporated by the researchers in the basic car-following models to describe the lateral behaviour of vehicles. Most of the existing lane changing models are rule-based models. In case of mixed traffic, drivers exploit their manoeuvring capability depending on the type of vehicle and take advantage of weak lane discipline. This peculiar behaviour of vehicles cannot be modelled by the existing models. Hence, to model such traffic condition, a detailed micro-level knowledge of the existing traffic stream and the behaviour of vehicles while manoeuvring is needed.

2.5.2 Parameters Used in 2D Models Developed by different Authors

Keeping in view of the Indian heterogeneous and no lane disciplined traffic behaviour. Different authors have tried to develop the driver behaviour model to describe such traffic stream. Table 2.4 describes the different criteria or parameters used by various authors to describe such complex traffic behaviour other than the parameters used for 1D traffic.

Table 2.4 Different traffic stream criteria implemented by different authors to represent no-lane based heterogeneous traffic

Authors	Road Type	Shoulder type	Median Type	Vehicle Type	Over Taking Criteria	Lateral Clearance / Vehicles Placement	Passing speed	Steering Angle
Palanswamy et al., (1985)	*	*	*	*			*	
Ramanayya, (1988)	*	*	*	*	*	*	*	
Chakroborty et al., (2004)	*	*	*	*				*
Arasan and Koshy, (2005)				*	*	*	*	
Dey et al., (2008)	*			*	*	*	*	
Maurya, (2007)	*	*	*	*	*	*	*	*
Mathew et al., (2013)	*			*	*	*		

From the Table 2.4, it can be observed that the overtaking, lane changing and the vehicle heterogeneity are also introduced to the basic models. However, the real world traffic swerving or weaving manoeuvre of the vehicles or steering angle are not examined on field (Maurya, 2007). Mathew et al., (2013), used very fine strips to identify the lateral movement of the vehicles. It does not include the behaviour of 2Ws from real traffic. The congested traffic behaviour are not studied by various authors. A large scale validation of these models based on the field data is needed. Though the variability in road geometry as well as the effect or road edge is considered by Chakroborty et al. (2004), the impact of variability in edge conditions on the driving behaviour are not included in the model.

2.5.3 Parameters required to Model Indian Mixed Traffic

In case of Indian traffic conditions, the roads are having different types of geometric features with various types of edge conditions. The heterogeneity of vehicles in Indian traffic leads to a complex traffic behaviour. The impact of road features such as shoulder, median, road width, horizontal and vertical alignment etc. on driver behaviour need to be studied. A large scale validation with field data is required. The driving behaviour of mixed no-lane based traffic is divided in three categories.

Mixed Traffic (Vehicle heterogeneity)

The mixed traffic included multiple type of vehicles in the same traffic stream with different manoeuvring or driving capabilities and different size (length or width) of the vehicles.

Road Characteristics

The roads include different width of roads with variability in horizontal and vertical alignment and different median and shoulder types.

Weak Lane disciplined traffic

Weak lane discipline leads lateral movements with in lanes and integrated movements by interacting with all surrounding vehicles at once. Occupying any lateral space within the road width leads multiple leader following, weaving and filtering manoeuvre.

Hence to study the driving behaviour in no-lane based mixed traffic and to incorporate the above traffic behaviours the following manoeuvring/behaviour are important to study from field traffic;

a) *Longitudinal manoeuvre*: Longitudinal acceleration/deceleration with their operating speed
b) *Lateral manoeuvre*: Lateral acceleration as a measure of lateral manoeuvre
c) *Road Characteristics*: Impact of road characteristics (road width, median condition, etc.) on vehicle manoeuvre.

Therefore, longitudinal acceleration/deceleration, lateral acceleration and the impact of road characteristics are important parameters to study such traffic stream and their accurate measurement and analysis at micro level is necessary to understand the driver behaviour. The following sections describe the brief literature review conducted on these parameters in mixed traffic.

2.6 Studies on Vehicle Manoeuvre

Longitudinal interaction of vehicles in traffic stream has been studied since long time. However, the lateral behaviour of vehicles (a most important criterion for the Indian condition) has not been explored much until now. In India, due to no-lane discipline and mixed traffic condition, the lateral movement of vehicles are high comparing to countries with proper lane discipline. In such conditions, the driving task can be defined as tracking a path or a lane along a given roadway. An important skill in driving is the perception of the lateral and longitudinal forces, which results as change in the direction of motion of the vehicles. The absence of lane behaviour implies that a driver not only interacts longitudinally with the vehicles ahead but also laterally with vehicles on its sides. The speed choice of the vehicle will also depend upon the lateral acceleration of the vehicles, especially in curve driving. In the past, some work has been already carried out to know the vehicles lateral movement behaviour. These studies have been conducted in different countries, explored the change in behaviour of vehicles lateral position with respect to different traffic condition, traffic parameters (speed), driver behaviour, day time or night time driving conditions, etc. The relation between the dynamic parameters (speed and lateral/longitudinal acceleration), can very well represent the driving behaviour of vehicles in mixed and no-lane disciplined traffic. A better knowledge of road user behaviour can contribute to a safer traffic environment.

2.6.1 Studies on Lateral Acceleration

The main source of information on which the driver decides his manoeuvers is the lateral acceleration. Indeed, the driver controls his speed or trajectory to keep this acceleration in a comfortable range and to insure a safety margin (Felip & Navin, 1998; Reymand et al., 2001). Though the longitudinal interaction of the vehicles in traffic stream has been studied for quite a long time, however, the lateral behaviour of the vehicles (one of the most important criterion for the weak lane disciplined mixed traffic conditions) has not been explored much. A study was conducted to find the relation between longitudinal speed and lateral acceleration on curves during normal driving (Ritchie et al., 1968) and result showed that lateral acceleration was inversely proportional of speed at curves Reymand et al. (2001). It was concluded that drivers adjust their speed in curves so that maximum vehicle lateral accelerations decreases at high speeds. It was predicted that extreme values of lateral acceleration in curves decrease quadratically with speed in accordance with the experimental data obtained from a vehicle driven on test track and a motion based driving simulator. Again Odhams & Cole (2004) have conducted a study which reviews the existing published models of speed choice and compares the models by fitting them to experimental data gathered in a driving simulator experiment. The results show a clear drop-off in lateral acceleration with increase in the speed. Ungoren & Peng (2004), studied on lateral speed estimation methods. Lateral speed is one of the most important vehicle dynamic variable for Vehicle Stability Control systems and is also crucial for other chassis control functions such as four-wheel-steering. Biral et al. (2005) found relationship between longitudinal and lateral acceleration with speed, by using empirical data. Longitudinal acceleration remains constant in lower to medium speed and linearly decreases with the increase in speed at medium to high speed). Similarly, the lateral acceleration increases from low to medium speeds and then linearly decreases at medium to high speed conditions. From the literature it has also been found that, lateral acceleration up to 4 m/s^2 is easy to deal by majority of the average drivers and 4-6 m/s^2 is difficult to deal whereas 6-8 m/s^2 cannot dealt by the drivers (Jimenez et al., 2008). Dijksterhuis et al. (2011), studied the effect of steering demand on lane keeping behaviour. The main purpose of this study is to investigate the sensitivity and relation between performance, subjective, and physiological indices of mental effort expenditure for several levels of steering demand. In this study steering demand was increased by exposure to narrow lane widths and high density oncoming traffic while speed was fixed in all conditions to prevent a compensatory reaction. Xu et al. (2015), stated that lateral acceleration negatively related to driving speed. Eboli et al. (2016) proposed a relationship between lateral and longitudinal accelerations with speeds.

Lateral acceleration is a useful parameter for representing the realistic lateral behaviour of vehicles while generating simulation models for such traffic conditions. Also, it can be converted into the lateral force coefficient of a highway, which is a key factor for lateral stability and driving safety. The lateral acceleration as a measurement of lateral comfort is directly related to the horizontal alignment and lateral stability of a vehicle. Hence, both the lateral and longitudinal parameters are interdependent and goes on simultaneously known as two-dimensional (2D) driver behaviour. Therefore, the study of longitudinal and lateral control of vehicles in a comprehensive manner is necessary to understand and analyse the driving behaviour in mixed traffic stream. Several methods are used to find the lateral characteristics of the vehicles in the literature.

2.6.2 Studies on Longitudinal Acceleration

Vehicular speed and acceleration rates are two important factors for road safety condition evaluation. In the past, various speed profile models and acceleration/deceleration profile models are developed for different applications. The acceleration/deceleration are the two major inputs to predict the operating speed in micro-simulation models. In the past studies, the acceleration and deceleration rates are both assumed to be equal to 0.8 m/s^2 (Lamm et al., 1988)or 0.85 m/s^2 (Echaveguren & Basualto, 2003; Richl & Sayed, 2011). In some studies they are assumed to be within certain range, based on the current operating speed which usually yields a smaller acceleration at a higher speed (Liu et al., 2010). Brooks reported that vehicle's acceleration decreases with the increase in their speed (Brooks, 2012). Researchers have also used experimental data to model the acceleration rate-speed relationship (Moon & Yi, 2008).

As these models do not differentiate between acceleration and deceleration, they are unable to capture the significant differences in the magnitudes of acceleration and deceleration caused by differences in the dynamic properties of vehicles (Fitzpatrick et al., 2000; Camacho-Torregrosa et al., 2013; Montella et al., 2014). Thus, the results are not likely to accurately reflect actual vehicle operating characteristics. In some studies, acceleration/deceleration rate is modelled for different curved road segments (Shao et al., 2011; Fitzpatrick et al., 2000; Altamira et al., 2014). Tokunaga et al. (2005) used acceleration/deceleration data of mountainous roads to analyse the driver behaviour. Deceleration rates are also useful parameters in predicting speed in traffic micro-simulation models. Limited work is done in past on deceleration modelling for cars and light commercial vehicles in comparison to acceleration modelling (Akcelik & Biggs, 1987; Bennet & Dunn, 1995 and Wang et al., 2005). Majority of studies (Wang et al., 2004; RaiChowdhury & Rao, 1989; Akcelik & Biggs, 1987; Akcelik & Beseley, 2001; Bham & Benekohal, 2002) were conducted on acceleration behaviour on the signalized intersections. Various authors conducted a series of tests in the real traffic to find the acceleration/deceleration ranges of different vehicles in the past. Table 2.5 describes the acceleration/deceleration range observed by the different authors.

Table 2.5 Acceleration/Deceleration (A/D) ranges observed by different authors

Authors	Acceleration (m/s^2)	Deceleration (m/s^2)
(Loutzenheiser, 1938)	1.74m/s^2-0.45m/s^2 (Cars)	-
(Beakey, 1938)	-	3.57m/s^2-4.02m/s^2 (Cars)
(Pline, 1992)	0.42-2.87m/s^2 (Max), 0.18- 1.82 m/s^2 (min)	-
(Roess et al., 2011)	2.25 -1.38m/s2 (cars), 0.48 -0.09 m/s2 (Trucks)	-
(John & Kobett, 1978)	-	1.07 m/s^2
(Bester, 1981)	-	0.6-1.9m/s^2
(Lee et al., 1984)	-	0.28-0.96m/s^2
(Bennet & Dunn, 1995)	-	1.39-2.34 m/s^2
(Mehar et al., 2013)	$2.19e^{-0.03v}$ for empty HV, $1.65e^{-0.04v}$ for Half loaded HV $0.9865e^{-0.03v}$full loaded HV	-
(Bokare & Maurya, 2014)	0.55 m/s^2 (Truck) 0.76 m/s^2 (3W*) 0.99 m/s^2 (2W**) 2.21 m/s^2 (Diesel Cars) 2.51 m/s^2 (Petrol cars)	0.81m/s^2 (Truck) 1.04m/s^2 (3W*) 1.17m/s^2 (2W**) 4.53m/s^2 (Diesel cars) 3.88m/s^2 (Petrol Cars)

* 3W-Motorized three-wheeler, **2W- Motorized 2W

In India, very limited studies have been conducted on acceleration/deceleration behaviour

(RaiChowdhury & Rao, 1989 and Dey & Biswas, 2011). Arasan & Koshy (2005), concluded that, acceleration rate depends on speed range and vehicle type. Rate of acceleration decreases with increase in speed. Lower rates of acceleration are reported for heavy vehicles like buses, trucks and light commercial vehicles as compared to cars, motorized 3Ws and 2Ws. The maximum and average acceleration at different speeds (ranging from standstill condition to a higher speed) for different vehicle types is measured by Mehar et al. (2013). Maurya & Bokare (2012) and Bokare & Maurya (2016) studied the acceleration/deceleration behaviour of different vehicle types in Indian traffic and observed that deceleration behaviour is different for different vehicle types. But the study was conducted at the signalized intersection at a short stretch under controlled condition to replicate the signalized intersection lead vehicle acceleration/deceleration. Due to weak lane disciplined heterogeneous traffic at intersections the data results in inconsistent and difficult to analyse.

2.6.3 Methodologies Used for Collecting Lateral and Longitudinal Acceleration Data

In the past various authors have used different techniques to measure the lateral position or the lateral placement of vehicles on the road. However, the lateral manoeuvring of the vehicles are measured by measuring the steering angle/ heading angle, and the lateral acceleration and lateral speed of the vehicles. Most of the studies were conducted in the past were simulator based studies. Only a few field studies were conducted in the past to measure the lateral acceleration or heading angle as a measure of lateral manoeuvre of vehicles. Ritchie et al. (1968), recorded the lateral acceleration data using an accelerometer fastened to the floor of the car. Yang (2012), determined the vehicle heading angle by using the image based technique via an in-vehicle camera.

The longitudinal interaction of vehicles in a traffic stream has been studied from quite a long time. Various researchers used different methods of data collection for speed and A/D modelling. Beakey (1938), determined the acceleration rate by measuring the travel time of the vehicle at multiple locations. Akcelik & Biggs (1987), used the chase car method to collect the acceleration data. Bennet & Dunn (1995), used the computerized data logger (Vehicle Detector Data Acquisition System, VDDAS) to collect the speed and deceleration. Some researchers like Snare (2002); Wang et al. (2004); Rakha et al. (2001) used the GPS equipped vehicle to collect the speed and distance data. The GPS is becoming very popular amongst researchers due to its lesser human involvement and accuracy.

2.6.4 Summary

After reviewing the literature related to lateral/longitudinal acceleration and speed studies, it is observed that majority of studies have reported acceleration behaviour of passenger cars only. Most of the studies were conducted to study the maximum acceleration capabilities of vehicles. The maximum acceleration capabilities of vehicle is used by drivers during emergency driving condition. Very few studies are found to report the acceleration models of vehicles plying on Indian roads. Though deceleration capabilities of vehicle is an important parameter deciding stopping distance and delay at signalized intersection. Very limited studies reported the deceleration behaviour of vehicles on roads with heterogeneous and no-lane disciplined traffic. The heterogeneity of traffic stream leads to the vehicles with lesser accelerating capabilities which interfere with the movement of vehicles with high acceleration capabilities. Therefore, separate acceleration deceleration studies are needed for such traffic stream. Further, it has also been found that, only limited studies have been conducted on lateral acceleration and their relationship with vehicular speed which is an important parameter regarding the road safety condition evaluation. Further, no such study was conducted in heterogeneous and weak lane disciplined traffic stream. Therefore, the present paper analyses the acceleration behaviour of different type of vehicles (longitudinal acceleration/deceleration and lateral acceleration) with respect to their driving speed on straight mid-block section for normal driving condition in mixed and weak lane disciplined traffic on Indian roads. The lateral behaviour of different vehicles are studied by analysing the lateral acceleration of different vehicle types on such roads. Also the lateral acceleration models were established for straight road section to represent the lateral manoeuvre of different vehicle in such traffic condition. The overall driving behaviour is observed by plotting the g-g diagram, considering both the lateral and longitudinal acceleration/deceleration. The relationship of both the lateral and longitudinal acceleration are studied for different vehicle types.

2.7 Studies on Vehicles' Lateral Placement

Many researchers (Porter et al., 2004 and Zhao et al., 2015) have interpreted lateral placement as the distance of the centre point of the vehicle from the roadway centreline (Auberlet et al., 2010). It is defined as the placement of the rear left wheel of a vehicle from the edge of the road (Dey et al., 2006). It is also stated as a distance between lane edge of highway and middle of vehicle (Suh et al., 2006). Another author Rasanen (2005) in his study, has used the distance between the barrier line dividing the opposite directional traffic, and the inner wheel of the vehicle as lateral position of the vehicle. Some have enumerated lateral position as the distance between the carriageway centreline and the nearest edge of the vehicle keeping in mind its variable dimension (Bunker & Parajuli, 2006). Another author who carried out his research on lateral positioning where he defined the same as the location of the outermost tire of the front axle of the car from the edge way of the road (Hallmark, 2012). A rare definition was used in which the gap between the centreline of the road and the left-side mirror (right-handed traffic) was calculated as the position of the vehicle in the lateral perspective of the roadway (Sagberg, 2006).

In a country like India the way a vehicle moves is pretty difficult to apprehend. The positioning of the vehicle has been studied for over the past few decades by various researchers globally and some parameters have been found to be directly affecting it. Amongst them some have been described in the following sub-sections.

1. Impact of edge or centre line of the road on lateral placement of vehicles
2. Impact of traffic and stream parameters on lateral placement of vehicles

2.7.1 Effect of lateral placement due to edge or centre line of the road

Edge line and centreline (in the form of a thick line or two lines) plays a crucial role in vehicle's position. It can also be made with rumble strips, horizontal lines at regular intervals (Sagberg, 2006). Sagberg (2006) observed a decrease in speed value by 2.7km/hr after providing rumble strips as centreline of the road. There was a shift in lateral position of about 30-38cm for road with new painting and 12-20 cm for road with rumple strips. Auberlet et al. (2010) concluded that drivers tend to drive closer to the centre of the road in existing conditions and closer to the centre of the lane under the centred rumble strips. Zhou et al. (2014) observed that average lateral placement (defined as the placement of centroid of the vehicle with the centre of the lane) tends to decrease with the increase in width of inside shoulder. Standard deviation of lateral position was opposite in nature, increasing with increase of inside shoulder's width, suggesting driver's tend to fluctuate with the more available space. Further, experiments were conducted on 2-lane rural roads in Pennsylvania to find out the effects of low cost centreline rumble strips (CRS) on lateral placement of vehicles (Porter et al., 2004). A shift of 0.47ft was observed for one site and for the other a shift of 0.25ft was observed.

Similarly, edge line, the outermost line in the roadway tends to affect the vision of the driver who is propelling along the highway. Woods (1972) observed that, vehicles tend to move away from the centre line and towards the edge, when there is more lateral clearance between edge or traffic lane and the bridge curb. Middleton (1976), stated that drivers had a tendency to drive closer to the centre of the road in the absence of edge line, irrespective of speed, vehicle type and at all levels of traffic volume. Armour (1985) observed that edge line had no effect on the lateral placement of the vehicles from an experimental study. Also, shoulder type and its width has an effect to the lateral position of vehicles. Van Driel et al. (2004) deduced that applying an edge line to a road without centreline reduces the speed of the vehicles.

2.7.2 Effect of Lateral Placement due to Traffic and Stream Parameters

The vehicle moving on the road tends to have a definite size (length, width and height), wheel and axle configuration, turning radius and power-to-weight ratio all of which affects the driving path of it. Hence, the lateral position is directly or indirectly related to all these static parameters. Similarly, the vehicle dynamic parameter like operating speed has a major impact on the lateral placement of vehicles.

Van Driel et al. (2004) concluded that traffic volume like opposing vehicles or vehicles in the same directions and also the circumstances like day or night have no effect on speed and lateral position of vehicles. However, Dey et al. (2006) observed that slow moving vehicles move at the edge while fast ones move towards centre of the road. They introduced a placement factor based on the percentile of lateral position of vehicles. Bunker & Parajuli (2006) analysed the lateral positions for passenger cars, semi-trailers and B-Double type vehicles when they were under the influence of opposing vehicles. It is observed that size was inversely proportional to the spread of vehicles' lateral positioning. Further, Rasanen (2005) revealed that for oncoming vehicles there was an overall shift of 15-20 cm towards the edge of the road, i.e. vehicles tend to move away from the centreline in presence of opposing traffic.

Hallmark (2012) used an odds ratio of a near lane to describe relation between speed and lateral placement of vehicles. Balaji et al. (2013) deduced that there is linear relation of speed and lateral placement for 3-wheelers, heavy and slow moving vehicles whereas quadratic relationship existed in case of 2-wheelers and cars. Also a trend of increase in speeds with the vehicle moving in the centre of the road in case of 3-wheelers, slow moving vehicles as well as for heavy vehicles. Stodart & Donnell (2008) stated that there was no appreciable endogenic relationship observed between speed and lateral position differentials. Curve direction affects lateral position of the vehicle whereas adjacent curve radii affects vehicular speed. Middleton

(1976) revealed that higher the speed of the vehicle, closer it drove to the centre of the road. He also found linear relationship between lateral position and speed of vehicles. The relations clearly state that vehicles with higher speed will have greater or positive lateral placement values suggesting that a vehicle with higher speed tends to travel along the centre of the road, irrespective of the edge line condition. Wong & Nicholson (1993) observed that vehicle's tendency to encroach the edge line was seen to be quite high.

2.7.3 Methodologies Used for collecting Lateral position data of vehicles

Tamiya et al. (1996) suggested an Optical spread spectrum radar for lateral detection in vehicles. But there are certain limitations of the radar based sensors; radar can sense a lot of these materials, but the energy of the returning waves is so small that precise alignment with the signal is paramount. This introduces techniques such as guided wave radar, or special antenna. Measuring materials with a low dielectric constant is not always impossible, just very challenging. The radar sensors are more costly. Teshima et al. (2006), also suggested a vehicle lateral position estimation method based on matching of top view images. The proposed method does not rely on extraction of features such as lines, flow vectors or lane markers, but based on matching of warped top-view images between two consecutive frames. Hallmark (2012) conducted a study on the curve road section on speed and lateral position of vehicles. Data were collected by using Z configuration pneumatic road tubes. They followed the methodology used by Finley et al. (2008) and Porter et al. (2004) that uses pneumatic road tubes set up in a Z configuration. Yang (2012) determined the vehicle heading angle by using image based technique via an in-vehicle camera.

In India there are very few studies has been conducted on the lateral behaviour of the traffic. Dey et al. (2006); studied on the lateral placement of vehicles under mixed traffic conditions. Again Balaji et al. (2013), conducted a study on lateral placement and speed of vehicles on 2-lane roads. They also followed the same method as Dey et al. (2006). Data were collected by dividing the lane width into sections of 25 cm each with self-adhesive cloth tape and these were numbered seriatim from pavement edge to the centre of road. The placement of left rear wheel of a vehicle crossing the section was recorded by video recording and analysed manually to get the vehicles' lateral position. Accuracy of such approach of vehicle's lateral position measurement is always poor and questionable. In our present study a sensor based assembly has been developed to directly measure the lateral gap of each vehicle passing near road edge. The details of the sensor assembly is described in the methodology section.

2.7.4 *Summary*

The review of literature on lateral characteristics of vehicles revels that change in lateral position depends on various traffic parameters, road condition as well as the geometric condition of the road. Most of the studies has been carried out in developed countries with lane disciplined condition. But, due to no-lane discipline and mixed traffic condition, in India the lateral movement of vehicles are high. Although the relationship between speed and lateral position is important in understanding curve negotiation, the relationship is not well understood. Numerous studies had been conducted using different methods and technologies to find the lateral position of vehicle on road. Most of the studies were limited to analysis of lateral movement of vehicle on curves. Studies related to vehicle's lateral characteristics on straight road with mixed and no-lane-disciplined traffic were found important to understand the vehicle's lateral movement behaviour in a traffic stream for realistic traffic simulation model. Among the few studies carried out in India were based on limited data and manual data analysis. Therefore, accuracy of such results can always be challenged.

Hence this study is important for the realistic traffic flow model simulation, vehicle/driver behaviour of the vehicles due to various traffic features like vehicles ahead, vehicles to the side, the mixed traffic condition, etc. Again, most of the studies were conducted on curved roads. Studies related to behaviour of vehicles lateral position in no (or weak) lane disciplined traffic have not been found. Therefore, studies on vehicle's lateral movement on straight roads in Indian traffic streams needs to be conducted to analyse the weaving motion of vehicles and in such traffic.

2.8 Concluding Remarks

The driving behaviour in Indian traffic stream includes both lateral and longitudinal manoeuvre simultaneously. This driving behaviour generates various complex manoeuvring like swerving, filtering, multiple leader following etc. From the detailed review of the microscopic models of driving behaviour, it is observed that the microscopic models developed for lane based traffic cannot model such complex driving behaviour. One of the major challenge in modelling such traffic lies in identifying the parameters required to describe such driving behaviour. The performance of a microscopic model highly depends on the accuracy of data obtained. Hence, a proper understanding of the driver behaviour on real world traffic stream is needed. Some of the gaps observed from the literature survey are listed below.

1. Though the basic Car-following and Lane changing models describe the longitudinal and lateral behaviour of vehicles, they are not able to describe the integrated driving behaviour (lateral and longitudinal simultaneously) independently.
2. The parameters used in the existing 1D microscopic driver behaviour models does not describe the peculiar driving pattern of no lane based mixed traffic streams (2D traffic).
3. Most the models developed for no-lane based mixed traffic (2D traffic) implemented the similar basic principles used in 1D (lane based homogeneous) traffic models. Also, the weaving manoeuvres implemented in the model does not validated with the real world traffic.
4. To understanding the vehicle manoeuvre (integrated driving manoeuvre) on the Indian roads (real world traffic stream), the lateral manoeuvre along with the longitudinal behaviour of vehicles are important to study.
5. The impact of road features such as road width, shoulder and median width, horizontal and vertical alignment etc., on driver behaviour is need to be studied and implemented in the comprehensive 2D driver behaviour model.
6. Due to the mixed traffic i.e. heterogeneity in vehicle type and their static/dynamic characteristics, the lateral placement of vehicles plays a major role on the Indian mixed traffic stream.

In the present study, the authors tries to build a bridge between the gaps of studying the driving behaviour on Indian traffic stream. The manoeuvring of different type of vehicles on such traffic stream are observed based on the dynamic parameters like operating speed, lateral and longitudinal acceleration/deceleration of vehicles. The lateral placement of different type of vehicles with different static and dynamic characteristics are studied on different roads with different width and flow conditions. The Impact of road edge or median type (geometry of the median) on the lateral gap maintaining behaviour of different vehicles travelling on the adjacent lane are studied. To study the above parameters from real traffic stream, various different methodologies for data collection and extraction are implemented. The next Chapter describes the methodologies in details for collecting data from field.

3 Methodology for Data Collection and Extraction

3.1 Introduction

The heterogeneous, no-lane based traffic of India comprises of vehicles with various static and dynamic characters. Due to no-lane discipline, the vehicles occupy any lateral position on the entire cross section of the road. Due to this, the vehicles manoeuvring in mixed traffic exhibit different patterns of driving behaviour maintaining shorter headways, tailing, swerving and filtering etc. In such traffic stream, the drivers have to control the vehicles' position along both the longitudinal and lateral direction simultaneously. As observed from the literature review, most of the existing models do not describe the driving behaviour of mixed traffic stream due to the lack of proper understanding of driver behaviour on the real world traffic stream. Hence, to describe the driving behaviour, it requires the knowledge of the surrounding traffic environment of the vehicle and also its relation to the subject vehicle. The performance of microscopic model highly depends on the accuracy of data obtained from the real traffic stream. As observed from the literature, the dynamic parameters like operating speed, lateral acceleration and longitudinal acceleration are the three major parameters to describe the manoeuvring of different type of vehicles on the no-lane based mixed traffic stream. Similarly, the lateral manoeuvre of vehicles can be studied by obtaining the lateral positioning of the vehicles on the no-lane based traffic.

In the present chapter, the methodologies used to collect the vehicles manoeuvring, and their lateral positioning is described in detail. The present study is divided into two broad categories.

1. Study of vehicles' manoeuvre using the dynamic parameters like operating speed, lateral acceleration and longitudinal acceleration/deceleration of the different type of vehicles.
2. Study the impact of road characteristics on the lateral positioning of different type of vehicles.

The lateral positioning of the vehicles again studied by studying the lateral placement of different type of vehicles on the entire cross-section of roads with different width. Then the impact of the geometry of road median/edge on the lateral gap maintaining behaviour of different vehicles travelling in the adjacent lane. The details of study methodology for obtaining the above parameters are described in the flowchart presented in Figure 3.1.

In the present chapter, the methodology of data collection for obtaining the research objectives are described in three subsections.

a) Study of vehicle manoeuvring using the dynamic parameters of vehicles.
b) Study of lateral placement of vehicles over entire cross-section of different roads.
c) Impact of median/edge geometry on lateral gap maintaining behaviour of vehicles.

The vehicle dynamic parameters like speed, lateral acceleration and longitudinal acceleration/deceleration are measured by using the GPS based instrument known as Video VBOX. The lateral gap maintained by different vehicles travelling on the entire road is measured using top-view image processing software. For achieving a higher accuracy in lateral gap data, the lateral gap maintaining behaviour of different vehicles from the median is measured using a sensor based assembly with a video camera. The details of data collection methodologies and the selected sites for data collection are presented in the subsequent sections.

3.2. Study of Vehicular Manoeuvre Using Dynamic Parameters

During vehicle motion, driving dynamics deals with the physical laws as regards the vehicle's properties and road characteristics. From the literature survey, it has been observed that the longitudinal and lateral acceleration values can be seen as the synthesis between the vehicle dynamics and driving behaviour selected according to the driver's motion perception and the risk level he/she accepts. In case of no-lane based heterogeneous traffic, drivers have to control of vehicle along both the longitudinal (direction of motion) and lateral direction (i.e. the width of the roadway). Hence, in such traffic condition, the lateral and longitudinal acceleration and operating speed are the three major vehicular parameters to determine the driving behaviour of vehicles.

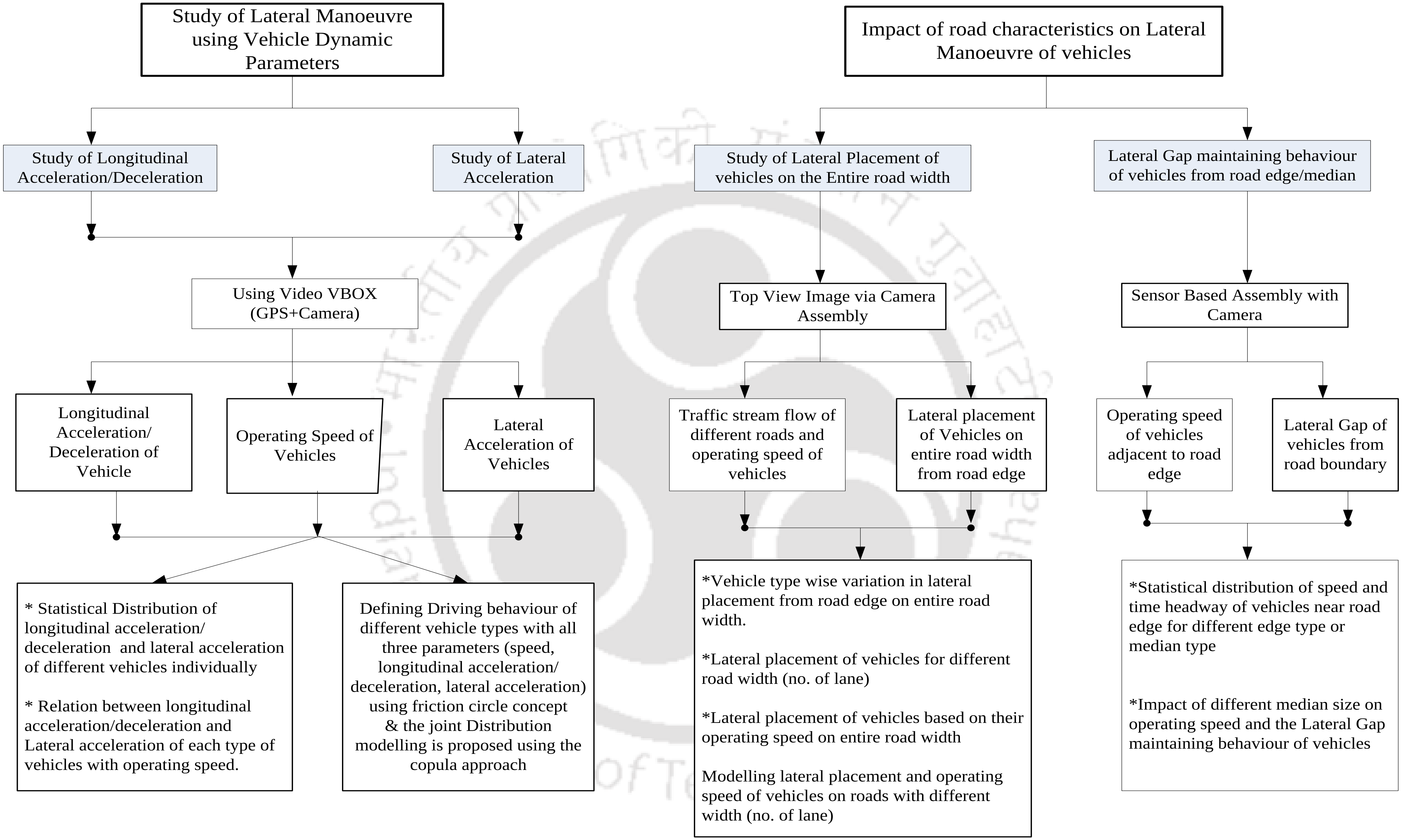


Figure 3-1 Depicts the Study methodology for Obtaining the Research Objective

3.2.1 Methodology for Data Collection and Extraction

In the past various authors used different technologies to collect the vehicle dynamic parameters like lateral acceleration, steering angle, heading angle, lateral speed, longitudinal speed and longitudinal acceleration etc. Most of them used the instrumented vehicle technique, i.e. the subject vehicle was installed with different instruments to collect the dynamic of the vehicle. Some of the authors used image-based technology fixed to the subject vehicle and the top-view image are used to obtain the dynamic parameters of vehicles. However, some of the authors used the GPS based instrument fixed to the vehicle to collect the vehicle trajectory data or the dynamic parameters of vehicles from the highly accurate vehicular position data. In the present study, the GPS based technology is used to collect the dynamic parameters of vehicles.

Data is collected by using GPS based instrument named as Video VBOX (Racelogic, 2015). VBOX is a kind of high accuracy GPS which provides the vehicle position (with sub-meter accuracy) and speed (with 0.1 km/h accuracy) at 10 Hz data logging frequency. Video V-Box along with a display unit (for real-time monitoring) are installed in the subject vehicles (here after referred as an instrumented vehicle) which was used for data collection. Five different types of vehicles (H-Back cars, Sedan cars, SUV cars, Motorized 3Ws and 2Ws) are used as instrumented vehicles for collecting data on different Indian roads. H-Back, Sedan and SUV are the three different type of cars with different configurations (refer Table 3.1), generally plying on the Indian roads (Gear Heads, 2011). In the present study, only the diesel cars are used for data collection. Hence only the details of diesel car are presented in Table 3.1. It can be observed from Table 3-1, that power to weight ratio of H-back, Sedan and SUV cars are significantly overlapping. However, in the present study all three categories of cars are considered separately as this is the popular way to classify the cars among the driver community. Figure 3.2 depicts all the five instrumented vehicles with the Video VBOX data logger.

VBOX GPS data logging is an easy to use and highly capable unit. The accuracy of the VBOX data logger is tasted by the manufacturer of the VBOX automotive using Doppler Shift method in the GPS carrier signal. The accuracy of data logging is given in Table 3.2.

Table 3.1 Details of the three types of cars available in India (Gear Heads, 2011)

Type of Diesel Cars	Total Weight in pound	Max. Break Horse Power (BHP)	Power to Weight Ratio (hp/pound)
H-Back Cars	2381-2853	62-93	29-39
Sedan Cars	2540-3221	67-128	22-40
SUV Cars	4017-4910	103-197	22-45

Table 3.2 Accuracy level of different parameters measured by the VBOX Data logger (Racelogic, 2015)

Velocity	0.1 km/h
Absolute positioning	2 m
Distance	0.05% (<50 cm per Km)
Acceleration	50% (
Acceleration/Braking test time	0.01 s
Lap time	0.01 s
Stopping distance	± 1.8 cm
Heading	0.01°

Figure 3-2 (a) Details of Video VBOX data recording Unit (b) Video VBOX installed in a car (c) Motorized two-wheeler (2W) (d) Motorized three-wheeler (3W) (e) H-Back Car (f) Sedan Car (g) SUV car

There are many authors who conducted test regarding the accuracy measurement of GPS data logger used for VBOX. Many researchers like, Durrant & Hill (2005), Adnan et al. (2013), Xiaolong et al. (2010) and Katzourakis et al. (2012), etc. analysed the accuracy of the VBOX data logger and proved that it has an improved accuracy level of data recording facility. Durrant & Hill (2005), presents a number of real-world tests to evaluate the performance of various aspects of the GPS's performance. They observed that due to higher data logging frequency the noise of speed data are significantly higher. Also, the GPS corrections only improve the positional errors, however they does not have any direct impact on speed and distance. Adnan et al. (2013), studied the errors while comparing the VBOX GPS device with other speed measuring devices like, automatic traffic classifiers (ATC), radar gun, laser gun, manual count etc. Katzourakis et al. (2012), stated that a GPS receiver could measure velocity with accuracy of 5 cm/s using Doppler shift of the GPS carrier waves by improving the position accuracy.

The lateral and longitudinal acceleration/deceleration data along with operating speed of the vehicles are extracted from the recorded VBOX data using VBOX-Tools software as shown in Figure 3.3. Data collected from different cities of India using different vehicle types are extracted.

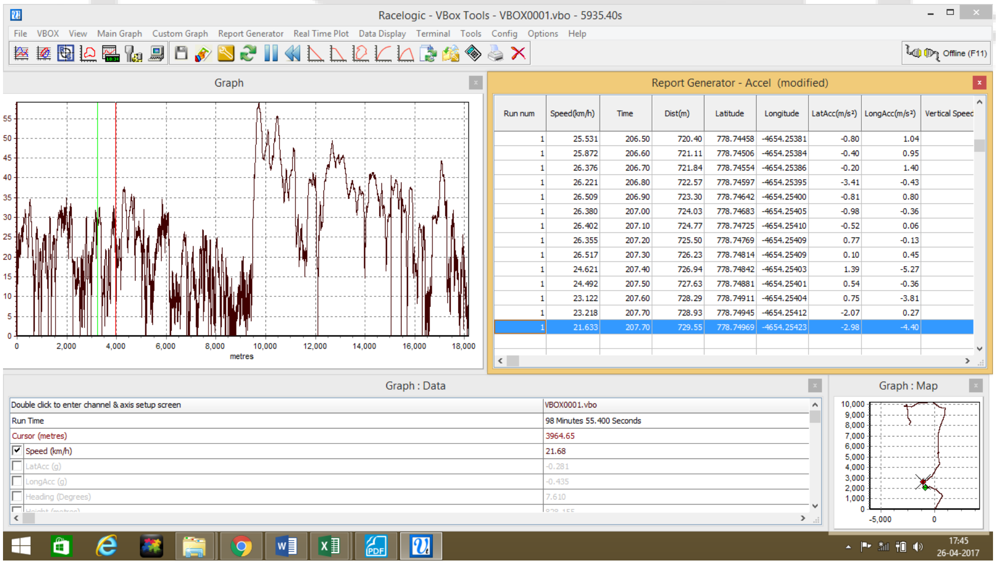


Figure 3-3 Snapshot of VBOX Tools Data Extraction Software

3.2.2 *Details of Sites Selected for Data Collection*

Data are collected from five major cities of India (Kolkata, Bengaluru, Mumbai, Pune and Delhi) using the instrumented vehicles, for generalizing the study in a more broad area and including the different type of traffic conditions of different regions of the country. The road trajectories include straight roads, curves and roads with a different number of lanes in each city. Data was collected on sunny weather, during moderate flow conditions to ensure the vehicle interaction. The road surface was in good condition, and proper visible lane markings were present. The maps trajectories of all five cities where data had been collected are shown in Figure 3.4.

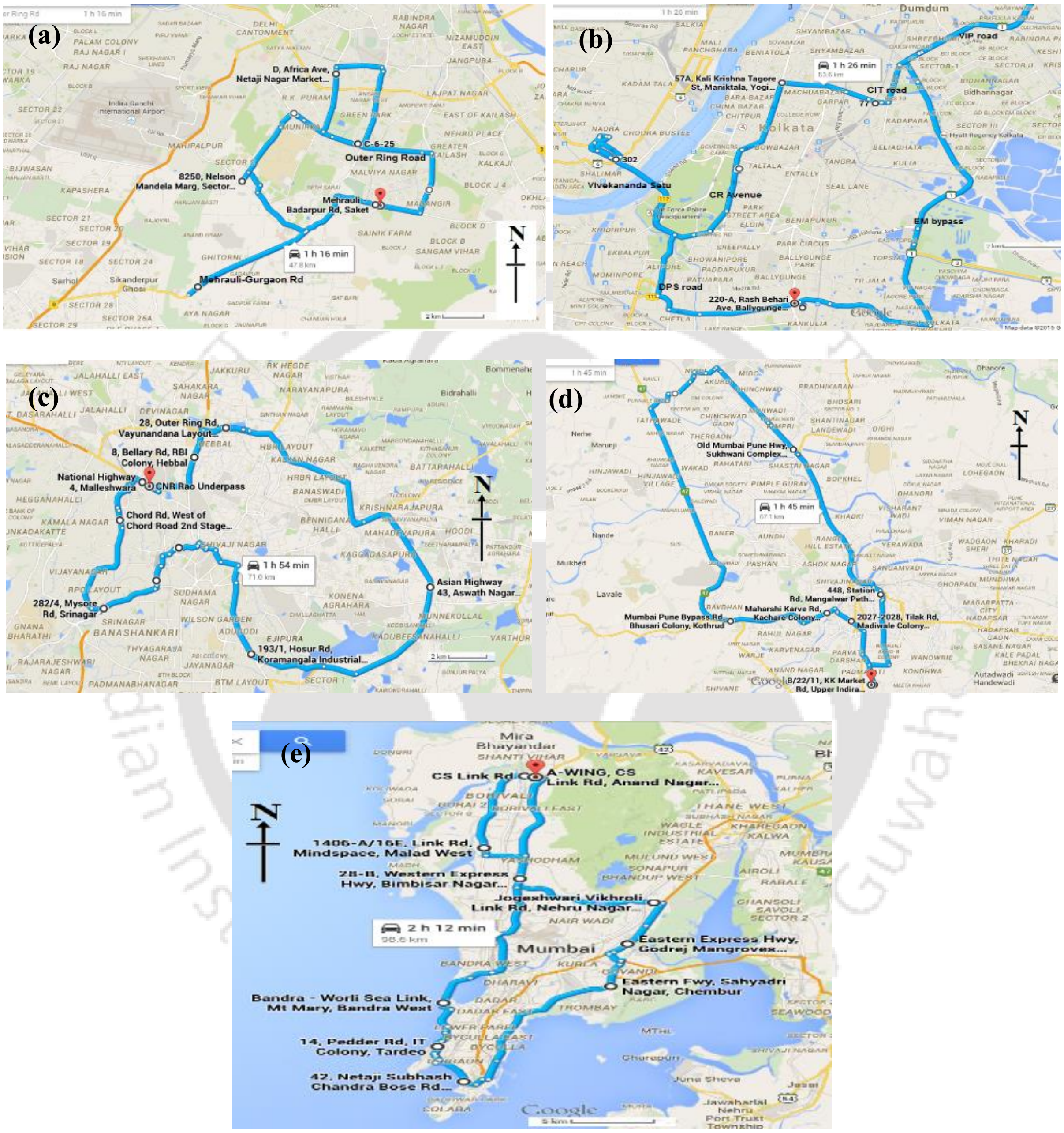


Figure 3-4 Maps Showing the Road Trajectory of data collection in five major cities of India (a) Delhi (b) Kolkata (c) Bengaluru (d) Pune and (e) Mumbai (blue lines in the maps indicates roads for data collection)

The details of data collection sites (data collection trajectory details) and the different vehicle types used for data collection are provided in Table 3.3. The length of entire road trajectory used for data collection throughout the country was around 255 km for motorized 3Ws, SUV cars and Sedan cars, 215 km for H-back cars and 175 km for motorized 2Ws.

Table 3.3 Site Details & Vehicle Types Used for Data Collection

City Name	Trajectory Length for each vehicle(km)	Number of lanes		Vehicle Type					Month of Data Collection
		2-lane	3-lane	Passenger Cars: SUV	Passenger Cars: Sedan	Passenger Cars: Hutch -Back	Motorized 3W	Motorized 2W	
Delhi	40	✓	✓	✓	✓	✓	✓		December 2013
Kolkata	40	✓	✓	✓	✓	✓	✓	✓	November 2014
Bengaluru	70	✓	✓	✓	✓	✓	✓	✓	November 2014
Pune	65	✓	✓	✓	✓	✓	✓	✓	December 2014
Mumbai	40	✓	✓	✓	✓		✓		July 2014

2-lane- One way of 4-lane divided road, 3-lane-One way of 6-lane divided road, Motorized Three-wheeler is referred as 3W, and Motorized two-wheeler is referred as 2W in the later part of the study.

The lateral and longitudinal acceleration data along with operating speed are extracted from the recorded VBOX data of five different cities using VBOX-Tools software for five different type of vehicles. To study the behaviour of longitudinal and lateral acceleration and their relationship with operating speed of different vehicles during normal driving, data from straight mid-block sections are analysed. Then the importance of longitudinal and lateral acceleration on vehicular stability and design consistency analysis is observed by analysing the data from the full trajectory including different road geometries (straight, curved, turning and roads with different width) are analysed.

3.3 Study of Vehicles Lateral Placement on Entire Road Cross-section

Study of lateral placement of vehicles is important as it helps to determine the lane distribution factor, the optimum operating speed in various lanes of the roads and the safety aspects of the road like the clearance from the median edge and shoulder edge. Lateral placement, thus, becomes a major parameter in case of weak lane disciplined and mixed traffic. Previous studies have shown that lateral placement depends on various other factors like roadway geometry, traffic condition, gap availability between vehicles etc. Apart from very few studies, the effect of road width has not been dealt in detail. Even these studies (on the effect of road width on lateral placement) are restricted to 2-lane undivided sections only. Similar to road width, the effect of vehicle size or even vehicle type is evaluated, and it is limited to cars and trucks only. Hence, the need to study the relationship between speed and lateral placement over the various road width for a different type of vehicles become an important aspect of research which has not been investigated by the researchers.

3.3.1 *Methodology for Data Collection and Extraction*

In the past, many authors used different technologies to collect the vehicle position or placement data (refer Chapter-2, Section-2.7.3). Most of the studies used the image based technologies or video recording technique to measure the lateral placement. In the present study, a novel approach of semi-manual data extraction via video recording is used for the data extraction. The top-view video is collected from the selected road section from six different cities of India. The video is collected such that the four corners of the vehicle and both the edge of road boundary can be marked. The vanishing point methodology is used to convert video image coordinates into real-world coordinates. The software was developed by Budhkar & Maurya (2015). The accuracy of the software was checked by the author (Budhkar & Maurya, 2015). The algorithm for using the software is presented below.

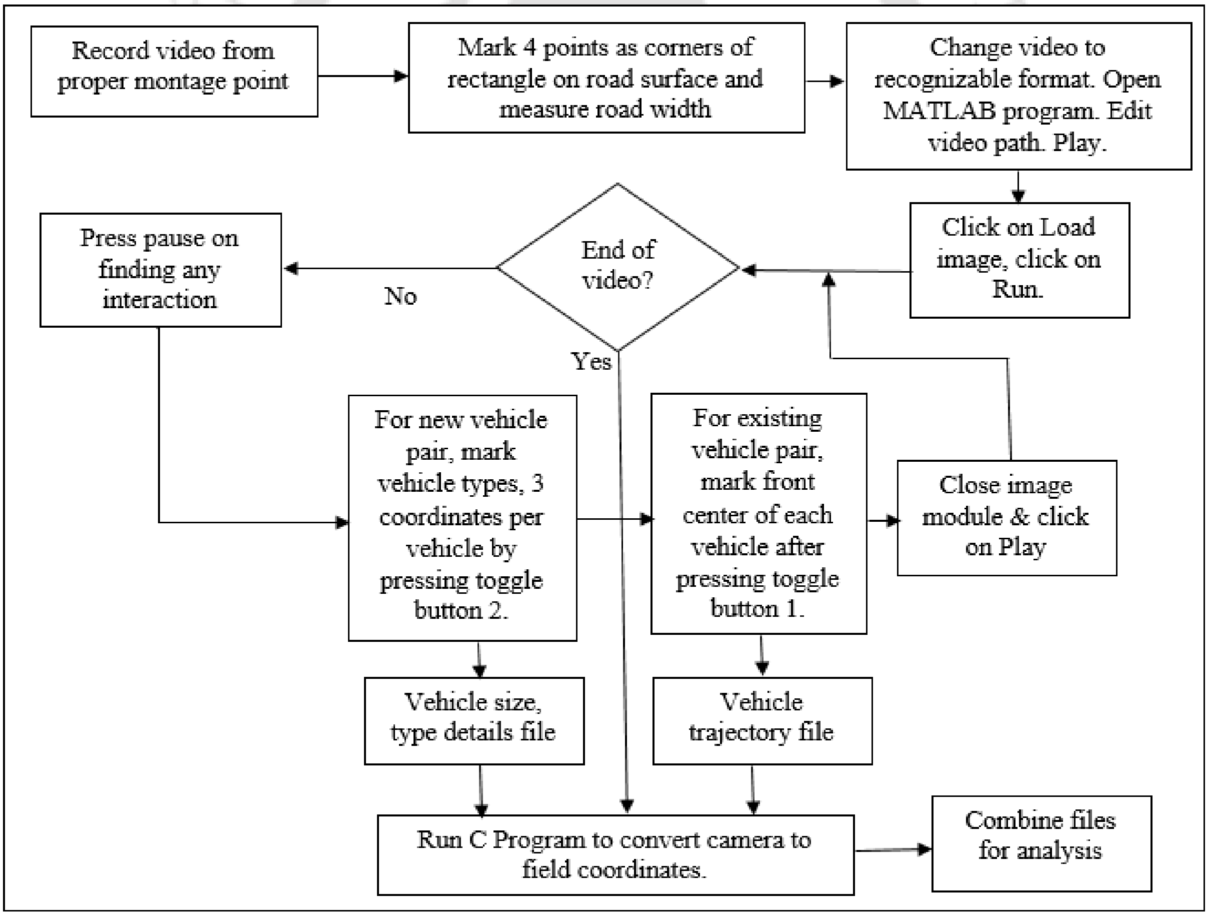


Figure 3-5 Algorithm of the Developed software for extracting the data (Budhkar & Maurya, 2015)

A MATLAB programme is used to note the image coordinates at specific frames. The conversion from the image coordinate to real-world coordinates (x, y, z) is carried out in a C program. The snapshot of developed software for extraction of the data is presented in Figure 3.6.

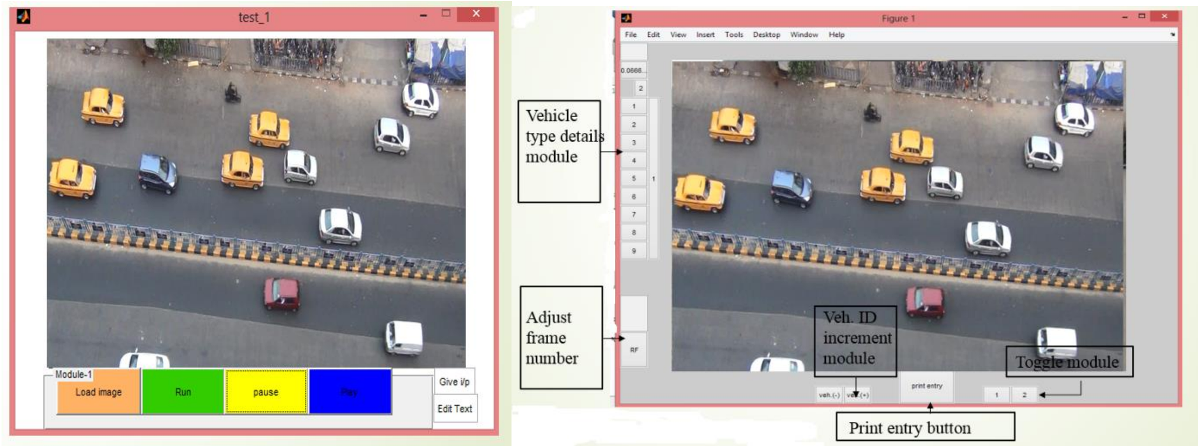


Figure 3-6 Snapshot of developed software while data extraction in MATLAB

The software gives real-world coordinates and calculates parameters such as vehicle size, inter vehicular gap, centre line separation between the vehicles, spacing between the road edge and the vehicle, the instantaneous speed of the vehicle along with the user classified vehicles.

3.3.2 Details of Sites Selected for Data Collection

To incorporate the variability in carriage way widths of Indian roads, a wide variety of roads (4-lane divided, 6-lane divided, 8-lane divided and 10-lane divided) were selected. The details of these roads are shown in Table 3.4. These sites from different cities are chosen based on the following criteria:-

- The road surface should be in good condition with proper visible lane markings.
- Road stretch should be straight, without any significant curvature and gradient.
- The pedestrian movement should be negligible.
- Road stretch should not have merging or diverging arms near by the study zone and also hindrance like bus stop, parking lot, curve, cross walk etc. should be completely absent
- Non-motorized vehicles’ presence should be negligible.

Based on above criteria, four roads with different carriageway widths (ranging from 2-lane to 10-lane divided) are chosen, and video data of traffic stream is collected from a high vantage point. The data has been collected from 11 different sites comprising of the above road characteristics. The following are the site details for each road section (Table 3.4).

Table 3.4 Details of the selected road sections to study the lateral placement of vehicles

	Road type	Location	Road width (m)	Median width (m)	Shoulder width(m)	Month of Data Collection	Duration of Data Collection
1	4-lane divided	Guwahati, Guwahati bypass	7.6	4.67	Earthen shoulder	January 2015	10:30-13:30
2		Pune, Mharte pul	8.12	0.23	Not available	December 2014	11:00-13:00
3		Kolkata, Tollygunge	8.67	0.49	1.93	November 2014	10:00-12:00
4	6-lane divided	Bangalore, Mekhiri Circle	10.79	1.65	1.47	November 2014	16:30-19:30
5		Bangalore, BEL Underpass	9.47	2.05	0.46	Nov 2014	16:00-18:30
6		Mumbai, Link road	10.8	1.71	3.47	July 2014	18:30-20:00
7		Jogeshwari Vikhroli Link road. Mumbai	10.5	1.72	Not measurable	July 2014	15:30-16:30
8		Pune, Pune bypass	9.74	1.95	Earthen shoulder	December 2014	11:00-13:30
9		Kolkata, Gariahat road	12.35	0.36	Not measurable	November 2014	15:30-18:30
10	8-lane divided	Gurgaon, Delhi	14.71	2.48	Earthen shoulder	January 2015	10:00-12:30
11	10-lane divided	Mumbai, Western Express Highway	17.7	1.87	3.11	July 2014	10:00-11:30

3.4 Lateral Gap Maintaining Behaviour of Vehicles from Road Edge (Median)

The absence of lane behaviour implies that a driver not only interacts longitudinally with the vehicles ahead but also laterally with vehicles on its sides. Hence the weaving manoeuvre of the vehicles high. Including the traffic parameters, the road side features like road boundaries also effect the lateral behaviour of the traffic. The lateral position refers to the sideways position in relation to the road markings or to another predefined part of the road. Speed and lateral vehicle position are often the measures used to evaluate the changes in driver behaviour, after implementation of on-road engineering treatments, such as pavement markings and rumble strips etc. Another safety question of roadside infrastructure is whether drivers perceive a roadside element as an obstacle or not. It is known that drivers will move away from an object that they perceive as an obstacle. The researchers faced the problem of measuring the position of a vehicle on the road while driving. While there are numerous ways to measure the longitudinal distance the vehicle has driven, the lateral position of the vehicle has been proven to be more difficult to measure.

