CAPACITY ANALYSIS OF MULTILANE DIVIDED URBAN ROADS UNDER THE INFLUENCE OF SIDE FRICTION IN HETEROGENEOUS TRAFFIC CONDITIONS

Submitted in partial fulfilment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

by

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CERTIFICATE

This is to certify that the thesis entitled "**CAPACITY ANALYSIS OF MULTILANE DIVIDED URBAN ROADS UNDER THE INFLUENCE OF SIDE FRICTION IN HETEROGENEOUS TRAFFIC CONDITIONS**" being submitted by **PALLAVI GULIVINDALA** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Department of Civil Engineering, **NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL** is a record of bonafide research work carried out by her under my supervision and it has not been submitted elsewhere for award of any degree.

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DECLARATION

This is to certify that the work presented in the thesis entitled **"CAPACITY ANALYSIS OF MULTILANE DIVIDED URBAN ROADS UNDER THE INFLUENCE OF SIDE FRICTION IN HETEROGENEOUS TRAFFIC CONDITIONS"** is a bonafide work done by me under the supervision of **Dr. Arpan Mehar** and was not submitted elsewhere for the award of any degree. I declare that this written submission represented my ideas in my own words and where others ideas or words have been included; I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea / data / fact / source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Dedicated to

My

Beloved Parents

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(PALLVI GULIVINDALA)

ABSTRACT

Urban arterials exhibit deteriorated capacity and poor level of service in many developing countries in recent times. The increase in vehicular population on urban roads is one of the major reasons to reach the congestion stage which exhibit a picture that the roadway is not able to cater the higher demand. In addition to the vehicular population, interference of the road side activities with the ongoing traffic flow is another major cause for deteriorating performance of traffic flow characteristics. These road side activities usually occur on edge of the road or on the shoulder or sometimes on the carriageway itself at dense urban streets which is referred as side friction. Side friction includes presence of several activities such as pedestrain movement, street vendors, bus-stops, auto-stands, on-street parking etc. Some of these activites may occur for some time of the day or the whole duration of the day and sometimes these activities cover certain width of the road. The interaction of these activities with traffic stream affects the ongoing vehicular traffic flow behavior and results in deteriorated capacity of the urban arterials. Therefore, the present study attempts to analyse the presence of side friction and its impact on traffic stream parameters such as stream speed, PCU values of subject vehicle types, and roadway capacity.

Field data was collected on different locations of the multi-lane divided urban roads at mid-block sections in two cities of India namely Telangana and Andhra Pradesh. The videography technique was used for collection of traffic flow data on four-lane and six-lane divided carriageways. Roadside friction data were also recorded during videography survey along with traffic flow data. Although there are sevral side friction activities present on the roadway but some of them cause reduction on traffic flow performance. The factors considered for present study include pedestrian movement on the road, parking manuovers, entry-exit vehicles and wrong movement of vehicles. All the side friction parameters are quantified though regression analysis and provided with weighing factors for each of the side friction activity. The influence of the total side friction on stream speed at selected study sections is analysed and further classified into various levels from very low side friction to high side friction. It is found that the reduction in stream speed is quite significant at medium to higher levels of side friction. However, no significant change in stream speed is observed at low levels of side friction. Speed-prediction models are proposed as a function of traffic volume and side friction and validated with field data.

As there are six different vehicle types such as car, motorized two wheeler, motorized three wheeler, Bus, light commercial vehicle, non-motorized vehicles identified in the field. The PCU values of all vehicle types have been examined to check their sensitivity under various factors namely traffic volume, side friction, proportional shares and carriageway width. The study established linear relations to predict PCU of subject vehicle types through multiple regression analysis under various factors affecting it. The study also deploys the soft computing method as an adaptive neuro-fuzzy inference system (ANFIS) to model and optimize PCU of selected vehicle types based on specified criteria. A comparative analysis showed that the PCUs suggested by ANFIS model are yielding better reliable values than that conventional multiple linear regression (MLR) model values on low to high side friction levels. The study finds side friction is a noticeable factor that causes a significant change in the PCU of a vehicle type and capable of altering traffic flow measurements.

Further, influence of side friction on capacity of the urban mid-block sections has been analysed. Capacity values of the selected road section are determined by developing speed and volume diagram. The capacity of section with very low side friction is determined and reductions in capacity values are estimated. It has been observed that the reduction in capacity is found to be significant at various levels of side friction. The carriageway width is another parameter identified as influencing the capacity of roadway section to a great extent. Study suggested adjustment factors for determining road capacity based on side friction and carriageway width. Further, capacity model for the multilane divided urban roads is proposed in the study considering lower to higher side friction levels, prevailing traffic and roadway conditions.

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GLOSSARY OF TERMS

2W	Motorized Two-wheelers
3W	Motorized Three Wheelers
A_c	Projected area of the vehicle type car
A_i	Projected area of the subject vehicle type ‘i’.
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
C	Capacity
CBD	Central business districts
C_o	Base capacity
CSIR	Central Scientific and Industrial Research
CW	Carriageway width of the road
EEV	Vehicles entering and exiting roadside premises
f_{cw}	Adjustment factor for carriageway width
f_{sf}	Adjustment factor for side friction
H_0	Null hypothesis
HCM	Highway Capacity Manual
HV	Heavy Vehicles
IHCM	Indonesian Highway Capacity Manual
INDO-HCM	Indian Highway Capacity Manual
IRC	Indian Road Congress

k	density
LCV	Light Commercial Vehicle
LOS	Level of Service
MCU	Motor Cycle Unit
MEU	Motorcycle Equivalent Units
MLR	Multiple Linear Regression
MoRTH	Ministry of Road Transport and Highways
N	Number of observations
N_{EE}	Frequency of entry-exit vehicles
N_{WM}	Frequency of wrong movement vehicles
NH	National Highways
Ni	frequency of the parked/stopped vehicle
NMV	Non-Motorized Vehicle
N_P	Frequency of pedestrians
N_{PSPU}	Frequency of pedestrians and stopped/parked vehicles in pedestrian units
PA_i	Projected area of the parked vehicle type
PA_p	Projected area of the pedestrian
PCU	Passenger Car Unit
PCU/hr	Passenger Car Units per hour
PED	Pedestrian flow
PEU	Equivalent pedestrian unit of the parked vehicle type
P_i	Proportional share of the traffic volume for vehicle type i
PIARC	Permanent International Association of Road Congress

PSV	Vehicle stops and parking maneuvers
q	flow
Q	Traffic volume (pcu/hr).
R^2	Coefficient of regression
RFSI	Road Side Friction Index
RMSE	Root Mean Square Error
RW	Relative weights of each activity type
SF	Side friction (Events/hr)
SMV	Slow-moving vehicles
SSR	Speed Spread Ratio
u	speed
V	Average stream speed (km/h),
V/C	Volume –capacity ratio
V_{10}	10th percentile speed
V_{15}	15th percentile speed
V_{85}	85th percentile speed
V_c	Mean speed of the vehicle type car
V_i	Mean speed of the subject vehicle type ‘i’
V_m	Mean stream speed (Km/h)
W	roadway width

Chapter 1

INTRODUCTION

1.1 GENERAL

A road network is considered to be an important structure for the development of the economy of a country. A significant expansion in the road network is taken place over the last two and half decades. The development and maintenance of the road network is undertaken by several bodies including central and state government agencies. The Indian road network has total length of 58, 97,671 km which is second largest after United States of America with 66.45lakh km as on 31.03.2017 (Basic Road Statistics of India, 2016-2017). Based on the length of the road network, the density of the Indian road network is estimated as 1.80km per sq km and it is almost equivalent to the Germany's road network density. As per the reported data on 31.03.2017, the paved or surfaced length of the Indian road network is estimated as 63.24% which is quiet significant number for a developing country (Basic Road Statistics of India, 2016-2017).

Urban roads are having a length of 5, 26,483km which accounts to an amount of 8.93% out of total road network in India. The length of the urban road network is increased from 5, 09,730km as on 31.03.2016 to 5, 26,483km as on 31.03.2017 which accounts to an amount of 3.29%. Also, the share of the urban road network decreased by 9.10% as on 2017 to 8.93% as on 2016 compared to other category of roads. Figure 1.1 shows the expansion of the urban road network length in km from 1960-61 to 2016-17.

1.2. CLASSIFICATION OF URBAN ROADS

An urban road is defined in several ways by various countries. As per Highway Capacity Manual (HCM, 2010), an urban arterial is a road having series of signalized intersections at close intervals and high density access points. As per Indonesian Highway Capacity Manual (IHCM, 1996), an urban arterial is a road having permanent development along all or almost all of its length on at least one side of the road. As per Indian Roads Congress (IRC: 106, 1990), an urban arterial is a road primarily meant for through traffic usually on a continuous route. As per Indian Highway Capacity Manual (Indo-HCM, 2017), Urban road is the one with a relatively high density of driveway access located in an urban area and having traffic signals with a minimum spacing of one kilometer.

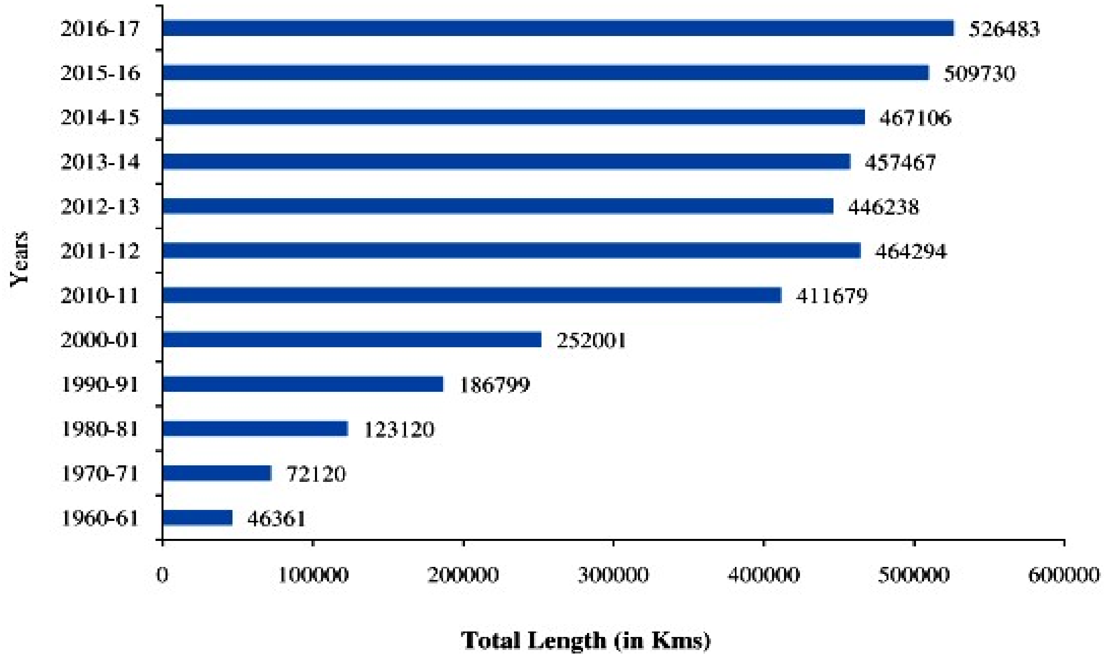


Figure 1.1 Expansion of urban roads in India (Source: MoRTH 2017)

The urban roads in India are classified based on the number of lanes within undivided or divided roadway section. Also they are classified based on the functionality of the roads type in total road network. Undivided urban road is defined as the one which allows the traffic to move on any side of the road without any segregation (median). Depending upon the number of lane available for the traffic flow, they are termed as 2-lane undivided, 4-lane undivided and 6-lane undivided roads. On the other hand, a divided urban road is defined as the road with traffic movements physically segregated by median. Similar to undivided urban roads, divided roads are also classified as 4-lane divided, 6-lane divided and 8-lane divided based on the number of lanes available for the traffic flow.

As per the hierarchy of the urban roads in the total road network, functional classification is made into four main categories of urban roads in India.

- Arterials
- Sub-arterials
- Collector streets
- Local streets

Arterials are the streets which serve as principal network for through movement of the traffic flow. The essential requirement of an urban arterial is continuity to provide efficient movement of the through traffic. Major travel movements take place between central business district and outlaying residential buildings or between major sub-urban centers. Arterial roads are generally divided highways with full or partial access. The spacing of the urban streets is less than 1.5km at highly developed CBD areas and at more than 8km at sparsely developed urban areas. Usually parking activities, loading-unloading activities are not allowed on urban arterials. Also pedestrians are restricted to move on the roadway and allowed to cross at intersections only.

Sub-arterials are primarily meant for through traffic on a continuous route with somewhat lower levels of travel mobility compared to arterial streets. The spacing of sub arterials is generally 0.5km in CBD areas and about 3 to 5 km in sub urban fringes. Collector streets collect and distribute traffic from local streets to arterial streets and vice-versa. And they also provide access to arterial streets. Full accessibility is allowed on these streets with fewer restrictions in parking activity. Local streets primarily meant for access to residential areas, business or any other abutting properties. These streets allow parking activities and pedestrian movements with no restrictions. These streets do not carry higher volumes of traffic in general.

1.3. MIXED TRAFFIC CONDITIONS

Indian traffic behavior is highly heterogeneous in nature as it consists of more than ten vehicle categories such as car, motorized two wheelers, motorized three wheelers, bus, light commercial vehicles, non-motorized vehicles etc. All these vehicles have their own static and dynamic characteristics, and make use of the available road width without any physical segregation. These vehicle categories contribute to different proportions in the traffic stream results in more heterogenic nature which affects the capacity of the roadway adversely. Some vehicle categories such as non motorized vehicles move at lower speeds and some vehicles such as passenger car move at higher speeds. The speed differences between the varieties of vehicles tend to interrupt flow of the vehicles and affect the traffic performance. The seepage behavior of vehicles i.e. smaller size vehicles such as two wheelers tend to occupy the vacant spaces available between the bigger size vehicles creating worst operating conditions. Non-lane discipline nature is another factor to be considered which affect the traffic performance. Because of the non-lane discipline nature, capacity is expressed for overall roadway width rather than lane basis as considered for homogeneous lane based system. In addition to the mixed traffic, interference of the road side activities with the ongoing traffic flow causes turbulence in the traffic stream results in deteriorated service quality performance of the roads. When all these aspects are in combination, it creates more number of problems to traffic engineers in analysing the mixed traffic conditions. It is impractical to estimate the capacity of the roadways using the methodological approaches suggested under homogeneous conditions as they cannot be apllied for the mixed traffic conditions such as India.

1.4. CAPACITY OF URBAN ROADS

As per Indo-HCM (2017), capacity is defined as "It is the maximum number of vehicle per unit of time that can be handled by a particular roadway component under the prevailing roadway and traffic conditions". There are several factors that influence the capacity of urban roads including geometrical factors, traffic factors and environmental factors. Geometrical factors include width of the lane, width of the shoulder, number of lanes, existence of intersections, alignment etc. When the width of the lane is not sufficient, it forces the vehicles to move closer laterally which affects the speed as well as capacity of the roads. And the use of shoulder width by any activity such as on-street parking results in reduction in capacity of the urban roads. Environmental factors refer to the weather conditions such as presence of rain, fog, mist etc. these factors influence the visibility on the roads resulting in reduction in the capacity of roadways. Traffic factors include the type of traffic conditions whether it is uniform or mixed, driver and vehicular characteristics, road-side friction activities. The mixed traffic conditions reduce the capacity to a greater extent due to the varied proportions of the vehicle types such as heavy vehicles, non-mortised vehicles resulting reduction in the stream speed. The size of a vehicle also plays important role in affecting the capacity as large sized vehicles occupy more space on the roadway that cause congestion and lead to reduction in capacity. Side friction occurs for a short duration but results in high encroachment by occupying portion of the roadway width. The interaction of these activities with the ongoing vehicular stream affects the traffic flow behavior, reduces the actual capacity and causes congestion on a part of urban roads.

1.5. PROBLEM STATEMENT

Substantial increase in the length of road networks and vehicle ownership demanding high traffic volume to be served that resulting in recurrent and non-recurrent congestions on urban roads. The urban arterials need more attention in understanding, analysing the traffic flow behavior as capacity of such roads are decreasing significantly due to several factors prevail under heterogeneous traffic conditions. The methods those are considered for estimating capacity under homogeneous conditions cannot be applied for the Indian conditions in its present form as many additional factors involve while dealing heterogeneous traffic volume. Side friction has a great impact on the performance of traffic which got lesser attention for analysing the traffic stream models. Most of the studies indicated the importance of side friction for analysing the capacity of the urban roads even under homogeneous traffic conditions. IRC: 106-1990 has suggested capacity values of urban roads for Indian conditions and recognised the importance of significant side friction factor such as on-street parking. However, it does not suggest clear methodology to incorporate these factors for estimating capacity. Also Indo-HCM (2017) has given the procedure to estimate the capacity of urban roads by incorporating adjustment factors for side friction and access points. However, it has given adjustment factors for on-street parking movements and bus-stops. The influence of pedestrians which is dominating in the Indian traffic conditions is not considered. Therefore, a proper methodology is needed that incorporate the side friction to quantify actual capacity.

1.6. OBJECTIVES & SCOPE OF THE STUDY

The primary objective of the present research work is to analyse the capacity of the 4-lane and 6-lane urban mid-block road sections under the influence of road side friction. The principle objectives of the research are presented in this section.

- To study the variation of stream speed with side friction and develop speed prediction model by quantifying the side friction on urban roads.
- To determine dynamic passenger car units of different vehicle types for multi-lane divided urban roads and study the variation of PCUs with roadway and traffic parameters.
- To develop capacity model for urban roads by incorporating side friction as one of the major influencing factors.

The present study has been focused on estimation of capacity of multi-lane divided urban arterial roads having level terrain with straight alignment under mixed traffic conditions. Field data collected on 4-lane and 6-lane divided urban mid-block sections is used to analyse the traffic flow behavior and to estimate the capacity of the study sections. Also, the field data is used to quantify the side friction events and classify into various levels. A regression model is developed to predict the stream speed using side friction and volume which is useful for traffic engineers as it avoids tedious data extraction process. For studying the variation of PCU of vehicle types, a soft computing tool ANFIS is used in the present study for achieving the better accuracy in estimates. Finally, an equation is proposed to estimate the capacity of the urban roads with derived adjustment factors for side friction.

1.7. OUTLINE OF THE THESIS

Chapter1 presents an overview of statistics of the road network and its growth in India over past years. And it covers the classification of urban roads and the problems of mixed traffic in Indian conditions. It includes a brief introduction to capacity of urban roads and factors affecting it. The need for research, objectives and scope of the research are also presented in this chapter.

Chapter 2 covers the review of studies done on various topics such as capacity of urban roads, stream speed and PCU of vehicle types under homogeneous and heterogeneous traffic conditions.

Chapter 3 explains the detailed research methodology adopted for the present study with the help of flow chart.

Chapter 4 presents the locations for field survey and their characteristics. Also, field data collection, method of data extraction such as speed data, volume data and side friction data from the video recordings is discussed.

Chapter 5 deals with the analysis of the data collected on the study sections such as speed analysis, estimation of traffic volume and analysis of roadway side friction. Also the conversion of traffic volume to PCU is explained in this chapter.

Chapter 6 presents a detailed approach to quantify the side friction on urban roads. It also deals with the classification of side friction into various levels based on the relationship between stream speed and side friction. A speed prediction model is proposed in this chapter to estimate the stream speed under the influence of side friction and traffic volume.

Chapter 7 deals with the estimation and analysis of PCU values for different vehicle categories using field data. The analysis of variation of PCU of vehicle types with different roadway and traffic characteristics such as traffic volume, side friction, proportional share and roadway width is discussed in this chapter. Further, development of MLR models and ANFIS models to estimate PCU of vehicle types are discussed.

Chapter 8 presents the development of speed-flow relationship which is used for the estimation of capacity for both 4-lane and 6-lane divided urban roads. The influence of side friction and roadway width on capacity is analysed in this chapter. Finally, the development of capacity model using adjustment factors based on side friction and roadway parameter is discussed.

Chapter 9 includes major conclusions and significant contributions of the research work. Limitations of the study and scope for future research are also highlighted.

Chapter 2

LITERATURE REVIEW

2.1. GENERAL

Many studies in the past are dawning attention towards understanding of the traffic flow behavior and capacity of roadway. Different methodologies to estimate the capacity of roadways in the past developed for various traffic conditions such as homogeneous and heterogeneous traffic are discussed. Studies related to the influence of side friction on traffic flow characteristics are reviewed in detailed manner. The studies performed on PCUs of vehicle types to find capacity and level of service under mixed traffic conditions are covered in the detailed manner.

2.2. STUDIES ON CAPACITY OF URBAN ROADS

There are several methods available in the literature to estimate the capacity of urban roads. Few of them are direct empirical methods and few of them are indirect methods. The direct empirical methods are estimated based on headways, traffic volume, speed and density etc. The indirect empirical methods are estimated based on the values/procedures suggested by capacity manuals such as IRC (106:1990), HCM (2010) and based on simulation techniques. Some of them are discussed in this section including uniformed and mixed traffic conditions. It has been found that common factors such as geometry, traffic flow and environment are found to be influencing on capacity of urban roads. The study also found many evidences that any type of side friction on the roads is another factor for distracting driving behavior and influencing capacity of roads especially under mixed traffic conditions. The following sections present the review of adequate number of previous studies related to present study.

2.2.1. UNDER HOMOGENEOUS TRAFFIC CONDITIONS

The traffic flow studies were carried out even before the first study which is available in the literature openly accessible in the web. One of the pioneering studies performed by Greenshields (1934) who analysed the relationship between fundamental traffic parameters namely traffic flow, speed and density using the field data. A linear relationship was fitted between stream speed and traffic density and suggested a polynomial fit curve between stream speed and traffic flow. The maximum flow, free flow speed and jamming density of the given roadway are suggested based on relations established between variables. Figure 2.1 shows the relationship suggested between traffic volume, speed and density.

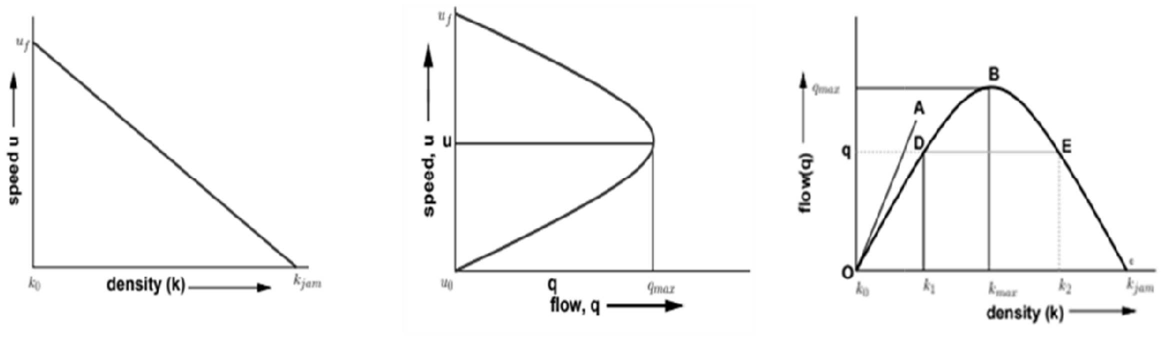


Figure 2.1 Relationship between fundamental parameters speed (u), flow (q) and density (k)

The fundamental traffic flow diagrams suggested in Figure 2.1 provides maximum traffic flow at optimal density and critical speed level. The study concluded that the capacity of the roadway depends on the intercept and slope of the fitted curve between speed and flow data. The speed-flow diagram developed with corresponding density values is depicted in Figure 2.2.

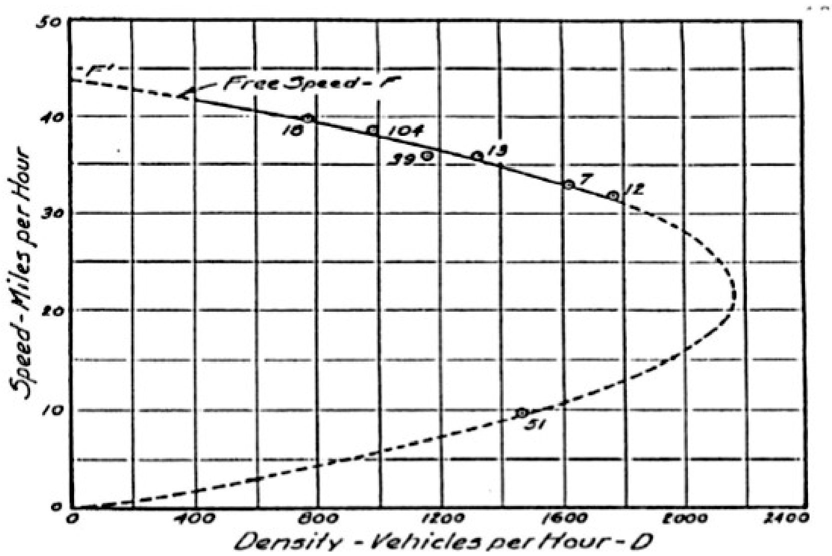


Figure 2.2 Fundamental speed-flow diagram (Greenshields, 1934)

With advancements in the methods of evolution, several studies (Greenberg 1959; Underwood 1960; Edie 1961; Ceder and May 1976; Persaud and Hurdle 1988; McShane and Roess 1990; Nielsen and Jørgensen, 2008) are performed around the world which attempted to define relationship between speed and traffic flow. Hoban (1987) stated that the simple linear relationship between speed and volume data can be used to represent behavior of stream on rural highways under uniformed traffic conditions. The study opined that the capacity of a roadway depends upon the intercept and slope of the straight line fitting between speed and volume data. Many of the studies have come out in multi-regime models as the single regime curve failed to predict the traffic flow behavior with the change in traffic conditions. Hall et al. (1992) developed a three-regime model based on the traffic flow and speed data collected from a freeway segment in USA. The model is divided in three regimes as uncongested segment, queue discharge segment and within a queue segment. In the first segment, speed does not change up to one third of the flow and later it starts decreasing in more or less linear pattern. In the second segment, the speed drops over a certain flow level which is called as maximum flow and in the third segment the speed drastically reduced due to the delay caused by the queuing. Figure 2.3 shows all three regimes in speed-flow relationship.

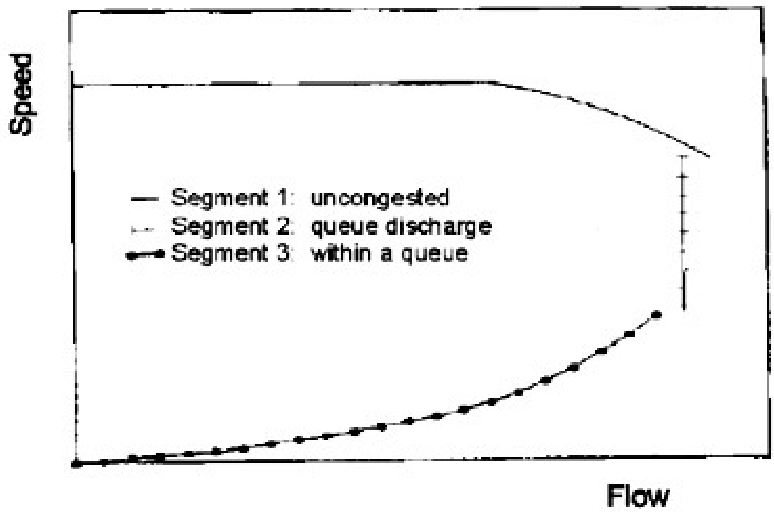


Figure 2.3 Speed-flow diagram based on three regimes (Hall et al. (1992))

Aerde (1995) proposed a single regime model for developing speed-flow-density relationships. The model was calibrated for freeways and urban arterial roads at microscopic and macroscopic levels of analysis. The proposed model overcomes the drawback of Greenshields model which does not always fit data under different roadway and traffic conditions. Figure 2.4 shows the speed flow diagram developed for an urban arterial in Toronto.

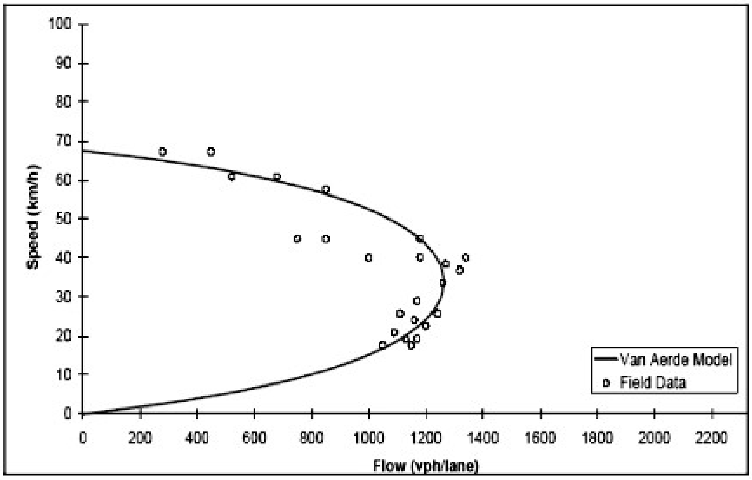


Figure 2.4 Speed-flow curve with the field data for urban road (Aerde, 1995)

HCM (2010) provides the relationship between speed and flow for urban arterials considering junctions with signals in one kilometer length of the roadway. Figure 2.5 shows the speed-flow relationship according to HCM (2010).

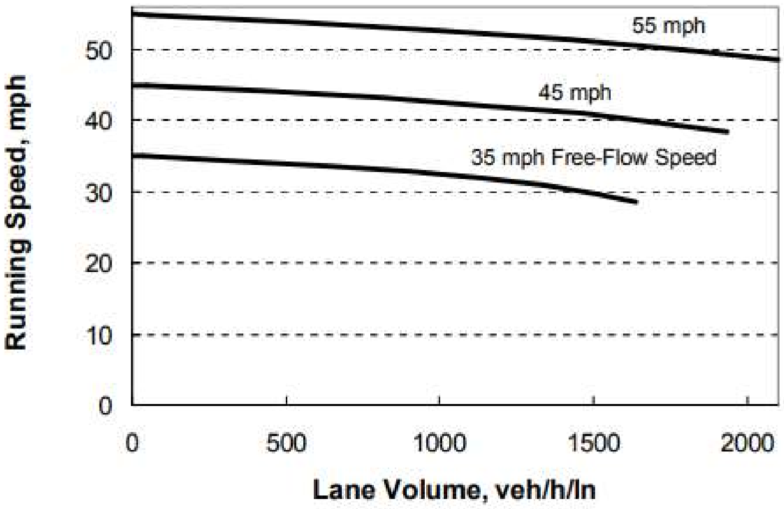


Figure 2.5 Speed-flow relationship for urban street segment (HCM, 2010)

In Figure 2.5, the average speed of the vehicles showed consistently decreasing trend from lower to higher flow levels, which states the larger variation in the speed of the vehicles. Brilon and Geistefeldt (2006) developed the random capacity concept for freeways. The authors proposed the methodology to estimate roadway capacity for freeways based on statistics of the life time data analysis. The study used "product limit theorem" to explain more reliable capacity than the methods available in literature. The study stated that the estimated capacity values of the freeways are following Wiebull distribution. The outcomes in the study are compared with the previous studies performed under both interrupted and uninterrupted traffic conditions.

Aerde and Raka (2006) developed speed-flow relationship between fundamental traffic flow parameters on freeway segments in Netherland. A model was fitted using field data by normalizing the least squared error between predicted and observed traffic stream data to find optimum capacity. Figure 2.6 shows speed-flow curve of freeways in Netherland.

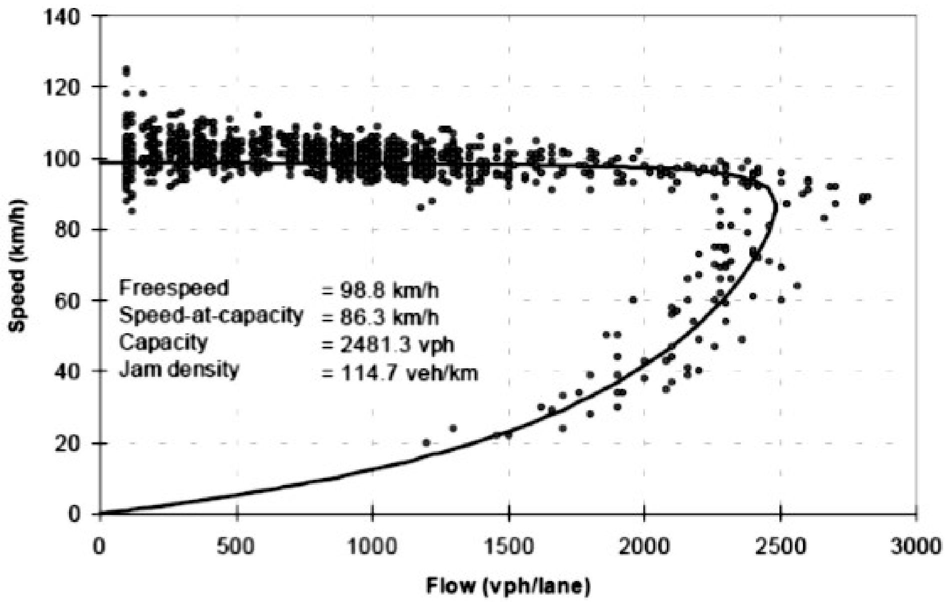


Figure 2.6 Speed-flow curve for freeway segment (Aerde and Raka, 2006)

Mathew et al. (2010) analysed speed data collected at ten different sites for estimating free-flow speed based on posted speed limit sign. Five urban arterials, two freeways and three rural highways are considered for data collection. The study finds that freeways have higher stream speed compared to urban arterials and highways under base traffic conditions.

Sinha et al. (2012) estimated the capacity of four lane urban roads in Thailand using speed-flow relationship. Six different roadway sections are considered for the data collection and estimated static PCU values for different vehicle types as observed in Thailand (OTP, 2009). Capacity of sections determined in the study is based on speed-flow relationship. The study found that the increase in percentage of motorcycles increases the capacity of selected road sections.

2.2.2. HETEROGENEOUS TRAFFIC CONDITIONS

Sarna et al. (1989) estimated capacity of urban arterial using field data collected from 24 locations of both divided and undivided roads in Delhi and Mumbai cities. The fundamental speed-flow relationship was used to determine capacity values. The capacity value for the sections selected in Mumbai city is reported as 930PCU/hr/lane for 2-lane, 1450PCU/hr/lane for4-lane and 1950PCU/hr/lane, for 6-lane roads. The capacity values of roads in Delhi city are reported as 880pcu/hr/lane, 950pcu/hr/lane and 114300pcu/hr/lane for 2-lane, 4-lane and 6-lane roads respectively.

IRC (106:1990) suggests design service volumes all categories of urban roads such as arterials, sub-arterials and collector streets. The guideline suggests, LOS C should be maintained on urban roads for better throughput and capacity. At LOS C, traffic volume is equal to 0.70 times the capacity which is known as design service volume. Table 2.1 shows the design service volumes by IRC for different categories of urban roads.

Table 2.1 Design service volume recommended for urban roads

Type of carriageway	Total design service volume		
	Arterial	Sub-arterial	Collector

2-lane (one-way)	2400	1900	1400
2-lane (Two-way)	1500	1200	900
3-lane (one-way)	3600	2900	2200
4-lane undivided (Two-way)	3000	2400	1800
4-lane divided (Two-way)	3600	2900	----
6-lane undivided (Two-way)	4800	3800	----
6-lane divided (Two-way)	5400	4300	----
6-lane divided (Two-way)	7200	----	----

Chandra et al. (1995) estimated capacity of urban mid-block sections in Delhi using field data. The study used enveloping techniques to develop speed-flow relationship suggested by Sarna et al. (1989). Design service volume is suggested as 890pcuhr/lane and 780pcu/hr/lane for divided roads and undivided roads respectively considering no parking zones and no pedestrian cross traffic conditions. Further, Chandra and Sinha (2001) studied effects of directional split on capacity of two lane roads. The capacity values found to be reduced significantly when the directional split are used greater than 50/50. Study reported that the capacity value decreases with increase in the proportion of slow moving vehicles present in the traffic stream.

Chandra and Kumar (2003) analysed the influence of roadway width on capacity under mixed traffic conditions. Field data collected data on ten different two lane road sections in Indian states varying the width from 5.5 to 8.8m. The authors used the dynamic PCU method (Chandra and Sikdar 2000) and estimated the PCU values of different vehicle types. A relationship between PCUs and roadway width is analysed and proposed equations to estimate the PCU of vehicle types considering average speed of vehicle types. It is observed that PCU of vehicle types increases with the increase in roadway width irrespective of the size of vehicle types. Study proposed speed-flow relationship and estimated capacity using Greenshields model. The estimated capacity value for a roadway with 7.2m width is reported as 2818pcu/hr. A relationship established between capacity and carriageway width finds a significant change in capacity due to change in carriageway width. The study also proposed capacity adjustment factors for lane width for different roads. The study concluded that the provisions of additional 0.3% lane width leads to 14% increment in capacity and 0.6% lane width leads to 24% increment in capacity.

Chandra and Prasad (2006) estimated the capacity of multilane divided urban roads in India. The capacity values obtained from the field found to be quite higher (within the range of 2800-3000pcu/hr/lane) when compared to Korean Highway Capacity Manual and Indonesian Capacity Manual values. This is due to the presence of higher proportions of two wheelers in traffic composition. For every 10% increment in proportion of two-wheelers resulted in 9% increment in capacity of the urban roads. Arasan and Krishnamurthy (2008) estimated the capacity of four lane urban roads in India using simulation approach. Field data collected on four lane urban roads was used as inputs for the simulation runs. The simulation model 'Heterosim' was used for simulating all cars traffic conditions and determined the capacity as 3250pcu/hr for a width of 7.5m simulated section.

Patel and Joshi (2012) studied capacity and LOS of the urban arterials under mixed traffic conditions. Field data was collected on six-lane urban arterial road in Surat city, India. The study established speed-volume relationship using field data. To obtain unobserved data for determining capacity, artificial neural network (ANN) technique was used for completing speed volume curve. The speed-flow curve was divided into four regimes based on the traffic conditions two in free-flow and two in congested flow conditions. Different equations are proposed for each regime based on the relationship between speed and volume. Capacity estimated for the section based on the multi-regime modeling concept is 2480 vehicles per lane in one direction of travel. Further, LOS has been studied for the existing multi-regime capacity curve based on V/C ratio as threshold value. The division of LOS into different levels are done using K-means algorithm and is classified into 6 different LOS categories from A to F.

Dhamaniya and Chandra (2013) analysed the speed characteristics of mixed traffic flow conditions on urban arterial roads. Different sections of four and six lane sections of in three metropolitan cities are considered for data collection. The analysis of speed distribution was carried out for individual vehicle type and for mixed traffic stream by establishing speed profiles. It is found that the speed data is following normal distribution in case of individual vehicle types but failed to fit for the mixed traffic. Therefore, authors estimated Speed Spread

Ratio (SSR) to know the distribution of the speed data. The authors stated that speed data follows normal distribution when the proposed SSR value is equal to one and suggests a range of 0.86-1.11 on six lane roads for the speed data to follow normal distribution.

Dhamaniya and Chandra (2013) proposed equations for predicting the speed of different vehicle categories on urban arterials under mixed traffic conditions. The simultaneous equations are proposed in the study to preidct the speed of different vehicle categories. The influence of traffic volume and composition on speed was analysed and found that the reduction in the speed is less for smaller size vehicles in compared to bigger size vehicles as traffic volume increases. And the speed of heavy vehciles (HV) and car are reducing with the increase in their own proportion at higher volume levels. However, no significant reduction is observed at lower volume levels.

Suresh and Umadevi (2014) estimated the capacity of urban mid-block sections on four-lane divided sections (two lanes on either side) using empirical methods. Field data is collected on ten different study sections in Chennai is extracted from the recorded video. Time headway, volume and speed of the vehicles are used to estimate the capacity by different methods. In this study three direct empirical methods are used such as headway method, selected maxima method and fundamental diagram method to estimate the capacity. The average headway estimated from distribution analysis is used for determining capacity study sections. Later, the capacity was normalized for 7m carriageway width and used PCU values of vehicle types suggested by IRC (106:1990) for converting traffic flow in pcu/hr. Also, the capacity is estimated from the fundamental diagram method at each study section using the envelope curve developed over the speed-flow relationship. The average capacity values estimated based on headway, maxima method and fundamental diagram are 5649, 5336 and 5416pcu/hr respectively. It is concluded that the capacity values obtained from the three methods are higher than the values mentioned by IRC values.

Gajjar and Das (2016) estimated capacity of urban roads in Mumbai city using data collected on urban arterials, sub-arterials and collector roads. PCU values based on the traffic composition suggested by IRC (106:1990) were used for estimating capacity values. Study suggested LOS for each study section based on V/C ratio estimated in the analysis. It is observed that the observed capacity values are higher than the IRC capacity values with a variation of 5-70%.

Biswas et al. (2017) developed speed-prediction model using artificial neural network approach on urban roads under mixed traffic conditions.Field data was collected on six lane divided mid block road sections in New Delhi, India. Speed model was developed using ANN approach by taking traffic volume as input variable and speed as output variable in the absence of side friction elements. The predicted speed values are compared with the existing models such as volume based regression model and density based regression model. It is concluded that the proposed volume based ANN model is performing well for each vehicle category.

Dhamaniya and Chandra (2017)studied the influence of operating speed on capacity of urban mid-block sections. Field data was collected on 12 road sections including six-lane and four-lane divided roads. Speed-flow relationship was established from the Greenshield's model, and capacity values suggested in a range 1482 to 2043 pcu/hr/lane for four-lane roads and 1500 to 2105 pcu/hr/lane for six-lane roads. Further, relationship between lane capacity and operating speed is established. second degree polynomial equation was suggested to estimate the lane capacity based on operating speed. The model is succesfully validated with two more study sections as difference between predicted and observed capacity values is found less than 1 percent. Figure 2.7 shows the variation of lane capacity with operating speed .

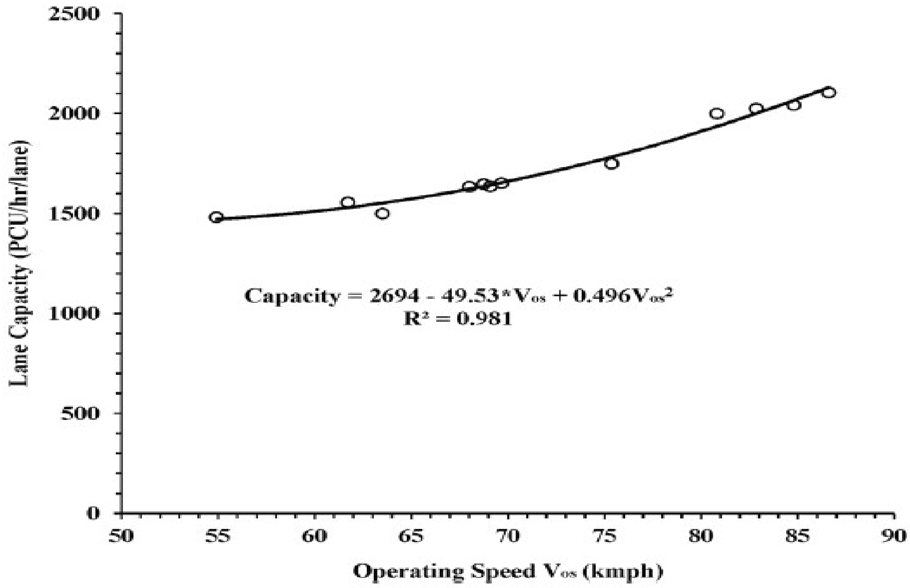


Figure 2.7 Relationship between lane capacity and operating speed

2.3. STUDIES ON SIDE FRICTION

Bang (1995) studied the influence of side friction on speed-flow relationship on rural and roadways in Indonesia. The study estimated relative weights using regression anaylsis by taking space mean speed as dependent variable and side friction parametrs as independent parametrs. The results obtained from the study were included in the development of Indonesian Highway Capacity Manual (IHCM, 1997). It was found that the capacity value reduced with increase in side friction level. Also, geometric design and pavement maintenance management considered as influencing factors for increasing side friction and there by resulted in reduction in speed and capacity of roadways. Table 2.2 shows the weighing factors assigned to various friction elements by the IHCM, (1995) for the urban roads and interurban roads

Table 2.2 Relative weights for different friction elements (IHCM, 1995)

Event type	Code	Relative weight	
		Urban roads	Interurban roads

Pedestrian flow (walking ped/h + crossing ped/h, 200m)	PED	0.5	0.6
Vehicle stops and parking maneuvers (events/h,200m)	PSV	1.0	0.8
Vehicles entering and exiting roadside premises (veh/h,200m)	EEV	0.7	1.0
Slow-moving vehicles (veh/h)	SMV	0.4	0.4

Bang and Heshen (2000) developed a methodology to estimate capacity of roadsand intersections in China. Field data was collected on 144 inter urban and township road links to estimate PCU values, and free flow speeds. The data is used for developing speed-flow-density relationships for all roads. Equation 2.1 shows the relation for estimating the capacity.

$$C = C_O * FC_{CW} * Fc_{SP} * FC_{SF} \quad (2.1)$$

where, C is the capacity (pcu/hr), C_o is the base capacity (pcu/hr), FC_{CW} is the adjustment factor for carriageway width, $FC_{SP}$is the adjustment factor for directional split and FC_{SF} is the adjustment factor for side friction.

Koshy and Arasan (2005) analysed the influence of bus stops on traffic flow characteristics under mixed traffic conditions. For this, the suitability of the traffic flow simulation model, HETEROSIM (Arasan and Koshy 2005) is deployed for simulating mixed traffic conditions forexamining the influence of curb-side bus-stops and bus-bays on traffic flow characteristics. Further, influence of location of bus stops on the reduction of speed of the different vehicle types is analysed under various traffic and roadway conditions. The influence of dwell time on speed of the traffic on 7.5m wide road is analysed under various traffic flow levels at curb-side bus-stop and bus-bay locations. It is found that up to 2000vph the influence of dwell time 10s, 20s and 30s are same for bus bays and dwell time 10s and 20s are same for curb side bus stops. Figure 2.8 shows the variation of speed with volume at different bus-stop locations at 20s dwell time. It is concluded that there is 25% speed reduction occurred with curb side bus-stop at traffic volume as 2400vph with 20s dwell time which can be used as a threshold value for the replacement of curb side bus-stop with bus bays on urban roads.

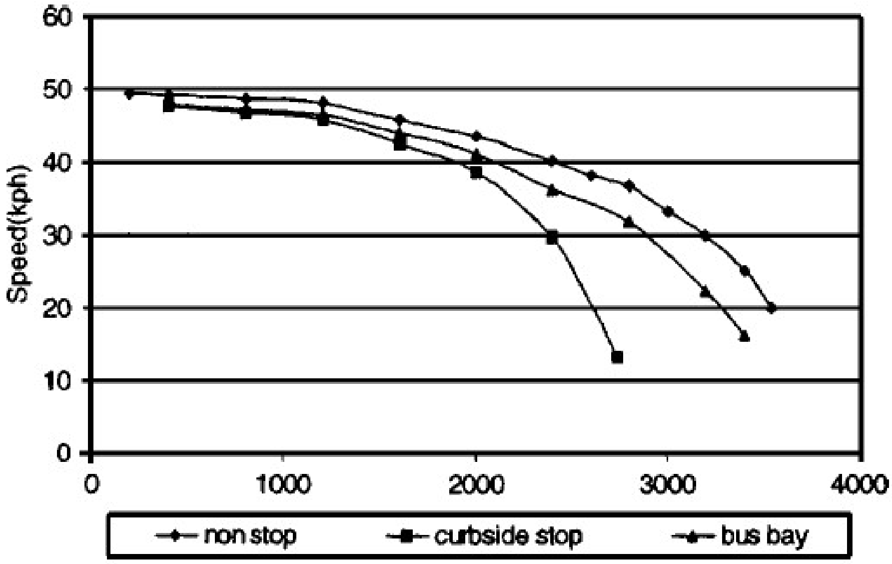


Figure 2.8 Variation of speed with volume at different bus-stop conditions at 20s dwell time

Chiguma (2007) examined the impact of side friction on traffic performance of urban arterials in Indonesia. Macroscopic and microscopic analysis was performed by the author and analysed the effect of side friction on traffic flow performance. The study estimates weighing factors for different side friction activities through regression analysis. A term 'FRIC' was introduced which a unit of measure of side friction. FRIC was estimated based on the combined weighted side friction factors. The influence of individual side friction parameter on speed was studied and concluded that the side friction factors are significantly affecting the speed on two lane two way roads.

Munawar (2011) analysed the effect of side friction activities on speed and capacity on Indonesian roads and compared the results from IHCM (1997) capacity standards. A multiple regression model is developed to estimate the speed and capacity of the roads. Side friction factors such as pedestrian movement, on-street parking, number of heavy vehicles, entry-exit vehicles, and stopped vehicles were considered as independent parameters. The study concluded that at higher level of side friction, a significant reduction in the stream speed was observed. Also, parked/stopped vehicles and pedestrian movements have observed significantly to influence the speed and capacity of the roads.

Chand et al. (2014) estimated the capacity drop on urban arterials due to the presence of curb-side bus stops. Field data was collected on seven sections of 6-lane-divided urban arterial roads in New Delhi. The study was performed with roadway sections including with and without any bus-stop locations. From the field data, speed-flow relationship was developed and capacity was estimated for both of the cases. The capacity estimated for the base condition i.e. without any side friction was 6314pcu/hr. The reduction in the base capacity was observed as 8 to 13% when compared to the capacity of the sections with bus stops. Also, it was observed the reduction in the capacity of sections with curb side bus stops is more in compared to the bus stops with bus bay conditions.

Pal and Roy (2016) studied the influence of side friction on travel speed and LOS on rural highways in India. The study demonstrated a methodology to quantify road side friction based on the projected area of the vehicles present on the roadway and position of side friction elements present on it. The roadway is divided into three parts and each consisting of two parts with 1.0m as edge strip and one part in the middle strip. Based on the position of presence of side friction element weight factors were calculated in each strip. A new term RSFI is introduced known as Road Side Friction Index which combined the weight factors for all types of side friction on all the strips. The impact of side friction elements on travel speed was examined by developing speed-flow curves at different side friction levels was estimated. It was found that 50% reduction in the operational speed was observed with side friction. Figure 2.9 shows the partitions on the roadway for the analysis of side friction

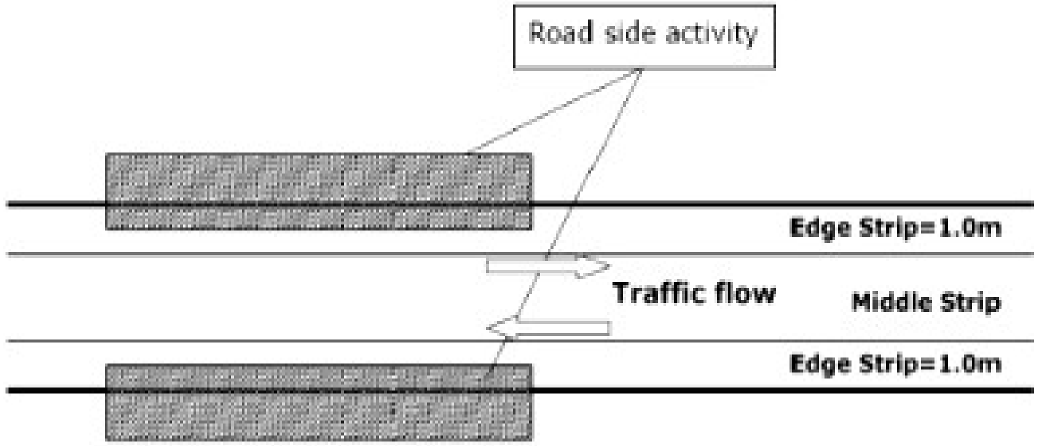


Figure 2.9 Details of strips marked on the roadway

Salini et al. (2016) analysed the influence of side friction on the traffic characteristics on urban roads in India. The side friction factors considered for the study are number of buses stopping at bus stops, pedestrian movement along and across the roadway and on-street parking. Speed-prediction models were developed through multiple regression analysis for both individual and combined side friction parameters. It was observed that reduction in the speed was observed at sections having at least on side friction parameter. It was found that an amount of 50% reduction in the average speed is observed at volume more than 3000 PCU/hr.

Rao et al. (2017) evaluated the influence of road side friction activities on the capacity of the urban roads in Delhi. In this study, a total of 12 sections are considered for the data collection including 2 sections with ideal roadway characteristics, 2 sections with bus-bays, 3 sections with curb-side bus stops and 5 sections with on-street parking facilities. The influence of bus stops and bus bays on stream speed is analysed and 49-57% reduction in stream speed is observed. Also, 45-67% reduction in the average stream speed is observed due to the on-street parking facility. The variation of capacities at all the study sections is analysed by using IRC PCU values (IRC: 106-1990) and Dynamic PCU method. It is found that there is 10-53% reduction in capacity has been observed due to bus-bays and bus stops using both types of PCU methods. Also 28-63% reduction in capacity was observed due to on-street parking facility.

Salini and Ashalatha (2020) analysed the influence of side friction on traffic charactrestics of urban arterial roads in India. The side friction factors considered for the study are number of buses stopping at bus stops, pedestrian movement along and across the roadway and on-street parking. The influence of side friction was analysed and side friction parameters were classified into five groups such as very low, low, medium, high and very high based on the average speeds at different levels of service. The reduction in the speed was observed about 34% when all combination of side friction factors present at the study section. The capacity for ideal section was estimated using speed-flow curve as 3068pcu/hr. The amount of reduction was observed in the capacity values are 11-22%, 14-30% and 18-26% where bus–stops, pedestrainas and combined side frction are present on the study sections. Figure 2.10 shows the comparison of the speed-flow diagram of ideal section with section having bus stop.

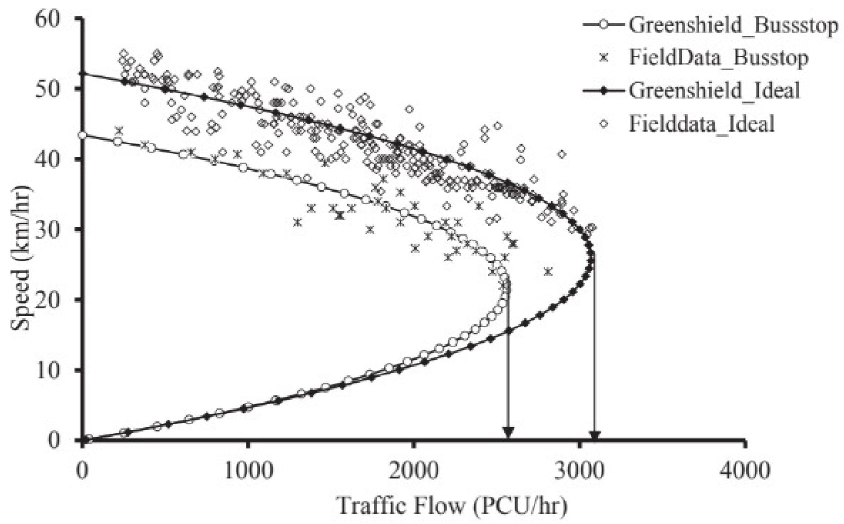


Figure 2.10 Comparison of speed-flow diagram of sections with and without side friction

Pal and Roy (2019)studied the impact os side friction on traffic performance onhighways. The study mainly focused on the analysis of the side friction on stream speed, capacity and levels of service. By using the V/C ratio and percentage speed reduction, authors recommended five threshold limits for level of service. Golakiya et al. (2019) analysed the impact of pedestrian crossing on capacity at urban mid block sections. Author compared the capacities with and without pedestrian cross flow at 22 urban mid block sections and stated that there is no reduction found in the capacity when the pedestrian flow is upto 220 pph and 32% reduction is foundwhen the flow 1,550 pph.

2.4. STUDIES ON ESTIMATION OF PCU

It is believed that the vehicular, roadway and environmental factors are significantly affecting the PCUs of vehicle types under both uniformed and mixed traffic conditions. There are several methods available in the past studies estimating PCU values on various highways and urban roads sections i.e. headway method, homogeneous coefficient method (Permanent International Association of Road Congress (PIARC)), walker's method (Werner and Morall, 1976), multiple linear regression method (Aerde and Yagar, 1984), simultaneous equation method (Himes and Donnell 2010, Dhamaniya and Chandra, 2016), Huber method (Huber, 1982) and speed based method (Biswas, 2020) etc. These methods are proposed by collecting field data on various highways and urban roads using single or combination of parameters such as flow rate (Huber 1982), density (Tiwari et al. 2000), headway (Saha et al. 2009), volume to capacity ratio (Fan 1990), average speed (Aerde and Yagar 1984; and Chandra et al. 1995), delay (Cunagin and Messer, 1983), size of vehicle types (Tanaboriboon and Aryal 1990), etc. Also, recent studies have proposed PCU estimation methods based on area occupancy (Kumar et al. 2017), time occupancy (Mohan and Chandra 2018), level of service (Mehar et al. 2014), effective area (Pooja et al. 2018), directional split (Aggarwal 2011). Few of the studies that are carried out on homogeneous and heterogeneous traffic conditions are explained here.

2.4.1. HOMOGENEOUS TRAFFIC CONDITIONS

Huber (1982) used the average travel time measure to estimate PCU of vehicle types under free flow conditions on multilane highways. The study compared the PCU values of two different traffic streams such as a stream with trucks on one stream and with passenger cars only. It is found that the influence of slow moving vehicles have negligible effect at lower levels of traffic volume. However, increase in the volume levels increases interaction between the vehicles that results in increase in the PCU values of vehicles types such as truck. Equation (2.2) shows the estimation of PCU by Huber.

$$PCU = \left(\frac{1}{P}\right)\left[\frac{q_b}{q_m} - 1\right]+1 \quad (2.2)$$

where, PCU is the passenger car unit, P is the proportion of trucks, q_b and q_m are the flow rates of base and mixed traffic conditions at common LOS.

Aerde and Yager (1984) estimated PCU values of vehicle types based on relative speed of speed reduction for two lane highways. The study developed a methodology which involved multiple linear regression analysis to estimate the free speed of vehicle types and their corresponding speed reduction coefficients. The PCU of vehicle type is determined by calculating the ratio of coefficients of the subject vehicle types to the passenger car. Krammes and Crowley (1986) used field data to estimate PCU value of trucks on urban freeways. PCUs were determined based on three approaches namely V/C ratio, equal density, and spatial headway. As the truck's physical size is larger than size of passenger cars, their impact is more on the nearby vehicles which leads to significance of position of trucks in the traffic stream. Therefore, actual position based on the headway analysis is an important parameter in estimating the PCU value which is carried out by the spatial headway approach. The authors compared the three methods and concluded that the spatial headway approach as the most appropriate approach in case of urban freeway.

Tanaboriboon and Aryal (1990) estimated PCE factors based on the time headway observed between medium and large sized vehicles in Thailand. The study categorized size of the vehicles into small, medium and large and used reciprocal of time headway to estimate capacity value. It was observed that the medium sized vehicles did not influence the roadway capacity significantly. Finally, study concluded that the presence of large sized (trucks and buses) vehicles in large amount leads to increase in the headways between the other vehicles following it in the traffic stream causing a reduction in their PCU values.

Fan (1990) estimated PCU of vehicle types using multiple linear regression technique for Singapore expressway. Traffic volume and speed data were collected from field using video recording method. The traffic volume is collected for 15 minute interval when v/c ratio is more than 0.7 only. The traffic flow rate was taken as independent variable in the regression equation. The PCU value of motor cycles was obtained as 0.4 which is lesser than 0.75 formerly used in Britain. And, the PCU values of light trucks, heavy trucks and buses were obtained as 1.3, 2.6 and 2.7 respectively those are found to be more than the values used in the countries US and Europe. The study concluded that the smaller size vehicles have lesser effect on the traffic in compared to bigger size vehicles.