From the literature review, it is observed very limited studies related to the interaction of vehicles with various road elements like road edge, medians, kerbs, roadside environment, etc. Most of the studies regarding the on-road guidance systems and road furniture are carried out in the driving simulator. There are very fear studies conducted in real traffic streams. Such studies mostly conducted in developed countries generally use methods like video recording, use of piezoelectric sensors, pressure sensitive electrical tape switches, etc. Those methods do not measure the lateral placement of vehicles directly. Among the few studies carried out in India were based on limited data and manual data analysis. Therefore, the accuracy of such results can always be challenged. Literature review yields no study related to the measurement of clearances maintained by vehicles from road elements in Indian traffic conditions with modern and sophisticated instruments.

3.4.1 Methodology for Data Collection and Extraction

In the present study, a sensor-based assembly is developed by me and Manis Kumar (a under graduate student) to measure lateral clearances maintained by vehicles from road elements (like road edge, divider, kerb footpaths, etc.). This developed assembly helps in measuring the, (i) Lateral clearance maintained by vehicles from road elements, and (ii) Speed of the vehicles. The operation is semi-automotive with very little human intervention.

Two ultra-sonic sensors are placed along the side of the road at a known distance. As a vehicle passes in front of sensor 1, the Sensor 1 gets activated and start receiving the reflected waves from the vehicle. Based on the travel time of emitted wave and reflected wave, lateral clearance of the vehicle from the sensor is calculated. A similar process is repeated at sensor 2. As sensors are places apart with a known distance, the travel time of the vehicle for the distance is determined from the time difference of actuation of both the sensors. Based on the measured travel time speed of the vehicle is calculated.

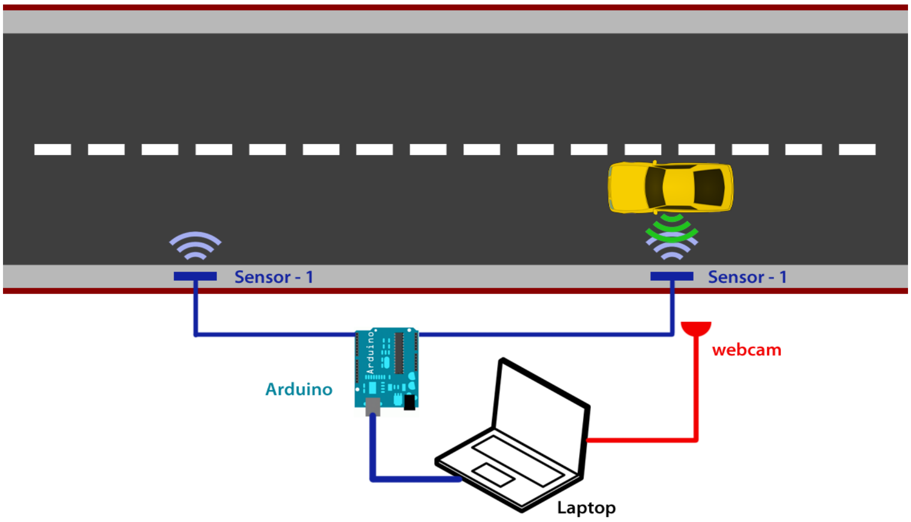


Figure 3-7 Details of the sensor assembly installed on a road

Following instruments are required in developing the sensor assembly for collecting lateral gap data from the road edge.

1. Ping Sensors: These are the low cost, non-contact and easy-to-install measurement ultra-sonic distance measuring device. They provide a range of 2cm to 300cm distance measurement. These sensors work on sonar principle. They send out a burst of ultrasonic waves and wait for echoes to return to them. If any echo is received, the time lag (in microseconds) between the transmitted signal and received echo signal is obtained. This time lag value can be used to calculate the distance of the reflecting surface from the sensor using the following expression;

Distance (in cm) = Microseconds/58

Where Speed of sound in air = 340 m/s

Thus 1 cm corresponds to approximately 29 microseconds. Since the ultrasonic signal travels back and forth, it must be halved to receive actual distance. Thus microseconds divided by 58 (=29X2) gives the distance of the object from the sensor in cm.

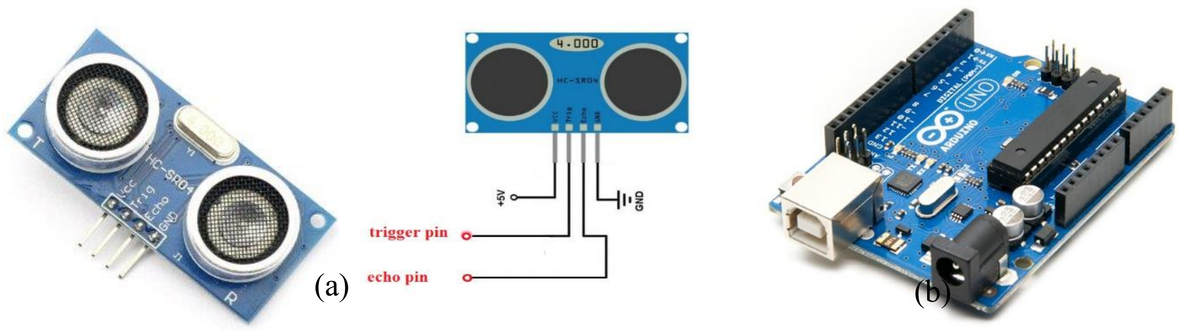


Figure 3-8 Represents the (a) Ultrasonic ping sensor with all its connections (b) Arduino Uno Micro controller board

2. Arduino UNO: The Arduino Uno is a microcontroller board based on the ATmega328. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button.

3. SD Card: A micro-SD card is used with the Arduino UNO board to record the data. Two web cameras have been connected to the laptop for taking the snapshots. Whenever a vehicle passes in front of the sensor 1 the first sensor gets activated and starts recording the distance data with respect to the time stamp. Then as soon as the sensor activates the camera got activated and it starts taking the snapshot of the section. Whenever any non-zero values are coming in sensor, the camera gets activated. This instruction is given through a code written in MATLAB program. The snap shots of each camera are being stored on the laptop with their time stamp. A similar procedure is followed for sensor-2 also. The Figure 3.9 shows the full set-up layout.

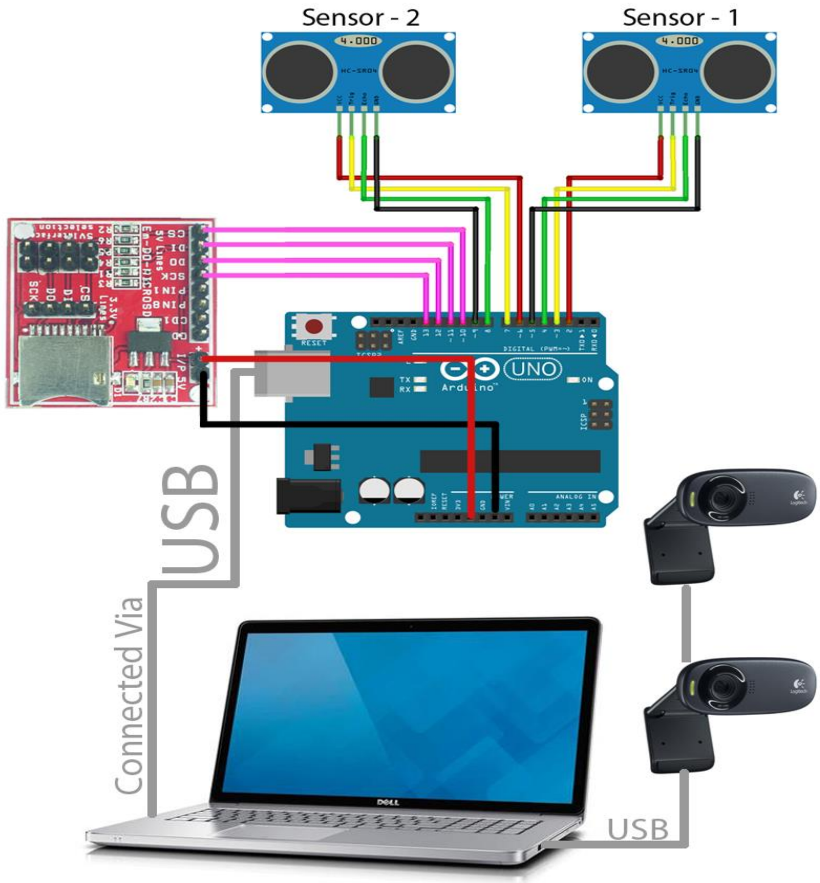


Figure 3-9 A complete layout of Sensor assembly with two cameras

This assembly solves the problem of manual data collection from videos which is a time-consuming process. The vehicle type identification is easier with this model. The camera is properly synchronized with the sensor. Hence the error due to manual data synchronization can be reduced through this model. To counter the problem of limited battery backup, extra battery packs can be kept for the laptop model being used for data acquisition. Another solution is maybe keeping a 12-V lead acid battery along with portable 200 W inverter. These items can be carried in a small vehicle to the data collection site. The complete working procedure of this set-up is shown in flow chart in Figure 3.10.

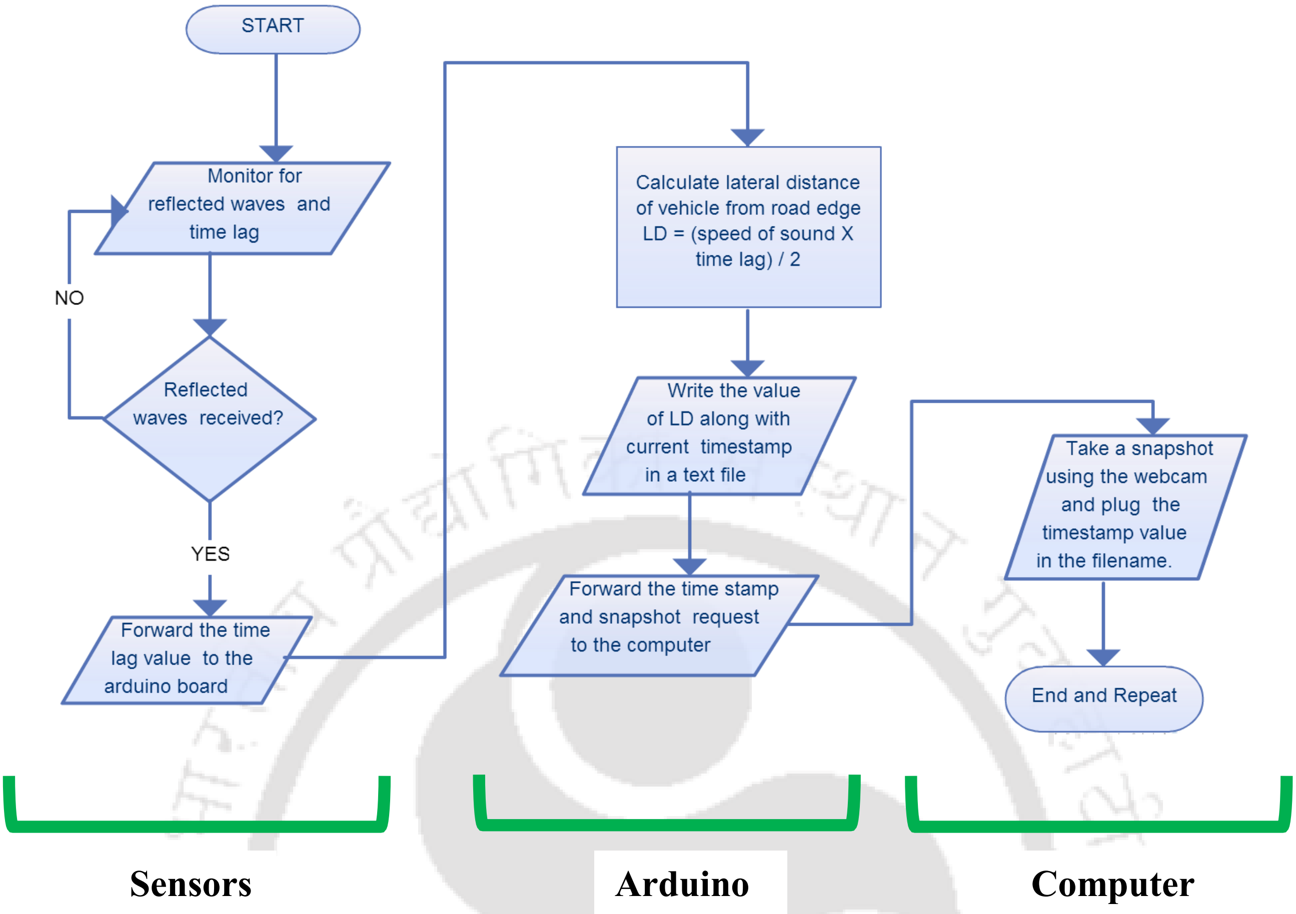


Figure 3-10 Presents the complete working procedure of the Sensor Assembly

To avoid the garbage or unwanted data, a limit has been fixed through the program for the number of data. The sensor will take only 5 data for each vehicle passing in front of it. Hence the corresponding camera will also take five number of snapshots corresponding to each sensor reading. Then by comparing the sensor reading and snapshot it will be easy to identify the vehicle type.

The sensor assembly has been so designed that it measures the lateral clearances with an accuracy of ±5 cm. Thus, the developed assembly aids in measuring the following;

1. The lateral clearance maintained by vehicles from road elements.
2. Speed of different vehicles in the traffic mix

Since we are using the sensor time stamp for speed calculation, there might be an error due to the time lag between consecutive vehicle detections. The data collection frequency of the sensors is 30-35 Hz. Therefore, the time gap between readings varies between 0.0286-0.033 seconds. The maximum error will correspond to the maximum time lag, i.e. 0.033 seconds. For reliability condition, let maximum time lag of 0.035 seconds. If the distance between the two sensors be D_0 (m) and the speed of the vehicle be v_0 (m/s), the vehicle should take time t_0 to cross this distance at the original speed. Hence, the time to cross the sensor, $t_0 = D_0/v_0$. Considering the error (δt) as 0.035 seconds, recorded speed will be $v' = D_0/(t_0-\delta t)$.

Hence, the percentage of error (%) = $(v'-v_0)*100/v_0$.

Thus, the error in measured speed will depend upon;

- Sensor distance (D0)
- True speed (v0) of the passing vehicle.

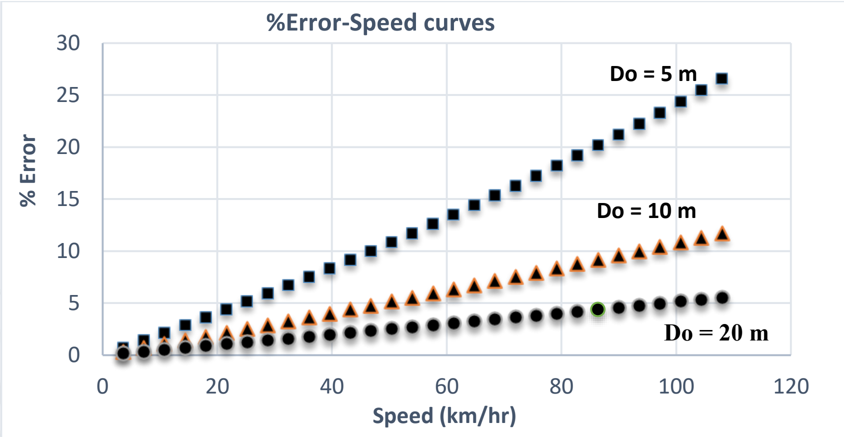


Figure 3-11 Maximum percentage error which may occur in speed measurement using the proposed sensor assembly

From Figure 3.11, it can be observed that as the distance between sensors increases the error in the speed of vehicles decreases. For a distance of 20m between the sensors, then 5% error is detected for a vehicle travelling at 100 km/h. Hence, in the present study, the 20m distance has been used between the sensors while collecting the data using the sensor assembly.

The sensor assembly is placed along the edge of the road with all the proper setup as mentioned above. The sensors are fixed at such a height where it can detect all type of vehicles (motorized 2Ws, 3Ws, Car, Bus, and Truck etc.) in the mixed traffic stream. The height of placement of sensor is based on the height of different vehicles, i.e. the seat height of 2Ws and the chassis height of different type of cars, buses and trucks. A height of 0.8 meter from the carriageway is fixed for the sensor placement at the road boundary.

This assembly helps in large-scale data collection of the lateral clearances maintained by the vehicles from the road elements. Data was collected on straight mid-block sections of roads with different median facilities. The impact of the different lane positions (such as the Median Lane, ML and Shoulder Lane, SL) has been analysed for all sections on average travel speed. The lateral clearance of each vehicle type from the road edge of SL/ML is calculated.

3.4.2 Details of Sites Selected for Data Collection

Data have been collected from different cities on dry and sunny weather condition, during morning hours (9 AM to 12 PM i.e. 4 hours). The road surfaces were in good condition with proper lane markings. The details of the all the sites with the median details are given in the Table 3.5.

Table 3.5 Site Details with the Median type and their details are shown in the following table

Sl No	Road Type	Location	Width of Divider	Height of Divider	Height of Bush/fencing	Divider type
1	4-lane Divided	NH-217 BAM	0.45 m	0.45 m	-	Raised kerb
2		Inner Ring road, Delhi	0.85 m	0.35 m	0. 9 m	Raised kerb (bushes)
3		Airport road(BBSR)	0.90 m	0.30 m	-	Raised kerb
4		SH-57 Delhi	1.1 m	0.30 m	-	Raised kerb
5		NH-37 GHY	1.1 m	0.30 m	-	Raised kerb
6		City road (BBSR)	1.2 m	0.30 m	1.2 m	Raised kerb (fencing-bushes)
7		City road (BBSR)	1.8 m	0.30 m	-	Raised kerb (Trees)
8		NH-5 BBSR	2.0 m	0.20 m	1.1 m	Raised kerb (fencing-bushes)
9		NH-5 BAM	2.0 m	0.20 m	-	Raised kerb
10		City Road (BBSR)	2.5 m	0.45 m	-	Raised kerbs (Small Trees)
11		NH-40 GHY	4.5 m	0.20 m	-	Raised kerb
12	6-lane Divided	NH-8 Delhi	2.0 m	0.30 m	1.0 m	Raised kerb (Crash barrier)
13	8-lane Divided	NH-1 Delhi	4.0 m	0.20 m	1.1 m	Raised kerb (Fencing-Bushes)

The data is collected from different median types of 4-lane divided roads are divided into different groups with respect to their width and height of medians. The sites for data collection are selected according to their flow level (Similar range of flow per lane) (refer Table 3.6).

Speed, flow and vehicle composition of ML & SL of all highways are calculated from the field data to know the traffic condition of all three types of roads. Lane specific average speed for each vehicle type on different roads are computed. A statistical analysis is done to see the difference in the lane specific traffic characteristics (i.e. speed, time headway) of different roads. A MATLAB program is used to analyse the data. The speed and lateral clearance of each passing by vehicle are calculated with respect to the time and vehicle type. Hence, the speed and lateral clearance of each vehicle with respect to its vehicle type are analysed for ML (Median Lane) and SL (Shoulder Lane) of all the sections.

Table 3.6 Site details for the Lateral Gap analysis

	Height / Width	≤0.3 m	> 0.3, ≤0.5 m
4-lane Divided Highway	≤ 0.8 m	No Data Available	NH-217 Flow= 310 PCU/h/Lane
	0.8 to 2.0 m	NH-37 Flow=434 PCU/h/Lane	(Inner Ring Road)Delhi) Flow=1215 PCU/h/Lane
	2.0 to 3.2 m	NH-5 (BAM) Flow=312 PCU/h/Lane	Bhubaneswar Flow=473 PCU/h/Lane
	3.2 to 4.4 m	NH-203 Flow=312 PCU/h/Lane	No Data Available
	≥4.4 m	NH-43 Flow=324 PCU/h/Lane	Bhubaneswar Flow=468 PCU/h/Lane

3.5 Concluding Remarks

In the present chapter the detailed methodology for achieving the research objectives are explained briefly. The method for data collection and extraction is described in three sections; i) Data for Vehicle dynamic parameter analysis and ii) Data for lateral placement analysis of different vehicles on entire road cross section and iii) Data for lateral gap maintaining behaviour of vehicles from road boundary (median), travelled at the adjacent lane. The Instruments required for collecting different data, and the details of the site from where data are collected are described in detail. The further processing of the extracted data and their analysis for studying the vehicle manoeuvre based on their dynamic parameters and the impact of road characteristics on lateral placement of vehicles are described in the subsequent chapters as depicted by the flow chart presented in Figure 3.1.

4 Study of Dynamic Parameters of Vehicles

4.1 Introduction

On the heterogeneous and no-lane disciplined traffic, the abreast (side by side facing same way) manoeuvre of vehicles depends upon the driver behaviour, vehicle type and most importantly the traffic parameters such as vehicle speed and acceleration. In the present study, all the three kinetic parameters are used altogether to analyse the driving behaviour of different vehicles on different roads. From the literature, it has been observed that driving behaviour is analysed based on the driving dynamic equilibrium. The driving behaviour of vehicles in mixed no-lane disciplined traffic can be represented by the relation between the dynamic parameters (speed and lateral/longitudinal acceleration) of vehicles. The study of longitudinal and lateral control of vehicles in a comprehensive manner is necessary. Lateral acceleration is a useful parameter for representing the realistic lateral behaviour of vehicles while generating simulation models in mixed traffic conditions. Also, it can be converted into the lateral force coefficient of a highway, which is a key factor for lateral stability and driving safety. The lateral acceleration as a measurement of lateral comfort is directly related to the horizontal alignment and lateral stability of a vehicle. Hence, both the lateral and longitudinal parameters are interdependent and go on simultaneously known as two-dimensional (2D) driver behaviour. In the present chapter, the driving behaviour of vehicles is studied by studying the longitudinal and lateral acceleration parameter with respect to the speed of vehicles on different straight roadway facilities of India. Though the super-elevation rate and lateral stability are the important characteristics in case of curved road sections, in Indian roads the abreast driving of the vehicles on straight road sections also leads to the serpentine motion of different vehicles. Hence studying both the longitudinal and lateral behaviour became an important issue in the present scenario.

The present chapter is divided in two main sections, Study of Longitudinal Acceleration/Deceleration (A/D) and ii) Study of Lateral Acceleration.

4.2 Study of Longitudinal Acceleration/Deceleration (A/D) Behaviour of Vehicles

The present study explores the operating speed and longitudinal/lateral acceleration of different vehicles, i.e. Sports Utility Vehicles (SUV), Sedan and Hatchback (H-Back) Cars, motorized three-wheelers (3W), and two-wheelers (2W) on roads of different major cities of India. The details of data collection sites, instrumented vehicles used and their extraction procedures are provided in the section-3.2 of chapter 3. The longitudinal acceleration data along with longitudinal speed are extracted from the recorded VBOX data using VBOX-Tools software. Data from five different cities for different type of instrumented vehicles are extracted. The behaviour of longitudinal acceleration and deceleration are studied for different type of vehicles on the straight mid-block sections during normal driving conditions in moderate to high flow condition. Statistical t-test is conducted to see the hypothetical difference between the data from different cities. The data with no significant difference between different cities are combined to see the general behaviour of different vehicle types. The percentile distribution and the probability distribution plots were developed to see the variability for different vehicle type. The vehicle type wise lateral acceleration data with no statistical difference at 5% significance level from different cities are combined to generate the model for longitudinal acceleration/deceleration. The 85th percentile values A/D data w.r.t. the operating speed is modelled for combined data of each type of vehicle.

4.2.1 Variation of Longitudinal A/D Behaviour with Different Road Width

The vehicle trajectory data was collected in different cities including roads of different number of lanes, i.e. different width of the roadway. The variation in A/D behaviour of all five type of vehicles are studied by comparing their A/D on different roads. The Figure-4-1 and 4-2 present the lane wise variation of average A/D over speed separately. The A/D of different vehicles are clustered over each 5 km/h speed. It can be observed from Figure 4-1 and 4-2 that there is no difference between the A/D behaviour of all five vehicles for 2-lane and 3-lane roads. T-tests are conducted between the A/D behaviour of different vehicles for each city to know the significant mean difference between the 2-lane and 3-lane roads by assuming equal variance with hypothetical mean difference of zero. The details of t-test results are presented below in Table 4.1.

From Table 4.1 it is clear that there is no significant difference between the longitudinal A/D for 2-lane and 3-lane roads of each city for all four type of vehicles (t-statistics > t-critical). Hence, it can be concluded that the road width does not have a significant impact on the longitudinal A/D behaviour of vehicles. So, for further analysis of longitudinal A/D, the combined data of 2-lane and 3-lane roads are used for each vehicle type. In the next subsection, the variation of longitudinal A/D behaviour of different vehicles are studied.

Table 4-1 Details of t-test for all four type of vehicles (2W is not included*) of each city

	Vehicle Type	Acceleration		Deceleration	
		t-stat	t-critical	t-stat	t-critical
Delhi	3W	-0.90	1.74	0.57	1.74
	H-Back	1.11	1.72	0.09	1.72
	Sedan	-0.70	1.74	0.43	1.71
	SUV	2-lane Data not available			
Kolkata	3W	-0.87	1.78	-0.89	1.78
	H-Back	-0.14	1.70	-0.15	1.70
	Sedan	-0.80	1.70	0.37	1.70
	SUV	-0.60	1.71	-0.62	1.71
Bengaluru	3W	0.59	1.73	0.22	1.73
	H-Back	-0.93	1.78	0.25	1.79
	Sedan	0	1.73	-0.24	1.73
	SUV	1.29	1.74	-0.46	1.74
Mumbai	3W	-1.20	1.73	0.31	1.73
	H-Back	Data not available			
	Sedan	1.08	1.70	0.28	1.70
	SUV	-0.57	1.71	-0.28	1.70
Pune	3W	1.26	1.74	0.54	1.74
	H-Back	0.12	1.72	0.22	1.71
	Sedan	-0.84	1.71	-0.73	1.71
	SUV	0.38	1.71	-0.62	1.71

3W-Motorized three-wheeler, H-back, Sedan and SUV are three type of cars, t-stat-T-statistics value
* as the VBOX data of motorized 2W are not available for 3-lane roads of each cities

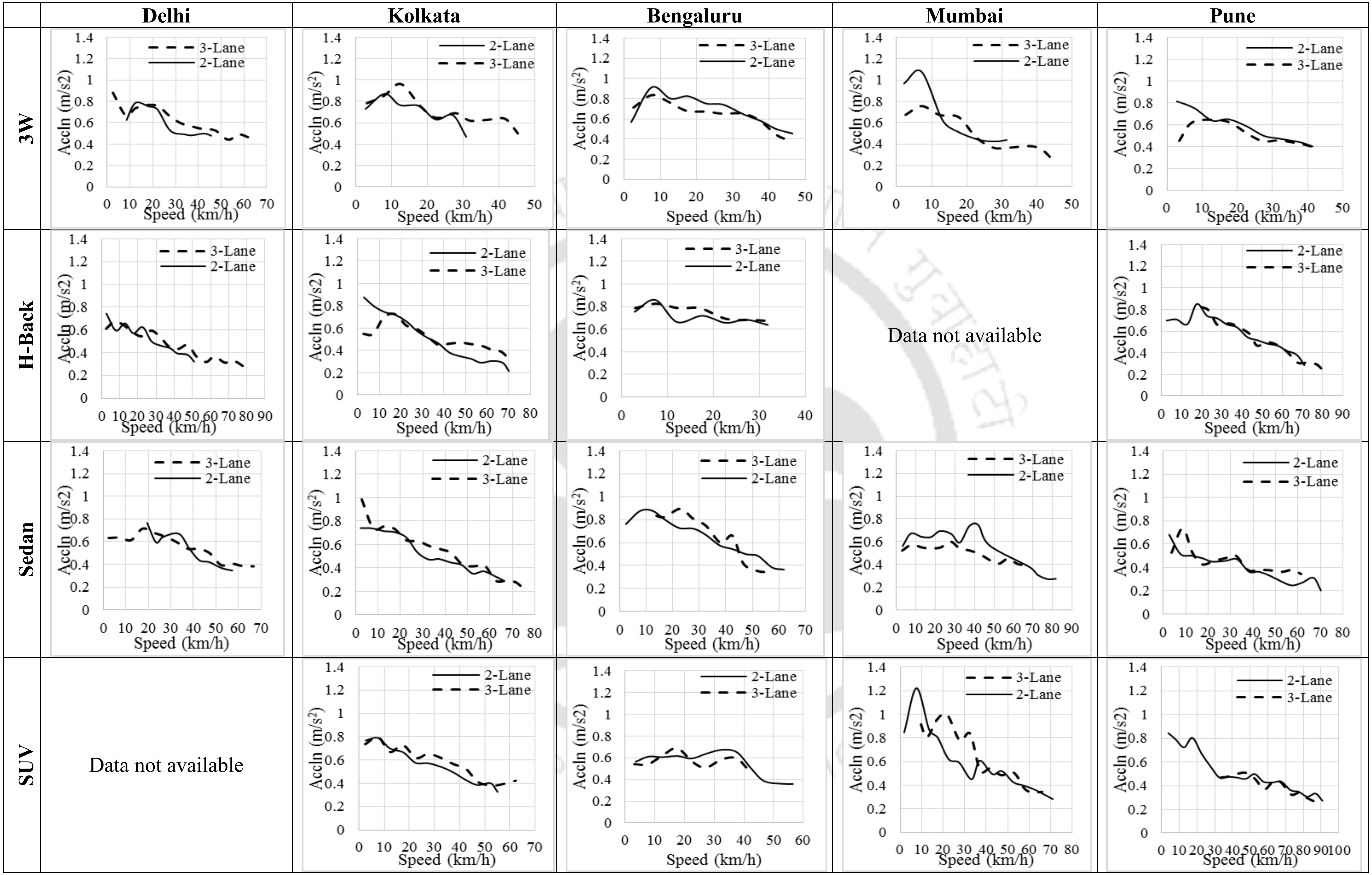


Figure 4-1 Variation in Longitudinal Acceleration with operating speed for roads with different number of lanes (2-lane/ 3-lane) Accln represents longitudinal Acceleration

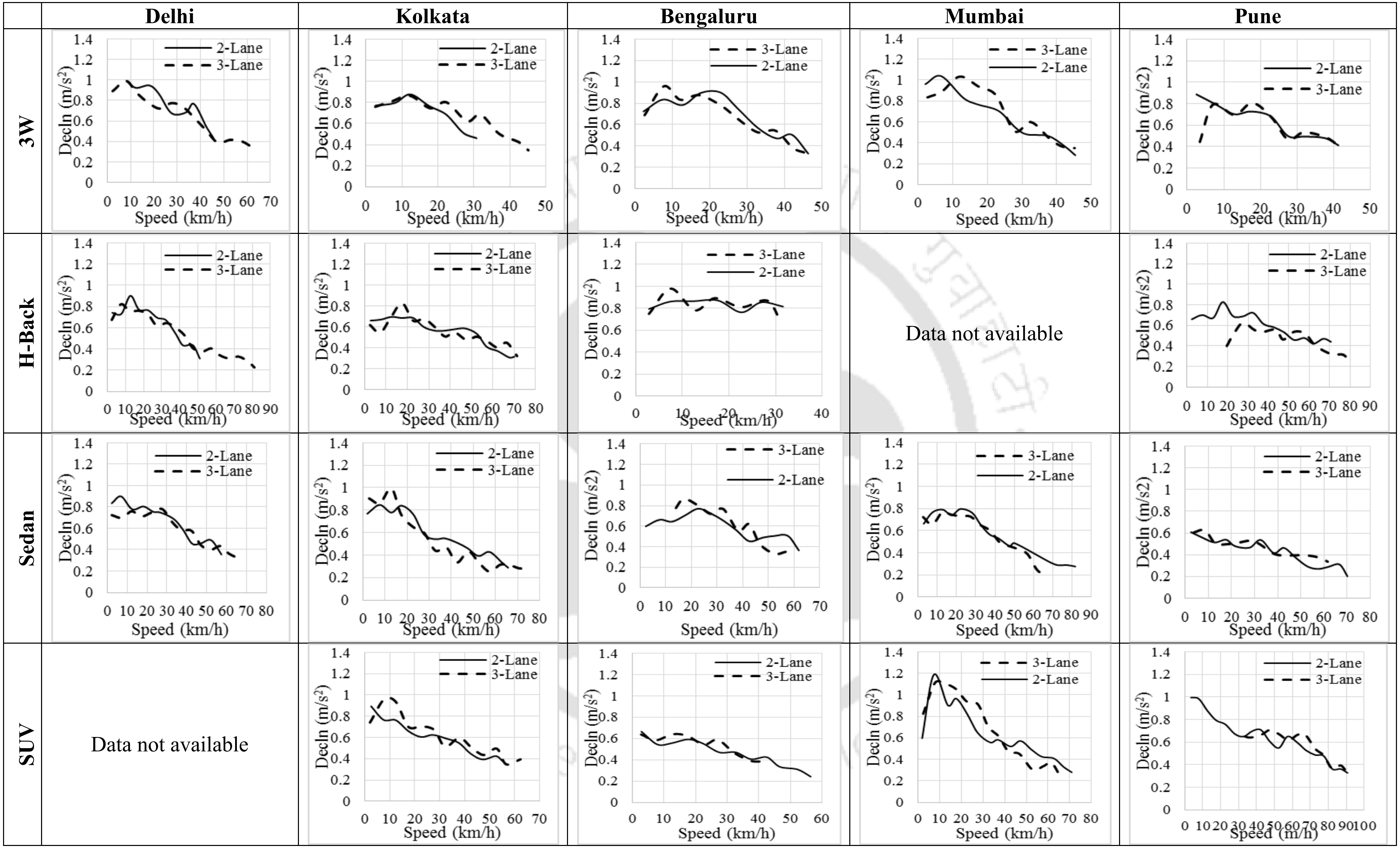


Figure 4-2 Variation in Longitudinal Deceleration with operating speed for roads with different number of lanes (2-lane/ 3-lane) Decln represents longitudinal Deceleration

4.2.2 Variation of Longitudinal A/D for Different Type of Vehicles

The variation in longitudinal A/D of different vehicle type are studied by plotting the A/D of different vehicles with their operating speed for each city separately. The A/D of different vehicles are clustered over each 5 km/h speed. The average value of A/D with each speed group are plotted below. The A/D data of 2-lane and 3-lane roads are combined, as there is no significant difference is observed in the previous subsection.

From the Figure 4-3, it can be observed that motorized 2W have higher longitudinal A/D rates comparing to other vehicles. The A/D rates are higher at lower speed conditions (i.e. speed up to 30 km/h) and then it decreases gradually with increase in operating speed of all vehicles. Initially, at lower speeds, vehicles accelerate to the maximum possible to attain the desired maximum speed afterwards it decreases with the increase in speed. At lower speed (up to 30 km/h) the acceleration values are higher for all type of vehicles. Again, it is observed that vehicle cannot apply break or decelerate suddenly while driving at higher speed (>50 km/h) during the normal driving conditions. It decelerates slowly or gradually and applies the maximum brake/deceleration after reaching to a safe lower speed (<30km/h). It can be observed that for normal driving conditions at straight mid-block sections, the range of average longitudinal A/D varies between 0.2 m/s^2 to 1.2 m/s^2.

Analysis of variance (ANOVA) test is conducted to see the significance of the A/D samples of all five type of vehicles at 5% significance level ($p < 0.05$). The result of the ANOVA test is presented below in Table 4.2.

Table 4-2 Detail of ANOVA test conducted between different types of vehicles for each city

City Name	Acceleration			Deceleration		
	$F_{critical}$	$F_{statistics}$	Pvalue	$F_{critical}$	$F_{statistics}$	Pvalue
Delhi	3.16	10.34	3.49×10^{-4}	3.00	5.37	5.63×10^{-3}
Kolkata	2.63	16.39	3.65×10^{-7}	2.63	9.53	2.31×10^{-5}
Bengaluru	2.58	17.66	1.03×10^{-8}	2.63	40.98	6.24×10^{-13}
Mumbai	3.55	0.88	0.42	3.55	1.42	0.26
Pune	2.66	13.27	1.76×10^{-6}	2.66	13.82	1.18×10^{-6}

It is observed that P_{value} is less than 0.05 in all cities except Mumbai, where P_{value} indicates the estimated probability for rejecting or accepting the null hypothesis. It is also observed that, $F_{statistics} > F_{critical}$ where $F_{statistics}$ describes the statistically expected level of difference in the population and $F_{critical}$ value is the number that the test statistics must exceed to reject the null hypothesis. From Table 4.2 it is concluded that, the null hypothesis are

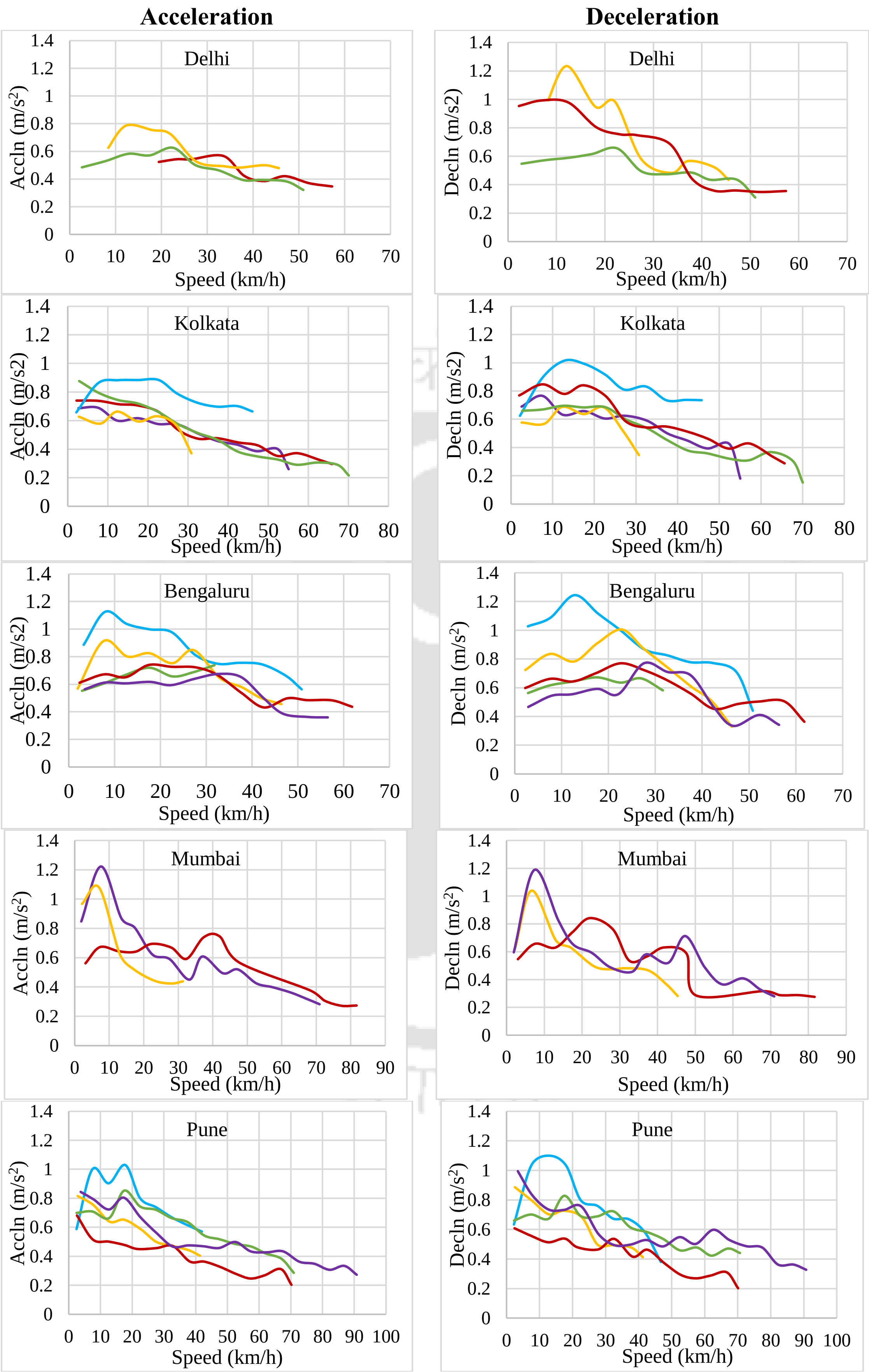


Figure 4-3 Variation in Longitudinal A/D with operating speed of different vehicle types

Motorized two-wheeler (2W), Motorized three-wheeler (3W), H-Back, Sedan and SUV cars accepted for all cities except Mumbai. Hence, a significant difference is observed between the A/D data of different vehicle types for all cities. Hence, the longitudinal A/D behaviour of different vehicles are studied further for different vehicles separately.

4.2.3 Variation of Longitudinal A/D for Different Cities

The longitudinal A/D data are collected from five major cities of India from five different regions with five type of instrumented vehicles. The vehicles are driven by drivers of different regions. Hence, to know the variation in driving behaviour of drivers in different cities, a comparative study of A/D behaviour of five type of vehicles in different cities is done. The average A/D of all type of vehicles (combined data of 2-lane and 3-lane roads) as there is no significant difference are observed (refer subsection-4.2.1) with respect to their operating speed are plotted separately for different cities.

It can be observed that the average A/D of different vehicle follows similar trend for different cities. Analysis of Variance (ANOVA) test is conducted for each vehicle type data collected from different cities to know the significance difference between them. A significant difference is observed in few cases like acceleration data of H-Back and Sedan cars between Delhi-Pune cities and Bengaluru-Pune cities respectively at 5% significance level. Similarly, there is a significant difference between the deceleration data of Sedan cars between Delhi-Pune cities and also SUV cars between Bengaluru-Pune and Bengaluru-Mumbai cities. The following Table presents the details of ANOVA test results for different cities.

From Table 4.3, it can be observed that there are very less pair of cities where the significant difference between means are observed for A/D of different vehicles at 5% significance level. So, for further analysis the A/D data of each vehicle type from different cities are combined to see the general behaviour of different vehicles at no-lane disciplined mixed traffic throughout the country.

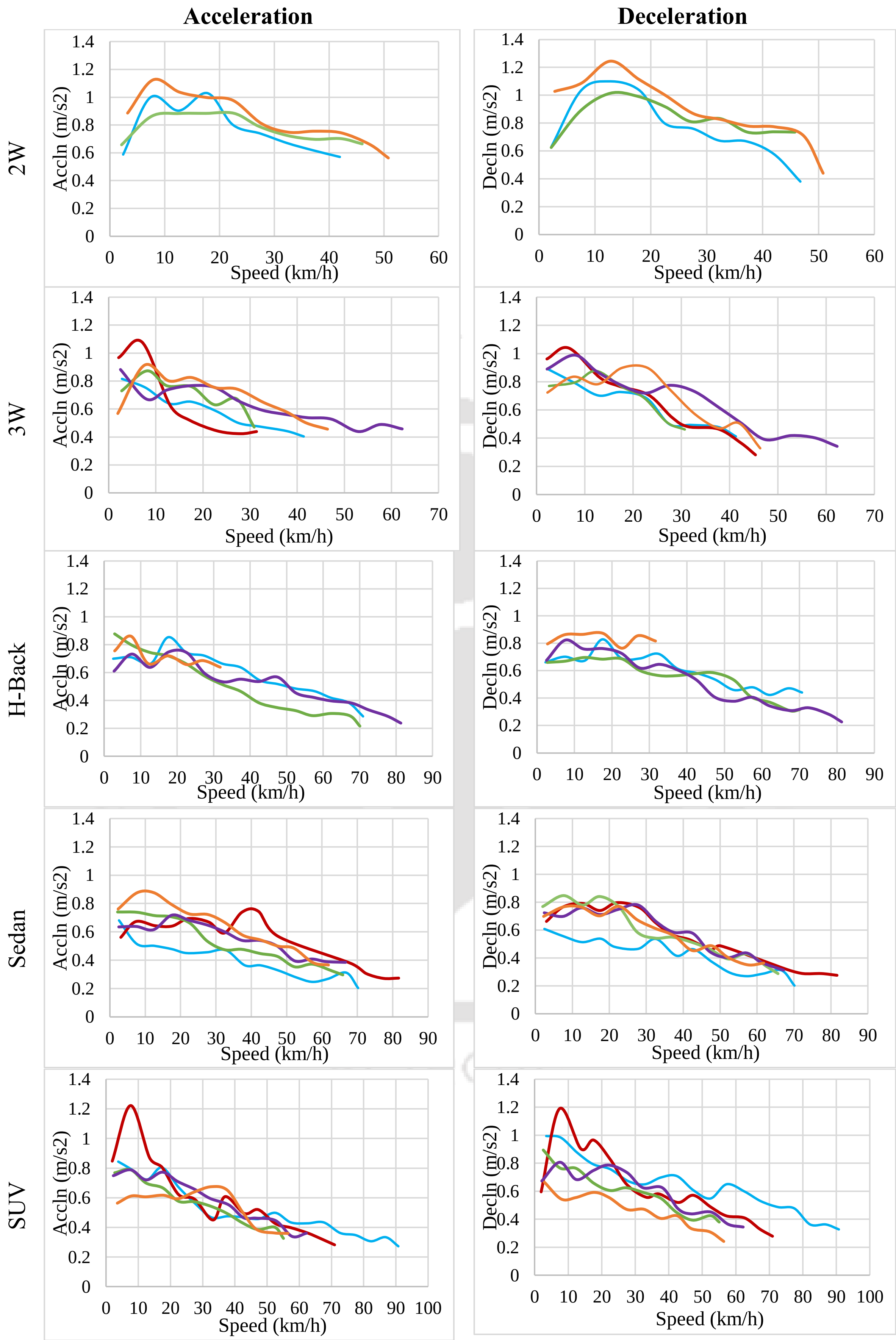


Figure 4-4 City wise variation of Longitudinal A/D of different vehicles

Pune, Mumbai, Kolkata, Delhi, Bengaluru

Table 4-3 Detail result of ANOVA test conducted for different vehicle types of different pair of cities

Pair of Cities	Acceleration					Deceleration				
	2W	3W	H-Back	Sedan	SUV	2W	3W	H-Back	Sedan	SUV
Mumbai Pune	×	0	×	0	0	×	0	×	0	0
Kolkata Pune	0	0	0	0	0	0	0	0	0	0
Kolkata Mumbai	×	0	×	0	0	×	0	×	0	0
Delhi Pune	×	0	1	0	0	×	0	0	1	0
Delhi Mumbai	×	0	×	0	0	×	0	×	0	0
Delhi Kolkata	×	0	0	0	0	×	0	0	0	0
Bengaluru Pune	0	0	×	1	0	0	0	×	0	1
Bengaluru Mumbai	×	0	×	0	0	×	0	×	0	1
Bengaluru Kolkata	0	0	×	0	0	0	0	×	0	0
Bengaluru Delhi	×	0	×	0	0	×	0	×	0	0

(×)-No significant data, (0)-There is no significant difference between the means at 5% significance level, (1)-Significantly different between means at 5% significance level.

4.2.4 Study of Longitudinal A/D for Combined Data from all Cities

The longitudinal acceleration is divided into two parts, i.e. acceleration data and deceleration data. The data with no significance difference between different cities are combined for each vehicle type to see the general behaviour of acceleration and deceleration (A/D) of different vehicles. Further, no significant difference is observed between the longitudinal A/D on roads of 2-lane and 3-lane in each direction indicating no impact of road width on the longitudinal behaviour of vehicles (as described in subsections-4.2.1). Hence, the longitudinal A/D behaviour is studied by combining the data of 2-lane and 3-lane roads.

The percentile distribution and the probability distribution plots are developed to see the longitudinal behaviour variability for different vehicle type. The variation of 85th and 95th percentile values of longitudinal acceleration/deceleration with the operating speed are modelled for each vehicle types separately.

4.2.4.1 Distribution of Longitudinal Acceleration/Deceleration (A/D)

The percentile distributions of A/D are plotted to see the individual behaviour of a different type of vehicles in the mixed no lane based traffic. The following figure depicts the distribution of combined A/D data for various vehicle types.

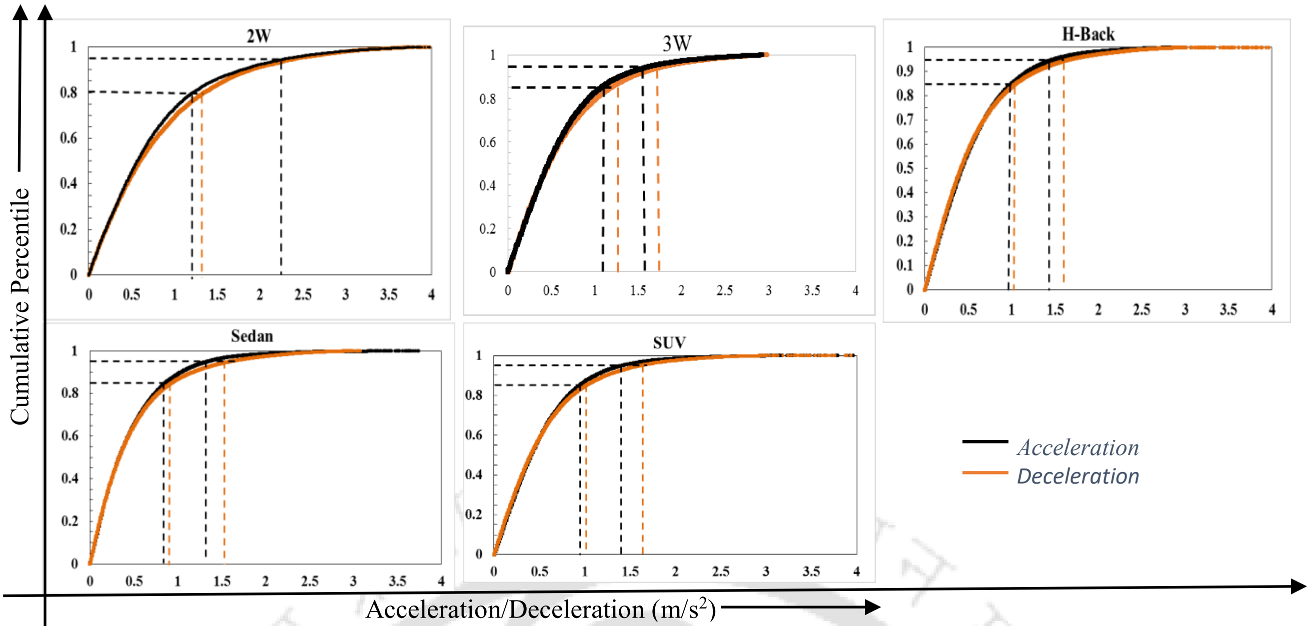


Figure 4-5 Percentile Distribution A/D rates for all five different vehicle types

Figure 4-5 depicts the cumulative frequency curves of longitudinal A/D for each type of vehicles. The cumulative percentile curve of A/D increases and then maintains a constant value after attaining the maximum value. The breakpoint is the point from where the slope of A/D trend changes. It has been observed that the breakpoints of the cumulative percentile curves do not appear exactly at 85th percentile value in all cases. The breakpoint lies somewhere between 85th and 95th percentile. In most of the design practice, the value of 85th percentile is taken for design purposes. Hence, a fresh evaluation of the concept of the 85th percentile for design purposes may be needed. This result is similar to the findings by Xu et al. (2017). The 85th and 95th percentile values are also indicated in Figure 4-5 as well as presented in Table 4.4. It is observed that the 85th and 95th percentile values of deceleration are greater than acceleration for all vehicles. The deceleration characteristics and the braking performance depends on the braking coefficient provided to the road surfaces (f), the pavement conditions, the tire condition and type of braking system. The deceleration rate can increase up to ($f.g$). On the other hand, the acceleration capability of a vehicle is dependent on its mass, the resistance to motion and power of the vehicle (power to weight ratio). The difference in acceleration rates for different vehicles is quite significant in mixed traffic stream (because of heterogeneity in vehicle types). Hence, it is important to analyse the A/D behaviour separately.

It has been observed that the 85th percentile acceleration values are different for different vehicle types. The values are higher in the case of motorised 2W and 3W; then it reduced for cars (H-Back, Sedan and SUV cars). This indicates more frequent application of acceleration/braking by motorized 2W and 3Ws while passing/filtering through the traffic to achieve their desired speed. Table 4.4 lists the 85th, 95th percentile A/D rates extracted from cumulative percentile curves.

Table 4-4 Observed 85th and 95th percentile A/D rates for different vehicles at different roads (2-lane/3-lane)

	Acceleration (m/s^2)			Deceleration (m/s^2)		
	Average	85th Percentile	95th Percentile	Average	85th Percentile	95th Percentile
2W	0.78	1.45	2.33	0.83	1.58	2.43
3W	0.57	1.07	1.65	0.61	1.18	1.82
H-Back	0.54	1.04	1.54	0.56	1.04	1.66
Sedan	0.53	0.95	1.45	0.56	1.06	1.77
SUV	0.52	0.94	1.38	0.55	1.03	1.63

In the past, though many studies have been conducted on the A/D measurement of vehicles, most of them refer to the maximum acceleration capabilities applied by the drivers. However, drivers rarely use their maximum capabilities of vehicles acceleration/braking except for any emergency situations. Those maximum capability values may not be useful in design except for fixing bounding values for safe driving. Hence, in the present paper, the A/D values are obtained from the normal driving conditions. It can be observed that the 85th and 95th percentile deceleration values of all five type of instrumented vehicles are higher than 1 m/s^2. However, the 85th percentile acceleration values lie below 1m/s^2 except motorized 2Ws and 3W which is higher than the adopted value of 0.85 m/s^2 for both A/D by Echaveguren & Basualto, (2003). This is due to the presence of vehicles with different acceleration or braking capabilities in the mixed traffic stream. These characteristic percentile values can be used in the operating speed prediction models and also can be used to establish the bounding values in case of simulation models.

To describe the detailed statistical properties of A/D, the probability distribution function is analysed for all the five type of vehicles. Various distributions were tried to fit the combined data of different cities (for each type of vehicles). Lognormal, Gamma, Burr and Weibull distributions are fitted well to the data for all vehicle types at 5% significance level. To know the best-fitted distribution amongst all four, Log-Likelihood (LL) value, Akaike Information Criterion (AIC) value and Bayesian Information Criterion (BIC) values are estimated for all these probability distribution functions (PDF). The formulations for the same are presented below.

$$LLF(x) = \ln(\text{PDF of } x) \quad \text{......} \quad 4\text{-}1$$

$$AIC = 2 \times (no.\text{ of fitted model parameters}) - 2 \times (\text{maximum LL}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 4\text{-}2$$

$$BIC = (\text{no. offitted model parameters}) \times ln(\text{no. of observations}) - 2 \times (\text{maximum LL}) \ldots\ldots\ldots\ldots.. 4\text{-}3$$

Separate probability density functions of A/D behaviour of different vehicle types at 5% significance level and the best-fitted distributions are presented in Table 4.5. Though different distributions are fitted well to the A/D data, Weibull and Gamma distributions are best-fitted distributions for most of the vehicle types (except Sedan car) with different shape and scale parameter. The deceleration data of Sedan car follows Burr distribution as the best-fitted distribution at 5% significance level. The best-fitted distributions for A/D behaviour of all five types of vehicle on different roads (2-lane & 3-lane data are combined) are presented in Figure 4-6 and 4-7 respectively. The list of different parameter values of all the best-fitted distributions shown in the above figure is presented below in Table 4.5.

Table 4-5 Comparison of performance measures for various probability models fitted for A/D of different vehicles

	Acceleration				Deceleration			
	Distributions	**LL**	**AIC**	**BIC**	**Distributions**	**LL**	**AIC**	**BIC**
2W	LogNormal	-17022	34048	34063.07	LogNormal	-11026	22056	22071
	Gamma	-10729	21462	21477.07	**Gamma**	**-10982**	**21968**	**21983**
	Burr	-29175	58356	58378.6	Burr	-26887	53780	53802
	Weibull	**-10634**	**21272**	**21287.1**	Weibull	-16007	32018	32033
3W	LogNormal	-7838.9	15681.8	15697.15	LogNormal	-8289	16582	16597.8
	Gamma	**-7829.9**	**15663.8**	**15679.1**	Gamma	-19760	39524	39539.2
	Burr	-38082	76170	76193.02	Burr	-34662	69330	69352.8
	Weibull	-22132	44268	44283.35	**Weibull**	**-8204**	**16412**	**16427.2**
H-Back	Lognormal	-21874	43752	43769.6	Lognormal	-65484	130972	130989
	Gamma	**-21696**	**43396**	**43413.6**	Gamma	-21853	43710	43727
	Burr	-120670	241346	241372.4	Burr	-120220	240446	240472
	Weibull	-68381	136766	136783.6	**Weibull**	**-21365**	**42734**	**42751**
Sedan	Lognormal	-51888	103780	103797.1	Lognormal	-89697	179400	179425.3
	Gamma	-14373	28750	28767.06	Gamma	-16120	32244	32260.9
	Burr	-96228	192462	192487.6	**Burr**	**-15054**	**30112**	**30128.9**
	Weibull	**-13708**	**27420**	**27437.1**	Weibull	-45226	90456	90472.9
SUV	Lognormal	-51039	102082	102098.9	Lognormal	-44886	89776	89792.81
	Gamma	-12411	24826	24842.94	Gamma	-14411	28826	28842.81
	Burr	-90009	180024	180049.4	Burr	-83148	166302	166327.2
	Weibull	**-12366**	**24736**	**24752.9**	**Weibull**	**-13915**	**-27834**	**27850.8**

2W-Motorized two-wheelers, 3W-Motorized three-wheelers, SUV, Sedan and H-Back are three different types of passenger cars, LL-Log-Likelihood Value, AIC- Akike's Information Criterion, BIC- Baysian Information Criterion

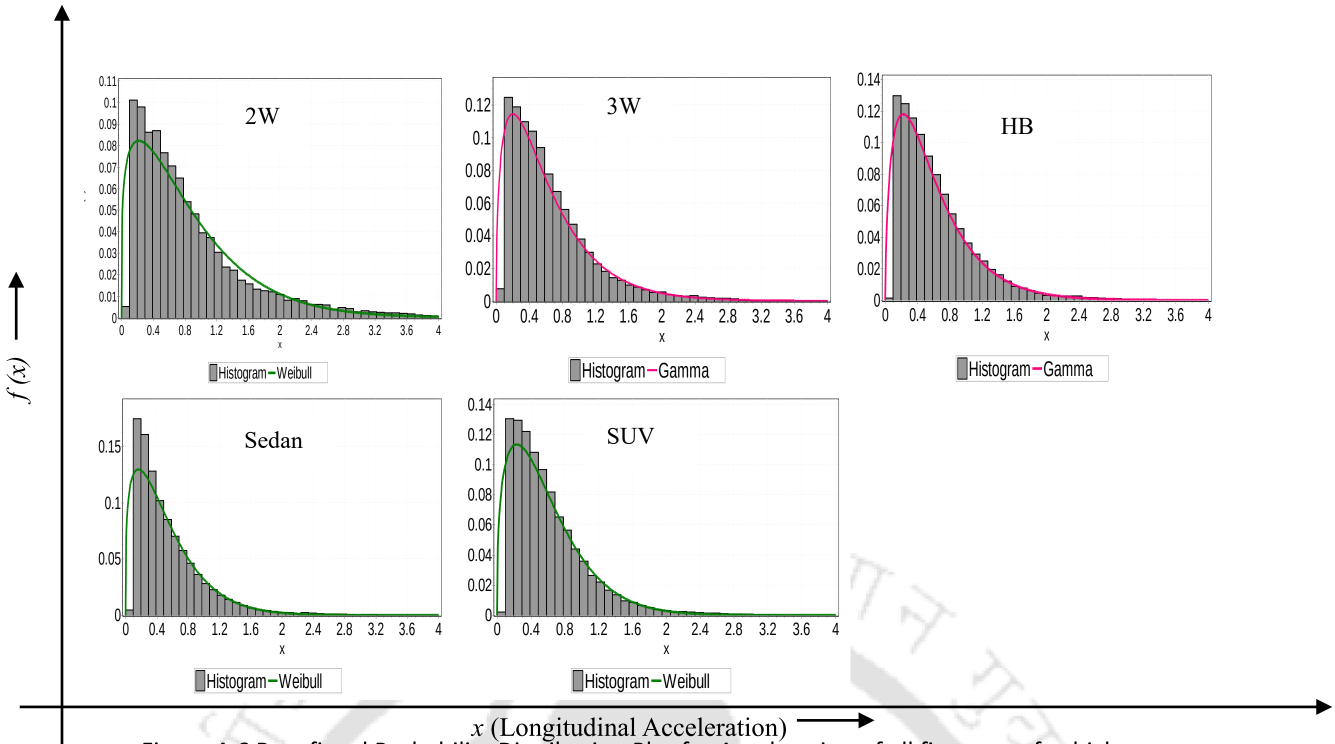


Figure 4-6 Best fitted Probability Distribution Plot for Acceleration of all five type of vehicles

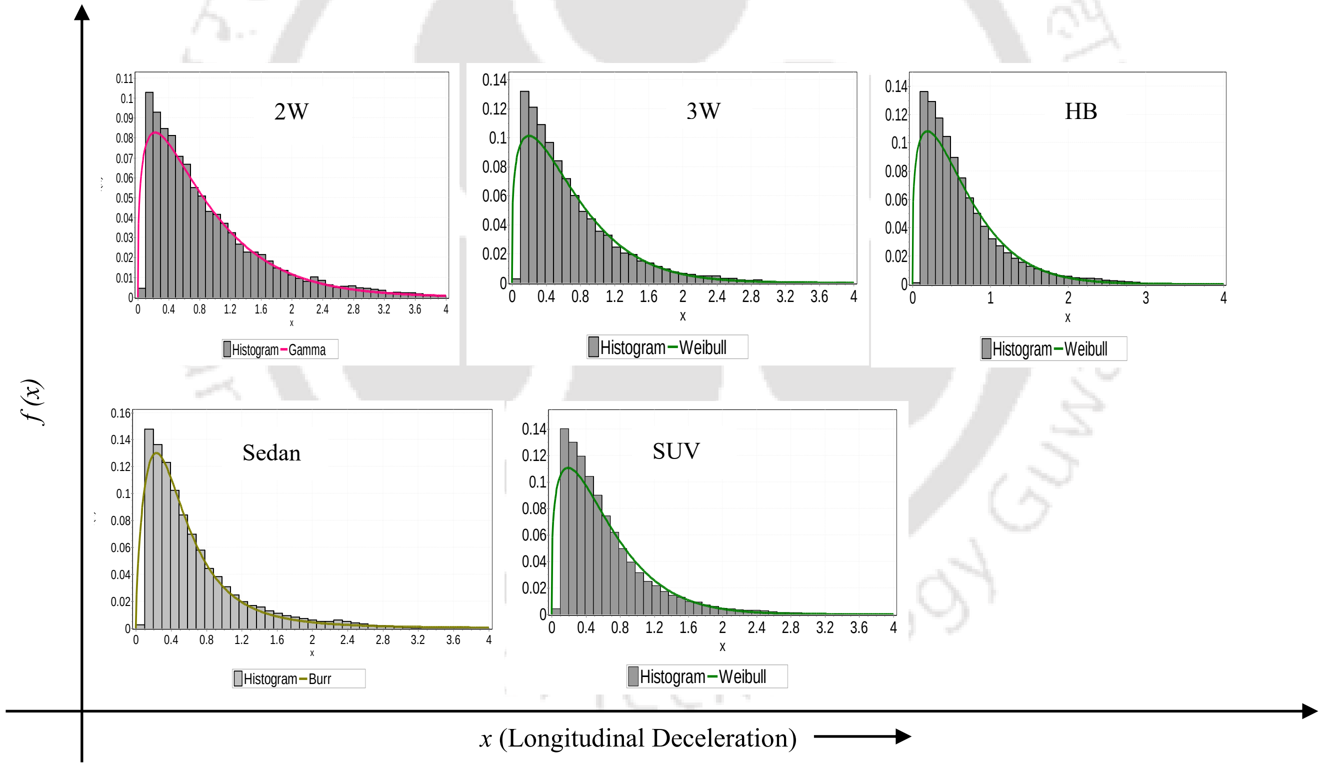


Figure 4-7 Best fitted Probability Distribution Plot for Deceleration of all five type of vehicles

Table 4.6, presents the shape parameters of Weibull distributions fitted to different vehicles A/D have nearly the same value which indicates different distributions with the same moment skewness. In the case of Gamma distribution, the value α >1 shows that the Gamma distributions assume a mounded (uni-modal), but the skewed shape. The scale parameter (β) can stretch or compress the range of both Gamma and Weibull distributions.

Table 4-6 Parametric values of all the best-fitted distributions to different vehicles on different roads

	Acceleration		Deceleration	
SUV	Weibull	α=1.3487, β=0.63165	Weibull	α=1.26740, β=0.6520
Sedan	Weibull	α=1.265, β=0.556720	Burr	κ=1.8655, α=1.6176, β=0.73534
H-Back	Gamma	α=1.5887, β=0.37620	Weibull	α=1.2598, β=0.66852
3W	Gamma	α=1.4763, β=0.41987	Weibull	α=1.2513, β=0.71535
2W	Weibull	α=1.218, β=0.889730	Gamma	α=1.3429, β=0.65155

(α=shape parameter, β=scale parameter; for gamma distribution & Weibull distributions, k, α=shape parameter, β=scale parameter parameters of Burr distribution)

The probability distribution (PDF) of the longitudinal A/D of the different vehicle indicates that the PDF of all five type of vehicles follows similar distribution (Weibull/Gamma) in all cases except few (Deceleration of Sedan; Burr), at 5% significance level. Hence, it can be concluded that longitudinal manoeuvrability of different vehicles on the mixed traffic stream can be explained in a better way by considering other traffic parameters (flow, density, speed). In our present study, it is not possible to measure the flow and density of the whole trajectory as the trajectory length is very high (>40 km) in all different cities. Though the density has a direct impact on the traffic speed, speed is considered as a stream parameter in this study. Therefore, the variability of longitudinal A/D with speed at the normal driving condition on straight road sections are explored in the next section.

4.2.4.2 Effect of Driving Speed on Longitudinal Acceleration/Deceleration (A/D) Behaviour

To study the effect of speed on A/D behaviour in such traffic stream, the data collected from different cities are combined based on various vehicle types and clustered with various speed groups of 5km/h. The 85^{th} and 95^{th} percentile A/D values are calculated for each different speed groups. Best fitted linear regression lines are obtained for such calculated 85^{th} and 95^{th} percentile A/D values corresponding to different speed groups of vehicles and plotted in Figure 4-8 and 4-9 along with all scattered data of A/D values with speed.

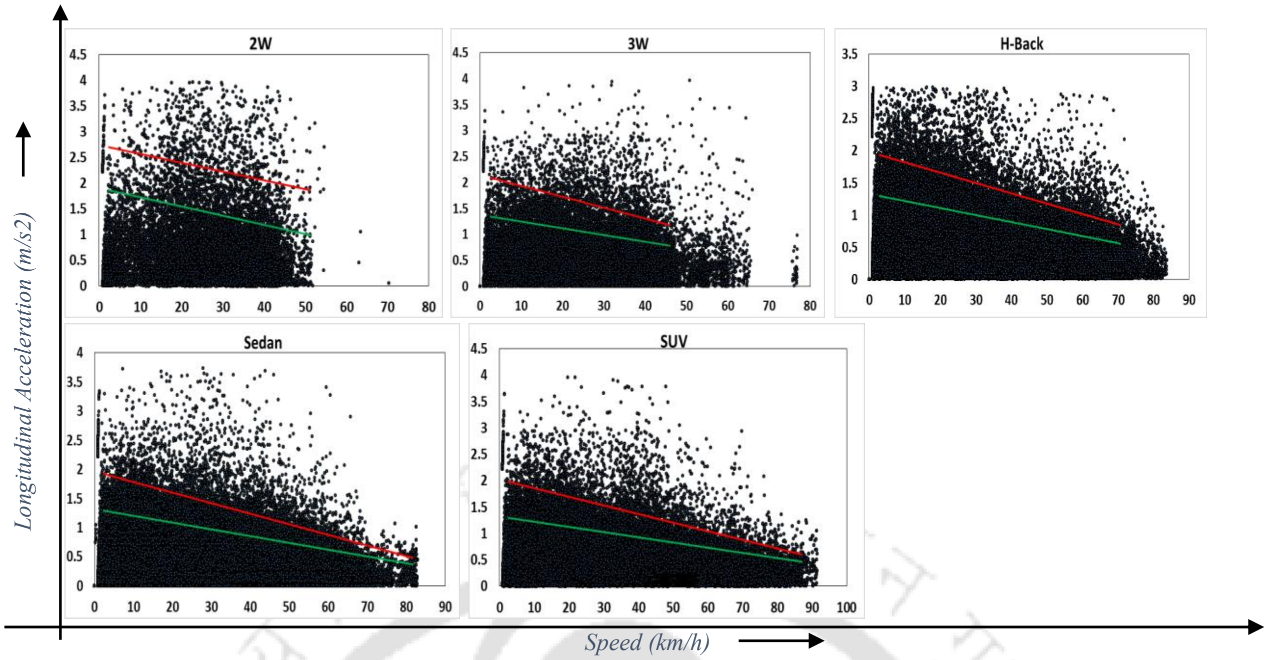


Figure 4-8 Fitted regression models on the scattered Acceleration data of all five type of vehicles

95th percentile and 85th percentile

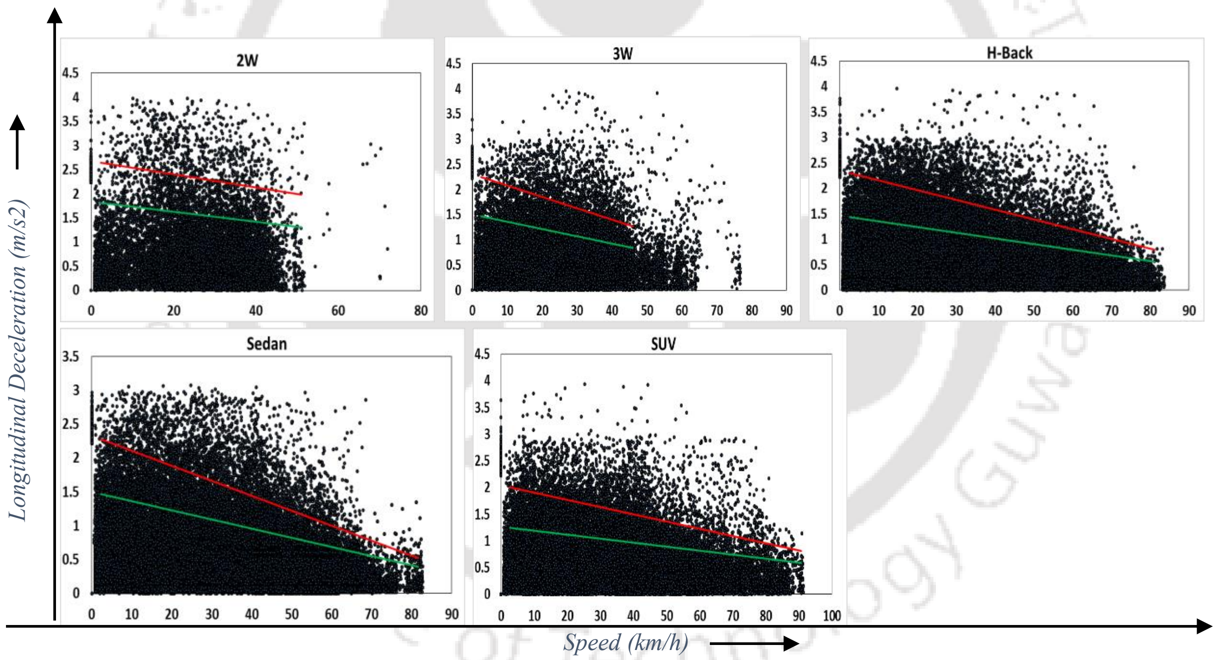


Figure 4-9 Fitted regression models on the scattered Deceleration data of all five type of vehicles

95th percentile and 85th percentile

It can be observed that both the 85th and 95th percentile A/D curve shows a linearly decreasing trend for all vehicle types. Observations depict that the maximum accelerations and deceleration occur at lower speed when the vehicle starting from rest (or approach to rest in deceleration case), the ability to accelerate/decelerate decreases with increase in vehicular speeds. This linearly downward trend is modelled, and statistical tests are conducted to model the 85th and 95th percentile trend of A/D behaviour of all vehicle types. The general linear trend of A/D behaviour is given in Equation 4-4.

$$A\ or\ D = m(v) + n \qquad \text{......4-4}$$

where *A or D*=acceleration or deceleration; *v*=vehicular speed; *m* and *n*=regression coefficients

Table 4.7 describes the details of A/D models' coefficients and the statistical evaluation results (i.e. the r-squared value and Root Mean Squared Error values) of the models describing the A/D behaviour respectively. The R-square value and the RMSE value for each fitted model is calculated. The lower values of RMSE indicates a better fit of the linear models at 5% significance level.

Table 4-7 Regression model coefficients and its statistical evaluation for 85th and 95th percentile **Deceleration** and **Acceleration** data

	Deceleration									
	85th Percentile					**95th Percentile**				
	m	***n***	**R-squared**	**RMSE**	**MAPE**	***m***	***n***	**R-squared**	**RMSE**	**MAPE**
2W	-0.0103	1.837	0.8568	0.0673	18.70	-0.0135	2.678	0.7403	0.1373	16.76
3W	-0.0144	1.498	0.7960	0.1144	19.43	-0.0226	2.304	0.8106	0.1717	17.79
H-Back	-0.0094	1.283	0.7674	0.1195	11.65	-0.0150	2.021	0.8355	0.1523	17.69
Sedan	-0.0135	1.497	0.8871	0.1208	17.39	-0.0220	2.384	0.9465	0.1365	12.95
SUV	-0.0075	1.269	0.8843	0.0780	13.41	-0.0136	2.045	0.9289	0.1082	17.89
	Acceleration									
2W	-0.0180	1.911	0.9057	0.0943	19.14	-0.0170	2.746	0.8254	0.1265	13.12
3W	-0.0129	1.378	0.9627	0.0398	17.21	-0.0208	2.143	0.8220	0.1520	17.53
H-Back	-0.0108	1.332	0.8781	0.0928	12.10	-0.0159	1.976	0.8425	0.1580	14.15
Sedan	-0.0116	1.326	0.9414	0.0753	18.16	-0.0180	1.963	0.9145	0.1430	15.30
SUV	-0.0087	1.246	0.9721	0.0406	11.72	-0.0136	1.836	0.8826	0.1362	8.14

The model fitted to different vehicle data are validated using a new set of data collected from a different city (Guwahati). The MAPE values are obtained to see the accuracy of the predicted linear equation for the 85th and 95th percentile data of longitudinal A/D. As per the Lewis Scale of measurement by Ronald and Kenneth (1982), the MAPE values indicate good fit of the models for the 85th and 95th percentile A/D values.

4.3 Study of lateral Acceleration

The present section focuses on the analysis of the lateral behaviour of vehicles in mixed traffic condition on straight mid-block section of Indian roads. This study includes the observations on the lateral behaviour of different vehicle types (SUV cars, Sedan cars, Hatchback cars, motorized three-wheeler (3W) and two-wheeler (2W)) and the effect of longitudinal speed on lateral behaviour (i.e. lateral acceleration) of vehicle on different types of roads of five metropolitan cities of India in moderate traffic conditions. Analysis of Variance (ANOVA) test has been conducted to know the significance difference between the lateral behavior with respect to the vehicle type as well as the different city. The effect of number of lanes and the effect of different cities on the lateral maneuvering behavior of drivers are studied.

4.3.1 Variation of Lateral Acceleration Behaviour with Different Road Width

Data has also been collected from different roads with different number of lanes (2-lane/3-lane) roads of different cities by using the five types of instrumented vehicles. The average lateral acceleration over 5 km/h speed range is plotted against operating speed of each type of vehicles for different cities (Figure 4-10). It can be observed that the lateral acceleration variation of both the 3-lane and 2-lane roads follow the similar pattern with the operating speed [i.e. it increases at the lower to medium speed range (>30 km/h) and then decreases with the increase in speed at the medium to higher speed ranges (<30 km/h)]. The lateral acceleration of 2-lane roads are always higher than the 3-lane roads in all vehicle cases in all cities. The statistical t-tests are conducted for each type of vehicles in each cities to know the difference in mean at 5% significance level by assuming equal variance with hypothetical mean difference of zero. The detail results t-test are presented in Table 4.8. From Table-4.8, it can be observed that the t-statistics is always higher than the t-critical values indicating significant difference between the lateral acceleration of 2-lane and 3-lane roads for all five type of vehicles in different cities. This indicates that the lateral acceleration of vehicles are impacted by the road width (no. of lane). Hence for further analysis, the lateral acceleration of 2-lane and 3-lane roads are studied separately for each type of vehicles.

Table 4-8 Details of t-test for all five type of vehicles on 2-lane and 3-lane roads of each city

	Delhi		Kolkata		Bengaluru		Mumbai		Pune	
	t_{stat}	$t_{critical}$	t_{stat}	$t_{critical}$	t_{stat}	$t_{critical}$	t_{stat}	$t_{critical}$	t_{stat}	$t_{critical}$
3W	1.75	1.73	-2.13	1.78	-2.43	1.74	-2.43	1.74	-1.76	1.74
H-Back	1.79	1.72	-1.90	1.81	-1.82	1.73	No Data		-1.77	1.71
Sedan	1.74	1.71	-1.88	1.70	-2.93	1.71	-2.93	1.71	-1.84	1.71
SUV	No Data		-3.00	1.73	-2.44	1.79	-2.44	1.79	-3.01	1.71

3W-Motorized three-wheeler, H-back, Sedan and SUV are three type of cars, t-stat-T-statistics value

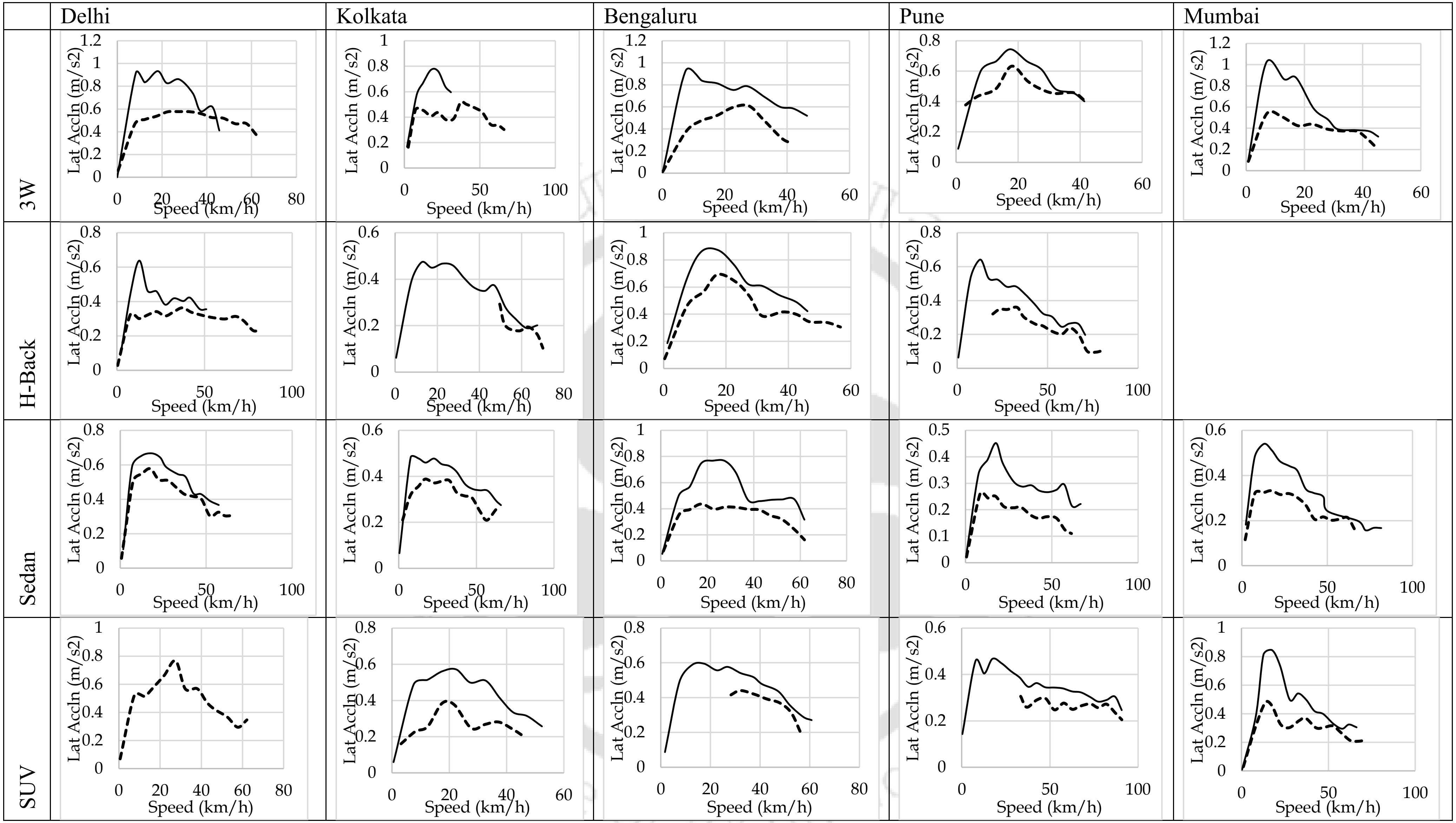


Figure 4-10 Variation in lateral acceleration of different vehicles on 2-lane and 3-lane roads of different cities separately (2W-Motorized two-wheeler, 3W-Motorized three-wheeler, H-Back, Sedan and SUV are three types of passenger cars, the dotted lines and solid lines indicates the average lateral acceleration of 3-lane 2-lane road respectively)

4.3.2 Variation of Lateral Acceleration for Different Type of Vehicles

Lateral acceleration is an important lateral characteristic of a vehicle which decides the weaving rate of the vehicle. The data pertaining to the lateral acceleration at different longitudinal speeds during all trips of a vehicle has been sorted. In order to see the average behaviour, lateral acceleration values are averaged over every 5 km/h longitudinal speed range and plotted against the longitudinal speed. The result of all five type of vehicles for all five different cities of India (i.e. Kolkata, Mumbai, Pune, Delhi and Bengaluru) only for 4-lane divided roads (2-lane) and 6-lane divided roads (3-lane) are presented below in Figure 4-11.

From the above figure, it can be observed that there exists a relationship between the lateral acceleration and the longitudinal speed for all vehicle types. It is also observed that for all class of vehicles, lateral acceleration values are low at near zero speed and it quickly increases with the increase in speed (lower to medium speed, i.e. up to ≈15 km/h). Further, a maximum lateral acceleration value is attained with the increase in the speed. The Hatchback, Sedan and SUV, all three types of cars have more or less same type of lateral behaviour. The average lateral acceleration lies within 0.4 m/s^2, whereas the 2W and motorized 3W have high average lateral acceleration than the cars, i.e. up to 1 m/s^2. The average lateral acceleration values remain low (as compared to the maximum lateral acceleration values) at speed greater than medium speed, i.e. speed >30km/h approximately. This states that the lateral manoeuvrability is generally high at lower speed and reduces at higher speed. This behaviour is because the driver does not feel safe for high lateral weaving at higher speed. It is also observed that 2W shows the highest lateral acceleration than the other vehicles. It can be concluded that the lateral manoeuvrability increases with the decrease in the size of the vehicles.

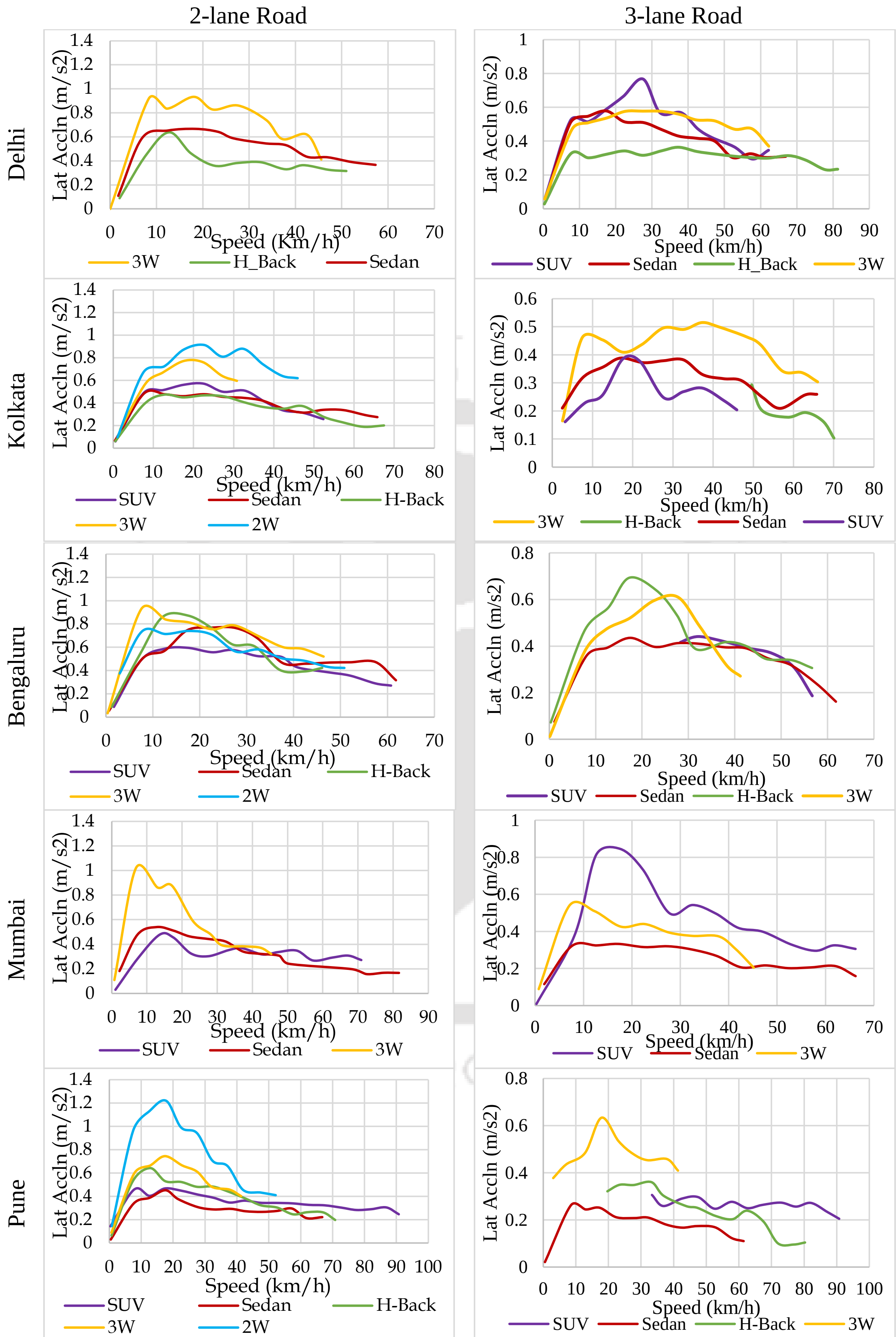


Figure 4-11 Vehicle type wise variation of average lateral acceleration w.r.t. operating speed on 4-lane and 6-lane (2-lane and 3-lane roads) divided roads for five different cities of India

Analysis of variance (ANOVA) test is conducted to see the significance of all five type of vehicles. It is observed that P_{value} is less than 0.05, where P_{value} indicates the estimated probability for rejecting or accepting the null hypothesis It is also observed that, $F_{statistics} > F_{critical}$ where $F_{statistics}$ describes the statistically expected level of difference in a population and $F_{critical}$ value is the number that the test statistics must exceed to reject the test. Hence, the lateral acceleration for all five types of vehicles on both 4-lane and 6-lane divided roads (2-lane and 3-lane roads) are significantly different at 5% significance level. The null hypothesis assuming equal mean is rejected. The details of the ANOVA test results are presented in Table 4.9.

Table 4-9 Results of ANOVA test conducted for different vehicle types on different cities on 2—lane and 3-lane roads separately

City Name	2-lane Road			3-lane Road		
	F_c	F_s	P	F_c	F_s	P
Delhi	2.45	4.85	0.01	2.03	7.20	3.58×10^{-4}
Kolkata	2.50	8.34	2.69×10^{-5}	2.53	13.10	4.20×10^{-6}
Bengaluru	2.58	2.77	0.03	2.38	3.05	0.02
Mumbai	2.45	6.21	0.09	2.45	5.87	0.07
Pune	2.24	7.52	4.53×10^{-5}	2.16	4.08	1.19×10^{-6}

4.3.3 Variation of Lateral Acceleration for Different Cities

In the present section, a comparative study has been done of all five type of vehicles (SUV cars, Sedan cars, Hatchback, motorized 3W and 2W) for both 2-lane and 3-lane roads of all five cities.

Analysis of Variance (ANOVA) test is conducted between the different cities average lateral acceleration data of different vehicles. The null hypothesis is assumed as the samples have equal variance with zero difference in mean at 5% significance level. The result of ANOVA test conducted for different cities are presented below (Table 4.10) for each vehicle types at both 2-lane and 3-lane roads.

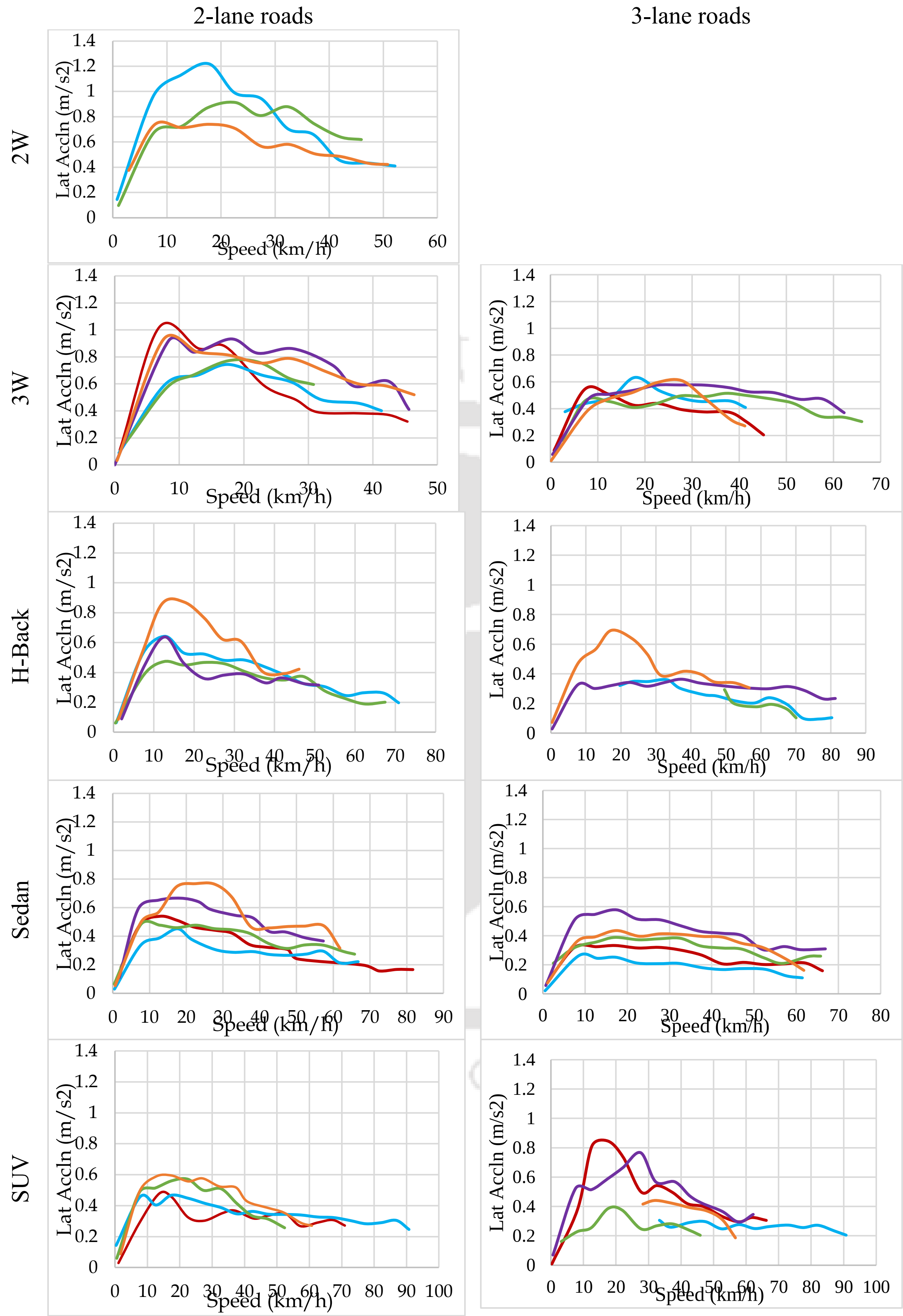


Figure 4-12 City wise variation of Longitudinal A/D of different vehicles

Pune, Mumbai, Kolkata, Delhi, Bengaluru

Table 4-10 Detail results of ANOVA tests conducted for different vehicle types of different pair of cities

	2-lane roads					3-lane roads			
	2W	3W	H-Back	Sedan	SUV	3W	H-Back	Sedan	SUV
Mumbai Pune	×	0	×	0	0	0	×	0	1
Kolkata Pune	0	0	0	0	0	0	0	0	0
Kolkata Mumbai	×	0	×	0	0	0	×	0	1
Delhi Pune	×	0	0	1	×	0	0	1	1
Delhi Mumbai	×	0	×	0	×	0	×	1	0
Delhi Kolkata	×	0	0	0	×	0	0	0	1
Bengaluru Pune	0	0	1	1	0	0	0	0	0
Bengaluru Mumbai	×	0	×	0	0	0	×	0	0
Bengaluru Kolkata	0	0	1	0	0	0	1	0	0
Bengaluru Delhi	×	0	1	0	×	0	1	0	0

(×)-No significant data, (0)-There is no significant difference between the means at 5% significance level, (1)-Significantly different between means at 5% significance level.

From Table 4-10, it is observed that the lateral acceleration of motorized 2W and 3W have no difference in mean at 5% significance level across different cities for both 2-lane and 3-lane road. However, in case of SUV, Sedan and H-back cars, there is no significance difference between different cities except few cases. To study the generalized behaviour of lateral acceleration throughout the country, the variation with respect to different cities are included for further analysis. Hence, the lateral acceleration data for different cities are combined for each vehicle type.

4.3.4 Study of Lateral Acceleration with Combined Data of Different Cities

The lateral acceleration is one of the important parameter, which describes the vehicles lateral behaviour on the road. As observed from the previous chapter (Chapter-2), the lateral acceleration is one of the key factors for lateral stability and driving safety. In case of mixed and no-lane disciplined traffic, the lateral manoeuvre of vehicles is quite prominent. In the present study, to get more generalized result, the lateral acceleration data from all cities are extracted and combined for different vehicle type for 2-lane and 3-lane roads separately only on straight mid-block sections as discussed in next sections. The distribution of lateral acceleration on different roads, i.e. roads with different number of lanes for all five types of vehicles are plotted, and impact of operating speed on lateral acceleration is analysed. The 85th and 95th percentiles values of the lateral acceleration were obtained for each speed groups and modelled to see the trend of extreme lateral acceleration behaviour of different vehicles.

4.3.4.1 Distribution of Lateral Acceleration

Figure 4-13 show the cumulative percentile distribution of the lateral acceleration for combined data (five different cities data) for five type of instrumented vehicles for 2-lane and 3-lane roads separately. The difference in percentile distribution of different vehicles lateral acceleration with respect to 2-lane and 3-lane roads are studied. The 85th percentile of lateral acceleration decreases for 3-lane roads from 2-lane roads. For 2W the 85th percentile lateral acceleration of 4-lane divided roads (2-lane) is highest, and then it decreases successively for 3W, H-Back, Sedan and SUV.

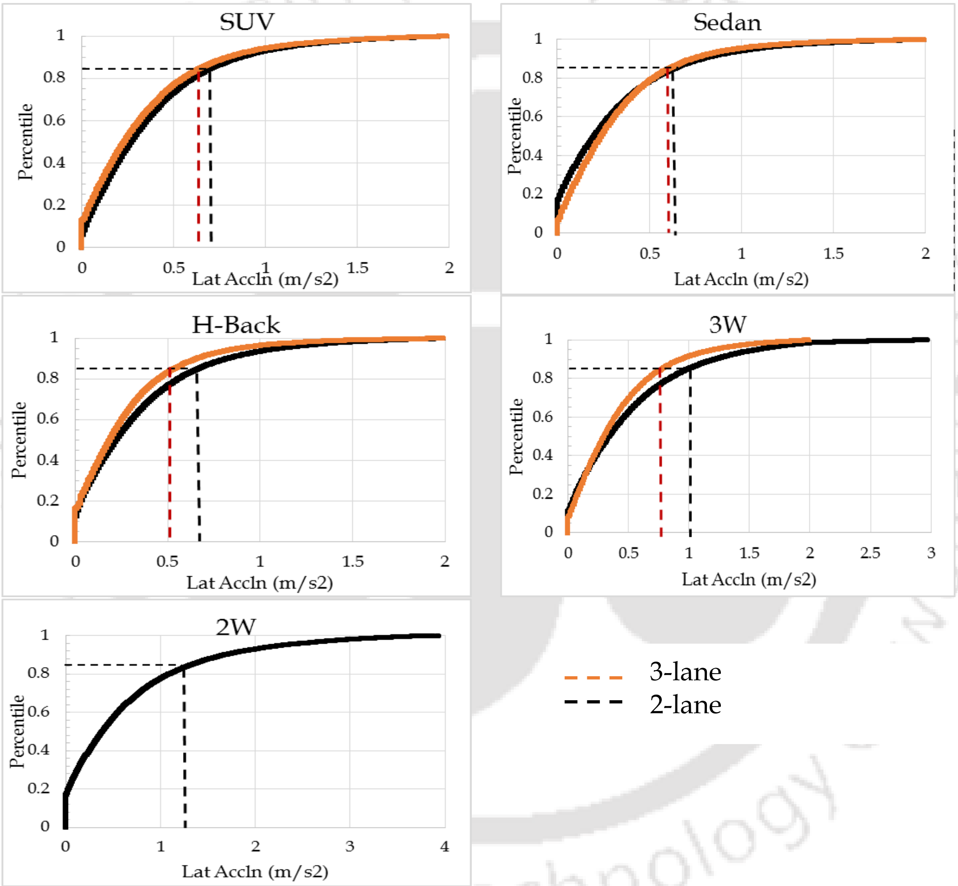


Figure 4-13 Percentile Distribution of lateral acceleration for 4-lane and 6-lane roads (2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan and SUV are three categories of passenger cars)

According to past literature, the threshold value of lateral acceleration for comfort is 1.8 m/s^2 with medium comfort and discomfort levels of 3.6 m/s^2 and 5 m/s^2 (Kilinc & Baybura, 2012; Dixon & Rohani, 2008; Voigt et al., 2003; Cheng, 2007). In the present study, the 2-lane and 3-lane roads have medium comfort level, and this comfort level accounted for more than 85% of the data. The result is similar to the values obtained by Xu et al. (2015). The lateral acceleration values were all smaller than 3 m/s^2, and most were smaller than the threshold value of comfort for normal driving conditions on straight mid-block sections. The 85th percentile values of lateral acceleration for different vehicle types on different roads are presented below in Table 4.11. It can be seen that motorized 2W and 3W are having a higher average lateral acceleration compared to all type of cars.

Table 4-11 City wise 85th percentile Lateral Acceleration values for different vehicle types

Vehicle type	Number of Lanes	Lateral Acceleration (m/s^2)		
		Average	85th	95th
2W	2-lane	0.83	1.78	2.09
	3-lane	Data not available		
3W	2-lane	0.55	1.33	2.54
	3-lane	0.48	0.90	1.63
H-Back	2-lane	0.40	0.94	1.66
	3-lane	0.34	1.05	2.22
Sedan	2-lane	0.33	0.95	1.76
	3-lane	0.39	0.79	1.55
SUV	2-lane	0.38	0.96	1.93
	3-lane	0.38	1.05	1.98

Further, a significant reduction in lateral acceleration values is observed in case of 3W from 2-lane to 3-lane road. This reduction may be caused as driver feels less constrained on wider roads which reduces number of such manoeuvrability. However, such behaviour could not be observed consistently in case of cars.

To describe the detailed statistical properties of lateral acceleration, the lane wise probability distribution function for both types of roads (i.e. 2-lane and 3-lane) are analysed for all the five type of vehicles. Various distributions were tried to fit in the combined data of different cities (3-lane and 2-lane roads). Johnson SB, Normal, Exponential, Gamma and Burr distributions are fitted well to the data for all vehicle types at 5% significance level. To know the best-fitted distribution for all five vehicle types, the Log-Likelihood (LL) value, Akike's Information Criterion (AIC) value, and Bayesian Information Criterion (BIC) values are estimated for all these probability distribution functions as presented by Equation 4-1, 4-2 and 4-3, for longitudinal acceleration/deceleration. The probability density functions of lateral acceleration for different vehicle types at 5% significance level and the best-fitted distributions are presented below in Table 4.12.

Table 4-12 Comparison of performance measures for various probability models fitted for lateral accelerations of different vehicles on 2-lane and 3-lane roads

		4-lane Divided Roads (2-lane)					6-lane Divided Roads (3-lane)				
	Distributions	**KS**	**P**	**LL**	**AIC**	**BIC**	**KS**	**P**	**LL**	**AIC**	**BIC**
2W	Normal	0.17199	0.28435	-31847	63698	63714					
	Exponential	0.16449	0.33397	-48860	97722	97730					
	Gamma	**0.21458**	**0.23788**	**-21321**	**42646**	**42662**					
	Burr	0.21193	0.23788	-72011	144028	144053					
3W	Normal	0.18532	0.2076	-75520	151044	151062	0.17556	0.2076	-19619	39242	39258
	Exponential	0.13988	0.36465	-134500	269002	269011	0.16127	0.21238	-51462	102926	102934
	Gamma	**0.10998**	**0.66363**	**-37455**	**74914**	**74932**	**0.11395**	**0.62059**	**-8546**	**17097**	**17113**
	Burr	0.11346	0.62575	-242580	485166	485194	0.11359	0.62445	-86440	172886	172911
H-Back	Normal	0.17828	0.46397	-18481	36966	36983	0.19316	0.36603	-8437	16879	16895
	Exponential	0.1832	0.4301	-81448	162898	162906	0.20963	0.27417	-70403	140808	140816
	Gamma	**0.14607**	**0.70811**	**-4168**	**8340**	**8357**	**0.15844**	**0.61186**	**1145**	**-2286**	**-2269**
	Burr	0.15397	0.64671	-138210	276426	276452	0.16362	0.57188	-115000	230006	230031
Sedan	Normal	0.18721	0.40353	-24338	48680	48698	0.18062	0.44768	-18792	37588	37605
	Exponential	0.19256	0.36972	-137930	275862	275871	0.20016	0.32477	-111150	222302	222311
	Gamma	**0.15422**	**0.64476**	**-793.7**	**1591.4**	**1609**	**0.14173**	**0.74125**	**-784.2**	**1572.5**	**1590**
	Burr	0.16253	0.58025	-230370	460746	460773	0.14252	0.73526	-181770	363546	363572
SUV	Normal	0.179	0.45893	-25836	51694.23	25836	0.17509	0.4866	-12997	25998	26015
	Exponential	0.18673	0.40669	-125220	250451	125220	0.18954	0.38856	-69659	139320	139328
	Gamma	**0.13985**	**0.75537**	**-5144**	**10310**	**5144**	**0.14439**	**0.721**	**-1746**	**3497**	**3514**
	Burr	0.13426	0.79614	-204720	409473	204720	0.14335	0.729	-114560	229126	229151

2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan and SUV are three categories of passenger cars; one way of 6-lane divided roads (3-lane), One way of 4-lane divided roads (2-lane).

It can be observed that Normal, Exponential, Gamma and Burr distributions are the distributions fitted well to all vehicles at 5% significance level. Gamma distribution is resulting in the maximum LL value and minimum AIC/BIC values for all the vehicle types in all road conditions. The best-fitted distributions (Gamma PDF) for different vehicles at different roads are shown below in Figure 4-14. The parameters for all the best-fitted distribution are presented below in Table 4.13.

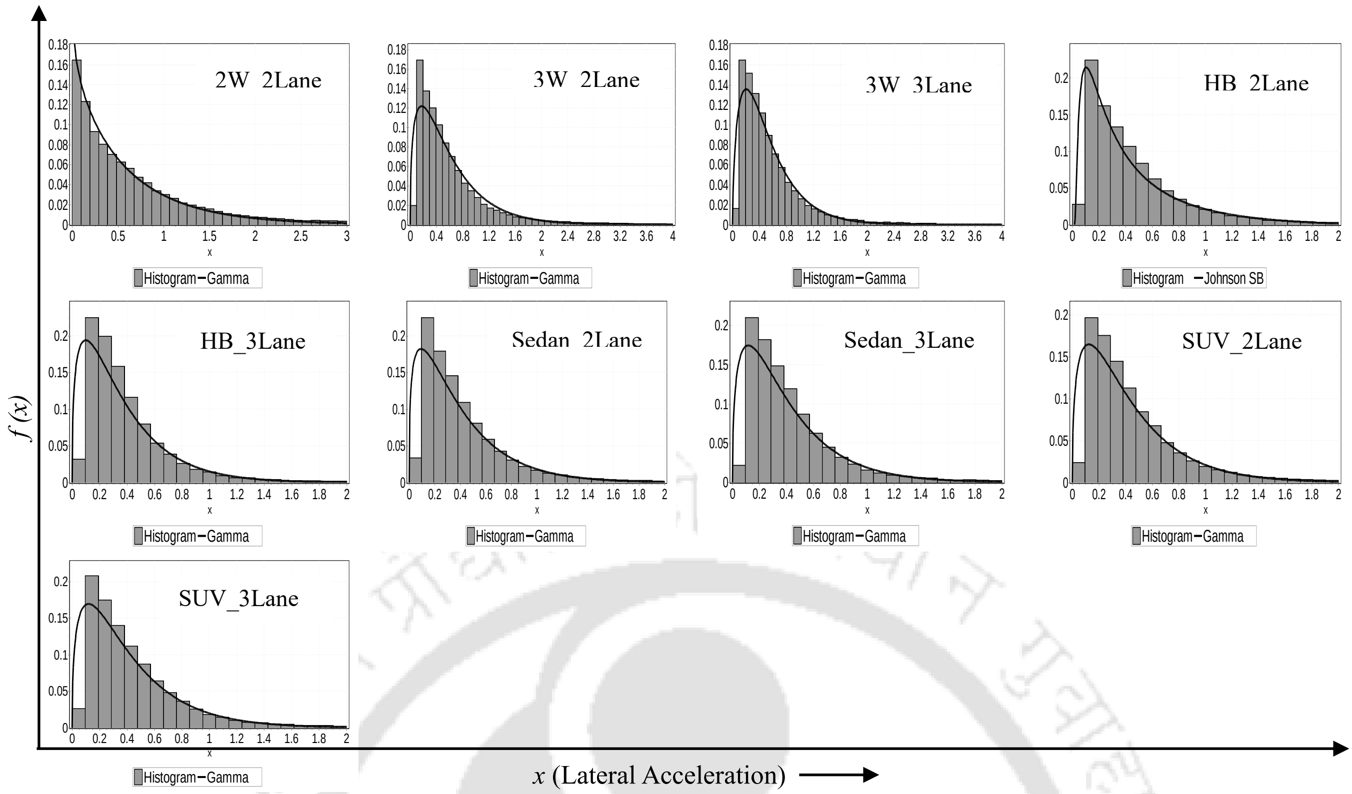


Figure 4-14 Probability Distribution of 2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan & SUV (three categories of passenger cars), 6-lane divided roads, i.e. 3-Lane one way roads, 4-lane divided roads (2-lane)

Table 4-13 Detail Parameters of different PDFs of Lateral Acceleration

SUV	3-lane	Gamma Distribution	α=1.7991, β=0.23495
	2-lane		α=1.799, β=0.24088
Sedan	3-lane		α=1.8483, β=0.22075
	2-lane		α=1.7725, β=0.22774
H-Back	3-lane		α=1.9199, β=0.19462
	2-lane		α=1.6715, β=0.42285
3W	3-lane		α=1.6352, β=0.31834
	2-lane		α=1.4164, β=0.41443
2W	2-lane		α=1.3864, β=0.52477

(α=shape parameter, β=scale parameter; for gamma distribution & σ=scale parameter, μ=location parameter; for Normal distribution)

From the above table, it is observed that the shape and scale parameters of Gamma distributions fitted to different vehicles have nearly same values of α and β. The value α >1 indicates that the Gamma distributions assume a mounded (unimodal), but skewed shape. The similar values of shape parameters of all the different population groups indicate they are the different distributions with the same moment skewness. The scale parameter (β) has the effect of stretching or compressing the range of Gamma distributions. Table 4.13 indicates a similar stretch of the Gamma distributions fitted to different vehicles with same moment skewness.