Al-Kaisy et al. (2005) estimated PCU values of heavy vehicle type on both freeways and highways during the congestion. The study used both empirical data and simulation data generated by INTEGRATION tool for the estimation of PCU values. PCU values were analysed with different grades of the terrain during congestion. It is concluded that the PCU values were showing increasing trend with increase in magnitude of the grade percentage and length. Also, the PCU values were showing decreasing trend with increase in proportion of heavy vehicles in the traffic stream.

Rahman and Nakumara (2005) proposed an equation to estimate PCU of non-motorized vehicles based on the speed data collected on urban mid-block sections in Dhaka city of Bangladesh. The study estimated speed ratio of the passenger cars to non-motorized vehicles under base and mixed traffic flow conditions. It is found that the average speed of the passenger car reduced significantly due to the presence of rickshaws in mixed traffic conditions. Equation (2.3) shows the expression to estimate PCU values of non motorized vehicles.

$$PCU_{NM} = 1 + \frac{S_b - S_m}{S_b} \qquad (2.3)$$

where, PCU_{NMV} is the PCU of non-motorised vehicles, S_b is the average speed of passenger cars in base traffic flow conditions and S_m is the average speed of passenger cars in mixed traffic flow conditions. Figures 2.11 and 2.12 show the variation of PCU of rickshaws with flow rate and proportion of vehicles.

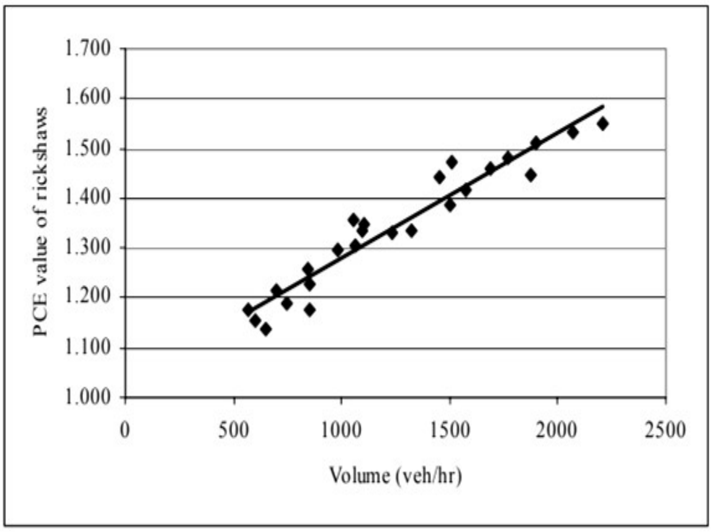


Figure 2.11 Variation of PCU of rickshaws and flow rate

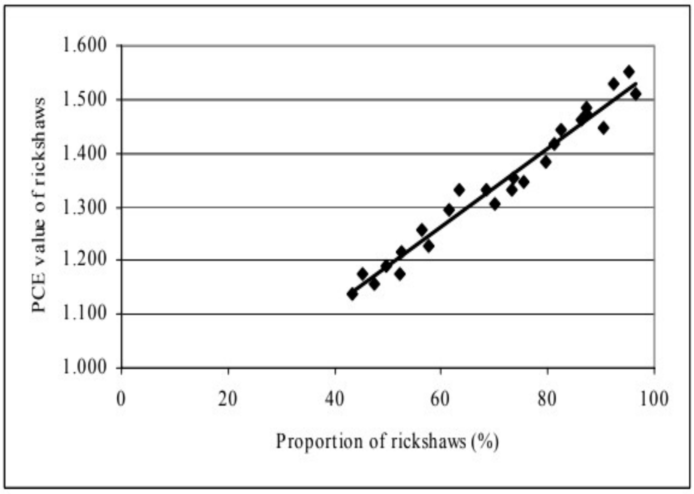


Figure 2.12 Variation of PCU of rickshaws and its proportion

It is observed that PCU values of rickshaws increased with increase in flow rate and proportion of rickshaws. This is due to the increase in the speed difference between passenger cars and rickshaws at higher percentage. Minh et al. (2005) found the equivalency units of motorcycles in the traffic stream in Vietnam with high proportions of motorcycles in the traffic stream. The study proposed a motorcycle equivalency unit (MCU) based on speed and projected area of vehicle types. Speed-volume relationship was developed for motorcycle traffic by converting all the vehicles into common unit using MCU. The study also studied the speed characteristics at different traffic and roadway conditions. It was found that exclusive motor cycle lanes were showing higher average speed compared to undivided and mixed traffic roadways.

In another study of similar kind, Cao and Sano (2012) proposed a methodology to estimate the Motorcycle Equivalent Units (MEU) instead of PCU for analyzing the capacity values of urban roads in Vietnam. The definition of MEU is the number of motorcycles that can be displaced for one vehicle of a specified type running at the speed of that vehicle. For the estimation of MEU values, two factors i.e. occupation of the vehicles surrounding the motorcycles and speed are considered. The authors proposed an Equation (2.4) to estimate MEU values of vehicle types.

$$MEU_k = \frac{\bar{V}_{mc}}{\bar{V}_k} \times \frac{\bar{S}_k}{\bar{S}_{mc}} \qquad (2.4)$$

where, MEU_k= Motorcycle equivalent of the vehicle type *k,*

$\bar{V}_{mc}$ = Mean speed of the motorcycles (m/s),

$\bar{V}_k$ = Mean speed of the vehicle type, *k*(m/s),

$\bar{S}_{mc}$ = Effective mean-space for motorcycles (m^2)

$\bar{S}_k$ = Effective mean-space for vehicle type, *k* (m^2)

Field data collected on 12 different study sections including four-lane, six-lane and eight-lane divided roads with raised medians. The relationship between mean stream speed and effective mean space of the vehicle types is analysed with high coefficient of correlation. The MEU values of different vehicle type's bus, mini bus, car and bicycle are obtained as 10.5, 8.3, 3.4, and 1.4 respectively. The capacity values determined in the study are 13,358 MEU/hr for two-lane, 21,725 MEU/hr for three-lane and 24,335 MEU/hr for four-lane per direction of travel.

2.4.2. UNDER HETEROGENEOUS TRAFFIC CONDITIONS

Ramanayya (1988) estimated PCU value of vehicle types namely motorized two-wheeler, truck and tractor-trailer on two-lane roadway sections through traffic simulation model i.e.

MORTAB (Model for depicting Road Traffic Behavior), developed for mixed traffic conditions. The study proposed PCU values of vehicle types based on proportional share of slow moving vehicles in terms of equivalent design vehicle units at different levels of service. As the LOS decreasing from A to C, the PCU of vehicle types were showing decreasing trend.

Indian Roads Congress (IRC 106: 1990) provided static PCU values of vehicle types based on traffic composition of the vehicle categories. PCU values were suggested based on the proportion of vehicles in the traffic stream. Table 2.3 gives the PCU values of the vehicle categories for Indian urban roads based on traffic composition.

Table 2.3 PCU values of different vehicle types (IRC 106: 1990)

Vehicle type	Equivalent PCU factors	
	Composition (%)	
	5%	10% and above
Fast vehicle		
Two wheelers, motor cycle etc.	0.5	0.75
Passenger car, Pickup van	1.0	1.0
Auto-rickshaw	1.2	2.0
Light commercial vehicle	1.4	2.0
Truck or Bus	2.2	3.7
Agricultural tractor trailer	4.0	5.0
Slow vehicle		
cycle	0.4	0.5
Cycle rickshaw	1.5	2.0
Tonga (Horse drawn vehicle)	1.5	2.0
Hand cart	2.0	3.0

Chandra et al. (1995) derived a methodology to estimate PCU of vehicle types on the basis of space requirement of the vehicles. A mathematical equation to estimate the PCU of vehicle types is proposed.PCU of a vehicle type is calculated as shown in Equation (2.5)

$$PCU_i = \frac{V_c/V_i}{A_c/A_i} \tag{2.5}$$

where, V_c and V_i are mean speed of the vehicle type car and subject vehicle type 'i' and A_c and A_i are projected area of the vehicle type car and subject vehicle type 'i'.

Chandra et al. (1997) estimated PCUs using different methods available in literature based on field data collected on two-lane highway in India. These methods include Walker's method, headway ratio method, homogenization coefficient method, multiple-linear regression method, and simultaneous equation method. Study compared all PCU methods and concluded that PCU values of vehicle types depend on the method of estimation used for particular traffic conditions.

Chandra and Sikdar (2000) studied the influence of various traffic and geometric factors on PCU of vehicle types under mixed traffic conditions on urban roads. By using modeled simultaneous equations (Chandra et al. (1994)), authors estimated the speed of the vehicle types. The influence of traffic volume and composition on PCU of vehicle types is analysed. It is observed that PCU of vehicle types decreasing with an increase in its own proportion of the traffic and increase in traffic volume leads to smaller PCU value of vehicle types. The influence of road width on PCU of vehicle types is also studied. Figure 2.13 shows the variation of PCU of the vehicle type Bus with respect to carriageway width.

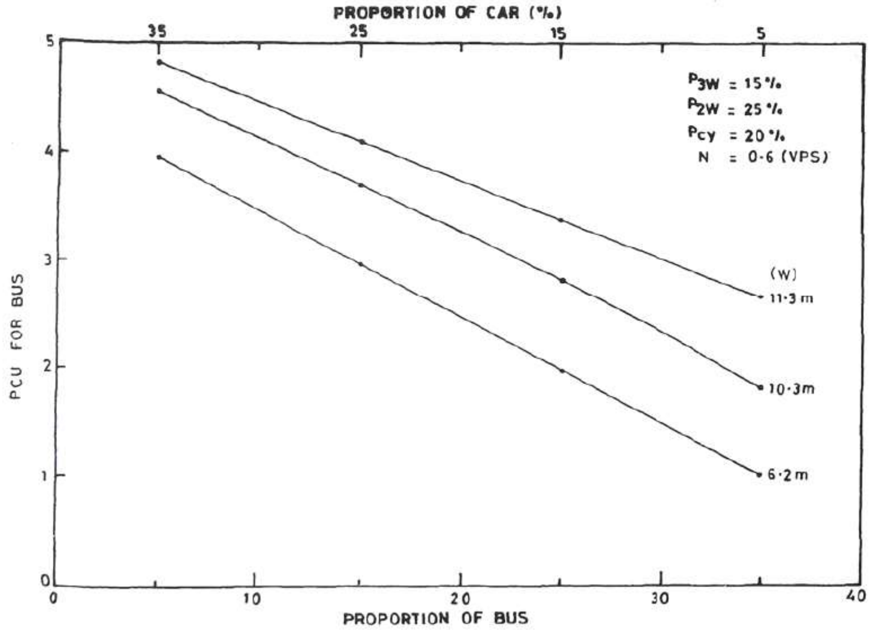


Figure 2.13 Variation of PCU of Bus with road width

It is clear that with the increase in proportion of bus, PCU of bus is decreasing and it is increasing with the increase in road width. Further, the combined influence of traffic volume, composition and road width on PCU of the vehicle type is explained by a computer program. Chandra and Kumar (2003) investigated the effect of lane width on dynamic PCUs estimated in the study for vehicle types Truck, Bus, motorized two-wheeler etc. by using field data collected on two–lane roadways. The authors observed that the PCU values of subject vehicle types were decreased with increase in the width of roadway.

Basu et al. (2006) estimated the PCU of vehicle types under the influence of traffic volume and traffic composition on urban mid-block roads. For this, four different vehicle categories are considered on the selected study sections such as heavy vehicles (HV), car with new technology (NC), car with old technology (OC) and two-wheeler (TW). Here, passenger car is termed as 'Cars' with new technology. The reduction in the stream speed was analysed with the increase in traffic volume and composition with vehicle types NC and OC. The reduction in the stream speed is termed as 'Marginal Damage (MD)' and PCU of vehicle types is estimated with reference to vehicle type OC which is shown in Equation (2.6)

$$PCE_{i,v,m} = \frac{MD_{i,v,m}}{MD_{OC,v,m}} \quad (2.6)$$

where, $MD_{i,v,m}$= Marginal damage caused by subject vehicle type 'i' at base volume 'v' and composition 'm. $MD_{OC,v,m}$= Marginal damage caused by old technology car 'OC' at base volume 'v' and composition 'm. Further, the non-linear behavior of stream speed with variation in traffic volume and composition is analysed using neural network approach. It is concluded that, PCE of vehicle types is increasing with increase in traffic volume for all vehicle types and with the increase in the proportional share of the vehicles, PCU of vehicles types HV, NC are increasing whereas PCU of TW has not been affected.

Mallikarjuna and Rao (2006) studied the PCU of vehicle types bus, truck and motorized two-wheeler by using simulation technique. The PCU values were estimated using area occupancy method. The study stated that with the increase in own proportion of vehicles, the PCU values of the vehicles have shown decreasing trend irrespective of the size of the vehicle types. Aggarwal (2008) developed Fuzzy based model to estimate the PCU of Bus on highways. The study estimated PCU values by taking different carriageway and traffic characteristics such as width, type, conditions of shoulder, directional split and traffic composition and percentage of slow moving traffic. The study compared the results with the previous study available in the literature on PCU and concluded that the estimated PCUs are highly accurate.

Arasan and Arkatkar (2010) studied the influence of roadway width and traffic volume on PCU of different vehicle types under mixed traffic conditions through microscopic traffic simulation. HETEROSIM simulation model is used to study the vehicular interactions at various traffic volume levels for estimating PCUs. Field data collected on four lane and six lane roads was used to develop speed-flow curves and determined capacity for a four lane divided section with carriageway width of 8.75m as 4600pcu/hr and for a six lane divided section with carriageway width of 12.5m as 7200pcu/hr. The study also found the influence of traffic volume on PCU vehicle types. For larger size of vehicles other than standard passenger car, PCU values are found to be decreasing with at higher volume levels and increasing with at lower volume levels. And, for the smaller size vehicles, observed trend is vice-versa. Further, the influence of road width on PCU of vehicle types was also found that the PCU of all vehicle types are increasing with the increase in the road width.

Paul and Sarkar (2013) estimated PCU values of different vehicle categories on urban roads of New Delhi, India. The study used the dynamic PCU method suggested by Chandra et al. (1995) to estimate PCU values. A modification to method was done by suggesting the use of influencing area instead of projected area of vehicles for estimating PCU. The influence of proportion of heavy vehicles and non-motorized vehicles on different vehicle categories is analysed. It is found that with increase in proportion of heavy vehicles, PCU of two wheelers decreases whereas increase in proportion of non-motorized vehicles leading to reduction in PCU of two wheelers. This situation is vice-versa in case of PCU values of bus category. And it was found that PCU of three wheelers does not change with the proportion of heavy and non-motorized vehicles.

Dhamaniya and Chandra (2013) proposed methodology to convert mixed traffic stream to homogeneous traffic without using PCU factors. The study has collected volume and speed data from six urban road locations in India. The study proposed a term stream equivalency factor (K) in estimating the PCU value of the vehicles on urban roads. A multiple linear equation is given to estimate K based on traffic composition and traffic volume. Equation (2.7) shows the regression equation to estimate stream equivalency factor (K).

$$K = 1 + a_1.P_{cb} + a_2.P_{hv} + a_3.P_{3w} + a_4.P_{2w} + a_5.\frac{1}{N} \qquad (2.7)$$

where, K is stream equivalency factor, a_1 to a_5 are regression coefficients, P_{cb}, P_{hv}, P_{3w} and P_{2w} are proportion of big cars, heavy vehicles, three wheelers and two wheelers respectively, N is the total number of vehicles per hour.

Mehar et al. (2014) estimated PCU values of different vehicle types at different level of service on multilane highways in India. The study used simulation tool VISSIM to generate the speed and traffic volume based on field collected the data. With the generated data, speed-flow curves were drawn for traffic with cars and one more vehicle category from the available vehicle categories. The proportion of the other categories varied to analyse its influence on PCU values. It is concluded that with the increase in volume to capacity ratio, PCU of vehicle type decreases. The study suggested PCU values of vehicle types for four and six lane divided highways at different levels of service and traffic composition. Srikanth and Mehar (2018) compared ANFIS, ANN and MLR methods by estimating PCU values using field data. The authors stated that the ANFIS is predicting PCU of vehicle types very accurately with the minimal root mean square error in comparison to the other two methods used in the study.

Pooja et al. (2018) estimated dynamic PCU values of vehicle types under the influence of neighboring vehicles in the mixed traffic conditions. For estimating the PCU values, data collected from two-lane undivided and four lane urban roads in India are considered. PCU values of vehicles were estimated by taking the effective area and speed for six cases considering subject vehicle, adjacent vehicle and leader vehicles. It is found that the PCU values of two lane undivided roads are higher compared to the PCU values of four lane divided roads. Pooja et al. (2019) also provided a detailed review of literature on PCU considering all types of roadway links and intersections. The study emphasized the influence of neighboring vehicle types on PCUs under six different traffic scenarios and suggested the use of effective area of vehicle types instead of projected area. The study also addressed a need for incorporating the effect of side frictions in determining PCU of vehicles.

2.4. SUMMARY

The review of literature on urban roads is presented in detail in this chapter including the studies on estimation of capacity of urban roads under homogeneous and heterogeneous traffic conditions. Studies on influence of side friction on various aspects such as speed, PCU of vehicles and capacity are discussed. Also, many studies on estimation of PCU and the factors effecting PCU values are discussed under homogeneous and heterogeneous traffic conditions. Although, there are several studies done to investigate the effect of side friction factors on capacity but they are limited to the specific traffic and roadway conditions. Many studies use existing guidelines for calculating side friction by choosing predefined values. In fact, there is no research found on derivation of adjustment factor for side friction to directly find actual capacity of urban roads under highly mixed traffic conditions like India. Also, research lacks enough evidence of whether urban road side-friction and its magnitude affect PCU of a subject vehicle type. Hence, a detailed analysis on finding the impact of side friction on traffic parameters is presented in this study.

Chapter 3

STUDY METHODOLOGY

3.1. GENERAL

The present chapter deals with the methodology adopted to estimate the influence of side friction on the traffic flow characteristics and capacity of the urban roads. It involves several stages including defining the site selection, field data collection, data analysis and modeling. A detailed framework is presented with respect to analysis of speed characteristics, estimation of PCU of vehicle types and determination of capacity of the urban road sections.

3.2. METHODOLOGY FLOW CHART

A detailed research methodology is proposed to analyze the capacity of urban road sections. First step is the preliminary stage which explains detailed literature related to the formulated problem and defining the study objectives. The second step involves the selection of study locations, method of data collection and type of data required for the analysis. Third step involves data analysis and capacity estimation which explains the detailed analysis of three major parts. It includes analysis of speed with the influence of side friction, estimation of PCU using conventional and soft-computing approaches and determining capacity using speed-flow relationship. Further, model is developed to estimate the capacity based on influencing variables on divided multilane urban roads and drawing significant conclusions based on the present study. Figure 3.1 shows the proposed research frame work for the present study.

3.2.1. PRELIMINARY

It includes framing the research problem and identification of the suitable study locations. The roadway sections are selected based on observing various conditions such as variation in traffic flow, composition, geometrical characteristics and side friction levels. The locations selected for the study include mid-block road sections having straight alignment in plain areas.

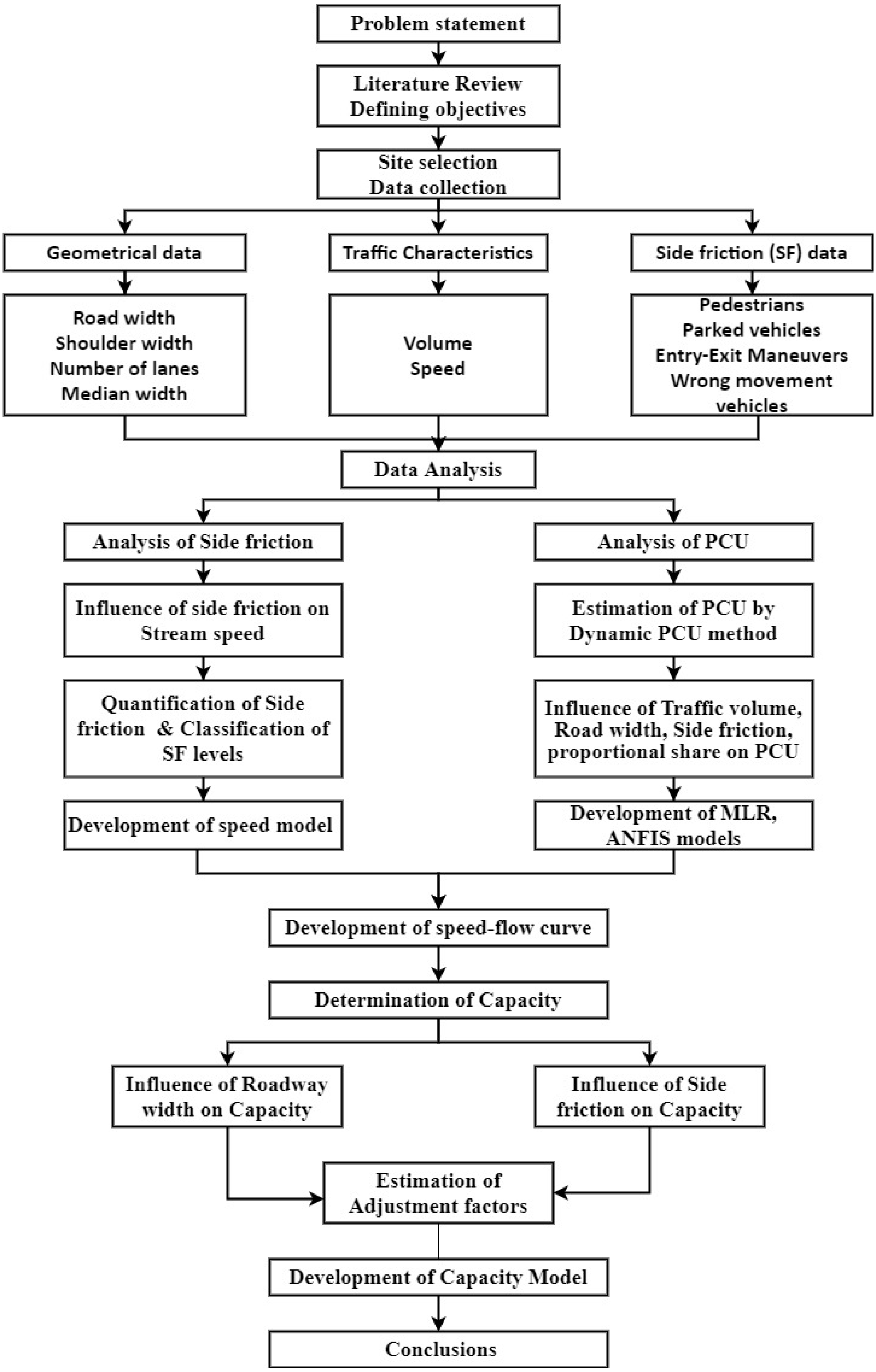


Figure 3.1 Proposed research methodology flow chart

3.2.2. DATA COLLECTION

Field data collection on selected roadway sections is performed by using video-graphic method. A high definition camera was mounted on higher elevation at study locations so that it covers the trap length which is marked on the road for the purpose of analysis. The data obtained from the field to carry out present study includes geometric data, traffic data and side friction data. Geometric data include several road physical features such as width of the road, width of the median, width of the shoulder, number of lanes. Such data is also used in analysing traffic flow behavior and developing capacity model. Traffic data includes vehicle data, speed data and volume data. Vehicle data refers to the dimensions of the vehicles such as width and length. Speed data pertains to each vehicle types was obtained from road sections by trap length method. The start time and end time are noted when a vehicle passes through the trap length to obtained speed data. Traffic volume data and composition are extracted from the video recordings. Side friction elements include movement of the pedestrians alongside of the road, on-street parking facility, entry and exit maneuvers of the vehicles and wrong way movement of the vehicles. All these features are extracted from the video in a specified stretch of the study section.

3.2.3. DATA ANALYSIS

The field data collected from roadway sections is used to analyse the traffic flow behavior of the urban roads. The analysis of spot speed data of each vehicle types was carried out to understand the statistical distribution at various sections. A model for predicting speed is proposed for mixed traffic conditions. The traffic flow behavior was analysed by development of speed-volume relationship for each of the section selected for the study. Further, capacity values are determined by fundamental relationship and using proposed model in the analysis after estimating PCUs of vehicle types observed on urban road sections. A detailed overview of data analysis has been provided in the following paragraphs as given under.

- **STREAM SPEED-SIDE FRICTION**

Analysis of speed data was carried out using spot speed data collected for each vehicle types and statistical distributions are fitted to understand the speed behaviour. A multiple linear regression analysis was performed for predicting the average speed of traffic stream for selected study sections. Various influencing variables are considered for analysis such as side friction, traffic volume. Based on regression analysis, weights for different side friction elements are obtained and total side friction was determined for each road sections. The estimate of total side friction was used for prediction of average stream speed for traffic observed at selected road sections.

- **ESTIMATION OF PCU**

Passenger Car Unit (PCU) for each vehicle type is calculated by using dynamic method suggested by Chandra and Kumar (2000). Relationship between PCU of vehicle type with other factors such as traffic volume, side friction, carriageway width and proportional share of the vehicle types was analysed. PCU models are developed based on the influencing parameters by using multiple regression analysis. Another method Adaptive Neuro Fuzzy Inference System (ANFIS) is also used to model the PCU of vehicle types and MLR & ANFIS models are compared to see the performance of the models.

3.2.4. DETERMINATION OF CAPACITY AND MODEL DEVELOPMENT

Capacity of roadway section is estimated from the speed-volume plot developed for each road section. The influence of side friction on capacity of roadway section is analysed. The study suggests adjustment factors for side friction and roadway width for determining capacity. Capacity model is developed for multilane divided urban mid-block section by incorporating derived values of adjustment factors for side friction and roadway width.

3.3. SUMMARY

A research methodology is discussed in this chapter in the detailed manner using a flow chart. Study methodology is explained on speed analysis, estimation of side friction, estimation of PCU of vehicle types and development of capacity model. The next chapter deals with the field data collection and analysis.

Chapter 4

ROADWAY LOCATIONS AND FIELD DATA COLLECTION

4.1. GENERAL

Field data was collected at different locations of the multi-lane divided urban roads at mid-block sections in India. The locations for field survey and method of data collection are described in this chapter. The present chapter also provides the detail of location characteristics, data requirements and procedure followed for conducting field surveys to collect essential field data for the study.

4.2. SELECTION OF STUDY LOCATIONS

Location characteristics greatly influence the traffic performance of any urban road. For the present study, the ideal location characteristics of a road with 7.0m carriageway width, shoulders width of 1.5m, median width of 1.2m, low or no side friction and flat terrain with straight alignment is considered. Field data is collected on two different cities namely Warangal and Nellore in India. Warangal is located in Telangana state, where six different locations were identified for field data collection.

Section I, Hanmankonda road situated on NH 163 (18°00'22.9"N 79°34'13.2"E), which is 8 km away from Kazipet railway station, four lane divided road with dense urban area comprising commercial buildings on both sides of the roadway. Section II, Subedari road located on NH 163 (17°59'31.5"N 79°32'17.1"E), which is 4 km away from Kazipet railway station, four lane divided road with medium dense land use. Section III, Kazipet road, located on NH 163 (17°59'16.3"N 79°31'45.5"E), which is 2.5 km away from Kazipet railway station, four lane divided road with low dense land use activity as it consists of sub-urban road environment. Section IV, MGM hospital road, located nearer to NH 163 (17°59'29.1"N 79°35'34.9"E), which is 3.5 km away from Warangal railway station, six lane divided road having dense land use activity with curbside bus stop on the side of the road. Section V, D-mart road, on NH 163 (17°59'44.4"N 79°32'57.3"E), which is 6 km away from Kazipet railway station, six lane divided road with medium dense land use activity. Section VI, Temple road, located on NH 163 (17°59'41.3"N 79°35'26.7"E), which is 5.2 km away from Warangal railway station, six lane divided road which is a sub- urban road with low land use activity. Some other roadway sections were located in Nellore city situated in the state of Andhra Pradesh, India.

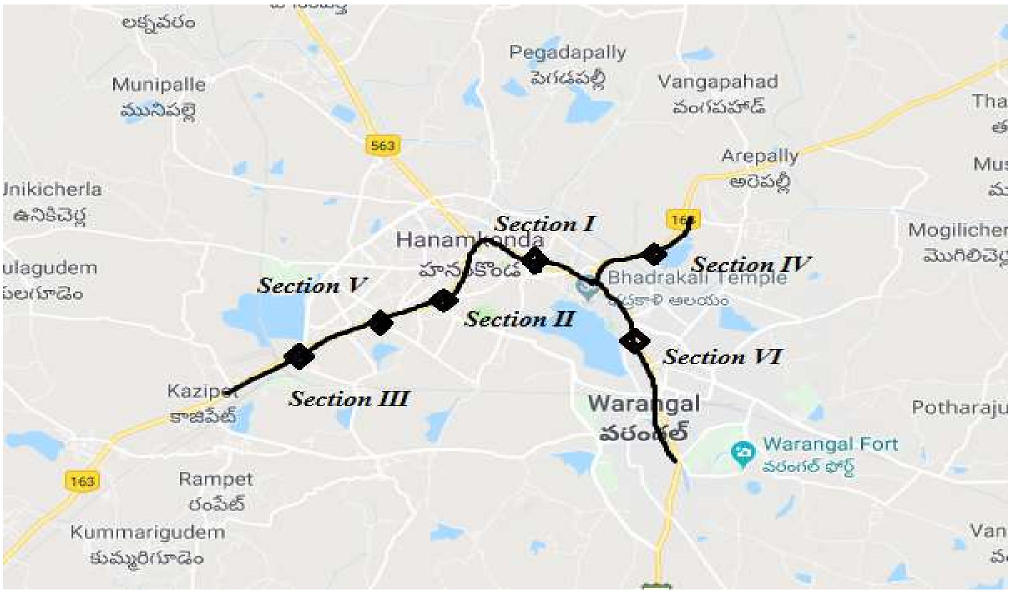


Figure 4.1 Selected roadway sections in Warangal city

Section VII, Mini bypass road, located at 2.5km away from Nellore RTC bus-stand (14°27'03.2"N 79°59'00.5"E) which is a four lane divided sub arterial road with low land use activity on the sides of the road. Section VIII, Grand Trunk road located at 2.5km away from Nellore RTC bus-stand (14°27'01.0"N 79°59'20.3"E) which is a four lane divided sub arterial road with medium land use activity (curb-side bus stop) on the sides of the road. Figures 4.1 and 4.2 show the location of the selected roadway sections in Warangal and Nellore cities respectively. Snapshots of study sections are given in Figures 4.3 to 4.6.