The lateral acceleration distribution on 2-lane and 3-lane roads for different vehicles indicates that, the PDF of both types of roads follows similar distributions. The similar distributions indicate that lateral manoeuvrability of different vehicles does not depend only on the road width or number of lane. However, other traffic parameters like speed, density etc. have a major impact on the lateral manoeuvre of vehicles on mixed no-lane disciplined traffic. In the next section the variability of lateral acceleration with respect to speed at different width of road, i.e. number of lane.

4.3.4.2 Effect of Driving Speed on Lateral Acceleration

It has been observed from the literature that, lateral acceleration has an inverse relationship with speed. Most of the previous studies were conducted in the lane disciplined traffic and on curved road sections. In the present study the behaviour of lateral acceleration w.r.t. speed for straight roads in mixed and no-lane disciplined traffic on 2-lane and 3-lane one way roads are studied. The model is developed for the 85th percentile lateral acceleration data for different operating speed. The 85th percentile value of lateral acceleration data for different speed ranges (say every 5 km/h group size) is modelled. These 85th percentile lateral acceleration models are plotted over the scatter data of lateral acceleration and speed for different vehicle types, obtained from different cities. It can be observed that, the lateral acceleration follows a non-linear relationship with operating speed of the vehicles.

From the above Figure 4-15, it is observed that in case of 2W the significant data is not available for 3-lane roads. The Two-term exponential model fitted well for all the cases at 5% significance level. The general form of the proposed models is presented in Equation 4-5.

$$y = (a \times e^{bx}) + (c \times e^{dx}) \qquad 4\text{-}5$$

where Y=Lateral Acceleration of different vehicles in m/s2

x=Operationg speed of different vehicles in (km/h)

a,b,c&d are the regression constants

In case of Two-term exponential function, there are two decay modes.The two-term exponential model fitted the data well as compared to the single term exponential function at 5% significance level.

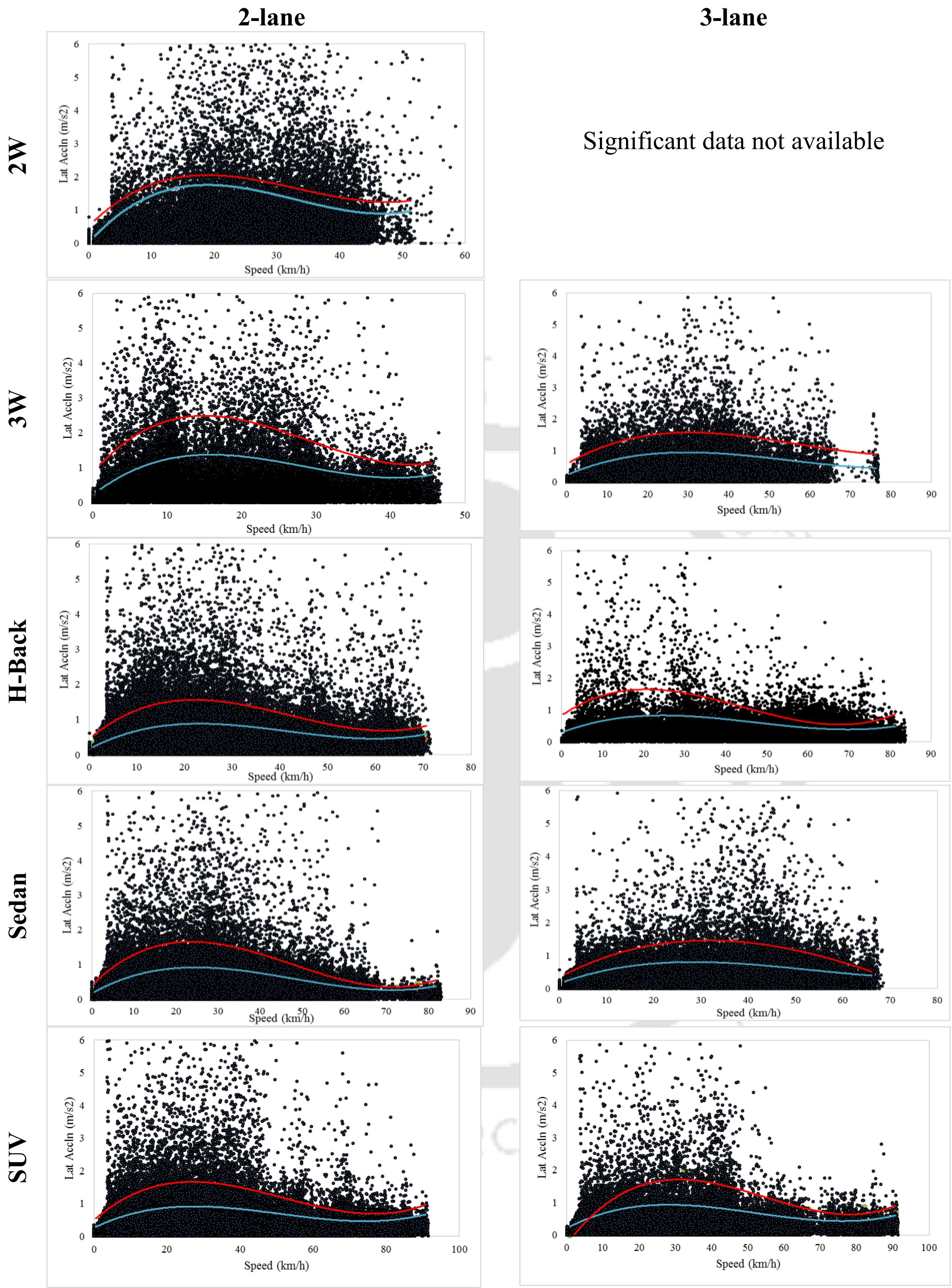


Figure 4-15 Fitted regression models on the Lateral acceleration scattered data of all five type of vehicles on different road (2-lane/3-lane) 2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan and SUV are three categories of passenger cars, ——— 85th percentile, and ——— 95th percentile lateral acceleration

Table 4-14 Details of all the fitted regression models

		a	*b*	*c*	*d*	R-square	RMSE	MAPE
2W	2-lane	-2.5370	-0.1219	2.3450	-0.0301	0.8084	0.1539	18.72
	3-lane	*Data not available*						
3W	2-lane	1.3550	-0.0248	-1.425	-0.1127	0.8251	0.08833	17.94
	3-lane	1.0300	-0.0183	-1.0940	-0.1582	0.8641	0.1259	18.26
H-Back	2-lane	0.8551	-0.0183	-0.9633	-0.1618	0.8874	0.0540	16.38
	3-lane	-1.0700	-0.0791	1.058	-0.0181	0.8292	0.0554	12.75
Sedan	2-lane	0.8291	-0.0166	-0.9158	-0.1813	0.8407	0.0837	18.56
	3-lane	0.8597	-0.0092	-0.8973	-0.1653	0.8107	0.0673	17.92
SUV	2-lane	0.7202	-0.0138	-0.8216	-0.2039	0.8054	0.0707	11.84
	3-lane	-2.4070	-0.0784	2.3950	-0.0344	0.8334	0.0812	14.96

2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan and SUV are three categories of passenger cars

It has been observed that, lateral acceleration increases with the increase in speed at the lower speed ranges i.e. less than 20 km/h. Then it obtains the maximum value of lateral acceleration within the speed range of 15 to 25 km/h speed, for all vehicle types in all cities. Afterwards, the lateral acceleration decreases with the increase in speed. This is due to the higher weaving action of vehicles at a lower speed depending on the surrounding traffic. The vehicle feels safe to veer frequently at a lower speed, whereas at higher speed vehicle feels unsafe to veer laterally. It is observed that at higher speed the lateral acceleration follows an inverse relationship with increase in speed, magnitude of lateral veer reduces. The threshold value for changing the lateral behaviour lies around 20 km/h speed range for all type of vehicles. It is also observed that, motorized 2Ws obtain a higher lateral acceleration comparing to all vehicle types due to its high manoeuvrability. The lateral acceleration decreases as the size of vehicles increases (or manoeuvrability decreases). The 95% of lateral acceleration data lies within ±2 m/s^2 and 85% of data lies below ±1 m/s^2 for all vehicle types.

The adjusted R-square value and the RMSE (Root Mean Squared Error) value for each fitted model are also presented in Table 4-14. It can be observed that the model presents the observed data with more than 80% adjusted R-square value in all cases. Adjusted R-squared, incorporated the model's degrees of freedom. RMSE is the square root of the variance of the residuals. It indicates the absolute fit of the model to the data or how close the observed data points are to the model's predicted values. In the present study, the lower values of RMSE indicates better fit of the models at 5% significance level.

The model fitted to different vehicle data are validated using new set of data collected from different city (Guwahati). The MAPE values for both the predicted and observed 85th percentile lateral acceleration are obtained and also presented in Table 4.14 above. As per the Lewis Scale of measurement by Ronald and Kenneth (1982), the MAPE values indicate good fit of the predicted models for the observed data of 85th percentile lateral acceleration. The 85% of lateral acceleration data lies below the predicted line for each vehicle type.

4.4 Concluding remarks

In the current study, different types of vehicles (three types of cars, motorized 3W and 2W) equipped with Video VBOX (GPS based instrument) are driven in different traffic streams (varying from low flow to high) of different roads (4-lane to 6-lane divided roads) located in five different cities of India. Trajectories of several such vehicles (obtained from Video VBOX at 10 Hz) are collected by driving them more than 250 km each and analysed for their speed, longitudinal and lateral acceleration and deceleration (A/D) values. Observed A/D values in the study represent the A/D limits of different vehicles under normal driving condition. Some of important observations of this study are listed below.

(1) Cumulative percentage curve of longitudinal and lateral A/D represents that A/D trends do not change their slope significantly (also referred as breakpoint) at exactly 85th percentile value. The breakpoint lies in between the 85th and 95th percentile. Hence the use of 85th percentile value philosophy for design purpose needs a relook.

(2) The A/D limits (at 85%) are found comparable for each vehicle type. However at 95th percentile level A/D show significance difference (i.e. for SUV cars acceleration and deceleration values are 1.38m/s^2 and 1.63m/s^2 respectively). The difference in lateral acceleration (i.e. 0.95 m/s^2 for cars to 1.78 m/s^2 for motorized 2W at 85th percentile level) due to the heterogeneity in vehicle types (change in the dynamic and static capability of different vehicles).

(3) The probability distribution (PDF) of the longitudinal A/D of all type of vehicles follows Weibull and Gamma distributions at 5% significance level except deceleration of Sedan cars. However, PDF for lateral acceleration exhibit Gamma distribution at 5% significance level for all vehicle types.

(4) The 85th and 95th percentile A/D curves with the operating speed, depict a linearly decreasing trend for all five type of vehicles. The maximum acceleration occurs at lower speeds (vehicle starting from rest), the ability to accelerate decreases with increase in vehicular speeds. However, the lateral acceleration increases with the

increase in speed initially and attains the maximum value at around 20 km/h speed for all type of vehicles. Lateral acceleration decreases with further increase in speed. The $85^{th}/95^{th}$ percentile lateral acceleration model with respect to the operating speed of vehicles follows a two-term exponential relationship at 5% significance level for all vehicle types.

(5) Using both the longitudinal A/D and the lateral acceleration data, the g-g diagram produces an interaction envelope known as 'driver capability envelope' for all type of vehicles. It can be observed that the size of the interaction envelope for motorized 2W is higher than motorized 3W and cars. This indicates that the size of the interaction envelope increases with the increase in vehicle manoeuvrability.

(6) The lateral acceleration increases linearly with the increase in the longitudinal acceleration for all vehicles. This indicates that for all vehicles, higher manoeuvrability exists at lower speeds as longitudinal acceleration are higher at lower speed.

The relation between the dynamic parameters (speed and lateral/longitudinal acceleration), can very well represent the driving behaviour of vehicles in mixed traffic with no-lane discipline. These A/D values and lateral acceleration can be used in the operating speed prediction models and also to establish the bounding values in case of simulation models. The probability distribution models and the A/D behaviour with operating speed of different vehicles can also be used in simulation models for the realistic representation of such traffic stream. The model for lateral acceleration can be used for evaluation of vehicles lateral weaving in simulated trajectories for such traffic. Also, the lateral acceleration is an indicative of the lateral force coefficient of the highway, which is a key factor for lateral stability and driving safety. The lateral acceleration (a measure of lateral comfort) is directly related to the horizontal alignment and can be used to determine the applicable range of super-elevation ratios. The present study is limited to straight mid-block sections of 4-lane and 6-lane divided roads in plain terrain.

5 Driving Behaviour Analysis using Dynamic Parameters of Vehicle

5.1 Introduction

From the literature survey it has been observed that the lateral and longitudinal acceleration and operating speed are the three major vehicular parameters to determine the driving behaviour of a vehicle. Also, g-g diagram or the friction circle/ellipse is one of the practical methods for characterizing driving behaviour in terms of the vehicle dynamics and risk perception level of the driver. The g-g diagram or the friction circle method is used to characterize the driver behaviour of five different type of vehicles. Racer drivers use the concept of friction-circle to conceptualize their limit. A g-g diagram is used to translate this concept. The force produced by an individual tire is limited by friction between the tire and road. These limits can be represented by a friction circle (lateral and longitudinal acceleration on x-axis and y-axis respectively). The tire-force ellipse and tire force circle are referred as friction-circle and friction ellipse illustrate the concept of tire-road interaction, i.e. the limiting force for both braking and steering (combined tire-force) (Brach & Brach, 2011). Equation of the tire-force circle/ellipse is used in the development of vehicle dynamic simulation software. The resulting diagram is simplified to a basic circular shape by considering the identical tire concept. Based on Newton's second law of motion the friction force and acceleration are associated with each other. The accelerations of a vehicle can be measured more easily than the frictional forces. Hence, the driver behaviour is evaluated by using friction-circle concept presented by the g-g diagram (Figure 5-1).

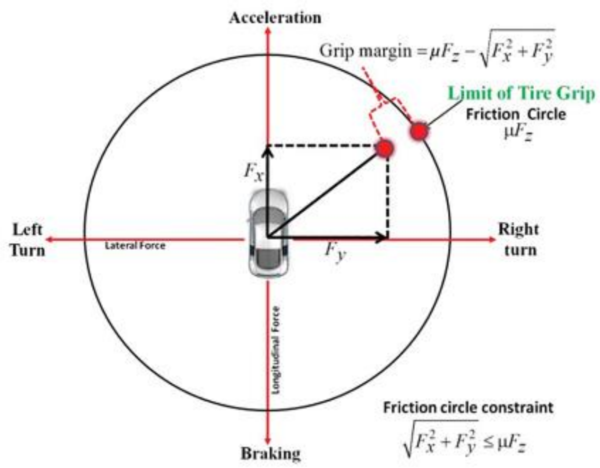


Figure 5-1 Friction Circle (Singh & Taheri, 2015)

In the following sections the longitudinal and lateral acceleration are studied for all five type of vehicles from the combined data obtained from the five different cities of India. To see the interaction between the lateral and longitudinal acceleration more clearly the relationship between the two dynamic parameters are established for all five vehicle types. Then, the driving behaviour of vehicles on the roads of different regions are studied based on the dynamic equilibrium of the vehicles or the concept of friction circle (g-g diagram).

5.2 Interaction between the Vehicle Dynamic Parameters

The longitudinal and lateral acceleration are plotted on the operating speed of the different vehicles in Figure 5-2 and 5-3 respectively. The scatter plots indicate that there is an inverse relation of speed with the lateral and longitudinal acceleration at the higher speed ranges (i.e. speed > 20-30 km/h). However, at the lower to medium speed both the acceleration follows a different trend with the increase in speed. The lateral acceleration is lower at the near zero speed then it increases with the increase in speed up to medium speed (i.e. speed < 30 km/h) (Figure 5-2). However, there is no such variation in longitudinal acceleration is observed at lower speed ranges (Figure 5-3).

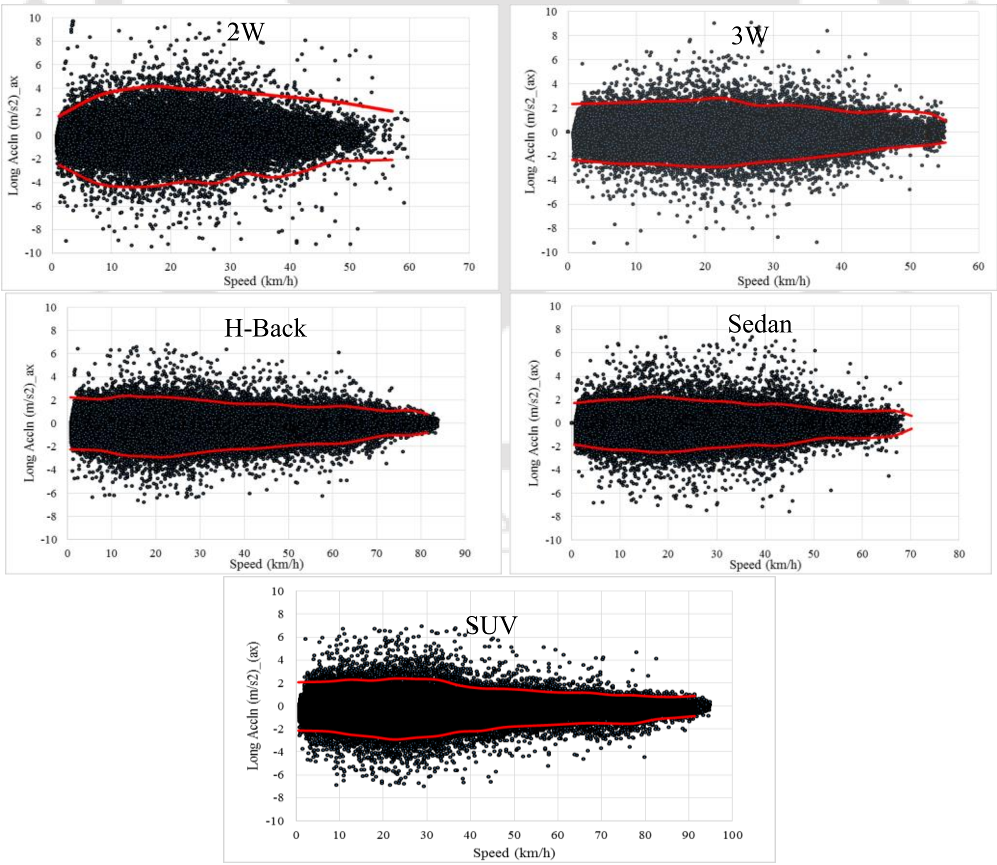


Figure 5-2 Scatter plot of longitudinal acceleration (a_Y) on Operating Speed of Different vehicles (— 99 percentile limit)

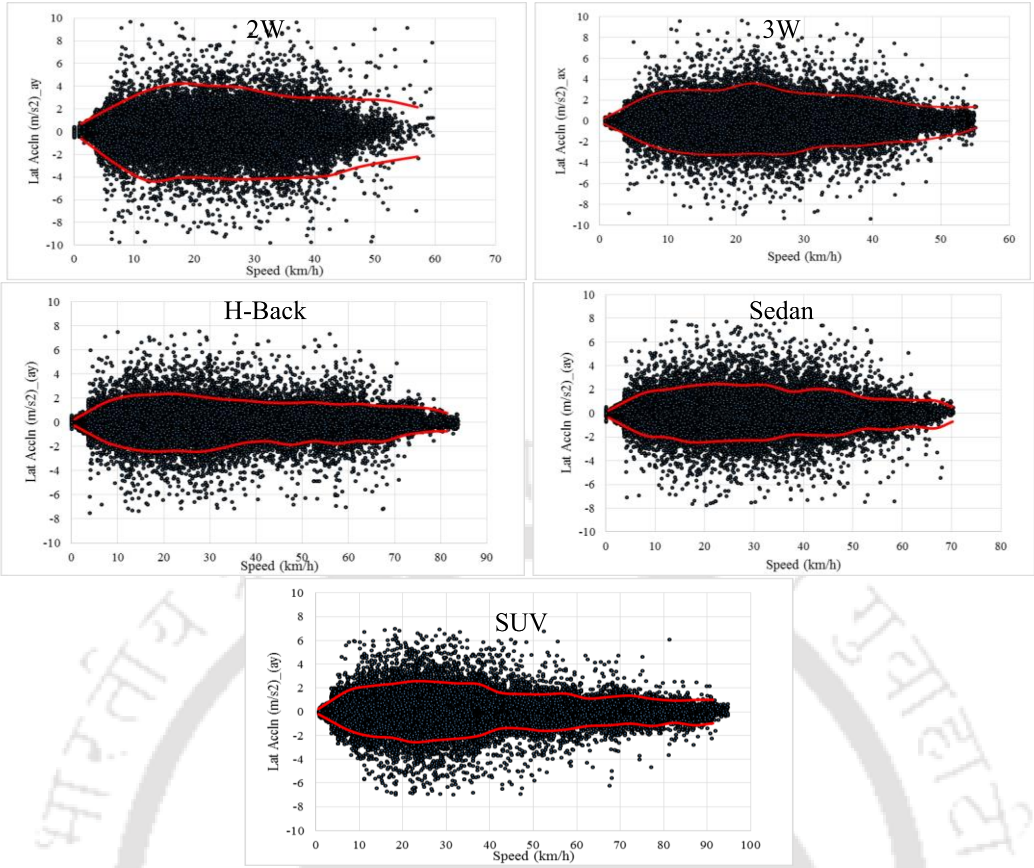


Figure 5-3 Scatter plot of Lateral acceleration (a_x) on Operating Speed of Different vehicles (—— 99 percentile limit)

The decreasing trend at higher speed indicates that the drivers perceive higher risk with speed over a certain limit yielding a reduction in the accelerations range (lateral and longitudinal). This limit is different for each driver. The limit shown in the above figures are the 99 percentile limit, (i.e. 99% data lies within the limit curve shown in the above figure). It can also be observed that in all vehicle cases only a few observations of the lateral acceleration were found at lower speeds (i.e. the near zero speed < 5km/h). A similar result was observed by (Bosetti, et al., 2014) at the curvature roads less than 10m radius. However, in our present study, the detail data of the road curvature and turnings are not available.

To see the interaction between the lateral and longitudinal acceleration more clearly the relationship between the two dynamic parameters are established for all five vehicle types. The average lateral manoeuvre for different acceleration or deceleration values of different vehicle types is presented in the following Figure 5-4. It can be observed that the average lateral manoeuvre of all type of vehicles linearly increases with the increase in longitudinal acceleration/deceleration behaviour of the drivers. In case of mixed traffic condition, the vehicle tries to overtake and frequently veer to pass through (filter) the traffic. In the meantime the vehicle accelerates or brake to avoid the collision. Hence as the veering manoeuvre increases the acceleration or braking also increases. From Figure 5-4, it is also clear that the lateral and longitudinal manoeuvre (accelerating/braking) of the vehicles or the veering manoeuvre of motorized 2W is higher than the cars.

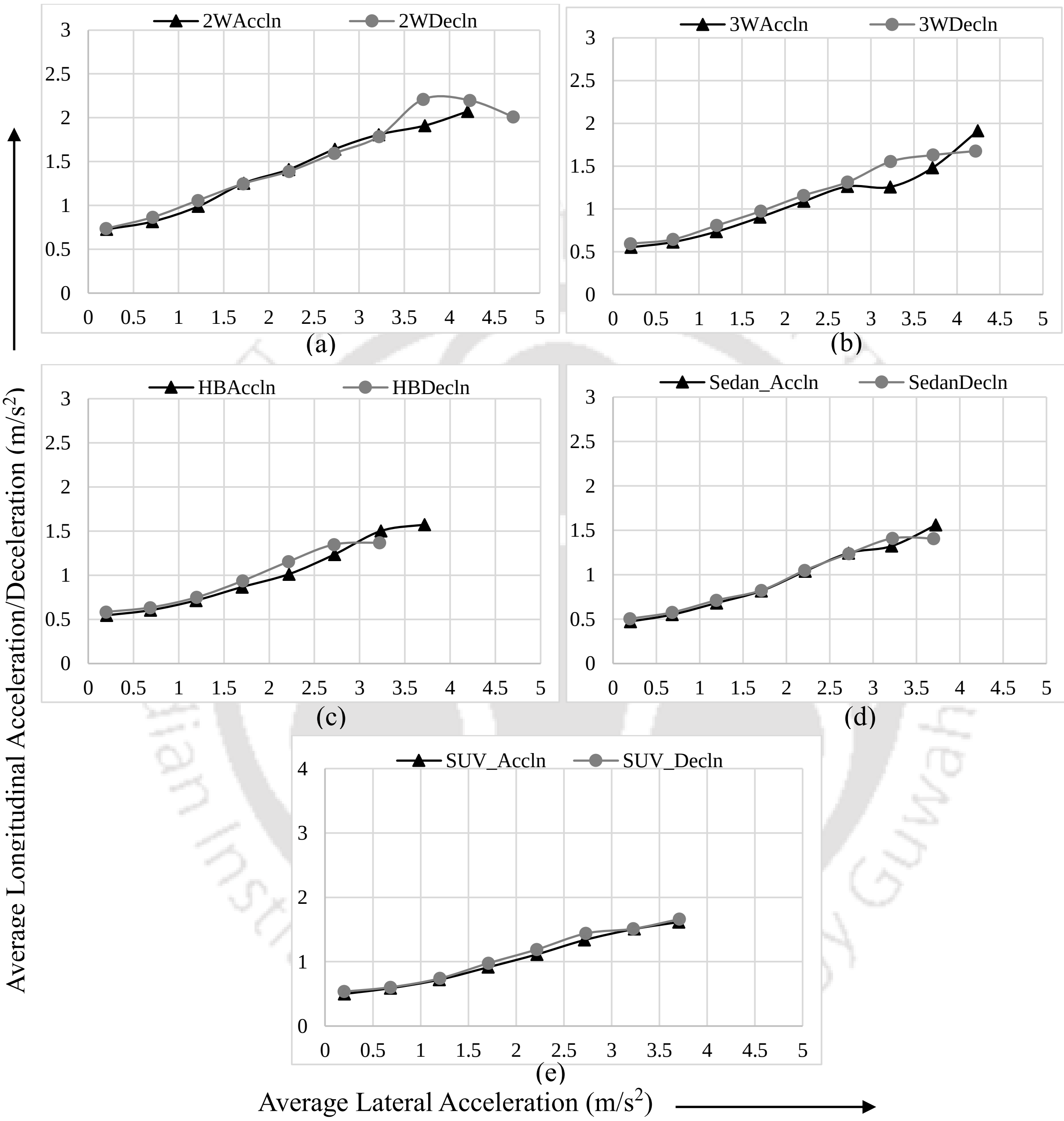


Figure 5-4 Relation between the average lateral acceleration with the average longitudinal acceleration/deceleration (a) 2W, (b) 3W (c) H-Back cars (d) Sedan cars (e) SUV cars

5.3 Driving Behaviour Analysis using g-g Diagram

In the present section, the driving behaviour of vehicles on the roads of different regions are studied based on the dynamic equilibrium of the vehicles. All the three parameters (operating speed, lateral/longitudinal acceleration and braking coefficient) are used altogether to analyse driver's safe or unsafe driving behaviour on different roads using g-g diagram with friction circle concept.

A vehicle is subjected to an acceleration vector ($\bar{a}$), which have two components, longitudinal acceleration in the direction of mobility (a_{long}) and lateral acceleration in the transverse direction of mobility (a_{lat}) of the vehicle.

$$|\bar{a}| = \sqrt{\left(a_{long}\right)^2 + (a_{lat})^2} \quad 5\text{-}1$$

By considering longitudinal and lateral friction, and the concept of the ellipse of adherence, (Eboli, et al., 2016) obtained a circumference representing a limit between the safe and unsafe driving conditions. Assuming a constant value of friction factor and there is no super elevation, obtained the formulation for acceleration vector;

$$\left(a_{long}\right)^2 + (a_{lat})^2 = (g.\mu)^2 \quad 5\text{-}2$$

where, g= gravitational acceleration

μ= maximum permissible coefficient of friction or braking coefficient

The above equation represents a circumference radius of $(g.\mu)$, cantered at origin, where lateral and longitudinal accelerations are plotted on x-axis and y-axis respectively (Figure 5-5).

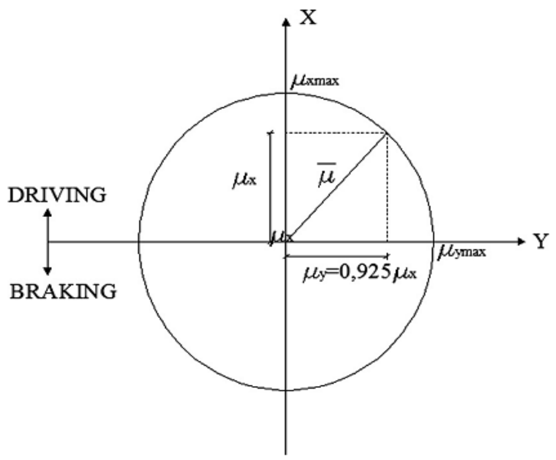


Figure 5-5 Limit between safe and unsafe driving conditions using an ellipse of adherence (Eboli et al., 2016)

By using the friction coefficient factors for dry pavement condition for rural roads, the limit curve of acceleration vector ($\bar{a}$), as a function of speed was obtained. The braking coefficients provided by different countries are different according to their design guidelines. To see the correlation between longitudinal and lateral acceleration and to analyse the driver behaviour g-g diagram is plotted. The g-g diagram is the most effective way to represent the driving behaviour by considering both the dynamic parameters (lateral and longitudinal acceleration) (Hisaoka et al., 1999; Vaiana et al., 2014; Biral & Lot, 2009; Biral et al., 2005). The g-g diagram for all five type of vehicles (2W, 3W, H-Back, sedan and SUV cars) are plotted by combining both the longitudinal and lateral acceleration (a_x anda_y). The diagrams show, the lateral accelerations and longitudinal accelerations normalized with respect to gravity in both horizontal and vertical axis respectively as the representation of friction circle in Figure 5-5. The Positive longitudinal acceleration indicates acceleration whereas negative indicates the deceleration of the vehicles. Similarly, the positive and negative lateral acceleration indicates right and left turning of the vehicles respectively.

The longitudinal and the lateral accelerations are the combinations of vehicle dynamics and diver's perception to the risk level he/she accepts to manoeuvre. So, the g-g plot is considered as the representation of actual driver behaviour performance. As, both the longitudinal and lateral friction (μ_x and μ_y) occur in both the directions (x and y), the resultant force should be represented by the edge of the friction circle (μ) [refer Equation 5-1], assuming a hypothetical tire producing a maximum of only 1.0g of acceleration. If the driver needs to speed up with the turning movement simultaneously the maximum friction provided by his/her tires are limited to total 1.0g. The outer circle shown in the Figure 5-6 are the maximum friction limit circle taken as 1.0g. The g-g diagram of all the vehicles indicates that maximum data are scattered around zero. The inside circle indicates the design friction limit of the road as per IRC:66, (1976) and IRC:86, (1983).

It can be observed that the g-g diagrams of all five type of vehicles produce interaction envelopes which are small subset of the adherence circle or the friction circle of the tire. These envelopes represent "driver capability envelope" as mentioned by Biral et al. (2005). It can be observed that the interaction envelops of the vehicles decreases as the size of vehicle increases. The g-g diagram for motorized 2W has occupied the largest area followed by 3W and then the cars.

In Figure 5-6, the g-g diagrams of all five type of vehicles produce interaction envelopes which are a small subset of the adherence circle or the friction circle of the tire. These envelopes represent "driver capability envelope" as mentioned by Biral et al. (2005). In all cases, the driver takes a certain amount of risk while driving at higher than the design limits on plain terrain. The percentage of data points lies out of the design limit circle (inner circle) is very less, i.e. below 1% for all type of vehicles (0.91% for 3W, 0.42% for H-Back, 0.49% for sedan and 0.52% for SUV cars) except motorize 2W (i.e. 3.33%).

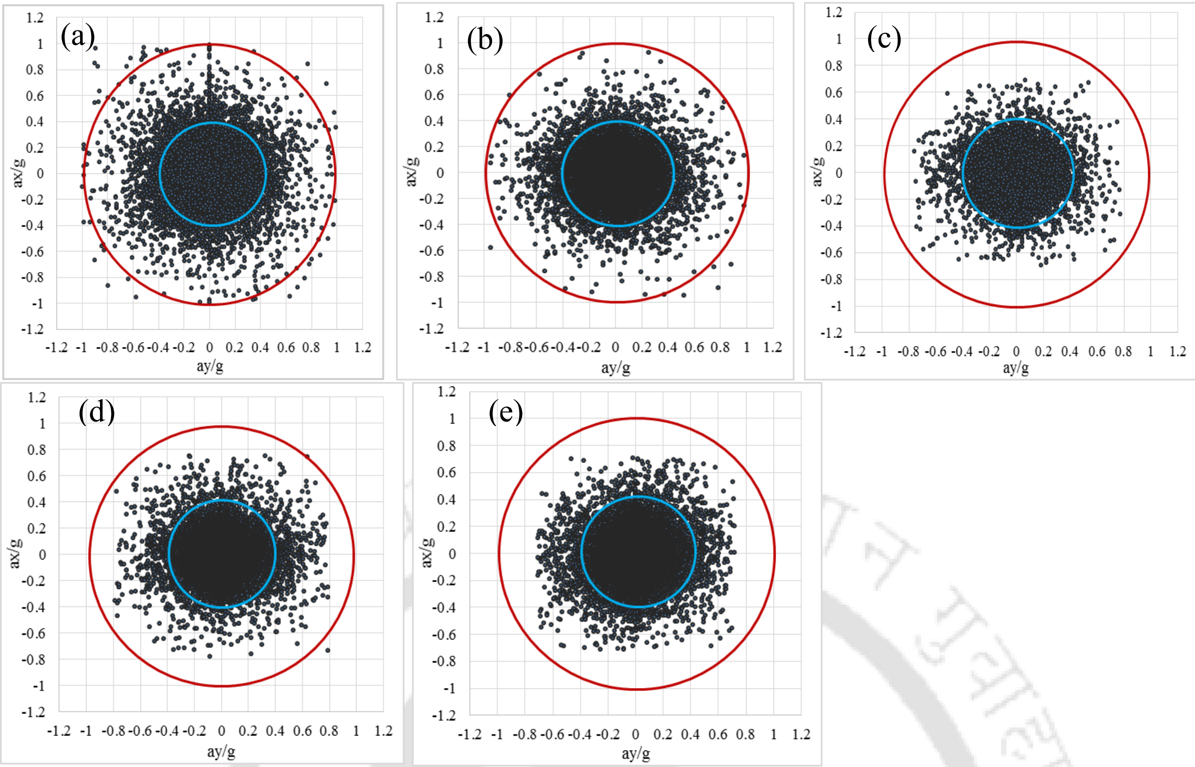


Figure 5-6 Normalized longitudinal and lateral acceleration (g-g plot) for (a) 2W (b) 3W (c) H-Back (d) Sedan & (e) SUV cars

There are nearly 1% vehicles takes a risk against skidding according to our design limit except for 2W. In the case of motorised 2W, the abrupt lateral manoeuvre of the vehicles are quite high in case of no-lane disciplined traffic due to their frequent lane change and overtaking manoeuvres. Hence the scattering of data is high in case of motorised 2W. Also, the motorised 3W have the higher weaving manoeuvre than the cars (H-Back, Sedan and SUV).

5.3.1 *Representation of g-g Diagram in three-Dimensions (3D)*

The g-g diagram can be viewed in more detail by plotting the lateral and longitudinal acceleration on three-dimensional plots for all five type of vehicles. The lateral and longitudinal acceleration data for each type of vehicles are grouped in six equal intervals of speed every 20 km/h ranging from zero to 100 km/h. The resulting plots show the lateral and longitudinal acceleration for different speed groups plotted along the z-axis (Figure 5-7).

It is observed that the g-g diagrams change their size with speed. At lower speed (0-20km/h) the g-g diagram covers a lesser area compared to the speed group of 20-40 km/h. In the case of lower to medium speed the size of the g-g diagram enlarges in all vehicle classes except motorised 2Ws and 3W. In case of motorized 2W and 3W, the area covered by the g-g diagrams do not change significantly as larger lateral and longitudinal A/D values are observed for both

2W and 3W at lower speeds itself. For all three type of cars, the size of g-g diagram shrinks with the further increase in speed. In all speed groups, the shape of the g-g diagram is approximately round. The shape and size of each g-g diagram changes with the driving capability of a different vehicle on plain terrain.

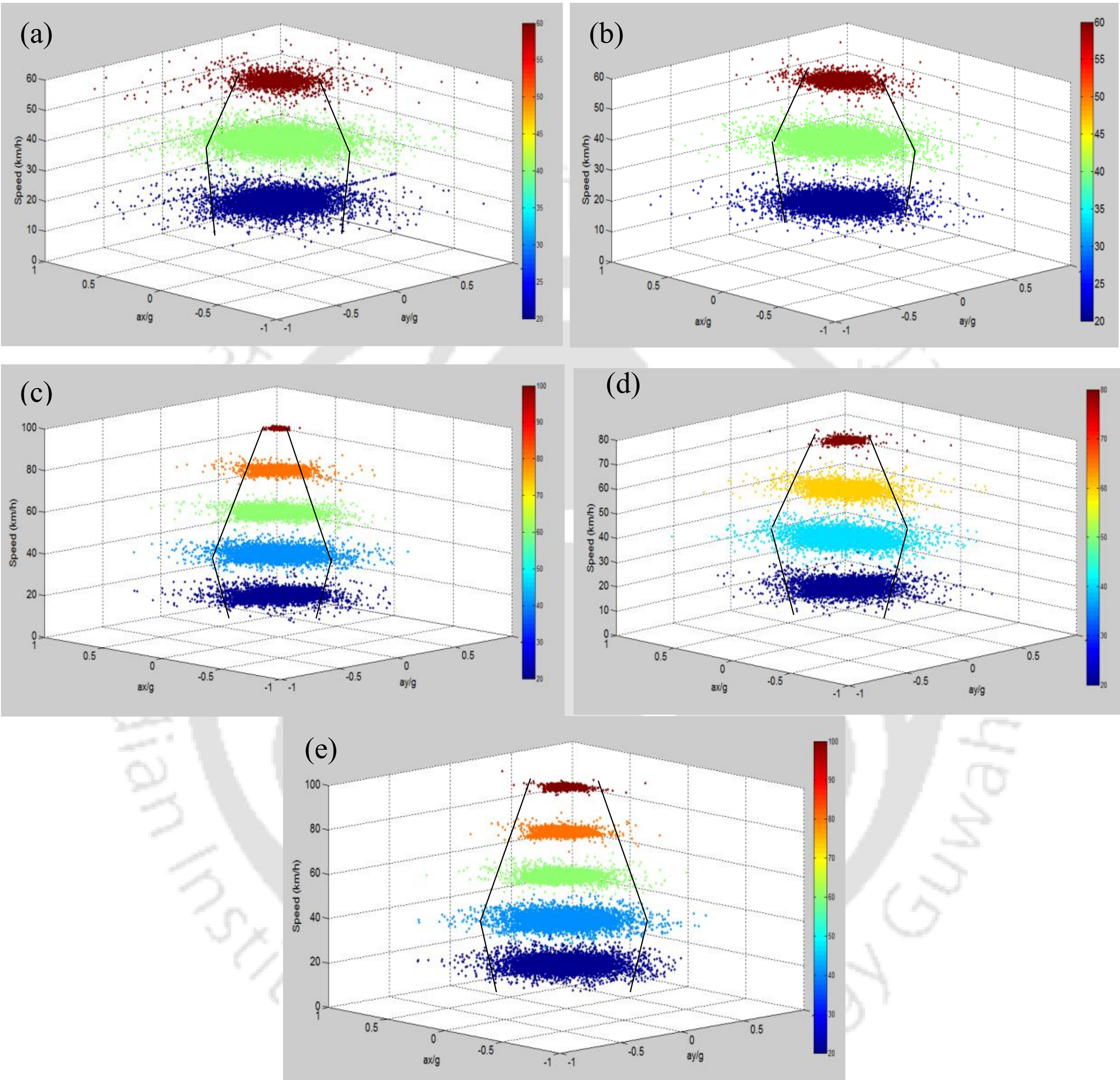


Figure 5-7 3D Plot showing the Longitudinal and Lateral Acceleration Collected from field at different intervals of speed (a) 2W (b) 3W (c) H-Back (d) Sedan and (e) SUV Cars

5.3.2 Acceleration Limit Curve

The resultant acceleration and the g-g diagram can easily demonstrate the safe or unsafe behaviour of a driver. The Acceleration limit for safe driving is calculated by Eboli et al. (2016) for every operating speed according to the provided maximum permissible longitudinal/lateral coefficients of friction for the respective design speed presented in Figure 5-8 below.

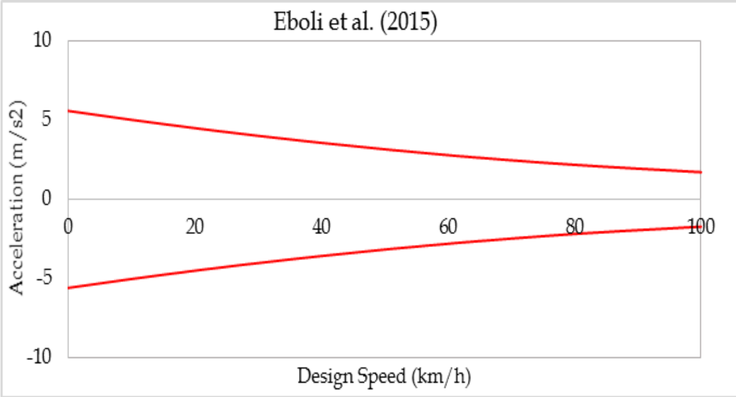


Figure 5-8 Safe Acceleration Limit Curve (Eboli et al., 2016)

The relationship between the acceleration vectors, $|\bar{a}|$, and operating speed of different vehicles is obtained in this section to represent the safe/unsafe driving behaviour of different vehicle types on mixed traffic stream by using the proposed approach of Eboli et al. (2016). The acceleration limit vs. speed curve by Eboli et al. (2016), shown in Figure 5-8 presents a clear drop down of the resultant acceleration ($\bar{a}$) with the increase in speed. In Indian traffic condition, the limit curve is obtained for the design criteria of the country as per IRC:66 (1976) and IRC:86 (1983) as mentioned in Section-5.3. The coefficient of lateral friction for curved road design is taken as 0.15, and the coefficient of longitudinal friction are presented in Table 5-1 as per the design guidelines.

Table 5-1 Values of Coefficient of Friction Limits Based on (IRC:66, 1976)

Design Speed (km/h)	20	25	30	40	50	60	65	80	100
Coefficient of Friction (μ)	0.40	0.40	0.40	0.38	0.37	0.36	0.36	0.35	0.35

The resultant coefficient of friction (μ) is calculated based on the given coefficient of friction, as mentioned in Equation 5-1. The resultant acceleration limit ($\bar{a} = \mu . g$) is calculated for different design speed of vehicles based on the given coefficient of friction (depicted below in Figure 5-9).

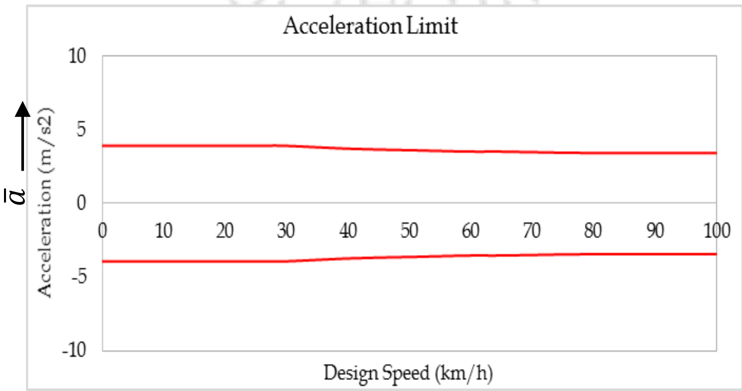


Figure 5-9 Safe Acceleration Limit Curve for Indian Roads

It can be observed that acceleration limit remains constant up to medium speed (≈30km/h) range and afterwards it decreases with the increase in design speed at medium to high operating speed. In the present study, the data was collected mainly in urban roads. The design speed of urban roads varies from 30 to 80 km/h (30 Km/h on Local streets, 50 km/h on Collector streets, 60 km/h on Sub-arterial and 80 km/h on Arterial roads). The city-wise scatter diagram for different vehicles are plotted to see the safe (least aggressive driving) and unsafe (most aggressive driving) condition. Figure 5-10 presents the city wise driving behaviour of all type of instrumented vehicles separately.

From the Figure 5-10, it has been observed that the points of resultant acceleration are scattered widely around mean in lower speed ranges i.e. below 40 km/h speed. Data points cross the limit curve frequently in the lowers speed ranges. This is due to the higher interaction with the adjacent vehicles, which leads to frequent lateral and overtaking manoeuvre of the vehicles in the no-lane disciplined mixed traffic conditions. Higher speeds are obtained by the drivers at relatively lower congested conditions, where the vehicles interaction are relatively low. Hence, the driver mainly focuses on the longitudinal interaction and his/her reactions are in terms of longitudinal acceleration and deceleration. Also, the driver feels unsafe to higher veering manoeuvre at higher speed conditions. Hence the lateral acceleration remains low at the higher operating speed of vehicles. The data points are clustered within ±2 m/s^2 acceleration limit after 40 km/h speed in all vehicle cases, which is also below the acceleration limit curve obtained by Eboli et al. (2016). Only a very less percentage of data crosses the safe limit. It is also observed that, though the resultant acceleration limit (obtained from the design friction coefficient values) decreases with the increase in speed, there is a very less difference in the maximum resultant acceleration limit of zero speed and 100 km/h speed. These obtained limits are also higher compared the values obtained by Eboli et al. (2016).

From the scatter plot of resultant acceleration presented in Figure 5-10, one can observe that the percentage of data points outside the safety domain are very small. The 99% of data points lie within the safety domain curve for all type of cars (H-Back, Sedan, and SUV), as shown in Table 5-2. However, for motorised 2W and 3W, the data lies outside the safety limit curve are more than 3% and 2% respectively. Though the longitudinal acceleration capability of cars is higher than that of motorised 2W and 3W, the resultant acceleration of both the vehicles is high compared to the cars. This is due to their higher lateral acceleration values compared to cars. This indicates that the lateral manoeuvre of 2W and 3W are high in all operating speed conditions. In case of Pune, the percentage of data points lies outside the limit curve are very high compared to other cities (i.e. 8.39%). From the video it is observed that the filtering and passing action of 2W were very high in Pune. Hence the lateral and longitudinal manoeuvre of 2W was very high compared to other cities indicating a risky driving condition.

Table 5-2 Percentage of external data points lies above the limit curve

City Name	Vehicle Type				
	2W	3W	H-Back	Sedan	SUV
Delhi	×	1.18	0.38	0.89	0.19
Kolkata	3.30	1.95	0.12	0.41	0.13
Bengaluru	1.41	2.04	1.28	1.69	1.28
Pune	8.39	1.30	0.49	0.12	0.66
Mumbai	×	0.46	×	0.49	0.43

One of the main observation from the present study is that the unsafe behaviour of vehicles is mostly observed at lower to medium operating speed (i.e. below 30 km/h speed). This observation is due to the frequent interaction in the lateral and longitudinal direction of the subject vehicle in the urban roads with mixed, and no-lane disciplined traffic. Hence, mostly the driver take the risk to pass or filter through the traffic at moderate speed conditions to overtake the slow-moving vehicles. However, in the case of Eboli et al. (2016) it is observed that the higher lateral manoeuvre is observed at higher speeds (40-60 km/h). Due to the lane disciplined traffic, vehicles shift laterally only at the time of overtaking or lane changing (from high-speed lane to lower speed lanes or vice versa). This behaviour is observed during the moderate to the high speed of vehicles for lane-based traffic i.e. 40 to 60 km/h.

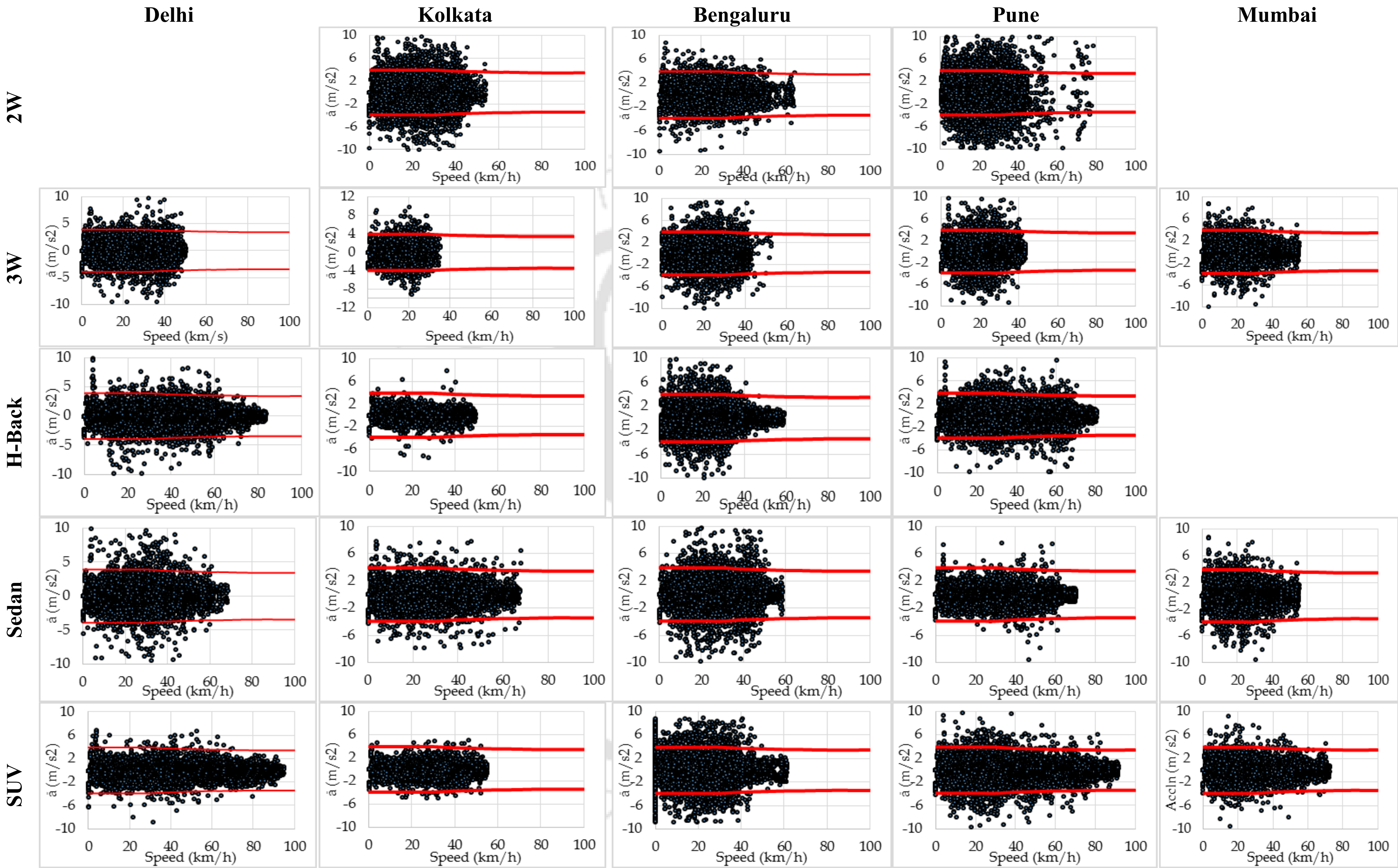


Figure 5-10 Scatter diagram of safe/unsafe behaviour of different vehicles on different city roads (2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan, and SUV are three categories of passenger cars)

5.3.3 Spatial Representation of Acceleration Limit Curve

The acceleration trend in space illustrated the exact locations of the trajectory where the driver experience sudden acceleration or braking as well as the points where lateral acceleration is above the road design lateral threshold. This study can give a useful contribution in terms of improvement of road safety. The safety domain defined is useful for finding those points of the roadway where the driver is unsafe, in order to give him information about his behaviour, let him raise the threshold of attention and let him take preventive measures.

To identify the safe or unsafe behaviour of the driver throughout travelled path (entire trajectory), the resultant acceleration ($\bar{a}$) trend with respect to the distance travelled of the vehicles are plotted. The safe/unsafe points in the entire road are identified by relevant exceeding limits. In case of unsafe behaviour of driver, the acceleration extends outside the safety domain. Therefore, such spatial plots helps in detailed analysis of risk driving conditions (the points where the drivers are taking risk while driving throughout the entire trajectory). Further, such plots highlight the design inconsistency of the road stretch using the indicator as the points where drivers' acceleration extends beyond safety domain. The acceleration trend with distance travelled are generated for different vehicles travelled in each city individually. Though the data collection trajectory is very long for each cities, only the first 5 km (5000 m) stretch are presented in Figure 5-11.

Figure 5-11 indicates that in the case of a motorised 2W, the acceleration exceeds the limit curve in most of the stretches of the total trajectory compared to other vehicle types. In the case of cars in all three cities (Delhi, Kolkata, and Mumbai), the points are more concentrated (follow the limit curve) and they exceed the safety domain at very few points. A safe and attentive driving behaviour is observed by the high-speed vehicles (all cars). It can be concluded that the randomness of the points reduces as the size and capability of vehicles increases. The unsafety of the drivers emphasised by the external points lying outside the limit curve indicating higher lateral/veering manoeuvre of vehicles. This veering manoeuvre indicates higher overtaking and frequent lane changing behaviour of all types of vehicles which implies most unsafe behaviour of the driver. It can be observed from the study that Bengaluru and Pune drivers are comparatively more aggressive than Delhi, Kolkata, and Mumbai. In case of Bengaluru and Pune, the high-speed vehicles also show an unsafe condition at many road sections within the selected 5000 m path.

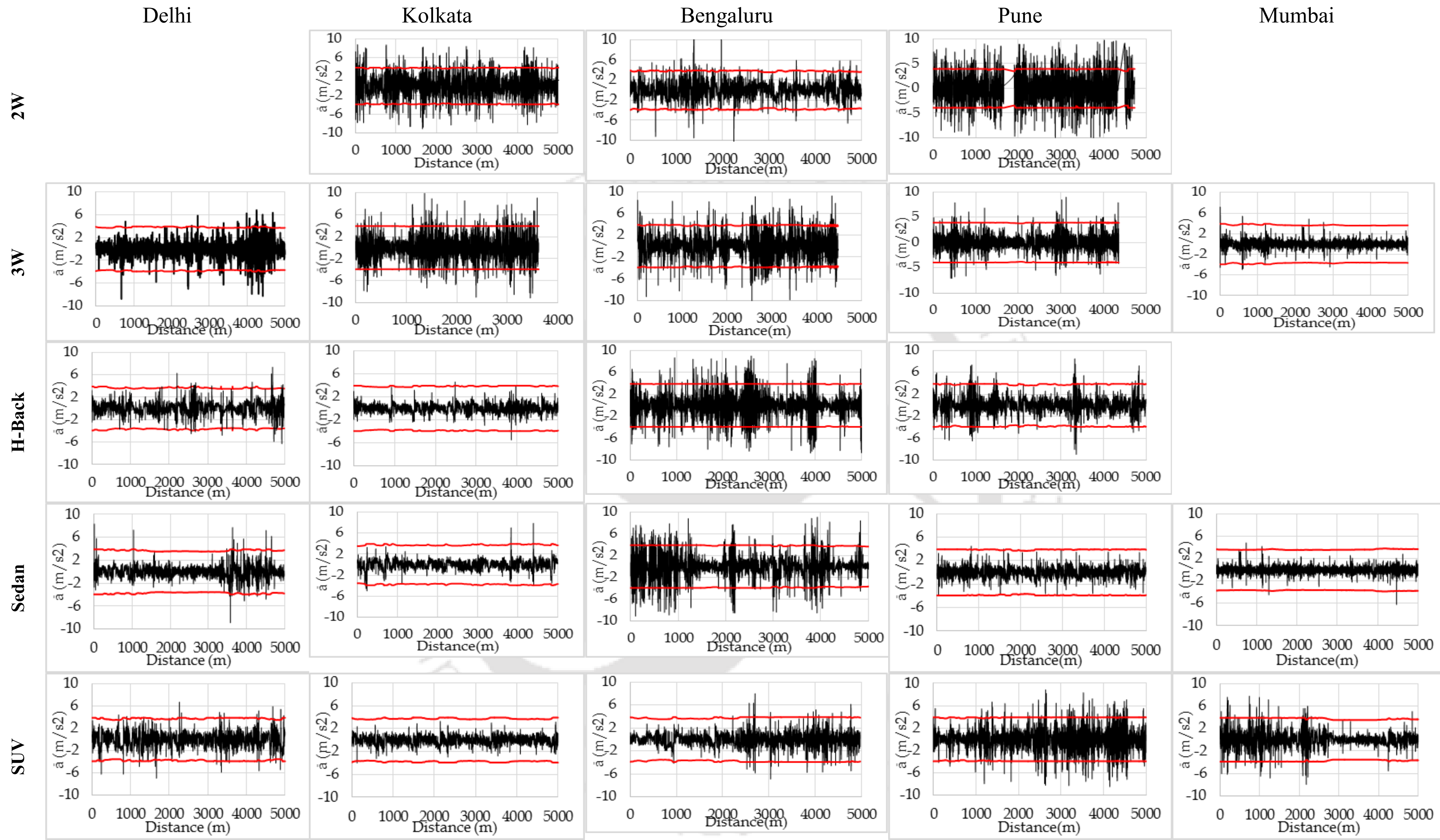


Figure 5-11 Acceleration trend in space for safe/unsafe behaviour of different vehicles on different cities (2W-Motorized Two-Wheeler, 3W-Motorized Three-Wheeler, H-Back, Sedan and SUV are three categories of passenger cars

However, the city-wise acceleration presented in Figure 5-10 indicates that most of the data points lie within the safety envelope for all types of cars (less than 1% data lies outside the safety limit curve) except motorised 2Ws and 3Ws. This study can give a useful contribution regarding the improvement of road safety. The safety domain defined is helpful in identifying those points/sections of the roadway where majority drivers show unsafe (risk taking) behaviour. Safety at such identified points/sections can be improved by providing necessary preventive measures or warning the drivers about it.

5.4 Joint Distribution Modelling of Vehicle Dynamic Parameters Using Copula

As studied in the previous sections, the knowledge of lateral and longitudinal acceleration/deceleration (A/D) distributions are important in microscopic traffic flow studies for developing and validating microscopic traffic simulation models for the no-lane based heterogeneous traffic stream. The distribution of each individual parameters (lateral and longitudinal acceleration/deceleration are presented in the previous sections (sub-subsection-4.2.4.2 & 4.3.4.1). It is also observed that there is a dependence between the operating speed and lateral and longitudinal A/D of vehicles. Multivariate distributions can be a more viable approach to represent the dependence structure of microscopic parameters of traffic stream. However, it is difficult to establish the multivariate joint distribution of different variables/parameters as all the univariate marginal distributions are assumed to be characterized by the same family (Genest & Favre, 2007) and the increasing number of parameters may increase the difficult in the mathematical formulations. The variability in distribution of lateral and longitudinal A/D with the operating speed can be presented jointly by using the copula approach. To overcome this difficulty, the copula approach has been widely applied and documented by various authors (Bhat & Eluru, 2009; Bhat & Sener, 2009; Zou et al., 2014; Kim & Mahamassani, 2014; Zou & Zhang, 2016; Zou et al., 2017). Zou et al (2014) applied the Farlie-Gumbel-Morgenstern (FGM) copula function to formulate the bivariate distribution for freeway speed and headway data. Again, the similar copula function was also used by Rossi et al. (2014a), Rossi et al. (2015) to represent vehicle speed and headway simultaneously. Zou & Zhang (2016), presented a multivariate distribution of speed, time headway and vehicle length and they showed that the trivariate Gaussian copula can represent the dependence structure of the three variables. A large number of bivariate and trivariate copula functions have been documented in recent years. The choice of particular copula function depends on the nature of the data used. The present section describes the applicability of copula approach, to capture the potential dependence among microscopic traffic variables (operating speed, lateral acceleration and longitudinal acceleration/deceleration) and their joint probabilistic behaviour.

5.4.1 Concept of Copula

A copula is a joint distribution function with standard uniform univariate margins U[0,1] that links a stochastic multivariate relationship with pre-specified univariate marginal distribution functions. The copula theory can be employed to construct 2-dimensional probability distributions for any marginal distributions. Given two continuous random variables (X_1, X_2) with cumulative distribution functions $\left(F_1(x_1), F_2(x_2)\right)$, a joint bivariate cumulative distribution function (CDF) $F(x_1, x_2)$ can be generated using the following expression:

$$F(x_1, x_2) = C_\theta\left(u_1 = F_1(x_1), u_2 = F_2(x_2)\right) \quad \text{...5-3}$$

The function C (copula) is a CDF joining marginal distributions $F_1(x_1), F_2(x_2)$. In case of marginal distributions of continuous variables, by differentiating $F(x_1, x_2)$, the 2-dimensional copula density function can be obtained as:

$$f(x_1, x_2) = c_\theta[F_1(x_1), F_2(x_2)]f_1(x_1)f_2(x_2) \quad \text{...5-4}$$

where $c_\theta[F_1(x_1), F_2(x_2)]$ is the density of the copula and is obtained by computing the second partial derivative of the copula on the two variables:

$$c_\theta[F_1(x_1), F_2(x_2)] = \frac{\partial^2 C}{\partial u_1 \partial u_2} \; and \; u_1 = F_1(x_1), u_2 = F_1(x_2) \quad \text{...5-5}$$

Because the dependence structures modelled through the copulas are separated from the univariate marginal distributions, an appropriate copula function is the one which suitably elucidates the dependence features of the data. Several techniques have been used in the literature to evaluate the degree of correlation between the random variables. There are two commonly used non-parametric methods of detecting correlation that are based on the concept of concordant and discordant pairs of observations are, Kendall's τ (Kendall, 1938) and Spearman's ρ_s (Spearman, 1904). Kendall's τ measure of dependence between the random variables (X_1, X_2) is defined as the probability of concordance minus the probability of discordance and is expressed as:

$$\tau(X_1, X_2) = P\left(\left(X_1 - \widetilde{X_1}\right)\left(X_1 - \widetilde{X_2}\right) > 0\right) - P\left(\left(X_1 - \widetilde{X_1}\right)\left(X_1 - \widetilde{X_2}\right) < 0\right) \quad \text{...5-6}$$

Where, $(\widetilde{X_1}, \widetilde{X_2})$ is an independent copy of (X_1, X_2). The second non-parametric measure of dependence i.e. Spearman's rank correlation coefficient ρ_s is three times the difference between the probability of concordance and the probability of discordance:

$$\rho_S(X_1, X_2) = 3\left(\mathbb{P}\left((X_1 - \tilde{X}_1)(X_2 - \breve{X}_2) > 0\right) - \mathbb{P}\left((X_1 - \tilde{X}_1)(X_2 - \breve{X}_2) < 0\right)\right) \quad \text{5-7}$$

where (X_1, X_2), $(\tilde{X}_1, \tilde{X}_2)$ and $(\breve{X}_1, \breve{X}_2)$ are the three independent identically distributed random vectors each with a common joint distribution function $F(.,.)$ and margins F_1 and F_2. More specifically, let A_1 and A_2 denote the number of concordant and discordant pairs for n observations; and $R(\tilde{X}_1)$and $R(\tilde{X}_2)$ denote the ranks of a pair of variables (X_1, X_2), Kendall's τ and Spearman's ρ_S can then be defined as

$$\tau = \frac{A_1 - A_2}{0.5n(n-1)} \quad \text{5-8}$$

$$\rho_S = \frac{\sum_{i=1}^{n} R(\tilde{X}_{1i})R(\tilde{X}_{2i}) - n\left(\frac{n+1}{2}\right)^2}{\sqrt{\left(\sum_{i=1}^{n} R(\tilde{X}_{1i})^2 - n\left(\frac{n+1}{2}\right)^2\right)\left(\sum_{i=1}^{n} R(\tilde{X}_{2i})^2 - n\left(\frac{n+1}{2}\right)^2\right)}} \quad \text{5-9}$$

Besides Kendall's τ and Spearman's ρ_S measure of dependence, the traditional Pearson's product-moment correlation coefficient r that is a measure of linear dependence between X_1 and X_2 poses several limitations. Unlike the rank-based dependence measures, the Pearson's correlation coefficient is a parametric technique that largely depends upon the marginal distributions of the population. It performs better than rank-based measures only for bivariate elliptical distributions (including bivariate normal distribution). Therefore, considering the advantages of rank-based dependence measures that both are not dependent on the margins, Kendall's τ and Spearman's ρ_S are commonly used to characterize the dependence structures in the copula literature, rather than the traditional Pearson's correlation coefficient.

A rich set of copula types have been generated using the method of inversion, geometric methods and algebraic methods (Nelsen, 2006) and each of the copula is characterised by a different dependence structure θ on the data. Also it is to be noted that Kendall's τ and Spearman's ρ_S are functions of the respective copula and the dependence parameter, and are not dependent on the marginal distributions. A brief overview of the copula functions, that includes the Gaussian copula, the Farlie-Gumbel-Morgenstern (FGM) copula and various Archimedean copulas like the Gumbel-Hougaard copula, the Frank copula, the Clayton copula, the Ali-Mikhail-Haq (AHM) copula and the Joe copula, and dependence structures of each copula type is presented in Table 5-3.

Table 5-3 Characteristics and association measures of bivariate copulas

Copula type	Function $C_\theta(u,v)$	θ domain	Kendall's τ and domain	Spearman's ρ_S and domain
Gaussian	$\int_{-\infty}^{\varphi^{-1}(u)}\int_{-\infty}^{\varphi^{-1}(v)} \frac{1}{2\pi\sqrt{1-\theta^2}}\exp(-\frac{s^2-2\theta st+t^2}{2(1-\theta^2)})dsdt$	$\theta \epsilon [-1,1]$	$\frac{2}{\pi}\sin^{-1}\theta$ $\tau \epsilon [-1,1]$	$\frac{6}{\pi}\sin^{-1}\left(\frac{\theta}{2}\right)$ $\rho_S \epsilon [-1,1]$
F-G-M	$u_1u_2[1+\theta(1-u_1)(1-u_2)]$	$\theta \epsilon [-1,1]$	$\frac{2}{9}\theta$ $\tau \epsilon \left[-\frac{2}{9},\frac{2}{9}\right]$	$\frac{1}{3}\theta$ $\rho_S \epsilon \left[-\frac{1}{3},\frac{1}{3}\right]$
Gumbel	$\exp\left(-\left[(-\ln u_1)^\theta+(-\ln u_2)^\theta\right]^{1/\theta}\right)$	$\theta \epsilon [-1,\infty)$	$1-\frac{1}{\theta}$ $\tau \epsilon (0,1)$	No closed form
Frank	$-\frac{1}{\theta}\ln\left(1+\frac{(\exp(-\theta u_1)-1)(\exp(-\theta u_2)-1)}{\exp(-\theta)-1}\right)$	$\theta \epsilon (-\infty,\infty)$	$1-\frac{4}{\theta}[1-D_F(\theta)]$ $\tau \epsilon (-1,1)$	$1-\frac{12}{\theta}(D_1\|\theta)-D_2(\theta)$ $\rho_S \epsilon [-1,1]$
Clayton	$\left(u_1^{-\theta}+u_2^{-\theta}-1\right)^{-1/\theta}$	$\theta \epsilon (0,\infty)$	$\frac{\theta}{\theta+2}$ $\tau \epsilon (0,1)$	Complicated expression $\rho_S \epsilon (-1,1)$
A-M-H	$\frac{u_1u_2}{1-\theta(1-u_1)(1-u_2)}$	$\theta \epsilon [-1,1]$	$\frac{3\theta-2}{3\theta}-\frac{2(1-\theta)^2}{3\theta^2}\ln(1-\theta)$ $\tau \epsilon (-0.182, 0.333)$	$\left[[12(1+\theta)di\{\ln\}(1-\theta)-24(1-\theta)\ln(1-\theta)]/\theta^2\right]-\frac{3(\theta+12)}{\theta}$ $\rho_S \epsilon [-0.271, 0.478]$
Joe	$1-\left[(1-u_1)^\theta+(1-u_2)^\theta-(1-u_1)^\theta(1-u_2)^\theta\right]^{1/\theta}$	$\theta \epsilon [1,\infty)$	$1+\frac{4}{\theta}D_J(\theta)$ $\tau \epsilon [0,1)$	No simple form $\rho_S \epsilon [0,1)$

$D_F(\theta)=\frac{k}{\theta^k}\int_0^\theta \frac{t^k}{\exp(t)-1}dt,\ k=1,2;\qquad di\{\ln\}(x)=\int_1^x \frac{\ln t}{1-t}dt$

In this study, the selection process of copula functions for bivariate and trivariate probability analysis was performed intuitively (Chowdhary et al., 2011). This process resulted from designated acceptable dependence domains and nature of association of the data under consideration. A set of copula functions have also been employed to build the 2-D probability distribution by assessing suitable goodness-of-fit measures whereas for trivariate analysis, the elliptical Gaussian copula has been considered in this study. The trivariate Gaussian copula can be defined as

$$C_{\boldsymbol{P}}(u,v,w) = \phi_{\boldsymbol{P}}[\phi^{-1}(u),\phi^{-1}(v),\phi^{-1}(w)] \quad \text{……5-10}$$

in which

$$\phi_{\boldsymbol{P}}[\phi^{-1}(u),\phi^{-1}(v),\phi^{-1}(w)] = \int_{-\infty}^{\varphi^{-1}(u)}\int_{-\infty}^{\varphi^{-1}(v)}\int_{-\infty}^{\varphi^{-1}(w)} \frac{1}{2\pi^{3/2}|\boldsymbol{P}|^{1/2}} exp\left(-\frac{1}{2}\boldsymbol{w}^T\boldsymbol{P}^{-1}\boldsymbol{w}\right) d\boldsymbol{w} \quad \text{……5-11}$$

where $\mathbf{P} = \begin{bmatrix} 1 & \rho_{12} & \rho_{13} \\ \rho_{12} & 1 & \rho_{23} \\ \rho_{13} & \rho_{23} & 1 \end{bmatrix}$ is the symmetrical correlation matrix with $\rho_{ij} \epsilon [-1,1]$; $\mathbf{w} = (\mathrm{w}_1, \mathrm{w}_2, \mathrm{w}_3)^T$ represents the corresponding integral variables.

The primary argument for the choice of Gaussian copula stems from its capability to model all ranges of dependence $(-1,1)$ for multidimensional case. It has a property that as the number of dimensions (n) in a Gaussian copula increases, the number of parameters in the multivariate density function also increases in the order of n^2. With a view to model the general positive and negative dependence structures among the three microscopic traffic variables, the trivariate Gaussian copula can therefore be a convenient choice and is hence, employed in this study.

The most difficult problem in implementing copula theory is the estimation of unknown parameters of the copula. Some commonly used approaches that are mostly employed for estimating copula parameters are Inference from Margins (IFM) approach (Joe, 1997), maximum pseudo-likelihood method and approach based on the rank correlation (Genest & Rivest, 1993). Another straightforward approach for estimating the dependence parameter resorts to the approach based on rank correlation. This approach utilises the relationship between the dependence parameter θ and the two rank-based estimators Kendall's τ and Spearman's ρ_S. Kojadinivic & Yan (2010) proved that Kendall's τ performs significantly better than Spearman's ρ_S; also the expression of Kendall's τ is explicit for all copula families. Due to these advantages, inversion of rank correlation coefficient Kendall's τ method is widely used for estimating the dependence parameter θ. This method is very simple and the marginal distributions need not be modelled to obtain an estimate of θ. In the current paper, parameters of bivariate Gaussian, FGM and Archimedean copulas are computed using the approach based on Kendall's τ while for the trivariate case, maximum pseudo-likelihood estimator is used.

5.4.2 Field Data and Relationship between Different Microscopic Variables

The dataset used for analysing the longitudinal A/D or lateral acceleration of vehicles to study the vehicle dynamic parameters in the previous sections (Section-4.2. and 4.3) are also used in this present study. The data was collected using the Video VBOX installed in different type of test vehicles from different cities of India as described in Chapter-3. All the collected trajectory data are then extracted and analysed as described in section-4.2 and 4.3 of this chapter. It is observed that a linearly increasing trend is observed for the 85th percentile longitudinal acceleration/deceleration (A/D) data with operating speed of vehicles. However a nonlinear two term exponential relationship is observed for 85th percentile lateral acceleration data with operating speed of vehicles. In case of lateral acceleration increases at lower speed conditions i.e. speed < 20 km/h and afterwards it decreases with increase in speed. The 85th percentile data points are obtained for different speed by dividing the data in different speed groups of each 5km/h. For each speed group of 5km/h, the data lies between the 84th and 86th percentile values are extracted and considered as the 85th percentile data. Similarly the 85th percentile lateral acceleration data corresponding to both acceleration and deceleration separately are obtained of all five type of vehicles (motorized two-wheeler (2W), three-wheeler (3W), H-back, sedan and SUV cars). Figure 5-12 presents the trend of the 85th percentile acceleration data with operating speed of motorized 2W.

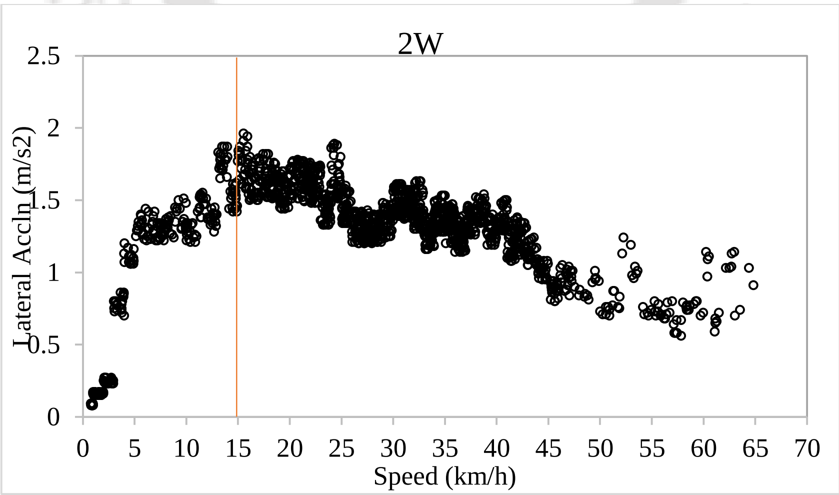


Figure 5-12 85th percentile lateral acceleration trend with operating speed of motorized two-wheelers (2W)

From the Figure 5-12, it can be clearly observed that after 15 km/h speed there exists a decreasing trend of lateral acceleration with the operating speed of vehicles. The lower speed data are not considered due to the lesser sample size. Similar trend of the lateral acceleration is observed for all type of vehicles. Hence, in the present section, for the further analysis of copula, the data after 15km/h speed are considered for all five type of vehicles.

5.4.3 Dependence of Microscopic Variables

Table 5-4, presents correlations of the microscopic traffic variables using the two rank-based dependence measures- Kendall's τ. Results of the correlation coefficients reveal that significant negative association exists between speed and lateral acceleration, speed and longitudinal acceleration/deceleration (A/D), whereas positive dependent relationship exists between lateral and longitudinal A/D.

Table 5-4 Correlation co-efficient of traffic variables

	Longitudinal Acceleration			Longitudinal Deceleration		
Variables	Speed_ LatAccln	Speed_ LongAccln	LatAccln_ LongAccln	Speed_ LatAccln	Speed_ LongDecln	LatAccln_ LongDecln
2W	-0.5707	-0.7410	0.5544	-0.5609	-0.7056	0.4861
3W	-0.7055	-0.8228	0.8909	-0.6438	-0.6117	0.6579
H-Back	-0.9222	-0.8084	0.7389	-0.7225	-0.7681	0.6507
Sedan	-0.8928	-0.8564	0.8818	-0.8584	-0.8564	0.8402
SUV	-0.7653	-0.9012	0.8290	-0.7593	-0.81177	0.7893

We further examined the dependence among speed, lateral and longitudinal A/D by rank-scatter plot, chi-plot (Fisher & Switzer, 1985) as depicted in Figures 5-13 and 5-14. Figure 5-13 depicts the dependence between speed, lateral and longitudinal acceleration, however, Figure 5-14 depicts the dependence between speeds, lateral and longitudinal deceleration of all five type of vehicles.

The chi-plot is a rank-based graphical method in which the n pairs of (X_i, Y_i) are transformed into n pairs of $(\lambda_{ni}, \chi_{ni})$ to reveal more detailed information regarding the nature of association between X and Y. Specifically, for a given pair (X_i, Y_i), let

$$H_{ni} = \frac{1}{n-1} \sum_{j \neq i} I\{X_j \leq X_i, Y_j \leq Y_i\},$$

$$F_{ni} = \frac{1}{n-1} \sum_{j \neq i} I\{X_j \leq X_i\}, \text{ and } G_{ni} = \frac{1}{n-1} \sum_{j \neq i} I\{Y_j \leq Y_i\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5\text{-}12$$

where $I\{A\} = 0,1$ according as the condition is false or true. According to Fisher and Switzer (1985), the chi-plot is a scatter plot of the pairs (λ_i, χ_i) where,

$$\chi_{ni} = \frac{H_i - F_i G_i}{\sqrt{F_i(1 - F_i)G_i(1 - G_i)}}$$

and $$\lambda_{ni} = 4 \operatorname{sign}(F_i - 0.5)(G_i - 0.5) \max\{(F_i - 0.5)^2, (G_i - 0.5)^2\}$$

Fisher & Switzer (1985) and Fisher & Switzer (2001) argue that $\lambda_{ni}, \chi_{ni} \in [-1,1]$ where λ_{ni} is a measure of the distance of the pair (X_i, Y_i) from the bivariate median and to avoid spurious observations, they recommended that only the corresponding pairs should be plotted for which $|\lambda_i| \le 4\left(\frac{1}{n-1} - 0.5\right)^2$. They also suggested that 'control limits' $\pm {}^{c_p}/_{\sqrt{n}}$ be drawn and taken as 'confidence band' in chi-plots to measure the degree of dependence between the variables considered, where the c_p values are 1.54, 1.78 and 2.18 corresponding to α being 0.10, 0.05 and 0.01 respectively. Dashed lines in the chi-plot of Figures 5-13 and 5-14 correspond to the 95% confidence band and almost all the points are observed to fall outside the confidence band for all cases. Since the area inside the confidence band signifies absolutely independent, we can conclude that apparent dependent relationships exist between speed and lateral acceleration; speed and longitudinal (A/D) and lateral and longitudinal (A/D) of all five type of vehicles.

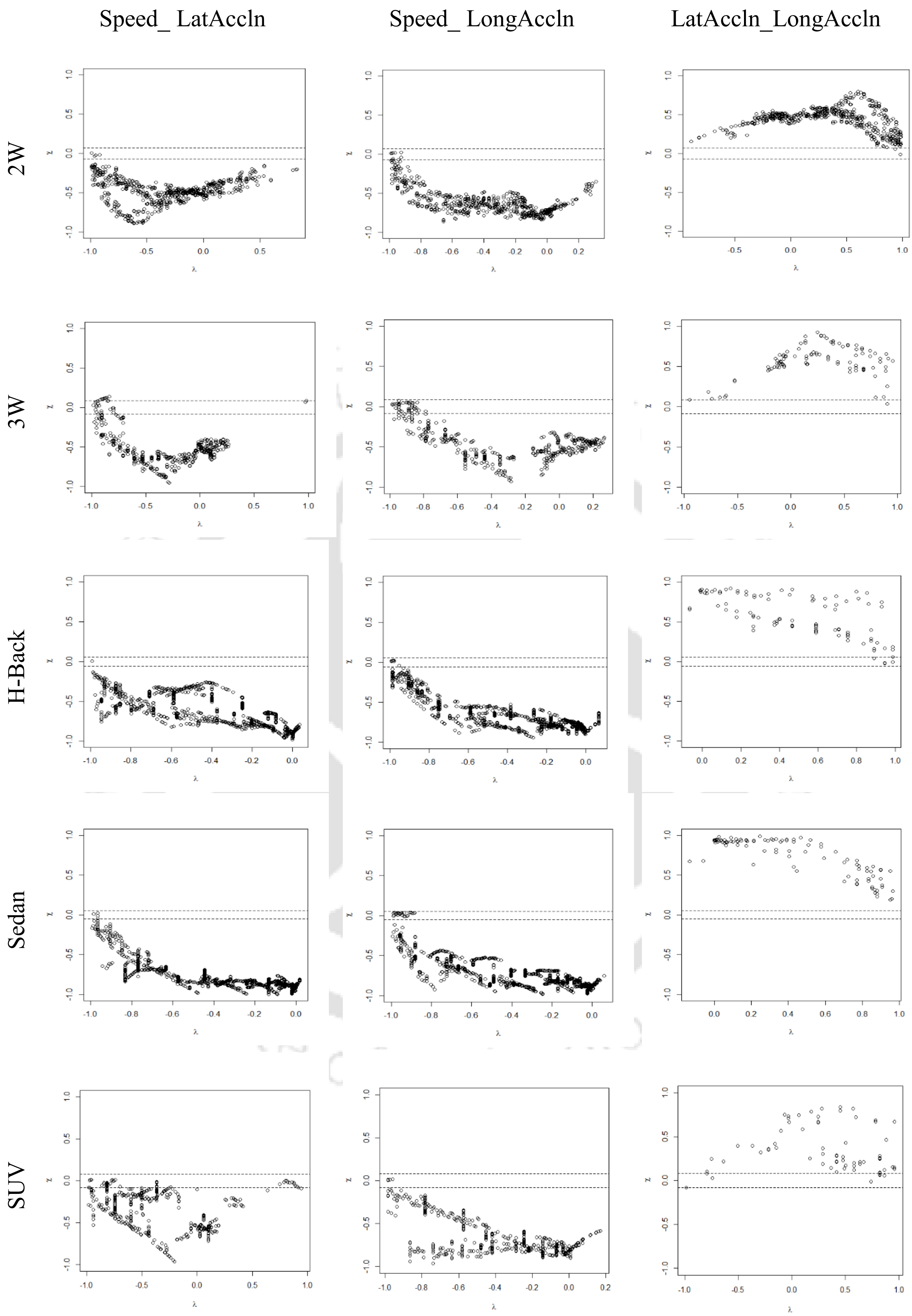


Figure 5-13 Dependence of speed, lateral acceleration and longitudinal Acceleration of all five type of vehicles using chi-plot

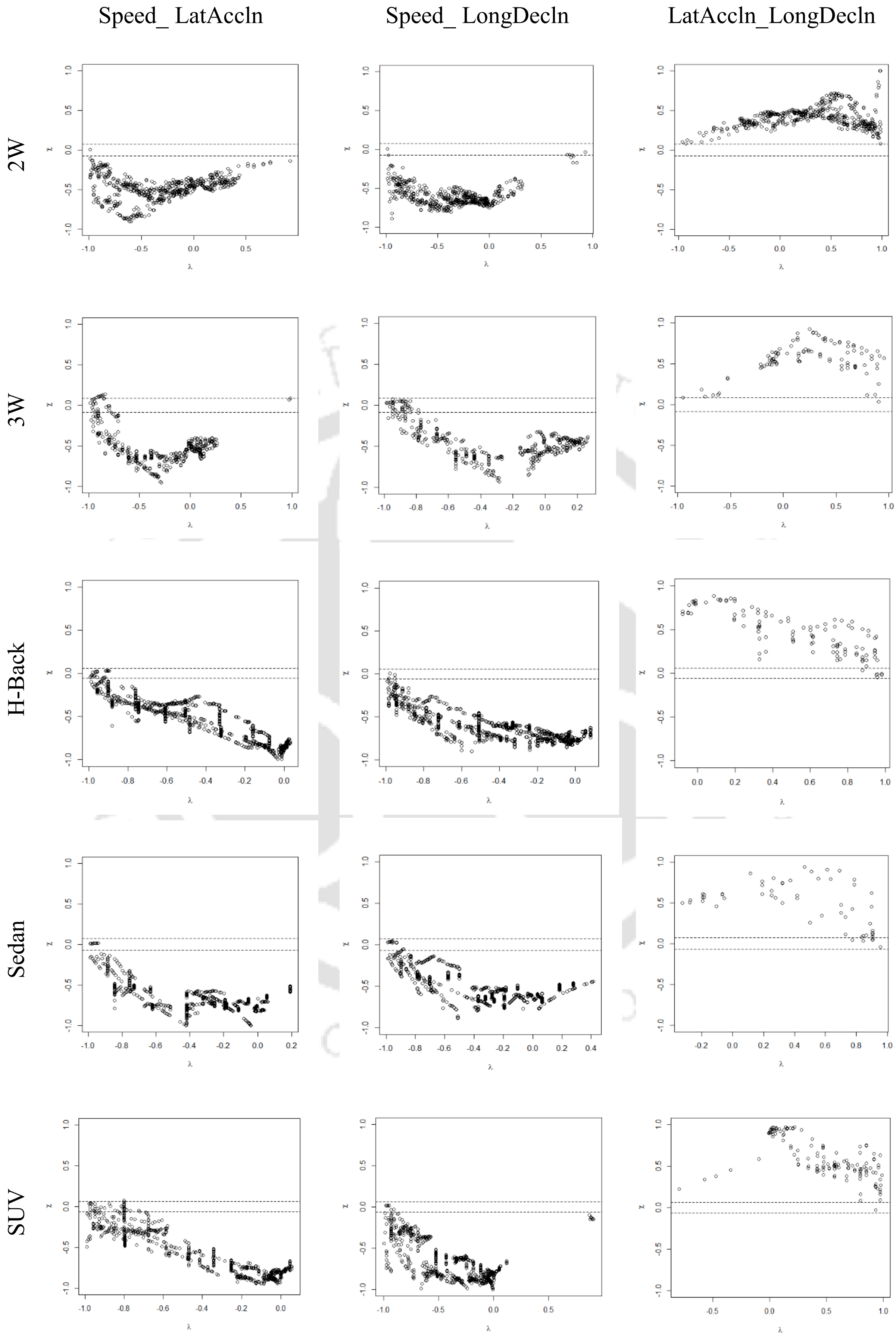


Figure 5-14 Dependence of speed, lateral acceleration and longitudinal Deceleration of all five type of vehicles using chi-plot

5.4.4 Modelling joint dependence structure using copulas

The first step in fitting copula is to determine the appropriate marginal distributions for each of the microscopic variables. In an attempt to find an appropriate distribution for representing longitudinal acceleration data for all vehicle types, several (≈49) single distribution models were implemented in Easyfit software which ranks the fitted distributions based on goodness-of-fit tests and accordingly three statistical models fitted well to our data at 5% significance level. To know the best fitted distribution amongst all three, Log-Likelihood (LL) value and Akike's Information Criterion (AIC) values are estimated for all these probability distribution functions (PDF) (refer Equation 4-2 and 4-3). According to AIC and log-likelihood, the best fitted model is the one for which log-likelihood value is the largest and the corresponding AIC is the lowest. Table 5-5 presents the performance of the selected distribution (marked in **bold**) models and their corresponding results. Based on the goodness-of-fit index, AIC and log-likelihood criterion.

The bivariate models for speed and lateral acceleration, speed and longitudinal A/D, and lateral and longitudinal (A/D) are constructed by assessing suitable bivariate copula functions in comparison with their observations, and their parameters (ϴ) are estimated using inversion of tau's method. Given the domain of Kendall's τ and the estimated correlation values of the observed data (Table 5-4), some copulas (Gumbel, Clayton and Joe) could not account for the negative association between speed and lateral acceleration, speed and longitudinal (A/D). Also the FGM and A-M-H copula are not applicable in our cases as they can model the correlation for $\tau \epsilon [-0.22, 0.22]$ and $\tau \epsilon (-0.182, 0.333)$ respectively. Furthermore, to verify the goodness-of-fit of the theoretical bivariate distribution with the empirical distribution, the dependence parameter values along with the log-likelihood function are listed in Table 5-6.

From Table 5-6, it can be observed that Frank copula and Gaussian copula show the highest log-likelihood values for most of the two-dimensional models in all type of vehicles. Although bivariate Archimedean copulas (Frank and Joe) are observed to provide good fits for the microscopic variables, the multivariate Archimedean copulas lack the flexibility of modelling negative dependence relationships among the variables for higher dimensions ($n \geq 3$). On the contrary, unlike Archimedean copulas the multivariate Gaussian copulas can model all ranges of dependence structure $(-1,1)$. Thus, considering the advantages of trivariate Gaussian copula over multivariate Archimedean copulas, the trivariate Gaussian copula model is constructed in this study to accommodate both the negative and positive associations among the three microscopic variables.

Table 5-5 Comparison of performance measures for various distribution models fitted for marginal of each variable

	Longitudinal Acceleration								
	Fitted Distributions	**Speed**		Fitted Distributions	**Longitudinal Acceleration**		Fitted Distributions	**Lateral Acceleration**	
		LL	AIC		LL	AIC		LL	AIC
2W	Gamma	-2511.75	5027.506	Gamma	-173.825	351.649	Gamma	21.1192	-38.2385
	Lognormal	**-2510.48**	**5024.956**	Lognormal	-186.635	377.27	**Weibull**	**71.7804**	**-139.561**
	Normal	-2545.45	5094.9	**Normal**	**-166.908**	**337.8161**	Normal	57.1054	-110.211
3W	Normal	-1744.57	3493.133	Weibul	110.9042	-217.808	Weibul	80.2534	-156.507
	Weibul	**-1736.76**	**3477.51**	**Normal**	**105.3459**	**-206.692**	Normal	66.8304	-129.661
	Gamma	-1748.7	3501.396	Gamma	100.1953	-196.391	**Gamma**	**929.1248**	**-1854.25**
H-Back	Gamma	-3938.37	7880.749	**Lognormal**	**157.0739**	**-310.148**	Normal	912.8859	-1821.77
	Normal	-3947.89	7899.781	weibul	96.3928	-188.786	weibul	904.258	-1804.52
	Weibul	**-3935.64**	**7875.27**	gamma	146.7381	-289.476	**gamma**	**918.413**	**-1832.83**
Sedan	Normal	-5021.81	10047.63	Weibull	34.92311	-65.8462	Weibull	313.4489	-622.898
	Weibull	**-5004.78**	**10013.56**	Gamma	68.666	-133.332	**Gamma**	**318.244**	**-632.489**
	Lognormal	-201923	403850.6	**lognormal**	**72.6704**	**-141.341**	Lognormal	286.5036	-569.007
SUV	Normal	-3728.08	7460.159	**Lognormal**	**358.2292**	**-712.458**	Weibull	472.0816	-940.163
	Weibull	**-3707.67**	**7419.334**	Weibull	293.2723	-582.545	Gamma	512.8939	-1021.79
	Lognormal	-3719.28	7442.554	Gamma	352.9695	-701.939	**Lognormal**	**518.6604**	**-1033.32**
	Longitudinal Deceleration								
	Fitted Distributions	**Speed**		Fitted Distributions	**Longitudinal Deceleration**		Fitted Distributions	**Lateral Acceleration**	
		LL	AIC		LL	AIC		LL	AIC
2W	Gamma	**-2216.07**	**4436.138**	Gamma	-97.1162	198.2325	Gamma	-188.306	380.6119
	Weibull	-2240.9	4485.789	Weibull	-102.93	209.8599	**Weibull**	**-117.672**	**239.3437**
	Normal	-2242.16	4488.321	**Normal**	**-90.0652**	**184.1306**	Normal	-137.195	278.3907
3W	Normal	-1688.75	3381.501	**Weibul**	**-52.8511**	**109.7023**	**Weibul**	**81.0019**	**-158.004**
	Weibul	**-1684.23**	**3372.454**	Normal	-63.1056	130.2113	Normal	59.85079	-115.702
	Gamma	-1686.6	3377.207	gamma	-72.9532	149.9065	Gamma	41.579	-79.158
H-Back	**Gamma**	**-3561.29**	**7126.586**	Normal	-7.9525	19.905	Normal	912.8859	-1821.77
	Normal	-3574.12	7152.24	weibul	-8.8085	21.617	weibul	904.258	-1804.52
	Weibul	-3562.45	7128.905	**gamma**	**11.2741**	**-18.5483**	**gamma**	**918.413**	**-1832.83**
Sedan	Gamma	-4314.23	8632.452	Gamma	-217.298	438.595	Gamma	313.4489	-622.898
	Normal	-4275.67	8555.34	Weibul	-260.907	525.8129	**Lognormal**	**318.244**	**-632.489**
	Weibul	**-4258.43**	**8520.866**	**Lognormal**	**-203.374**	**410.748**	Weibull	286.5036	-569.007
SUV	Weibull	-3250.78	6505.561	**Lognormal**	**198.6561**	**-393.312**	**Lognormal**	**448.3317**	**-892.663**
	Lognormal	-3255.25	6514.505	Weibull	146.6363	-289.273	Weibull	396.0244	-788.049
	Gamma	**-3242.17**	**6488.34**	Gamma	191.1433	-378.287	Gamma	441.0721	-878.144

Table 5-6 Estimated parameters Θ and their corresponding log-likelihood values for different copulas

			Longitudinal Acceleration					Longitudinal Deceleration				
	Variables	Parameter, Goodness of fit	Gaussian	Archimedean copulas				Gaussian	Archimedean copulas			
				Gumbel	Clayton	Frank	Joe		Gumbel	Clayton	Frank	Joe
2W	Speed and Lat Accln	θ	-0.7811	NA	NA	-7.1956	NA	-0.7714	NA	NA	-6.9699	NA
		LL	**-2169.37**	NA	NA	-2205.6	NA	**-2119.35**	NA	NA	-2160.185	NA
	Speed and Long Accln	θ	-0.9184	NA	NA	-13.576	NA	-0.8951	NA	NA	-11.6770	NA
		LL	**-2136.34**	NA	NA	-2133.9	NA	**-1994.41**	NA	NA	-1909.92	NA
	Lat Accln and Long Accln	θ	0.7649	2.2442	2.4885	6.8245	3.3287	0.6915	1.9459	1.8919	5.48941	2.5649
		LL	-246008	-106464	-359082	**-103507**	-115472	-83862	-46270	-127885	**-44754**	-131047
3W	Speed and Lat Accln	θ	-0.8949	NA	NA	-11.6689	NA	-0.8475	NA	NA	-9.2312	NA
		LL	**-1279.52**	NA	NA	-1333.37	NA	-1482.97	NA	NA	**-1406.95**	NA
	Speed and Long Accln	θ	-0.9615	NA	NA	-20.797	NA	-0.8196	NA	NA	-8.2502	NA
		LL	**-1090.8**	NA	NA	-1183.22	NA	**-1444.3**	NA	NA	-1467.9	NA
	Lat Accln and Long Accln	θ	0.9370	4.4044	6.8088	15.7813	7.58445	0.8591	2.9236	3.8473	9.7153	4.6568
		LL	-49963	-49701	-57490	-44532	**-44125**	-42146	-45731	-204520	-43022	**-2304.13**
H-Back	Speed and Lat Accln	θ	-0.9222	NA	NA	-13.9677	NA	-0.9065	NA	NA	-12.5240	NA
		LL	**-2082.14**	NA	NA	-2117.77	NA	**-1894.16**	NA	NA	-1905.659	NA
	Speed and Long Accln	θ	-0.9551	NA	NA	-19.082	NA	-0.9344	NA	NA	-15.41	NA
		LL	-2722.6	NA	NA	**-2697.90**	NA	**-2676.30**	NA	NA	-2732.5	NA
	Lat Accln and Long Accln	θ	0.9171	3.8310	5.6613	13.4486	6.4469	0.85326	2.8633	3.7266	9.4634	4.5382
		LL	-53847.73	-372098	-38976	**-358389**	-687399	**-392072**	-411875	-404212	-403508	-412914
Sedan	Speed and Lat Accln	θ	-0.9858	NA	NA	-35.5994	NA	-0.9753	NA	NA	-35.5994	NA
		LL	-2989.45	NA	NA	**-2762.73**	NA	-2989.46	NA	NA	**-2762.73**	NA
	Speed and Long Accln	θ	-0.9747	NA	NA	-26.103	NA	-0.9747	NA	NA	-26.498	NA
		LL	-3417.3	NA	NA	**-3230.5**	NA	-2652.91	NA	NA	**-2451.72**	NA
	Lat Accln and Long Accln	θ	0.9828	8.4649	14.9298	32.1260	15.6737	0.9686	6.5259	10.5181	23.2662	11.2741
		LL	-87934.7	-79393.7	-710047	**-57849.0**	-98479.8	-78654.9	-77007	-624364	**-61574**	-98593.9
SUV	Speed and Lat Accln	θ	-0.9328	NA	NA	-15.2043	NA	-0.9294	NA	NA	-14.7740	NA
		LL	-2511.03	NA	NA	**-2371.04**	NA	-2197.93	NA	NA	**-2095.78**	NA
	Speed and Long Accln	θ	-0.9880	NA	NA	-38.8070	NA	-0.9566	NA	NA	-19.454	NA
		LL	-2282.4	NA	NA	**-2201.51**	NA	-2571.3	NA	NA	**-2434**	NA
	Lat Accln and Long Accln	θ	0.9641	5.8500	9.7000	21.6197	10.4593	0.9457	4.7461	7.4923	17.1654	8.2631
		LL	-823974	-164618	-196594.9	**-147755**	-965489.8	-986949	-147522	-896329	**-135872**	-89257.5

Note-NA means parameter θ for the respective copula is not applicable because Gumbel, Clayton, and Joe copulas can model the correlation for $\tau \epsilon [0, 1]$, LatAccln-Lateral acceleration and LongAccln-Longitudinal Acceleration

The parameters of the trivariate Gaussian copula are estimated using inversion of tau's method. The estimated parameters (ρ) of the trivariate Gaussian copula and their log-likelihood values are presented below in Table 5-7.

Table 5-7 Parameters and the LL values obtained for the trivariate Gaussian copula

Vehicle	Longitudinal Acceleration		Longitudinal Deceleration	
Type	Parameters	LL	Parameters	LL
2W	ρ_{12}= -0.7811 ρ_{13}= -0.9184 ρ_{23}= 0.7649	-192172	ρ_{12}= -0.7714 ρ_{13}= -0.8951 ρ_{23}= 0.6915	-184879
3W	ρ_{12}= 0.8949 ρ_{13}= -0.9615 ρ_{23}= 0.9370	-125437	ρ_{12}= -0.8475 ρ_{13}= -0.8196 ρ_{23}= 0.8591	-135629
H-Back	ρ_{12}= -0.9222 ρ_{13}= -0.9551 ρ_{23}= 0.9171	-169543	ρ_{12}= -0.9065 ρ_{13}= -0.9344 ρ_{23}= 0.85326	-158762
Sedan	ρ_{12}= -0.9858 ρ_{13}= -0.9747 ρ_{23}= 0.9828	-116792	ρ_{12}= -0.9753 ρ_{13}= -0.9747 ρ_{23}= 0.9686	-135835
SUV	ρ_{12}= -0.9328 ρ_{13}= -0.9880 ρ_{23}= 0.9641	-187787	ρ_{12}= -0.9294 ρ_{13}= -0.9566 ρ_{23}= 0.9457	-197787

$\rho_{12}, \rho_{13}, \rho_{23}$ represents the parameters for the trivariate Gaussian copula for speed-lateral acceleration, speed-longitudinal A/D and lateral and longitudinal A/D respectively.

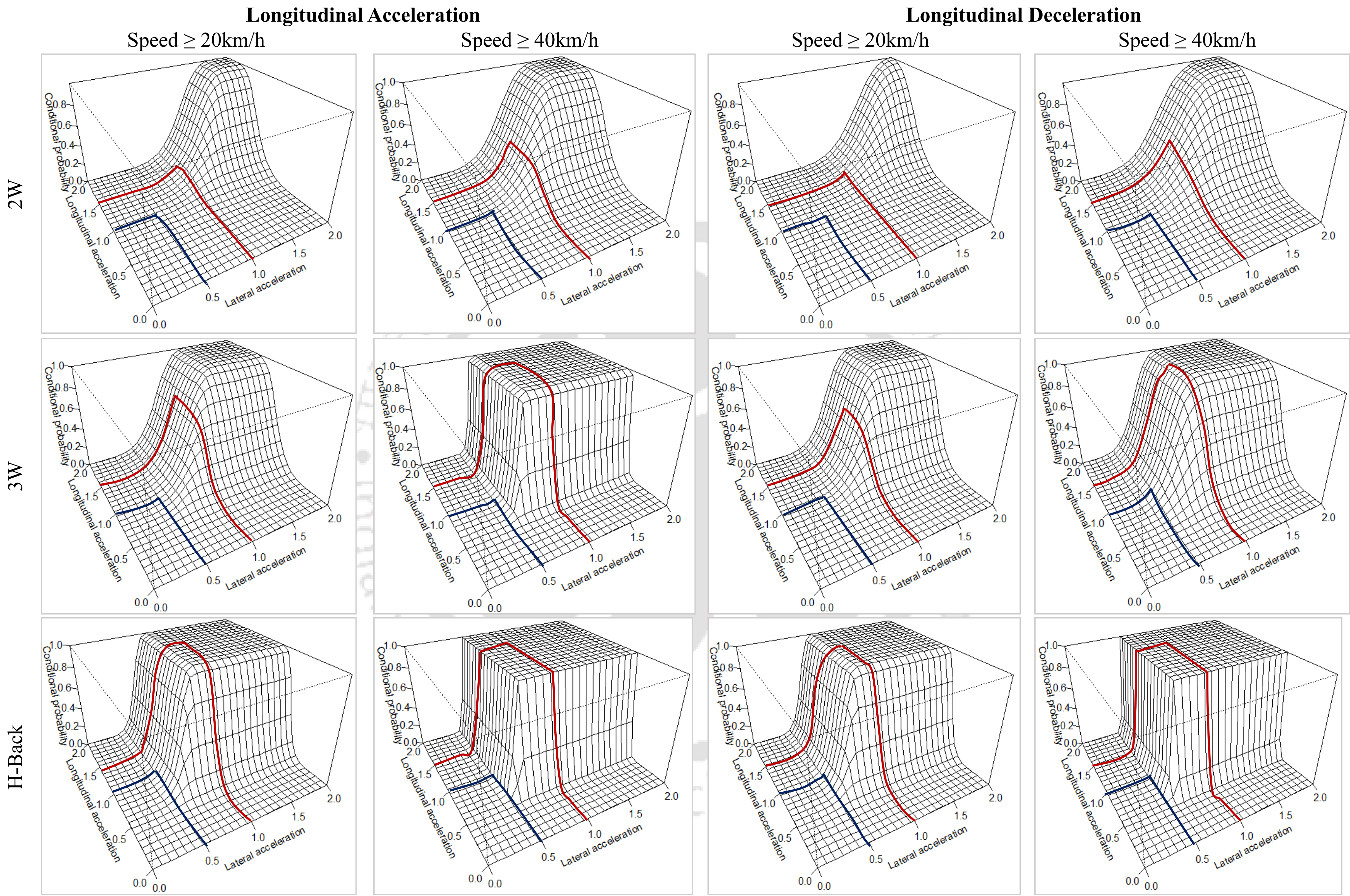
5.4.5 Conditional Probability distribution using Copula

The conditional probability distributions for different combinations of the microscopic variables exceeding a certain threshold can be expressed as

$$\mathbb{P}(U_1 \leq u_1 1, U_2 \leq u_2 \,|U_3 \geq u_3) = \frac{C(u_1,u_2) - C(u_1,u_2,u_3)}{1-u_3} \ldots\ldots\ldots 5\text{-}13$$

where $u_1 = F_1(x_{lat}), u_2 = F_2(x_{long}), u_3 = F_3(x_{speed})$; lat, long represent lateral acceleration and longitudinal A/D respectively.

Figure 5-15 shows the conditional joint probability distributions for lateral acceleration and longitudinal A/D given $speed \ \geq 20 km/h$ and $speed \geq 40\ km/h$ for all five type of vehicles (2W, 3W, H-back, Sedan and SUV cars).



Longitudinal Acceleration
Longitudinal Deceleration
Speed ≥ 20km/h
Speed ≥ 40km/h
Speed ≥ 20km/h
Speed ≥ 40km/h
2W
3W
H-Back
Conditional probability
Longitudinal acceleration
Lateral acceleration

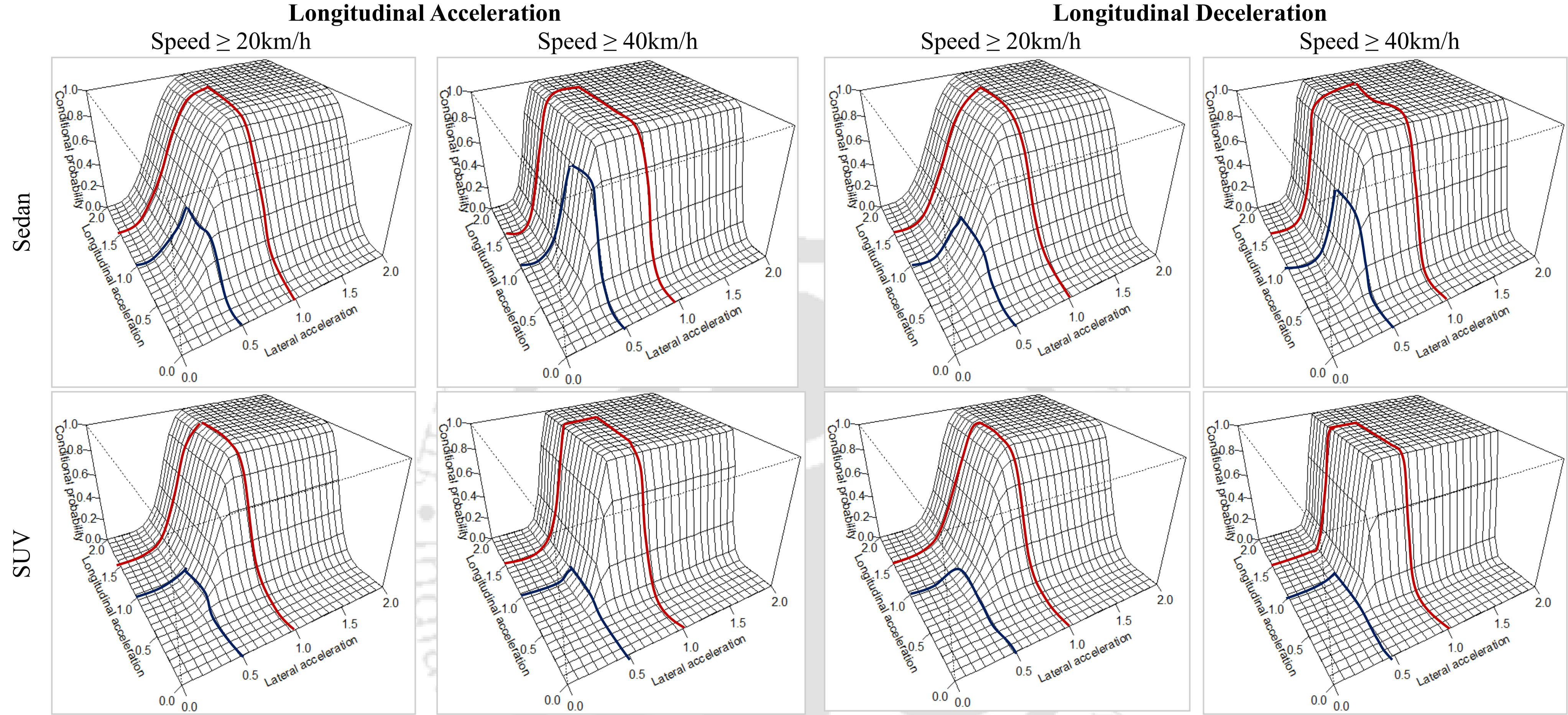


Figure 5-15 Conditional probability for lateral and longitudinal acceleration and deceleration separately with speed ≥ 20 km/h and speed ≥ 40 km/h

As observed from Figure 5-15, the conditional probability of lateral acceleration and longitudinal A/D decreases with the increase in conditioning (speed). The conditional non-exceedance probabilities for lateral and longitudinal acceleration of motorized 2W (longitudinal (A/D) ≤ 1m/s^2 and lateral acceleration ≤ 0.5m/s^2) with speeds exceeding thresholds of $speed$ ≥ 20 km/h and $Speed$ ≥ 40 km/h are observed to be 0.1 and 0.18 respectively. Similarly, for sedan cars, the conditional non-exceedance probabilities for lateral and longitudinal acceleration longitudinal (A/D) ≤ 1 m/s^2 and lateral acceleration ≤ 0.5 m/s^2) with speeds exceeding thresholds of $speed$ ≥ 20 km/h and $Speed$ ≥ 40 km/h are observed to be o.52 and o.825 respectively, which implies that the probability of maintaining same lateral and longitudinal A/D values increases at higher speeds. This indicates that at higher speed conditions a larger percentage of riders maintain lower lateral and longitudinal A/D values comparing to the lower speed conditions. Similar type of observation is observed for deceleration of all type of vehicles. Hence, from this observation it can be concluded that at higher speed conditions the probability of higher lateral and longitudinal manoeuvring decreases for all type of vehicles. It is also observed that the probability of obtaining higher lateral and longitudinal A/D is higher in case of motorized 2W and it decreases for 3W followed by H-back, sedan and SUV cars. This indicates a higher manoeuvring action of smaller vehicles comparing to cars. It is also observed that probability of lateral and longitudinal manoeuvre is less while the vehicle is decelerating compared to accelerating condition. This information can be useful to determine the propensity of risks associated with the riders.

The non-exceedance conditional probability of vehicle speeds is of particular importance in traffic operation and safety studies to essentially help in adopting suitable traffic management strategies. This is because for a particular exceedance or non-exceedance probability value P, the values lateral acceleration, longitudinal A/D and speed for the respective variables can be obtained from the 3-D Gaussian distribution for this probability P. Based on the results of this study and the graphical analysis of the conditional probabilities, it can be concluded that a sufficiently accurate method to model the dependence structures of all three vehicle dynamic parameters is to use the trivariate Gaussian distribution.