Figure 4.2 Selected roadway sections in Nellore

Figure 4.3 Roadway in Warangal city (Section I)

Figure 4.4 Roadway in Warangal city (Section II)

Figure 4.5 Roadway in Warangal city with curb side bus stop (Section IV)

Figure 4.6 Roadway in Nellore city with curb side bus stop (Section-VIII)

4.3 FIELD DATA COLLECTION AND EXTRACTION

Field inventory and traffic flow data was collected on all selected study sections on typical weekdays in clear weather conditions. Video-graphic method is used to record the traffic flow operations for one direction of travel. A high definition camera was placed at elevated point assuring that it is covering the whole roadway section. Traffic video recording was performed for a period of 6 hours from 6.00 AM to 9.00 AM and from 2.00PM to 5.00PM on selected roadway sections. The recorded video was replayed on a wide screen LED in a laboratory and extracted essential traffic flow data.

4.3.1. ROADWAY DATA

All the geometrical deatils of the study sections such as width of the roadway, width of the median, width of the shoulders and trap length are measured manually with the help of the tape. The details of each selected roadway section are given in Table 4.1. It is noted that paved shoulders refer to shoulders with bituminous surface over it and unpaved shoulders refer to shoulders with no bituminous surface over it.

Table 4.1 Details of the study sections

Section	Name of the road	Type of road	Type of shoulder	Carriageway width (m)	Shoulder width(m)	Median width(m)
I	Hanmakonda road	Four lane divided	Unpaved	7.0	0.5	0.5
II	Subedari road	Four lane divided	Unpaved	8.5	1.0	1.2
III	NITW Road	Four lane divided	Paved	7.0	1.5	1.2
IV	MGM road	Six lane divided	Paved	10.5	0.5	1.2
V	Dmart Road	Six lane divided	Paved	10.5	1.0	1.2
VI	Bhadrakali temple road	Six lane divided	Paved	10.5	2.5	1.2
VII	Mini bypass road	Four lane divided	Unpaved	7.0	2.5	1.2
VIII	Grand trunk road	Four lane divided	Paved	7.0	1.5	1.2

4.3.2. VEHICLE TYPE DATA

The traffic flow on selected roads carry heterogeneous vehicles those are different in terms of their physical and operational characterestics. Several number of vehicle categories are observed to play on the roadway section. However, for the present study several vehicle categories are merged into six vehicle types for simplifying the data analysis, such as Car (Micro, Minivan, jeep, SUV, Sedan, Hatchback), 2W(motorized two wheeler i.e. Motor bike), 3W (motorized three wheeler i.e. Auto rickshaw), Bus (36 to 60 persons seating capacity), LCV (light commercial vehicle i.e. tempo, Mini trucks), NMV (non-motorized vehicle such as bicycle and hand drawn cart). The dimensions and power characteristics of vehicle types are taken from the previous study (Madhuri.K (2016)) given in Table 4.2.

Table 4.2 Dimensions of vehicles

Vehicle type	Notation	Length(m)	Width (m)	Power performance (cc)
Passenger Car	Car	3.5	1.70	1200
Two wheeler	2W	1.80	0.69	125
Three wheeler	3W	2.91	1.34	145
Light commercial vehicle	LCV	3.35	1.60	395
Bus	Bus	12.00	2.60	5675
Non-motorised vehicle	NMV	1.78	0.63	*NA*

The passenger car in the study is defined as Car with an average length of 3.5 m and average width of 1.70 m, having engine power up to 1200cc (e.g. Honda Brio).

4.3.3. SPEED DATA

The spot speed data was collected on all selected roadway sections using an appropriate trap length. The video-graphy method is used to record the traffic flow operation for estimating the speed of vehicles passing through the trap length by noting their travel times. Two reference lines are marked with appropriate distance apart ranging from 25m to 50m depending upon the posted speed limit of the selected urban roads. The observer also walked across and along the road to ensure the reference lines of the trap distance to represent entry and exit lines during video recording Figure 4.7 shows the procedure for measuring the speed at study Section II by using the trap length method. Figure 4.8 shows the schematic diagram of the data collection process for the present study. The travel time of each vehicle passing through trap length is noted down from the recorded video using a digital stop watch with an accuracy of 0.01 sec. The space mean speed of vehicles was measured at every 1 minute time interval.

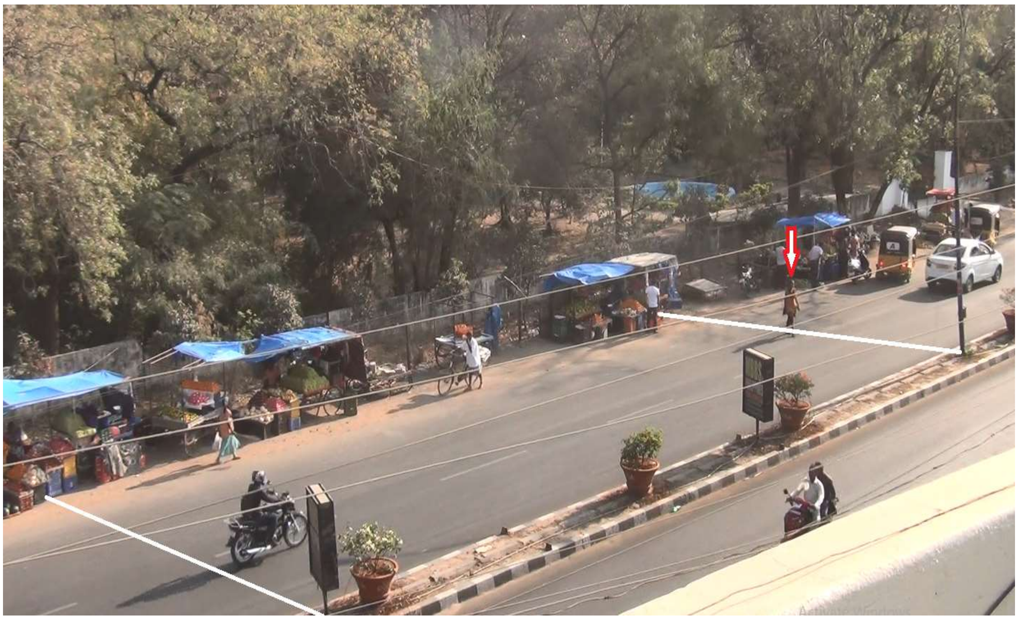


Figure 4.7 Trap-length marking for study section II

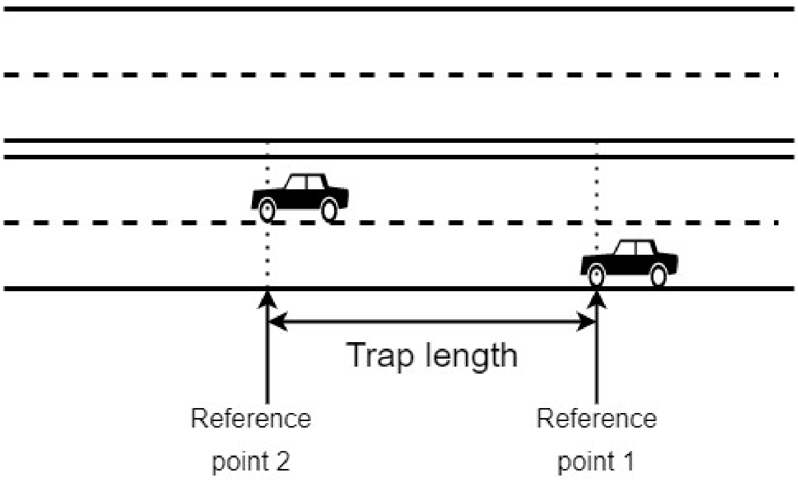


Figure 4.8 Schematic diagram of data collection process

4.3.4. VOLUME DATA

The traffic volume data was obtained from the video files recorded at all the study sections. The classified volume count was made from video played on a wide screen LED in the transportation software laboratory. The vehicles passed through a marked reference line were counted at every 1 minute interval. Traffic count made on different roadway sections was aggregated to find hourly traffic volume. Traffic volume data observed on all sections is given in Table 4.3. Traffic composition of different vehicle types is observed from the collected volume data which is shown in Chapter 5.

Table 4.3 Hourly traffic volume at study sections

Section	Time period	Average Hourly Traffic (Veh/hr)
I	6.00AM-7.00AM	837
	7.00AM-8.00AM	1094
	8.00AM-9.00AM	3369
	2.00PM-3.00PM	1540
	3.00PM-4.00PM	2859
	4.00PM-5.00PM	3543
II	6.00AM-7.00AM	770
	7.00AM-8.00AM	935
	8.00AM-9.00AM	2885
	2.00PM-3.00PM	2684
	3.00PM-4.00PM	2455
	4.00PM-5.00PM	2732
III	6.00AM-7.00AM	570
	7.00AM-8.00AM	637
	8.00AM-9.00AM	1572
	2.00PM-3.00PM	2253
	3.00PM-4.00PM	2267
	4.00PM-5.00PM	2347
IV	6.00AM-7.00AM	892
	7.00AM-8.00AM	1046
	8.00AM-9.00AM	2685
	2.00PM-3.00PM	2547
	3.00PM-4.00PM	1701
	4.00PM-5.00PM	2479

V	6.00AM-7.00AM	645
	7.00AM-8.00AM	869
	8.00AM-9.00AM	3192
	2.00PM-3.00PM	3737
	3.00PM-4.00PM	2986
	4.00PM-5.00PM	3895
VI	6.00AM-7.00AM	1683
	7.00AM-8.00AM	2667
	8.00AM-9.00AM	3607
	2.00PM-3.00PM	2309
	3.00PM-4.00PM	3470
	4.00PM-5.00PM	4304
VII	7.00AM-8.00AM	1428
	8.00AM-9.00AM	2453
	3.00PM-4.00PM	1896
	4.00PM-5.00PM	2551
VIII	7.00AM-8.00AM	1587
	8.00AM-9.00AM	2551
	3.00PM-4.00PM	2258
	4.00PM-5.00PM	2607

4.3.5. SIDE FRICTION DATA

Side friction on the selected roadway sections was observed during entire survey period. Videography method was used for recording various activities prevailing on roadside. The roadside activities were observed for the direction of traffic under consideration within 50m section. The side friction data is extracted at 5 min interval from the video film by noting the frequency of various activities such as pedestrian movement, parking maneuvers, entry-exit vehicles and wrong movement vehicles. The details of the side friction activities on different roadway sections are given in Table 4.4.

Table 4.4 Details of the side friction activities

Sections	Name of the road section	Observed Side friction activities
I	Hanmakonda road	Pedestrians Parked vehicles Entry-exit manoeuvres Wrong way vehicles
II	Subedari road	Pedestrians Parked vehicles Wrong way vehicles
III	NITW Road	Pedestrians Parked vehicles
IV	MGM road	Pedestrians Parked vehicles Wrong way vehicles
V	Dmart Road	Pedestrians Parked vehicles
VI	Bhadrakali temple road	Pedestrians Parked vehicles Wrong way vehicles
VII	Mini bypass road	Pedestrians Parked vehicles
VIII	Grand trunk road	Pedestrians Parked vehicles Entry-exit manoeuvres Wrong way vehicles

The roadside activities along the length of the road were also observed on each selected study section and spacing between the stationary road side elements was noted. It has been observed that the continuous occupancy of the roadside elements at Section V mainly consists of continuous parked vehicles along the roadway. On Section III, no stationary road side activity was recorded during the entire data collection period. On Section I, high dense activities were observed with lesser gap between the stationary roadside activities. From the observation of the side friction activities occupancy on the road at each section, trap length is fixed to measure the side friction. Table 4.5 provides the summary of side friction data on different roadway sections.

Table 4.5 Occupation of side friction details at the study sections

<table>
<tr><th rowspan="2">Sections</th><th colspan="3">Length (m)</th><th colspan="3">Gap (m)</th></tr>
<tr><th>Max</th><th>Min</th><th>Avg</th><th>Max</th><th>Min</th><th>Avg</th></tr>
<tr><td>I</td><td>44</td><td>9</td><td>24</td><td>14</td><td>7</td><td>10</td></tr>
<tr><td>II</td><td>42</td><td>25</td><td>33</td><td>34</td><td>10</td><td>21</td></tr>
<tr><td>III</td><td colspan="6">NA</td></tr>
<tr><td>IV</td><td>97</td><td>18</td><td>58</td><td colspan="3">28</td></tr>
<tr><td>V</td><td colspan="3">120</td><td colspan="3">NA</td></tr>
<tr><td>VI</td><td>18</td><td>8</td><td>13</td><td colspan="3">62</td></tr>
<tr><td>VII</td><td colspan="6">NA</td></tr>
<tr><td>VIII</td><td colspan="6">NA</td></tr>
</table>

From Table 4.5, the average length of the stationary side friction activities is observed as 50m. Therefore, a length of 50m is fixed as trap length to measure the side friction activities at each study section.

4.4. SUMMARY

The selection of study sections and location characteristics of the each study section are discussed in this chapter. The methodology to collect the data at these study sections is described in detailed manner. The extraction of data such as volume, speed and side friction factors from the video recordings is discussed. Also, different vehicle categories and their physical characteristics are also described. Hourly traffic volume for each study section is also discussed and different side friction elements considered at each study section is described.

Chapter 5

FIELD DATA ANALYSIS

5.1. GENERAL

In this chapter, the analysis of field data is carried out for understanding the traffic flow behavior and assessing the capacity of roadway sections. This includes speed analysis, estimation of traffic volume, and analysis of roadway side friction. Speed analysis has been carried out for assessing the characteristics of speed data obtained for different vehicle types from study sections. Traffic composition on selected roadway sections was extracted from observed traffic volume. The traffic volume count made for the study sections have been analysed and it converted in terms of passenger car units for further analysis. Roadway side friction data as observed at each study section has been analysed for each study locations.

5.2. ANALYSIS OF SPEED

Speed is an important parameter in the field of traffic engineering. It is used as one of the performance measures to evaluate the traffic stream performance which in turn helps in designing geometry of the roads, controlling traffic operations, road improvement practices, congestion management, travel time assessment etc., (Kadiyali, 2002). According to IRC (1990) and Indo-HCM (2017), speed is defined as 'the rate of motion of individual vehicles or of traffic stream' measured in meters per second (m/s) or more generally in kilometers per hour (Km/hr). The present study deals with the space mean speed and it is defined as the mean speed of the vehicles in a traffic stream at any instant of time over a certain length of the road. Speed data was collected from the selected sections by defining the trap-length of appropriate size on the roadway as explained in Chapter 4.

To understand the speed behavior, preliminary statistical analysis of speed data is carried out. For instance, cumulative frequency profiles using speed data are drawn by taking a suitable class interval. Figure 5.1 shows the cumulative speed profiles of different vehicle types observed at the study section I which is a four lane divide road. It is observed that the vehicle type Car has the higher variation in speed data in compared to other vehicle types.

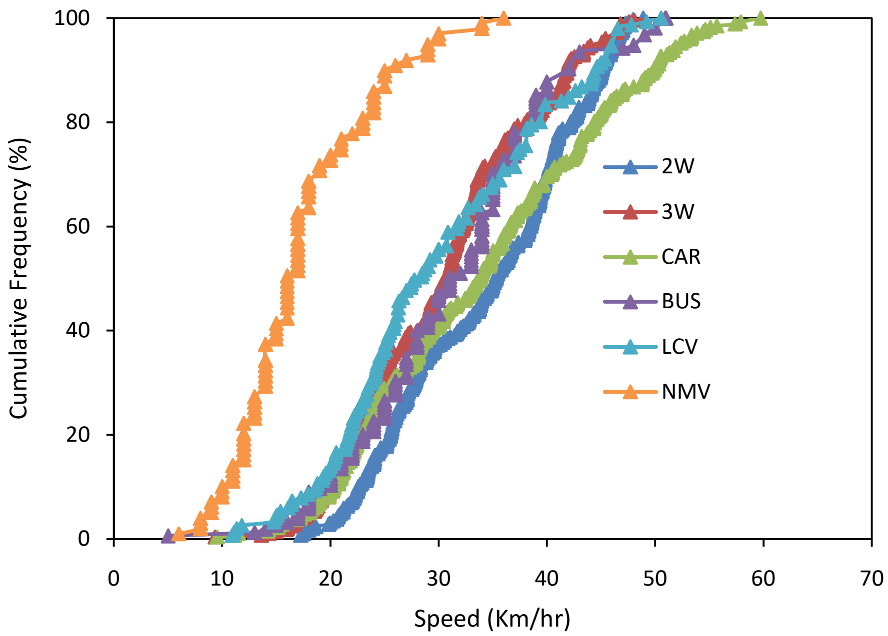


Figure 5.1 Cumulative speed profiles of section I

Further, the descriptive statistical parameters such as minimum, maximum, average, 15th percentile and 85th percentile speed are calculated and the details are given in Table 5.1. It is observed that the Section III has the highest variation in speed of all vehicle types among four-lane divided roads, whereas the highest variation in speeds was observed on Section VI among six-lane divided roads. It is observed that the vehicle Type Car has the highest mean speed and 85th percentile speed among all vehicle types on both four and six lane divided road sections. The difference of mean speed between vehicle Type 2W and Type Car is found to be lower on four lane urban roads and the difference of mean speeds of vehicle Type 2W and Type Car is significant on six-lane urban roads. Moreover, there is no significant difference was found in 85% percentile speed of vehicle Type 2W on both four and six lane divided roads. Vehicle Type 3W and Type Bus are observed to be moving with similar mean speed on all selected four lane divided sections whereas the mean speed of vehicle Type 3W is found to be higher than vehicle Type Bus on the six-lane divided road sections. The LCVs are observed to be travelling at higher mean speed when compared to 3Ws on both four and six lane divided road sections. The vehicle Type NMV has no significant change in the mean speeds whether observed on four-lane and six-lane divided roads.

Table 5.1 Speed parameters of vehicle types at different sections

Section	Vehicle type	Speed parameters (Km/hr)						
		Maximum	Minimum	Average	15th percentile	85th percentile	N	Standard deviation
I	2W	48.90	14.24	34.17	24.08	43.94	286	8.39
	3W	50.94	9.32	30.35	21.19	40.91	282	8.30
	Car	59.73	9.54	33.91	21.86	46.53	273	11.13
	Bus	58.38	4.90	31.50	21.53	39.36	155	9.52
	LCV	49.23	10.94	29.91	20.44	41.67	151	9.48
	NMV	36.36	6.21	17.42	11.67	24.40	99	6.26
II	2W	53.20	33.16	39.40	34.79	47.00	286	5.25
	3W	53.55	24.48	33.74	29.74	42.88	286	5.36
	Car	60.11	30.74	39.76	35.10	48.90	286	6.24
	Bus	55.98	11.07	32.52	28.91	35.02	244	5.92
	LCV	55.22	19.52	33.55	28.37	37.21	250	5.89
	NMV	21.01	7.41	14.17	11.59	16.75	207	2.62
III	2W	66.11	29.50	42.67	34.63	58.83	295	10.67
	3W	60.89	29.39	40.75	33.59	55.46	295	9.35
	Car	100.07	21.00	52.54	35.81	76.32	280	18.02
	Bus	75.85	15.80	38.31	27.21	52.04	250	12.36
	LCV	65.54	24.71	49.14	30.42	61.21	83	13.50
IV	2W	61.01	28.96	41.19	32.57	48.93	275	7.66
	3W	62.60	24.79	38.89	29.68	47.06	275	7.63
	Car	83.21	26.24	41.72	33.17	51.94	275	9.32
	Bus	47.72	14.45	32.56	24.35	42.36	212	8.00
	LCV	54.67	15.09	34.64	27.28	44.28	196	8.27
	NMV	38.58	12.94	17.65	14.30	20.53	111	5.04

V	2W	50.52	26.80	37.89	30.81	46.23	234	6.80
	3W	46.63	24.58	33.98	27.35	41.48	234	6.10
	Car	61.93	25.98	40.73	32.71	51.43	234	8.75
	Bus	54.00	25.52	32.11	28.83	33.38	183	5.95
	LCV	55.96	46.75	49.96	46.75	52.86	17	3.09
VI	2W	68.11	33.11	51.44	36.04	50.70	228	2.18
	3W	59.25	30.44	44.69	32.76	46.73	228	1.86
	Car	80.67	26.84	62.31	35.60	62.24	228	3.35
	Bus	57.72	19.74	47.06	28.11	48.26	228	4.89
	LCV	49.19	24.71	39.49	29.83	47.23	222	3.67
	NMV	23.79	10.87	15.53	13.56	17.31	194	2.15
VII	2W	52.05	39.37	46.01	42.06	48.59	186	3.73
	3W	44.89	40.64	42.72	41.40	43.94	186	1.25
	Car	57.07	25.29	41.17	35.79	47.95	164	9.35
	Bus	81.20	23.58	38.54	33.13	43.90	125	13.10
	LCV	54.55	36.12	40.38	37.03	43.72	112	5.42
	NMV	33.23	17.28	22.91	18.21	25.60	26	4.69
VIII	2W	50.17	39.56	43.66	40.13	46.31	178	3.12
	3W	40.45	32.14	36.06	33.51	39.57	178	2.44
	Car	64.29	36.12	44.65	36.78	51.47	156	8.29
	Bus	47.06	39.56	43.81	40.93	46.59	96	2.21
	LCV	51.80	23.08	40.17	33.55	49.02	112	8.45

The speed distribution of vehicle types are analysed at all the study sections. Speed is a random variable and it expected to follow the normal distribution. By taking a suitable class interval, frequencies of speed data were calculated for developing the distribution profiles of vehicle types. Expected frequencies were calculated by assuming a normal distribution function to fit the observed data. Chi-square test is applied to test the difference between expected and observed frequencies for confirming the distribution fit at 5% level of significance. If the Chi-square value is less than the tabulated value (critical value) of Chi-square then the null hypothesis will be accepted saying that speed of a given vehicle type is following the normal distribution. Figure 5.2 shows the speed frequency profiles of vehicle type Car at Section I.

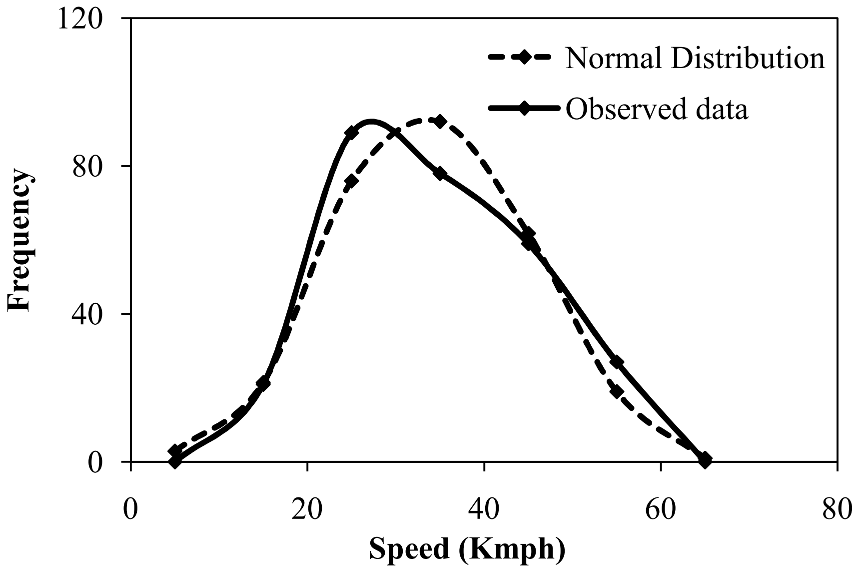


Figure 5.2 Speed distribution curve for vehicle type Car at section I

In this case, calculated Chi-square value is estimated as 10.74 which is found to be less than tabulated Chi-square value as 14.06 that confirms that the null hypothesis cannot be rejected as the speed data follows normal distribution at 95% confidence level with 7 degrees of freedom.

Further, fitting of the normal distribution is tested for average stream speed profile for each study location. The chi-square values are calculated based on the normal distribution parameters such as mean (μ) and standard deviation (σ). And the calculated chi-square values are compared with the critical chi-square value i.e. 14.06 at 95% confidence level with 7 degrees of freedom. Table 5.2 shows the results of distribution fitting to stream speed at different study sections. It is observed from Table 5.2 that all study sections except Section V and VIII are not following normal distribution as their calculated chi-square values are more than critical chi-square values.

Table 5.2 Result of distribution fitting at different study sections

Section	Parameters (Normal distribution)	Chi-square (Calculated)	Normal distribution
I	σ=6.63 μ=31.65	65.378	Not following
II	σ=2.95 μ=35.82	31.142	Not following
III	σ=9.41 μ=43.87	131.88	Not following
IV	σ=7.31 μ=37.92	45.784	Not following
V	σ=3.84 μ=34.58	11.075	Following
VI	σ=5.90 μ=37.95	171.02	Not following
VII	σ=8.27 μ=34.65	17.661	Not following
VIII	σ=2.69 μ=40.15	0.6875	Following

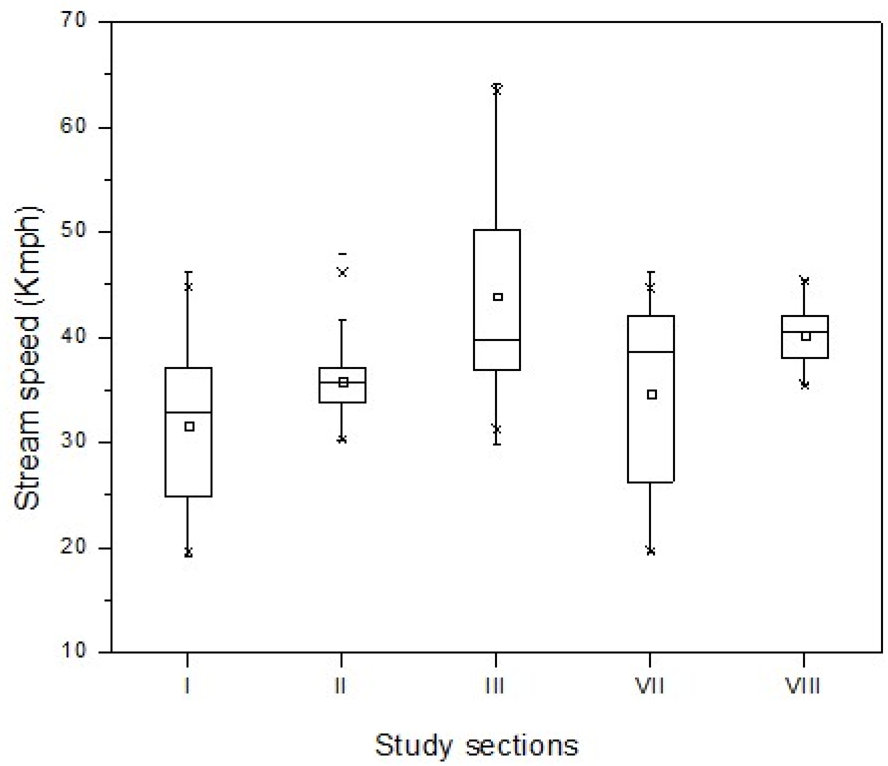


Figure 5.3 Box plot of speed data for four lane roads

Figure 5.3 shows the box plot developed using the speed percentiles with the data collected from four lane divided road sections. It is observed that the Section III has highest mean speed and Section I has the lowest mean speed. The highest mean speed on Section III is observed due to the low road side activity. Figure 5.4 shows the box plot developed using the speed percentiles estimated for six lane divided road sections. It is observed that the Section VI has the highest mean speed as it has negilible amount of road side activities.

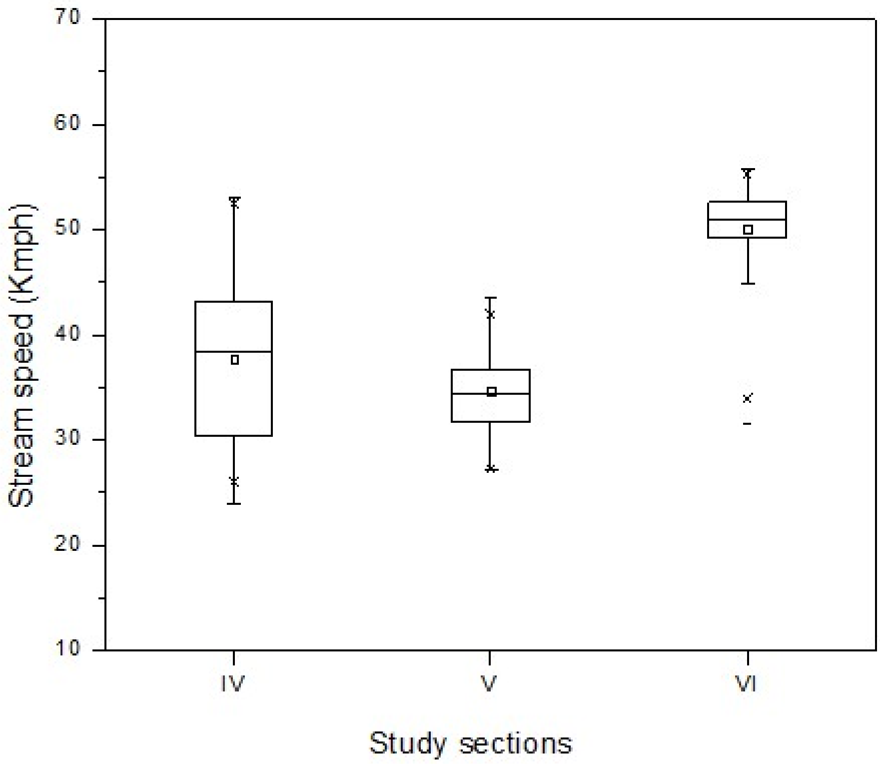


Figure 5.4 Box plot of speed datafor six lane roads

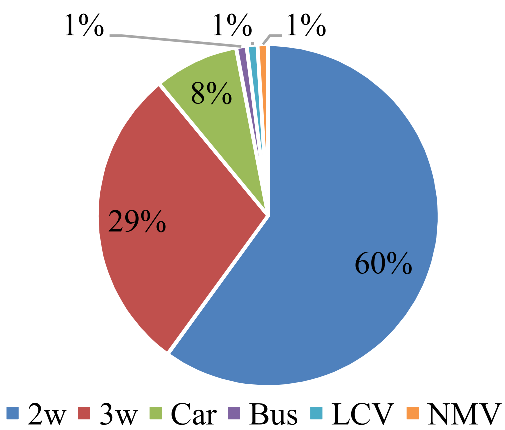
5.3. ANALYSIS OF TRAFFIC VOLUME

The classified vehicle count data is extracted from the recorded video at 1 minute interval for estimation of traffic volume. The 5 minute moving total is obtained from the extracted data for further analysis. The descriptive analysis of traffic volume is performed and the useful information such as minimum, maximum and average values are obtained with respect to each roadway section as given in Table 5.3.

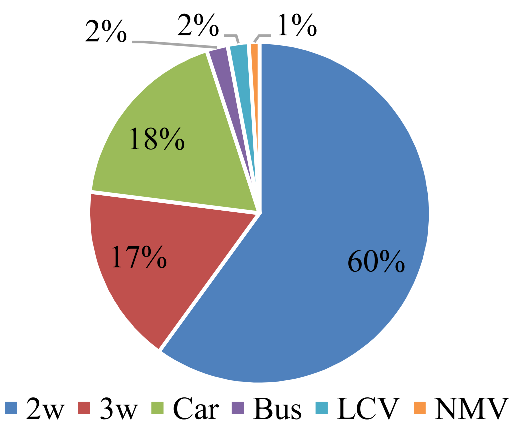
Table 5.3 Details of the traffic volume at study sections

Section	Traffic volume (veh/hr)		
	Maximum	Minimum	Average
I	4068	684	2559
II	3348	612	2356
III	2976	456	1784
IV	3288	780	2137
V	4140	444	2255
VI	4644	1380	3171
VII	2998	1256	2014
VIII	3960	1458	2396

The traffic composition of the traffic observed at each section is obtained as shown in Figure 5.5. It is observed that vehicle Type 2W is dominating in the traffic stream due to its high percentage in compared to other vehicle types. 3W vehicle type has equal proportion compared to 2W at section VII and is lesser compared to 2w at other study sections. The percentage of car is observed to be the lowest at sections VII and VIII which is near about 20%.



(a)



(b)

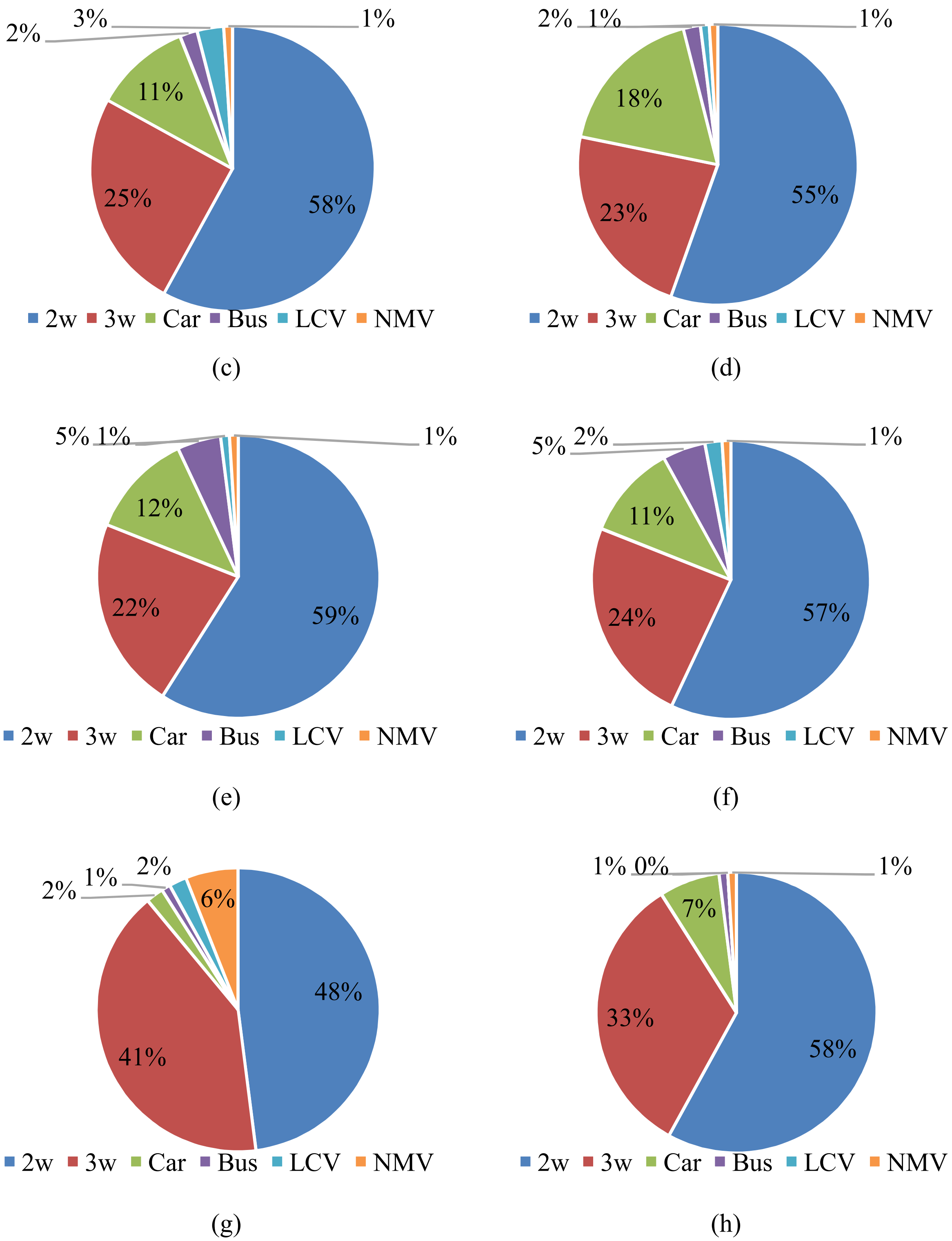


Figure 5.5 Vehicle composition at (a) Section I, (b) Section II, (c) Section III, (d) Section IV, (e) Section V, (f) Section VI, (g) Section VII, (h) Section VIII

5.4. CONVERSION OF TRAFFIC VOLUME

On the selected urban road sections, traffic stream consists of several vehicle types such as two wheeler, bus, three wheeler, LCV, NMV and passenger car. The heterogeneous traffic volume observed at roadway sections is essentially converted into homogeneous traffic volume by selecting appropriate car equivalency unit known as passenger car unit (PCU). The PCU value defined for each vehicle type is used as multiplying factor to convert heterogeneous traffic volume into a traffic volume consists of equivalent number of passenger cars.

The popular methods suggested in literature have proven well under less heterogeneous traffic conditions where the vehicle types other than passenger car are few in number. The heterogeneous traffic conditions as prevailing on Indian roads, vehicles with widely varying physical and kinematic characteristics influence the traffic flow behavior and its measurements. Therefore, dynamic PCU method is used in the present study for conversion of traffic volume that considers both static and dynamic properties of vehicles. Chandra et al. (1995) introduced dynamic PCU to convert highly heterogeneous traffic volume for urban mid-block roadway section. Speed represents the true interaction between vehicles and shows the dynamicity nature of the traffic. As interaction among the vehicles is based on their speeds and physical size, the dynamic PCU of a vehicle type is calculated based on the speed ratio and area ratio of passenger car to the subject vehicle type. The expression for estimating PCU values is given by Equation (5.1).

$$PCUi = \left(\frac{Vc}{Vi}\right) / \left(\frac{Ac}{Ai}\right) \tag{5.1}$$

where, PCU_i = Passenger car unit of the subject vehicle type ‘i’,

V_c = Average Speed of the passenger car,

V_i = Average Speed of the subject vehicle type ‘i’,

A_c = Projected area of the passenger car,

A_i = Projected area of the subject vehicle type ‘i’.

The passenger car is defined as a vehicle type Car with a length of 3.5m, width of 1.70m and having engine power 1200cc. The PCU of vehicle types are estimated at every 5 min interval and converted the heterogeneous traffic volumes in the terms of PCU per hour. The descriptive analysis of the estimated PCU values of each vehicle type is performed and the results are presented in Table 5.4.

Table 5.4 Estimated dynamic PCU of vehicle types

	Minimum	Maximum	Mean	Std.Dev	N
2W	0.14	0.37	0.21	0.03	1040
3W	0.48	1.16	0.74	0.09	1012
Bus	3.42	8.68	5.73	0.81	829
LCV	0.50	1.71	0.98	0.14	774
NMV	0.13	1.01	0.43	0.14	566

The highest variation among PCU values is found for Bus and the lowest variation is observed in case of vehicle Type 2W. The speed difference between Car and 2W is low which resulted in lower variation in PCU value of vehicle Type 2W. The average speed of the Car is higher than the average speed of Bus during low volume. If volume increases the effect of area of bus starts dominating that reduce the speed of car and make it equal to speed of Bus. These two aspects resulted in higher variation in PCU of Bus.

5.5. ANALYSIS OF ROADWAY SIDE FRICTION

According to Indo-HCM (2017), side friction is defined as the physical features that are likely to impede the traffic flow. Side friction activities are generally observed on urban roads in and around city centers or commercial zones. In the present study, significant side friction activities have been observed on some of the roadway sections. The type of general activities those are observed on roads are; movement of pedestrian and slow moving vehicles near potential shopping centers (shopping malls), street vendor occupations, provision of curb side bus stops, on-street parking, frequently stopped vehicles to pick up the passengers etc. To simplify the analysis, various activities those are considered to be affecting the uninterrupted movement of vehicles are grouped and termed as side friction elements.

Table 5.5 Frequency of side friction events at all study sections

Section	Side friction element type	Frequency (Events/hr)		
		Maximum	Minimum	Average
I	Pedestrians	1356	72	599
	Parked	216	24	86
	Entry-exit manoeuvres	192	12	69
	Wrong way vehicles	48	12	27
II	Pedestrians	240	36	116
	Parked	120	12	61
	Wrong way vehicles	132	12	37
III	Pedestrians	72	12	32
	Parked	24	12	8
IV	Pedestrians	636	84	218
	Parked	156	12	60
	Wrong way vehicles	60	12	19
V	Pedestrians	516	48	197
	Parked	180	12	104
VI	Pedestrians	192	12	73
	Parked	48	12	21
	Wrong way vehicles	144	12	33
VII	Pedestrians	56	12	24
	Parked	26	12	14
VIII	Pedestrians	316	48	126
	Parked	156	24	56
	Entry-exit manoeuvres	98	12	24

	Wrong way vehicles	46	12	16

The side friction elements in the present study are observed from video data and frequency of each element within study section was obtained as explained in Chapter 4. The frequency of side friction events as observed at study sections is given in Table 5.5. The pedestrian movement as one of the side friction elements is found to be dominating on all the roadway sections. The individual side friction element has been analysed over the time period and trends have been observed. Figure 5.6 and 5.7 provide variation of the individual side friction activity over given time interval on study Sections I and II respectively.

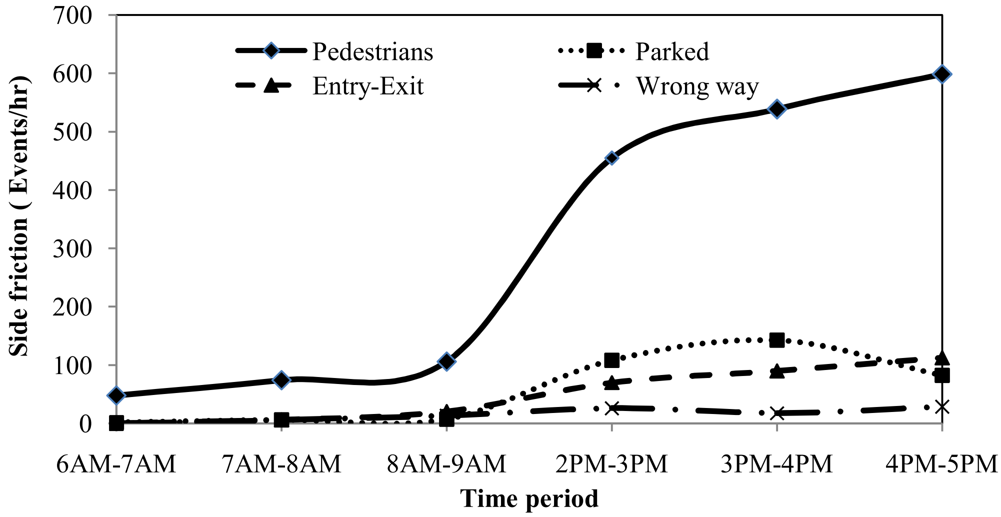


Figure 5.6 Variation of side friction events over time at section I

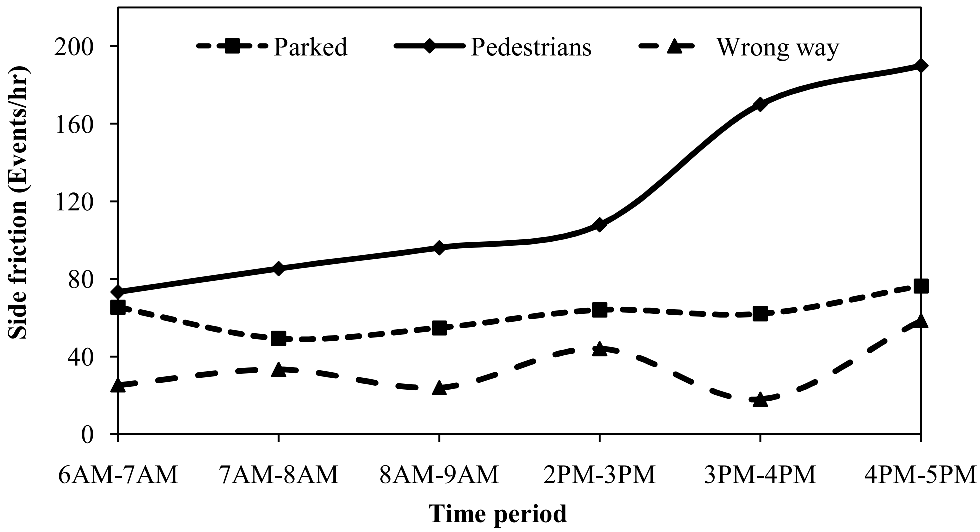


Figure 5.7 Variation of side friction events over time at Section II

It is observed that pedestrian activity at Section I is rising highly in compared to other activities. The parked vehicles and wrong way vehicle movements are not following certain trend and are more or less constant throughout the time period, whereas frequency of pedestrian activity is gradually increasing during the day time and is observed to be very high during evening time. The details of hourly side friction events for each study section are given in Table 5.6. It is observed that the occupation of side friction events is high in the evening time particularly from 3PM-5PM and low in the morning time.

Table 5.6 Total side friction at different roadway sections

	Side friction (Events/hr)					
Section	6AM-7AM	7AM-8AM	8AM-9AM	2PM-3PM	3PM-4PM	4PM-5PM
I	49	83	127	557	664	710
II	164	168	175	216	250	305
III	48	56	138	146	158	162
IV	211	224	257	414	368	280
V	198	254	222	273	246	352
VI	60	71	120	130	144	144
VII	*NA*	86	148	128	194	*NA*
VIII	*NA*	248	268	312	358	*NA**

NA-Not Available*

5.6. SUMMARY

The analysis of traffic flow data collected from the field has been discussed in present Chapter. Speed profile each vehicle type has been analysed. It is found that the highest and lowest speed variations are found for the vehicle types Car and NMV respectively. The traffic composition obtained for the road sections showed that more than 50% of the traffic comprises of 2Ws in the traffic stream. The study also estimated traffic volume by converting heterogeneous type traffic flow into homogeneous one by using dynamic PCU method. The side friction data reveals that pedestrian activity on the side of the road dominates over other activities as the frequency of pedestrian activities are higher throughout the observation time period.

Chapter 6

ANALYSIS OF SIDE FRICTION

6.1 GENERAL

This chapter presents the methodology to quantify the side friction on urban arterials. The influence of side friction on traffic flow characteristics has been analysed and presented different levels of side friction based on their influence on stream speed.

6.2 ROADWAY SIDE FRICTION

The increase in vehicular population on urban roads specifically in developing countries results in congestion which exhibits a scenario that a roadway is not able to cater the increased demand. In addition to the vehicular population, the interference of ongoing traffic flow with the road side activities is a major cause of deterioration of roadway service performance. These road side activities are usually occur on the edge of road or on shoulders or sometimes on carriageway of a busy urban streets referred as side friction. Side friction includes several activities such as street vendors, busstops, auto-stands, on street parking etc. The street vendoring causes movement of the pedestrians along and acorss the road for buying nesserary things from road side. Also, it attracts passengers to stop for a while and leads to on-street parkings road side. Bus-stops and auto-rikshaw stops are the additional spots where frequent pick up and drop activities take place. Entry and exit of vehicles from parking facilities reserved for shopping malls and other commecial complex occur as additional side friction and that also invite wrong way vehicle movement on roadway. Some of these activites may occur for short duration and sometimes occur for longer duration by occupying certain width of carriageway. The interaction of these activities with traffic stream affects the ongoing vehicular traffic flow and causes recurrent congestion on urban roads. Although there are sevral side friction factors that influences the traffic performance, for the present study pedestrian movement on the road, parking manuovers, entry-exit vehicles and wrong movement vehicles have been considered for analysis.

6.3 QUANTIFICATION OF SIDE FRICTION

The main side friction activities observed on roadway sections are extracted from the videos at 5min interval. Further, identified activities are categorised into two different groups such as static type and dynamic type. The static types are referred as parked vehicles and pedestrians, and dynamic types are referred as entry-exit vehicle maneuvers, wrong way vehicle movements. The basic assumption made in the study is the movement of pedestrians along the road considered as negligible in compared to movement of the vehicular traffic. All these activities are summed to get the frequency of the combined side friction for a roadway section. However, the effect of these road side activities is found to be varied with the movement of traffic flow. Therefore, the sensitivity of individual road side activities are examined by estimating weighing factors based on its effect on stream speed. Table 6.1 shows the frequencies of each road side activity at 5minute interval for selected roadway sections.

Table 6.1 Frequency of road side activity for study sections

Activity type	**Frequency (Events/hr) at roadway section**			
	I	**II**	**VI**	**IV**
Pedestrians	600	120	72	228
Parked vehicles	456	348	36	600
Entry-exit	48	*NA*	*NA*	*NA*
Wrong movement	24	36	24	24

** NA: Not observed at the study section*

6.3.1. STATIC SIDE FRICTION MEASUREMENT

The static side friction activities such as presence of pedestrians and parked vehicles are combined together for measurement of static side friction. A procedure suggested by Pal and Roy (2016) is followed for estimating total static side friction. According to the procedure, equivalent pedestrian units (PEU) are calculated for each parked vehicle type within the influencing area. The expression used for converting parked vehicle types into equivalent number of pedestrian units is given in Equation (6.1).

$$PEU_i = \frac{PA_i}{PA_p} \quad (6.1)$$

where, PEU_I = Equivalent pedestrian unit of the parked vehicle type

PA_{i} =Projected area of the parked vehicle type

PA_{p} = Projected area of the pedestrian

The PEU of vehicle type is estimated by taking the ratio of projected area of parked vehicle type to the projected area of pedestrian. Table 6.2 shows the PEU values estimated for each parked vehicle type. Projected are of the vehicles are taken from the field study conducted in the previous study (Madhuri.K, (2016)).

Table 6.2 PEU of parked vehicle types

Travel Mode	Projected area (m^2)	PEU
Pedestrian	0.50	1.00
2W	1.23	2.46
3W	3.90	7.80
Car	7.27	14.53
Bus	31.20	62.40
LCV	5.35	10.69
Bicycle	1.12	2.23

Further, PEU of vehicle type is multiplied with the frequency of parked/stopped vehicle types to achieve uniformity in measurement of static side friction. The PEU values are used for estimating frequency of static side friction by combining both pedestrian and parked vehicles. The expression for finding the static side friction is given in Equation (6.2) in terms of PSPU (events/hr) i.e. pedestrians and stopped/parked vehicles in terms of pedestrian units.

$$N_{PSPU} = N_P + \sum_{i=0}^{n} (PEU_i \times N_i) \quad (6.2)$$

where, N_{PSPU}= Frequency of pedestrians and stopped/parked vehicles in pedestrian units

N_P= Frequency of pedestrians

PEU_i= Equivalent pedestrian unit of the parked/stopped vehicle

N_i = frequency of the parked/stopped vehicle

6.3.2. COMBINED SIDE FRICTION MEASUREMENT

Side friction (SF) is calculated by estimating weighing factors of the events or activities observed on the road side. Chiguma (2007) estimated the standardised coefficients and weighing factors of road side friction elements using regression method. Similar methodology is adopted in the present study to find the relative weight of each road side activity. The regression analysis was performed by considering stream speed as dependent variable for finding relative weights of activities observed on the road side. The relative weights of side friction elements as calculated on the selected road Sections I, II and VI are given in Table 6.3, 6.4 and 6.5 respectively.

Table 6.3 Results of regression analysis for Section-I

Variable	Coefficients	t- value	p-value	Relative weights
constant	36.78	73.16	0.000	
PSPU	-0.05	-8.78	0.000	1.00
Entry-exit	-0.54	-4.22	0.000	0.48
Wrong way	-0.11	-0.34	0.732	0.04

The data of Sections I, II and VI is combined and regression analysis is repeated by keeping the speed as dependent variable and side friction events as independent variables. Table 6.6 shows the result of the regression analysis performed for the aggregated data of selected sections.

Table 6.4 Results of regression analysis for Section-II

Variable	Coefficients	t- value	p-value	Relative weights
constant	37.15	72.82	0.000	
PSPU	-0.05	-6.06	0.000	1.00
Wrong way	-0.18	-1.56	0.125	0.30

Table 6.5 Results of regression analysis for Section-VI

Variable	Coefficients	t- value	p-value	Relative weights
constant	37.93	59.03	0.000	
PSPU	-0.12	-2.35	0.023	1.00
Wrong way	-0.29	-2.31	0.125	0.98

Table 6.6 Results of regression analysis for combined data

Variable	coefficients	t-value	p-value	Relative weight
Constant	37.06	138.39	0.000	
PSPU	-0.05	-11.88	0.000	1.0
Entry-exit	-0.53	-6.29	0.000	0.5
Wrong movement	-0.21	-2.52	0.013	0.1

Relative weights are measured based on standard coefficients and multiplied with the frequency of side friction events to get the total side friction. The total side friction in the present study is calculated by using the Equation (6.3). Total side friction is the summation of all road side activities determined based on their weighing factors. It is clear that static side friction activity has more impact compared to other activities, thus it has more weightage relative to other activities.

$$SF = RW_1 * (N_{PSPU}) + RW_2 * (N_{EE}) + RW_3 * (N_{WM}) \quad (6.3)$$

where, SF= Side friction (Events/hr)

N_{PSPU} = Frequency of pedestrians and parked/Stopped vehicles

N_{EE} = Frequency of entry-exit vehicles

N_{WM} = Frequency of wrong movement vehicles

RW = Relative weights of each activity type

6.4 EFFECT OF SIDE FRICTION ON SPEED

The total side friction is estimated for each study section and correlated it with average stream speed. Figure 6.1, Figure 6.2 and Figure 6.3 showing the variation of side friction with stream speed observed at Section I, II and VI respectively.

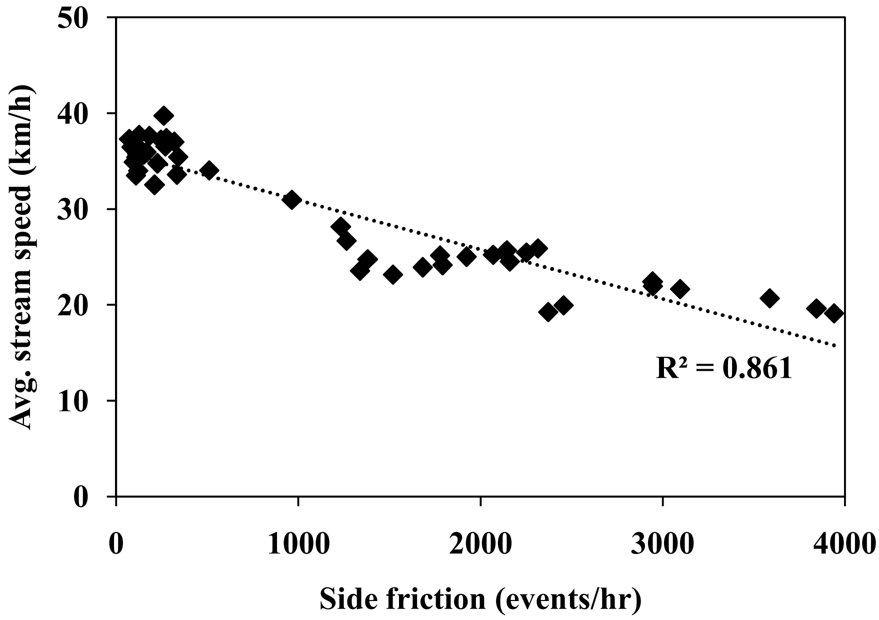


Figure 6.1 Variation of stream speed with side friction at Section I

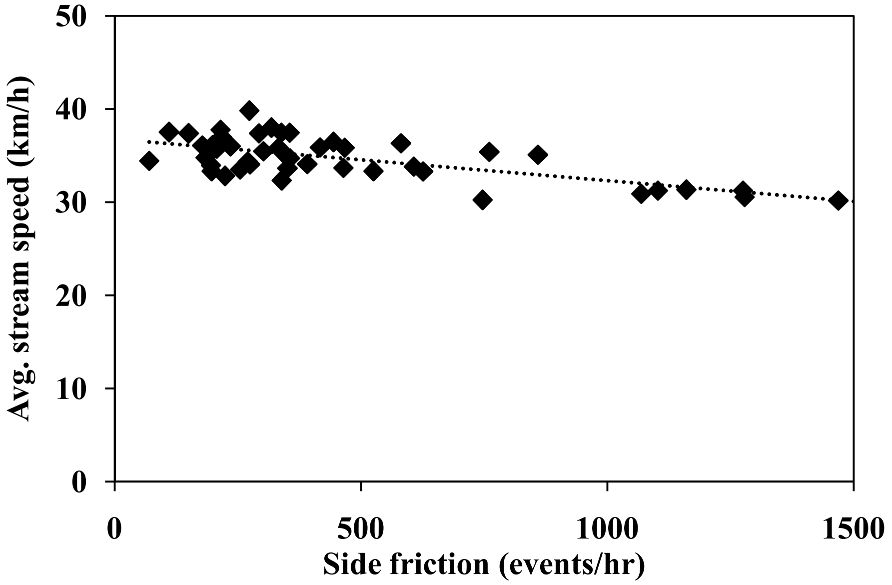


Figure 6.2 Variation of stream speed with side friction at Section II

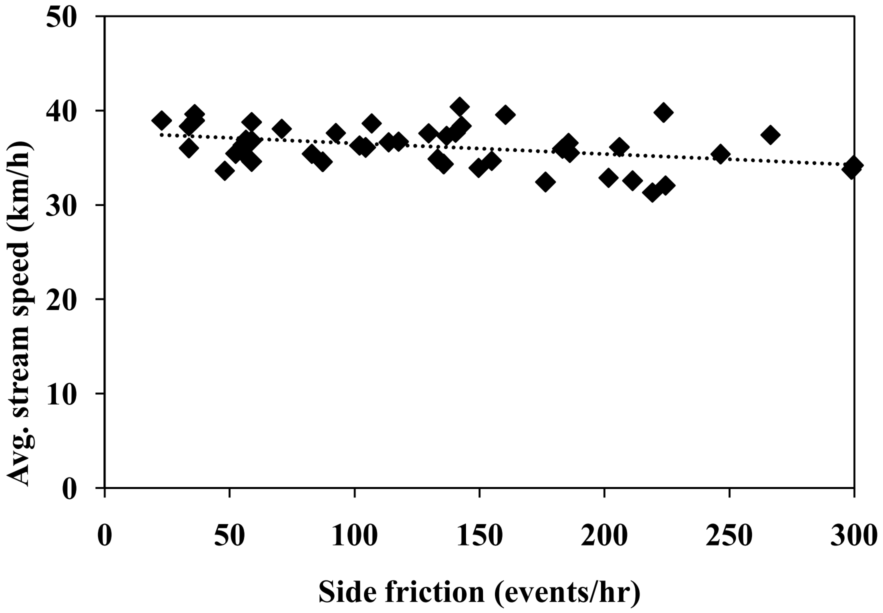


Figure 6.3 Variation of stream speed with side friction at section VI

It may be observed that the average stream speed is gradually reducing with the increase in total side friction on the study sections. A slight decrease in the average stream speed has been observed with increase in total side friction at study Section II. The carriageway width of the study Section II is higher than Section I. Therefore the influence of side friction at on speed is less at this location even at higher number of side friction events. However, there is no significant change in the average stream speed observed with increase in the total side friction on Section VI.