5.5 Concluding Remarks

The dynamic parameters like speed, lateral and longitudinal acceleration can very well represent the driving behaviour of vehicles in a mixed no-lane disciplined traffic. The lateral as well as the longitudinal force coefficients, generated by the tire and road interaction while driving, are the key factors for vehicle stability and the driving safety. The proposed methodology can be used to characterise the driving style i.e. cautious or aggressive behaviour of the driver. The tire-forces model (g-g diagram) is used to implement safety margin concept.

The driving behaviour (adoption of safe or unsafe driving) is analysed by considering dynamic parameters like operating speed, lateral and longitudinal accelerations of the vehicles on straight roads of plain terrain. The proposed g-g diagram can easily demonstrate the safe or unsafe behaviour of a driver. The normalised accelerations with gravity (a_x/g and a_y/g) are plotted, and compared with the friction circle obtained from the design coefficient of friction. The friction points lie outside the safety envelop are considered as the risk-taking driving behaviour and is considered as unsafe. It is observed that in all cases the drivers of different vehicles adopts the safe driving in case of plain terrain roads (i.e. nearly 99% data lies within safe limit envelope "g-g diagram") except the motorised 2Ws (97%). It is observed that the motorised 2Ws are the most risk-taking drivers compared to cars.

The proposed diagram for resultant acceleration and design speed (safety domain curve), can easily demonstrate the safe or unsafe driving behaviour. The acceleration trend with the progressive (distance) interpret the exact locations of the trajectory where the driver experience sudden acceleration or deceleration (braking) additionally the points where lateral acceleration crosses the lateral threshold of the road design as stated by Eboli et al. (2016). It can be concluded from the present study that in all cases the drivers (different regions of the country) mostly drive within safe limit except 2Ws. Motorized 2Ws mostly cross the safety domain very frequently.

This study also investigated the applicability of the copula based approach to model the joint distribution of longitudinal descriptors [operating speed, longitudinal (A/D)] and lateral descriptor [lateral acceleration] of five different type of vehicles (motorized 2W, 3W, H-back, Sedan and SUV cars) for no-lane based traffic streams. An initial assessment on the strength of association of the traffic variables corroborated strong negative correlation between speed and lateral acceleration, speed and longitudinal A/D, and positive dependence between lateral and longitudinal A/D.

To accurately reproduce the dependence structures between the associated variables, a variety of copula functions including the Gaussian copula and various Archimedean copulas like the Gumbel-Hougaard copula, the Frank copula, the Clayton copula, and the Joe copula were employed in this research. The results of the study confirmed that Frank copula and Gaussian copula are the best fitted model for describing the bivariate dependence of the considered variables, in most of the vehicles cases. Conversely, owing to the enhanced flexibility in accommodating all ranges of dependence $(-1,1)$ over multivariate Archimedean copulas, the multivariate Gaussian copula provided a convenient way to model the joint behaviour of all three vehicle dynamic parameters.

In light of the research conducted in this study, the recommendation is to use trivariate Gaussian copula for the amelioration of the realistic representation of riders' behaviour in lane-based as well as in no-lane based traffic streams, by suitably accommodating the dependent relationships between the longitudinal and lateral descriptors of different type of vehicles. The work undertaken in this study provides a framework for generating the traffic variables simultaneously by accommodating the dependent relationship and can have extensive applications in safety evaluation, planning, design of roadway systems and in traffic operation studies. Also the study of dynamic parameters of vehicles using friction circle concept can contribute to the road safety improvement. The defined safety domain is an important tool for finding the points on the trajectory, where the driving behaviour is safe/unsafe to inform him about his driving behaviour and produce the threshold of attention to take preventive measures.

6. Lateral Placement of Vehicles over Roads of Different Width

6.1 Introduction

In India, due to no-lane discipline and mixed traffic condition, the lateral movements of vehicles are high in comparison to vehicles in lane-disciplined traffic of developed countries. As discussed in Chapter 2, the lane discipline is strictly followed in homogeneous traffic conditions. The linear clearance maintained by the vehicles with respect to vehicles in front may be sufficient to describe vehicle manoeuvring process. In the mixed no-lane discipline traffic, vehicles travel abreast due to their variations in size and non-standard widths; so it becomes essential to consider the clearances in lateral direction in addition to that in a linear direction for defining the flow logic. Due to the absence of lane behaviour, vehicles not only interact longitudinally but also interact laterally with the vehicles around it. Road features/elements (like road edge conditions, divider conditions, etc.) also affect the vehicle's movement and its lateral placement depending upon whether drivers perceive a roadside element as an obstacle or not. Vehicles will move away (or maintains certain clearance) from an object/road elements that they perceive as an obstacle.

According to Highway capacity manual, lane position is crucial to traffic performance on multilane highways. This is due to the diverse effects of lanes on driver's behaviour and traffic flow. Generally, heavy and slow vehicles move in left lanes because of low speed and partially due to prohibition on using right lanes (assuming left traffic regulation). In multilane traffic, distribution of lane use depends on vehicle's size and operating characteristics. Lane distribution is a parameter used when two or more lanes are available for traffic in a single direction, and the volume distribution varies widely, depending on traffic regulation, traffic composition, speed and volume, the number of locations of access points, the origin-destination patterns of drivers, the development environment, and local driver habits. Further, traffic composition in India includes widely varying vehicles in terms of their size and operating characteristics. The minimum linear and lateral clearances desired by individual driver-vehicle units, to continue their movement, form the most important parameters of the simulation model. In the present chapter, the lateral placement of the vehicles studied in two sections.

1. Study of lateral placement of vehicles throughout the entire width or cross-section of the

road, based on the data collected from the top view video recording technique.

2. Study of lateral gap maintaining behaviour of the vehicles from the road edge (median) according to their geometric variability, based on the data collected from the sensor based assembly.

6.2 Study of Lateral Placement of Vehicles on Cross-section of Roads

In the present section, the lateral placement or gap maintaining behaviour of vehicles from road edge/median are described with the operating speed of vehicles on different type of roads. This study has three broad categories. Initial portion deals with the basic description of data, and the basic stream behaviour of different roads are analysed. Initially, the extracted data are processed for further analysis. Then the analysis of lateral placement distribution of different type of vehicles over various types of roads are presented – how different vehicles vary on the similar type of road, how each vehicle varies on different type of roads. Then the speed-lateral placement model is developed. The operating speed of different type of vehicles on different type of roads are predicted using its lateral placement. An improvement of this model is also proposed by incorporating flow as another parameter.

6.2.1 Stream Details and Initial Data Processing for Further Analysis

The details of data collection procedure and site details are described in Chapter-3. The details of traffic stream are described based on the traffic composition and stream flow values of each road section where the data have been collected. Data are collected from eleven different sites with different number of lanes (different road widths). The following table describes the details of traffic composition and an average flow of the stream. The buses and trucks are combined due to very low data of each vehicle type. It can be observed that due to the city road the percentage of cars, motorized two-wheeler (2W) and three-wheeler (3W) have a dominant percentage in all sites.

Table 6-1 Traffic composition and flow values of all the sites selected for data collection

Site Number	Average Flow*	Traffic Composition in Percentage (%)				
		Buses and Trucks	Cars	3W	2W	LCV
1	1063	19.29	40.78	3.14	31.29	5.49
2	1959	2.73	17.16	12.49	63.27	4.34
3	1194	8.98	47.41	23.98	16.48	3.16
4	1750	4.69	42.71	7.99	42.67	1.96
5	720	15.40	30.58	3.43	44.02	6.58
6	1010	5.20	23.61	43.88	25.24	2.08
7	2327	8.62	43.98	19.02	25.4	2.97
8	911	7.89	41.74	1.90	40.36	8.12
9	754	4.79	71.50	5.14	16.71	1.86
10		6.75	67.84	1.13	24.28	0
11	1415	4.53	48.74	20.91	20.14	5.05

2W- Motorized Two-wheeler, 3W- Motorized Three-Wheeler, LCV- Light Commercial vehicle, * indicates average flow per lane of each site in PCU/h

The spread of lateral placement data across the road cross section is explained by clustering the placement data with different groups. The clustering of the data is done with a defined bin size of lateral placement. When plotting a frequency data, it should be able to depict the proper trends which one wants to see. A very small bin size tend to produce too many wiggles in the graph and makes it too complicated to decipher. A large bin size tends to hide many important details of the variation that one needs to know.

In this light, some authors (Dubey et al., 2012; Mahapatra et al., 2016) have studied about the histogram interval determination procedures and came up with the following procedures for determining bin width;

1. (Sturges, 1926): As per this rule the bin width is,

$$h = (b-a)/(1+\log 2N) \quad \text{......6-1}$$

where a=lower limit; b=upper limit; N= no. of sample

2. (Scott, 1979)

$$h = 3.5\sigma * (n)^{-1/3} \quad \text{......6-2}$$

where, σ= standard deviation of the observations; n= total no. of observations.

3. (Freedman & Diaconis, 1981)

$$h = 2*IQR * (n)^{-1/3} \quad \text{......6-3}$$

where IQR= Difference between 75th percentile speed and 25th percentile speed; n= no. of sample

Also, in case of determining lateral placement under heterogeneous conditions, authors had used a bin size of 0.25m to find out vehicle's lateral placement (Balaji et al., 2013; Dey et al., 2006). In our present study the bin width of 0.25m and 0.5m including the bin width calculated from the above-mentioned formulae are used to identify the ideal bin size.

In this analysis, all the above three methods have been tried along with the one used by these authors. A trial bin size of 0.5m was also tried for the selection of a bin width from previous studies by Balaji et al. (2013) and Dey et al. (2006) for 2-lane two-way roads whereas here the analysis extends up to 10-lane bidirectional roads. The lateral placement data with different bin width calculated for each vehicle of the individual city to see the pattern of lateral placement distribution.

It is observed that the preliminary bin size of 0.25m is very small to describe the lateral placement behaviour. It causes large fluctuations in the data with many non-existing bumps and local modes. Also, the bin width calculated from the existing formulas (Sturges, 1926; Scott, 1979 and Freedman & Diaconis, 1981) have very large values of bin width exceeding 0.75m in all cases and 1.0m in most of the cases. This large bin width wastes much of the important information and underlying trends of the observed data. However, the bin width of 0.5m shows an appropriate trend of lateral placement in all cases. The similar results are obtained for all sites.

6.2.2 Vehicle Type wise Variation in Lateral Placement on Different Roads

The present section deals with the variation in the distribution of lateral placement for a different type of vehicles on different roads (with different width). In our present study three types of passenger cars are mainly observed in the Indian traffic stream (H-Back, Sedan and SUV cars). Data for three different type of vehicles are extracted separately to see their variation in driving behaviour. First, the variation in lateral placement distribution of all three types of cars observed. Then the lateral placement of all type of vehicles are observed in the next subsection.

6.2.2.1 Lateral Placement of different type of Cars

There are three most common types of cars (Hatchback, Sedan and Sports Utility Vehicles) are observed (refer Car And Bike Team, 2016). In this section, the relative frequency distribution of lateral placement of all three type of cars is plotted individually with the selected bin width of 0.5m. For each 0.5m width of the road the number of cars plying are presented with relative frequency distribution plot. This analysis is conducted for each different site.

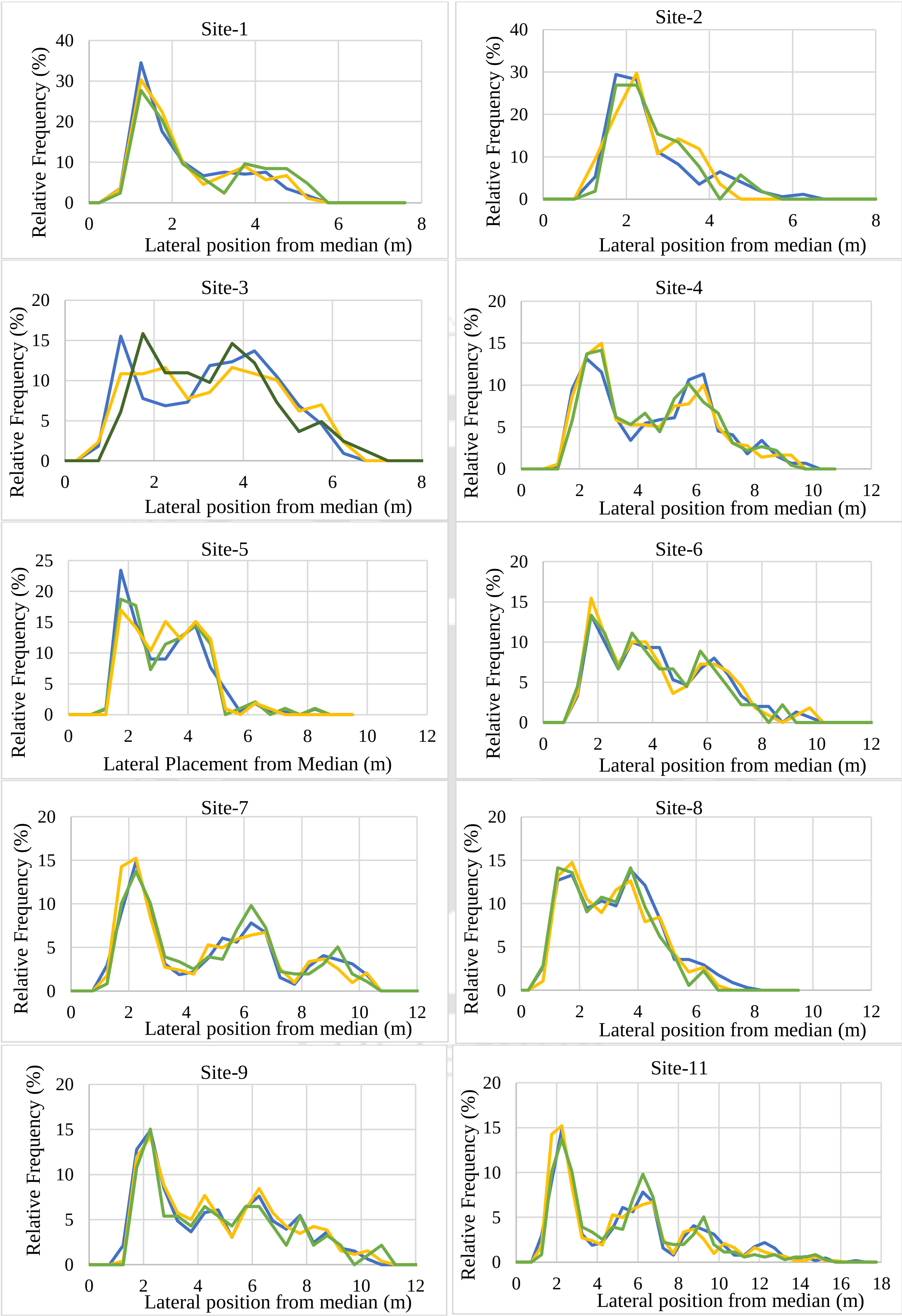


Figure 6-1 Frequency Distribution of Lateral Placement of all three type of cars (H-back, Sedan & SUV) over the road cross section (Width), (Note-Data for site-10 (8-lane divided road are extracted as cars only without categorizing the type of cars)

Figure 6-1 presents the distribution of lateral placement for cars (H-back, Sedan and SUV) of all Sites are presented individually. The ANOVA test is conducted to see the statistical significance between the distribution of lateral placement for each type of cars for all sites. The result of ANOVA (Analysis of Variance) test indicates that there is no significant different between the lateral placement of all three type of passenger cars while manoeuvring on different roads at 5% significance level. Hence, in the present study, the data for all three passenger cars are combined and categorized as cars to study their lateral placement behaviour.

6.2.3 Variation in Lateral Placement of Different Vehicle Types on Different Roads

As discussed in Section-1, different vehicles with various static and dynamic characteristics have different manoeuvre capability. This manoeuvring includes lateral placement of vehicles on the entire road width, i.e. cross-section of the road. The following sub-section describes the analysis of lateral placement of different vehicles (cars, motorized two-wheeler; 2W, motorized three-wheeler; 3W, LCV, buses and trucks) on 4-lane, 6-lane, 8-lane and 10-lane divided roads.

6.2.3.1 Lateral Placement of Vehicles on 4-lane Divided Roads

The lateral placement of different type of vehicles on the entire road width of 4-lane divided roads for each site (Site-1, 2 and 3) are obtained. The frequency distribution of each type of vehicles on all three sites of 4-lane divided roads are presented below in Figure 6-2.

Sites 1 and 3 are mainly dominated by cars, but Site 2 has a very high frequency of 2Ws. It can be observed that 75% to 90% of the cars are seen to move on the median-sided lane for Sites 1 and 3 however for Site 2 it is almost equally distributed on both the lanes. This may be due to the difference in their flow level (PCU/h/lane) of each site (refer Table 6-1). 2Ws and 3Ws mainly tend to avail the shoulder-sided lane in all three cases. 3Ws have a spread of around 70% along the shoulder-sided lane due to their slow speed. Goods carrying vehicles whether trucks or light-commercial-vehicles (LCVs) move mainly along the median sided lane in case of 4-lane divided roads. Their proportion on the median-sided lane varies from 55% to 80%. However, in case of Site-2, the trucks and buses shift towards the shoulder side of the road. This may be due to the high flow conditions; the heavy vehicles try to avoid the frequent overtaking, passing and filtering through the traffic, hence shifts to the shoulder side of the road to maintain a consistent linear maneuver. It is observed the flow values of the traffic stream have a significant impact on the lateral placement of cars and the heavy vehicles like buses and trucks. The F-tests are conducted between the placements of vehicles of different sites. The

Table 6-2 presents the results of the F-tests for each vehicle.

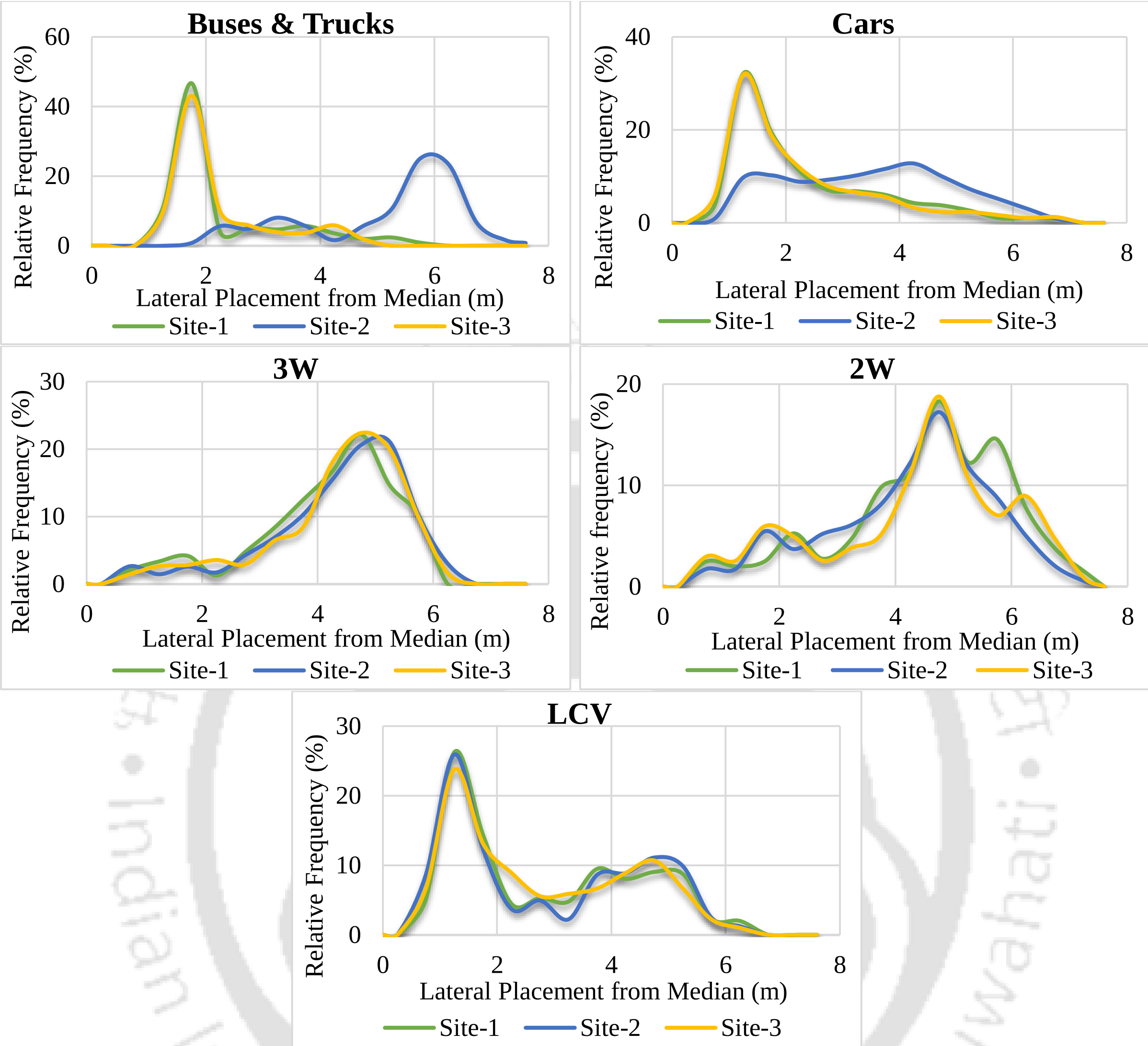


Figure 6-2 Distribution of vehicle's lateral placement of three different sites on 4-lane divided roads

Table 6-2 Results of F-test for the placement data between different sites for each type of vehicle on 4-lane divided roads

Vehicle Types	Site-1 & Site-2		Site-2 & Site-3		Site-1 & Site-3	
	$F_{statistics}$	$F_{critical}$	$F_{statistics}$	$F_{critical}$	$F_{statistics}$	$F_{critical}$
Buses & Trucks	2.3864	2.3334	0.4345	0.4285	1.0369	2.3334
Cars	3.0700	2.3334	0.4313	0.4285	1.0171	2.3334
3W	1.0485	2.3334	1.0497	2.3334	1.0011	2.3334
2W	1.2412	2.3334	1.2733	2.3334	1.0258	2.3334
LCV	1.0929	2.3334	1.1368	2.3334	1.0401	2.3334

It can be observed from Table 6-2, that distribution of lateral placement of buses & trucks and cars in Site-2 are significantly different from Site-1 and Site-3. This indicates that the flow values (refer Table 6-1) have a significant impact on the lateral placement of vehicles. However, in case of other vehicles like two-wheelers (2W), though the flow value is very high in Site-2 and the composition of 2W is more than 60%, the distribution pattern of 2Ws on the entire road width remains similar for all three sites. This may be due to the safety concern of the 2W drivers. Due to the higher manoeuvring capability of 2W, while travelling near the median, 2Ws face hindrance due to the presence of other larger vehicles. Hence, they tries to move away from the median. Similarly, the 3Ws due to their slower speed moves at the shoulder sided lanes so that the commuters can board and alight from them. As seen in case of trucks and buses, the goods carrying vehicles (LCVs) also move at the median side of the road. The placement data of different vehicles obtained from different sites with no significance difference are combined to see the overall distribution of different vehicles on the entire road width of a 4-lane divided road (2-lane road) (refer Figure 6-3).

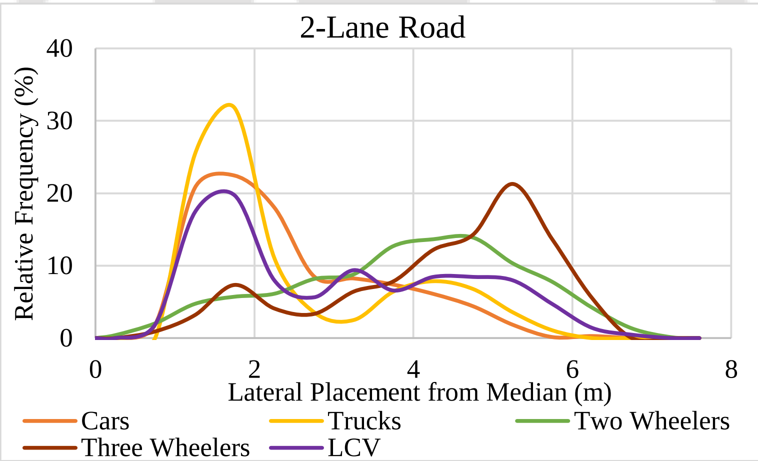


Figure 6-3 Lateral placement of different vehicles on 4-lane divided (2-lane) road

It can be observed that in case of 2-lane roads the cars (75-90%), heavy vehicles (trucks & buses) and LCVs (55-80%) moves near the median side of the road. However, the smaller vehicles like motorized 2Ws and 3Ws (70%) moves away from the median, i.e. towards shoulder side of the road.

6.2.3.2 Lateral Placement of Vehicles on 6-lane Divided Roads

Lateral placement of different vehicle types on 6-lane divided roads obtained from Sites 4, 5, 6, 7, 8 and 9. Sites 4, 8 and 9 almost have similar traffic composition with almost equal composition of two-wheelers and cars, but Sites 5, 6 and 7 have majority of 2Ws, 3Ws and cars respectively. Also, Site-9 has a tremendously high number of cars. Figure 6-4 presents the lateral placement of different vehicles on different sites.

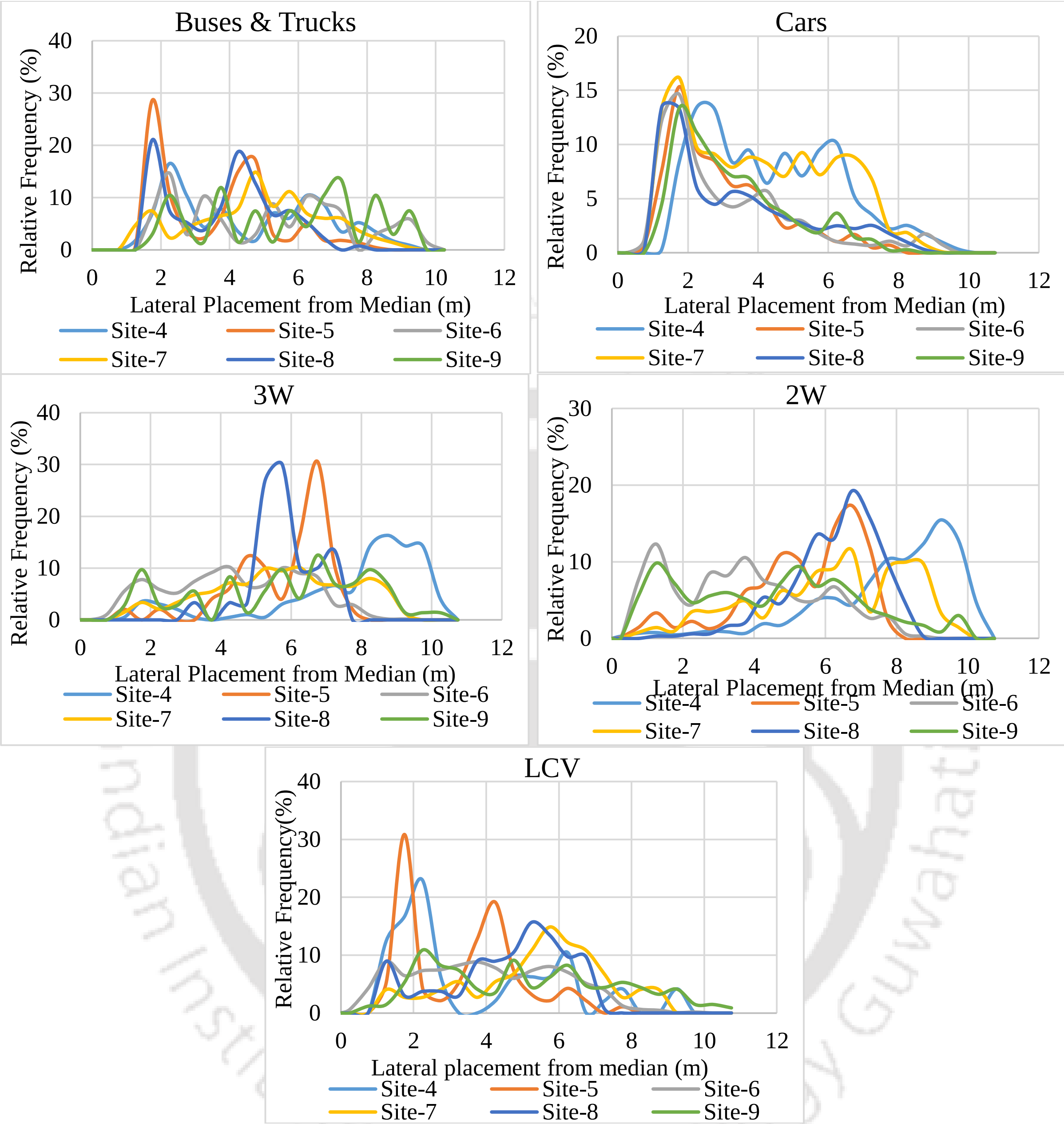


Figure 6-4 Distribution of vehicles lateral placement of six different sites on 6-lane divided roads

Majority of the cars, the fastest vehicles on any road as seen from the speed values, are in the median-sided lane (40% to 60%) closely followed by the middle lane (35% to 50%). However, for Site-4 and 7, cars spread on the entire road width. This may be due to the heavy flow of those particular sites. Motorized 3Ws due to slow speed move along the shoulder side though they encroach somewhat into the lane adjacent to it. This trend is different for Site 6, where they move throughout the road because nearly 45% of the vehicle composition are 3Ws. Heavy vehicles (trucks and buses) move away from the median in most of the cases except at Site 5 and 8. It is a high volume of trucks (15% and 8% for Sites 5 and 8 respectively) which causes them to move along the median side of the road. Two-wheelers are seen to move along the shoulder side and the one adjacent to it for all site except Site 6. At Site 6, nearly 70% of the vehicles are small vehicles (3Ws and 2Ws), so there is a very high rate of maneuverability on the road and free space for two-wheelers to move on the entire width, especially on the median side. Majority of the LCVs moves away from the median (55% to 80%), except for Site 4, to make way for the faster moving vehicles. For Site 4 it may be that due to high flow they are unable to move out from the median-sided lane. However, in case of Site-5, 40-50% of the 3Ws moves at the median side closely followed by the middle lane. Statistical F-tests are conducted between the lateral placements of different vehicles on different sites. Table 6-3 presents the detail results of the F-test.

Table 6-3 Results of F-test for the placement data between different sites for each type of vehicle on 6-lane divided roads

Sites	Buses & Trucks	Cars	3W	2W	LCV
Sites 4-5	0	1	0	0	1
Sites 4-6	0	1	1	1	1
Sites 4-7	1	0	0	0	1
Sites 4-8	0	1	0	0	1
Sites 4-9	1	1	1	1	1
Sites 5-6	0	0	1	1	1
Sites 5-7	1	1	0	0	1
Sites 5-8	0	0	0	0	1
Sites 5-9	1	0	1	1	1
Sites 6-7	1	1	1	1	0
Sites 6-8	0	0	1	1	0
Sites 6-9	1	0	1	1	0
Sites 7-8	1	1	0	0	0
Sites 7-9	0	1	1	1	0
Sites 8-9	1	0	1	1	0

0-No significance difference between the two sites, 1-significantly different at 5% significance level.

The placement data of different vehicles obtained from different sites with no significance difference are combined to see the overall distribution of different vehicles on the entire road width of a 6-lane divided road (3-lane road) (refer Figure 6-5). It can be observed that in 3-lane roads 40% to 60% cars travel in the median-sided lane, closely followed by the middle lane (35% to 50%). Similarly, 55-80% of heavy vehicles and LCVs moves near the median side lane and nearly 70% of 2Ws and 3Ws shifts towards shoulder side of the road.

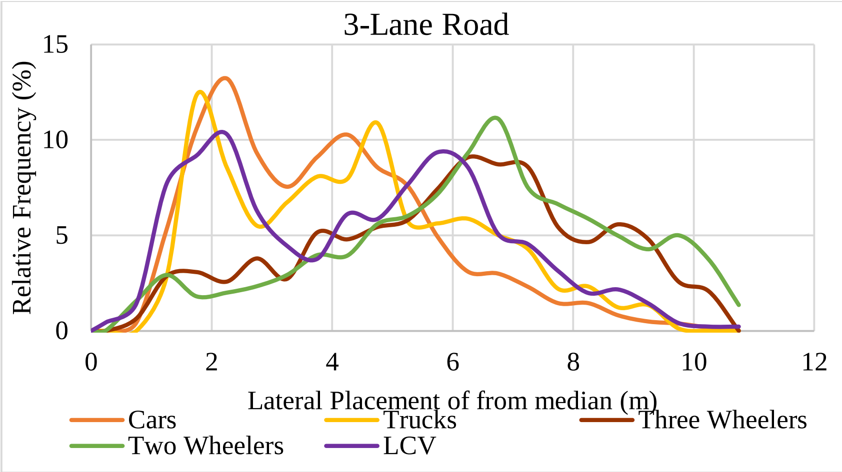


Figure 6-5 Lateral placement of different vehicles on 6-lane divided (3-lane) road

6.2.3.3 *Lateral Placement of Vehicles on 8-lane Divided Road*

Lateral placement of different vehicle types on 8-lane divided road obtained from Site 10 is plotted in Figure 6-6. This section is mainly dominated by the cars whose composition is nearly 68% as seen in Table 6-1. Majority of the cars are moving in the lane adjacent to the median sided lane (38% approximately) though quite a few of them move on the median sided as well (28% approximately). Motorized 3Ws are moving in the shoulder-sided lane and the one adjacent to it (48% on each lane). Buses and trucks have completely shifted towards the outer lanes (60-80%). This is understandable as the cars mainly dominate the road, so they do not allow these slow vehicles to move on the lanes closer to the median. Motorized 2Ws are still seen to move on the shoulder, and the adjacent to shoulder sided lanes, their proportions being 47% and 40% respectively.

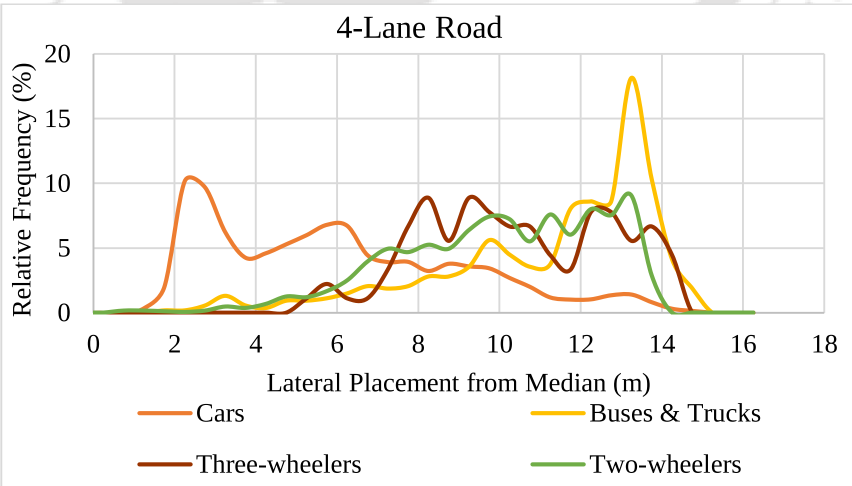


Figure 6-6 Lateral placement of different vehicles on 8-lane divided (4-lane) road

6.2.3.4 *Lateral Placement of Vehicles on 10-lane Divided Roads*

Lateral placement of different vehicle types on 10-lane divided road obtained from Site 11 is plotted in Figure 6-7. It is quite clear that cars are almost equally placed on the two lanes near the median side. Their numerical values being 40% and 37% approximately. Motorized 3Ws are throughout the road width with a majority on the adjacent to the shoulder-sided lane and the central lane. Being a wide road, they generally do not avail the shoulder-sided lane. One-fifth to two-fifth of the buses, trucks and LCVs move on each of the three central lanes. 2Ws are distributed almost on the entire road width.

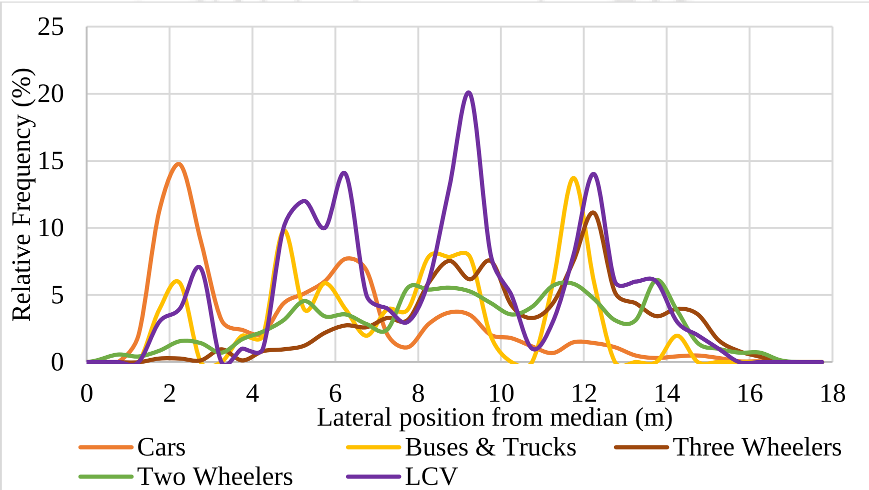


Figure 6-7 Lateral placement of different vehicles on 10-lane divided (5-lane) road

6.3 Impact of Lateral Placement on Operating Speed of Vehicles

In case of heterogeneous traffic stream, very few researchers (Bharadwaj et al., 2016) have tried to model speed using lateral placement. The vehicle's position on the road is an important parameter which guides how fast the vehicle moves. Also, from the fundamental relationship, it is known that speed is also dependent on the flow value of the traffic stream. Hence, it is justifiable to include both lateral placement and flow values to model the operating speed of vehicles. Now, the main objective is to study the effect of speed of each vehicle type due to the variation in lateral placement. The basic assumptions are i) Speed is considered to depend on lateral placement and flow only and ii) Flow is assumed to be constant for a duration of 1 minute. Hence, there is a need to determine the spatial domain of the road section using which the model can be developed. The spatial bin size should such that it can report the stream characteristics without losing too much information. For this data were clubbed into trial bins of 0.5m, 1.0m and 2m. The speed and lateral placement of most critical vehicle (motorized

2Ws) were used for this procedure. 2Ws have the least vehicle width, and they can move almost anywhere on the road, so it is justifiable that if there is no variation for this vehicle type, there shall not be any variation for any other type of data. Thus, lateral placement and speed of the vehicles were averaged over spatial domains and these data were compared with the original data and within themselves. A statistical test known as ANOVA (ANalysis Of VAriance) was used, and the data of 2Ws from Site 2 are reported below in Table 6-4. From this data, it is seen that there is not much difference between the data statistically (p>level of significance (0.05) and F<F-critical). Thus 2.0m can be easily deployed to create the model.

Table 6-4 Results of ANOVA test for the spatial domain determination (from 0.5m, 1.0m and 2.0m using the 2Ws data of Site-2

Lateral placement range (in m)	Lateral placement results			Speed results		
	p-value	F	F-critical	p-value	F	F-critical
0 to 2	0.7	0.48	2.67	0.99	0.02	2.67
2 to 4	0.97	0.07	2.62	0.92	0.16	2.62
4 to 6	0.98	0.06	2.63	0.95	0.12	2.63
6 to 8	0.91	0.17	2.95	0.16	1.84	2.95

The following is the procedure for the model development for the 4-lane divided section.

Step 1: Using a spatial domain of 2m and temporal domain of one minute, average speed and average lateral placement of each vehicle type for different Sites are obtained.

Step 2: Now, for a vehicle type, say cars, 60% of the above data for cars are randomly selected from each site. The model parameters are checked statistically by noting their p-value. It may be noted that a p-value below the level of significance (alpha – 0.05) will justify the parameter in the equation.

Step 3: Linear regression model is developed.

Step 4: The equation is validated using the remaining 40% data of hatchback cars from both the sites. MAPE (Mean Absolute Percentage Error) is then calculated for this equation to report the fir of the modelled data to the estimated data.

Step 5: Step 2 to Step 5 is repeated using the similar concept but by incorporating flow as another factor as another factor.

The basic model is based on the concept that speed directly related to the lateral placement of the vehicle (Balaji et al., 2013; Bharadwaj et al., 2016), presented in Equation 6-4.

$$speed = a + b * lp \quad \text{......6-4}$$

Where '*speed*' is the speed of the vehicle in km/hr, '*lp*' is the lateral placement of the vehicle in meters (m), *a* & *b* are regression coefficients.

Now, a modification is tried as given in Equation 6-5, where the flow is also included in the equation. It is justifiable to include flow it is known that speed depends upon the flow condition.

$$speed = a1 + b1 * lp + c1 * q \quad \text{...... 6-5}$$

Where, '*speed*' is the speed of the vehicle and '*lp*' is the lateral placement, and *a*, *b* & *c* are the regression coefficients.

6.3.1 *Operating speed prediction model using Lateral Placement of Vehicles on 4-lane Divided Roads*

Using a spatial domain of 2m and temporal domain of one minute, average speed and average lateral placement of each vehicle type are obtained. For developing the model for speed prediction the 60% data for all three sites (Site-1, 2 and 3) of 4-lane divided roads are randomly selected and combined to incorporate all type of flow conditions. The Figure 6-8 presents the relationship between lateral placement and speed of different type of vehicles on 4-lane divided roads. It is found that the lateral placement decreases linearly with the decrease in speed. Table 6-5 presents the details of regression constants of fitted models to a different type of vehicles on 4-lane divided roads at 5% significance level. Again, the operating speed is predicted for each vehicle type based upon the lateral placement and flow per minute of that road based on Equation 6-5. With the remaining 40% of the data, the validation is performed for both the models and the MAPE values are obtained.

Table 6-5 Details of the fitted models of Speed vs Lateral placement of vehicles on 4-lane divided roads

Type of vehicle	4-lane divided roads				
	Without Flow		With Flow		
	a	*b*	*a1*	*b1*	*c1*
Buses and trucks	26.564	-1.351	26.942	-1.361	-0.0001†
Cars	30.112	-1.244	37.068	-1.4044	-0.0021
Motorized three-wheelers	30.836	-2.19	30.865	-2.19	0†
Motorized two-wheelers	31.724	-1.969	33.613	-1.938	-0.0006†
LCVs	26.975	-1.508	31.172	-1.365	-0.0013

†parameters with significant p-values

The negative sign for 'b' suggests that as the vehicle, irrespective of the type decreases the speed as it moves away from the median. Also, the flow value, wherever significant has a negative parameter, indicating that with an increase of flow value speed of the vehicle will decrease. The observed and predicted values for different vehicles, from both the models (without flow and with the flow) of 4-lane divided roads, are presented below in Figure 6-8. From the Figure 6-8, it is observed that the model for operating speed including flow of the stream as a parameter predicts better than the model without flow, especially for cars (high-speed vehicles).

The residual plot and the normal probability plots for the predicted data with both the models are obtained (refer Figure 6-9 and 6-10). The resulting points in the Normal probability plot lie approximately on the straight line with an intercept zero. Also, the residuals fluctuation is more or less random in all residual plots. Hence, our predicted model is appropriate for the observed data. Both the models are validated with the remaining 40% data for all type of vehicles, and the MAPE value are also obtained (refer Table 6-6).

Table 6-6 MAPE values obtained for the validation data of 4-lane divided roads

Type of vehicle	4-lane Divided Roads	
	MAPE Without Flow	MAPE With Flow
Buses and trucks	16.29	16.12
Cars	18.85	16.5
Motorized three-wheelers	9.63	9.61
Motorized two-wheelers	15.3	15.7
LCVs	13.26	13.83

From the MAPE (Mean Absolute Percentage Error) values (refer Table 6-6) it can be concluded that predictions are excellent for all type of vehicles for 4-lane divided roads as per Lewis Scale of measurement by Ronald and Kenneth (1982). From the MAPE values, it is clear that for high-speed vehicles like cars whereas no improvements were found in the models of motorized 3Ws, 2Ws and LCVs by including flow as a parameter.

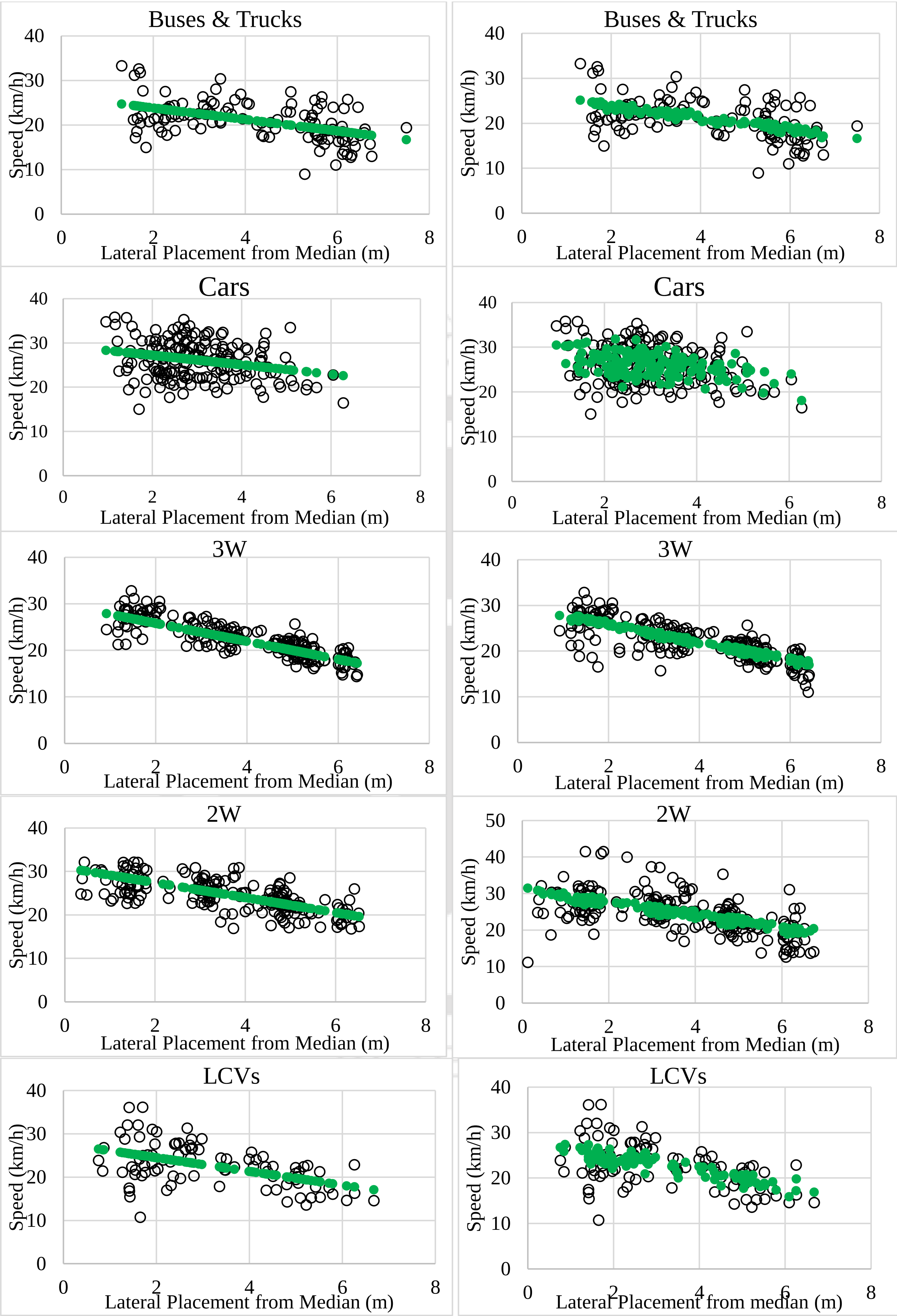


Figure 6-8 Observed and predicted speed of different vehicles on 4-lane divided roads for both the models (without flow and with flow)

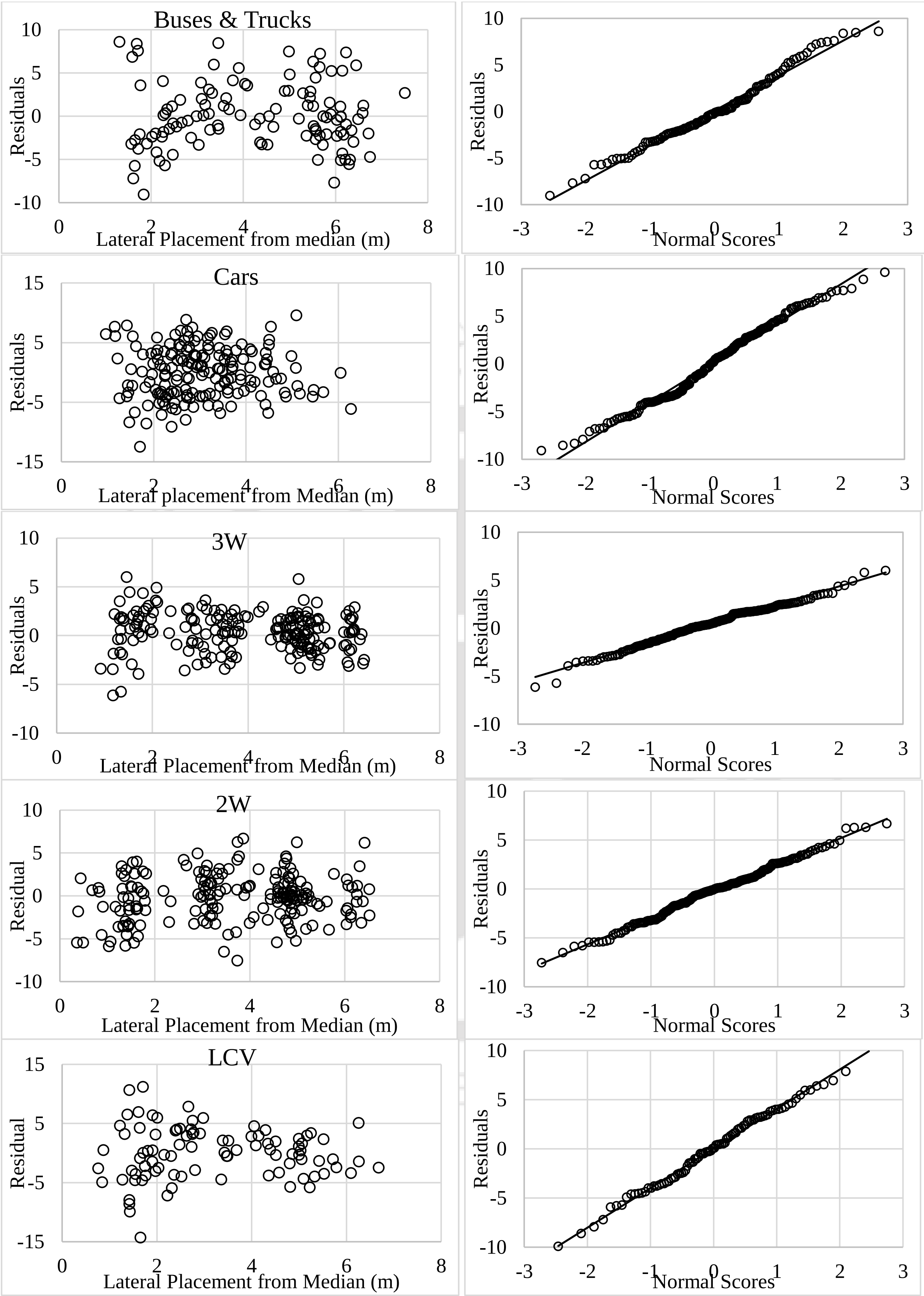


Figure 6-9 Residual plots and the normal probability plots of the fitted models of different vehicles without considering flow

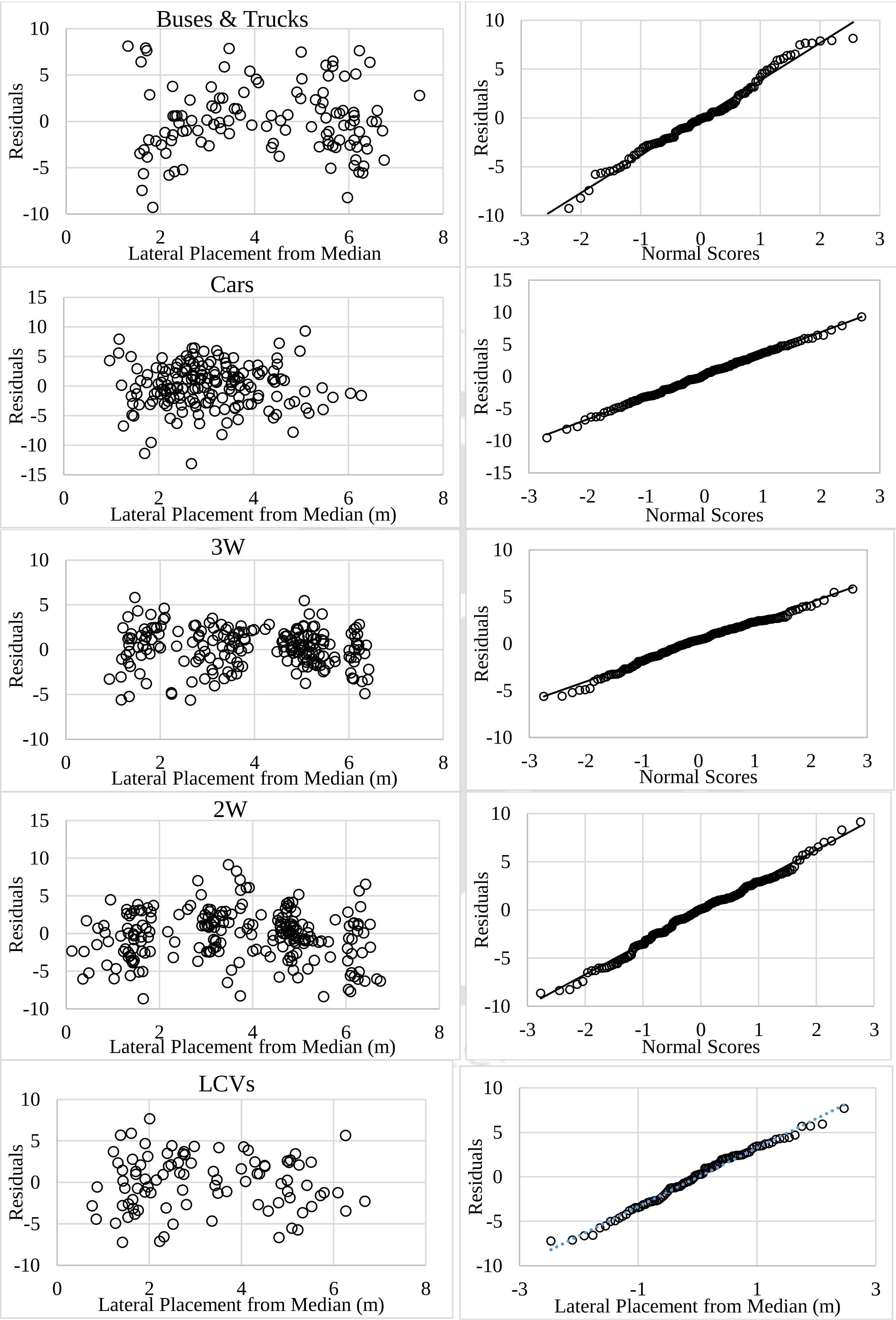


Figure 6-10 Residual plots and the normal probability plots of the fitted models of different vehicles considering flow

6.3.2 *Operating speed prediction model using Lateral Placement of Vehicles on 6-lane Divided Roads*

For developing the speed prediction model of 6-lane divided roads, 60% data of four different sites (Site 5, Site 6, Site 8 and Site 9) are combined. The data are fitted to both the models (refer Equation 6-4 and 6-5) i.e. without considering flow and considering flow as a model parameter as described in case of 4-lane divided roads. Table 6-7 presents the details of the model constants for both the models fitted to different vehicles of 6-lane divided roads at 5% significance level. Also, the negative sign for 'b' suggests that as the vehicle, irrespective of the type decreases the speed as it moves away from the median. The observed and predicted values for different vehicles, from both the models (without flow and with the flow) of 4-lane divided roads, are presented below in Figure 6-11.