6.5 CLASSIFICATION OF SIDE FRICTION LEVELS

The side friction prevailing on different study sections are found to be changed along with the average stream speed. Therefore, stream speed is used for classifying the levels of side friction to understand its influence on traffic flow characteristics. For this purpose, the variation of average stream speed with side friction for the combined data is plotted. The average stream speed is found to be declining consistently with the increase in total side friction estimated and combined for all study sections. Figure 6.4 shows the variation of stream speed with side friction for the combined data.

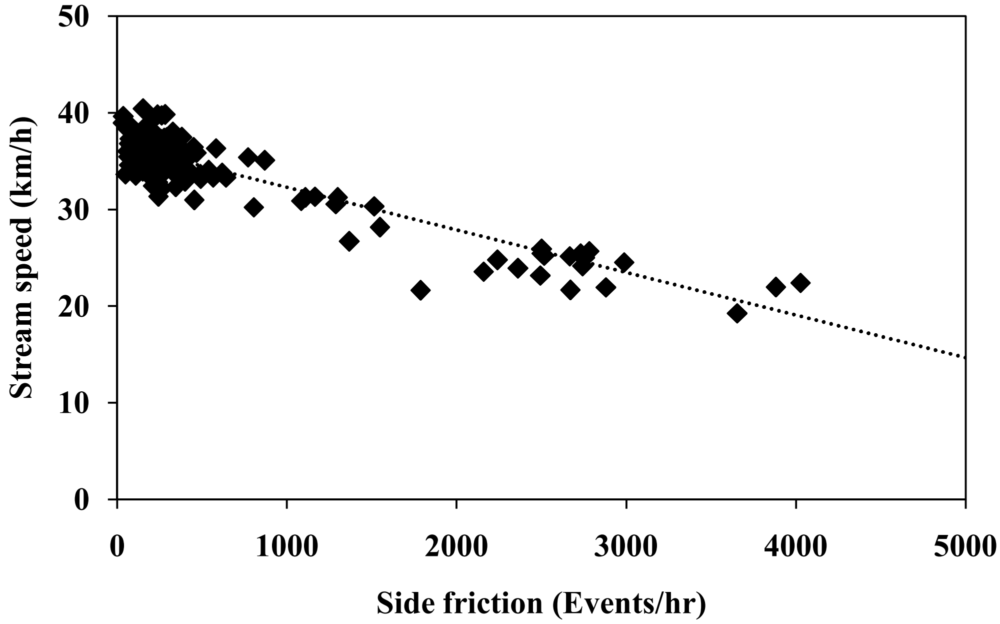


Figure 6.4 Variation of speed with side friction for the combined data

From Figure 6.4, at various levels the side friction is classified into four levels ranging from low to very high based on the variation in the average stream speed. Here, low level indicates the side friction events which are less than 500 events/hr, medium level indicates the presence of side friction events which are in between 500-1000 events/hr, high level indicates the presence of side friction events which are in between 1000-2000 events/hr and very high level indicates the side friction events which are more than 2000 events/hr. At lower levels of side friction, no significant change is observed in average stream speed whereas at higher levels the reduction is significant. Table 6.7 provides the quantity and level of side friction with reduced stream speed after combining field data.

Table 6.7 Levels of side friction at different speeds

SF (Events/hr)	Level of side friction	Average stream speed (km /h)	% Reduction in average speed
0-500	Low	34	-
500-1000	Medium	31	20
1000-2000	High	24	38
>2000	Very high	19	51

It may be observed that the reduction in the stream speed at higher level of side friction is estimated as 51 percent using avg. stream speed at low side friction level as reference value.

6.6 DEVELOPMENT OF SPEED PREDICTION MODEL

The effect of side friction on average speed of vehicular traffic stream has been analysed in the previous section. Further, study develops a model for predicting average stream speed based on traffic volume and side friction as influencing variables. Field data collected on Section I, II, and VI is used to perform multiple regression (MLR) analysis for the development of model. The coefficients of a multiple linear regression model are obtained by considering average stream speed as dependent variable. The result of MLR analysis is given in Table 6.8. The result showed that the t-value obtained for each independent variable is statistically significant at 95% confidence level as p-value obtained in the result for variables are very much smaller than 0.05.

Table 6.8 Result of MLR analysis for predicting average stream speed

	Coefficients	t-value	95% confidence interval	
			Lower bound	Upper bound
Constant	45.00	73.43	42.80	45.16
Flow	-0.005	-10.41	-0.005	-0.004
SF	-0.040	-12.25	-0.043	-0.029

An expression proposed for prediction of stream speed on multilane divided urban roads is given in Equation (6.4).

$$V = 45.0 - 0.04 \times SF - 0.005 \times Q \quad (6.4)$$

where, V = Average stream speed (km/h),

SF = Side friction (Events/hr)

Q =- Traffic volume (pcu/hr)

The validation of the speed model was also performed by using observed traffic flow and speed data on Section IV. The data obtained from Section IV is used for calculating average speed by using field input volume and side friction data. The average stream speed is estimated at every 5 min interval and compared with the actual speed observed in field (Section IV). The validation plot between predicted and observed stream speed is developed as shown in Figure 6.5. A non-parametric test such as Chi –square test was also applied to check whether the difference between the average speeds is significant. The theoretical chi-square value was obtained as 5.98 against the critical value (25.7) at 95% confidence level with 39 degree of freedom. Hence, null hypothesis was accepted as there is no significant difference between the modeled and observed average speeds of vehicular traffic stream.

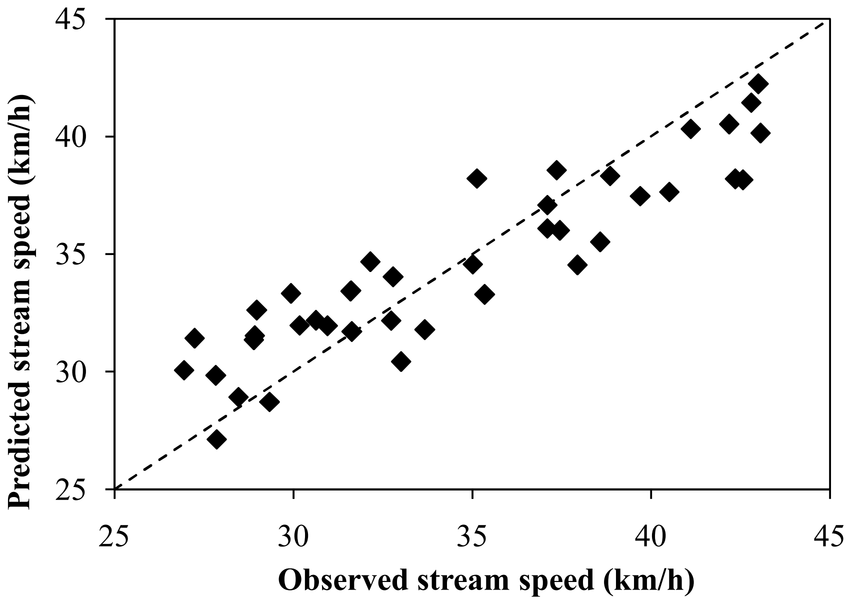


Figure 6.5 Validation of speed model

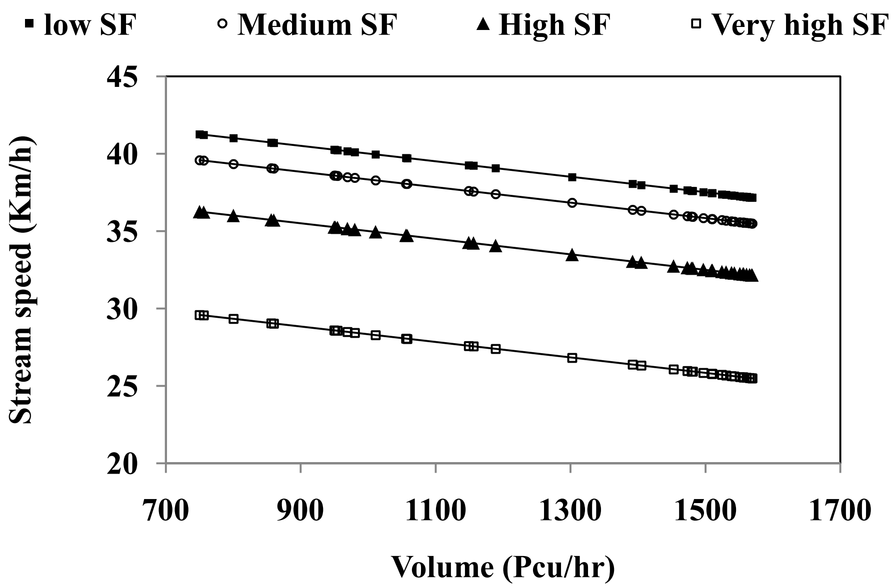


Figure 6.6 Variation of speed at different side friction levels for section IV

Further, average stream speeds from the proposed model are estimated at different levels of side friction on Section IV. Figure 6.6 shows the variation of average stream speed with different levels if side friction estimated from the proposed model. From Figure 6.6, a clear demarcation in average stream is observed among all the four levels of side friction. Also continuous reduction in the stream speed with increase in volume at various levels of side friction was observed.

6.7 SUMMARY

The quantification of the side friction on the urban roads is presented in this chapter. It is observed that the pedestrian activity considered as one of the road side friction event is found to be most influencing factor on all the study sections. The variation of speed with side friction at selected study sections is analysed and classification of side friction into various levels based on the stream speed is presented. At low level of side friction the average speed was observed as 34 km/h and at higher level the average speed was obtained as 19 km/h. Therefore, the reduction was measured as 51 percent which is quite significant. Also, Speed prediction model was developed taking flow and side friction as independent parameters. RMSE found as 14% and Chi- square test was performed to validate the model on the test site and found the speeds predicted were statistically significant.

Chapter 7

ESTIMATION OF PASSENGER CAR UNITS

7.1. GENERAL

This chapter deals with the estimation and analysis of PCU value for different types of vehicle using field data collected on various sections of urban roads. The PCU of subject vehicle types has been estimated using dynamic PCU method under varying side friction levels, roadway width, vehicles proportional share and traffic volume levels. The multiple linear regression analysis is performed for developing a model to estimate the PCU of subject vehicle types. Further, a proposed MLR model is also performed by using field data collected on road with similar characteristics. An ANFIS model is used in order to optimize the PCU vehicle types by considering traffic volume and roadway characteristics as different criteria. Further, a comparison is made between regression models and ANFIS model to examine the better performance of PCU values.

7.2. ANALYSIS OF DYNAMIC PCU

PCU or PCE is the term used as a factor for converting classified vehicular traffic volume into homogeneous one to simplify the planning, design and evaluation methodologies. The design and evaluation of traffic flow system depends on accurate estimation of traffic volume. The conversion of traffic volume is mainly based on the estimation of correct PCU values of vehicle types which is a challenging task in evaluation of traffic performance measures under the mixed traffic conditions. PCU estimation has been an interesting subject for a study from many decades. Mixed traffic condition involves several factors that impart uninterrupted traffic flow and affects it over the time especially on typical urban roads. Moreover, many factors such as vehicular characteristics, environmental characteristics, stream characteristics, roadway characteristics affect PCU values (Anand, 1999). Therefore, the influence of various factors related to traffic flow and roadway characteristics are analyzed in this chapter.

The study estimates PCUs of vehicle types using dynamic PCU method as. In the present Chapter, factors influencing PCUs have been considered based on the field collected data. The variables such as traffic volume, side friction, proportional share and carriageway width are considered for analysis. Variation of these factors on estimated PCUs of vehicle types considered in the present study is discussed in the following manner.

Traffic volume: The variation of estimated PCUs with respect to traffic volume as observed on different roadway sections is analysed. The PCUs of smaller size vehicles such as 2W and 3W are found to be decreased with increase in traffic volume. However, PCUs of bigger sized vehicle type such as Bus, LCV have not been affected much. Therefore, small sized vehicles are very much able to mobilise the traffic stream on urban roads even in the higher volume by vacating spaces. Figure 7.1, 7.2, 7.3 and 7.4 are showing the variations of PCU of vehicle types 2W, 3W, LCV and Bus respectively.

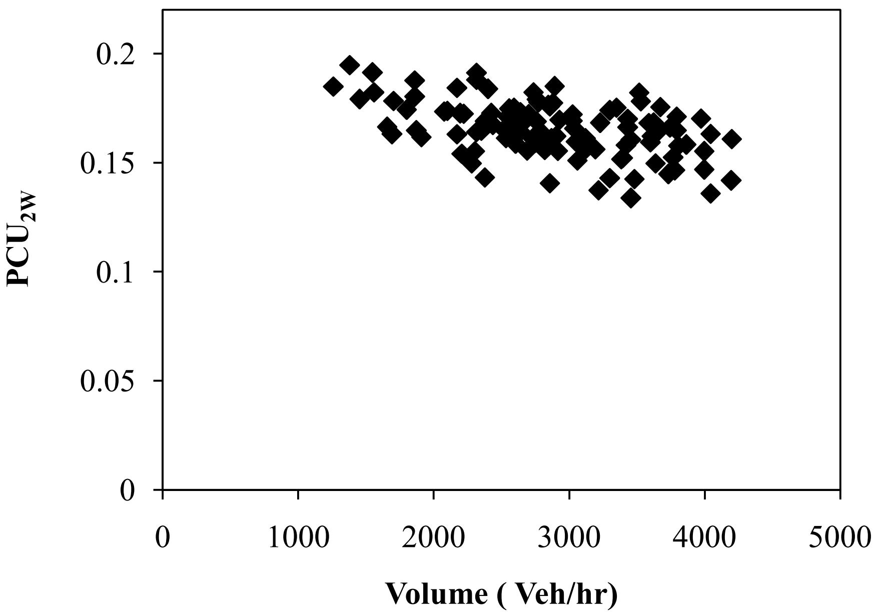


Figure 7.1 Variation of PCU of 2W with traffic volume

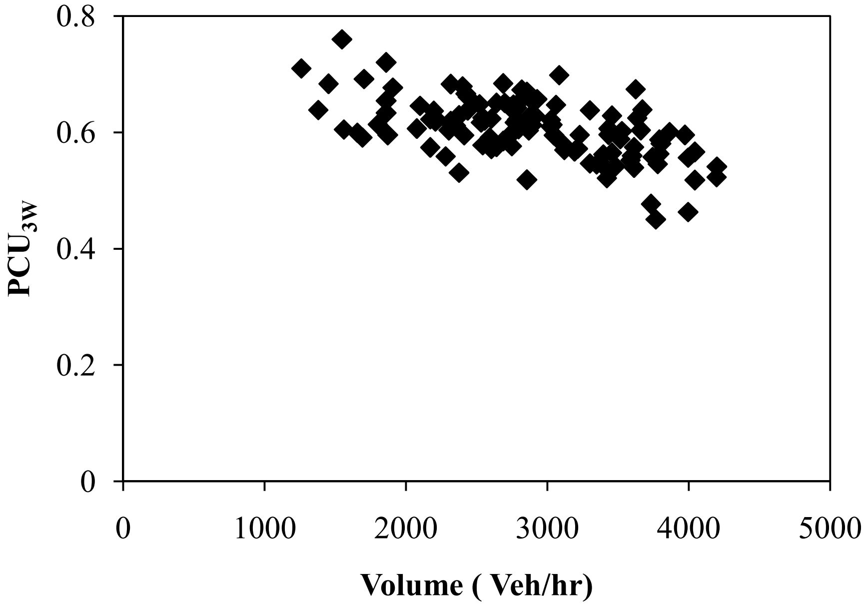


Figure 7.2 Variation of PCU of 3W with traffic volume

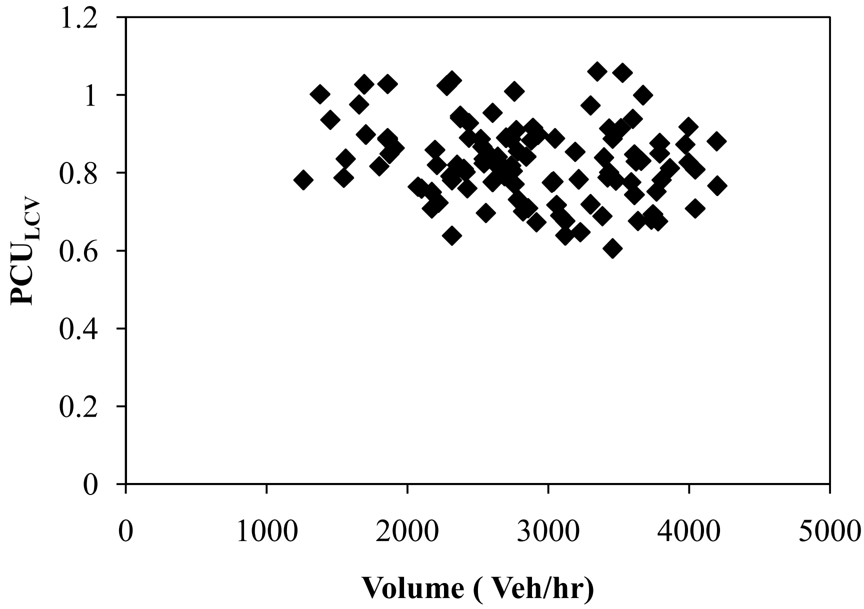


Figure 7.3 Variation of PCU of LCV with traffic volume

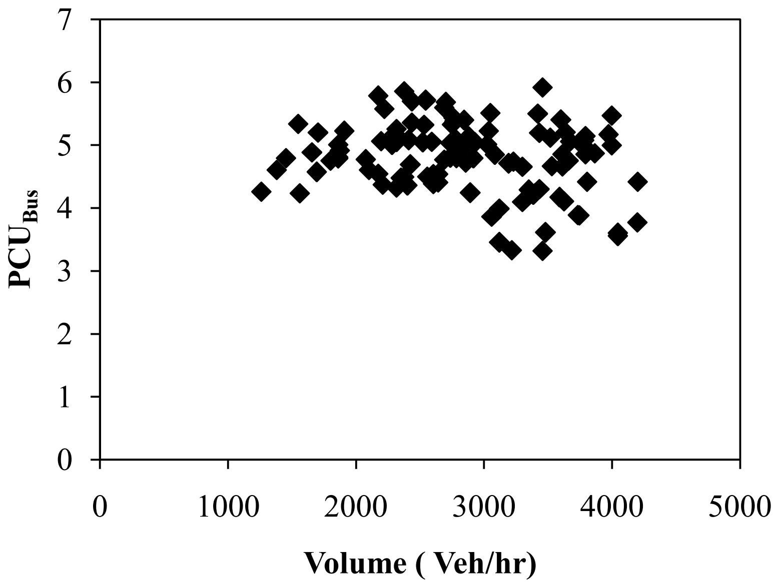


Figure 7.4 Variation of PCU of Bus with traffic volume

Side friction: PCU values estimated for selected vehicle types are varied with side friction observed at study locations. The change in PCU of vehicles is observed significantly with change in side friction levels lower to higher. For instance, PCU values at various side frictions are shown for Types 2W and Bus in Figure 7.5 and 7.6 respectively.

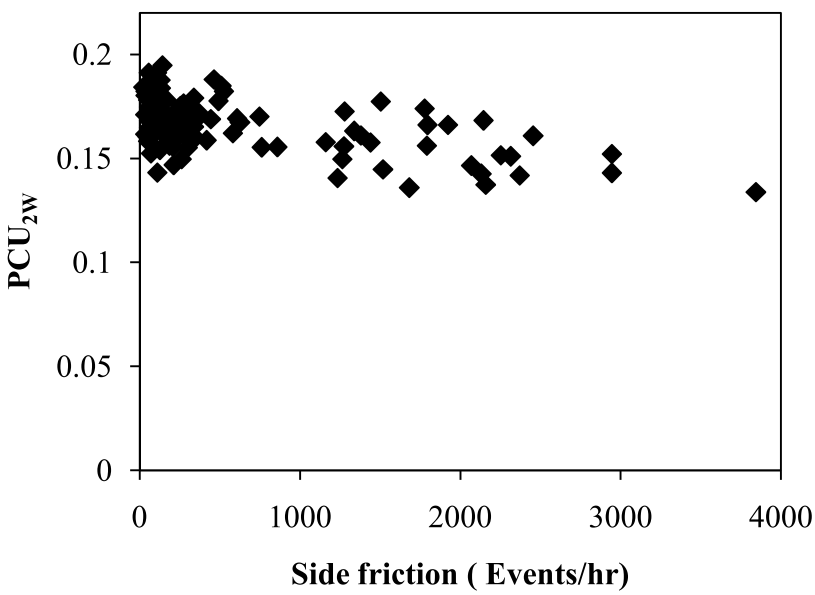


Figure 7.5 Variation of PCU of 2Wwith Side friction

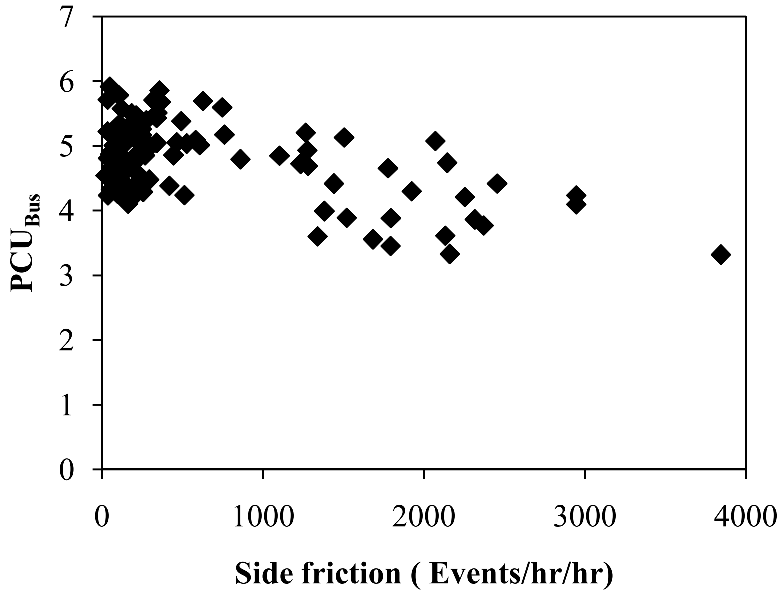


Figure 7.6 Variation of PCU of Bus with Side friction

Irrespective of the size of vehicles, PCUs of all observed vehicle types are found to be decreased with increase in side friction. However, at a lower side friction level the PCU of vehicle types are remained unchanged. It may be due to a higher side friction tends to increase the density of traffic stream that causes reduction in the stream speed.

Proportional share: The PCUs of a vehicle types estimated from field data have been analysed under different proportional share of their own vehicle types. As a result, the proportional share of subject vehicle types is found to be influencing on PCUs of vehicle types bus and 2W. However, no such variation has been observed in case of 3W, LCV, NMV types of vehicle. Figures 7.7 and 7.8 depict the PCU of vehicle types 3W and 2W with respect to their own proportional shares in the traffic stream.

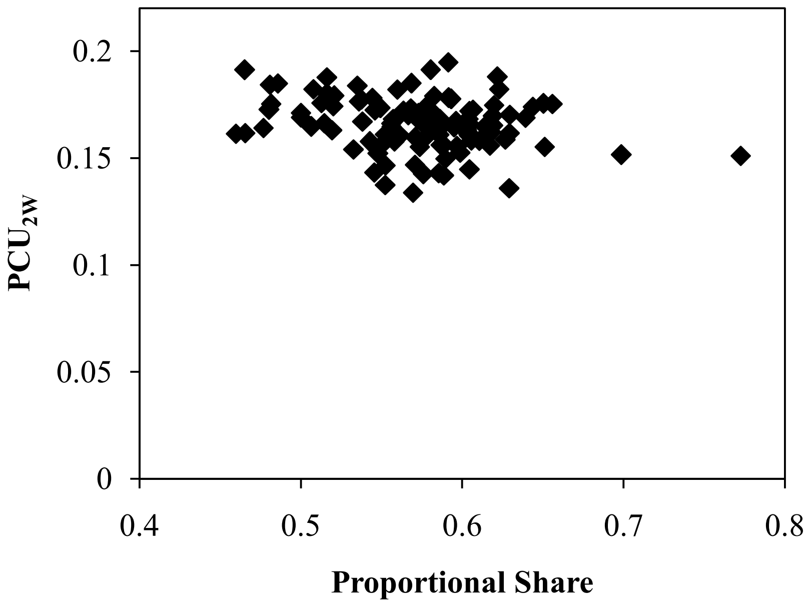


Figure 7.7 Variation of PCU of 2W with proportional share

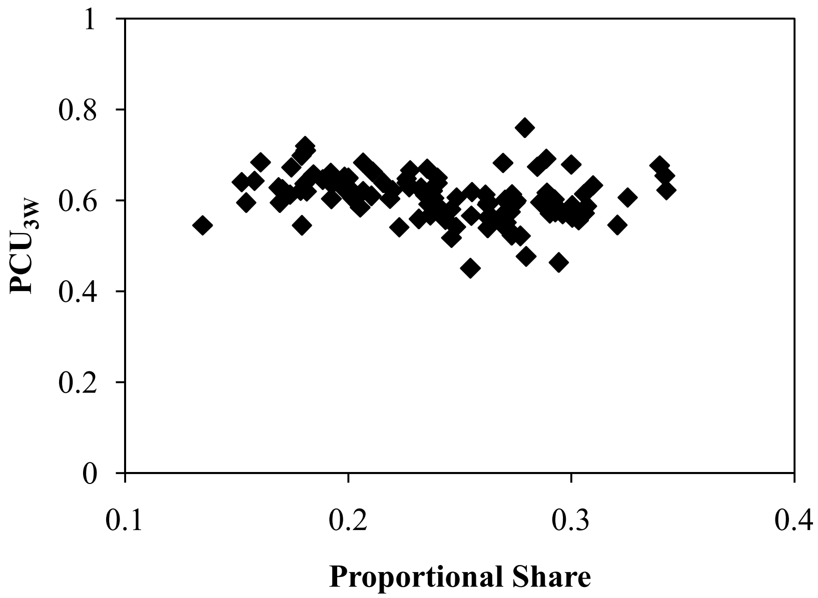


Figure 7.8 Variation of PCU of 3W with proportional share

Roadway width: Roadway width is an important parameter that can affect the PCU of vehicle types on urban arterials. The effect of roadway width on PCU of all subject vehicles was analysed in the present study. The results showed that the PCU of subject vehicles is found to be increasing with the increase in the roadway width due to increase in speed differences between vehicle type Car and subject vehicle types. It indicates a wider roadway provides more freedom for lateral and longitudinal movements especially under low volume conditions. The PCUs of subject vehicle types estimated in present study varied at different roadway widths are shown in Figures 7.9 and 7.10.

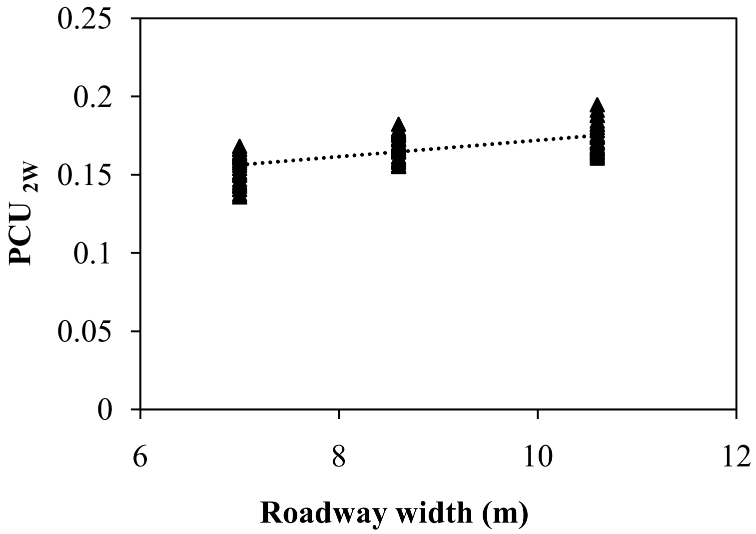


Figure 7.9 Variation of PCU of 2W with roadway width

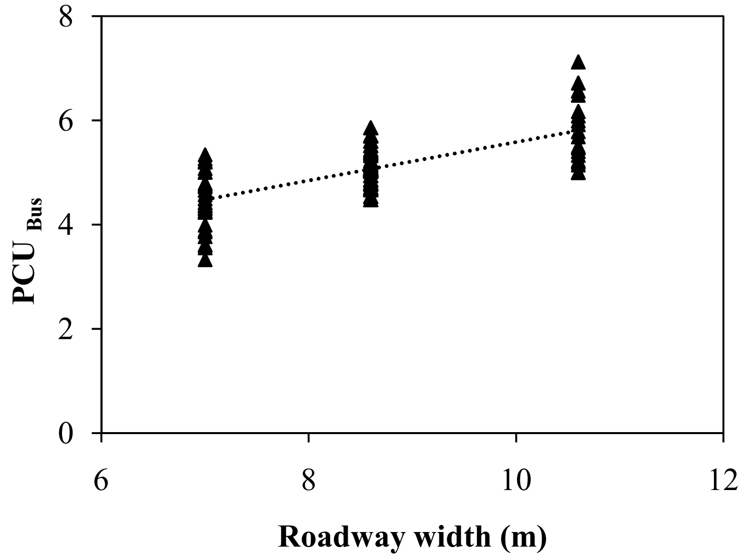


Figure 7.10 Variation of PCU Bus with roadway width

After analysing the factors affecting PCU of vehicle types, present study performs a detailed analysis on PCU using multiple linear regression (MLR) and Adaptive neuro-fuzzy inference system (ANFIS) methods. The factors identified in the preliminary analysis are used in the analysis such as traffic volume, side friction, proportional share and roadway width. A total five sections are considered for the analysis in which Section I, Section II and Section VI are used for the development of models and Section III and Section IV are used for the validation analysis. Further, comparison was made between both methods to check the accuracy in estimation of the PCU of vehicle types. And the basic structure of MLR and ANFIS methods used for the estimation PCU are explained in detailed manner in the following sections.