From Figure 6-11, it can be observed that there is a significant improvement in the predicted values of cars while including flow as a parameter. Hence, the flow has a significant impact on the model for high-speed vehicles like cars. The residual plots and the normal probability plots are also obtained for the developed models (refer Figure 6-12 and 6-13). The resulting points in the Normal probability plot lie approximately on the straight line with an intercept zero. Also, the residuals are randomly distributed. Hence, our predicted model is appropriate for the observed data.

Table 6-7 Details of the fitted models of Speed vs Lateral placement of vehicles on 6-lane divided roads

Type of vehicle	**Without Flow**		**With Flow**		
	a	***b***	***a1***	***b1***	***c1***
Cars	33.604	-1.301	38.016	-1.384	-0.0017
Motorized three-wheelers	33.655	-1.087	32.732	-1.074	0.0003†
Buses and trucks	32.059	-0.727	29.767	-0.817	0.0012
Motorized two-wheelers	37.808	-1.415	37.99	-1.419	-0.0001†
LCVs	37.207	-1.698	35.721	-1.624	0.0005†

†parameters with significant p-values

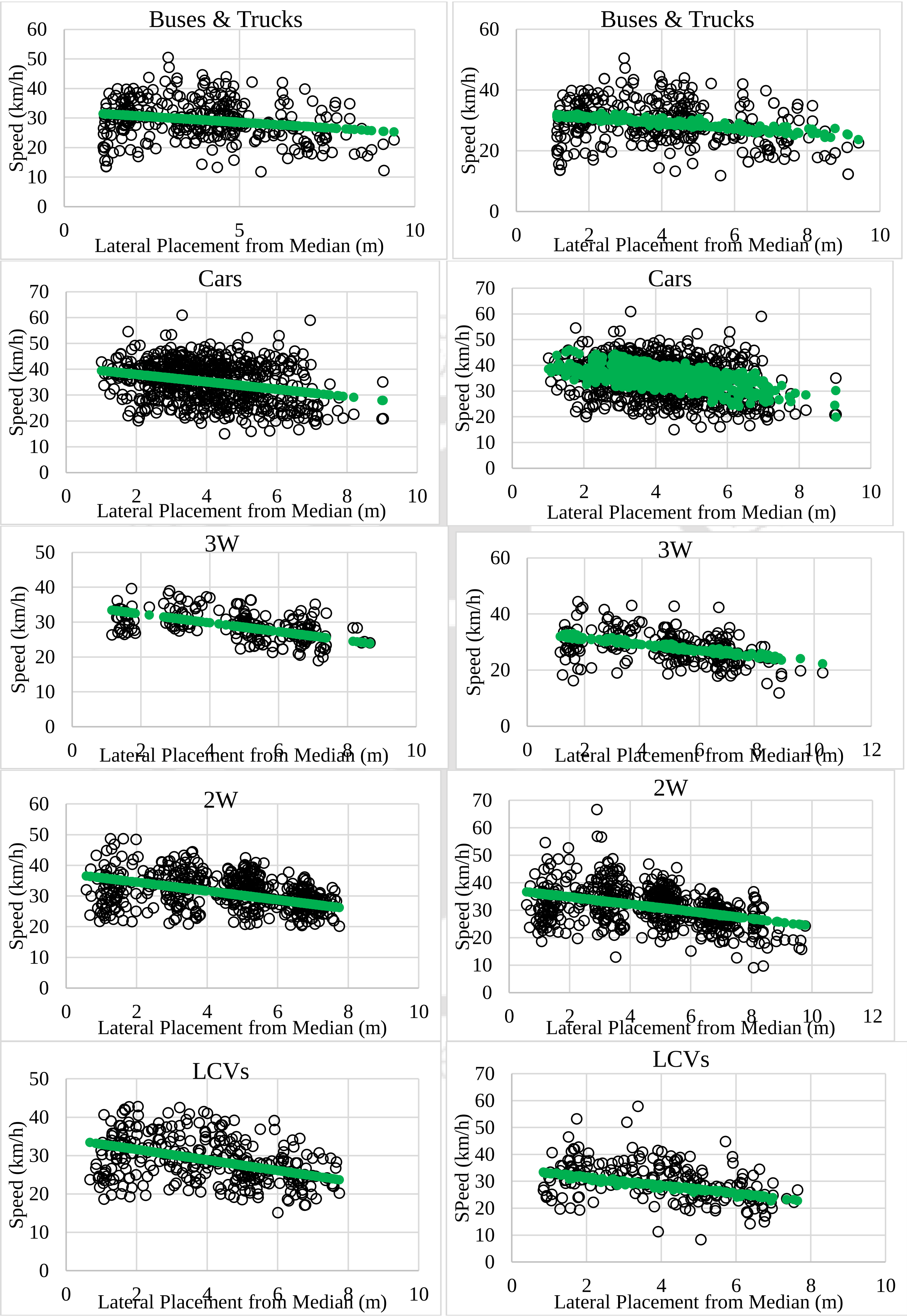


Figure 6-11 Observed and predicted speed of different vehicles on 6-lane divided roads for both the models (without flow and with flow)

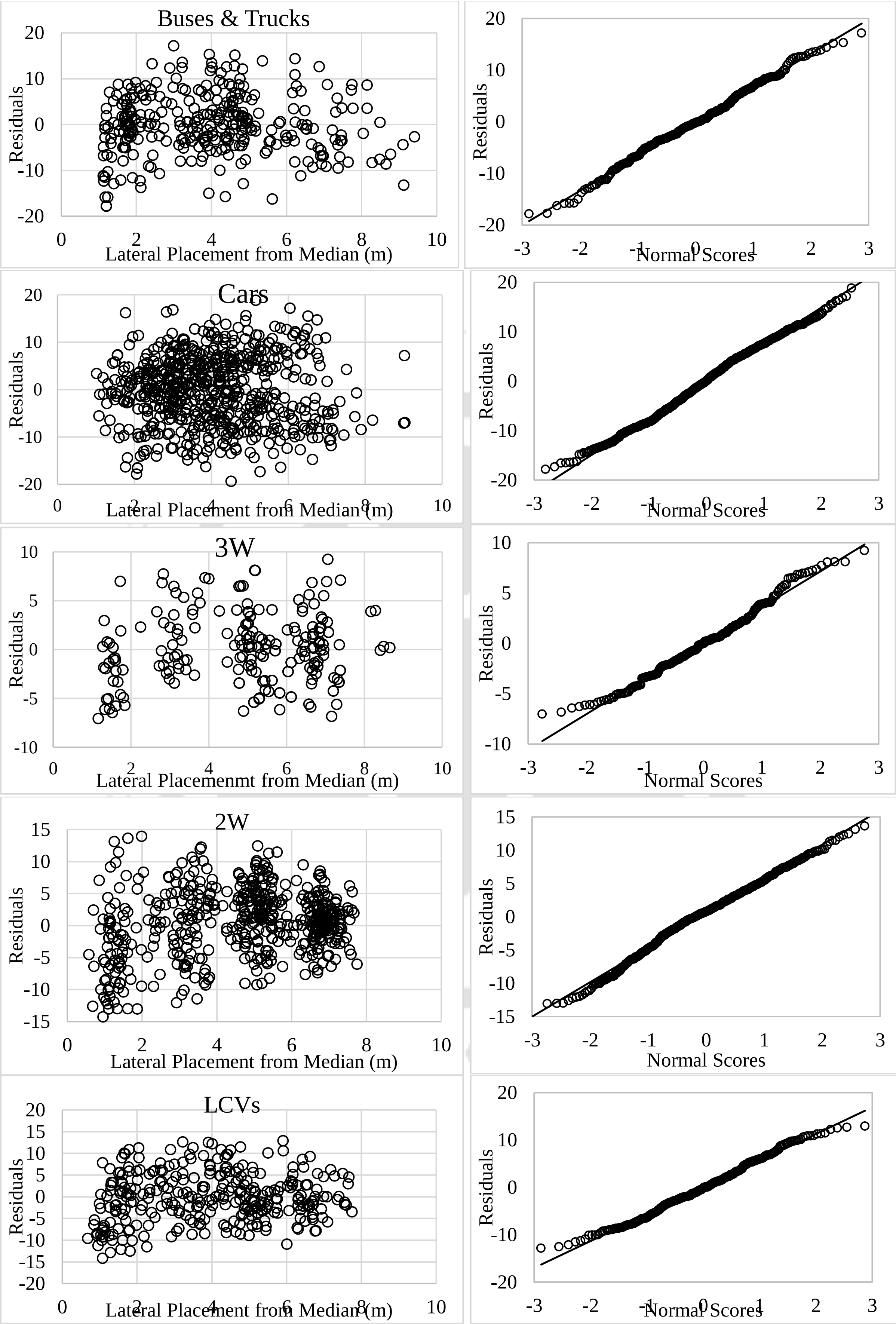


Figure 6-12 Residual plots and the normal probability plots of the fitted models of different vehicles without considering flow

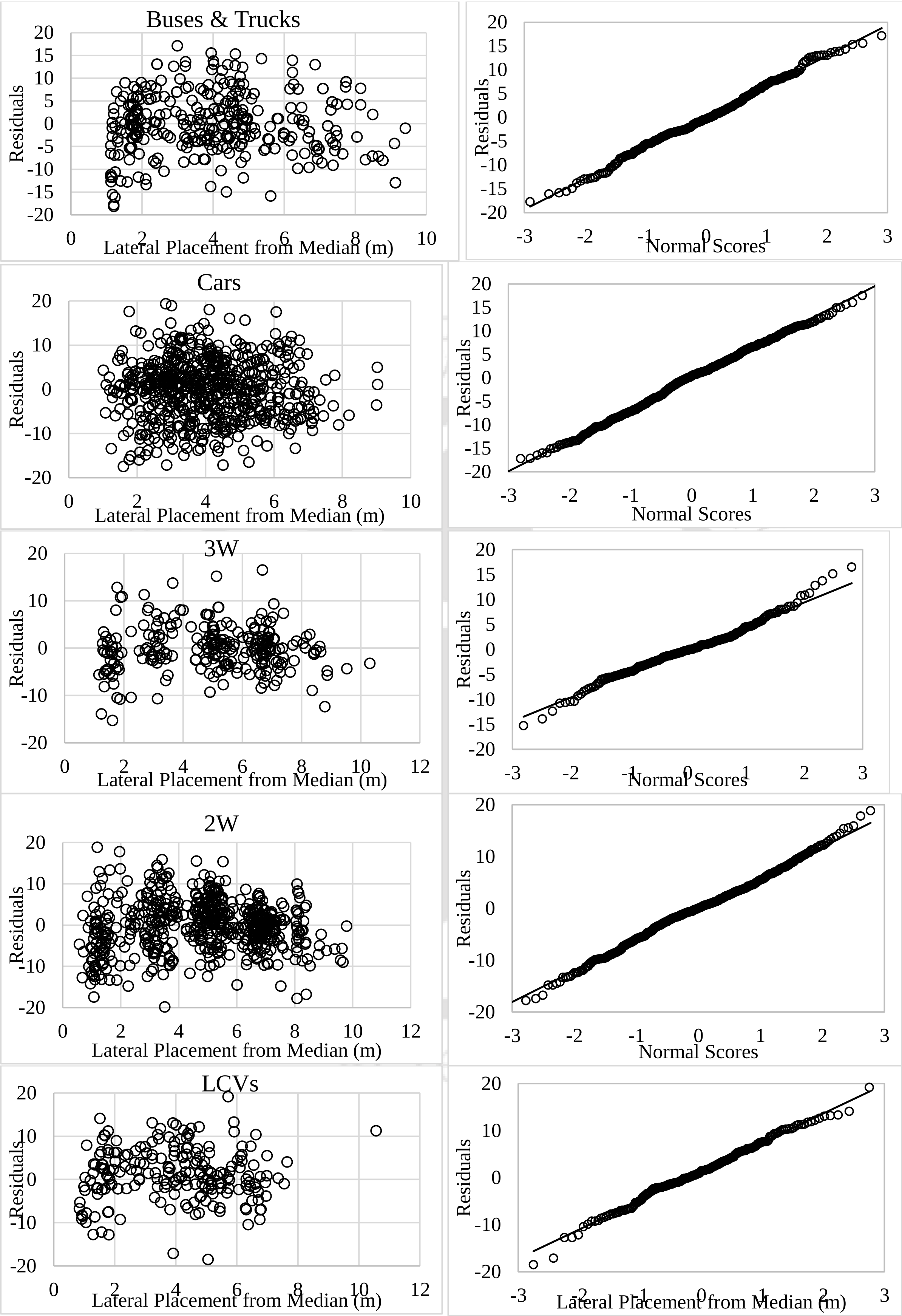


Figure 6-13 Residual plots and the normal probability plots of the fitted models of different vehicles considering flow

Both the models are validated with the remaining 40% data for all type of vehicles, and the MAPE value are also obtained (refer Table 6-8). From the MAPE values, it can be concluded that predictions are excellent for all type of vehicles for 4-lane divided roads as per Lewis Scale of measurement by Ronald and Kenneth (1982).

Table 6-8 MAPE values obtained for the validation data of 6-lane divided roads

Type of vehicle	**6-lane Divided Roads**	
	Without Flow	**With Flow**
Buses and trucks	19.05	19.56
Cars	21.09	22.49
Motorized three-wheelers	14.82	14.79
Motorized two-wheelers	16.07	16.05
LCVs	24.2	24.01

6.3.3 Operating speed prediction model using Lateral Placement of Vehicles on 8-lane Divided Roads

As discussed in the 4-lane and 6-lane divided roads (previous sub-subsections), the operating speed of different vehicles are predicted for 8-lane divided roads based on their lateral placement. Both the models (refer Equation 6-4 and 6-5) are fitted to the 60% data obtained from Site-10, and their suitability is tested. The Observed and predicted data for both the models are presented in Figure 6-14 for all type of vehicles at 8-lane divided roads.

It is found that for speed prediction, the flow has a significant effect on the speed-lateral placement model when the speed is high. However, as the speed decreases, the impact of flow on slower and smaller vehicles (motorized 2Ws and motorized 3Ws) decreases. The residual plots and the normal probability plots are also obtained and presented in Figure 6-15 and 6-16. The resulting points in the Normal probability plot lie approximately on the straight line with an intercept zero. Also, the residuals are randomly distributed. Hence, our predicted model is appropriate for the observed data.

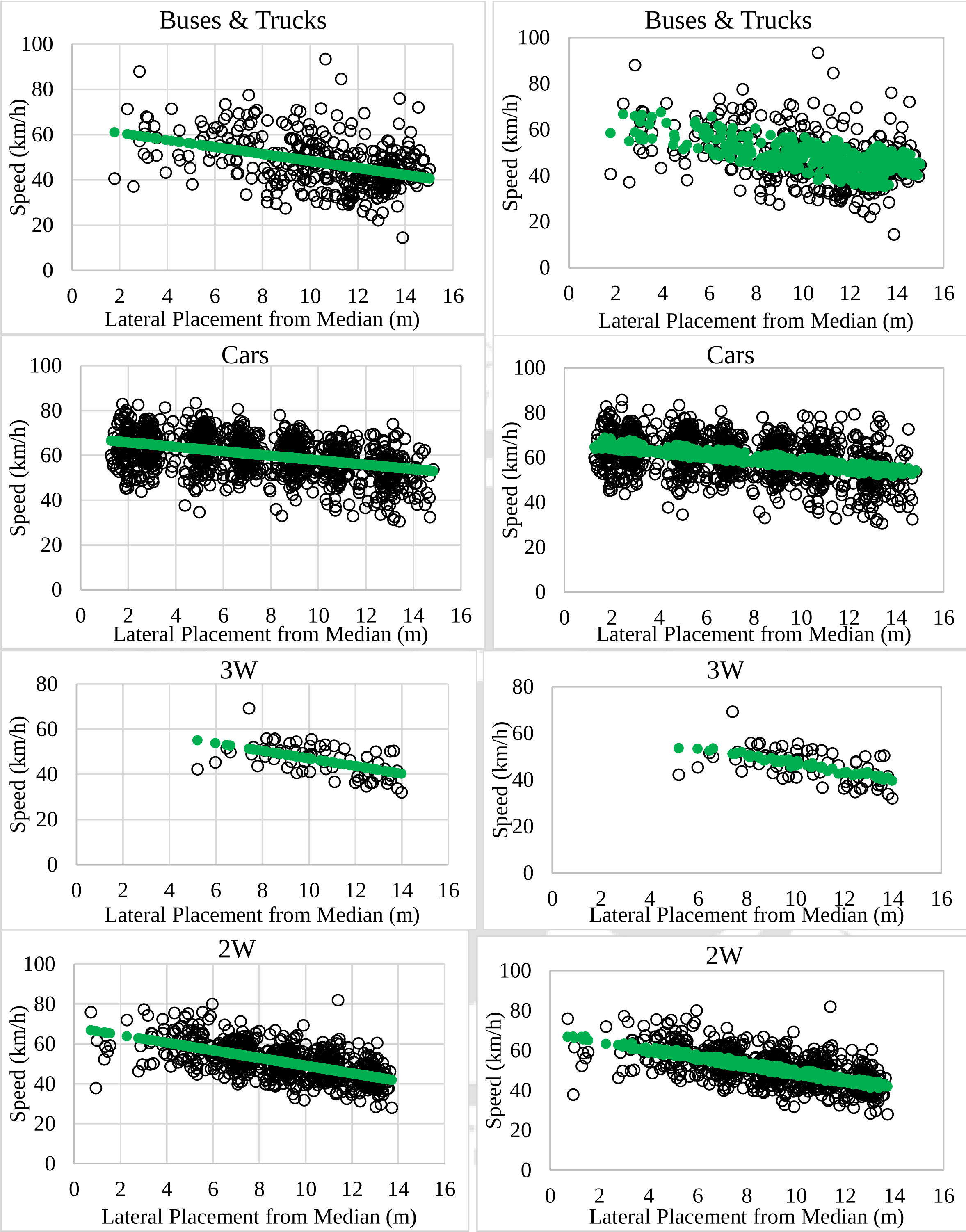


Figure 6-14 Observed and predicted speed of different vehicles on 8-lane divided roads for both the models (without flow and with flow)

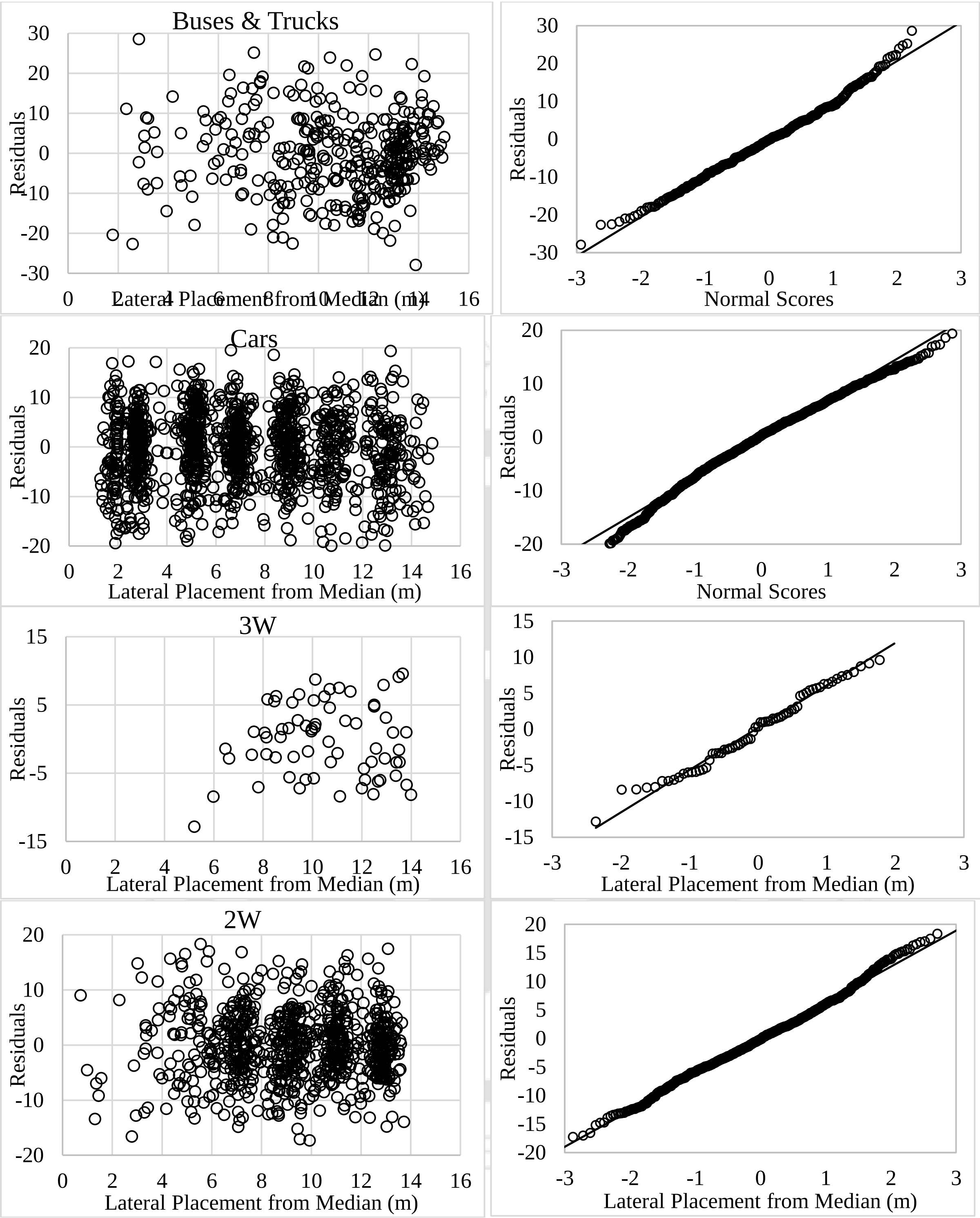


Figure 6-15 Residual plots and the normal probability plots of the fitted models of different vehicles without considering flow

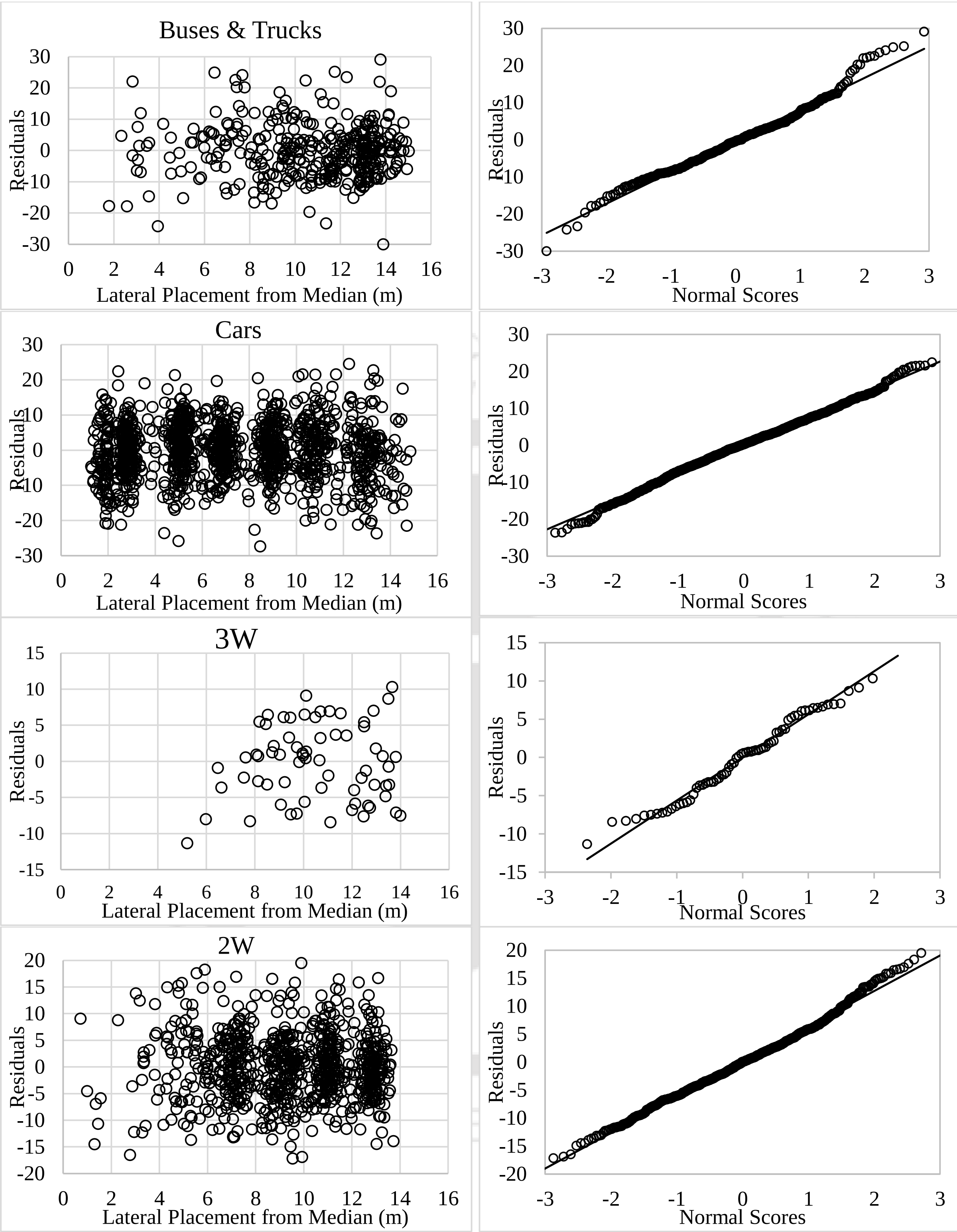


Figure 6-16 Residual plots and the normal probability plots of the fitted models of different vehicles with flow

Both the models are validated with the remaining 40% data for all type of vehicles, and the MAPE value are also obtained (refer Table 6-9). The MAPE values indicate that in case of 8-lane divided roads the flow of the stream has a significant impact on the lateral placement and speed model. The impact of flow on slower and smaller vehicles (motorized 2Ws and motorized 3Ws) decreases with the decrease in speed.

Table 6-9 MAPE values obtained for the validation data of 8-lane divided roads

Type of vehicle	Without Flow	With Flow
Buses and trucks	10.32	10.08
Cars	10.72	10.45
Motorized three-wheelers	18.42	15.95
Motorized two-wheelers	9.67	9.64
LCVs		

6.3.4 Operating speed prediction model using Lateral Placement of Vehicles on 8-lane Divided Roads

Both the models of speed and lateral placement (with flow and without flow) for different vehicles of 10-lane divided roads fitted with the 60% data of Site-11. The observed and predicted data for each type of vehicles are presented in Figure 6-17.

The residual plots and the normal probability plots for the predicted data of all vehicle type are obtained and presented in Figure 6-18 and 6-19. The randomly distributed residuals and the normal probability plots indicate a very good fit of both the predicted models (with flow and without flow).

Both the models are validated with the remaining 40% data for all type of vehicles, and the MAPE value are also obtained (refer Table 6-10). From the MAPE values, it can be concluded that prediction is excellent for cars, motorised 3Ws and motorised 2Ws. For rest of the cases, the prediction is good as per Lewis Scale of measurement by Ronald and Kenneth (1982).

Table 6-10 MAPE values obtained for the validation data of 10-lane divided roads

Type of vehicle	10-lane Divided Roads	
	Without Flow	**With Flow**
Buses and trucks	13.01	12.4
Cars	10.08	9.76
Motorized three-wheelers	7.74	7.66
Motorized two-wheelers	9.65	8.96
LCVs	10.59	10.61

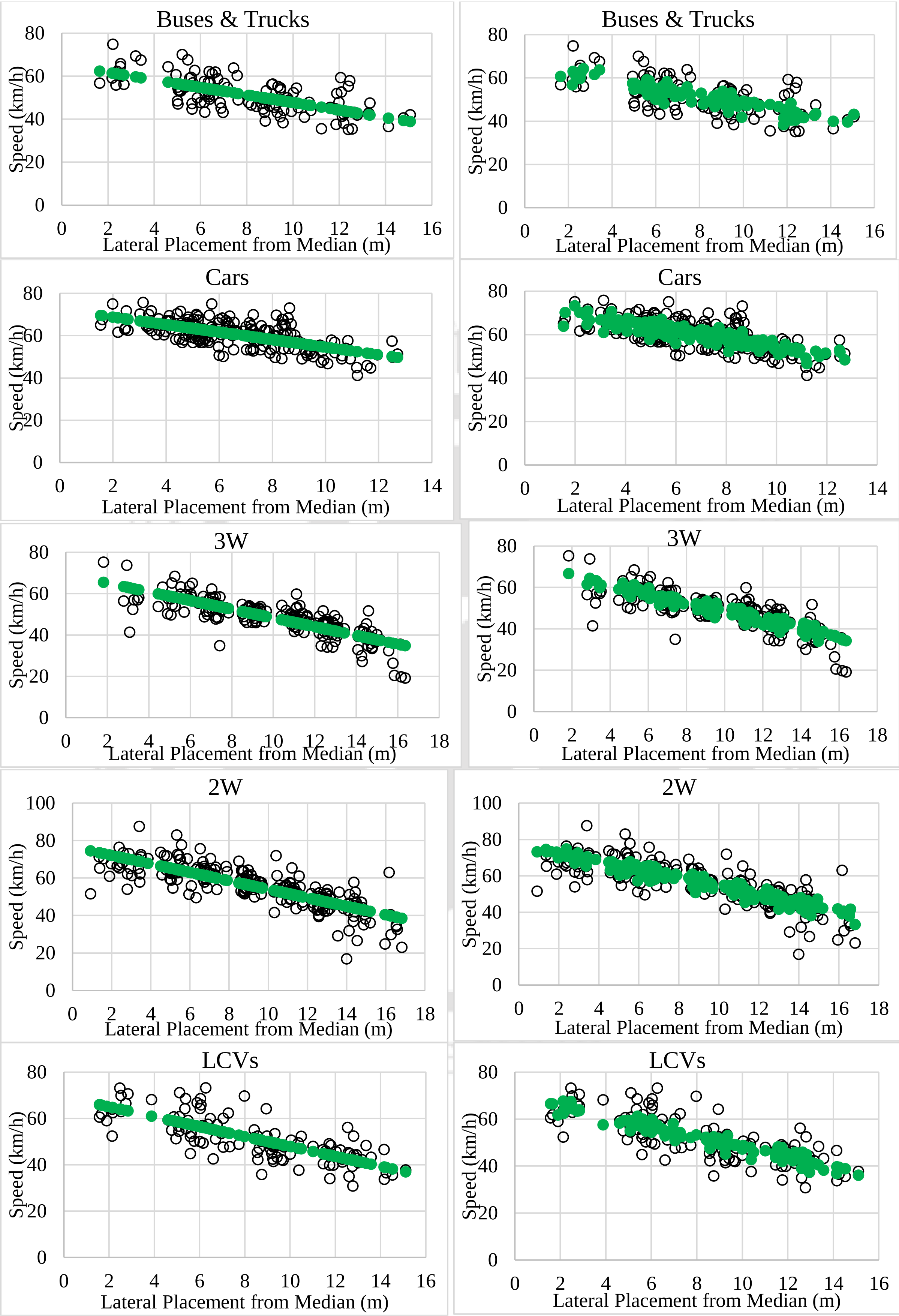


Figure 6-17 Observed and predicted speed of different vehicles on 10-lane divided roads for both the models (without flow and with flow

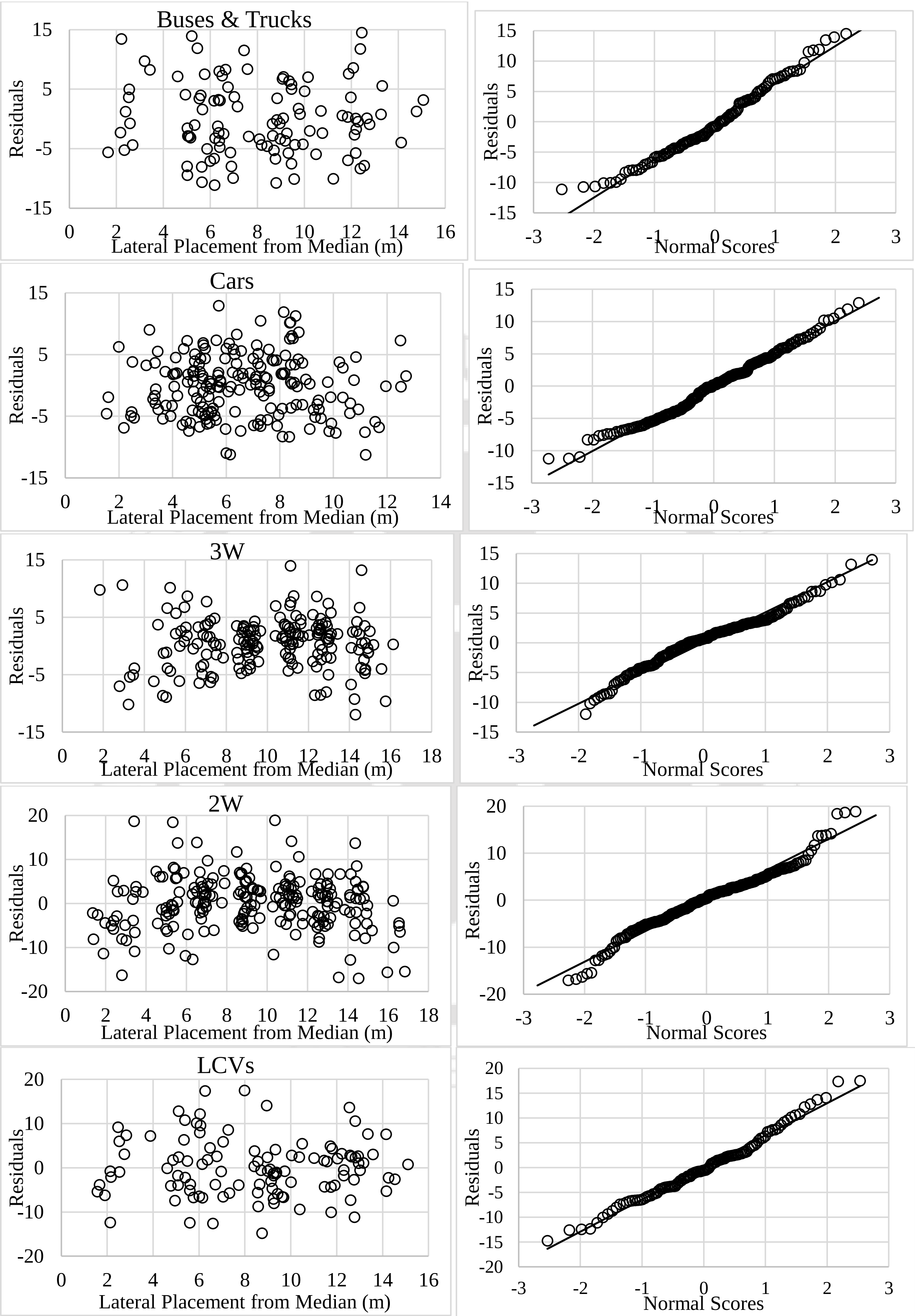


Figure 6-18 Residual plots and the normal probability plots of the fitted models of different vehicles without considering flow

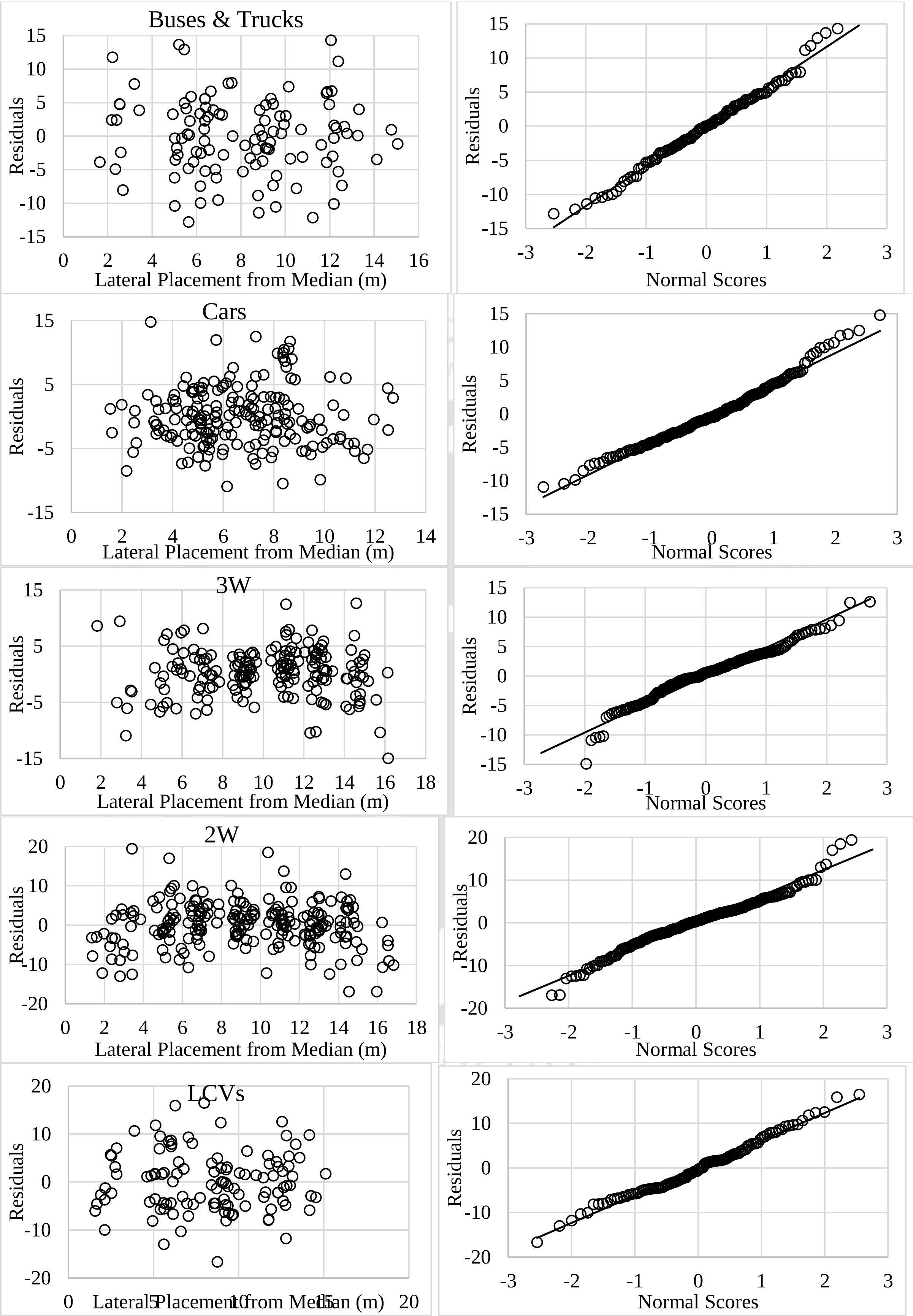


Figure 6-19 Residual plots and the normal probability plots of the fitted models of different vehicles with flow

6.4 Lateral Gap Maintaining Behaviour of Vehicles from Road Median

In homogeneous traffic conditions, wherein, the lane discipline is strictly followed, the linear clearance maintained by the vehicles with respect to the vehicles in front may be sufficient to describe the vehicle manoeuvring process. In mixed traffic, the lane discipline is absent, and the vehicles travel abreast due to the variations in their size and non-standard widths; so it becomes essential to consider the clearances in the lateral direction in addition to that in a linear direction for defining the flow logic. Road features/elements (like road edges conditions, divider conditions, etc.) also affect the vehicle's movement and its lateral placement depending upon whether drivers perceive a roadside element as an obstacle or not. Vehicles will move away (or maintains certain clearance) from an object/road elements that they perceive as an obstacle. According to Highway capacity manual, lane position is crucial to traffic performance on multilane highways. Also, Development of micro-simulation model requires a comprehensive understanding of microscopic and macroscopic parameters. Models of linear and lateral clearances are useful for many purposes such as finding influence areas, determining PCUs and development of geometrical design standards. The minimum linear and lateral clearances desired by individual driver-vehicle units, to continue their movement, from the most important ingredient of the simulation model.

In the present section impact of median type (width and height) on lateral gap maintaining behaviour of vehicles are studied using a sensor based assembly. For lateral clearance measurement, only the vehicles travelling at the near median lanes (i.e. adjacent to the road median) is taken into account. The data has been collected from on straight mid-block sections of different roads (4-lane divided highways) with different median facilities at free flow speed condition. The lateral clearance maintained by the vehicles is affected by traffic parameters like speed and flow of the stream. At free flow condition, Speed and flow are inversely related. Hence here only the effect of vehicular speed on lateral clearance is studied for three different road facilities. A sensor assembly (refer Chapter-3) consists of two ultrasonic sensors with a camera placed alongside the road at a known distance is developed to measure (i) Lateral clearance maintained by vehicles from road elements (ii) Vehicle's speed traveling near edge lane (ML). Operation of this assembly is semi-automatic with little intervention. It is observed that in case of 4-lane divided roads, median sided lane contains most of the cars and trucks. Hence, the models are developed only for cars and trucks. To see the minimum gap maintained by different vehicles from different medians, the lower 5% lateral gap data for different speed groups are extracted and modelled for cars and trucks. This indicates that 95% vehicles maintain larger gap than this. This section is divided into two parts, i) Model development and ii) Validation of Models

6.4.1 *Model Development for Minimum Lateral Gap maintained by Cars and Trucks*

The regression models are fitted for a lateral gap of cars and trucks using each vehicle's operating speed and size of median as variables. The regression models for the lateral gap are fitted by taking two dummy variables (i.e. width and height of median) and operating speed of the vehicle as independent variable. The simplest case of dummy coding is when the categorical variables have 'n' levels and are converted to 'n-1' dichotomous variable. The size of median are divided into different groups according to the design guidelines of India (IRC: SP 84, 2014; IRC: 86, 1983; IRC: SP 73, 2007). The width of medians are divided into four groups. The dummy coding of the categorical variables, width and height of medians are presented in Table 6-11.

Table 6-11 Dummy coding for different groups of height and width of medians

Width of Median		Categories	W1	W2	w3
i	W <1.2 m	1	1	0	0
ii	W ≥1.2 m & < 2.5 m	2	0	1	0
iii	W ≥2.5 m & < 4.5 m	3	0	0	1
iv	W ≥ 4.5 m	4	0	0	0
Height: (Barrier Kerb)		**Categories**	**H**		
i	H ≥ 200 mm & ≤ 350 mm	1	0		
ii	H > 350 mm & ≤ 800 mm	2	1		

Following Equation 6-6 and 6-7 are the fitted models for minimum lateral gap maintaining behaviour of cars and trucks respectively.

$$Gap_{cars}\,(m) = 0.662 + (0.031 * V) - (0.077 * W_1) - (0.190 * W_2) - (0.028 * W_3) + (0.209 * H) \quad \text{6-6}$$

$$Gap_{Trucks}\,(m) = 0.716 + (0.010 * V) + (0.408 * W_1) - (0.173 * W_2) - (0.373 * W_3) + (0.164 * H) \quad \text{6-7}$$

where *Gap*=Lateral gap maintained from the edge of the median (m), *V*=Operating speed of the vehicle, W_1, W_2 & W_3 are width groups of median according to design guidelines and *H*=Height group of median according to design guidelines. The residual plot and normal probability plots indicate a better fit of the predicted model. Figure 6-20 presents the observed and predicted data of cars and trucks with their residual plot and the normal probability plots.

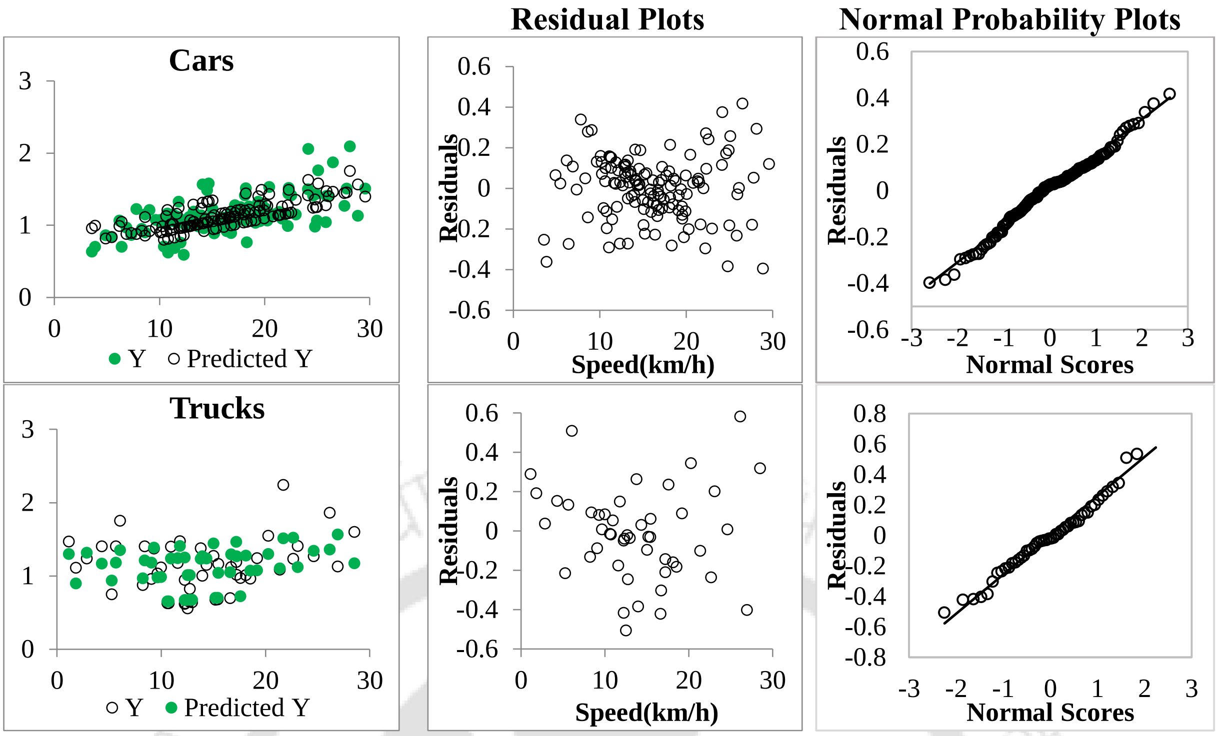


Figure 6-20 Observed and Predicted data with their residual plots and their normal probability plots

6.4.2 *Validation of the Developed Model*

The models are validated with a new set of data collected from a different site. The MAPE values are obtained (23.9 for Cars & 22.32 for trucks) for the validation site also. From the MAPE values, it can be concluded a better fit of the model to the data. Figure 6-21 presents the details of the observed and predicted minimum lateral gap maintained by cars and trucks from the median.

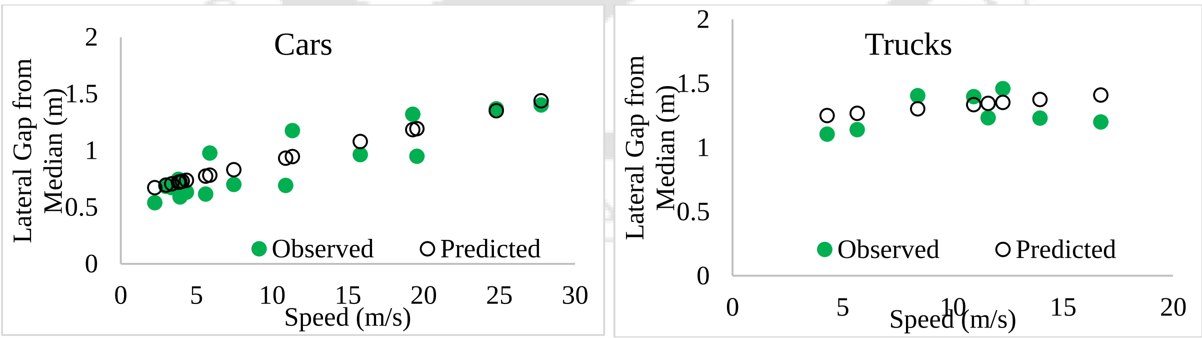


Figure 6-21 Observed and Predicted data of lateral gap for the validation site

The minimum lateral gap maintained by cars and trucks from medians with different width and height are obtained and presented below in Figure 6-22. The impact of different width are presented by considering a fixed median height of 0.3m (refer Figure-6-22a & 6-22c). Similarly, the impact of height is obtained and presented by keeping a fixed median width of 2.5m (Figure 6-22b & 6-22d).

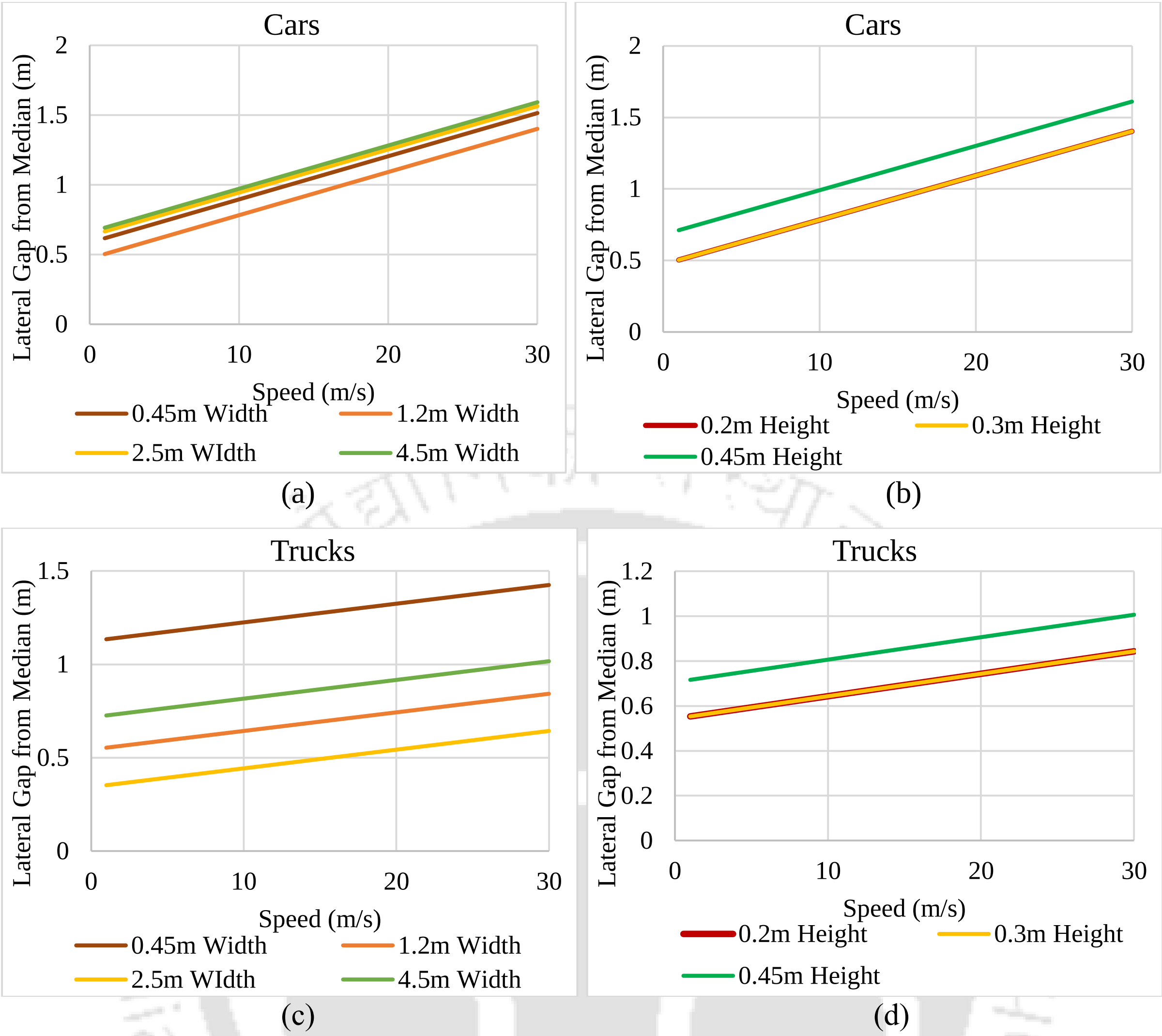


Figure 6-22 Minimum Lateral Gap maintained by Trucks and cars for different combination of Median Width and Height (a) Cars with different width (b) cars with different height (c) Trucks with different width (d) Trucks with different height

From Figure 6-22a & 6-22b, it can be observed that the lateral gap maintained by cars increases for medians with width, i.e. 2.5m and 4.5m and a height of 0.3m. There is no significant difference is observed between the 2.5m and 4.5m width medians with a standard height of 0.3m. It is observed that for a median width of 1.2m, cars feel safe to move closer to the median, which indicates that with the increase in width of medians for a standard height of 0.3m, vehicles move closer to the median. However, in case of 2.5m and 4.5m width of medians cars shifts away from the median. From the video analysis it is observed that in case of medians with larger widths (2.5m and 4.5m), the plantations are observed. In such cases, though the height of median kerb is lesser i.e. 0.3m, riders perceive the height of median including the plantations height. So, they moves away from the medians due to the safety concern. It is also observed that for a median height of 0.3m, trucks maintain the higher gap for 0.45m width of the median and it decreases with increase in width of median (i.e. 1.2m followed by 2.5m). However, for 4.5m width of median trucks shifts away from the median. This may be due to the height of plantation inside the median. In case of 2.5m width of median the plantation height was lesser compared to the 4.5m median width. Hence, for 2.5m width, though the car drivers perceive it as obstacles due to the lesser wheel height, the truck drivers does not. However, in case of 4.5m width of median, the larger height plantation works as obstacles at the road side. Hence the trucks moves away from the median.

Similarly, the impact of median height is also studied for a standard median width of 1.2m. It is observed that as the height of median decreases cars move away from the median. Similar observation is also observed in case of trucks. It is also observed that in all cases, the impact of operating speed has a higher impact on cars for the minimum lateral gap maintaining behavior from median, comparing to trucks.