7.3. MULTIPLE LINEAR REGRESSION (MLR) ANALYSIS

The oldest and traditional modeling technique is linear regression which has been used by many researchers. The general form of the regression equation is given in Equation (7.1)

$$Y = \alpha + \beta X^T + \varepsilon \qquad (7.1)$$

where, Y represents the dependent variable, X (X1, X2…) represents the independent variable, α represents constant and ε represents the standard error and any other error which is unexplained by the linear regression model. In the present study the regression analysis was performed by considering the PCU of vehicle type as dependent variable and side friction, traffic volume, proportional share and roadway width as independent variables.

7.3.1. DEVELOPMENT OF THE MLR MODEL

The effect of multiple parameters has been analyzed to develop a regression model for predicting PCU values of vehicle types. The multiple linear regression model (MLR) for estimating PCU was constructed by considering traffic volume, roadway width, proportional share and side friction as independent variables. A general equation for estimating PCU of subject vehicle type is given in Equation (7.2).

$$PCU_i = \alpha + (a \times Q) + (b \times W) + (c \times SF) + (d \times P_i) \qquad (7.2)$$

where, PCU_i = Passenger car unit of subject vehicle type i,

Q = vehicular volume per hour,

W	=	roadway width
SF	=	side friction events per hour.
P_i	=	Proportional share of vehicle type i
a,b,c	=	coefficients for variables
α	=	constant

The coefficients (α, a, b, c and d) of identified variables were obtained to propose the PCU models for each subject vehicle types. The values of coefficients along with statistical t-values (in the parenthesis) are provided in Table 7.1. The coefficients are found to be significantly affecting the PCU values as the t- value for each variable including intercept is greater than the critical t- value (1.96) at 95% confidence level.

Table 7.1 Results of MLR analysis

PREDICTOR	Estimated coefficients for vehicle types				
	2w	3w	Bus	LCV	NMV
Intercept	0.21 (12.62)	0.66 (31.25)	5.29 (40.46)	0.91 (71.47)	0.40 (5.17)
Traffic volume	N/A	N/A	N/A	N/A	-0.0001 (5.51)
Roadway width	0.002 (3.06)	N/A	N/A	N/A	0.023 (3.44)
Side friction	N/A	-0.0002 (3.31)	-0.003 (2.95)	-0.0007 (4.68)	N/A
Proportional share	-0.06 (3.01)	-0.17 (2.08)	-8.61 (2.23)	N/A	N/A

**N/A- Not significant*

The validation of PCU models developed in the study was performed with the field data collected at Section III and Section IV in Warangal city. The field data such as traffic volume, side friction, roadway width and proportional share of the subject vehicle types are used as inputs. The predicted values of PCU at every 5 min interval based on MLR are compared with the dynamic PCUs of vehicle types. The validation charts were developed to match predicted and observed dynamic PCUs for different subject vehicle types. Figure 7.11 shows the PCU validation charts for vehicle types 2W, 3W, Bus and LCV respectively. It is evident that the predicted PCUs are well matched with observed PCUs as their p-value (Chi-square test) is more than 0.05 for all the vehicle categories. Further, the PCU values of vehicle types are analysed based on adaptive neuro-fuzzy inference system for optimizing the dynamic PCUs.

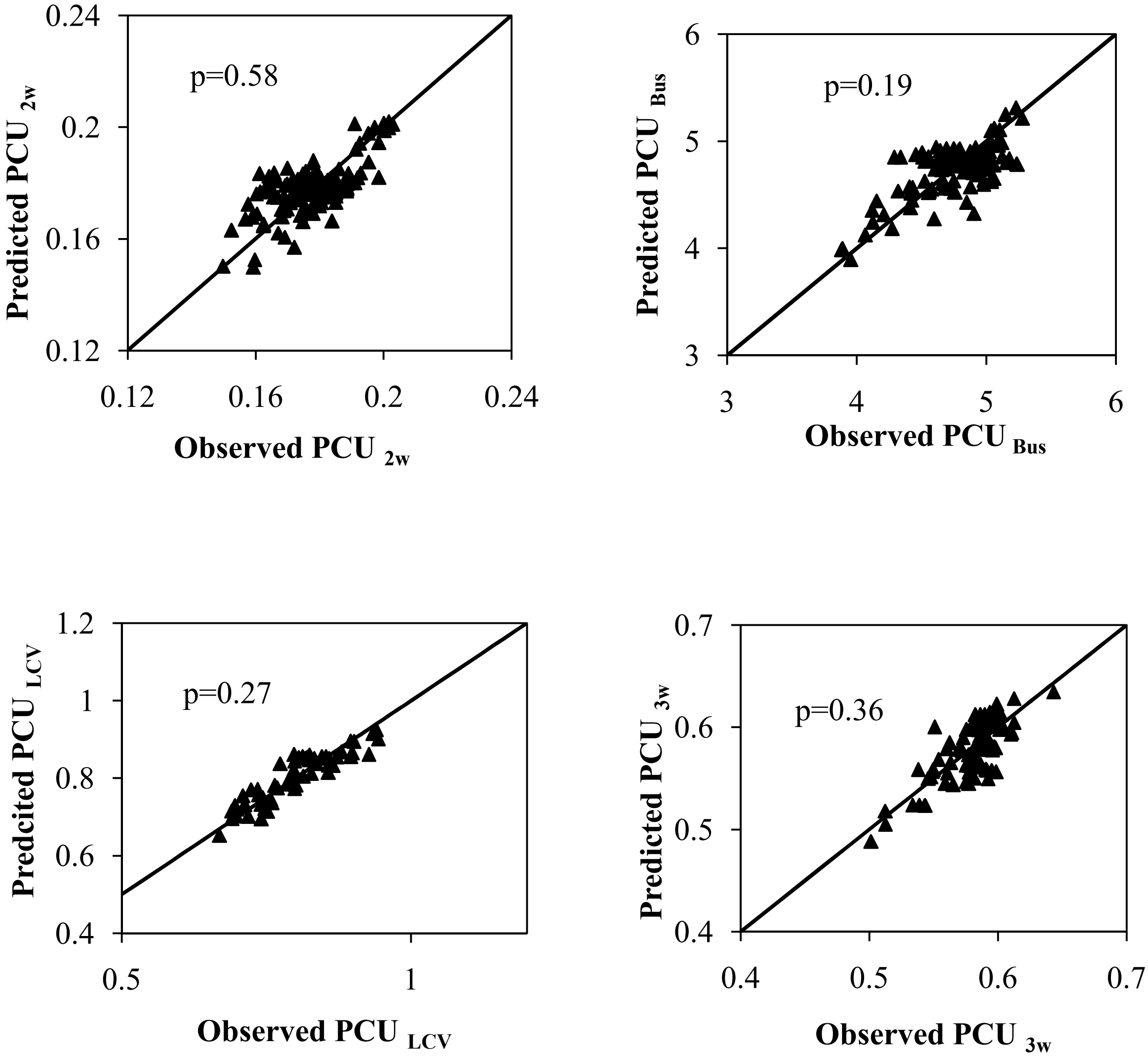


Figure 7.11 Validation charts for PCU for different vehicle types

7.4. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM

Adaptive Neuro-Fuzzy Inference System (ANFIS) is a combination of neural network and fuzzy logic which has the advantage of both approaches. The fuzzy system cannot learn from the data by itself but it can be easily understood. It uses linguistic variables (qualitative) rather than numeric terms. Whereas, neural networks can learn from data easily but it is difficult to interpret the data associated to it. Therefore, ANFIS works by the application of neural network learning methods to tune the parameters of a fuzzy inference system. Figure 7.12 shows the basic structure of ANFIS which consists of input, fuzzification, inference engine, rule base, de-fuzzification and output units. In the first step of fuzzy modeling, crisp input (Quantitative variable) is converted to fuzzy subsets by the use of membership functions.

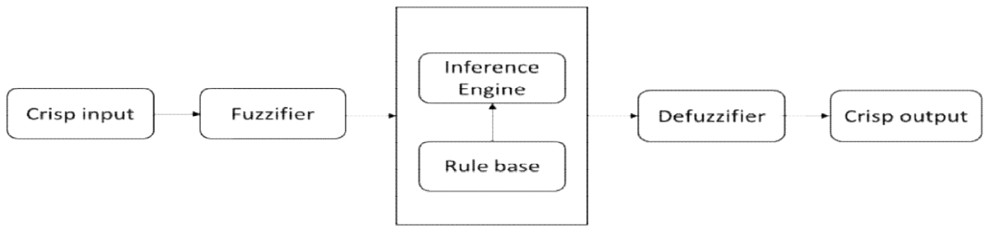


Figure 7.12 Basic structure of ANFIS

There are several membership functions in ANFIS modeling like Gaussian, triangular, trapezoidal and bell etc. These membership functions divide the input variable to several qualitative subsets by fixing the boundaries which is best suitable for the data type. Then, these fuzzy inputs are fed into the neural network block which consists of inference engine and rule base. Sugeno type inference method is used and number of rules is determined based on experience. To train the inference engine for proper selection of the rule base, back propagation method is used. After training, rules are fed into de-fuzzification unit. De-fuzzification is the last step of the fuzzy modeling. Further, the linguistic output is converted to crisp output by de-fuzzification method such as centroid method, weighted average etc.

7.4.1. DEVELOPMENT OF ANFIS MODEL

The ANFIS model involves fuzzification which generates initial fuzzy inference system by selecting the number of membership functions and type of membership functions for the input variables. The initial fuzzy model structure is illustrated in Figure 7.13. Gaussian membership function is adopted in the proposed fuzzy model and three rules are reated in the rule base based on the membership functions behaviour.

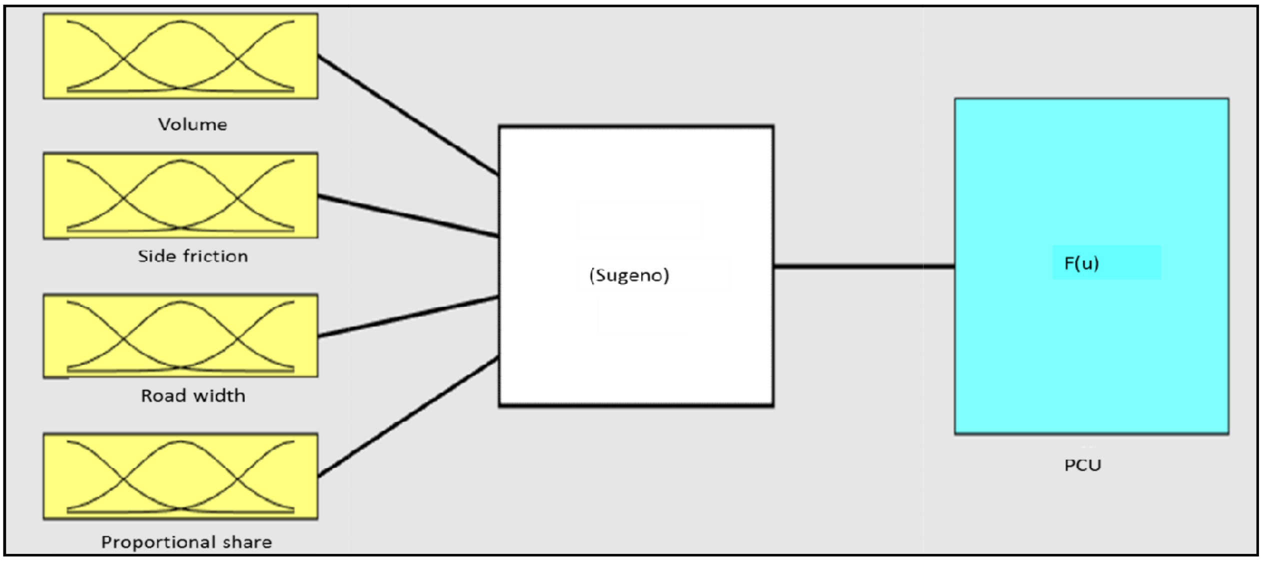


Figure 7.13 ANFIS model sturcture used in the study

The ANFIS model is constructed to find PCU of subject vehicle types by selecting traffic volume (Q), side friction, proportional share of own vehcile type and roadway width as influencing variables. For each input variables, three mebership functions are adopted and labelled as low, medium, high for the variables traffic voulme, side friction, proportional share. Also, as narrow, medium and wide for roadway width. Futher, the rules are created based on the membership functions behaviour and the inference model is trianed at different epoches until the minimal RMSE value occurs for each vehicle category. The output is extracted to a separate file and is compared with the observed PCU values. The comparison of the predicted ANFIS based PCU and observed PCU is shown in Figure 7.14 for 2W and Bus vehicle types.

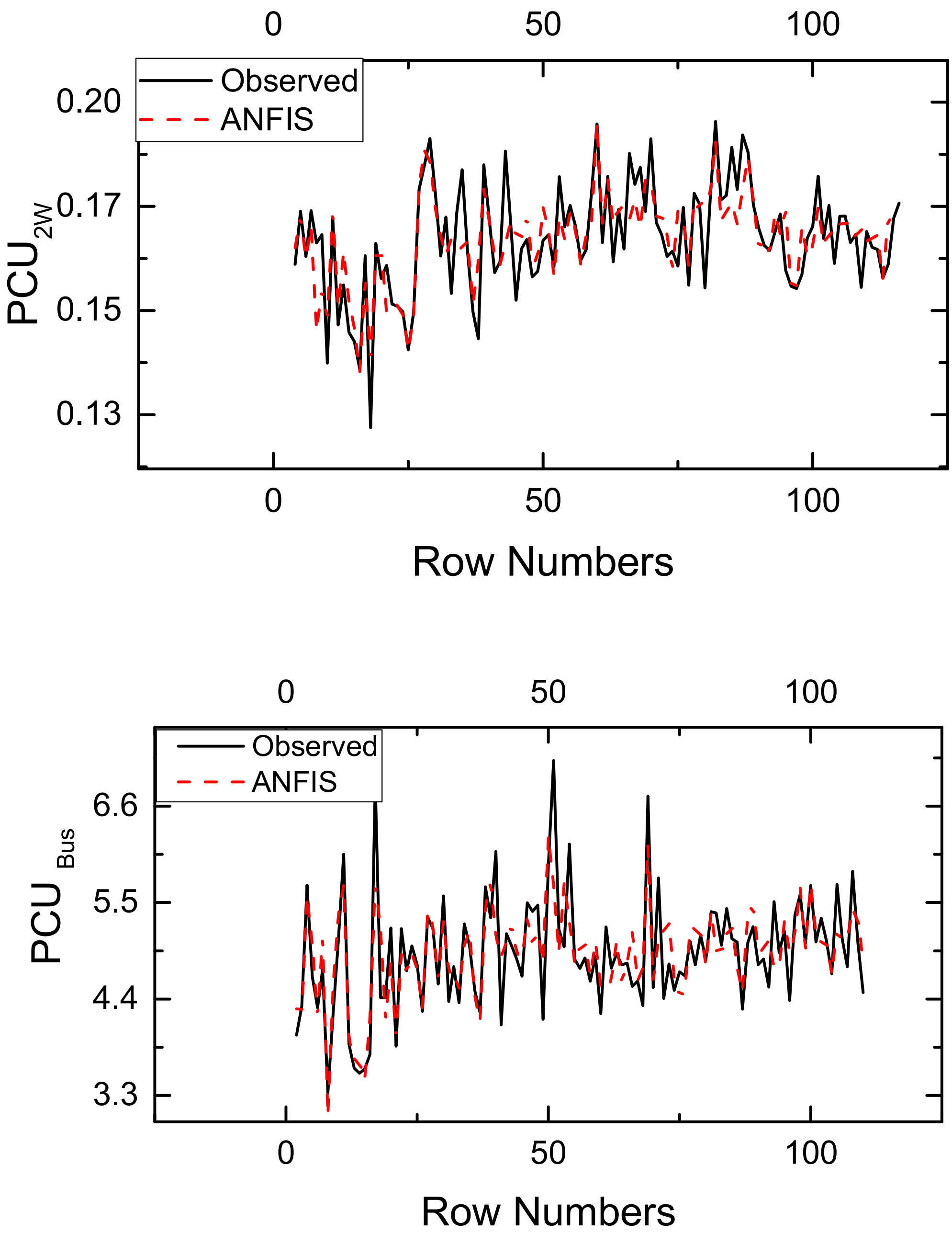


Figure 7.14 PCU values from ANFIS model and field

It is observed that the variation of PCU values of trained data of ANFIS model is precisely matching with the variation of PCU values of field data for both vehicle categories. The model can be used for predicting the PCU values of vehicle types by using the membership functions obtained from the model.

7.5. VERIFICATION OF MODELS

The verification of models is preformed based on finding the match between PCUs obtained from each model based on Root Mean Square Error (RMSE) values which is shown in Equation (7.3).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i - O_i)^2} \qquad (7.3)$$

where, E_i is the predicted value from the model, O_i is the observed value and N is the number of samples. The RMSE value is obtained between Model PCUs from both MLR and ANFIS methods and field observed value of PCUs. The comparison of RMSE is shown in Table 7.2. It is clear from the comparison that RMSE values of MLR model are low compared to ANFIS values.

Table 7.2 Comparison of MLR and ANFIS models

Vehicle Type	RMSE				
	2W	3W	Bus	LCV	NMV
MLR	0.13	0.03	0.05	0.10	0.12
ANFIS	0.08	0.01	0.03	0.06	0.06

The comparison of PCUs of vehicle types between observed, MLR and ANFIS at various traffic volume ranges for vehicle types 2W, Bus, 3w and LCV are shown in Figure 7.15, 7.16, 7.17 and 7.18 respectively. The traffic volume is divided into three different levels such as Low (<1000 veh/hr), Medium (1000-3000 veh/hr) and High (>3000 veh/hr). It is observed that at different levels of traffic volume MLR model is either over predicting or under predicting whereas ANFIS is predicting PCU values nearer to observed PCU pattern at any volume range. From the results the ANFIS model yielded the better performance than the MLR model which clearly states that ANFIS model can be used to predict PCU of vehicle types on multilane urbane roads under mixed traffic conditions at varying roadway width.

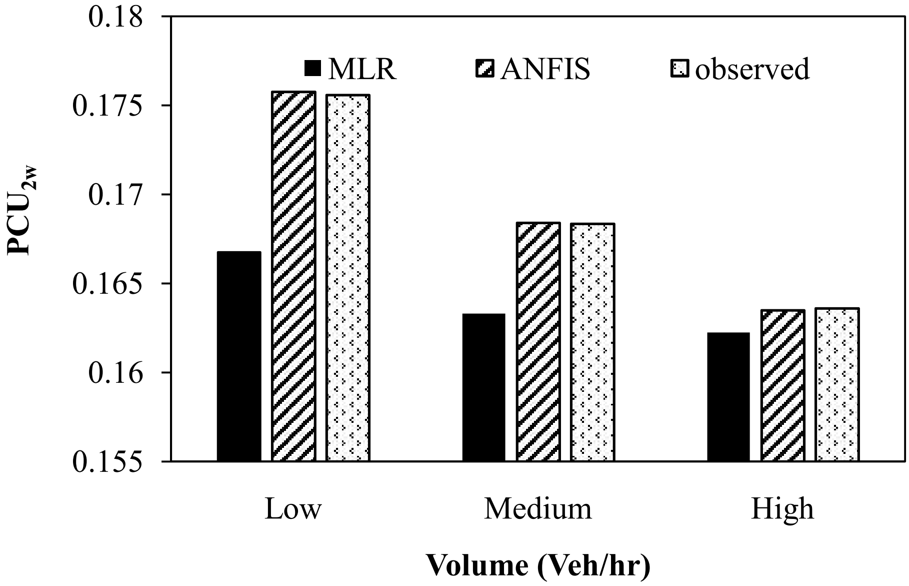


Figure 7.15 Comparison of PCUs of 2W at different volume levels

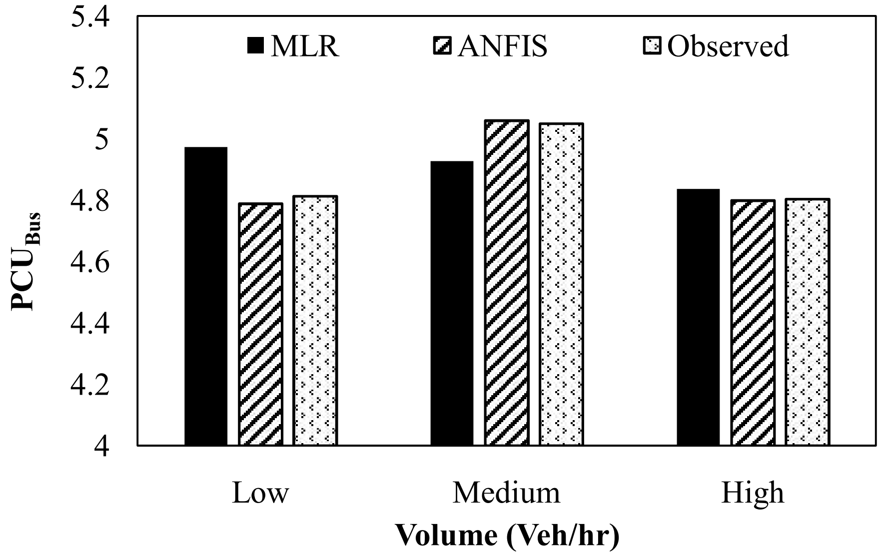


Figure 7.16 Comparison of PCUs of Bus at different volume levels

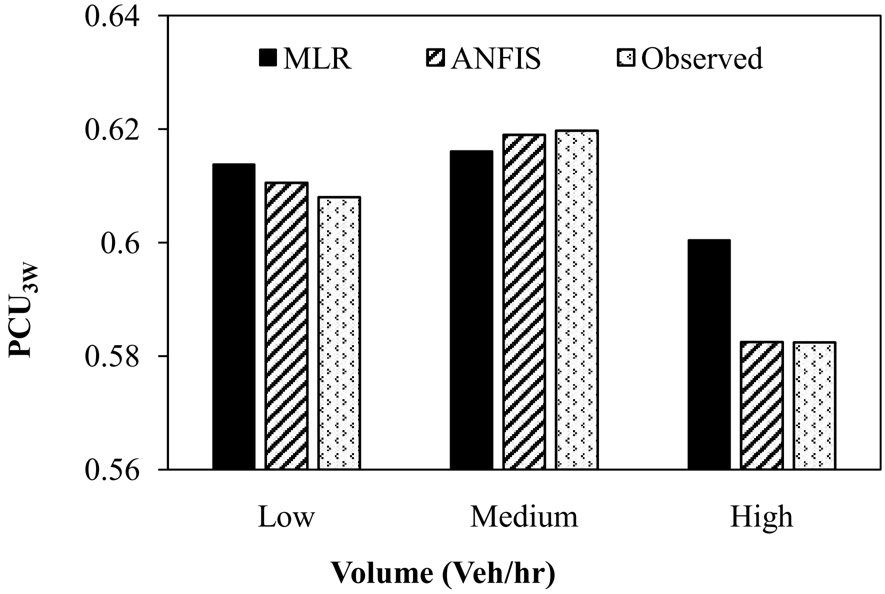


Figure 7.17 Comparison of PCUs of 3W at different volume levels

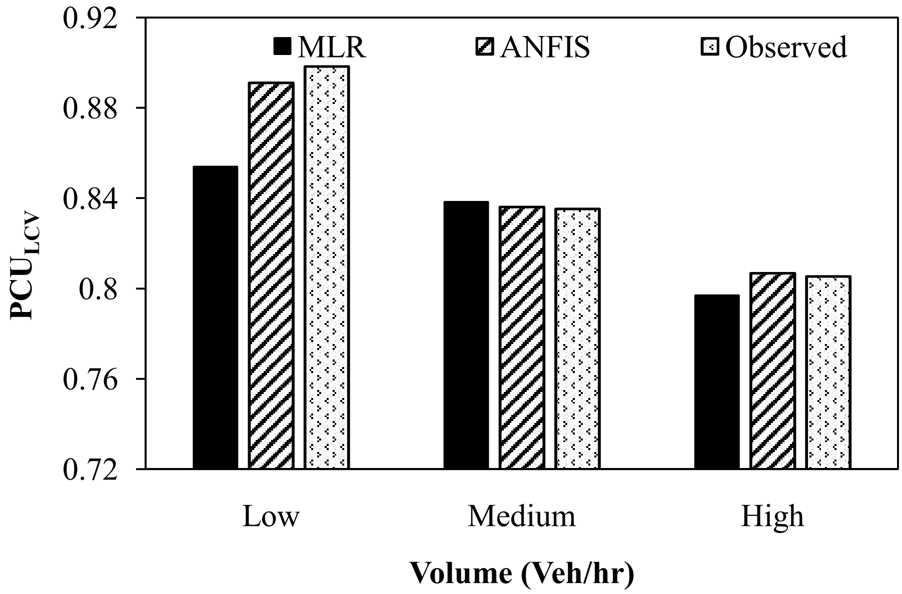


Figure 7.18 Comparison of PCUs of LCV at different volume levels

7.6. SUMMARY

This chapter presented the analysis of estimated PCUs under the influence of variables such as side friction, road width, proportional share and vehicular volume. Relationship between PCU of each vehicle types with traffic volume, side friction, proportional share and roadway width have been established. It is observed that increase in vehicular volume results in reduction of PCU of vehicle type for smaller size of vehicles whereas it has no effect on the bigger size of the vehicles. Side friction has minimal effect at lower levels on PCU but it has significant effect at medium and higher levels of side friction on PCU of all vehicle types. As the roadway width increases the PCU tends to be increasing and with increase in the proportional share of subject vehicle type PCU decreases for 2W and Bus and it has no effect on other types of vehicles. MLR and ANFIS models are developed to estimate the PCU of vehicle types and compared to test the performance of the best PCU model. It is observed that predicted PCU values from ANFIS are nearer to the dynamic PCU values that confirms the adoption of the ANFIS model for PCU estimation.

Chapter 8
ANALYSIS OF ROADWAY CAPACITY

8.1 GENERAL

Urban arterials exhibit deteriorated capacity and poor level of service in many developing countries in recent times. The present chapter deals with the estimation of capacity and its analysis based on various factors affecting it on urban roads**.** Capacity is estimated based on the speed flow relationship using field data collected from different roadway sections. The study applies statistical methods to obtain the adjustment factors for the estimation of appropriate capacity values for urban roads under varying roadway and traffic characteristics.

8.2. SPEED-VOLUME RELATIONSHIP AND CAPACITY

The speed-flow relationship is a key aspect for analyzing the traffic flow behavior. Traffic flow data collected on field sections are aggregated at 5 min interval for the speed-volume analysis. The classified volume count is converted to Passenger Car Equivalent Units (PCU) by using Dynamic PCU method. On urban roads, variety of the vehicles plays on the road with variation in the speeds from very low to high. Therefore, the space mean speed is estimated as weighted mean speed for the present analysis. The following expression as show in Equation 8.1 is used for estimating mean stream speed

$$V_m = \frac{\sum_{i=1}^{k} n_i v_i}{\sum_{i=1}^{k} n_i} \qquad (8.1)$$

where, V_m= Mean stream speed (Km/h)

k = Number of vehicle categories in the stream

V_i= Speed of each vehicle category 'i' in the stream

n_i= Number of vehicles of the category 'i'

The speed-flow relationship is developed for each section based on mean stream speeds and converted traffic volumes. Several popular models are available to fit speed-flow curve and estimate road capacity for the uninterrupted traffic flow stream (Greenshields 1934, Greenberg 1959; Underwood 1960; Edie 1961; Ceder and May 1976; Persaud and Hurdle 1988; McShane and Roess 1990; Nielsen and Jørgensen, 2008). In the present study the observed traffic flow data is failed to represent any of these popular stream models. However, these models are found to be suitable to fit whole traffic flow relationships under homogeneous traffic conditions. According to Ramanayya (1988), capacity specifications developed by the western countries are applicable only for homogeneous conditions and cannot be directly adopted for countries with heterogeneous traffic conditions. Therefore, the traffic flow data collected at field sections is used to develop speed-volume relationship, to understand the behavior of traffic flow and to determine capacity of the different sections. The capacity of sections is determined as the maximum volume which was observed to be sustained at the average stream speed measured at a breakdown point. The average stream speed corresponding to the maximum volume termed as critical speed is determined for each road sections using speed-flow diagram.

The speed volume diagram for six different multilane divided urban road sections is developed and capacity values are determined. Figure 8.1 presents the speed-volume diagram for roadway Section III.

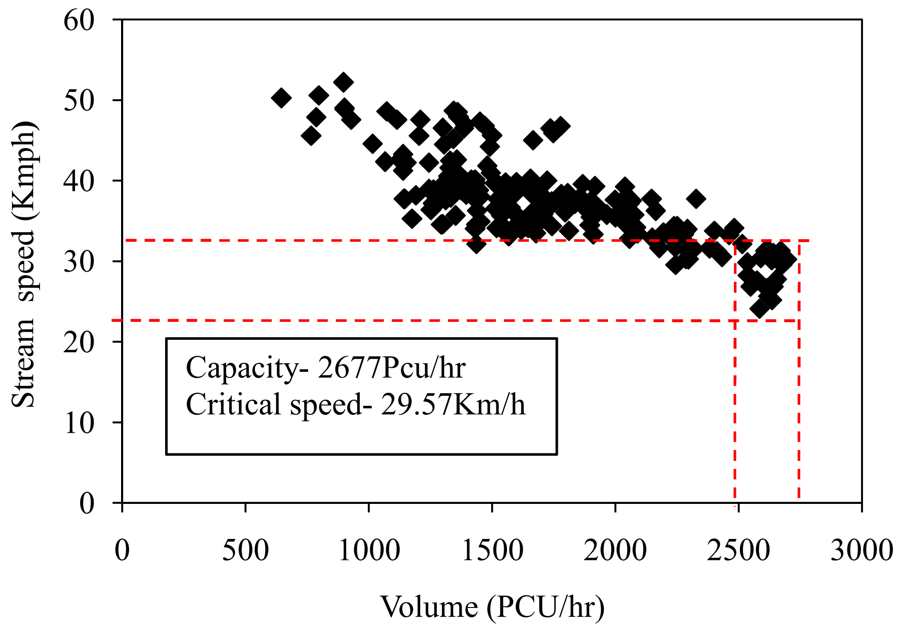


Figure 8.1 Speed –volume diagram for Section III

It is observed that the mean stream speeds at lower volume are reasonable good and reduce as volume increases from medium to high levels. Capacity for the study Section III is determined as 2677PCU/h from speed-flow diagram. Also, critical speed is taken as 29.57Km/h at maximum volume observed on speed volume diagram.