6.5 Concluding Remarks

In this present chapter, the lateral placement of different type of vehicles are studied by two different methods. The placement of vehicles on the entire cross-section of the road are studied from the top view video recording and the minimum lateral gap maintained by trucks and cars from the median are studied from the sensor-based data. The conclusions are divided into two different sections.

<u>Study of Lateral Placement of Vehicles on the Road cross-sections</u>

This study presents an analysis on the lateral placement of different vehicles (cars, motorized 3Ws, motorized 2Ws, trucks, buses and light commercial vehicles) on different road sections (4-lane, 6-lane, 8-lane and 10-lane divided). It is quite evident from the study that in narrower sections, the private and commercial vehicles (cars, LCVs and trucks) take up the median sided lanes, but the smaller vehicles (motorized 3Ws and 2Ws) occupy the shoulder sided lanes. With the increase of road width, faster-moving cars, slower moving motorized 3Ws as well as the heavy weighing trucks all move into the inner lanes for safety issues. Also, the vehicle with majority composition, occupies the entire road width, irrespective of the road type. Hence it can be concluded that road width and vehicle type along with traffic composition have an appreciable effect on the lateral placement of the vehicles in weak lane disciplined and mixed traffic.

For the speed-lateral placement and flow model, it is found that flow has a significant effect on the speed-lateral placement model when the speed is high. However, as the speed decreases, the impact of flow on slower and smaller vehicles (motorized 2Ws and motorized 3Ws) decreases. Another conclusion can be that errors are least for motorised 2Ws and motorised 3Ws.

Finding of this study can be used to validate the simulation models developed for such traffic streams along with other applications like the lane distribution factor, the optimum operating speed prediction in different portion (lane) of the roads.

For future scope, lateral placement data on more sites for 8-lane divided road and 10-lane divided road needs to be collected and analysed. Locations different flow values should also be investigated for further improvement of the models.

Study of Minimum Lateral gap Maintained by Vehicles from Median edge

In this part, the minimum lateral gap maintained by vehicles from the median are studied based on the type of median. It is found that the cars maintain higher gap than trucks. The median height and width have a significant impact on the vehicles travelling near to the road edge. The minimum lateral gap maintained by vehicles also increases with the increase in operating speed of vehicles travelling along the median lane (ML). This may be due to the driver's safety perception. The drivers feel unsafe while driving at the edge at higher speeds. Hence they maintain larger gap from the road edge. For the narrower width medians, i.e. width less than 0.5m, both cars and trucks move away from the median. The riders feel safe to move closer to the median with the increase in width of median. It is also observed that the height of median has a significant impact on lateral gap maintaining behavior of vehicles. Another important observation is that though the height of median is smaller (<0.3m), the plantation height inside the median has a significant impact on the lateral gap maintaining behaviour of vehicles with respect to the type of vehicles.

Finding of this study can be used while developing and to validate the simulation models developed for such traffic streams and the safety aspects of the road like the clearance from the edge of medians and shoulders. This study was limited to the 4-lane divided roads only. Also, the minimum lateral gap maintained by vehicles from the shoulder is not included in this study. Hence, in the future, the minimum lateral gap maintained by another different type of vehicles from both the road edges (median & shoulder) can also be studied for a different type of roads (roads with different widths).

7. Importance of Microscopic Parameters in Simulating No-Lane Based Heterogeneous Traffic Stream

7.1 Introduction

Due to heterogeneous and no-lane-based traffic, the traffic scenario in India is far different from that of developed countries, which leads to different maneuvering patterns of vehicles. Vehicles in weak lane disciplined traffic can occupy any lateral space along the entire width of roadway without any confinements for maneuvering. Interactions of vehicles in mixed traffic are more complex; they not only interact with the preceding vehicle but also with the surrounding vehicles. Many researchers have worked on modelling the heterogeneous traffic and developed the microscopic simulation models (as described in Chapter-2). Most of the efforts were based on limited field observations and in many of these models convenient assumptions were made regarding the vehicular lateral movement. Modelling driver behavior requires a detailed understanding of the vehicular interactions with the surrounding traffic and roadway features. Microscopic data of all vehicles are necessary to understand these type of traffic behavior. Different microscopic parameters describing the lateral maneuver of vehicles (lateral acceleration, longitudinal acceleration/deceleration and the impact of road characteristics like road width and median type etc. on the lateral placement of vehicles) on the Indian traffic stream have been studied from the field data in the previous chapters.

A simulation framework is essential to evaluate the detailed traffic performance at different roadway sections, implement the driver behavior models and hence simulate large-scale real-world traffic situations in great detail. In the present chapter, the importance of parameters and their behavior studied from the field data are evaluated with the parameters obtained from the existing micro-simulation framework, VISSIM.

VISSIM which is used in this study is a microscopic time step and behavior based simulation model. It can model traffic as well as the flow of pedestrians. It can analyze public and private transport operations making it a useful tool for evaluation of various alternatives for transportation planning. The road networks in VISSIM can be created either as lane oriented or space-oriented, i.e. vehicles can move anywhere on the road without lane restrictions. Any number of vehicle types can be created and overtaking of vehicles can be allowed on both the sides. All these features help in modelling heterogeneous traffic. Hence, in our present chapter, the parameters obtained from VISSIM are evaluated with the field data.

7.2 Calibration of VISSIM Parameters

Any model created in VISSIM needs to be calibrated to sufficiently represent field conditions. In calibration the default parameter values are changed till the error between the actual and simulated measure such as flow or travel time is less than the required threshold value. Calibration is the process in which the input parameters are refined so that the model accuracy replicates observed traffic conditions. In calibration, the parameters are adjusted so that the model outputs are similar to observed data. The various parameters that can be calibrated in VISSIM are longitudinal acceleration, desired speed, and clearance distance, emergency stopping distance waiting time before diffusion, lane change distance, standstill distance, minimum headway and other Wiedemann parameters.

Initially, a traffic stretch is simulated in VISSIM's Graphic User Interface (GUI) tool for its roadway characteristics and traffic conditions, similar to the field conditions. The field details are taken from the data collected from a 6-lane divided road of Bengaluru (Mekhri circle road). Various driver behavior parameters used as input are; i) Acceleration-deceleration curves are adopted from Chapter-4 (As studied from field) and ii) Lateral clearance maintaining behavior adopted from Budhkar (2017), used as inputs in the form of clearance maintained at 0 km/h and 50 km/h in the VISSIM model. Equation 7.1 presents the relationship to obtain lateral clearance between different vehicles w.r.t. their operating speed.

$$LC = m\bar{v} + c + \varphi \quad \text{......} 7\text{-}1$$

The lateral clearance values obtained from Equation-7.1 are used as input in VISSIM model for different vehicles (refer Table-7.1).

Table 7-1 Lateral clearance values for different type of vehicles used as input in VISSIM

Vehicle Type		Three-wheeler	Car	Bus	Two-wheeler	Truck	LCV
Average Lateral Distance (m)	0 km/h	1.14	1.17	1.35	1.18	1.35	1.49
	50 km/h	1.66	1.51	1.69	1.29	1.69	1.51

VISSIM uses Wiedemann-99 vehicle-following model in order to estimate the following behavior of simulated vehicles. The parameters for vehicle-following include look-ahead distance, look-back distance and Weidemann parameters, i.e. CC0 to CC9, need to be calibrated. However, all these parameters are not sensitive to the output obtained. Mathew & Radhakrishnan (2010) found that the parameters CC0, CC1, CC7, and CC8, maximum look-ahead and look-back distances are sensitive. In our present study, the upper and lower limits for variables to be optimized are adopted from Mathew & Radhakrishnan (2010). The upper and lower limits for different vehicle-following parameters used in VISSIM for optimizing traffic stream are presented in Table-7.2.

Table 7-2 Upper and lower limits for different parameters used in VISSIM for optimizing the traffic stream

Sl. No.	Parameter Name	Lower Limit	Upper Limit
1	CC0	0.0	4.0
2	CC1	0.0	4.0
3	CC2	0.0	10.0
4	CC7	0.1	1.5
5	CC8	0.0	4.0
6	Look ahead distance (max)	10.0	200.0
7	Look back distance (max)	10.0	200.0

The sensitive parameters are optimized within the ranges presented in Table-7.2, using Genetic Algorithms (GA), to obtain the behavior of simulated stream similar to the field traffic stream by minimizing the error between two streams. The GA consists of an objective function described by;

$$f = 2.0 - NRMSE_1 - NRMSE_2 \quad \text{......7-2}$$

$$NRMSE_2 = average(NRMSE_{car}, NRMSE_{Bike}, NRMSE_{Auto}) \quad \text{......7-3}$$

where, $NRMSE_1$ is the normalized root mean square error between obtained speeds for particular per-minute flow level of model and field (for 1 hour duration); and $NRMSE_{car}, NRMSE_{Bike}, NRMSE_{Auto}$ are the normalized root mean square errors between discretized frequency of speed distribution of car, bike and auto respectively between field and model. The normalized MSE was used since the speed distribution and speed-flow relationships provide different values of errors and they need to be normalized in order to be combined to calculate a resultant error term.

The algorithm begins by creating a random initial population of size 10, within the initial range mentioned in Table-7.2. The algorithm then creates a sequence of new populations. At each step, the algorithm uses the individuals in the current generation to create the next population.

The algorithm is run for several generations, and each generation produces an optimized value less than or equal to the earlier generations' value. The optimized values for the parameters CC0, CC1, CC7, CC8, Look ahead distance and Look back distance are 3.748, 1.495, 1.519, 0.625, 1.267, 194.504 and 142.930 respectively. The simulation model runs using the optimized parameter values, and information of macroscopic parameters can be obtained from the flow counters in VISSIM, whereas the microscopic parameters can be obtained using trajectory data of individual simulated vehicles by VISSIM.

7.3 Validation of VISSIM with Field Data

Validation is the process to determine whether the simulation model is an accurate representation of the real world traffic stream. In the present study, the macroscopic and microscopic parameters collected from the field are validated using the data obtained from VISSIM. The macroscopic validation includes the speed-flow-density curve, and the microscopic validation involve comparison of speed distribution and time headway distribution. Traffic data from a site (Site-4, Bengaluru 6-lane divided road) are used for validating VISSIM.

Relationship of per minute flow and average speed of vehicles from the field and VISSIM are extracted and validated with each other. The RMSE values (Root Mean Squared Error) for speed-flow diagram between VISSIM and field is obtained as 0.234 indicating that VISSIM performs similar to field condition. The microscopic parameters like speed and headway of each vehicle are extracted from field and VISSIM. The speed distribution of cars, motorized three-wheeler (3W) and two-wheeler (2W) are obtained from field and plotted with the VISSIM data. The RMSE values for speed distribution of cars, 2W and 3W between field and VISSIM are 0.248, 0.174 and 0.360 respectively, indicating that VISSIM can replicate the field condition.

Difference between arrival timing between two consecutive vehicles at a section over the entire width of the roadway is obtained from the field data. The arrival time difference (time headway) of field and VISSIM data are plotted against each other. The calculated time headways are divided into intervals of 0.5 seconds each. The K-S test is applied to the field and model data, and a P-value of 0.154 is obtained indicating that the VISSIM can replicate the field data properly.

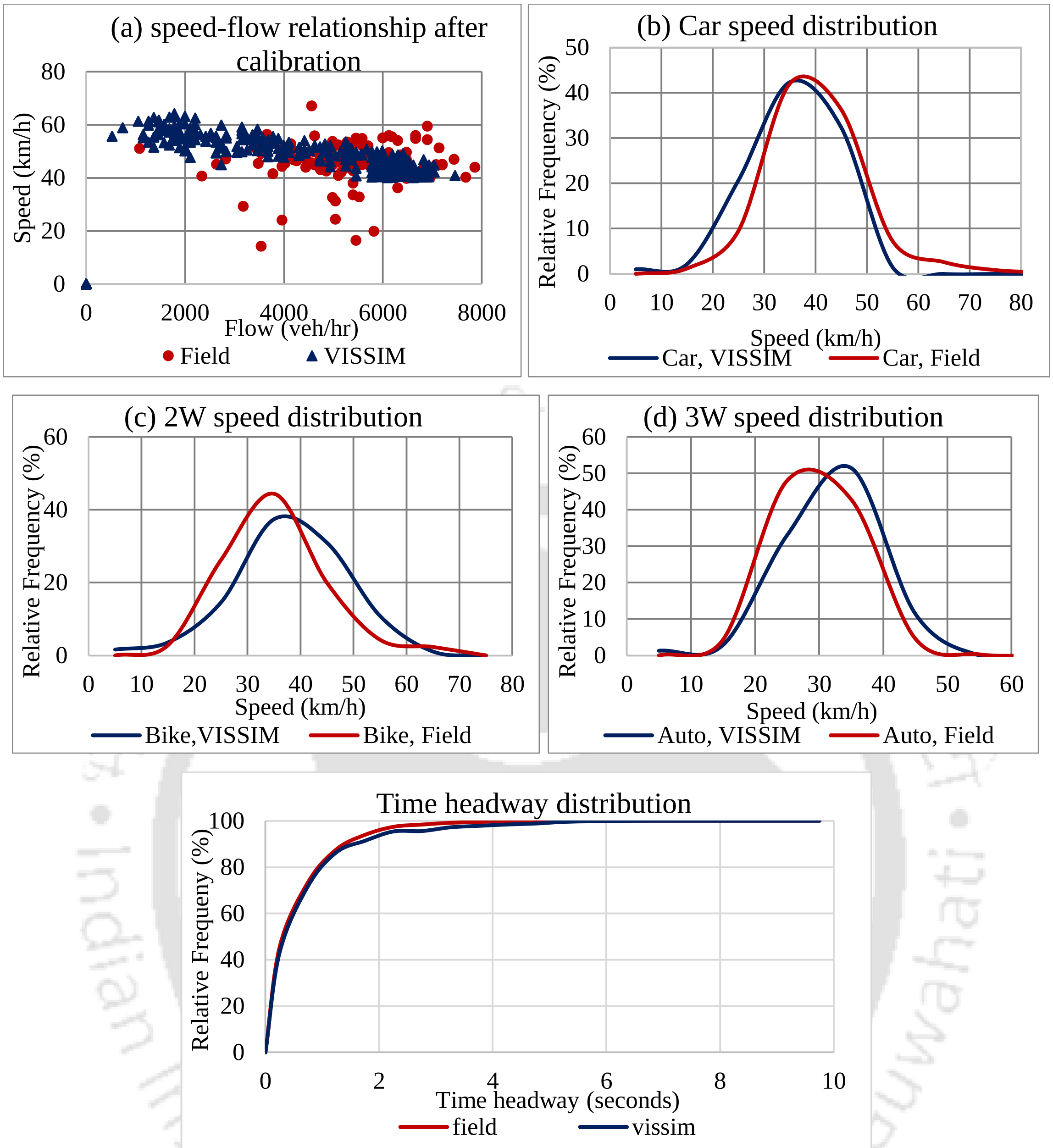


Figure 7-1 Comparison of streams of VISSIM and Field data for (a) Speed-Flow relationship, Speed distribution of (b) Cars (c) 2W (d) 3W & (e) Time headway distribution

7.4 Study of other Microscopic Parameters Obtained from VISSIM

In the present section, other microscopic parameters obtained from VISSIM are plotted with the parameters obtained from the field to study their behavior in more detail. The relationship between lateral and longitudinal acceleration and operating speed of vehicles, lateral placement of vehicles on entire road cross section and the minimum lateral gap maintained by vehicles from the median edge are plotted and studied with the VISSIM data.

7.4.1 Study of Lateral Speed and Lateral Acceleration

The lateral speed obtained from VISSIM for all three type of vehicles are plotted in Figure 7-2. It can be observed that the lateral speed of all three type of vehicles varies from 0-1m/s, with more than 80% data at 0 m/s. For all three type of vehicles, the distribution of lateral speed remains same. This indicates that VISSIM cannot represent the vehicles' lateral maneuver of field traffic which is a major parameter in case of no-lane based heterogeneous traffic. As VISSIM is one of the widely used micro-simulation frameworks in India, the lateral behavior of vehicles should be taken into consideration in detail to describe such traffic stream.

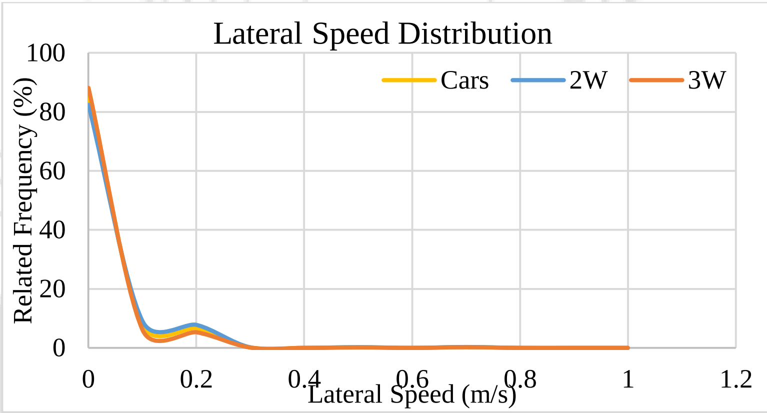


Figure 7-2 Distribution of Lateral Speed obtained from VISSIM for all three type of vehicles

As per literature review, it is found that the lateral acceleration is a useful parameter for representing the realistic lateral behavior of vehicles Chapter-2 (Section-5.1). The lateral acceleration obtained from VISSIM are plotted with the 85th percentile values for different speed. The absolute values of lateral acceleration for are obtained to find the overall maneuvering of different vehicles. The 85th percentile lateral acceleration of each type of vehicles (cars, 2W and 3W) corresponding to the operating speed is obtained. The 85th percentile lateral acceleration is also obtained from the developed model from the field data for each type of vehicles (refer Section-no., in Chapter-4). The lateral acceleration obtained from VISSIM and the lateral acceleration obtained from the model developed to represent field traffic are presented below in Figure 7-3.

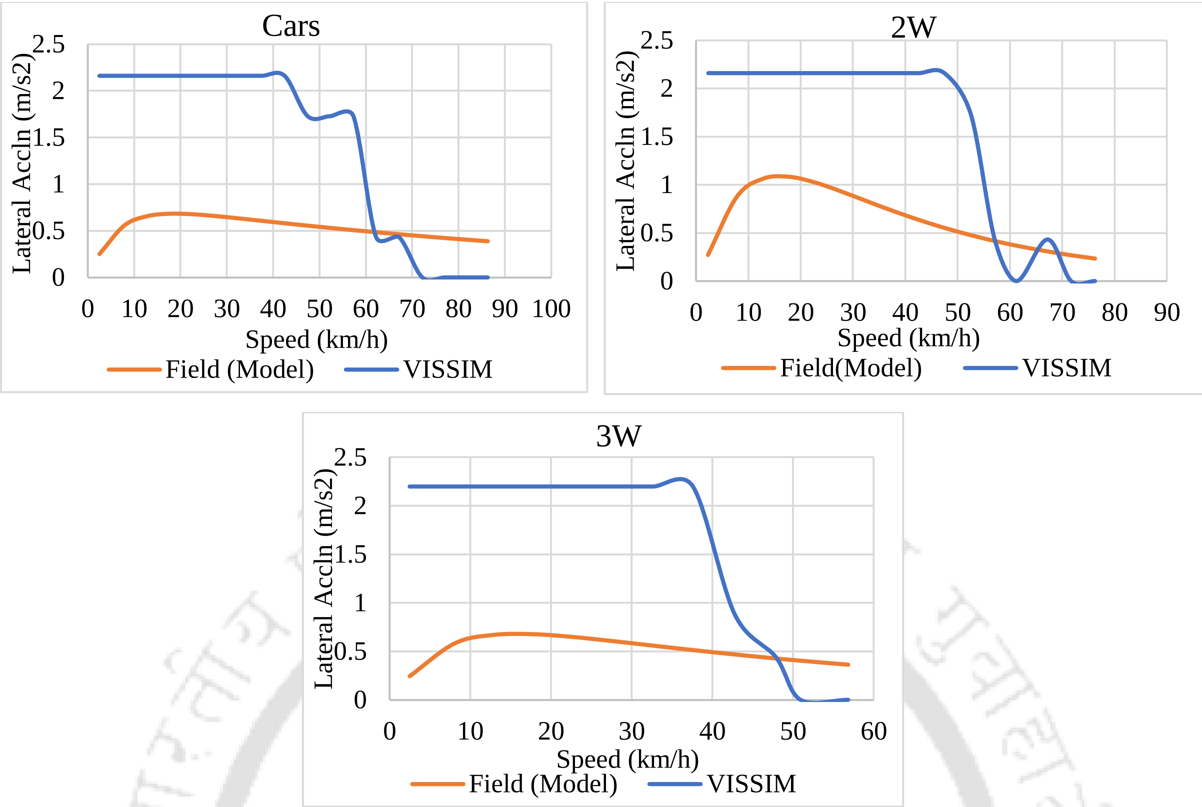


Figure 7-3 Comparison of Lateral Acceleration Obtained from the field and VISSIM

From Figure 7-3, it can be observed that the lateral acceleration obtained from VISSIM does not represent the model obtained from field data. The maximum values of lateral acceleration of all three type of vehicles, i.e. cars, 2W and 3W are higher than 2 m/s^{2}, and it remains constant up to 40 km/h speed. Also for all three type of vehicles, the range of lateral acceleration remains same. However, the maximum lateral acceleration obtained from model goes up to 0.7m/s^{2} for cars and 3W, and in case of 2W, it goes up to 1.2 m/s^{2}. Also, the 85th percentile lateral acceleration increases with increase in speed at lower speed (≈15 km/h), and it decreases with increase in speed at higher speed conditions (>15km/h) in the field.

7.4.2 Study of Longitudinal Acceleration/Deceleration (A/D)

Longitudinal acceleration/deceleration values during normal driving condition on straight mid-block sections are analyzed from the field data, and the models are developed for the 85th percentile values of A/D with operating speed for the different type of vehicles (refer Chapter-4). In the present sub-section, the longitudinal A/D values obtained from the VISSIM are analyzed and the 85th percentile A/D values are also plotted with the data obtained from the field model to see their behavior.

From Figure 7-4, it can be clearly observed that the 85th percentile values of longitudinal acceleration/deceleration (A/D) with respect to operating speed of vehicles, obtained from VISSIM can represent the field condition. The data obtained from the model developed for field traffic (refer Equation-4.4 of Chapter-4) are compared with the data obtained from VISSIM by conducting the statistical F-test for variances. Table-7.3 presents the details of the F-test results for all three type of vehicles. Hence, from this results it can be concluded that the VISSIM can represent the longitudinal maneuver of vehicles on no-lane based mixed traffic in micro-level.

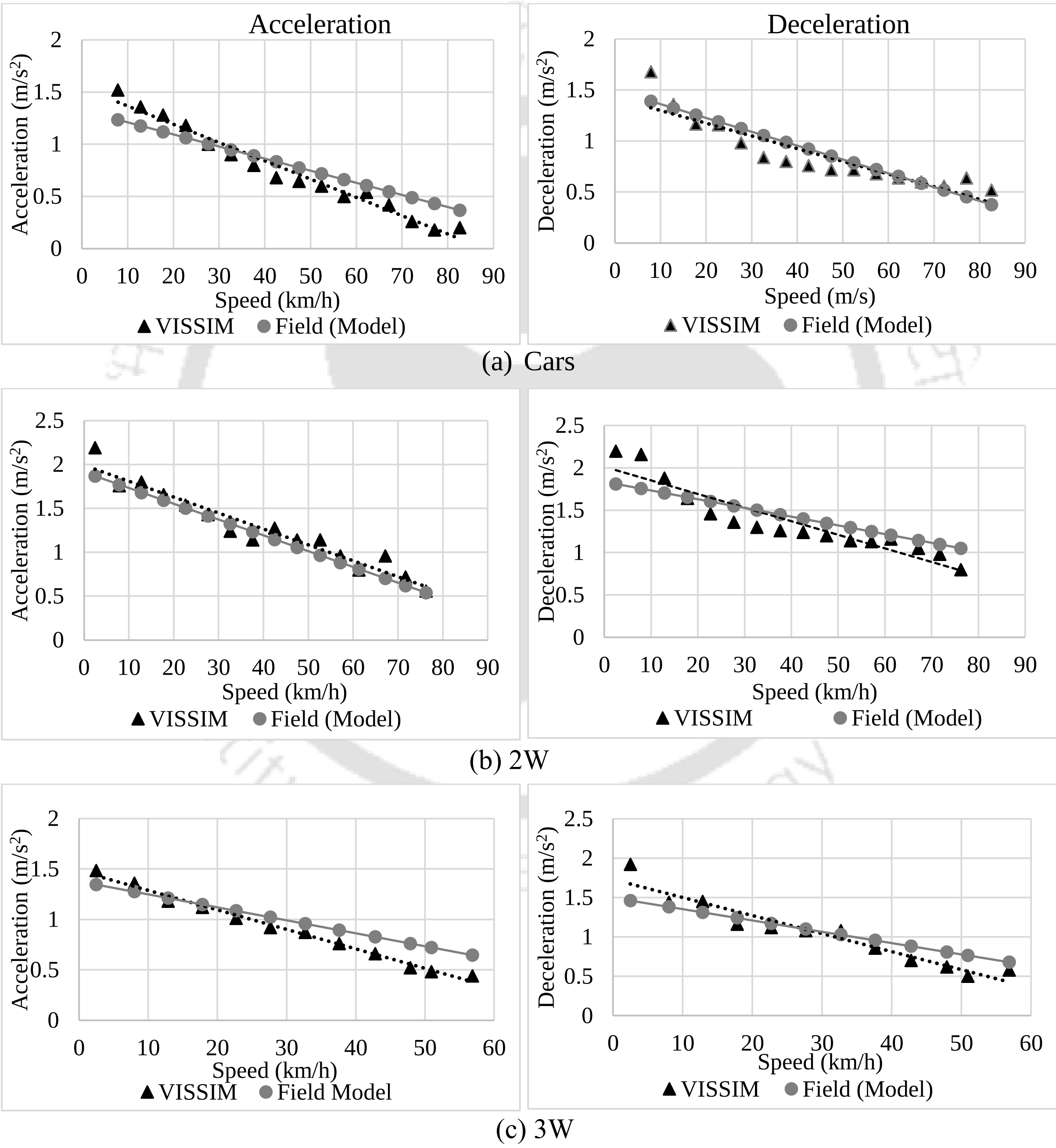


Figure 7-4 Comparison of Acceleration/Deceleration with operating speed of vehicles obtained from field model and VISSIM (a) Cars (b) Motorized two-wheeler (2W) (c) Motorized three-wheeler (3W)

Table 7-3 Details of the results of F-test conducted between the VISSIM data and Field (Model) data

Vehicle Type	Acceleration		Deceleration	
	$F_{Statistics}$	$F_{Critical}$	$F_{Statistics}$	$F_{Critical}$
Cars	2.349	2.403	1.030	2.403
Two-wheelers	1.086	2.403	2.109	2.403
Three-wheelers	2.732	2.817	2.268	2.817

7.4.3 Study of Lateral Placement of Vehicles on Entire Road Cross-section

The lateral placement of different type of vehicles on the entire road cross-section is obtained from the position data extracted from VISSIM. The distribution of lateral placement on the entire cross-section is studied by plotting the frequency distribution of lateral placement obtained from VISSIM, and a comparative study is done by plotting the placement of vehicles obtained from the field data obtained from the same site used for calibration (refer Figure 7-5).

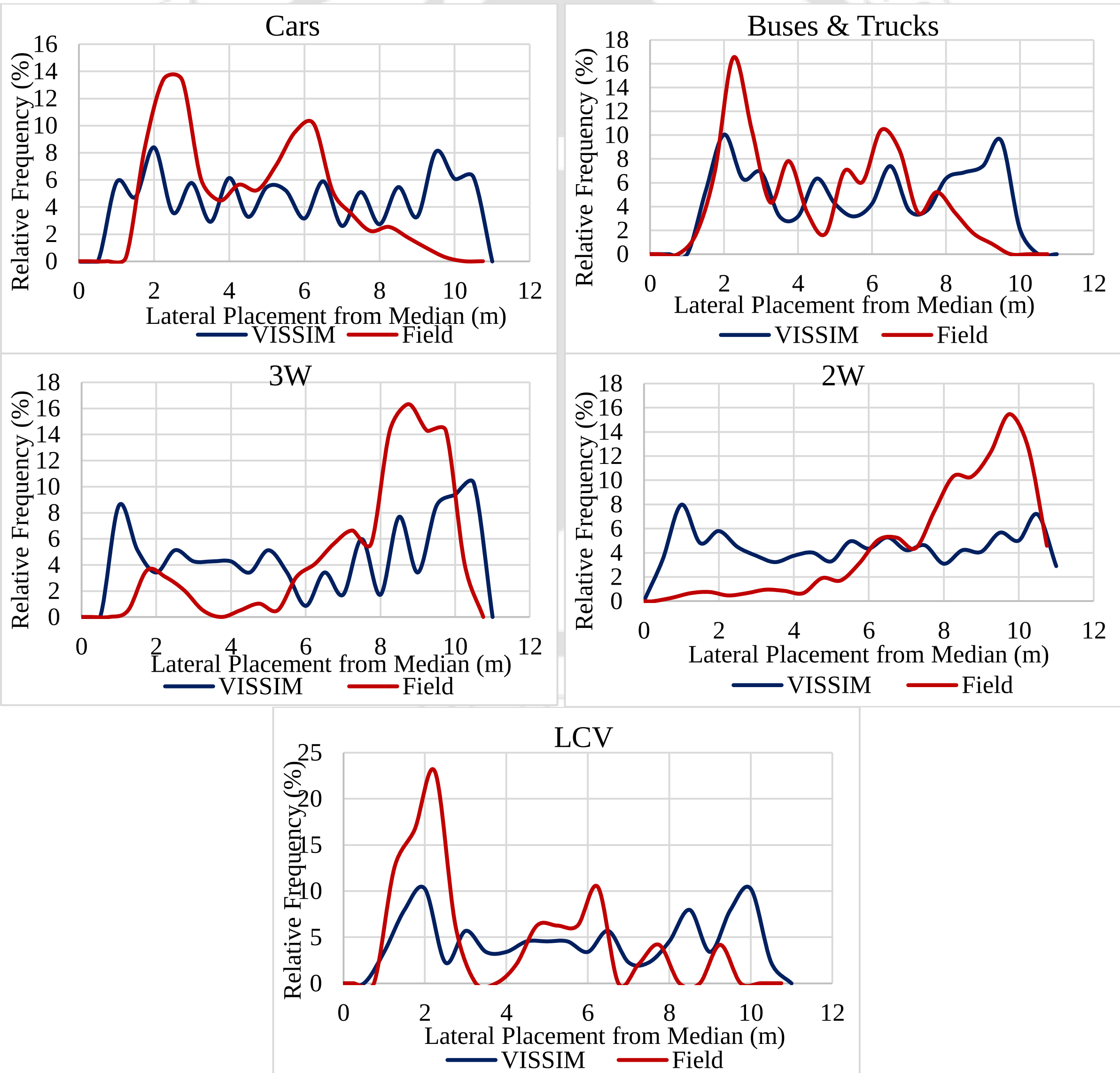


Figure 7-5 Distribution of lateral Placement of vehicles from VISSIM and Field data on entire road cross-section

From Figure 7-5 it can be observed that the lateral placement of vehicles obtained from VISSIM spread on the entire cross-section of the road. The placement of vehicles on the field does not match with the VISSIM data. It is observed that the cars, LCV, buses and trucks, etc. travel near the median of the road whereas 2W and 3W shifts towards the shoulder of the road. However, no such trend is observed for lateral placement of vehicles obtained from VISSIM data. This indicates that in VISSIM the vehicles are uniformly distributed along the width of the roadway. The statistical F-test is conducted between the field data, and VISSIM with a null hypothesis of equal variances and their results are presented in Table-7.4.

Table 7-4 Details of the F-test results conducted between the lateral placement distribution data of VISSIM and Field

Vehicle Type	$F_{Statistics}$	$F_{Critical}$	p-Value
Cars	0.293	0.488	0.002
Buses & Trucks	0.397	0.488	0.032
Three-wheelers	0.319	0.488	0.004
Two-wheelers	0.107	0.488	0.000
LCV	0.228	0.488	0.0005

From Table-7.4, it can be observed that the probability value less than 0.05(P-value < 0.05) indicates that the lateral placement of VISSIM and field data are significantly different at 5% significance level. Then the operating speed of vehicles with respect to their lateral placement on the entire road width is obtained for both VISSIM data, and field data based on the model developed in Chapter-6 (Section- 6.3, Equation-6-4.) and plotted in Figure 7-6 below.

From Figure 7-6, it can be observed that there is no variation in operating speed of vehicles are observed with respect to their lateral placement on the entire roadway in VISSIM. However, in case of the field the operating speed of vehicles decreases as the vehicles shifts towards the shoulder of the road. Hence, the data obtained from VISSIM does not represent the real world field condition.

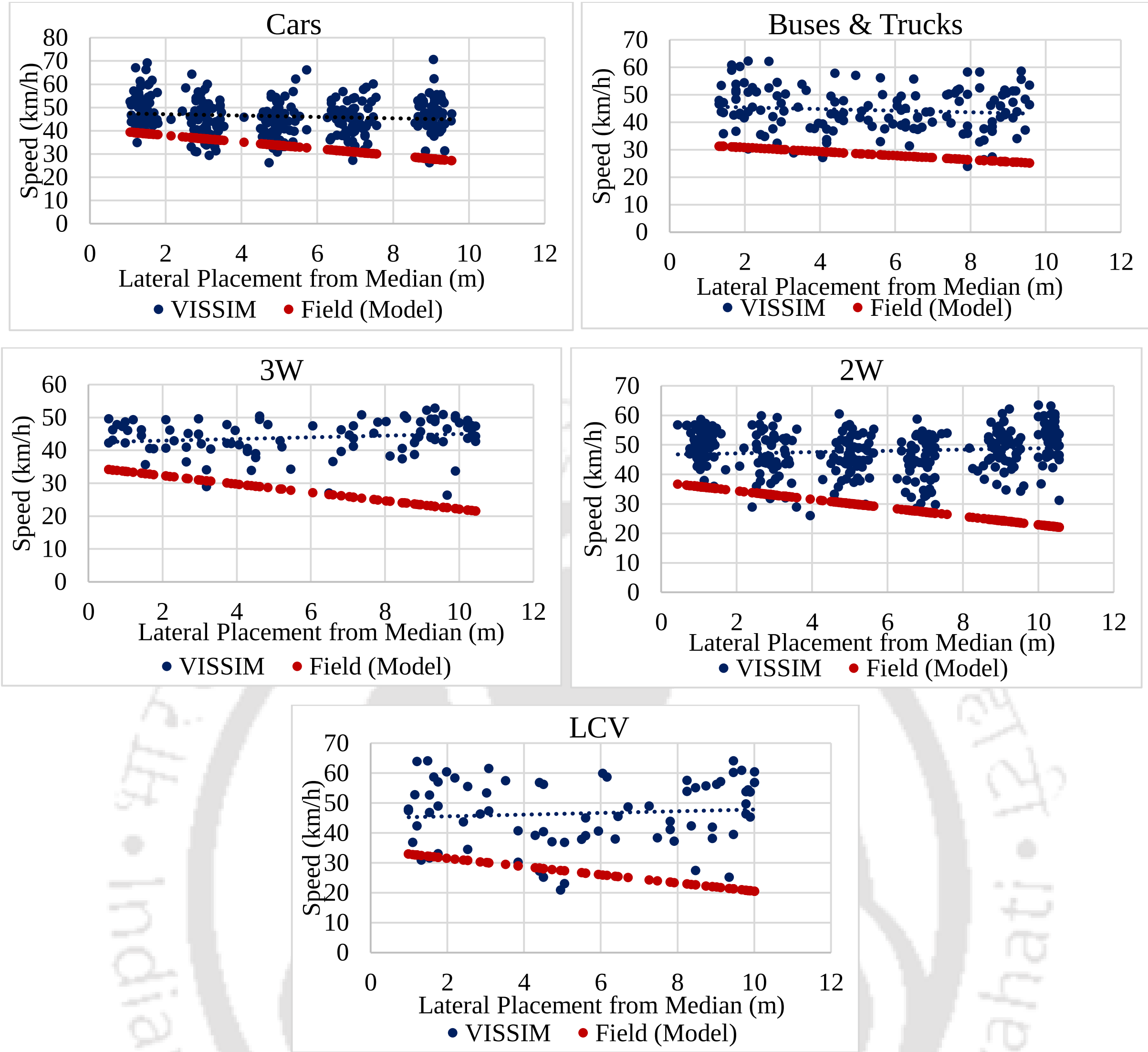


Figure 7-6 Comparison of Lateral placement Distribution obtained from VISSIM and field

7.4.4 Study of Minimum Lateral Gap maintained by Vehicles from Median

The minimum lateral gap maintained by cars and trucks from the median is calculated from the position data obtained from VISSIM. The lower 5% data (i.e. 95% vehicles maintain higher gap than this gap) are obtained and considered as the minimum lateral gap maintained by vehicles. The minimum lateral gap maintained by cars and trucks are also obtained based on the model developed from the field data for a median of width 1.5m and kerb height of 0.3m (refer Chapter-6, Section-6.4., Equation-6-6 &6-7.). Both the data obtained from VISSIM and the field (model) are plotted in Figure 7-7.

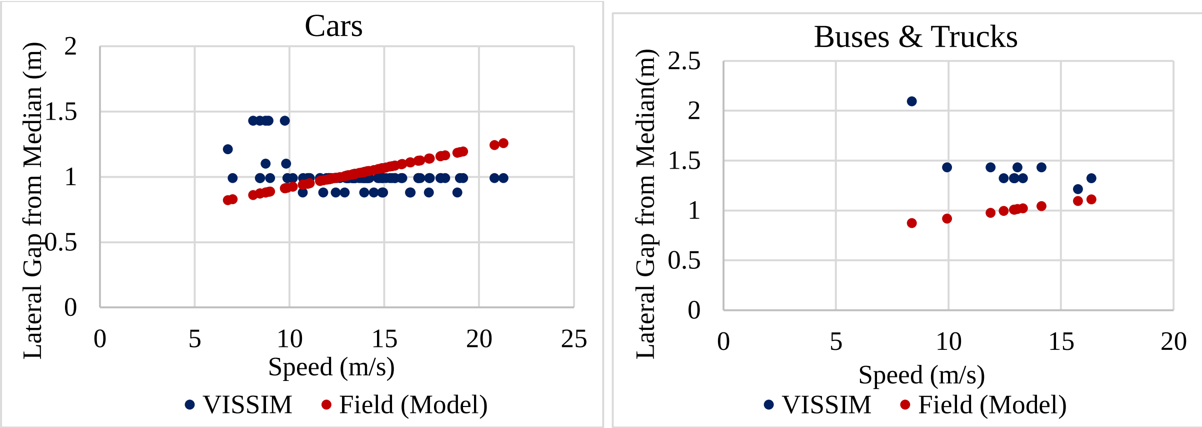


Figure 7-7 Minimum lateral gap maintained by (a) cars and (b) Trucks from the median

From Figure 7-7 it can be seen that in case of VISSIM, the minimum lateral gap maintained by both, cars and trucks lies in the similar range as obtained from the developed model from field data. The operating speed of vehicles does not have any impact on the gap obtained from VISSIM. However, in case of field condition vehicles maintain a higher gap from median with their increase in operating speed due to their safety concern. The MAPE error between VISSIM and field (model) are obtained for both cars and trucks. The MAPE value for the truck (MAPE=27.62) indicates a reasonable forecasting of the predicted model (refer Equation-6.6 & 6.7 of Chapter-6). However, for cars, the MAPE values (MAPE=16.42) indicates a good forecast of the predicted model. Though the minimum lateral gap maintained by cars and trucks, obtained from VISSIM can represent the field condition reasonably, the operating speed of vehicles does not have any impact on the gap maintaining behavior which is against the driver psychology.

7.5 Concluding Remarks

In this present chapter, the importance of the microscopic parameters (lateral acceleration, longitudinal A/D, operating speed, lateral placement maintained by vehicles on the entire road cross-section and the lateral gap maintaining behavior of vehicles from road edge/median, etc.) obtained from field are evaluated using a well-known commercially available micro-simulation framework VISSIM. VISSIM is calibrated and validated for both microscopic and macroscopic parameters of no-lane based heterogeneous traffic stream. Then the microscopic parameters which had been studied from the field traffic (i.e. lateral acceleration, longitudinal A/D, lateral placement of vehicles and the lateral gap maintaining behavior of vehicles from the median, etc.) are evaluated using the data obtained from VISSIM.

It can be observed that the parameters obtained from VISSIM can represent the longitudinal maneuvering behavior of vehicles as in case of field traffic. The longitudinal speed, time headway and acceleration/deceleration behavior of vehicles can be represented by the data obtained from VISSIM. However, the lateral maneuvering i.e. the lateral acceleration, lateral speed and the lateral placement of vehicles on the entire road width are not represented as in case of field traffic. In field traffic, it is observed that the minimum lateral gap maintained by vehicles from median, depends on the median size (width and height) and the operating speed of vehicles. Also the operating speed of vehicles are also depends on the vehicle type and their lateral placement on the entire width of the roadway. However, it is observed that in case of VISSIM no such relationship or trend is observed for lateral placement and lateral gap of vehicles. Also, the lateral acceleration which is a major representation of the lateral maneuver of vehicles, are very less in VISSIM. The lateral speed of all type of vehicles varies from 0-1m/s for all type of vehicles. However, in case of field traffic, due to no-lane based heterogeneous traffic the lateral maneuvering of vehicles are very high. Hence, one should incorporate these microscopic parameters while simulating the no-lane based heterogeneous traffic stream using VISSIM.

Hence, it can be concluded that while developing a new microscopic model or simulation framework and also modifying any existing model for such no-lane based heterogeneous traffic, these lateral parameters should be taken into account. The simulation framework or model should describe these microscopic behaviors properly to represent the real world field traffic in detail.

8 Conclusions & Future Scope

8.1 Introduction

In the present thesis, attempt has been made to study the microscopic parameters of non-lane based mixed traffic stream of India. In order to obtain these parameters, data are collected from the real-world traffic stream by using various techniques. The dynamic parameters (like lateral acceleration, longitudinal acceleration/deceleration, operating speed, etc.) of the different type of vehicles are obtained by running the instrumented vehicle (equipped with Racelogic Video VBox) over different roads of six cities of India. The lateral placement of different type of vehicles on the entire cross sections of roads with different widths are calculated with the help of a camera calibration technique for converting image coordinates from video to real-world coordinates. Also, the lateral gap maintaining behaviour of vehicles from the road edge/median are captured by using the ultrasonic sensor based assembly. Relationships between operating speed of vehicles with their lateral and longitudinal acceleration are obtained by fitting the regression model to the field data. The best-fitted distribution of all three dynamic parameters is obtained. The driving behaviour of different type of vehicles are analyzed based on the dynamic parameters of vehicles using the friction circle concept. The lateral placement of vehicles, (i.e. the distribution of vehicles laterally) on entire cross-section of the road are analysed. Then the operating speed model of different vehicles are obtained based on their lateral placement across the road section and flow of the traffic stream. The minimum lateral gap maintained by vehicles from the road edge/median is analysed based on their operating speed and size of the median. At last, these parameters obtained from the field are used to calibration and evaluation of commercially available micro-simulation framework, VISSIM. This chapter presents the summary of researchwork conducted in this thesis. The second section summarizes the important findings of this research work. The contribution of this research work for the scientific community is showcased in the third section. The last section explores the scope of future research in line of the issues discussed in this thesis.

8.2. Summary of the Research Work

The important findings of this research work are divided in three parts and presented in the subsequent sub-sections.

8.2.1. Study of Dynamic Parameters of Vehicles

The longitudinal acceleration/deceleration (A/D), lateral acceleration and operating speed are three major dynamic parameters which can describe the driving behaviour in no-lane based mixed traffic stream. All three dynamic parameters are evaluated for different type of vehicles on straight mid-block sections, and their best-fitted probability distributions are obtained. Also, their variation with operating speed of vehicles is studied. Significant findings obtainedfrom the study of all three parameters are listed below;

- It is observed that road width does not have significant impact on longitudinal acceleration/deceleration behaviour of vehicles while it has a significant impact on lateral acceleration. It is observed that the lateral acceleration of 4-lane divided road (i.e. 2-lane each side)is higher than 6-lane roads (3 lanes each side).
- From the cumulative percentile curve, it is found that the break point does not always lie exactly at 85^{th} percentile value for both longitudinal acceleration/deceleration and lateral acceleration of vehicles. Hence, the 85^{th} percentile design value concept should be reconsidered.
- The 95^{th} (85^{th}) percentile of acceleration values are 1.38(0.94) m/s^2, 1.45(0.95) m/s^2 and 1.54 (1.04) m/s^2 for SUV, Sedan and H-back cars respectively. However, the deceleration values for all three cars are 1.63 (1.03) m/s^2, 1.77(1.06)m/s^2 and 1.66 (1.04) m/s^2 respectively.
- The 95^{th} (85^{th}) percentile acceleration values for 2W and 3W are considerably higher than cars, i.e. 2.33 (1.45) m/s^2 and 1.65 (1.07) m/s^2 respectively with a higher deceleration of 1.82 (1.18) m/s^2 and 2.43 (1.58) m/s^2.
- The 95^{th} percentile values of lateral acceleration are <2 m/s^2 for SUV and Sedan cars, and it increases for H-Back cars followed by motorized 3W and 2W (up to 2.54 m/s^2). The 85% of lateral acceleration data for all type of vehicles lies below the medium comfort level (<1.8 m/s^2).
- The 85^{th} and 95^{th} percentile A/D of different vehicles follow a linearly decreasing trend with the operating speed of vehicles during normal driving conditions on straight roads.
- The relationship between 85^{th} and 95^{th} percentile lateral acceleration and operating speed of all five type of vehicles follow two-term exponential model for normal driving conditions on straight roads.
- It is observed that the friction circle concept (g-g diagram) can determine the driving behaviour of different type of vehicles using all three dynamic parameters (longitudinal A/D, lateral acceleration and operating speed).
- The proposed diagram for resultant acceleration and design speed (safety domain curve), can easily demonstrate the safe or unsafe driving behaviour. The defined safety

domain is an important tool for finding the points on the trajectory, where the driving behaviour is safe/unsafe to inform him about his driving behaviour and produce the threshold of attention to take preventive measures

- This study also investigated the applicability of the copula based approach to model the joint distribution of longitudinal descriptors [operating speed, longitudinal (A/D)] and lateral descriptor [lateral acceleration] of five different type of vehicles (motorized 2W, 3W, H-back, Sedan and SUV cars) for no-lane based traffic streams.
- The recommendation is to use trivariate Gaussian copula for the amelioration of the realistic representation of riders' behaviour in lane-based as well as in non-lane based traffic streams, by suitably accommodating the dependent relationships between the longitudinal and lateral descriptors of different type of vehicles.

8.2.2. *Study of Lateral Placement of Vehicles across the Road section:*

The lateral placement of different type of vehicles on the entire cross-section is studied for roads with different width (i.e. 2-lane, 3-lane, 4-lane and 5-lane on each side). It is observed that the road width (number of the lane), flow condition and lateral placement of vehicles have a significant impact on operating speed of vehicles. The important findings from the study of the lateral placement of vehicles are presented below:

- It is observed that in the case of 2-lane and 3-lane wide roads, 75% to 90% of cars travel near the median side of the roads.
- 55% to 80% trucks and light-commercial vehicles (LCVs) move mainly along the median-sided lane in case of 2-lane and 3-lane wide roads and shifts towards shoulder side in 4-lane and 5-lane wide roads.
- 50% of the road space towards shoulder side is covered by 70% of 2Ws present in the traffic stream. If one takes up 50% of the road on the shoulder side, it can be seen that nearly 60% of 2Ws move over this portion of the road for 4-lane, 6-lane and 10-lane divided roads and nearly 85% of them move in this portion of road for 8-lane divided road.
- The operating speed of vehicles as a function of lateral placement and flow of the traffic stream follows a linearly decreasing trend from median to shoulder for all roads and all type of vehicles.

8.2.3. *Impact of Median Type on Lateral Gap of Vehicles from Median:*

The size of the median (width and height) and operating speed of vehicles have a significant impact on the minimum lateral gap maintaining behaviour of vehicles.

- The lateral gap maintained by cars decreases with the increase in width of the median (i.e. from 0.45m width to 1.2m width). However, the height of plantation has a significant impact on the lateral gap maintain behaviour of vehicles. Similarly, the width of median have a similar impact on lateral gap maintaining behaviour of trucks also.
- The height of the median is highly correlated to the lateral gap maintained by vehicles from the median. The vehicles (both trucks and cars) shifts away from the median with the increase in height of the median due to their perception of risk to collision.
- It is also observed that operating speed of vehicles have a higher impact on lateral gap maintaining behaviour of cars comparing to trucks.

8.2.4. Importance of Microscopic Parameters in Simulating Non-Lane Based Heterogeneous Traffic Stream

A simulation framework is essential to evaluate the detailed traffic performance at different roadway sections, development of the driver behaviour models and hence simulate the large-scale real-world traffic situations in great detail. Modelling driver behaviour requires a detailed understanding of the vehicular interactions with the surrounding traffic and roadway features from the real-world traffic stream. Unlike the lane based traffic, in case of no-lane-disciplined traffic, it is difficult to get the field data on vehicular movement such that a detailed understanding of the traffic stream behaviour can be obtained. The identified important microscopic parameters obtained from the field data are compared with the parameters obtained from the simulated stream using a commercially available micro-simulation framework, VISSIM. Before the comparison study, VISSIM is well calibrated and validation with microscopic and macroscopic parameters which are generally used in available literature. The important observations of this study are listed below.

- It is observed that the longitudinal manoeuvring behaviour related parameters (longitudinal speed, time headway and acceleration/deceleration behaviour of vehicles) obtained from VISSIM shows similar behaviour to the field data.
- The lateral manoeuvring (i.e. the lateral acceleration, lateral speed and the lateral placement of vehicles on the entire road width) which impacts significantly the

manoeuvring behaviour in non-lane based heterogeneous traffic stream are not represented realistically by VISSIM.

- In field traffic, it is observed that the minimum lateral gap maintained by vehicles from the median, depends on the median size (width and height) and the operating speed of vehicles. However, in case of VISSIM, vehicle maintain an uniform gap from median irrespective of their operating speed which is against the drivers' perception of safety.

In case of field traffic, due to no-lane based heterogeneous traffic, the lateral manoeuvring of vehicles are very high. Hence, one should incorporate these microscopic parameters also in developing any simulation model for the no-lane based heterogeneous traffic stream.

8.3. Contribution of this Research

From the literature it has been observed that, to date no well acceptable theory exists that can model the 2D (longitudinal and lateral) driver behaviour of no-lane based heterogeneous traffic stream in a comprehensive manner. One of the major challenge in driver behaviour modelling lies in identifying the parameters that describe such type of typical driving behaviour or vehicle manoeuvre. In the present study, an attempt has been made to study the manoeuvring behaviour of different type of vehicles by identifying different lateral and longitudinal microscopic parameters (dynamic parameters like lateral and longitudinal A/D, operating speed, lateral placement of vehicles on entire road width, lateral gap maintaining behaviour of vehicles from the road edge, etc.) of such traffic stream. Though all these parametric studies are different based on their study methodology, these parameters are useful for evaluation of vehicles' lateral weaving in simulated trajectories and also while developing or validating simulation models for the realistic representation of such no-lane based heterogeneous traffic stream. The simulation framework or model should describe these microscopic behaviours properly to represent the real world mixed traffic in detail. Major contributions of each parameters are listed below.

- A/D values and lateral acceleration values of different types of vehicles measured from the field can be used in development and validation of the microscopic traffic simulation model. Further, the identified probability distribution models of A/D and lateral acceleration behaviour can be used for evaluation of vehicle's lateral weaving in simulated trajectories for such traffic and in realistic representation of such traffic stream.

- The lateral acceleration as a measurement of lateral comfort is directly related to the horizontal alignment and can be used to determine the applicable range of super-elevation ratios.
- The study of lateral placement of vehicles on the road cross-section can be used to develop and validate the simulation model's realistic representation of such traffic stream. The lateral placement can also be used to develop the lane distribution factor, the optimum operating speed in various lanes of the roads and the safety aspects of the road like the clearance from the edge of medians and shoulders, etc.
- The impact of median type on lateral gap maintaining behaviour of vehicles can also be used while generating simulation models and also a useful parameter for safety evaluation and capacity estimation of the roads.

The present studies are only limited to the straight mid-block sections with the normal driving of the traffic.

8.4. Future Scope

The research work carried out in this thesis can extended further in following directions:

- Dynamic parameters of vehicles can be studied for different type of vehicles on hilly terrain and for different horizontal and vertical road alignments.
- The driving behaviour of vehicles can also be studied in detail by segregating the data based on different type of road alignment and geometry.
- The lateral placement of vehicles can be studied on highways with different horizontal and vertical alignment etc., and also for different traffic features like roads with different traffic composition, stream flow and capacities, etc.
- The lateral gap maintaining behaviour of other type of vehicles from median can also be studied on different roads.
- Impact of shoulder condition on lateral gap maintaining behaviour of vehicles can be studied.
- The impact of plantation inside the median on lateral gap maintaining behaviour of vehicles can also be studied further.

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List of Publications

Conference Publications:

1. **Geetimukta Mahapatra**, Akhilesh Kumar Maurya, "Study of Vehicles Lateral Movement in Non-lane Disciplined Traffic Stream on a Straight Road", *Procedia-Social behavioral Sciences, Volume 104, 2 December 2013, Pages 352-359*, Second Conference of Transportation research Group of India.

2. A.K. Maurya, **G. Mahapatra**, A.K. Budhkar, P. Khandelwal, M. Kumar, C. Panda, "Sensor Based Measurement of Vehicle's Lateral Clearance with Road Edge", *Conference of Transportation Planning and Implementation methodologies for Developing Countries*, December 2014.

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5. **Geetimukta Mahapatra**, Sanhita Das, Akhilesh Kumar Maurya, "Effect of Sample size and Bin Size variation on traffic Speed study", Transportation Research Procedia, 14th World Conference on Transportation research, July 2016.

6. Subhadipto Poddar, **Geetimukta Mahapatra**, Akhilesh Kumar Maurya, "Study of Different Vehicles' Lateral Placement and Speed on Indian Roads", *Conference of Transportation Planning and Implementation methodologies for Developing Countries*, December 2016.

Journal Publications:

1. **Geetimukta Mahapatra**, Akhilesh Kumar Maurya, Anil Minhans, "Lateral movement of vehicles under weak lane discipline heterogeneous traffic", Jurnal of Teknologi, 2015.

2. **Geetimukta Mahapatra**, Akhilesh Kumar Maurya, "Dynamic Parameters of Vehicles under Heterogeneous Traffic Stream with No Lane Discipline: An Experimental Study", Journal of Traffic and Transportation Engineering: English Edition", ***(Accepted)***

3. **Geetimukta Mahapatra**, Akhilesh Kumar Maurya, "Defining Driving Behaviour Using Friction-Circle concept: An Experimental Study", European Transport \ Trasporti Europei, (Under Review)

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