Section I experiences consistent drop in the average speed due prevailing of higher side friction activity compared to other study sections that include pedestrian movement and on-street parking as major events on either side of the roadway. The capacity of the study section is estimated as 2179PCU/hr at critical speed of 25.22 Km/h. Figure 8.2 shows the speed-flow diagram at study Section I. Figure 8.2 reflects a clear demarcation between congested and uncongested speeds and shows high variations in the speeds at breakdown condition.

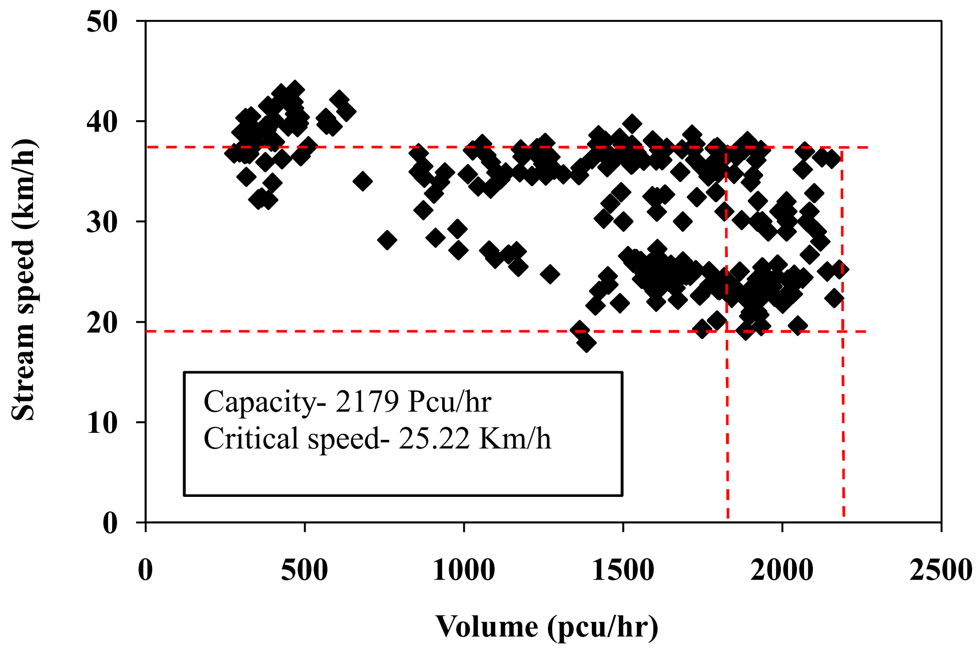


Figure 8.2 Speed –volume relation for section I

The capacity of Section II is determined as 2507 PCU/hr from speed-volume diagram. The critical speed at the level of maximum volume is found to be 27.53 Km/hr. Section II consists of lower to medium level of side friction. Hence, the range of average stream speed at maximum flow level (breakdown range of volume) is less wide as compared to Section I. The speed flow diagram used to determine capacity is shown in Figure 8.3.

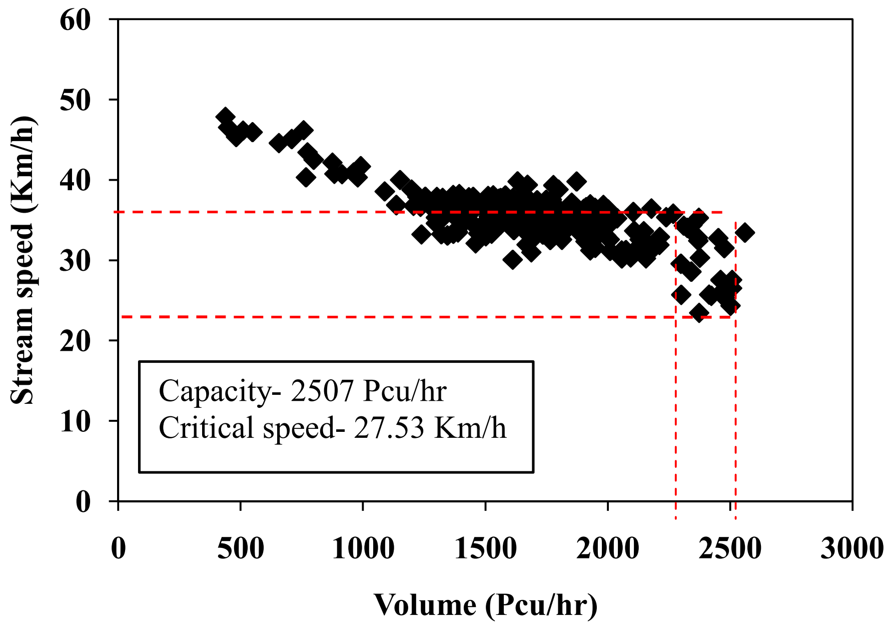


Figure 8.3 Speed –volume relation for Section II

Section IV has very high side friction level with on-street parking found as major event on this section. The capacity of the study section is determined as 2067Pcu/hr from speed-flow diagram. The critical speed at the level of maximum volume is found to be 28.9Km/hr. Figure 8.4 shows the speed-volume diagram for Section IV.

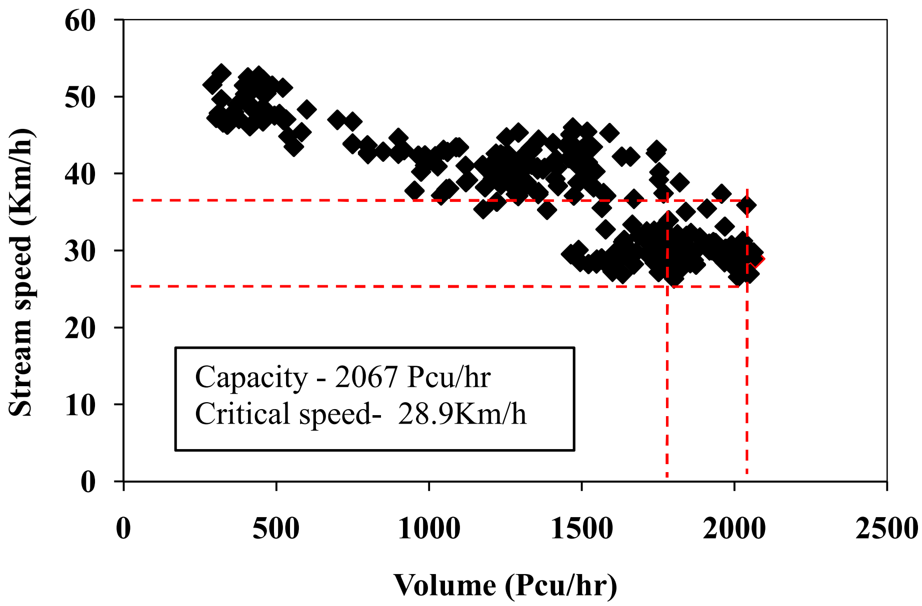


Figure 8.4 Speed –volume relation for section IV

The side friction observed at this section also falls under the category of very high levels which might have causing reduction in capacity of the roadway. However, variation of average speed at maximum volume level is only 8.4 km/h which is comparatively lesser than the variation found on Section I.

Section V consists of high level of side friction with on-street parking as the major concern. The capacity of Section V is determined as 3217 PCU/hr from speed-volume diagram. The critical speed at the level of maximum volume is found to be 28.56 Km/hr. The range of average stream speed at maximum flow level (breakdown range of volume) is less wide as compared to Section IV. The speed flow diagram used to determine capacity is shown in Figure 8.5.

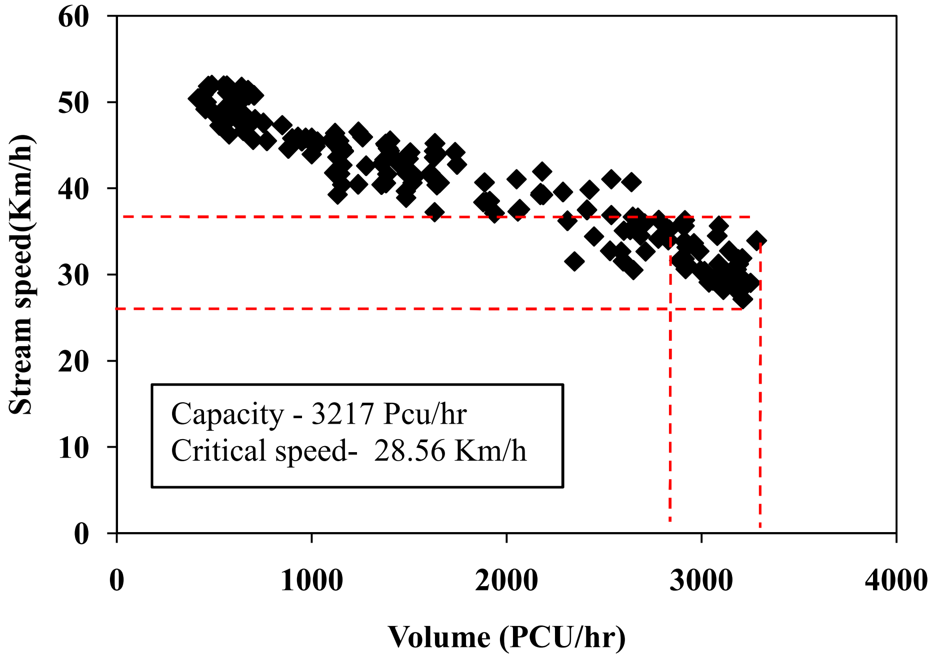


Figure 8.5 speed –volume relation for section V

Similarly, the speed-flow relationship is developed for study Section VI. Section VI is a six lane semi-urban road with negligible side friction activity. It is observed that the study section has not reached the stage of congestion and also no evidence of free-speed on it. Therefore, the capacity of the study section is not estimated as there were no particular boundaries found either for speed or for volume.

8.3. EFFECT OF SIDE FRICTION ON CAPACITY

The capacity value obtained for each section is compared with capacities suggested in Indian Highway Capacity Manual, INDO-HCM (2017) under specified traffic and roadway conditions. The base capacity value suggested in the INDO-HCM (2017) is 2700 PCU/hr for a four lane divided urban road section without any side friction. The capacity of each study section along with level of side friction level and side friction range is given in Table 8.1.

Table 8.1 capacity at study sections at different side friction level

Section	**Side friction level**	**Side friction range (Events/hr)**	**Capacity (Pcu/hr)**
I	High	1000-2000	2179
II	Medium	500-1000	2507
III	Low	<500	2677
IV	Very high	>2000	2067
V	High	1000-2000	3217

It is observed that there is higher reduction in capacity of the study sections observed at higher side friction range for four lane sections when compared to lower side friction range. Also, a very high level side friction scenario results in larger reduction in capacity from speed-flow diagram for six-lane sections. Figure 8.6 shows the variation of percentage reduction in capacity of the study sections with level of side friction. Significant reduction is observed in capacity of study sections with increase in side friction events. It is observed that the reduction in capacity for four-lane divided urban roads varied from 2 to 25% approximately and for six-lane divided urban roads the reduction in capacity varied from 18 to 52%.

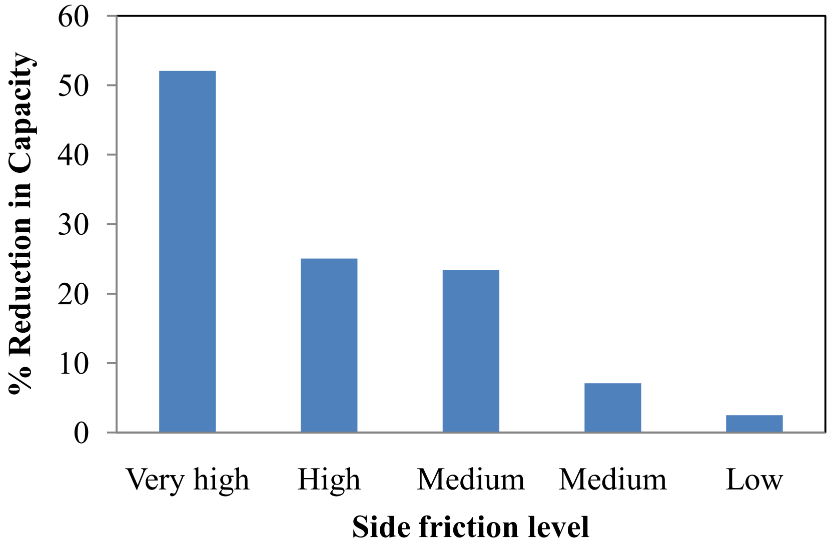


Figure 8.6 Estimated reductions in capacity values with side friction level

Also, the variation of side friction with the percentage reduction capacity is plotted and is shown in Figure 8.7. It is observed that the percentage reduction in the capacity is increasing with side friction range at study sections.

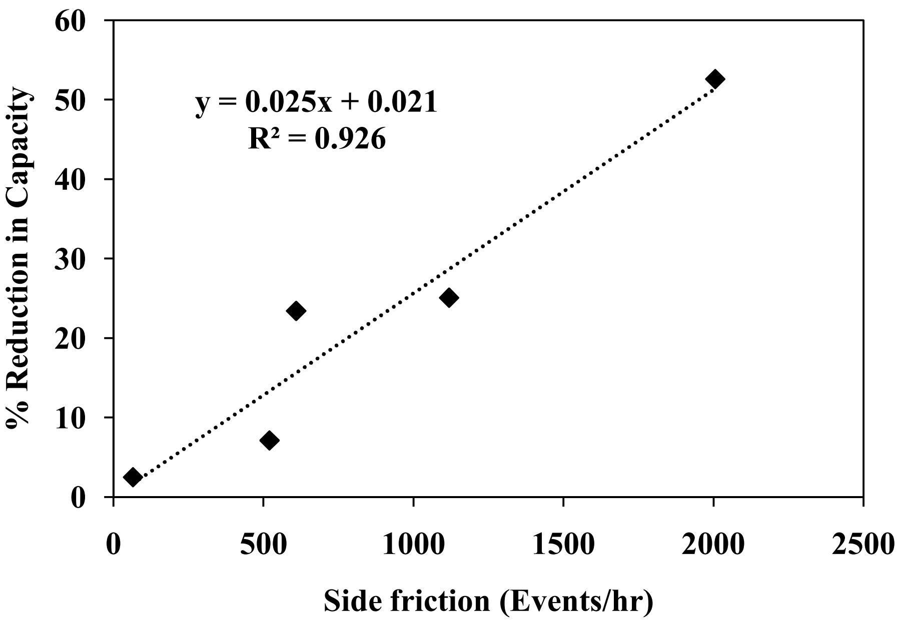


Figure 8.7 Percentage reductions in capacity with side friction

Average reduction in capacity of multilane divided urban road is found to be 22% with the effect of side friction. And it is observed that for every 2% increase in side friction events there is 3.2% reduction in the capacity of study sections. Hence, the side friction has very adverse effect on capacity which may deteriorate the level of service offered for a roadway facility.

8.4. CAPACITY MODEL

Present study evaluated the influence of several factors on the capacity of divided multilane urban roads. Field data collected at various roadway sections is used for further analysis. A method developed for estimating capacity is proposed and evaluated based on field data obtained from section under traffic flow and roadway characteristics. The process for developing capacity model by incorporating the effects of several factors identified in the present study is explained in detailed manner. The parameters and adjustment factors for developing capacity model are determined based on traffic and roadway characteristic.

8.4.1. ADJUSTMENT FACTOR FOR CARRIAGEWAY WIDTH

Width of carriageway is the one among the significant factors that affecting capacity of roadway facility. The adjustment factors for varying carriageway width are estimated based on the capacity determined for road sections. The capacity determined in present study is found to be increased significantly with the increase in carriageway width. A relationship is suggested to estimate the capacity by considering carriageway width alone as a variable is given in Equation 8.2.

$$C_1 = 308 \times CW, \text{ (if } CW >= 7.0\text{m)} \tag{8.2}$$

Where, C_1= Capacity (Pcu/hr) obtained from field data at study sections

CW = Carriageway width of the road (m).

Further the adjustment factors are estimated based on field capacity and base capacity values using the relationship suggested as Equation 8.3.

$$f_{cw} = \frac{C_{1,i}}{C_0} \tag{8.3}$$

Where, f_{cw}= Adjustment factor for carriageway width,

$C_{1,i}$= Capacity value from field data at carriageway width i,

C_0= Capacity value at 7m carriageway width

C_0 is used as 2700Pcu/hr as base capacity as specified in INDO-HCM (2017). Table 8.2 provides proposed adjustment factors values for different carriageway widths.

Table 8.2 Adjustment factors for carriageway width

Carriageway width (m)	7.0	8.5	10.5	14.0
Adjustment factor	1.0	1.2	1.5	2.0

8.4.2. ADJUSTMENT FACTOR FOR SIDE FRICTION

The relationship between capacity and side friction is very clearly described the percentage reduction in capacity with the increase in side friction is linear. It has been observed that the capacity of the urban road sections decreasing constantly with increase in side friction events. However, no significant change in capacity was observed at road section with lower side friction level. The side friction at medium to higher level showed higher reduction in capacity values. Therefore, capacity value determined at different sections is used to determine the adjustment factors of side friction. A relationship is proposed to estimate capacity using side friction as independent variable only. The expression to estimate capacity is given as Equation 8.4. Also, adjustment factors for side friction affecting base capacity are found from the Equation 8.5.

$$C_2 = 3117 - (0.253 \times SF) \quad (8.4)$$

Where, C_2= Capacity (Pcu/hr) obtained at study sections

SF = side friction (Events/hr)

$$f_{sf} = \frac{C_{2,i}}{C_0} \quad (8.5)$$

Where, f_{sf}= Adjustment factor for side friction,

$C_{2,i}$= Capacity value obtained at study section 'i;

C_0= Base capacity value with no side friction activity

C_0 is the base capacity value for divided multilane road section having 7m carriageway width with no side friction level. Base capacity value as 2700Pcu/hr as suggested in INDO-HCM (2017) is used for finding adjustment factors. Table 8.3 provides adjustment factors for side friction affecting base capacity. From Table 8.3, a decrease in adjustment factors is observed with the increase in side friction level.

Table 8.3 Adjustment factors at different side friction range

Side friction range (events/hr)	0-500	500-1000	1000-2000	2000-4000
Adjustment factor	1.0	0.9	0.8	0.7

The adjustment factors proposed for carriageway width and side friction are used for determining capacity of divided multi-lane urban roads. These adjustment factors will be used to adjust the base capacity of multilane divided road under mixed traffic conditions. A general relation that incorporating adjustment factors to find capacity is proposed by Equation (8.6). The base capacity of multi-lane divided urban road is adopted from Indo-HCM (2017) as 2700 Pcu/hr.

$$C = C_0 \times f_{sf} \times f_{cw} \tag{8.6}$$

Where, C = Capacity of the road section (PCU/hr)

C_0= Base capacity (Pcu/hr)

f_{sf}= Adjustment factor for side friction

f_{cw}= Adjustment factor for carriageway width

Further, the model is validated by using field data collected on two sections such as Section VII and Section VIII. Section VII and VIII are the mid-block sections of four lane divided urban roads. Section VII has low side friction and Section VIII has medium side friction activities on the roads. The speed and volume diagram established for the Section VII and VIII is shown in Figures 8.10 and 8.11 respectively.

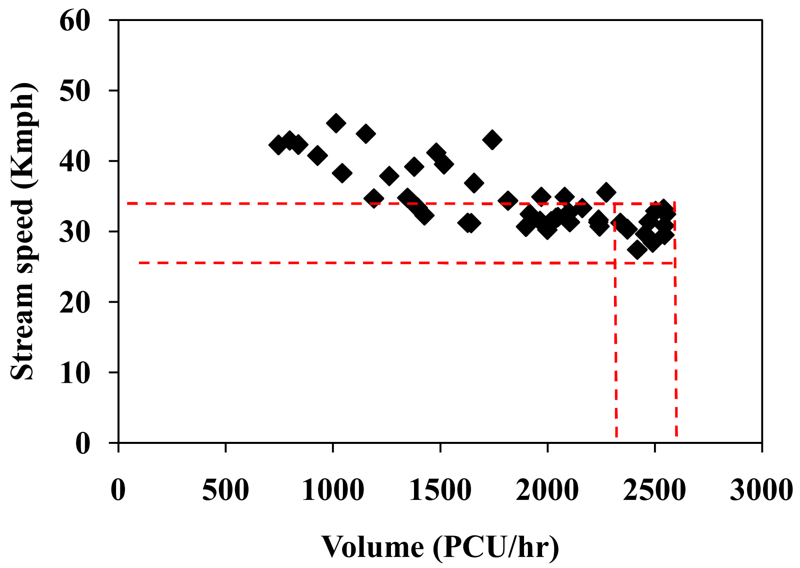


Figure 8.10 Speed –volume relation for section VII

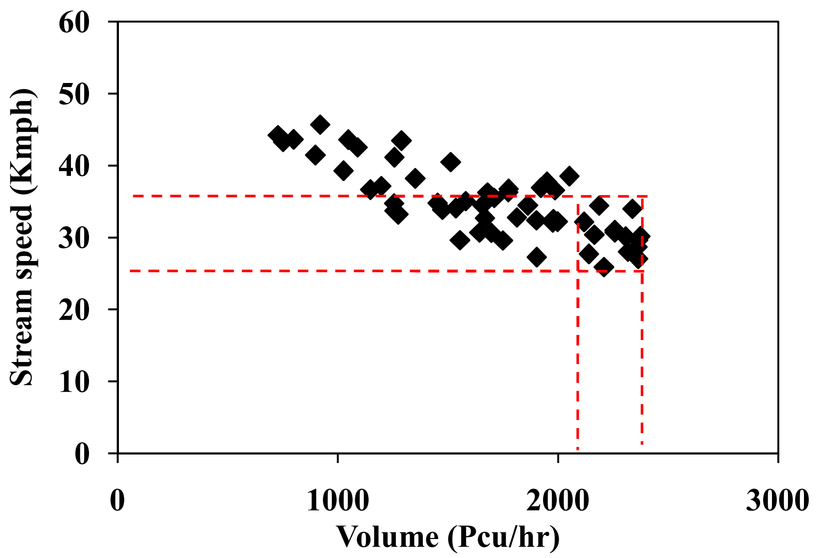


Figure 8.11 Speed –volume relation for section VIII

The capacity values of Section VII as determined from speed-volume diagram is 2545 PCU/hr and similarly for Section VIII is 2363 PCU/hr. For validation, capacity of selected sections are estimated using Equation 8.6 by incorporating adjustment factors of carriageway width and side friction corresponding to Sections VII and VIII. The adjustment factor for side friction on Section VII is used as 1.0 as it applicable to low side friction level whereas this value is used as 0.9 under medium side friction level for Section VIII. From the Equation (8.6), the calculated capacity value for Section VII is 2700 PCU/hr and for section VII is 2430 PCU/hr. Table 8.4 shows the details of observed capacity and predicted capacity of the study sections.

Table 8.4 Details of observed and predicted capacity of study sections

Section	**Observed Capacity (PCU/hr)**	**Predicted Capacity (PCU/hr)**	**Percentage Error**
VII	2545	2700	6.09
VIII	2363	2430	2.84
Mean	2454	2565	4.46

From the results it is observed that the average percentage error in predicting the capacity value is approximately 5% which is quite acceptable. Statistical t-test is performed to compare the mean capacity values obtained from both field sections. The t-stat value obtained from the t-test is less than the critical t-stat value which concludes the null hypothesis is accepted as the difference is found to be insignificant at 95% confidence level. Table 8.5 shows t-test for comparison of means of capacity of study section VII and section VIII.

Table 8.5 Results of t-test for comparing capacity values of section VII and section VIII

	Observed capacity	Predicted capacity
Mean	2454	2565
Variance	16562	36450
t-Stat	-2.52273	
t-critical	6.313752	
Remarks	Difference is insignificant	

It is concluded that the developed model is predicting the capacity values of the multilane divided urban roads correctly which confirms the adoption of the model. The developed model provides direct and simple determination of multi lane divided urban road capacity by incorporating one of the major influencing factors i.e. side friction.

8.5. SUMMARY

The present chapter demonstrates a methodology for estimating actual capacity of multilane divided urban roads by suggesting adjustment factors of side friction and roadway width. Speed-flow curves were plotted for all the study sections and capacity is estimated. The relationship between side friction and capacity is established and it is found that average reduction in capacity of multilane divided urban road is found to be 22% with the effect of side friction. And it is observed that for every 2% increase in side friction events there is 3.2% reduction in the capacity of study sections. Adjustment factors for side friction and roadway width are derived based on their relationship with capacity. Further, capacity model is developed for the multilane urban mid-block roads incorporating the adjustment factors for side friction and roadway width and is validated with two other study sections. The proposed capacity model proposed in the study is simple and provides a good estimate of capacity of urban road under prevailing roadway and side-friction conditions**.**

Chapter 9

SUMMARY & CONCLUSIONS

9.1. SUMMARY

Traffic flow data collected at different sections of four-lane and six-lane divided urban road are used to analyse the traffic flow characteristics. Various factors that present in the field are identified and the influence of each factor on traffic flow behavior is analyzed. Roadside friction identified as one of the major factors present on urban roads are quantified based on the weights assigned for a particular side friction activity. The present study develops prediction model to determine the average speed of vehicles based on side friction and traffic flow conditions. Influence of parameters such as traffic volume, side friction level, carriageway and traffic composition are examined for estimating PCU of vehicle types identified in the present study. Further, field traffic flow data is used to develop speed-flow diagrams to understand traffic flow behavior and estimate capacity. Capacity was estimated for all sections of the roads by observing the breakdown traffic conditions. The variables side friction and the carriageway width showed close correlation with capacity therefore adjustment factors are proposed find actual capacity. A capacity model is suggested to find actual capacity could be found by using adjustment factors as inputs for side friction level and carriageway width. Summarization of present study is shown in this chapter.

9.2. CONCLUSIONS

The following conclusions are drawn from the present study.

- Present study evaluates the weighing factors for various road side activities based on field data. Pedestrian movement and on-street parking are found to be the most significant side friction elements affecting stream speed of vehicular traffic stream as the relative weights estimated for these road side activities are comparatively higher.
- The side friction estimated on different roads is classified as low to very high levels. Low level indicates the side friction events less than 500events/hr, medium level between 500-1000events/hr, high level between 1000-2000events/hr and very high level is considered to be higher than 2000events/hr. At the higher side friction level, maximum reduction in the average stream speed of vehicles is found as 51%.

- Study develops speed model for urban roads having mixed type of side friction. The average speed on each study section predicted by proposed model is 37.21 Km/h, 35.51 Km/h, 32.21 Km/h and 25.55 Km/h under low, medium, high and very high side friction levels respectively.
- Dynamic PCU estimated for vehicle types are observed to be varying with different factors affecting it. The PCU of small sized vehicle type such as 2W showed a decreasing trend as traffic volume increased along with increase in proportion of its own vehicle type. It is due to the fact that the smaller sized vehicles easily mobilise even under higher levels of traffic volume and hence, it results in lower relative speeds and leads to decreased PCU values. However, PCU values of large vehicle types such as Bus and LCV are not significantly changed with traffic volume as observed at urban road sections.
- A soft computing method, Adaptive Neuro Fuzzy Inference System (ANFIS) is used for predicting and optimising PCUs of vehicle types by using field input variables. The PCU value of vehicle types obtained from ANFIS model are closely resemble with the field PCUs. The PCUs obtained from ANFIS model are better reliable than the PCUs predicted by conventional multiple linear regression (MLR) model as formulated based on lower RMSE values.
- Present study determined capacity of selected multilane roadway sections based on speed-volume diagram.The capacity of roadway sections as determined under various levels of side friction are given below.

Section	Side friction level	Side friction Range (Events/hr)	Capacity (PCU/hr)
I	High	1000-2000	2179
II	Medium	500-1000	2507
III	Low	<500	2677
IV	Very high	>2000	2067
V	High	1000-2000	3217

- It is clearly observed that the capacity values estimated for different sections are found to be influenced by the change in side friction levels. A maximum reduction in the value of capacity is found as 52%. This reduction in capacity is mainly found due to higher presence of parked vehicles and as well as the pedestrian activities along the roadway section.
- It is also revealed that at every 2% increase in the side friction amount causes 3.2% reduction in the capacity value. Hence, it may be concluded that the capacity of multilane divided urban road is affected significantly with a small amount of increase in the side friction.
- The present study estimated adjustment factors for two variables such as side friction and carriageway width for determining actual capacity of multilane divided urban roads under heterogeneous traffic conditions.

9.3. CONTRIBUTIONS OF THE STUDY

The present study signifies the importance of side friction factor along with other influencing factors for determining capacity of multilane divided urban roads. The side friction is classified in lower to higher levels with their ranges for easy estimation of average speed of traffic stream. The study proposed PCU values of vehicle types for typical multilane divided urban roads mid-block section by considering various roadway factors. Finally, study provides a method for determining actual capacity based on influence of side friction and carriageway width.

9.4. LIMITATIONS

- The present study did not consider the lane wise analysis of traffic measurements o examine side friction influence.
- The urban road length, network size and City size factors are not considered for analysis of capacity.
- The study does not confirm the evidence of free speed of vehicles on roadway sections due to unavailability of traffic flow data under free-flow condition.

9.5. FUTURE RESEARCH

- The detailed investigation on other factors may be considered as side friction by including more sections predominantly with such road side activities.
- Simulation analysis may be performed by generating more data for different levels of traffic flows by incorporating side friction on roadway
- The effect of geometric design elements may also be considered in modeling capacity for better planning of urban roads with side frictions.

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